A Multiple Regression Model to Predict Zebra Mussel Population Growth

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Summary

Zebra mussels (*Dreissena polymorpha*) are an invasive mollusk accidentally introduced to the United States by transatlantic ships during the mid-1980s. Because the mussels have few natural predators and adapt quickly to new environments, they have spread quickly from the Great Lakes into many connected waterways. Although the mussel is hardy, sometimes little or no growth is observed in lakes to which it has been introduced; extensive research indicates that the chemical concentrations in these bodies of water may be unsuitable for the mussels.

To quantify the relationship between chemical contents and mussel population growth, we first use the logistic equation,

$$\frac{dy}{dt} = ry\left(1 - \frac{y}{K}\right),$$

to model *Dreissena* population as a function of time. After modeling growth rates under a variety of conditions, we used multiple regression to determine which chemicals affect this growth rate. An extensive literature search supported our findings that population growth is linearly dependent on two primary factors: calcium concentration and pH. After further refining our model using the second set of data from Lake A, we obtained the regression equation

$$\text{maximum growth rate} = 2338\,[\mathrm{Ca}^{2+}] + 39202\,\mathrm{pH} - 334089,$$

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where the maximum growth rate is in juveniles settling per day, and $[Ca^{2+}]$ is in mg/L. Using this model, we predict that lakes B and C cannot support *Dreissena* population. Because the levels of calcium in Lake B are close to those required to support a *Dreissena* population, however, we advise the community near Lake B to use de-icing agents that do not contain calcium.

Environmental Factors Affecting *Dreissena*

A large body of research links environmental factors such as temperature, pH, calcium ion concentration, and alkalinity to the success or failure of zebra mussel populations. The two factors repeatedly most closely associated with survival are calcium concentration and pH. In a survey of 278 lakes, for example, Ramcharan et al. [1992] found no populated lakes with pH below 7.3 or Ca content below 28.3 mg/L. Recent studies have lowered the minimum Ca concentration to 15 mg/L for adults and 12 mg/L for larvae [McMahon 1996]. The upper bound for pH is somewhere near 9.4 [McMahon 1996]. The optimum conditions for growth are a pH of 8.4 and 34 mg/L of Ca [McMahon 1996].

Other requirements for survival include alkalinity, which must be kept above 50 mg/L [Balog et al. 1995], and dissolved oxygen, which must be above 0.82 ppm (approximately 10% of saturation) [Johnson and McMahon 1996]. *Dreissena* also cannot survive in magnesium-deficient water; they require a minimum concentration of 0.03 mM for a low-density population [Dietz and Byrne 1994]. Sulfate (SO_4) is also required in small amounts for survival [Dietz and Byrne 1999].

Zebra mussels can survive in an amazingly wide range of temperatures, but Van der Velde et al. [1996] determined that exposure to 34°C is lethal within 114 minutes and that any temperature above 25°C inhibits movement and feeding. Some individuals can tolerate short-term sub-freezing air temperatures [Paukstis et al. 1996].

Although not used by the mussels themselves, phosphorus and nitrogen are essential for freshwater phytoplankton survival, and phytoplankton are the main source of food for *Dreissena*. Densities of mussel populations are negatively related to both phosphates and nitrates; but iron, chlorine, and sodium have no relationship to the existence or density of populations [Ramcharan et al. 1992]. Chlorophyll content measures the density of phytoplankton and thus decreases drastically after the establishment of a zebra mussel colony [Miller and Haynes 1997].

Surprisingly, food availability is not an important factor once a zebra mussel is established. In one study, *Dreissena* were able to survive without food for 524 days with only a 60% mortality rate [Chase and McMahon 1995]. Once a population has acclimatized, limited reproduction can occur in brackish water below 7.0 ppt salinity [Fong et al. 1995], with little mortality even up to 10 ppt [Kennedy et al. 1996]. Potassium can be tolerated only in low concentrations up to 0.3–0.5 mM. Ammonia (NH_3) is lethal in doses as low as 2 mg/L [Baker et al. 1994]. An extensive literature search revealed no correlation between NH_4 and zebra mussel populations.

Constructing the Model

We need to quantify *Dreissena* population growth, then examine how this growth is affected by the environment. We use the logistic equation, a standard modeling device in ecology [Gotelli 1998]. We choose a continuous approach because of the huge number of individuals involved, and the logistic equation in particular because its simplicity allows us to make as few assumptions as possible.

Standard techniques for examining the influence of variables like calcium ion concentrations, pH, and temperature on *Dreissena* populations include multiple regression and discriminant analysis [Ramcharan et al. 1992]. We want to predict actual population growth rates and not just state whether or not a population could exist in certain conditions, so we use multiple regression to relate population growth to chemical concentrations.

Assumptions

- **Population growth rate is proportional to total population.**

  We assume that the growth rate of an area's population is proportional to the rate at which juveniles settle on plates there. This rate is, in turn, proportional to the total number of larvae present in the water, which is proportional to the total population. Thus, the population growth rate is proportional to the population level.

- **Carrying capacity is constant.**

  Larvae can be thought of as a resource necessary for juveniles to exist. Each breeding season, only a certain number of larvae are produced, so the population can increase only to a certain point. Thus, there is effectively a carrying capacity at work. We assume that this carrying capacity does not depend explicitly on time once the breeding season begins.

- **Migration, genetic structure, and age structure do not affect the population.**

  Although *Dreissena* populations spread quickly from one region to another, individuals can move only at a slow crawl. Thus, migration of existing population into or out of a region is negligible. Also, there is no evidence for the existence of individuals whose ages or genes dramatically affect their influence on the population, so we neglect age and genetic variation.

- **Predation is negligible.**

We assume that *Dreissena* are so numerous that any species that prey on them—and there are few—do not have a substantial impact.

- **Sites within a lake can be treated as distinct lakes.**

  Although all of the data came from a single lake, we model each site as a separate lake. That is, we assume that the introduction of mussels from another part of the lake is equivalent to their introduction into a fresh lake, and we model the population at the new site independently.

Population Growth Model: The Logistic Equation

We model a *Dreissena* population with the logistic equation

$$\frac{dy}{dt} = ry\left(1 - \frac{y}{K}\right),$$

where r is the intrinsic growth rate of the population and K is the carrying capacity. For simplicity, we let $a = r$ and $b = r/K$, so that

$$\frac{dy}{dt} = ay - by^2.$$

With the initial condition $y(0) = y_0$, the equation has closed-form solutions

$$y(t) = \frac{ae^{at}y_0}{a - by_0 + be^{at}y_0},$$

shown in **Figure 1**. Because the data from Lake A measure the population growth rate, what we really want to fit to the data is the derivative of this function,

$$y'(t) = \frac{a^2e^{at}y_0(a - by_0)}{(a + b(-1 + e^{at})y_0)^2},$$

whose graph is shown in **Figure 2**. We can convert the parameters a, b, and y_0 into the position, height, and full width at half maximum (FWHM) of this peak, making it easy to fit to data.

Because the first data set did not include information about changes in chemical concentration over time, we average the population growth rates over all years after the introduction of *Dreissena* and fit the model curve to this "average year" at each site. The position and width of the peak are fairly constant from site to site, as we expect, since the breeding season usually peaks around mid- to late August and lasts for about three months. The peak heights, however, are radically different at different sites, ranging from about 38,000 juveniles per day at site 2 (**Figure 3**) to just 1 juvenile per day at site 10. This variation can be explained only by the environmental conditions there, so we determine how these growth rates varied with chemical concentrations.

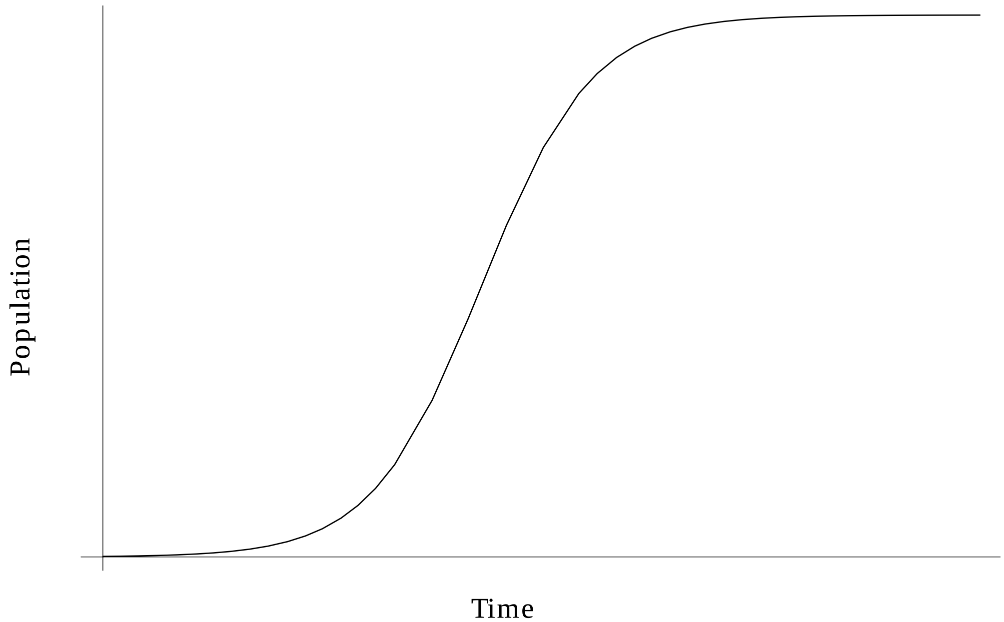

Figure 1. Solution to a generic logistic equation, $y' = ay - by^2$, with population plotted as a function of time.

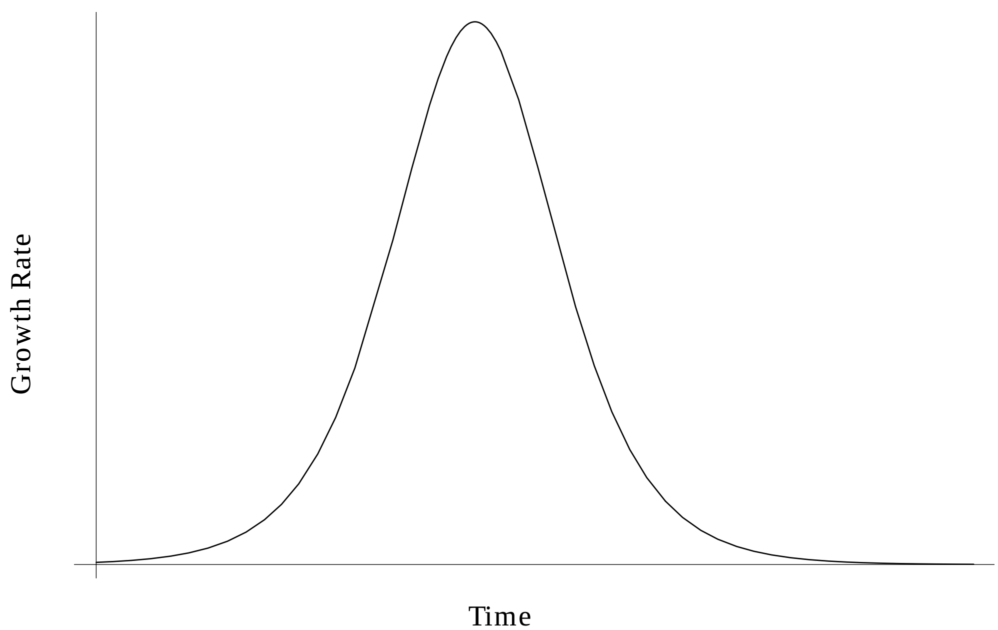

Figure 2. The derivative of the solution to a generic the logistic equation, showing the time rate of change of population. The peak corresponds to *Dreissena* breeding season in our model.

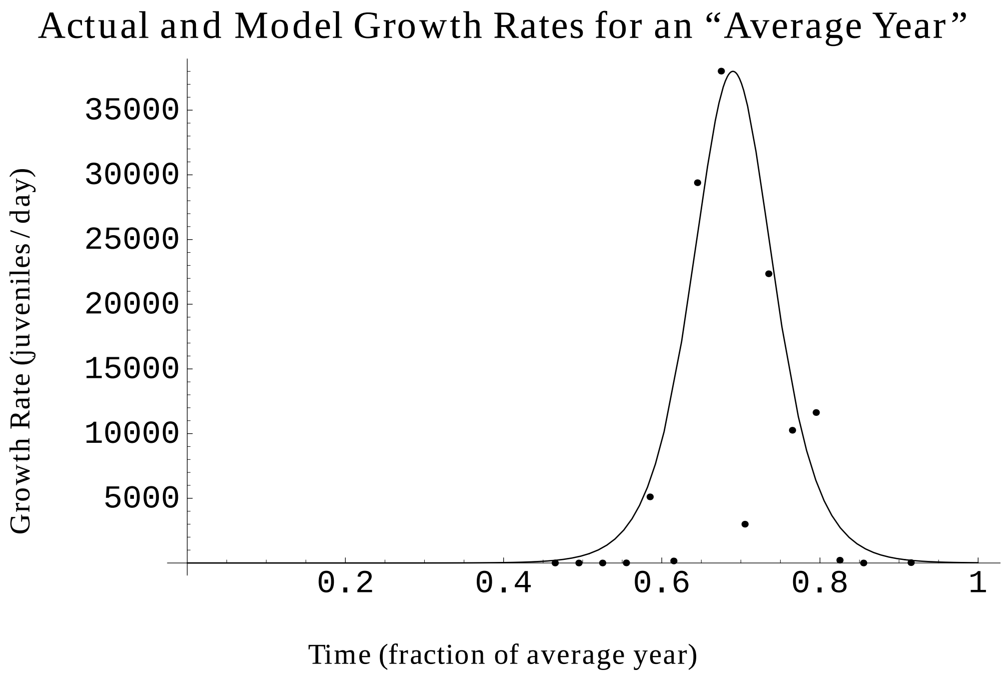

Figure 3. The derivative of the population growth model, along with data for an average year at Lake A (at site 2, the most populous site). The peak height of 38,000 is the quantity that best characterizes the population's success, so it is used in the regression analysis.

Influence of the Environment: Multiple Regression Analysis

To determine the effect of environmental conditions on growth rates, we must correlate the peak growth rates in the logistic model with the chemical concentrations at each site. To this end, we perform a multiple regression with peak growth rate as the dependent variable and some or all of the chemical concentrations as independent variables.

There are only 10 data points, far fewer than needed to separate the effects of all 11 variables. Fortunately, the literature provides guidance in selecting which variables to use. The dominant factors influencing the success of a *Dreissena* population are the concentration of calcium and the pH. Although alkalinity seems to be somewhat important, it is included in only the first data set; moreover, it also appears to be closely correlated with calcium concentration, so we exclude it. Another marginally important factor, dissolved oxygen, was not measured in the first data set. According to the literature, other chemical factors are negligible as long as they are present in trace amounts. Thus, we perform the regression on just two variables: calcium concentration and pH.

The equation we obtain is

$$\text{maximum rate} = 1687\,[\mathrm{Ca}^{2+}] + 55703\,\mathrm{pH} - 454995, \tag{1}$$

where the maximum growth rate is in juveniles settling per day and $[\mathrm{Ca}^{2+}]$

is in mg/L. Thus, by measuring the concentration of Ca^{2+} and the pH of the water, we can predict the population growth rate.

Tests and Refinements

The population growth model fits the data surprisingly well, considering its simplicity. Although in some cases the model could be strengthened by allowing two peaks of different heights, doing so would introduce at least one more degree of freedom and thus make it difficult to perform a meaningful regression with just 10 sites. Because we are interested in the overall success or failure of the population, we accept some inaccuracy in the population model in order to set up a better regression.

As a first check on the model, we use it to predict the growth rates at sites 1–10 in Lake A and compared the predictions to the actual rates (**Table 1**).

Table 1.

Actual growth rates in Lake A (first data set) vs. predicted growth rates, in thousands per day.

Site	Actual	Model
1	12	18
2	38	28
3	15	6
4	1	10
5	30	20
6	0.002	−100
7	0.003	0.2
8	0.2	9
9	3	14
10	0.001	3

Although far from perfect, the agreement gave us confidence that the model can give at least a qualitative idea of how well a *Dreissena* population will do in a given calcium concentration and pH.

For a second test of the model, we use it to predict the minimum pH and calcium concentration tolerable to *Dreissena*. At a pH of 7.7, which is typical of the data available for Lake A, the regression equation predicts that the lowest tolerable concentration of Ca^{2+} would be 15.4 mg/L—very close to the accepted value of 15 mg/L [McMahon 1996]. At a calcium concentration of 25 mg/L, also typical of freshwater lakes, the model predicts a minimum pH of 7.4; this is only slightly higher than the literature value of about 7.3.

Having established some confidence in our model, we test it against the second data set for Lake A. Because this data set does not include pH, we assume that the values reported in the first data set are accurate and use them in concert with the new calcium concentrations to predict growth rates (**Table 2**).

Although this agreement is coincidentally somewhat better than that with the first data set, we perform a new regression on both data sets at once to see

Table 2.
Actual growth rates in Lake A (second data set) vs. predicted growth rates, in thousands per day.

Site	Actual	Model
1	16	16.5
2	50	27
3	45	6
4	10	9.5
5	30	20
6	15	−10
7	0.02	−0.1
8	0.5	8
9	8	150
10	0.03	5

if we can improve the model. This gives us the new regression equation

$$\text{maximum rate} = 2338\,[\text{Ca}^{2+}] + 39202\,\text{pH} - 334089. \tag{2}$$

Using this new equation, we predict the peak growth rates at all ten sites, based on data from both sets. We found the results given in **Table 3**.

Table 3.
Actual growth rates in Lake A (from both data set) vs. predicted growth rates from combined regression, in thousands per day.

Site	Set 1	Model	Set 2	Model
1	12	30	16	28
2	38	32	50	30
3	15	11	45	10
4	0.001	12	10	12
5	30	20	30	19
6	0.002	−5	0.015	−5
7	0.0033	6	0.020	5
8	0.150	11	0.450	10
9	3	14	8	15
10	0.001	2	0.030	5

The revised model illustrates the sensitivity of the coefficients to changes in the data. Although the additional data incorporated are from the same physical locations as the first data set, they have a significant impact on the regression equation. This modification improves some predictions and worsens others.

Strengths and Weaknesses

Like any model, the one presented above has its strengths and weaknesses. Some of the major points are presented below.

Strengths

- **Applies widely accepted techniques.**

  The logistic equation is often used to model population growth under the conditions set forth in our assumptions [Gotelli 1998]. Multiple regression analysis has been used effectively in predicting *Dreissena* populations previously [Ramcharan et al. 1992].

- **Produces predictions in agreement with the data and other models.**

  Although agreement with the data provided is far from perfect, our model produces peak growth rates that are largely consistent with observed growth rates. The model also correctly predicts minimum [Ca^{2+}] and pH levels for *Dreissena* survival. Additionally, it is consistent with other models in the literature. Ramcharan et al. [1992], for instance, give a probability-of-survival model

  $$A = 0.045\,[\mathrm{Ca}^{2+}] + 1.246\,\mathrm{pH} - 11.696$$

  that is very nearly a constant multiple of our **(1)**.

- **Correctly predicts results at Lakes B and C.**

  Equation **(2)** predicts population growth rates of $-8{,}000$ juveniles / day for Lake B and $-145{,}000$ juveniles / day for Lake C. That is, the lakes are incapable of supporting mussel populations. This is consistent with the fact that both lakes are well below the minimum calcium and pH requirements.

Weaknesses

- **Extremely sensitive to changes in experimental data.**

  Based on the results described above, this seems to be a fairly substantial problem with the model. Given the extraordinarily small amount of data available, though, it is hardly remarkable that a change in any given peak value changes the model significantly. If more data were available, we would expect much better averaging-out of error and a regression equation with much better predictive power.

- **Neglects the effects of all factors but [Ca^{2+}] and pH.**

  Again, while this would initially appear to limit the predictive power of the model, the literature supports our selection of these two factors as the dominant ones influencing population growth [Ramcharan et al. 1992].

Results and Interpretation

To apply the model to the data for Lakes B and C, we assume that the values given for the concentrations are representative of the entire lake. With only one data point for each lake, we must extrapolate. Thus, the model's predictions might not hold in areas where the concentration or pH differs significantly from this value.

The model clearly indicates that there is no chance of zebra mussel infestation in Lake C, consistent with the fact that the pH in the lake is far too low to support a mussel population. The literature indicates zero growth at a pH below about 7.3; the highest measurement of pH in Lake C is 6.0, which is clearly far too acidic. In addition, the calcium concentration must be greater than 12 mg/L for larvae survival; Lake C is far below this cutoff, with a mere 1.85 mg/L at maximum.

The chemical data for Lake B are less clear cut. The pH is in the required range but the calcium concentration is too low for adult survival. Our model and the literature both indicate that it would take a significant shift in the lake's calcium content for it to support zebra mussels.

Although taken over the course of several years, the data for Lakes B and C are not spread out spatially. It is possible that some region in either lake has much higher pH and calcium concentrations. For example, Lake George in the Adirondacks was initially thought to be immune to zebra mussels because of the water chemistry, but they were later discovered in a small region near a culvert with elevated calcium concentrations. Scientists are now concerned about *Dreissena*'s potential to spread to other parts of Lake George, as the mussels have an amazingly ability to adapt once they have settled [Revkin 2000].

Other models strongly agree with our conclusions about Lakes B and C. Hincks and Mackie's model [1997] also found that zebra mussel populations depend only on pH and calcium concentration. Their formula,

$$p = \frac{e^L}{1 + e^L},$$

where

$$L = 134.7 - 3.659\,[\mathrm{Ca}^{2+}] - 15.868\,\mathrm{pH} + 0.43\,[\mathrm{Ca}^{2+}]\mathrm{pH},$$

predicts 100% mortality in Lake C and 99% in Lake B; a population might be able to make some headway if it could establish itself in Lake B.

Ramcharan et al. [1992] modeled the probability of a population becoming established, finding through discriminant analysis that only pH and calcium levels are significant factors. The discriminant function is

$$A = 1.246\,\mathrm{pH} + 0.045[\mathrm{Ca}^{2+}] - 11.696,$$

where A must be greater than -0.638 for a population to exist. This equation, which is nearly a constant multiple of our **(1)**, suggests that no populations would establish themselves in either lake.

Recommendations on De-Icing

Since the 1940s, America has used de-icing agents, primarily road salt (NaCl), to break the bond between road and ice. Ions in the water decrease the freezing temperature and melt the ice, promoting safer driving during icy weather by increasing the wheel/road traction. This proposal will show why Ice Ban or potassium acetate is a better candidate for de-icing near a lake, and discuss anti-icing as an alternative method of combating ice.

Using standard road salt near freshwater lakes is not a good idea. While doing so *might* have a negative effect on the zebra mussel population, it would certainly have a greater negative effect on other aquatic life. Since zebra mussels are able to adapt to environmental changes more quickly than other freshwater species, any change in the chemical content of the lake will probably result in an even greater abundance of mussels [Kennedy et al. 1996]. A good de-icing method should remove the road hazard without profoundly impacting any ecosystem.

Another consideration specific to zebra mussels is that de-icing chemicals used should not *promote* their growth. Common agents including calcium, such as calcium chloride and calcium magnesium acetate, should therefore not be used. This is especially important near lakes with low levels of calcium, such as Lake B, where the introduction of a source of calcium might lead to successful colonization by zebra mussels.

According to the comprehensive report *Liquid Road Deicing Environment Impact* [Cheng and Guthrie 1998], the common de-icing chemicals remaining include common road salt, magnesium chloride, potassium acetate, and Ice Ban. This authoritative report lays out the effects of each agent on vegetation, soils, water quality, aquatic life, and people. Sodium chloride (NaCl), the most common, tested worst of all. It damages vegetation, kills some freshwater fish, pollutes groundwater, and causes air-quality concerns. The primary concern with magnesium chloride is that the chloride readily separates from the compound and can pollute groundwater or freshwater lakes. The chlorine often tastes unpleasant to people, and it can kill freshwater fish.

Potassium acetate and Ice Ban, however, are less ecologically intrusive. Potassium acetate may affect plant growth slightly and is a mild skin and eye irritant. In very high concentrations, it has been shown to kill rats, but the report does not predict any animal deaths at normal concentrations. Acetate is biodegradable in soil and the remaining potassium has no negative affect on the surrounding environment. Ice Ban, on the other hand, is completely biodegradable. Since it is completely organic, it has no effect on the vegetation, aquatic life, or air quality [Cheng and Guthrie 1998]. We therefore suggest both potassium acetate and Ice Ban as possible de-icing agents, favoring the later as the most ecologically benign and less expensive.

Potassium acetate is available as a liquid de-icing agent under the names Enviro-MLT TM (from Midwest Industrial Supply), Cryotech CF7 or E36LRD (from Cryotech), or Safeway KA Liquid (from Clariant) [Cheng and Guthrie

1998]. Ice Ban is available from Ice Ban America. For your examination, we have included cost and other information in **Table 4**.

Table 4.
Data on de-icing materials and the anti-icing solution RWIS.

Company	Amount required per 1,000 sq ft	Cost / gal	Phone Number
Enviro-MLT	0.x	4.67	1.800.321.0699
Cryotech CF7	0.5	3.30	1.800.346.7237
E36LRD	0.5	2.80	1.800.364.7237
Safeway KA Liquid	0.4	4.00	1.419.479.8650
Ice Ban	0.76	0.75	1.888.488.4273
RWIS	variable	$3000 / unit	1.800.363.6224

De-icing, however, is no longer considered to be the best solution to the problem of icy roads. The Strategic Highway Research Program (SHRP), a five-year program started to investigate anti-icing roads, has led an anti-icing initiative in 9 states and shown it to be effective there. Currently, more than 20 states are experimenting with the strategy, including states like Michigan that have zebra mussel populations, making the solution especially relevant [Federal Highway Administration 1997].

Anti-icing is a preventative measure that stops the ice from bonding to the road. Simply put, the roads are salted before the snow hits. The precipitation remains slushy and wet instead of frozen and slick. The slush is easily plowed off the road, and the “salt” does not need to be replaced as often, since it is not plowed off with the ice. This leads to many other benefits, but first we discuss cost.

Instead of reacting to snow, the state’s Dept. of Transportation anticipates it from weather forecasts and road conditions. Many states have installed Road Weather Information Systems (RWIS), which report real-time information on pavement conditions. Installation is the major cost of the conversion. In states where there are at least 5 snowstorms a year, the initial cost is quickly offset [Chollar 1996].

There are several ways anti-icing has saved money. It requires less “salt” to keep the roads safe. Applying the chemical to the road before or early into a winter storm ensures that when the snow is plowed off the road, the anti-icing agent remains on the surface, while de-icing agents need to be reapplied after each plowing. Using less salt is also beneficial since de-icing agents are notoriously corrosive. This means that vehicles applying the “salt” are less corroded each year and don’t need to be replaced as often. The study predicted that overall the states could save almost $108 million a year [Federal Highway Administration 1997]. Less anti-icing agent on the road means less agent on the passing cars and less corrosion of the cars. Less “salt” also helps protect the environment by reducing pollution from foreign chemicals [Chollar 1996].

For this method, we recommend using de-icing agents (which also work as anti-icing agents) and the RWIS. In areas with only 100 hours of storms per winter, the savings in de-icing chemicals is $659.50 per mile sanded or salted; with an RWIS unit every mile, the savings pay for the cost of installation in five years [Chollar 1996].

Conclusions

We treated each data site from Lake A as an independent "lake," providing 10 data points. Using these data, previous work showing that zebra mussel population is linearly dependent on pH and calcium concentration, and multiple regression, we constructed a model for zebra mussel population. We refined the model using the second set of data taken from the same lake. The resulting model is good but would be better with data from more lakes.

We have presented a recommendation on how to de-ice roads near Lake B. Lake B lacks the high levels of calcium required to support zebra mussel populations, so we suggest that the local community not use de-icing salts containing calcium but an anti-icing strategy using environmentally non-intrusive chemicals, such as Ice Ban.

Report on Controlling Zebra Mussel Populations

To the Lakeside Community:

You are planning to control the zebra mussel population by introducing a nonindigenous species, the round goby fish. We strongly encourage you not do so. This report explains how round gobies can adversely impact the surrounding ecological system, without producing a substantial impact on the zebra mussel population.

What round gobies lack in size, they more than make up in aggression. Their fierce nature allows them to dominate prime spawning grounds, forcing native species to move elsewhere or die off. In addition to eating zebra mussels, the gobies will attack other fish species' eggs and young, thus diminishing the population of previously well-established species. With their well-developed sensory system, round gobies can feed in complete darkness—an obvious advantage over competitors. Round gobies can quickly come to dominate a new area. In the rocky parts of Calumet Harbor, for example, the population of gobies already exceeds 20 individuals per square meter—that's 20 fish in a space the size of a bathtub! Their presence has caused a significant drop in the biodiversity of the ecosystem.

Round gobies are zebra mussels' natural predator in their native habitat, the Black Sea. Adult gobies can eat an average of 47 mussels per day. However, this number isn't particularly impressive when there can be up to 1 million mussels per square meter. Experts agree that gobies are a hopelessly inadequate method for controlling a zebra mussel population.

Another reason not to introduce the gobies is the safety of the people in your city. The potential danger arises because zebra mussels are filter feeders, often processing a liter of water per day. The mussels accumulate pollutants from the water, particularly PCBs (polychlorinated biphenyl), in large amounts in their tissues. Usually these toxins are not passed on, falling to the lake floor when the mussels die. If round gobies eat the mussels, however, the toxins are passed to the gobies. Because many game fish eat gobies, the toxins are passed on again. This time, though, the toxins are passed to fish that might be sold and consumed; the threat to human health is obvious.

We would like to review some possible alternatives to solve your initial zebra mussel problem.

The most commonly considered method for removing zebra mussels is chemical treatment. This method does not take into account the fact that zebra mussels are amazingly tolerant of large ranges of all chemicals—much more so than other species. Raising the toxicity level high enough to ensure the complete removal of the zebra mussels would cause other species to die.

Some methods of removal are effective only in a laboratory and seem ridiculously unsuitable for use in an external body of water. Experiments have shown, for example, that electric current and ultrasonic cavitation can kill zebra mussels. Even if such a method could be controlled and implemented, it would undoubtedly harm other species. Inventions such as the vacuum pump and the blasting hose are not practical except in factories. It has been shown that the neurotransmitter serotonin forces the mussels to spawn before the proper season, thus killing the young. The suggestion of the use of serotonin has some promise; however, this chemical may affect other species, including humans. More research is required in this area.

We regret that we must close this presentation on a gloomy note. Currently, the only available method of controlling this species is to stop it from spreading to other lakes. Since zebra mussels usually spread on the hulls of boats, we encourage you to inform your residents about the following procedures to prevent the spread of zebra mussels as suggested by the Sea Grant Extension:

- Inspect your boat's hull carefully. If surfaces feel grainy, tiny zebra mussels may be attached. Scrape off any "hitchhiking" mussels.
- Drain all water from the boat, including the bilge water where they often reside.
- Dry your boat in the sun for two to five days, or use a pressurized steam cleaner to ensure the hull is sterile.
- Throw leftover live bait away or give it to someone to use at the same water body.

We also encourage you to post signs at boat launches in your area to promote these simple guidelines for boaters.

References

Baker, Patrick, et al. 1994. Criteria for predicting zebra mussel invasions in the mid-Atlantic region. Virginia Institute for Marine Science.

Balog, George G., et al. 1995. Baltimore city adopts a proactive approach to zebra mussel control using potassium permanganate. *Proceedings of the Fifth International Zebra Mussel and Other Aquatic Nuisance Organisms Conference*.

Chase, R., and Robert F. McMahon. 1995. Starvation tolerance of zebra mussels, *Dreissena polymorpha*. *The Fifth International Zebra Mussel and Other Aquatic Nuisance Species Conference*.

Cheng, K.C., and T.F. Guthrie 1998. *Liquid Road Deicing Environment Impact*. Levelton Engineering Ltd.: Richmond, B.C., Canada.

Chollar, Brian. 1996. A revolution in winter maintenance. *Public Roads*. `http://www.tfhrc.gov/pubrds/winter96/p96w2.htm` .

Dietz, Thomas H., Diondi Lessard, Harold Silverman, and John W. Lynn. 1994. Osmoregulation in *Dreissena polymorpha*: The Importance of Na, Cl, K, and particularly Mg. *Biological Bulletin* 187: 76–83.

Dietz, Thomas H., and Roger A. Byrne. 1999. Measurement of sulfate uptake and loss in the freshwater bivalve *Dreissena polymorpha* using a semi-microassay. *Canadian Journal of Zoology* 77 (2): 331–336.

Endicott, D., R.G. Kreis, L. Mackelburg, and D. Kandt. 1998. Modeling PCB bioaccumulation by the zebra mussel (*Dreissena polymorpha*) in Saginaw Bay, Lake Huron. *Journal of Great Lakes Research* 24 (2): 422–426.

Federal Highway Administration, U.S. Department of Transportation. 1996. *Manual of Practice for an Effective Anti-Icing Program*. `http://www.fhwa.dot.gov/reports/mopeap/mop0296a.htm` .

________. 1997. New technologies keep snow and ice—and winter maintenance expenses—under control. *Focus*. `http://www.tfhrc.gov/focus/archives/37snow.htm` .

Fong, P.P., K. Kyozuka, J. Duncan, et al. 1995. The effect of salinity and temperature on spawning and fertilization in the zebra mussel *Dreissena polymorpha* (Pallas) from North America. *Biological Bulletin* 189: 320–329.

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.

Gotelli, Nicholas J. 1998. *A Primer of Ecology*. 2nd ed. Sunderland, MA: Sinauer Associates, Inc.

Hincks, Sheri S. and Gerald L. Mackie. 1997. Effects of pH, calcium, alkalinity, hardness, and chlorophyll on the survival, growth, and reproductive success of zebra mussel (*Dreissena polymorpha*) in Ontario lakes. *Canadian Journal of Fisheries and Aquatic Sciences* 54: 2049–2057.

Johnson, P.D., and R.F. McMahon. 1996. Tolerance of zebra mussels (*Dreissena polymorpha*) and Asian clams (*Corbicula fluminea*) to varying levels of hypoxia. *The Sixth International Zebra Mussel and Other Aquatic Nuisance Species Conference*.

Jude, David J. 1997. Round gobies: Cyberfish of the Third Millennium. *Great Lakes Research Review* 3 (1): 27–34.

Kennedy, V.S., M. Asplen, and T. Hall. 1996. Salinity and behavior of zebra and quagga mussels. *The Sixth International Zebra Mussel and Other Aquatic Nuisance Species Conference*.

Marsden, J.E. and D.J. Jude. 1995. Round gobies invade North America. *Illinois Natural History Survey, University of Michigan, and Illinois-Indiana and Michigan Sea Grant Programs*.

McMahon, Robert F. 1996. The physiological ecology of the zebra mussel, *Dreissena polymorpha*, in North America and Europe. *American Zoologist* 36 (3): 339–363.

Michigan Sea Grant College Program. 1994. Potential control of zebra mussels through reproductive intervention.

Miller, Steven J., and James M. Haynes. 1997. Factors limiting colonization of Western New York creeks by the zebra mussel (*Dreissena polymorpha*). *Journal of Freshwater Ecology* 12 (1): 81–88.

Paukstis, G.L., F.J. Janzen, and J.K. Tucker. 1996. Response of aerially-exposed zebra mussels (*Dreissena polymorpha*) to subfreezing temperatures. *Journal of Freshwater Ecology* 11 (4): 513–520.

Ramcharan, Charles W., Dianna K. Padilla, and Stanley 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.

Ray, William J., and Lynda D. Corkum. 1997. Predation of zebra mussels by round gobies, *Neogobius melanostomus*. *Environmental Biology of Fishes* 50: 267–273.

Revkin, Andrew C. 2000. Invasive mussels turn up in lake thought to be immune. *New York Times* 149 (51354): B4.

U.S. Dept. of Transportation. 2001. Snow and Ice Control. `http://www.fhwa.dot.gov/winter/roadsvr/icebro.htm` .

Van der Velde, D., S. Rajagopal, and H.A. Jenner. 1996. Response of zebra mussel, *Dreissena polymorpha* to elevated temperatures. *Sixth International Zebra Mussel and Other Aquatic Nuisance Species Conference*.

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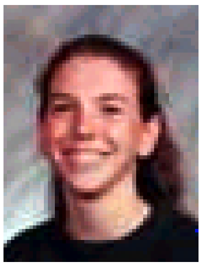

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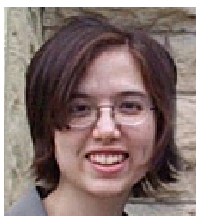

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