Identifying Potential Zebra Mussel Colonization

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Summary

Both environmental and anthropogenic factors influence the spread of zebra mussels to new areas. Variations in water quality can affect both proliferation and mortality, which greatly influence colonization rate. High levels of calcium and alkalinity in fresh waters tend to increase juvenile zebra mussel population. *Dreissena* also requires specific ranges of pH, temperature, and potassium concentration for propagation. Consumption by predators and spread by humans also influence colonization and population dynamics.

We develop a lumped-parameter stochastic model using data from a lake with known water quality, using optimal water quality parameter ranges for zebra mussel survival. The model predicts the susceptibility to colonization of a lake with known water quality.

We find a significant probability for seasonal colonization in Lake B but negligible probability for Lake C.

The use of de-icing agents in the vicinity of Lake B may increase the probability of colonization, due to elevated calcium concentrations in the lake.

Literature Review

History

The zebra mussel originated in the Caspian and Black Sea regions. By the early 19th century, a well-developed population was established throughout

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the major drainages of Europe in connection with extensive canal building [USGS 2001]. Researchers surmise that the zebra mussel first arrived in North America in the mid-1980s in a ballast tank of a commercial vessel; the first recorded population appeared in Lake St. Clair, Canada [Herbert et al. 1989]. By 1990, the zebra mussel habitat encompassed the Great Lakes and soon after entered the Mississippi River drainage via the Illinois River. Today, zebra mussels exist in at least 21 states [USGS 2001].

Factors Influencing Propagation

Physical Mechanism of Propagation

Anthropogenic activities are considered the most influential factor in spreading zebra mussels [Mackie and Schloessler 1996]. Zebra mussels attach themselves to firm surfaces including boat hulls, nets, buoys, and floating debris [Balcom and Rohmer 1994; Ram and McMahon 1996]. A zebra mussel dislodged in transport can start a new population.

Natural dispersion mechanisms include birds, water currents, insects, and other animals [Mackie and Schloesser 1996; Hincks and Mackie 1997]. When carried by currents, microscopic zebra mussel larvae, called *veligers*, can quickly disperse themselves [Mackie and Schloesser 1996]. The mussels can travel large distances in the two- to three-week free-swimming veliger stage [Rice 1995].

The species has demonstrated resilience to long-overland trips. Zebra mussels survive longest under cool, moist conditions, similar to the environment in a boat hull [Payne 1992].

Habitat

Zebra mussel habitat includes freshwater lakes and reservoirs, as well as cooling ponds, quarries, and irrigation ponds of golf courses. However, the species can survive where salinity does not exceed 8 to 12 parts per thousand (ppt) [Mackie and Schloesser 1996].

Zebra mussels prefer hard substrates [Heath 1993] but can survive on soft sediment [Stoeckel et al. 1997]. Current velocities up to 2 m/s provide optimal settlement conditions, while speeds ranging from 0.5 m/s to 1.5 m/s best support growth [Rice 1995].

Water Quality

pH Zebra mussels have colonized areas with pH values ranging from 7.0 to 9.0. A pH of 7.5 promotes optimum growth [Rice 1995].

Potassium The optimal range of potassium in the environment is 0.5–1.5 mg/L, with survival at 2–3 mg/L [Dietz et al. 1996].

Calcium and Alkalinity Calcium and alkalinity are the strongest influences on zebra mussel growth and reproduction [Heath 1993]. Zebra mussels require a Ca^{+2} concentration of 12 mg / l and $CaCO_3$ concentration of 50 mg / l [Heath 1993]. Ramcharan et al. [1992] found that European lakes with pH below 7.3 and Ca^{+2} concentration below 28.3 mg/l lacked zebra mussels, but in North America there are numerous examples of invasion at far lower calcium concentrations.

Dissolved Oxygen Heath [1993] indicates a minimum oxygen threshold of 25% oxygen saturation, or 2 mg/l at 25°C. Dense overgrowths of zebra mussels may deplete dissolved oxygen enough to cause large die-offs of *Dreissena* and other aquatic species [Ramcharan et al. 1992].

Nutrients and Phytoplankton A water body's chlorophyll-*a* concentration is a factor in growth variability of the zebra mussel [Mackie and Schloesser 1996]. Zebra mussels compete with herbivorous zooplankton and fish for phytoplankton [Ramcharan et al. 1992]. Zebra mussels collect their food through ciliary filter feeding processes [McMahon 1996]; that filtering increases water clarity, and light penetration fosters growth in the lake's benthic population [MacIsaac 1996], which can increase the nuisance aquatic weed biomass.

Salinity Research suggests optimal salinity for adults is 1 ppt at high temperatures (18–20°C) and 2–4 ppt in lower temperatures (3–12°C) [Kilgour et al. 1994; Mackie and Schloesser 1996]. Rice [1995] suggests 1 ppt as optimal for growth and short-term tolerance of 12 ppt; but zebra mussels have high adaptive ability to nonideal conditions in salinity and other water quality parameters.

Temperature For reproduction, the zebra mussel requires prolonged periods above 12°C and maximum temperatures ranging from 18 to 23°C [Heath 1993; McMahon 1996]. It can't survive in temperatures greater than 32°C; the lower temperature survival threshold is 0°C [Heath 1993].

Predators Crustacean zooplankton and larval fish consume the larval stages of the mussel [Mackie and Schloesser 1996]. Adult *Dreissena* provide food for crayfish, fish, and waterfowl [Mackie and Schloessler 1996]. Fish observed consuming zebra mussels include yellow perch, white perch, walleye, white bass, lake whitefish, lake sturgeon, and the round goby [MacIsaac 1996; French 1993]. Potential consumers include the freshwater drum, redear sunfish, pumpkinseed, copper and river redhorse, and common carp. Round gobies consume 50–100 zebra mussels per day, depending on the size of the mollusk [Ghedotti et al. 1995]. Diving waterfowl consume significant amounts of zebra mussels in proper conditions. Hamilton et al. [1994] found the ducks devoured 57% of the autumn mussel biomass in Lake Erie; but due to icing over of the lake and consequent lack of winter predation, continued juvenile growth diminished the effects of the consumption.

Modeling Zebra Mussels

Zebra mussel populations demonstrate high sensitivity to small changes in water quality parameters. In some lakes, the long-term population size remains fairly constant, while populations in other lakes fluctuate greatly from year to year.

Modeling History

Some of the more common types of models developed include multivariate, bioenergetic, and probabilistic:

- Multivariate models have been used to determine the environmental factors that most influence the ability of *Dreissena* to establish viable populations [Ramcharan et al. 1992].
- Bioenergetic models focused on modeling individual zebra mussel growth as a function of certain environmental factors [Schneider 1992].
- Probabilistic models used discrete probabilities associated with environmental variables known to contribute to the successful colonization of freshwater bodies to evaluate the susceptibility of certain lakes to zebra mussel colonization [Miller and Ignacio 1994].

Model Development

Model Choice and Approach

We develop an analytical model that is transient, lumped-parameter, and stochastic.

We obtained from the literature ranges of water quality the parameters that are necessary for survival. Using a time step of one year, we determine the probability of survival based on those and determine the population. We use the data on Lake A to calibrate and verify the model's ability to predict colonization.

Data Considerations

The data files provided contain water quality and population data for Lake A. Shared by most files were calcium concentration (mg/L), chlorophyll concentration (μg/L), potassium concentration (mg/L), temperature (°C), and pH, all of which the literature shows are important factors.

We use the average juvenile population for a given year for comparison with the model results, regardless of the amount of data available for that year. Therefore, for each time step, we need an annual average and standard deviation for each parameter and each population. We assume that the average value is the average for the year.

Review of Literature

Calcium, alkalinity, phytoplankton, potassium, water temperature, and pH are important for survival. Because of the dependence between alkalinity and calcium concentration, we use only calcium. We use chlorophyll-*a* in place of phytoplankton to represent available food. We summarize in **Table 1** the ranges of water quality parameters required for survival.

Table 1.
Optimal water quality conditions for survival of each age class.

Age Group	Constituents									
	Ca (mg/L)		Chl-a (μg/L)		K (mg/L)		pH		Temp	
	LL	UL	LL	UL	LL	UL	LL	UL	LL	UL
Birth	20	50+	0	15	0.05	1.2	7.7	8.5	12	21
1	20	50+	0	15	0.05	1.2	7.7	8.5	12	21
2	15	50+	3	20	0.05	1.3	7.3	8.7	5	28
3	10	50+	8	30	0.05	1.5	5.2	9.3	0	31
4	10	50+	8	30	0.05	1.5	5.2	9.3	0	31

Methodology

The model uses assumptions about probabilities of survival at specific age classes.

Age Classes

We divide zebra mussels into four distinct age classes: class 1 (0–1 years), class 2 (1–2 years), class 3 (2–3 years), and class 4 (3–4 years). At the end of each time step (= one year), the population of each age class moves into the next age class, except that class 4 dies. Values for each water quality parameter are specified at each time step.

Survival Probabilities

The ranges of values for each parameter are divided into smaller ranges and assigned survival probabilities. A normal distribution is used to create a probability distribution for each parameter. For each age class, we take the mean of the optimal range found in the literature. Newborns and age class 1 use the same ranges and probabilities; classes 3 and 4 also use their own same ranges and probabilities; age class 2 has its own ranges and probabilities. A normal distribution is fit to the average; we assume that the limits of the optimal ranges in the literature represent one standard deviation from the mean.

Constraints and Assumptions

For each age group, the probabilities of survival at each time step for each of the water quality parameters are assumed to be mutually independent. Thus, the probability of survival of each age class is the product of the probabilities of its survival at each water quality value.

Additional constraints are also included:

- Age classes 2, 3, and 4 are able to reproduce in water above 12°C.
- The survival of eggs and larvae to age class 1 depends on their probability of migration out of the system and the probability of survival at the current water quality conditions. The probability of migration is calculated as a function of calcium concentration [Hincks and Mackie 1997].
- Since the number of eggs per adult female varies in the literature (4000–100,000), we use its value as a parameter for calibration.
- An initial number of juveniles (age class 1), specified by the user, is introduced at the first time step, and no additional veligers or juveniles enter the system from outside sources.
- The model allows the user to decide which parameters to consider in the probability calculations depending on the availability of data.

The model was programmed in Fortran 90 with a Lahey compiler under a Suse Linux operating system.

Calibration

The model was calibrated using the data in the files `LakeAChem1.xls` and `LakeAPopulation1.xls`. The water quality data are provided as the median, maximum, minimum, and 25th and 75th percentiles of data for 1992 to 1999. We assume that the median equals the mean and that the average difference between the mean and the 25th and 75th percentiles is the standard deviation.

We use a random number generator to create two sets of random numbers between 0 and 1, for n years. The value of each water quality parameter for each of the years is given by

$$X_i = \bar{X} + P_{\text{var}\ i} \times P_{\text{ran1}\ i} \times \sigma_X,$$

where

- X_i is the value of the parameter at time step i,
- $\bar{X}$ is the parameter mean,
- σ_X is the parameter standard deviation,
- $P_{\text{ran1}\ i}$ is the random number at time step i, and

- $P_{\text{var } i} = \begin{cases} -1, & \text{if } P_{\text{ran1 } i} < 0.5 \\ +1, & \text{if } P_{\text{ran1 } i} \geq 0.5. \end{cases}$

Using this method, we created a file of n years of generated data for each parameter for each of 10 sites at Lake A. We calibrated the model for its ability to predict susceptibility of a location to colonization by varying the initial population of juveniles and adjusting the number of eggs per adult female.

At these sites, trends in the model results replicate trends in the populations. At a site susceptible to colonization, a higher initial population of juveniles yields faster establishment and propagation; at a site not susceptible to infestation, the population does not establish any structure and dies off. However, increasing the number of eggs per female produces colonization at some sites that were not possible at lower levels of egg production; at these sites, water quality is near a juvenile survival threshold. [EDITOR'S NOTE: Space does not permit reproducing the authors' graphs illustrating these conclusions.]

The model is qualitatively accurate. It predicts zebra mussel colonization where and under circumstances when colonization actually occurs, and predicts no colonization when observed juveniles are low or nonexistent. The ability of a population to proliferate is apparent in the development of a population age class structure over time; if an age structure is not established, the location does not experience successful colonization.

Verification

The model predicts whether or not colonization will occur, but the speed and magnitude of the colonization are not accurately approximated. Also, since the water quality levels were artificially generated from descriptive statistics, the performance of the model with actual data is unknown. With data on the annual accumulation of zebra mussels and the distribution of water quality constituents, as provided in the files `LakeAChem2.xls` and `LakeAPopulation2.xls`, the model can be tested, adjusted, and verified.

Figures 1 and **2** compare 5 of the 10 sites for the two data sets at Lake A; similar trends appear at each site. Running the model with the second set of data indicates that populations proliferate where they have been observed in high numbers. Though the model predictions for juveniles are an order of magnitude greater than the observed values, the model correctly predicts whether populations survive; we attribute the difference to incomplete calibration.

Model Sensitivities

The dominant model sensitivities in predicting the magnitude of proliferation are to the number of water quality constituents incorporated and to the initial juvenile population. When more probabilities are considered in the calculation, overall probability is lowered. Since the model was calibrated using all parameters, using fewer parameters results in a more conservative estimate,

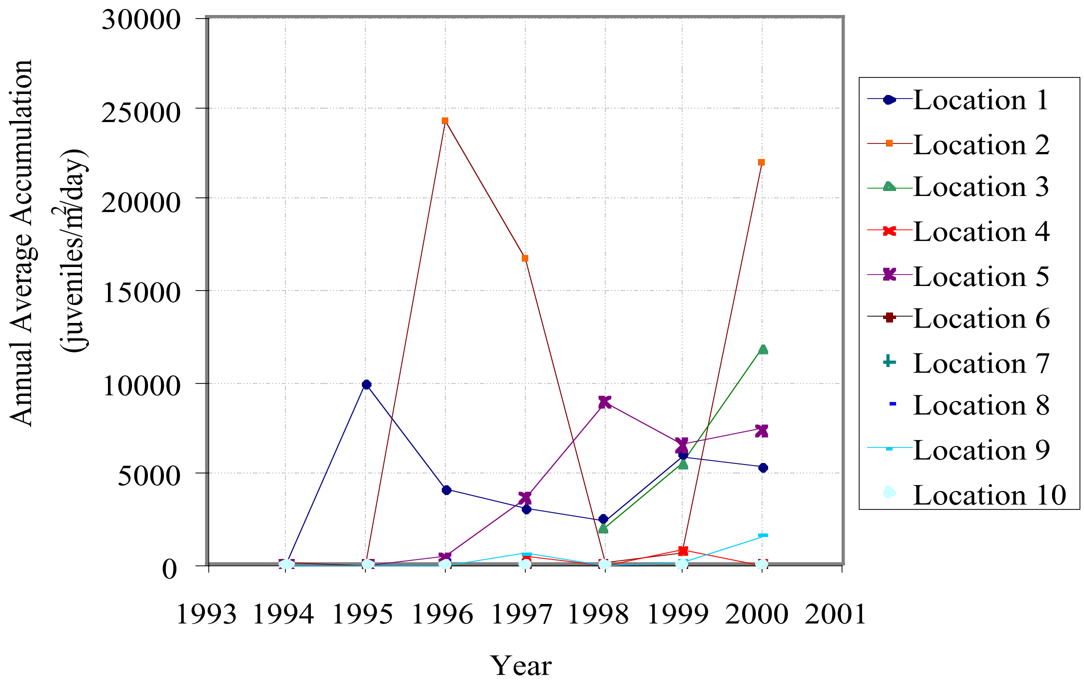

Figure 1. Annual average accumulation rates using the 1st population data for Lake A.

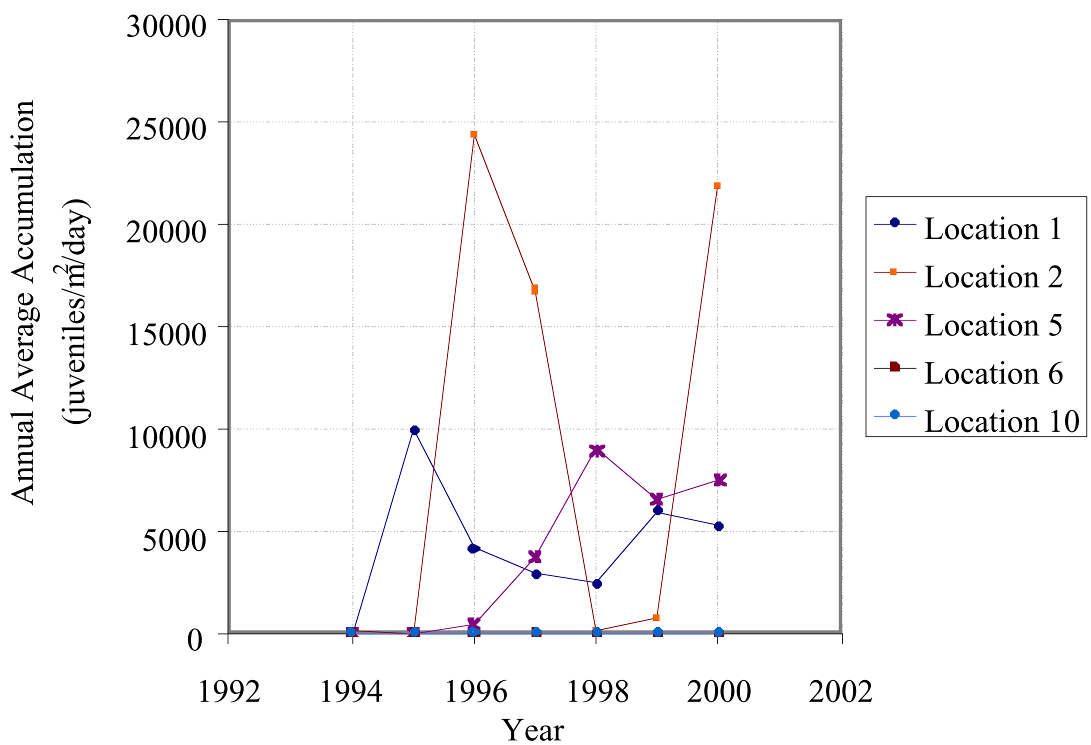

Figure 2. Annual average accumulation using the 2nd population data set for Lake A.

that is, the model over-predicts. The dominant factor in the rate of proliferation is the number of eggs or veligers that are allowed to survive.

Model Limitations

The model becomes more conservative as the number of variables considered decreases. It predicts either the occurrence of a large outbreak or that a population never establishes.

The model assumes that the survival probabilities for each parameter range are independent, but in actuality some parameters have strong dependencies, such as between pH and calcium concentration [Hincks and Mackie 1997].

Application

Lake B

Lake B is at the threshold for zebra mussel survival for the only variables on which we have data: pH, calcium concentration, and chlorophyll concentration. With so few water quality indicators, we expect a conservative estimate (i.e., an overestimate of survivability and colonization potential). We ran the model with an initial juvenile population of 1,000; only 10 survive to age class 2. A population introduced to Lake B will not proliferate.

Lake C

Lake C has a very low average pH and a low annual average calcium concentration; it is not suitable for colonization. The probability of survival predicted by the model is zero.

Impacts of De-icing Near Lake B

Many de-icing agents used to remove snow and ice from roads during the winter contain calcium salts, specifically calcium chloride ($CaCl_2$).

Repeated application of calcium chloride to roads may accumulate calcium in Lake B. A small increase in its available calcium level of 11.5 mg/L could allow colonization. The model indicates that a calcium concentration of 21.5 mg/L would allow zebra mussel colonization, but continuing low values for pH and and chlorophyll concentration force the colony to die out eventually.

Other de-icing agents, such as sodium chloride (NaCl), increase sodium concentrations in freshwater bodies, which can inhibit propagation of zebra mussels; however, zebra mussels can adapt to higher levels of salinity.

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Assessment of Introduction of the Round Goby

Ironically, the round goby and the zebra mussel both entered North American fresh waters by ballast-water discharge into the Great Lakes region at approximately the same time. They favor similar environments: slow water velocity and higher turbidity.

The diet of the round goby consists of small mollusks, especially the zebra mussel. The round goby has molar teeth well suited to crushing mollusk shells.

Biological control agents such as the round goby can have ecological advantages over chemical control. Natural enemies tend to be more specific to a certain pest, while chemical control measures often affect multiple species and the targeted pests can develop a tolerance to the chemical.

However, although the round goby can consume appreciable numbers of zebra mussels, the round goby violates the requirement of being specific to the target pest. They consume also the fry and eggs of habitat-sharing fish, including smallmouth bass, walleye, and perch, and their aggressive nature allows them to restrict native fish from utilizing optimal spawning locations.

After the zebra mussels reach a certain size, they are too large for the round goby. Spawning of larger mollusks then prevents the population from dying out.

During its filter-feeding process, the zebra mussel accumulates and stores pollutants, including PCBs. As the round goby consume the mussels, contaminants bioaccumulate in the fish. The accumulation pattern potentially continues as sport fish eat the round goby and as humans in turn consume the sport fish.

Thus, both environmental ethical and practical considerations require that additional alternatives be explored.

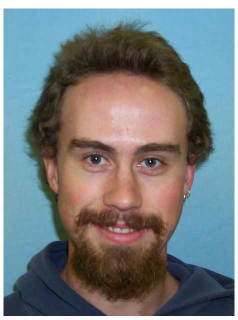
Research continues on types of biological control techniques other than round goby fish. Over the past 10 years, some microorganisms have shown promise of inducing very high zebra mussel mortality.

Until an ideal alternative exists, communities must take other measures to limit the spread of the zebra mussel. Since studies attribute the spread to movement of watercraft between bodies of water, an aggressive education campaign could inform recreational boaters and fishermen how to avoid contributing to proliferation of zebra mussels. If climate conditions necessitate de-icing of highways, a community should consider materials that don't promote zebra mussel growth.

About the Authors

David Stier attended high school in South Burlington, VT, before migrating to California in 1993. His current work activities include assessment of highway culverts in Northern California for anadromous [migrating upriver from the sea to breed in fresh water, as salmon do] fish-passage issues. He is also completing his senior year in Environmental Resources Engineering at Humboldt State University. David is an avid world traveler but unsure of his plans after graduation.

After graduating with honors with a B.S. in Environmental Resources Engineering, Marc Leisenring joined GeoSyntec Consultants in August, 2001. He has experience in both one- and two-dimensional hydrodynamic modeling, and now (with the ICM) also in stochastic modeling. As a Staff Engineering Specialist at GeoSyntec, his primary responsibilities have included technical analysis, report preparation and review, and preliminary design; future responsibilities may include model development and implementation, final design, and development of stormwater management plans.



Matthew Kennedy attended Santa Rosa Junior College in Santa Rosa, CA, before transferring to Humboldt State University in 1998. During the summers of 1998 and 1999, he worked with the Hydrology Research Group at the Pacific Northwest National Laboratory in Richland, WA. There he assisted in the development of hydrodynamic and water quality computer models of the Columbia River system. He graduated with honors in 2001 with a B.S. in Environmental Resources Engineering. Matthew is currently a research assistant at the University of Massachusetts, Amherst, where he is working on an M.S. in Environmental Engineering.