ZEBRA MUSSELS AND THE MID-ATLANTIC

Reports from the Sea Grant Programs of New Jersey, Delaware, Maryland Virginia and North Carolina

A Maryland Sea Grant Publication
College Park, Maryland

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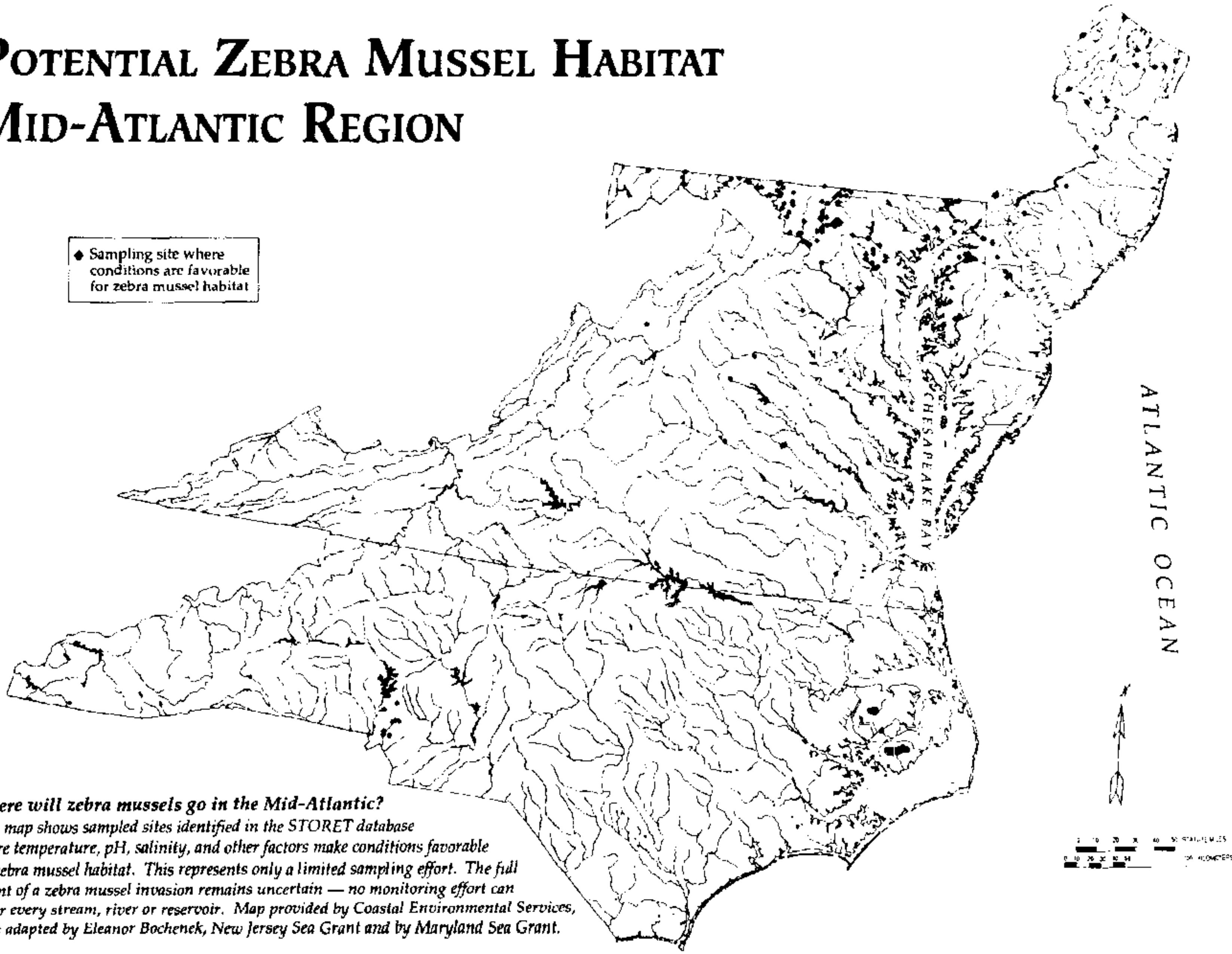

Where will zebra mussels go in the Mid-Atlantic?
This map shows sampled sites identified in the STORET database where temperature, pH, salinity, and other factors make conditions favorable for zebra mussel habitat. This represents only a limited sampling effort. The full extent of a zebra mussel invasion remains uncertain — no monitoring effort can cover every stream, river or reservoir. Map provided by Coastal Environmental Services, Inc.; adapted by Eleanor Bochenek, New Jersey Sea Grant and by Maryland Sea Grant.

Foreword

Dan Terlizzi
Maryland Sea Grant Extension

A popular aphorism maintains that there is a silver lining for every dark cloud. Zebra mussels have been the darkest cloud yet in the invasion biology of North America. Zebra mussel clean-up, prevention and treatment measures — which are expected to cost billions over the next decade in the Great Lakes region alone — promise to be a serious problem in the Mid-Atlantic and other regions as well. What fool with rose colored optics would look for a silver lining here? I believe that at some point in the near future we will review the threat posed by the zebra mussel invasion, recognizing the complacency we have tolerated for too long, and realize that *Dreissena polymorpha* taught a valuable — as well as expensive — lesson.

We have been well aware that shipping and ballast water discharge have been responsible for over 40 introductions in the Great Lakes region alone. We have become increasingly aware that there are ecological consequences to these introductions. These impacts seemed relatively mild until zebra mussels arrived. We had fair warning. As the list of aquatic nonindigenous species grew, we knew that introductions were occurring with serious frequency and that at some point a harmful invader was likely to be introduced. We were playing a kind of ballast biota roulette. There is to my knowledge no available method for predicting risk based on invasion frequency, although the work of Dr. Jim Carlton and his colleagues has taken a significant step in getting there. Clearly, we can ill afford a disastrous introduction like the zebra mussel every 25, 50, or even 100 years. And yet it appears that disruptive introductions may actually occur in shorter intervals of about 10 years.

The First Mid-Atlantic Zebra Mussel Conference was organized for two purposes: preparation and prediction. Preparation, as a key to preventing disruption of utilities, has become necessary after witnessing the Great Lakes experience. This spirit of preparedness has been the motivation behind establishment of the Mid-Atlantic Sea Grant Network's zebra mussel outreach program, funded by the National Oceanic and Atmospheric Administration (NOAA). Prediction is important in the region's planning for zebra mussels. It will allow us to direct educational efforts at high risk areas and to assist resource managers in making decisions about boating regulations, monitoring and treatments.

I believe that the conference provides an invaluable educational base. The risk reports prepared by the individual states will be useful guides in directing educational efforts and evaluating the success of our predictions in the future. Further information from the second evaluating the success of our predictions in the future. Further information from the second Mid-Atlantic Zebra Mussel Conference (June 1-3, 1994 in Atlantic City, New Jersey) is available from New Jersey Sea Grant. A list of zebra mussel materials produced by all the Sea Grant programs in the Mid-Atlantic Region, *Zebra Mussel: Present Threat, Future Danger?*, is available from the Delaware Sea Grant College, Lewes, Delaware. The Zebra Mussel Information Clearinghouse ((716) 395-2516), sponsored by the New York Sea Grant Extension, also provides research reports, periodicals, and bibliographies.

A program on this scale requires a good deal of cooperation and assistance. The Zebra Mussel Conference planning committee included: Tracey Bryant, Ed Christoffers, Barbara Doll, Bill DuPaul, Jack Greer, Ron Klauda, Roger Mann, Garry Smythe, Daniel E. Terlizzi, and Alex Wypyszinski. Private industry gave invaluable support to the program. Robin Tolliver and Jeannette Connors provided most of the organizational support and cheerfully handled the registrations. Ilse Grove assisted in draft preparation. We all owe a great deal to Jim Falk of Delaware Sea Grant for his very capable coordination of projects and reports. The Sea Grant booths of the entire Mid-Atlantic Region represented an impressive display of outreach materials and served to further demonstrate the cooperative spirit that has characterized this project from the outset.

Dan Terlizzi
Maryland Sea Grant Extension Program
Annapolis, Maryland

Overview

Criteria for Predicting Zebra Mussel Invasions in the Mid-Atlantic Region

Patrick Baker, Shirley Baker and Roger Mann
Virginia Institute of Marine Science
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INTRODUCTION

The papers in this volume present a series of forecasts concerning the future of zebra mussels, *Dreissena polymorpha*, in mid-Atlantic states. What is the probability that zebra mussels will invade specific bodies of water within a given state? If they do invade, will they become economic and ecological pests as they have in portions of the Great Lakes? These and similar questions will be addressed, with the expectation that management strategies can be developed to delay, mitigate, or possibly even prevent zebra mussel invasions in some areas.

The probability of invasion is related to the frequency of inoculation and survival of zebra mussels in a body of water. A variety of dispersal mechanisms and the frequency and relative importance of each inoculation affect the overall chance that a reproducing population of zebra mussels will become established in a lake or estuary. The probability of invasion of a specific body of water, hereafter referred to as the *risk* of invasion, is the topic of the first portion of this chapter.

Prior experience with zebra mussel invasions in Europe and other parts of North America indicates that, initially, population growth is not limited by predators, parasites, or other biological factors. However, certain abiotic parameters seem to limit zebra mussel populations in Europe. Therefore, the criteria for predicting the success of zebra mussel invasion in the mid-Atlantic region are primarily physical environmental parameters, and especially aspects of water chemistry. The degree to which a particular body of water conforms to the known optimum physiological requirements for zebra mussels is here termed its *susceptibility*. The second part of this chapter is a review of the physiological requirements used to predict susceptibility. For an example of similar predictions for other regions, see Neary and Leach (1992).

A second species of *Dreissena*, designated the "quagga mussel" (its taxonomic identity is uncertain), has been found in parts of the Great Lakes and New York inland waters (May and Marsden, 1992). At present, nothing is known about the dispersal or physiological requirements of the quagga mussel, except that it lives with *Dreissena polymorpha* and dominates some deep-water populations (Marsden, 1993). Throughout this chapter, *Dreissena* is used to indicate both the zebra mussel and the quagga mussel.

INVASION RISK

Dispersal Mechanisms of Zebra Mussels

Invasion *risk* is defined as the probability that zebra mussels will inoculate a specific body of water in sufficient numbers to establish a viable population. As will be explained, risk is related to the number of zebra mussels inoculated, environmental conditions, and the mechanisms of inoculation.

Terminology for biological invasions merits a brief discussion. An *invasion* is the successful (reproducing) establishment of a species in an area in which it was previously absent. The vector for invasion can be either human-mediated or natural. When an invasion is known to be human-mediated, it can be termed an *introduction*. Thus, *Dreissena* was *introduced* to Lake St. Clair, Michigan, and from there *invaded* (by natural *dispersal*) Lake Erie and Lake Ontario. The actual event that leads to an introduction, such as the release of ballast water containing larvae, is termed *inoculation*, and the process by which the new species becomes a self-maintaining population is termed *establishment*. Thus, *inoculation* and *establishment* are events within an *introduction*, which is itself a specific form of *invasion*. These usages come from no single source, and alternate terms are used elsewhere, but the above are generally consistent with modern literature on aquatic biological invasions.

Population Establishment

One of the most difficult aspects of predicting biological invasions is forecasting when (how soon) an invasion will occur. *Dreissena* invaded the Great Lakes some time shortly prior to 1988 (Hebert *et al.*, 1989), but ballast water, the mechanism responsible for invasion, existed for decades before *Dreissena* became established (Carlton, 1993). Similarly, the rate and direction of dispersal by both natural and human-mediated means from the Great Lakes has often defied prediction. For example, *Dreissena* has been present in an upper portion of the Susquehanna River in New York since at least 1991 (Lange and Cap, 1992) but to date has not appeared in downstream portions. This absence does not mean that zebra mussels will not invade downstream, but we are unable to predict their invasion.

We have limited understanding of how some inoculations may be favored over others. *Dreissena* reproduces sexually, releasing male and female gametes into the water. Prior research on other aquatic organisms (Pennington, 1985; Lasker and Stewart, 1992) shows that gamete viability decreases dramatically with dilution. Therefore, low-density populations of benthic invertebrates have much lower reproductive success than high-density populations. Animals in the initial inoculation of *Dreissena* must be in sufficient proximity to spawn and produce offspring in sufficient quantities to, in turn, reproduce. Larvae disperse in the plankton and undergo high mortality; those that survive to settlement are widely scattered, and only larvae that settle near others can reproduce. Thus, the greater the founding population, the greater the chance of establishment, and the more quickly the population will attain high levels. Dispersal mechanisms that deliver many individuals to the same location are the most likely to spread invasions (Johnson and Carlton, 1993).

There are two practical aspects to the above observation. First, it is cost-effective for management agencies to concentrate first on major invasion vectors, rather than trying to prevent every possible mechanism for invasion. Second, when obtaining public cooperation in limiting *Dreissena* invasion, it is important to make individuals believe that their own reasonable efforts can make a difference in *Dreissena* invasion. The latter aspect has been discussed by Johnson and Carlton (1993).

Natural Dispersal

Larval Dispersal

Dreissena is unusual among freshwater bivalves in that it has planktonic larvae and postlarvae (Griffiths *et al.*, 1991; McMahon, 1991). Postlarvae drift passively with currents by means of long byssal threads (Martel, 1992). Planktonic larvae swim by means of the velum, a ciliated organ. Most bivalve larvae have swimming rates of less than 1 mm s^{-1} (Mann and Wolf, 1983; Jonsson *et al.*, 1991; Mann *et al.*, 1991) and therefore cannot swim against most currents. Juveniles and adults can crawl actively but not rapidly. *Dreissena* is more adapted to lakes (no net currents) or estuaries (bidirectional currents), than to rivers (unidirectional current) (Neumann *et al.*, 1993). Rivers with attached oxbow lakes, navigational locks, or other calm backwaters could probably support significant populations of *Dreissena* (e.g. Biryukov *et al.*, 1968). Estuaries in southern Russia, Ukraine, and Kazakhstan comprise the native range of *Dreissena*. The largest populations outside of the native range, in Europe and North America, live in lakes, estuaries, and other calm waters (Shtegman, 1968; Wolff, 1969; Stanczykowska, 1977; Griffiths *et al.*, 1991).

High densities of *Dreissena* in non-estuarine rivers can be maintained only by a continual input of individuals from upstream lakes or backwaters. Thus, streams without such areas cannot be successfully invaded by *Dreissena*. Unfortunately, most major North American rivers, including those along the eastern coastline of the U.S., have upstream reservoirs that could support *Dreissena* populations, given the correct water quality parameters. High densities of *Dreissena* can be attained in rivers downstream of lakes (e.g. Piesik, 1983; Neumann *et al.*, 1993). There are no data on the effect of reservoir size or flushing rates on downstream *Dreissena* population densities. For the present, all freshwater downstream of a lake capable of supporting *Dreissena* populations must be considered at risk of invasion.

Dreissena has a limited to tolerance to salt water, but most major eastern estuaries in North America have large freshwater tidal portions. Even in years of low freshwater input, significant portions of most estuaries remain fresh. *Dreissena* larvae and postlarvae could be retained within the estuary by the same mechanisms used by oyster larvae (Seliger *et al.*, 1982; Mann, 1988). A native species closely related to *Dreissena*, the false mussel *Mytilopsis leucophaeata*, is already present in oligohaline and freshwater portions of estuaries from New York to Texas (Abbott, 1974). Since pH and calcium levels of these estuaries are often ideal for *Dreissena*, they must be considered at risk of *Dreissena* invasion. Furthermore, fresh portions of estuaries will eventually be invaded if *Dreissena* populations are established in upstream lakes or reservoirs. The St. Lawrence River in Quebec and the Hudson River in New York are two North American examples of freshwater estuaries invaded from upstream (New York Sea Grant, 1992).

Adult and Juvenile Dispersal

Adults and juveniles of *Dreissena* crawl by alternately attaching and releasing byssal threads. Based on crawling rates of juvenile marine mussels (*Mytilus* spp. these authors, unpubl. data), *Dreissena* individuals can probably move several meters per day. A very short stream between a *Dreissena*-infested reservoir and an upstream, non-infested reservoir would probably not be a barrier against invasion by crawling individuals. Two examples of this situation include a series of ponds in a typical golf course and the network of ponds, canals, and ditches in many coastal cities in the mid-Atlantic region. *Dreissena* individuals probably cannot circumnavigate a waterfall or spillway or crawl up a rapidly flowing stream more than several hundred meters in sufficient numbers to establish a new population in an upstream reservoir.

Natural mechanisms such as amphibious animals could transfer byssally-attached adults or juveniles between very close but separate bodies of water. These mechanisms, reviewed by Carlton (1993), include aggregations attached to the carapaces of turtles migrating between nearby bodies of water. Certain species of turtle may become important in dispersing *Dreissena* within regions with many small lakes or in coastal regions with many small estuaries isolated from each other by low, narrow terrestrial barriers. This last condition is typical of the coastal plain from New Jersey to Texas. In the mid-Atlantic region, the eastern musk turtle (*Stenotherus odoratus*), a common species living in a variety of bodies of water, and the much larger snapping turtle (*Chelydra serpentina*) are noted for having heavy algal fouling (McCauley, 1945; Martoff *et al.*, 1980; J. Brown, Virginia Inst. Marine Science, pers, comm.).

Waterfowl have been suggested by a variety of authors as potential vectors of transport. Carlton (1993) reviews evidence for and against this mechanism of invasion. Birds could transport *Dreissena* many kilometers by a variety of means, although the actual numbers transported by any one bird would be small relative to the numbers that could be transported by almost any human-mediated process. The role of large flocks of migratory birds in dispersing *Dreissena* is worth investigating, however.

It should be noted that so far the spread of *Dreissena* across natural barriers in North America can be attributed to human actions alone. Thus, while amphibious animals may be mechanisms of invasion, most emphasis should be placed on controlling human-mediated dispersal mechanisms.

Human-Mediated Dispersal Mechanisms

Overland Transport

Overland transport of *Dreissena* by recreational vessels or the trailers that transport them has received attention as the primary mechanism for the invasion of inland lakes separated from other navigable waters. Either vessel hulls or their trailers are the most probable vector for the invasion of the upper Susquehanna drainage in New York state (Lange and Cap, 1992). Baltimore County, Maryland, has restricted the use of recreational vessels in several municipal reservoirs in response to this threat. McMahon and Payne (1992) have shown that *Dreissena* can survive several days out of water even at high temperatures (Carlton, 1993). Public education has focused on the potential for *Dreissena* attached to vessel hulls to be moved between lakes, but under certain circumstances, more *Dreissena* will probably be transported on strands of aquatic macrophytes that become entangled in boat trailers (Carlton, unpubl. data). Invasions that are known or suspected to result from overland transport have been fewer, so far, than expected. The reason may be that, normally, few individuals are introduced by a single inoculation.

Juveniles or adults will be transported overland by the above mechanisms. To be introduced to the new location, the *Dreissena* must detach from the vessel or trailer. Juveniles are generally more mobile than adults (Eckroat *et al.*, 1993). *Dreissena* attached to macrophytes entangled with the boat trailer may detach with the plant in the new body of water. Furthermore, a piece of plant with attached *Dreissena* could drift rapidly down a river until it reached a lake, where a population could be established. In contrast, adult *Dreissena* sinking individually into a river are less likely to reach a downstream lake or successfully establish a population.

Ballast Water, Bilges, Bait Wells

It may be due to chance that the Great Lakes were invaded by *Dreissena* before another North American body of water. It is believed that *Dreissena* was introduced into the Great Lakes by the release of ballast water containing larvae or postlarvae from the holds of ore carriers from Europe. Evidence for this route has been well documented (see Carlton, 1993, for review). Guidelines to prevent further introductions of exotic species by releasing ballast water into the Great Lakes have been established. However, compliance is not complete (J. Carlton, pers. comm.), and a single inoculation under optimal conditions may be sufficient to permit invasion. Furthermore, ballast water release into other North American freshwater ports remains undocumented. For example, the port of Richmond, Virginia, is visited regularly by container ships from Antwerp, Belgium, and other European ports (Meehan Overseas Terminal, Inc., 1991). Alexandria, Virginia, is visited six to seven times annually by ships from Quebec City, Quebec, where *Dreissena* is established in the St. Lawrence River (Robinson Terminal Warehouse Corp., Alexandria, Virginia, pers. comm.). The ballast water exchanged, though undocumented and unregulated, represents a potential introduction of *Dreissena* into Virginia. Port logs, sometimes available upon request, will no doubt reveal many further points of potential introduction.

Bait wells, bilge water, or shipments of live fish or bait harbor larvae or postlarvae for several days, although to date no specific examples of this means of transport occurring in North America are known. (See Carlton, 1993 for a review.)

Vessel Transport Between Estuaries

Once established in Lake St. Clair and Lake Erie in 1989, *Dreissena* was subsequently identified at many isolated points elsewhere in the Great Lakes and in the Erie Canal, New York. The vector of dispersal in these cases was thought to be vessel hulls with byssally-attached adults or juveniles (Griffiths *et al.*, 1991). Vessels moving rapidly upstream or across salinity barriers are a major mechanism for expanding the range of *Dreissena*. Postlarvae and juveniles attached to the hull of a recently moved vessel can detach at a new moorage and accumulate on nearby stationary substrate. Adults attached to the hull can also spawn at a new location. The relative importance of these two phenomena depends on the number of postlarvae or juveniles transferred in the first case, or the number of adults and the amount of time spent at the new moorage in the second case. The resettlement of postlarvae and juveniles from vessel hulls is likely to be favored during the reproductive season by vessels with relatively clean hulls that do not spend extended periods at any particular mooring. A high density of microscopic *Dreissena* postlarvae and juveniles would be unnoticed by persons visually inspecting vessel hulls in an attempt to prevent the spread of *Dreissena*. On the other hand, some vessels, especially barges, spend weeks or months at aparticular moorage, giving fouling organisms attached to their hulls multiple opportunities to spawn. In such cases, vessels with large fouling populations of adult *Dreissena* would be favored as a method for introducing this species.

Barges in particular represent a major vector for *Dreissena* dispersal because of their large hull areas, which are infrequently cleaned, and their long residence periods at any particular moorage. Once moved, barges may be moored for months or even years, giving any fouling organisms many opportunities to reproduce. In addition, freshwater regions are attractive to many vessel owners for long-term moorage because of the relative lack (prior to *Dreissena*) of fouling organisms. Although the hulls of other vessels traveling between estuaries are generally smaller and cleaner than barge hulls, the possibility of introduction via smaller vessels cannot be ruled out. Even a small, unnoticed portion of a hull could harbor tens of thousands of adult, juvenile, and postlarval *Dreissena*.

Given the ability of *Dreissena* to tolerate moderately saline waters for at least a short period, vessel traffic represents a major intracoastal vector for the spread of *Dreissena* between estuaries. *Dreissena*, present in both the Hudson and Susquehanna Rivers (New York Sea Grant, 1992), could potentially spread to most other estuaries with barge traffic between New York and Florida. At present no records on commercial or recreational traffic between freshwater estuarine ports in North America have been compiled. The length of time that *Dreissena* can tolerate full seawater, perhaps by completely closing their valves, is unknown. They can survive several days out of water, attached to pleasure craft hulls (McMahon and Payne, 1992), and several days without oxygen (Mikheev, 1968).

Introduction of *Dreissena* to a body of water via the hull of a vessel does not automatically ensure establishment. High survival of large numbers (e.g. millions) of *Dreissena* during the passage overland or in high salinity is required for a population to become established. Water conditions favorable for growth and reproduction in the host estuary and long moorage of the fouled vessel increase the probability of establishment.

Intentional Introduction

The possibility of deliberate, misguided introductions of *Dreissena* must be seriously considered. *Dreissena* populations, believed to be responsible for a dramatic increase in water clarity in Lake Erie (Wright and Mackie, 1990; Di Vincenzio, Newport News *Daily Press*, Dec. 5, 1991; Walker, 1991; Cohen, 1992; Greenberg *et al.*, 1992; MacIsaac and Sprules, 1992; Leach, 1993; Sisson, 1993), would probably have the same effect on any small lake to which they were successfully introduced. Water clarity, while of uncertain ecological advantage, is aesthetically attractive. Other reasons for intentionally introducing *Dreissena* could include increasing biodiversity, providing food for other organisms, or providing a new bait source. *Dreissena* are exceptionally easy to collect and transport. If *Dreissena* are used as bait, there is a risk of recreational fishermen dumping left-over bait into a pond or lake. Many previous introductions of freshwater mollusks are believed to have been carried out by private landowners, intentionally or through carelessness (Carlton, 1993). Because *Dreissena* larvae disperse, a small lake that retains and concentrates successive generations may be as much at risk from a single introduction as a large lake.

SUSCEPTIBILITY TO INVASION: PHYSIOLOGICAL REQUIREMENTS OF ZEBRA MUSSELS

This section reviews published data on the physiological requirements of *Dreissena* with respect to water quality and chemistry. Four common aspects appear critical to the persistence and reproduction of *Dreissena* populations: temperature, salinity, pH, and calcium content. Table I summarizes this information for adults and larvae.

Temperature

The 11-12° C temperature range at which adult *Dreissena* grow in European lakes (Stanczykowska 1977) corresponds to the values of 10-12° C reported by Mackie (1991) for *Dreissena* in the Great Lakes. Bij de Vaate (1989), however, observed that growth of *Dreissena* in the Netherlands occurred at temperatures as low as 6° C. In a review of European lakes with *Dreissena*, Strayer (1991) reported that the largest populations were in lakes with a mean annual temperature of only 6-9° C, inferring that temperatures exceeded that range only half of the year. Borcherding (1991), who reported gametic growth at temperatures as low as 2-4° C, suggested that reported differences could be due in part to food quality and quantity for different populations. Differences may also reflect methods of measuring or defining growth. Schneider (1992) predicted that growth rate is strongly affected by temperature, with slower growth rates at low temperatures. The minimum temperature tolerance for survival appears to be just above freezing (Strayer, 1991). Nowhere in the mid-Atlantic region are temperature regimes cold enough to limit *Dreissena* populations. The maximum temperature for adult *Dreissena* growth has been reported as 26-33° C (Stanczykowska, 1977).

Table 1. Physiological Requirements of Zebra Mussels.

	Temperature °C	Salinity ‰	pH	Calcium ppm
Adult Survival	0-33	0-12	7.0-?	unknown
Adult Growth	6-33	0-6	7.5-?	(34.5 - 76) (0-0.6‰)
Larval Growth	12-24 (17-18)	0	7.4-9.4 (8.4-8.5)	12-106+ (40-?)

Values expressed as ranges; optimum ranges are enclosed in parentheses. References are given in section on Physiological Requirements.

Gametogenesis in *Dreissena* has been reported to occur at temperatures as low as 2-4° C in the presence of good food quality (Borcherding, 1991). Spawning is known to occur at 12° C (Sprung, 1987; Bij de Vaate, 1989; Borcherding, 1991) and at 22-23° C (Haag and Garton, 1992). Sprung (1987) reported a loss of sperm motility in *Dreissena* at 26° C and zygote failure above 24° C. This last evidence indirectly supports predictions by Strayer (1991) that populations of *Dreissena* will be heat-limited in the southernmost regions of North America. Haag and Garton (1992), however, reported that *Dreissena* in Lake Erie spawned when water temperatures rose above 26° C; the maximum temperature at this time was 30° C. Therefore, temperatures as high as 30° C may not inhibit reproduction. In a review of climatological conditions in Europe, Strayer (1991) reported that the highest mean monthly temperature tolerated by *Dreissena* was 26.4° C. Optimum larval rearing temperatures in the laboratory were reported to be about 17-18° C by Sprung (1987).

In temperate regions with seasonal temperature fluctuations, there will always be optimal temperature windows during of the year for spawning. Hence, the temperature tolerance of adults is an important factor in the continued survival of populations. *Dreissena* tolerates extended periods of temperatures exceeding 25° C, so the majority of the United States and southern Canada are within the temperature tolerance of this species.

Salinity

Mackie and Kilgour (1992) reported an LC_{50} of 7.6‰ salinity at 96 hours for unacclimated adult *Dreissena* at 19° C. Over a period of 42 days, *Dreissena* that had been slowly acclimated had only 15% mortality at 8.0‰ salinity at 4° or at 10° C. Barber (1992), however, reported 100% mortality of adult *Dreissena* within 52 days in water slowly raised from 0‰ to 2.7‰ at 15° C. Wolff (1969) cited an unpublished source stating that *Dreissena* can survive salinities as high as 12.2‰, although the circumstances of exposure were not given. In the delta region of the Netherlands, adult *Dreissena* tolerate a constant salinity of 4‰ in ponds, but they are not found at mean salinities above 0.6‰ in estuaries, (Wolff, 1969). Wolff (1969) concluded that the higher mean salinities could be tolerated only if there were not tidally-driven fluctuations.

The apparent difference in the salinity tolerance of *Dreissena*, reported by Mackie and Kilgour (1992) and Barber (1992) (above), may reflect a strong interaction of salinity and temperature (with higher salinity tolerance at lower temperatures), or it may reflect physiological differences in the experimental animals. Hebert *et al.* (1989) and Garton and Haag (1991) reported high genetic variability among *Dreissena* in the Great Lakes. This genetic variability may be the source of differencies in physiological tolerances.

When plotting the potential spread of *Dreissena* in North America, it is safest to assume that they can tolerate salinities of at least 12.2‰ for a few days. A significant number of *Dreissena* fouling slow-moving vessels such as barges moved periodically between freshwater portions of estuaries, would survive during transport. For example, a barge fouled by *Dreissena* in the Susquehanna River in Pennsylvania or Maryland could probably be towed to a new anchorage (and a new watershed) in Philadelphia, Pennsylvania, or Alexandria, Virginia, without submitting the *Dreissena* to lethal osmotic stress. On the other hand, only areas with salinity below 1‰ are likely to maintain high *Dreissena* densities. Walton (1993) found *Dreissena* in salinities as high as 6‰ in the Hudson river, but high densities (>1000 m^{-2}) were maintained only at a site that never exceeded 3‰ salinity and was often fresh.

The salinity tolerances of *Dreissena* spawning adults, eggs, veliger larvae, or planktonic postlarvae, have not been reported. In a review of physiological tolerances of oysters of the genus *Crassostrea*, (Mann *et al.*, 1991) reported that the ranges of salinity tolerances for spawning adults or for larvae were equal to or less than those for adult survival.

pH, Calcium and Other Chemical Parameters

The pH values in North American fresh waters depend upon rainfall acidity and bedrock composition. Adult *Dreissena* have a heavy periostracum covering all but the oldest, thickest portion of the shell (pers. obs.). The periostracum in freshwater mollusks is thought to aid in prevention of shell dissolution (McMahon, 1991); *Dreissena* may thus be able to survive periods of relative acidity. The minimum pH tolerance of adult *Dreissena* appears to be 7.0, the point at which shell dissolution exceeds calcium uptake (Vinogradov *et al., 1993)*, but

Ramcharan *et al.* (1992), in a literature survey of European lakes, reported that significant populations of *Dreissena* persisted only above a mean pH of 7.5.

Larval development in *Dreissena* appears to be tightly regulated by pH. Sprung (1987) reported *Dreissena* egg survival at a pH range of 7.4-9.4. Optimal survival occurred at pH 8.4-8.5 and temperatures of 18-20° C. Even if these values vary among *Dreissena* populations under different rearing conditions, it appears that at least during the reproductive season, *Dreissena* requires slightly alkaline water.

Calcium, a major component of mollusk shells, appears to be limiting in some cases. Ca^{2+} (from $CaCO_3$) is expressed either as "hardness" (milliequivalents or meq), or as mg per liter. European lakes with large populations of *Dreissena* have hardness levels of about 1.73-3.16 meq (Strayer, 1991), or a minimum of about 34.5 mg Ca^{2+} l^{-1}, a mean of about 45-52 mg Ca^{2+} l^{-1}, and a maximum of 76 mg Ca^{2+} l^{-1} (Ramcharan *et al.*, 1992). These values should not be considered limits, but the range of calcium concentrations at which large populations of *Dreissena* have been reported to exist in Europe. Actual requirements for adult *Dreissena* have not been determined in the laboratory. Sprung (1987) reported minimum embryo survival at 12 mg Ca^{2+} l^{-1} and optimum survival at levels of 40 mg Ca^{2+} l^{-1} (2.0 meq) and above. Larvae grew relatively well at calcium levels of 106 mg l^{-1}, the maximum level tested.

Other salts, including $MgSO_4$, NaCl, $KHCO_3$, $NaHCO_3$, and $MgCl_2$, do not appear limiting to *Dreissena* embryos (Sprung, 1987). Potassium (KCl) is lethal at levels of about 100 ppm (LC_{50} for 24 hours) (Fisher and Stromberg, 1992), but concentrations rarely approach this level in natural waters. In a review of European lakes, (Ramcharan *et al.*, 1992) reported that the mean phosphate (PO_4) level of lakes with stable populations of *Dreissena* is about 0.12 mg l^{-1}, with a maximum level of 0.18 mg l^{-1} and a minimum of 0.05 mg l^{-1}. However, *Dreissena* populations have been reported in lakes with no measurable free phosphate. Phosphorus and nitrogen may have indirect roles on *Dreissena* population growth rates, since they are critical nutrients affecting the abundance of freshwater phytoplankton, the primary food source for *Dreissena*. Ammonia (NH_3) is lethal to *Dreissena* at a level of about 2 mg l^{-1} (Nichols, 1993), but this level is lethal to many other aquatic organisms as well.

Oxygen

With limited data, (Sprung 1987) concluded that *Dreissena* larvae survived for short periods at oxygen levels as low as 20% of saturation at 18° C. This oxygen level in natural systems is considered to be a hypoxic condition, which, if it persists for a significant period, causes problems far worse than zebra mussel infestations. During periods of heaviest pollution in the 1970s, hypoxia eradicated *Dreissena* from much of the Rhine River in Germany (Neumann *et al.*, 1993). The degree of adult survival under hypoxic conditions is unknown, but juvenile oysters have been shown to be significantly more tolerant of hypoxia than larvae (Widdows *et al.*, 1989). Thus, adult and juvenile *Dreissena* are probably more tolerant of hypoxia than larvae. Under anoxic conditions, 100% mortality of *Dreissena* occurs in about 6 days at 17-18° C, and in 3 days at 23-24° C (Mikheev, 1968). McMahon and Alexander (1991) concluded that *Dreissena* are poorly adapted for survival at low oxygen levels in warm water (25° C), which indirectly supports Strayer's (1991) predictions of a warm-water limitation to *Dreissena* invasion. In general, however, only severely stressed aquatic systems would have oxygen levels low enough to inhibit *Dreissena* invasions.

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Potential Range of the Zebra Mussel, *Dreissena polymorpha*, in and near Virginia

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INTRODUCTION

This chapter is devoted to predictions of the probability of invasion by the zebra mussel, *Dreissena polymorpha* (and the quagga mussel, *Dreissena* sp.) to specific bodies of water in Virginia. The criteria for these predictions are outlined in a previous chapter in this volume. Probability of invasion is divided into *risk* and *susceptibility*. *Risk* refers to the chance, relative to other sites, that a body of water will be inoculated with *Dreissena* in sufficient number to establish a population. Inoculation can occur by natural dispersal, but in the mid-Atlantic region, is most likely to occur through accidental introduction by humans, especially via boat traffic. *Susceptibility* of a body of water refers to the probability, based on known physiological requirements, that *Dreissena* could survive and reproduce. In this chapter predictions are made, concerning both risk and suceptibility, for several bodies of water in Virginia.

Original *Dreissena* populations are native to freshwater or brackish portions of estuaries with bidirectional water flow in eastern Europe and central Asia (Stanczykowska, 1977). Most subsequent invasions have occurred in lakes and freshwater portions of estuaries (Shtegman, 1968; Wolff, 1969; Stanczykowska, 1977; Griffiths *et al.*, 1991). Freshwater portions of estuaries and natural and artificial reservoirs in the mid-Atlantic region of the United States (here defined as drainages east of the Appalachian Mountains between New York and South Carolina) are therefore at risk from invasion by *Dreissena*, given correct water quality parameters. *Dreissena* populations cannot be maintained at high levels in freshwater rivers without an upstream reservoir or lake because of the planktonic larvae and postlarval stages.

TEMPERATURE-LIMITED SYSTEMS

None of the systems in the mid-Atlantic region fall below the minimum temperature requirements for *Dreissena* reproduction, but most estuaries and lowland reservoirs in South Carolina and Georgia have summer temperatures that may exceed *Dreissena* tolerances, based on reported European limits (Strayer, 1991) and reported physiological limits of zygotes and adults (Sprung, 1987; McMahon and Alexander, 1991). Reported European temperature limits for *Dreissena* may be based on geography as much as temperature, however, since the Mediterranean Sea acts as a southern barrier. The movement of *Dreissena* down the Mississippi River, tracked recently as far as Vicksberg, Mississippi (New York Sea Grant, 1993), should be closely monitored as a natural test of temperature tolerance of this species in North America.

ESTUARIES

Virtually all estuaries with permanent freshwater inputs in the mid-Atlantic region have tidal freshwater portions and are potentially suceptible to invasion by *Dreissena*. Examples of major estuaries (more than 1000 ha. of open, permanently fresh water) between New York and North Carolina include the Hudson River; the Delaware River; the Susquehanna, Potomac, Rappahannock, Mattaponi, Pamunkey, and James Rivers in Chesapeake Bay; Currituck and Albemarle Sounds, and Pamlico, Pungo and Neuse Rivers, in North Carolina (Coupe and Webb, 1984; U.S. Army Corps of Engineers, 1984; NOAA, 1985).

Estuaries can be invaded by *Dreissena* in several ways. If zebra mussels invade the freshwater portion of a river or a lake via overland routes with recreational vessels and become established, they will subsequently invade downstream waters. Alternately, estuaries can be invaded from the seaward direction by vessels traveling from other estuaries. Ballast water containing *Dreissena* larvae is a well-known vector. Under some circumstances, adult zebra mussels may also be introduced on the hulls of vessels that do not spend a large amount of time in high-salinity water.

Canals partially eliminate natural terrestrial and high-salinity barriers between major estuaries and smaller estuaries of the Intracoastal Waterway and may facilitate *Dreissena* transfer between basins. For example, the Chesapeake-Delaware canal, connecting oligohaline portions of those respective estuaries, is, at times of high freshwater runoff, fresh or nearly fresh at both ends (U.S. Army Corps of Engineers, 1985; NOAA, 1985; Mellor, 1986) and thus represents a route for natural invasion of the Delaware estuary by *Dreissena* from the Susquehanna drainage (Lange and Cap, 1992; New York Sea Grant, 1993). Two canals, the Dismal Swamp Canal and the Chesapeake and Albemarle Canal, connect the Elizabeth River estuary in southern Chesapeake Bay, Virginia, to freshwater portions of the Albemarle and Currituck Sounds in North Carolina. The freshwater portions of the two formerly separate estuaries are now a single body of water. The Alligator River and Pungo River Canal connect tidal fresh waters of Albemarle and Pamlico Sounds, respectively, in North Carolina. Similar examples can be found elsewhere along the Intracoastal Waterway. Even if high salinity regions act as barriers to natural range expansion by *Dreissena*, barge and other boat traffic carrying *Dreissena* along these canals could pass relatively quickly through high salinity areas. *Dreissena* can tolerate at least several days of relatively high salinity.

Dreissena has already invaded the Hudson River estuary (Walton, 1993), and appears poised to invade the Susquehanna River estuary (Lange and Cap, 1992; New York Sea Grant, 1993). These estuaries will serve as models of biological and economic impacts in other mid-Atlantic estuaries. In addition, they will serve as reservoirs of *Dreissena* to invade adjacent estuaries, particularly on the hulls of vessels travelling between estuaries, as discussed in the Introduction.

Some, but not all, of Virginia's freshwater and estuarine regions are at risk of or susceptible to, invasion and establishment by *Dreissena*. The risk of inoculation varies between estuaries, according to the level of boat traffic and other human factors. Susceptibility of establishment, on the other hand, varies according to water chemistry. In the following discussion for each estuary, values for pH and calcium are the maximum reported monthly averages for summer (May to September), based on existing water chemistry data.

Pocomoke River

The Pocomoke River is at low risk of inoculation and is not susceptible to establishment of *Dreissena*. Like other estuaries on the Delmarva Peninsula, the Pocomoke has relatively low freshwater inflow and no major upstream reservoirs for *Dreissena* to invade. There is little commercial vessel traffic into the estuary, although the channel is maintained to Snow Hill, Maryland, where there is a marina. Opportunities for inoculation, therefore, are relatively limited, relative to other Chesapeake Bay estuaries.

Water chemistry data for February, 1991, near the upstream tidal limit at Snow Hill showed low pH (6.1) and calcium content (4.3 ppm) (James *et al.*, 1991). If *Dreissena* were to invade this estuary, conditions would not favor high population levels.

Potomac River

The Potomac River is at high risk of inoculation and highly susceptible to establishment of *Dreissena*. The tidal freshwater portion of the Potomac estuary stretches from Washington, D.C., to Quantico, Virginia, in most years. There are few lakes adjoining the Potomac River estuary; therefore, the invasion of the Potomac River drainage by *Dreissena* on recreational vessels from an adjoining drainage is less likely to occur than in some other systems. The Virginia portion of the Potomac/Shenandoah drainage, for example, has only about 40 public boat ramps (most of which are on rivers) compared to more than twice that number for some other Virginia drainages of similar size (DeLorme Mapping Co., 1989). Resource managers have fewer major lakes to monitor in a program to prevent the introduction of *Dreissena*. Invasion could occur via intentional, misguided introduction to a farm pond or other small impoundment, however. This possibility can be prevented only through education of landowners and users.

Inoculation of the Potomac by *Dreissena* could also occur from the seaward direction, via ballast water of the hulls of incoming vessels. Ballast water containing *Dreissena* larvae or postlarvae is a distinct risk to the Potomac estuary. Bulk cargo ships from Quebec City, Quebec, arrive in Alexandria, Virginia, 6 to 7 times annually (Robinson Terminal Warehouse Corp, Alexandria, VA, pers. comm.). Alexandria is the largest port in the freshwater portion of the Potomac; Quebec City is on a portion of the St. Lawrence River that has established populations of *Dreissena* (New York Sea Grant, 1993). The amount of ballast water exchanged and the nature of the exchange are unknown. Commercial and recreational traffic into the Potomac estuary from adjoining estuaries is very high, and the Potomac is the closest Virginia estuary to the Susquehanna River, where *Dreissena* is already present.

Water chemistry data indicate that both pH (8.1-8.4, May to September at Washington, D.C.) and calcium content (32-40 ppm) (Prugh *et al.*, 1992) are suitable for *Dreissena* reproduction. If *Dreissena* becomes established in the Potomac estuary, it is likely to rapidly attain pest proportions. This region has already experienced invasion by and abundant growth of the asiatic clam, *Corbicula fluminea* (Phelps, 1991).

Rappahannock River

Susceptibility of the Rappahannock River to *Dreissena* invasion is moderate. The tidal freshwater portion of the Rappahannock estuary extends upstream from Fredricksburg, Virginia, to somewhere between Port Royal and Tappahannock, depending on freshwater inflow levels. Invasion of the Rappahannock could occur from several reservoirs of moderate size upstream. There are 11 public boat ramps in the freshwater portion of the Rappahannock drainage (DeLorme Mapping Co., 1989), as well as several large, privately maintained reservoirs, such as Lake of the Woods, which is surrounded by a housing development. Inoculation could also occur from the seaward direction via fouling on the hulls of vessels from nearby estuaries invaded by *Dreissena*; however, commercial and recreational movement from other estuaries to the Rappahannock is low to moderate.

The lower Rappahannock River has relatively low pH (7.8 in August at Fredricksburg) and very low calcium (5.2 ppm) (Prugh *et al.*, 1992). Based on these data, even if *Dreissena* becomes established here, it is not predicted to have high reproductive success in most years and is unlikely to maintain pest proportions.

Piankatank River

The tidal freshwater portion of the Piankatank River is at relatively low risk of inoculation and is not suceptible to establishment of *Dreissena*. The Piankatank and its adjoining freshwater tidal portion, Dragon Swamp, is the largest of a number of small estuaries on the west side of Chesapeake Bay with drainage basins entirely within the Coastal Plain region. As there are no large upstream reservoirs and no commercial traffic into freshwater tidal portions, the only likely mechanisms of *Driessena* inoculation would be via private introductions to upstream farm ponds or the hulls of small pleasure vessels from other estuaries. At the low pH (6.5 in July at Mascot) and low calcium (13 ppm) levels of the Piankatank, *Dreissena* would be unlikely to survive or reproduce (Prugh *et al.*, 1992).

Data for other small Virginia estuaries are limited. While some estuaries (e.g. the Pocomoke, discussed above) are known to be acidic, the pH and calcium levels of small- to medium-sized impoundments upstream varies dramatically within the same drainage (Virginia Department of Game and Inland Fisheries, unpubl. data). No small estuary, therefore, should be considered safe from *Dreissena* invasion until water quality has been measured and determined to be unsuitable for Dreissena growth and reproduction.

Mattaponi and Pamunkey Rivers

The Mattaponi and Pamunkey Rivers, which unite at West Point, Virginia, to form the York River estuary, are both at moderate risk of inoculation by *Dreissena* and are moderately susceptible to establishment of this species. As the York River is rarely fresh or oligohaline, ever at West Point (NOAA, 1985), freshwater portions of the Mattaponi and Pamunkey are normally distinct from each other. Small tributaries of the two subestuaries are very close to each other, though, and could be host to overland transmigration by animals such as turtles (see Introduction.)

Inoculation of either estuary by *Dreissena* could occur from upstream reservoirs that had been previously invaded overland. The Mattaponi River has several upstream reservoirs of moderate size and recreational use, such as Ni River and Caroline reservoirs. The Pamunkey drainage holds the relatively large Lake Anna (discussed separately in this chapter in the section on lakes). The Mattaponi and Pamunkey drainages contain 12 and 15 public boat ramps, respectively (DeLorme Mapping Co., 1989). Inoculation of the estuaries could also occur via *Dreissena* attached to hulls of vessels coming from invaded estuaries, but probability of invasion by this method is low, due to the relatively limited traffic. Barges with wood chips travel between the upper York River and other estuaries, but the major moorage site in the lower Pamunkey is rarely fresh, and the salinity regime probably is suboptimal for reproduction of *Dreissena*.

Both rivers, which are slightly acidic and have low calcium levels, provide marginal habitat for *Dreissena* growth and reproduction. Near Beulahville, pH of the Mattaponi in July is about 6.9, and calcium content is 3.7 ppm. Near Hanover, pH of the Pamunkey in June is about 6.9, with a calcium content of 9 ppm (Prugh *et al.*, 1992). Even if *Dreissena* becomes established, it is unlikely that it would attain pest proportions in either estuary.

James River

The James River is at high risk of inoculation by *Dreissena* and is highly susceptible to establishment of large populations. The freshwater tidal portion of the James River extends downstream from Richmond to Jamestown, including over 8000 ha of open freshwater on the Chickahominy and Appomattox Rivers. The James River drainage has many large reservoirs with heavy recreational use (high risk of inoculation), and some of these reservoirs could support *Dreissena* populations. Examples include Briery Creek Reservoir, Lake Chesdin, Swift Creek Reservoir, Lake Moomaw, and Little Creek Reservoir. (Lake Chesdin, the largest of these, is discussed separately under the section on lakes.) The danger of introduction via vessel hulls or trailers increases with the amount of recreational use, and the James River drainage has over 90 public boat ramps, mostly on lakes (DeLorme Mapping Co., 1989). In addition, during annual professional bass fishing tournaments on the tidal freshwater portions of the James and Chickahominy Rivers, many vessels are trailered in from other states where they may have been in *Dreissena*-infested waters only a day or two previously.

The risk of inoculation from the seaward direction is also high, via both ballast water and the hulls of incoming vessels. Large vessels containing varying amounts of ballast water regularly visit the port of Richmond from freshwater European ports (Meehan Overseas Terminal, Inc., 1991), some of which have large *Dreissena* populations. Whether freshwater ballast containing *Dreissena* larvae is acquired in Europe and released, undiluted by seawater in Richmond, is unknown, but it appears probable. Barge and other vessel traffic between industrialized areas of the James River and other estuaries in Chesapeake Bay is heavy. There is also heavy recreational traffic from other estuaries.

Conditions for *Dreissena* reproduction are favorable throughout much of the estuary. Two other non-native bivalves, *Corbicula fluminea* and *Rangia cuneata*, have already successfully invaded freshwater and oligohaline portions of this estuary (Diaz, 1977, 1989). The native bivalves *Mytilopsis leucophaeata* (a close relative to *Dreissena*), *Sphaerium transversum*, and *Pisidium casertanum* are also common in oligohaline and freshwater portions of the James River (Diaz, 1977). Near Cartersville, the pH of 8.1 in August and calcium content of 22 ppm (Prugh *et al.*, 1992) are within the minimum requirements for *Dreissena* reproduction.

Elizabeth River and Albemarle Sound

Tidal freshwaters of southeast Virginia, including the Elizabeth River and parts of the Albemarle Sound system, are at risk of inoculation by *Dreissena*, and some regions within this area are suseptible to establishment of the species. The Elizabeth, Nansemond, and Lynnhaven Rivers in southeast Virginia, Currituck Sound and the Pasquotank River in North Carolina (Albemarle Sound); and many lesser bodies of water form an extremely complex estuarine and freshwater system connected by the Intracoastal Waterway and many lesser canals. The northernmost portion of Currituck Sound is Back Bay in Virginia; other connected bodies of water include Lake Drummond (Dismal Swamp), Lafayette River (Norfolk), Rudee Inlet (Virginia Beach), and various small lakes in the cities of Virginia Beach, Chesapeake, Norfolk, and Suffolk. The freshwater portions of the Elizabeth, Nansemond, and Lynnhaven Rivers are relatively small. The Chesapeake and Albemarle Canal, the Dismal Swamp Canal, and lesser waterways are usually fresh, and all of Currituck Sound and most of Albemarle Sound are oligohaline or fresh water, depending on freshwater inflow (NOAA, 1985). All of these bodies of water are connected by a network of canals or ditches (refer to United States Geological Survey topographical maps). If *Dreissena* becomes established in any part of this system, it could eventually spread to all others.

Inoculation of the above region by *Dreissena* is most likely to occur via the heavy recreational and commercial traffic from other estuaries. Since there are few freshwater lakes in Virginia Beach with boat ramps, the risk of inoculation by *Dreissena* on the hulls of recreational vessels trailered from other systems is low. Conversely, thousands of small recreational vessels use creeks, canals, and oligohaline portions of the many small subestuaries in this area. Heavy barge traffic also travels along the Chesapeake and Albemarle Canal, part of the Intracoastal Waterway. *Dreissena* need become established in only one of the other Chesapeake estuaries; sooner or later it will appear in Virginia Beach or City of Chesapeake waterways on small vessel hulls.

The Chesapeake and Albemarle Canal is potentially important in aiding dispersal of *Dreissena*. Even if the canal does not serve as a reservoir for *Dreissena* recruits, it will provide temporary relief from osmotic stress for *Dreissena* fouling vessels that are traveling the Intracoastal Waterway. This could prolong the survival of *Dreissena* on vessels traveling in relatively high-salinity areas.

Some regions within southeast Virginia are susceptible to establishment of *Dreissena*; others are not. Back Bay, the northernmost extension of Currituck Sound, is normally fresh, but in some years, salinity can increase to 10‰ for extended periods, although the smaller tributary estuaries remain fresh (Norman and Southwick, 1991). The only bivalve that persists in Back Bay is the non-native oligohaline clam, *Rangia cuneata* (Lane and Dauer, 1991). Alkalinity and calcium levels for Back Bay are marginal for *Dreissena* reproduction (mean pH 7.7, calcium content of 10-20 ppm) (Sincock *et al.*, 1966), but the presence of *Rangia* infers that other species of bivalves, such as *Dreissena*, could survive there. Once established, *Dreissena* would survive high-salinity periods by persisting in freshwater tributaries.

The Dismal Swamp and the Dismal Swamp Canal, in contrast to Back Bay, have very low pH (maximum 6.7 in July) and calcium (7.2 ppm) (Lichtler and Marshall, 1979), probably much too low for the reproduction or extended survival of *Dreissena*. The Dismal Swamp Canal is therefore unlikely to be invaded by *Dreissena* or serve as a route for natural dispersal, but it remains a ready passage for dispersal by fouling on the hulls of vessels traveling between the Elizabeth River in the Chesapeake Bay system, and the Pasquotank River in the Albemarle/Pamlico Sound system.

Urban development in southeast Virginia has lead to the creation of many small lakes, most of which are connected by ditches or pipes to other waterways. Water quality and chemistry are unknown for most of these, but it is probable that at least some will have ideal conditions for *Dreissena*. For example, Smith and Whitehurst Lakes, in the Little Creek drainage adjacent to the Norfolk International Airport, are both fairly alkaline with sufficient calcium for *Dreissena* reproduction (Virginia Department of Game and Inland Fisheries, unpubl. data). Therefore, if *Dreissena* is introduced, the probability of it becoming established is high.

Table 1 summarizes the information for estuaries discussed above. The relative chance of inoculation, or risk, is given as high, moderate, or low, based on factors discussed above. Using available water chemistry data and published data on *Dreissena* physiological requirements, the relative threat of large populations of *Dreissena* becoming established after inoculation (suceptibility) is also given as high, moderate, or low. High indicates that *Dreissena*, once established, will rapidly attain high population levels and maintain those levels until the ecological community adjusts to the invasion. Moderate predicts that if *Dreissena* becomes established, it will reproduce successfully only during certain favorable periods and will attain pest proportions only occasionally. Low indicates that *Dreissena* is unlikely to reproduce successfully.

Table 1. Predicted Invasion Success in Freshwater Estuaries.*

Estuary	Risk	Susceptibility
Pocomoke River, MD & VA	low	low
Potomac River, MD & VA	high	high
Rappahannock River, VA	moderate	moderate
Piankatank River, VA	low	low
Mattaponi River/ Pamunkey River, VA	moderate	low
James River, VA	high	high
Elizabeth River, VA/ Albemarle Sound, VA & NC	high	high

*Estuaries are listed geographically from north to south. Risk refers to the relative chance that *Dreissena* will be introduced, and susceptibility refers to the relative chance that *Dreissena* will attain high population levels.

LAKES AND RESERVOIRS

All major rivers and many small rivers in the mid-Atlantic region have large artificial impoundments. It is unlikely that *Dreissena* could become established in a river system by a single inoculation into the river itself, but once it becomes established in a reservoir, it would then spread to downstream reservoirs and freshwater portions of estuaries. Only unfavorable water quality such as low pH and low calcium concentrations would then limit *Dreissena* population levels.

Water chemistry data are available for some Virginia lakes, discussed in alphabetical order hereafter, except where two or more adjacent reservoirs are discussed together. Water chemistry data, especially calcium levels, are incomplete for most lakes, and while risks have been assessed from available data, these data may not be representative of common conditions. The role of water chemistry in *Dreissena* survival and reproduction are discussed in the Introduction.

Claytor Lake

The risk of inoculation by *Dreissena* to Claytor Lake is high relative to other lakes, but its susceptibility to the establishment of large populations is only moderate. Claytor Lake is a multi-purpose reservoir (recreation, hydropower) on the New River (Kanawha River), a tributary of the Ohio River. It receives heavy recreational use, with eight improved public boat ramps, as well as an additional eight ramps on the New River upstream (DeLorme Mapping

Co., 1989). Thus, there are many opportunities for accidental inoculation of *Dreissena* attached to the hulls of small recreational vessels. Fields Dam impounds the New River upstream of Claytor Lake, but the reservoir is probably too small and its flushing rate too high to act as a reproductive refuge for *Dreissena*. Although *Dreissena* is already present in other portions of the Ohio River basin (New York Sea Grant, 1993), the probability of its dispersal upstream to Claytor Lake is low compared to the risk posed by human-mediated invasion. Surface waters are normally quite alkaline (7.3-9.3 in June), but calcium is generally low (9-10 ppm). Since in some years, however, calcium levels can attain 30 ppm (Virginia State Water Control Board, unpubl. data), the question of *Dreissena* reproductive success in Lake Claytor would depend on the varying water chemistry.

Flannagan Reservoir

John W. Flannagan Reservoir is at high risk of inoculation by *Dreissena*, but its susceptibility to establishment of large populations is only moderate. Flannagan Reservoir is on the Pound River, a tributary of the Ohio River via the Big Sandy River. The reservoir has three improved public access boat ramps; upstream tributaries hold two more ramps, and there are three more ramps on North Fork Pound River Lake (DeLorme Mapping Co., 1989). Thus, many opportunities for inoculation via the hulls of small recreational vessels exist. Although *Dreissena* is present in other portions of the Ohio River basin (New York Sea Grant, 1993), there is a low probability of dispersal upstream to Flannagan Reservoir compared to the risk of human-mediated invasion. The surface waters are alkaline (pH 7.6-8.9 in June), with low to moderate levels of calcium (9-29 ppm) (Virginia State Water Control Board, unpubl. data). If released into Flannagan Reservoir, *Dreissena* would survive, but in some years reproduction would be calcium-limited.

Harwood Mills Reservoir

Harwood Mills Reservoir is one of many small multi-use (fishing, municipal water storage) reservoirs in urbanized southeast Virginia. The risk of inoculation by *Dreissena* is low, but the lake is highly susceptible to establishment of this species, should it become introduced. Harwood Mills, on the headwaters of the Poquoson River in Newport News, has a single public boat ramp limited to craft without internal-combustion engines. This reduces but does not eliminate the possibility of *Dreissena* inoculation via the hulls of recreational vessels. Like the majority of small municipal reservoirs in southeast Virginia, it is moderately alkaline (pH 8.1 in June), with moderate levels of calcium (25 ppm) (Virginia Dept. Game and Inland Fisheries, unpubl. data). These conditions are favorable for *Dreissena* reproduction.

Of ten similar small reservoirs in the area surveyed by Virginia Department of Game and Inland Fisheries, six have water chemistry that would support high populations of *Dreissena*, three have chemistry that would support at least moderate populations, and only one (Kilby Reservoir) has water chemistry that would be unlikely to support *Dreissena* populations.

Kerr Reservoir and Lake Gaston

John H. Kerr Reservoir and Lake Gaston, just downstream, are at high risk of inoculation by *Dreissena*, and at least portions of both lakes are highly susceptible to establishment of large populations. Both reservoirs are large multi-use (recreation, hydropower) impoundments on the Roanoke River. Just below Lake Gaston in North Carolina is the Roanoke Rapids dam and reservoir. The Roanoke River ends in Albemarle Sound, North Carolina, which has an extensive freshwater portion. Kerr Reservoir and Lake Gaston have a total of about 50 public boat ramps and are heavily used by recreational boaters and fishermen. In addition, both are downstream of a variety of public-access reservoirs with over 80 public access boat ramps. These include Philpott Reservoir, Banister Lake, Smith Mountain Lake, and Leesville Lake in Virginia, and Hyco Lake, Mayo Reservoir, and After Bay Reservoir in North Carolina (Alexandria Drafting Co., 1981; DeLorme Mapping Co., 1989). On the basis of water chemistry in both Kerr Reservoir and Lake Gaston, which varies between stations, McMahon (1992) considered the susceptibility of Lake Gaston to be relatively low. Both lakes, however, have semi-enclosed branches in which water chemistry may differ, and in both lakes there are moderately alkaline regions (pH 6.9-9.3). Calcium levels for Kerr Reservoir are unavailable, but calcium content of the alkaline stations in Lake Gaston are about 24-44 ppm (Virginia State Water Control Board unpubl. data), and because of the proximity of the two lakes, it is safest to assume that Kerr Reservoir also has regions of moderately high average calcium levels.

Lake Anna

Lake Anna is at high risk of inoculation by *Dreissena*, but its susceptibility to subsequent establishment of this species is low. Located on the North Anna River, a tributary of the Pamunkey, it is the largest reservoir in the Pamunkey River drainage. The water source for the North Anna Nuclear Power Plant, Lake Anna is used heavily by recreational boaters and fishermen. The freshwater tidal portion of the Pamunkey River lies downstream. There are nine improved public access boat ramps on Lake Anna. Upstream of Lake Anna, Lake Orange has one public boat ramp, and Lake Louisa is surrounded by a housing development (DeLorme Mapping Co., 1989). McMahon (1992) considers Lake Anna to be highly susceptible to the establishment of large *Dreissena* populations, but unpublished water chemistry data provided by Virginia Power (Innsbrook Technical Center, Glen Allen, VA) suggest otherwise. Although pH often increases to 7.9 in some branches of Lake Anna during the summer, most of the lake is, on the average, acidic. Even where waters are alkaline, the calcium content remains too low (maximum about 6.0 ppm) for *Dreissena* reproduction.

Lake Chesdin

Lake Chesdin is at relatively high risk of inoculation by *Dreissena*, but its susceptibility to establishment of this species is low. Located on the Appomattox River (a tributary of the James), the lake has several public-access boat ramps and receives heavy recreational use from the nearby Richmond area. It has a water chemistry unsuited for *Dreissena*, however; the pH is variable (6.4-8.7) but acidic in summer in shallow areas, and calcium levels are very low (about 5-10 ppm) (Virginia State Water Control Board, unpubl. data).

Lake Gaston — See Kerr Reservoir

Lake Moomaw

Lake Moomaw is a rarity in Virginia: a large reservoir at relatively low risk of inoculation by *Dreissena*. If *Dreissena* were introduced, however, Lake Moomaw would be moderately susceptible to establishment of a large population. It is located on the Jackson River in the headwaters of the James River within a state wildlife management area, where recreational use is limited. DeLorme Mapping Co. (1989) shows no public-access boat ramps on or upstream of Lake Moomaw. The pH is alkaline (7.6-8.4) in shallow water in summer, and calcium levels are about 13-17 ppm (Virginia State Water Control Board, unpubl. data). These represent marginal conditions for *Dreissena* reproduction.

Leesville Reservoir — See Smith Mountain Lake

Philpott Reservoir

Philpott Reservoir is at relatively high risk of *Dreissena* inoculation, but it is not susceptible to establishment of this species. Located on the Smith River, a tributary of the Roanoke River via the Dan River, the Philpott Reservoir has 11 improved public access boat ramps. The water is moderately alkaline (pH 7.2-8.7) but low calcium levels (4-5 ppm) (Virginia State Water Control Board, unpubl. data), which would inhibit *Dreissena* reproduction. If *Dreissena* does become established, however, it will spread downstream to Kerr Reservoir and Lake Gaston, which have more suitable water chemistry for the mollusc.

Smith Mountain Lake and Leesville Lake

Smith Mountain Lake is a large reservoir on the headwaters of the Roanoke River, and Leesville Lake is directly downstream. Both are at high risk from inoculation by *Dreissena*, although the susceptibility of both lakes to establishment of large populations is only moderate. Two improved public boat ramps provide access to Leesville Lake, but there are more than 17 boat ramps for Smith Mountain Lake. Smith Mountain Lake is also the site of a large, annual professional bass fishing tournament. The pH of both lakes in shallow water during the summer is normally high (7.6-9.1), and calcium levels are about 15-17 ppm (Virginia State Water Control Board, unpubl. data). These conditions permit reproduction of *Dreissena*, although in some years lower calcium content may limit population levels. Downstream of these lakes are John H. Kerr Reservoir and Lake Gaston.

South Holston Lake

South Holston Lake is at realtively high risk of inoculation by *Dreissena*, and its susceptibility to subsequent establishment of large populations of this species is also high. South Holston Lake in southwest Virginia is a large multi-purpose reservoir (recreation, hydropower) on the South Fork Holston River, a tributary of the Tennessee River. The majority of the lake is within Tennessee, within a few hours' drive of other lakes in the Tennessee River system containing *Dreissena* (New York Sea Grant, 1993). There are 16 public access boat ramps on the lake, and two more upstream on the smaller Hungry Mother Lake. The pH of South Holston Lake is relatively stable and alkaline (6.9-8.6 in June and July), with moderately high levels of calcium (18-30 ppm), based upon data collected largely in the 1970s (Tennessee Valley Authority unpubl. data). These conditions are favorable for *Dreissena* growth and reproduction. Once introduced, it would rapidly attain pest proportions.

Western Branch Reservoir, Lake Meade

Western Branch Reservoir, Lake Meade, and some adjacent reservoirs are at moderate risk of inoculation by *Dreissena*, and highly susceptible to establishment of large populations of this species. Western Branch Reservoir on the Western Branch Nansemond River is the largest of seven impoundments in the Nansemond River drainage in southeast Virginia. Lake Meade is the largest of four impoundments on the Eastern Branch Nansemond River, but the drainages of these are very close to each other. Other lakes include Lake Prince and Lake Burnt Mills upstream of Western Branch Reservoir, and Lake Cohoon, Lake Kilby, and Spaetes Run Lake upstream of Lake Meade. Western Branch Reservoir has two public boat ramps on or upstream of it, and Lake Meade has four. All lakes are heavily used for recreational fishing by local fishermen (Virginia Dept. Game & Inland Fisheries, pers. comm.). Water chemistry data in all of these lakes shows moderately alkaline water (pH 8.2 at 2 m depth, June) and moderate levels of calcium (20-25 ppm), except in Lake Cohoon and Lake Kilby (no data is available for Spaetes Run Lake). Lakes Cohoon and Kilby are often acidic, and their levels of susceptibility are thus moderate or low. (Virginia Dept. Game and Inland Fisheries, unpubl. data). In the remaining four lakes, conditions are favorable for *Dreissena* reproduction. Once invasion occurs in any of those four lakes, *Dreissena* is likely to reach high population levels. Natural dispersal, perhaps by adults attached to turtles or other amphibious organisms, could then spread *Dreissena* to the other impoundments in the Nansemond drainage.

Table 2 summarizes the information for reservoirs discussed above. The definitions for risk and susceptibility are the same as for Table 1.

Table 2. Predicted Invasion Success in Virginia Lakes and Reservoirs.*

Lake	Drainage	Recreational Vessel Use	Other Uses	Risk	Susceptibility
Claytor Lake	Ohio	high	hydroelectric power	high	moderate
Flannagan Reservoir	Ohio	high		high	moderate
Harwood Mills Reservoir (Newport News)	Poquoson	moderate	municipal water	low	high
Kerr Reservoir	Roanoke	high	hydroelectric power	high	high
Lake Anna	Pamunkey	high	nuclear power plant	high	low
Lake Chesdin	James	high		high	low
Lake Gaston	Roanoke	high	hydroelectric power	high	high
Lake Meade	Nansemond	high		moderate	high
Lake Moomaw	James	low	wildlife mgmt. area	low	moderate
Leesville Lake	Roanoke	moderate		high	moderate
Philpott Reservoir	Roanoke	high		high	low
Smith Mtn. Lake	Roanoke	high		high	moderate
S. Holston Lake	Tennessee	high	hydroelectric power	high	high
W. Branch Reservoir	Nansemond	moderate	municipal water	moderate	high

*Reservoirs are listed alphabetically. Invasion Risk refers to the relative chance that *Dreissena* will be introduced. Establish Potential refers to the relative chance that *Dreissena* will attain high population levels. See text for explanation of terms.

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Zebra Mussels in North Carolina

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POTENTIAL IMPACTS

Numerous drinking water plants, industries, pulp and paper mills, power generation facilities, processing plants, golf courses and agricultural operations draw water from rivers, streams and reservoirs in North Carolina. More than 140 industries and public facilities are registered with the N.C. Division of Water Resources to draw more than 1 million gallons of water per day. This does not account for the numerous agricultural and golf course water-users within the state.

Zebra mussels that colonize docks, piers and pilings would affect shoreline property owners within North Carolina. Boat owners would be burdened by preventing and repairing damage to clogged motor intake lines and hulls and other exposed surfaces that are fouled. The Intracoastal Waterway provides a vital commercial link for the East Coast, with barge traffic transporting seafood, gravel, fertilizers, fuel and other products through numerous ports along the waterway and connecting river systems in North Carolina. The many recreational uses of the waterway include pleasure boating, sailing and yachting. Navigation through the Intracoastal Waterway could be inhibited by zebra mussels colonizing locks and other structures.

North Carolina provides habitat for 60 species of freshwater mussels. Human activities have already placed considerable stress on these mussels. Over half are listed as threatened, endangered or species of special concern. The U.S. Fish and Wildlife Service estimates that if North Carolina's larger rivers are colonized by zebra mussels, 13 species could be extirpated from our the state. Of those, four species could become extinct (Alderman, 1993). Their extinction would probably be a direct result of competition with the zebra mussel for food and space, coupled with existing stresses. If mid-sized and smaller rivers are also colonized, the death toll is expected to rise even higher.

North Carolina supports several important commercial and recreational fisheries. There are 1.7 million recreational anglers in our state who spend an estimated $900 million annually on fishing licenses, bait, tackle and guided fishing tours. The state could suffer economically if a zebra mussel infestation caused reductions in fisheries.

Even though zebra mussels have not yet reached North Carolina waters, a few of the large water-users have already incurred zebra mussel expenditures by monitoring for their arrival and developing plans of action for a potential colonization. In addition, some local economies have suffered when lakes were temporarily closed to boaters because of a potential invasion. For example, the town of Lake Lure, a small recreational and retirement community in the western part of the state, banned the sale of new boating permits in August, 1992, for fear of a zebra mussel invasion. As a result, business for local restaurant, campground, and marina owners decreased. The potential economic impacts of an actual invasion of North Carolina waters is even more significant.

WATER RESOURCES

North Carolina has approximately 2.5 million surface acres of fresh water with more than 50,000 man-made impoundments within these drainages including farm ponds, aquaculture facilities, drinking water supplies, detention facilities for water quality or flood control and recreational or multi-purpose lakes. Among the larger impoundments are Lake Gaston, Kerr Lake, Falls Lake and Jordan Lake. North Carolina also contains 2.3 million acres of estuaries, including the interconnected Currituck, Albemarle, Pamlico, Bogue and Core Sounds. This series of sounds is known as the Albemarle/Pamlico estuarine system and comprises almost 50 percent of the Mid-Atlantic's estuaries.

North Carolina is composed of three regions: the mountains, the Piedmont and the Coastal Plain. These regions are divided into 17 drainage basins. The Hiwassee, Little Tennessee, French Broad and the Watauga rivers form in the Appalachian Mountains, drain west into Tennessee, and eventually feed the Mississippi River. The New River begins in northwestern North Carolina, moves through western Virginia and drains into the Ohio River at the border between West Virginia and Ohio. These five river systems of western North Carolina are swift, rocky, wild and scenic and, therefore, of significant recreational value.

The Albemarle/Pamlico estuaries are fed by the Roanoke, Chowan and the Pasquotank rivers, which form in Virginia, and the Tar-Pamlico, Neuse and the White Oak rivers, contained within North Carolina. The Cape Fear River watershed originates near Greensboro, runs southeast and drains directly to the Atlantic Ocean at Wilmington. The Yadkin River drains a small portion of Virginia, runs through the Piedmont region and into South Carolina. The Atlantic-bound Lumbar, Catawba, Broad and Savannah river basins originate in North Carolina and flow into South Carolina.

ROUTES OF ENTRY

Zebra mussels have several potential routes for invading North Carolina waters. Currently in the Susquehanna, they are rapidly encroaching on the Chesapeake Bay, subsequently threatening North Carolina's Albemarle/Pamlico estuarine system through numerous linkages between the two estuarine systems. Zebra mussels, able to survive salinities of up to 12 ppt for several days, attach to barges or other slow-moving vessels and travel through the estuarine fringes into the mouths of uninfested freshwater rivers. Once there, barge and boat traffic will provide the mussels with an easy means of dispersing to other tributaries within the associated watersheds.

The Intracoastal Waterway connects the Elizabeth River, which feeds the Chesapeake Bay, to the Northwest River, which drains to Currituck Sound. Lynnhaven Bay, also linked to the Chesapeake Bay, is connected to the Currituck Sound by a canal built to ease flooding of areas in Virginia Beach, Virginia. Subsequently, Currituck Sound is linked to the Albemarle Sound at the Wright Memorial Bridge and through a man-made Intracoastal Waterway canal at Coinjock. Albemarle Sound and Pamlico Sound are connected through the Alligator-Pungo Canal, which is part of the Intracoastal Waterway, in addition to being connected near Manteo. Bogue and Core Sounds are also joined to the southern portion of the Pamlico Sound through natural linkages and the Intracoastal Waterway. These connections make all drainages feeding the Albemarle and Pamlico estuaries vulnerable to the migration of zebra mussels through the Chesapeake Bay.

The Susquehanna River is not the only source of zebra mussel entry into North Carolina's estuaries. They could also be introduced by the discharge of infested shipping ballast water into ports such as Wilmington or Morehead City.

Zebra mussels are currently in the Ohio River system. Therefore, upstream movement of zebra mussels through the Ohio River drainage network threatens the nearby New River watershed within North Carolina. Currently in the Tennessee River, upstream movement of zebra mussels also threatens the far-western drainages of North Carolina including the Hiwassee, Little Tennessee, French Broad and the Watauga.

RISK ASSESSMENT

The risk of colonization appears to be site-specific. Two major factors should be considered: mechanisms by which zebra mussels can be introduced to an area and the mollusks' ability to survive the environmental conditions of that area. Some areas within North Carolina have distinct environmental characteristics that may make them suitable for zebra mussel colonization, and these need to be carefully examined to determine their risk of colonization.

The Albemarle/Pamlico estuaries typically undergo fairly rapid temperature and salinity fluctuations, especially following rainfall. Zebra mussels can tolerate elevated salinity concentrations for short periods of time. However, they are unable to colonize, reproduce and proliferate in saline waters. Therefore, it is unlikely that dense colonies of zebra mussels will become established in the Albemarle/Pamlico estuaries. But the zebra mussel, constantly evolving through the process of natural selection, may develop a greater tolerance for higher salinities. European and Russian studies indicate that other species of *Dreissena* have greater salinity tolerances. There are also large freshwater areas within the Albemarle/Pamlico system such as the Currituck Sound, where *Dreissena* is more likely to survive and reproduce.

Surface water temperatures within the Piedmont and the Coastal Plain in the summer usually exceed the preferred range for zebra mussels, especially in the shallower fringes of the estuaries and lakes. In many of these areas, the deeper, cooler waters that the mollusks are more likely to colonize often have dissolved oxygen concentrations below desired levels. Another important characteristic is the drastic reduction in suitable attachment substrates for zebra mussels as the Atlantic-bound rivers of North Carolina approach the estuaries. However, recent evidence indicates hard substrates are preferable but not necessary to the establishment of a population. North Carolina is well known for the blue crab populations in its estuaries, and the male crabs that frequent the low-salinity waters will probably enjoy feasting on zebra mussels.

The acidity of our inland waters depends on the acidity of rainfall and bedrock composition, whereas the acidity, or pH, of estuarine waters is more dependent on the presence of salts, which act as buffers. Acidic waters such as the Great Dismal Swamp in northeastern North Carolina would not serve as suitable environments for zebra mussels.

A large number of North Carolina lakes are classified as eutrophic, with the highest concentration occurring in the Piedmont region. These algae-rich bodies of water would provide plenty of food for zebra mussels. However, many of the lakes within the state have calcium concentrations too low to support healthy populations. Lake calcium concentrations are typically less than 5 milligrams per liter (mg/l), which is well below the zebra mussel's lower limit of 12 mg/l. On the other hand, isolated limestone deposits are scattered throughout the state. The most important of these deposits occurs near Marshall, Madison County; south of Bakersville, Mitchell County; northwest of Winston-Salem, Forsyth County; and near Germanton, Stokes County. The presence of limestone (calcium carbonate) results in higher calcium concentrations required by zebra mussels. These areas and waters of the coastal plain, which tend to have higher calcium concentrations, would be the most likely to have problems with zebra mussel colonization. However, the zebra mussel will have to contend with salinity in the coastal plain region.

KEY DISPERSAL MECHANISMS

Many of North Carolina's larger lakes serve recreational needs for residents and visitors from other parts of the country. Of most concern are those who bring their boats from states where zebra mussel invasion has already occurred, such as Michigan, Illinois, Ohio, Pennsylvania, Tennessee and others.

Water is regularly transported to North Carolina drainages from the Mississippi, the Tennessee and other river networks through the sale of fish for bait and for stocking aquaculture operations. Preliminary investigation has shown that fish producers generally use well water to fill their live-haul trucks for transport, and many fish ponds are filled with well water or are located in very small upstream tributaries that are fed by watershed runoff rather than stream or river water (Rice, 1992). However, this is not true in all cases, and the potential for zebra mussel adults, larvae or eggs attaching to the fish must also be considered.

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A Preliminary Assessment of the Potential For Zebra Mussel Infestation in Maryland

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INTRODUCTION

The purpose of this paper is to examine Maryland's water resources in relation to the potential for invasion and colonization by the zebra mussel, *Dreissena polymorpha.* Maryland is situated at a central location in the Mid-Atlantic region for infestation by the zebra mussel. Nearby watersheds such as the Ohio River and the Susquehanna River, a major tributary to Chesapeake Bay, are presently supporting populations of zebra mussels. There is also easy access to Maryland's waters from freshwater systems such as the Great Lakes and Intracoastal Waterway and from foreign sources via the port of Baltimore, which is the state's major port. Fortunately, there has been time to make a preliminary estimate of the areas in Maryland that may be at risk and to consider methods for mitigating impacts from zebra mussels; ultimately, nature and circumstances will determine their effect upon this state.

Since zebra mussels were first detected in the Great Lakes region of North America in 1988, their economic and ecological impact has been substantial. The primary economic impacts result from zebra mussels attaching to hard substrates, such as water intake pipes, often in layers so thick that water flow is impeded or blocked. Their removal causes considerable expense, difficulty, and inconvenience. In recent years, in an effort to maintain pumping capacity and to prevent mechanical failures, numerous water users, primarily public utilities and public water supply facilities, have made considerable expenditures in zebra mussel control technology. These methods are designed to either prevent the settlement of zebra mussel larvae or remove zebra mussels after they have settled within intake pipes. From 1989 to 1991, the city of Monroe, Michigan, spent more than $300,000 for chlorination and cleaning of raw water intake pipes (LePage, 1993). In 1990, Canada's Ontario Hydro spent $10 million installing chlorination systems to prevent the settlement of zebra mussels (Weigmann *et al.*, 1991). The proactive risk assessments, control designs, and monitoring programs undertaken in regions such as Maryland, where zebra mussels have not yet been introduced, have also required sizable expenditures by the public and private sectors.

Many of the ecological effects of zebra mussels are still being determined. Most notable has been the decline in native mollusks in the family Unionidae. Not only do zebra mussels compete with native mollusks, but they also use the shells of the native mollusks as substrate for attachment; as many as 10,000 zebra mussels have been found attached to a single unionid mollusk (Schloesser and Kovalak, 1991). With such heavy infestations there are many deleterious changes: valve opening is restricted, burrowing ability is impaired, and phytoplankton availability is decreased by filtering by zebra mussels. There is also concern that the high filtering capacity of zebra mussels may alter the abundance and species composition of assemblages of zooplankton and other planktivorous species, affecting finfish and other aquatic organisms in the food chain (Yount 1990).

MARYLAND'S WATER RESOURCES

Maryland's water resources are quite vast for such a modestly-sized state. About 19.7% of the 12,303 mi^2 total area of Maryland is surface water. Of the surface waters, 28.9% is non-tidal inland waters, consisting of about 17,000 stream miles of tributary headwaters, 12 major reservoirs of over 100 acres in surface area, and an estimated 11,000 smaller ponds. The other 71.1% of Maryland's surface waters, composed of the Chesapeake Bay and 21 major tributaries, is either tidal or fresh (Walker, 1970; Carpenter, 1983).

The economic significance of these resources is more difficult to esstablish although the major uses can be identified. For example, there are 13,963 active water appropriation permits in Maryland, allowing withdrawal of both surface and ground water. Of these 1,456 are for "large" water appropriators, which withdraw up to 10,000 gallons daily. Of that number, 246 are surface water appropriators, 366 are agricultural appropriators—which use both ground and surface water—and the remaineder appropriate ground water (personal communication: J. Herring, Maryland Department of Natural Resources [Maryland DNR]).

Over 6.7 billion gallons per day of fresh and saline water are withdrawn from ground and surface sources. Fresh water, primarily suface water, comprises 21% of the withdrawals, while saline water acdounts for 79%. The primary water uses are for thermoelectric power generation, public water supply, industry, mining, and agriculture. Only 157 million gallons per day are consumed and not available for reuse. Of the tal water withdrawn, 81% is for thermoelectric power production, whith 93% of this water obtained from saline surface waters. Surface water accounts for 84.5% of the freshwater withdrawn, of which 55% is used for public water supplies (Wheeler, 1987).

Much of the water available for reuse can also be traked by NPDES permits for discarge outfalls. Municipal sewage treatment plants account for 360 permits, including 51 major permits allowing over 1 million gallons per day of discharge, (personal communication: S. Luckman, Maryland Department of the Environment [MDE]). Industrial users account for 1,143 active permits, including 48 major dischargers (personal communication: D. Jones, MDE).

Hydroelectric power generators are a special class of water users that may be affected by zebra mussels. Some, such as Conowingo Dam on the Susquehanna River in Maryland, are located downstream from areas where the presence of zebra mussels has been documented. This situation has required monitoring programs and consideration of control methods to deal with future zebra mussel populations.

Water-borne shipping is still a major industry in Maryland, although the volume of shipping handled in Baltimore Harbor has diminished greatly over the last 14 years, from 4200 ships in 1979 to 2200 ships in 1992 (personal communication: J. Hobson, Maryland Port Authority). This decline is the result of two major factors: an increase in the average size of individual ships, and the departure of some shipping lines from this area. Baltimore Harbor represents a potential entry route for zebra mussels into Maryland. Approximately 10 to 20% of the ships enter Baltimore Harbor directly from foreign ports; the remainder makes stops at other ports in the United States before arriving in Baltimore. The ships originate from more than 300 ports in approximately 100 countries. Shipping also may provide a pathway for zebra mussels to enter the Potomac River via the port of Alexandria, Virginia. The Intracoastal Waterway is also a possible pathway.

The potential for the introduction of non-indigenous aquatic species through ballast water discharge by transoceanic ships has been well documented (Carlton, 1985; Jones, 1991). In Oregon, Carlton (1993a) found that ballast water released from 159 ships originating in Japan contained a total of 367 taxa. Carlton (unpubl. data) estimated that more than 15 million metric tons (>4 billion gallons) of ballast water are discharged in the Chesapeake Bay annually from ships with foreign ports of origin.

Risk Assessment Approaches

The general environmental tolerances of zebra mussels are relatively well known for many parameters (Yount, 1990). Similarly, the transport vectors for the dispersal of zebra mussels are also understood. Carlton (1993b) identified 23 natural and human-induced vectors for the transport of zebra mussels.

Such information has been used to develop multi-parameter probability tables for risk assessment, based on the known susceptibility of surface waters to colonization (O'Neill, 1992). Multi-parameter maps, such as those developed by Neary and Leach (1992) for Ontario, can be used for risk assessment purposes. Calcium, pH, and salinity are among the most commonly used environmental parameters in such risk assessments.

Another approach to risk assessment is the development of an index, based on transport vectors, for the potential risk of colonization by zebra mussels in a given area. In the assessment of New York City's reservoirs to risk of infestation, Acres International developed a Dispersal Probability Index (DPI), based upon an evaluation of the potential for the introduction of zebra mussels via the 23 identified transport vectors (New York City Department of Environmental Protection, 1992).

Calcium

Zebra mussels need calcium for shell deposition and growth. In Europe, surface waters with large populations of zebra mussels have minimum calcium levels of 23 mg/L (Strayer, 1991) and mean calcium levels of 44.9 mg/L (Ramcharan, et al. 1992). Sprung (1987) found that only minimal survival of embryonic zebra mussels occurred at calcium levels of 12 mg/L. Similarly, Vinogradov *et al.* (1993) observed that water with calcium levels less than 12-14 mg/L was not adequate for normal calcium metabolism by zebra mussels. McCauley and Kott (1993) found that calcium concentrations < 8 mg/L resulted in the cessation of gill cilia activity.

A study of 632 freshwater stream reaches in Maryland, known as the Maryland Synoptic Stream Chemistry Survey (MSSCS), was conducted in the spring of 1987 by International Science and Technology Inc. (Knapp et al. 1988) for the Maryland DNR. Using conductivity and acid-neutralizing capacity data collected by this survey, regression equations were calculated to predict calcium levels. A map of these calcium levels shows large regions of the state with surface water levels of calcium below 12 mg/L (Figure 1), suggesting a low probability of zebra mussel survival and reproduction. The areas with low colonization potential occur in western Maryland, southern Maryland and the Eastern Shore. Regions with moderate calcium levels between 12 and 25 mg/L (Figure 2) include most of the remaining streams in southern Maryland and the Eastern Shore. These areas would be considered marginal for the survival of zebra mussels. Areas with calcium levels exceeding 25 mg/L (Figure 3) should support good zebra mussel growth and reproduction, and are found primarily in the center of the state. The single anomaly in western Maryland serves as a reminder that some locations may still need closer examination. These data are indicative of geologic and soil conditions of the watersheds which influence the downstream calcium loads. Water chemistry data for the twelve major fresh water reservoirs within these watersheds are currently being compiled by Maryland DNR.

pH

The pH of freshwater systems in Maryland is determined primarily by acid deposition, soil type, and the geology of underlying bedrock. Sprung (1987) determined that zebra mussel larvae will not develop successfully at pH values less than 7.4, with larval survival observed only in the pH range from 7.4 to 9.4. Vinogradov *et al.* (1993) found that zebra mussels are considerably more sensitive to acidification than other freshwater mollusks, with net losses of calcium, potassium, and sodium occurring at pH values less than 6.9.

Data collected by MDE from January, 1987 through September, 1992, in the tidal freshwater and oligohaline reaches of several Maryland tributaries (e.g., Potomac and Patuxent Rivers), indicates that these watersheds are relatively well buffered (personal communication: J. S. Garrison, MDE). The mean pH values, based on all stations, ranged from 7.2 to 8.0 during this period; the minimum pH was 6.1, while the maximum pH was 10.2. The greatest pH range at any individual site over the entire sampling period was 6.8-9.8. Within Maryland, those bodies of water with high pH values (>7.4) and the least amount of fluctuation will be more susceptible to colonization by zebra mussels.

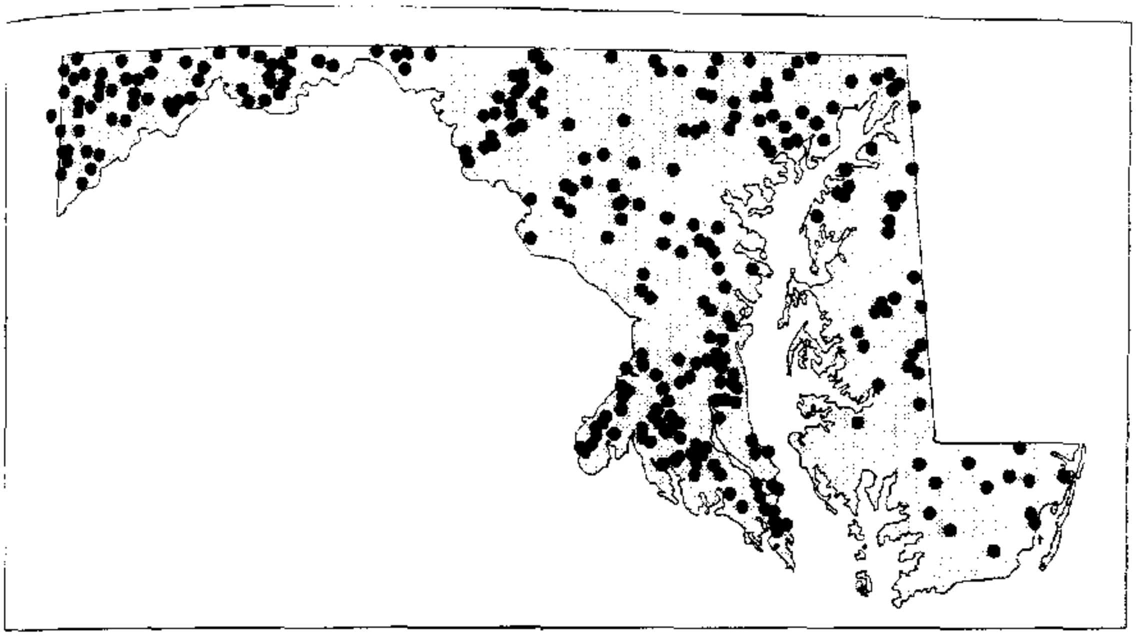

Figure 1. **Predicted Zebra Mussel Distribution (Based on 1987 MSSCS): Zero Probability Areas, Surface Water Calcium < 12 mg/L.** *Maryland Surface waters with predicted Ca levels < 12 mg/L based upon the regression of conductivity and acid neutralizing capacity data from 632 stream reaches.*

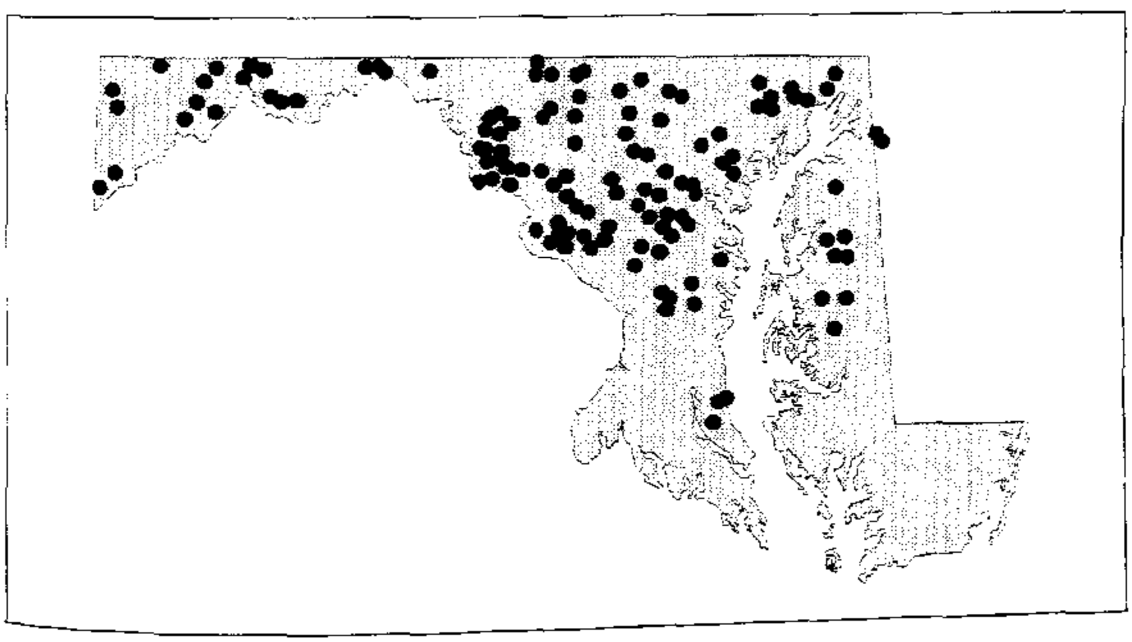

Figure 2. **Predicted Zebra Mussel Distribution (Based on 1987 MSSCS): Low to Moderate Probability Areas, Surface Water Calcium ≥ 12 and ≤ 25 mg/L.** *Maryland surface waters with predicted Ca levels ≥ 12 mg/L and ≤ 25 mg/L based upon the regression of conductivity and acid neutralizing capacity data from 632 stream reaches.*

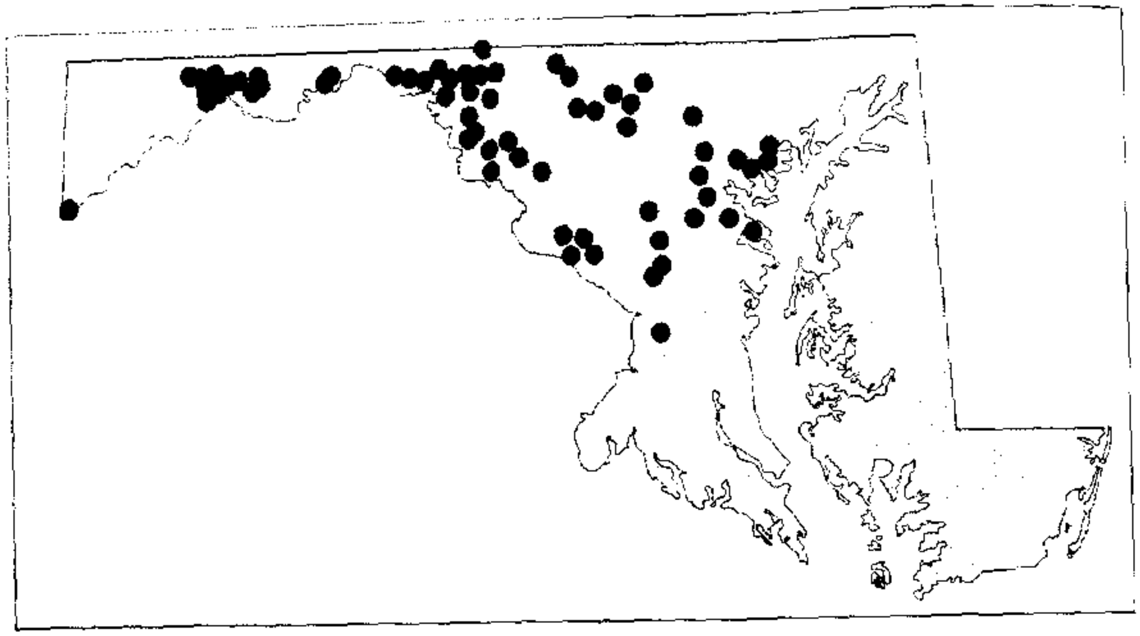

Figure 3. Predicted Zebra Mussel Distribution (Based on 1987 MSSCS): High Probability Areas, Surface Water Calcium > 25 mg/L. *Maryland surface waters with predicted Ca levels > 25 mg/L based upon the regression of conductivity and acid neutralizing capacity data from 632 stream reaches.*

Salinity

The zebra mussel, primarily a freshwater species, occurs in greatest abundance in waters with salinities less than 2 ppt. MacNeill (1991) concluded that the normal salinity range for *D. polymorpha* is 0.21-1.47 ppt, while the optimal salinity is 0.93 ppt, with a maximum salinity tolerance range of 11.6-12.3 ppt. Strayer and Smith (1993) determined that the upper salinity tolerance limit for zebra mussels ranged from 0.5 to 12.0 ppt. Mackie and Kilgour (1992) conducted 96 hour laboratory bioassays with zebra mussels under varying regimes of salinity and water temperature. Using Instant Ocean for salinity adjustments, they reported an LC_{50} for adults of 7.23 ppt at 20° C, with a decrease in salinity tolerance observed with increasing temperatures. At salinities greater than 8 ppt, significant effects on the growth and survival of zebra mussels occurred at all temperatures. At 18-20° C and salinities greater than 1 ppt, there was a reduction in the ability of zebra mussels to maintain somatic tissue, which suggests little accumulation of energy for gametogenesis in such salinity regimes. Mackie and Kilgour (1992) concluded that zebra mussels are limited to areas of lower salinity than their apparent tolerances would indicate, probably due to veliger sensitivity. Figure 4 shows those areas in the Bay drainage where average salinities of 0-4 ppt (from 1949 to 1991) allowed a moderate to high probability of zebra mussel infestation.

In general, salinity levels decrease from the lower to the upper reaches of the Chesapeake Bay. The higher density of salt water entering the southern end of the Bay may limit the bottom areas amenable to zebra mussel survival in areas that appear to have suitable surface

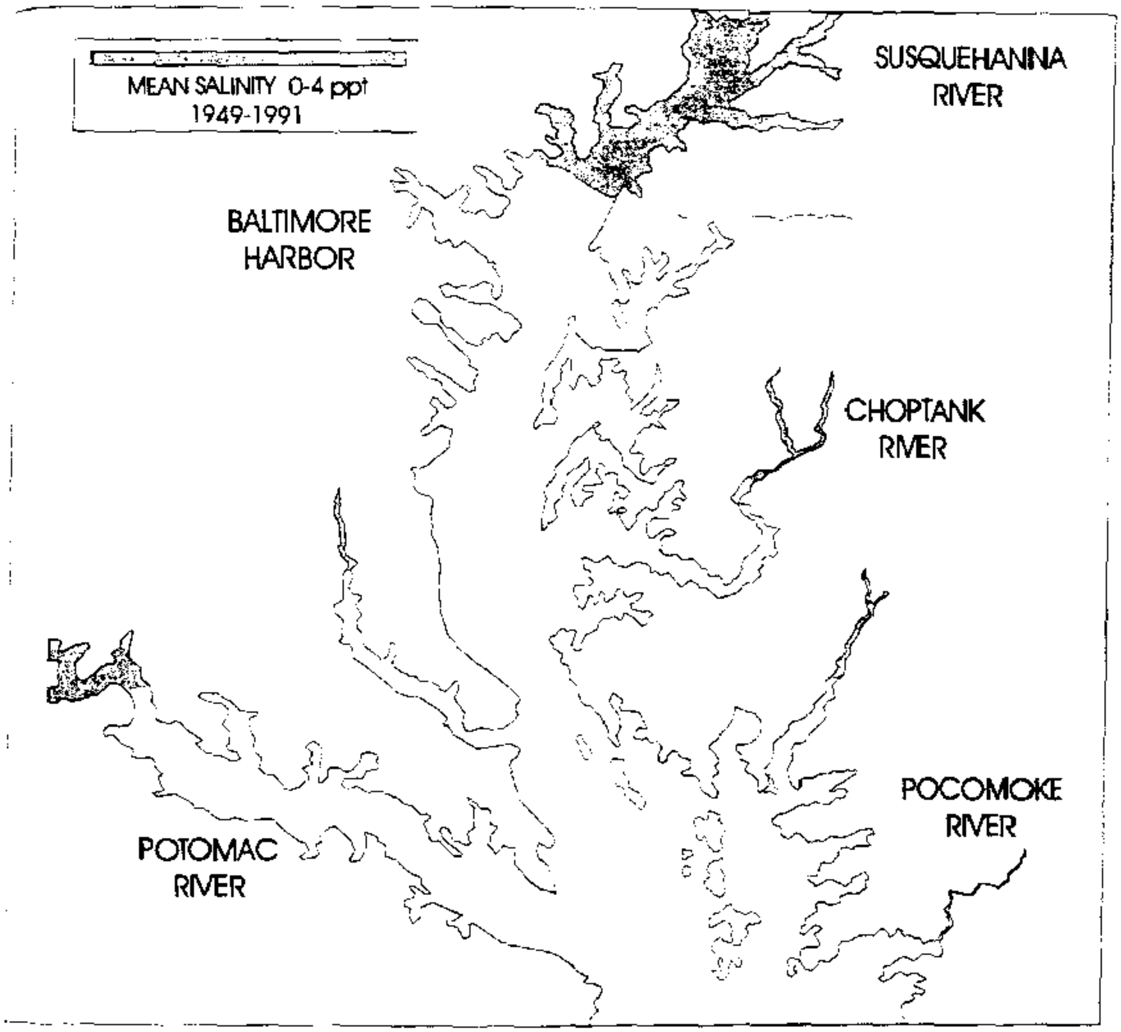

Figure 4. Tidal Waters of the Chesapeake Bay Drainage Basin in Maryland Potentially Susceptible to Zebra Mussel Colonization.

salinity levels. In addition, the Coriolis Effect caused by the rotation of the earth causes the salt wedge entering the Bay to shift eastward, further reducing the likelihood of zebra mussel survival in the main stem of the Bay along the eastern shore. As a result, fresh water also tends to run down the western side of Chesapeake Bay, which may promote the distribution of larval zebra mussels from populations in the Susquehanna River.

Fresh water inflow is near its maximum in the spring when potential zebra mussel spawning activity would reach its peak. In autumn, when fresh water inflow has been reduced, surface salinities reach considerably higher levels in much of the Bay, and populations of newly arrived or recently spawned zebra mussel veligers are likely to be affected.

The Potomac River, like most estuarine tributaries, demonstrates a similar variation in salinity by season. Summer thunderstorms and hurricane events are more likely to cause rapid changes in salinity within brief periods in the river than in the mainstem of the Bay. The ability of zebra mussels to survive such salinity changes will be very important in determining their potential spread into and within estuarine systems.

Other Environmental Factors

Streams warrant specific discussion because they differ from other bodies of water in terms of their energy sources, which ultimately affect the ability of zebra mussels to colonize streams. Streams derive relatively little of their energy from in-stream primary production (i.e., autochthonous input), in comparison to riverine, estuarine, and lentic systems. Most of their energy input comes from allochthonous sources, such as direct litter fall (i.e., leaves, branches, and twigs) and inputs from nearby sources of wood and leaves (Wallace *et al.*, 1992). In their fast-flowing regions, streams have low phytoplankton densities, which increase as stream gradient and flow velocity decrease (Smock and Gilinsky, 1992). The most abundant primary producers in streams are periphyton (e.g., diatoms, green and blue-green algae), filamentous algae and aquatic plants (personal communication: J. Allison, MDE), which can withstand conditions such as flow instability, storm flows, and the abrasion resulting from high suspended sediment loads (Mulholland and Lenat 1992). Because of the limited availability of phytoplankton in streams and their importance to zebra mussels as a food source, successful zebra mussel colonization and spread may be precluded even when other water quality conditions are optimal. Strayer (1991) found a strong correlation between stream size and the presence of zebra mussels in Europe; they are rarely found in streams less than 30 m wide but frequently found in larger streams.

Potential Routes of Entry into Maryland's Waters

Zebra mussels are close to Maryland waters. They are already present in the Chesapeake Bay watershed; veligers were collected in the upriver reaches of the Susquehanna River in Johnson City, New York, in 1991, 1992, and 1993. However, no zebra mussels have been reported from monitoring efforts in the Pennsylvania or Maryland segments of the Susquehanna River. The three potential pathways for zebra mussel introduction are the Susquehanna River,

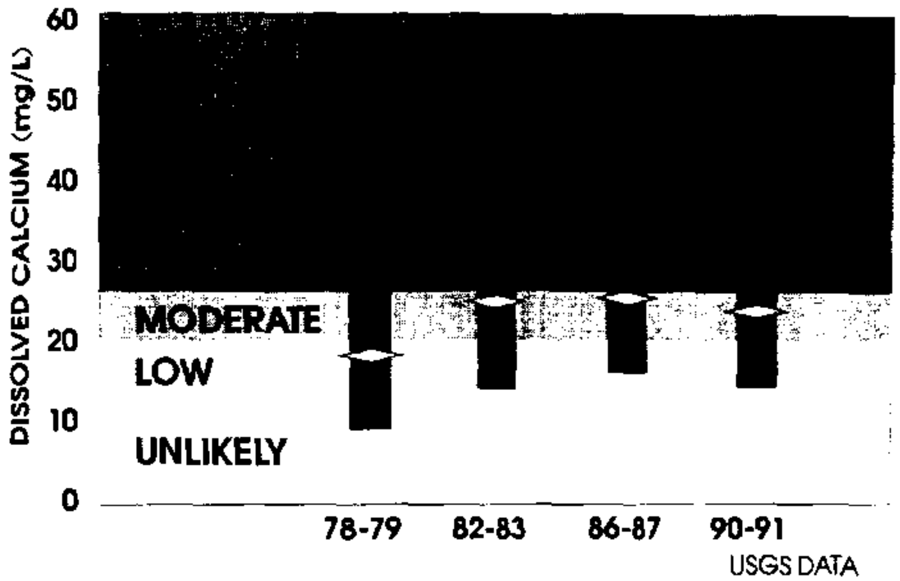

Figure 5. ***Probability of Zebra Mussel Survival, Susquehanna River (at Conowingo, Maryland).*** *Probability of zebra mussel survival in the Susquehanna River based on Ca levels from 1978-1991. Diamond symbol = median and black bar = range.*

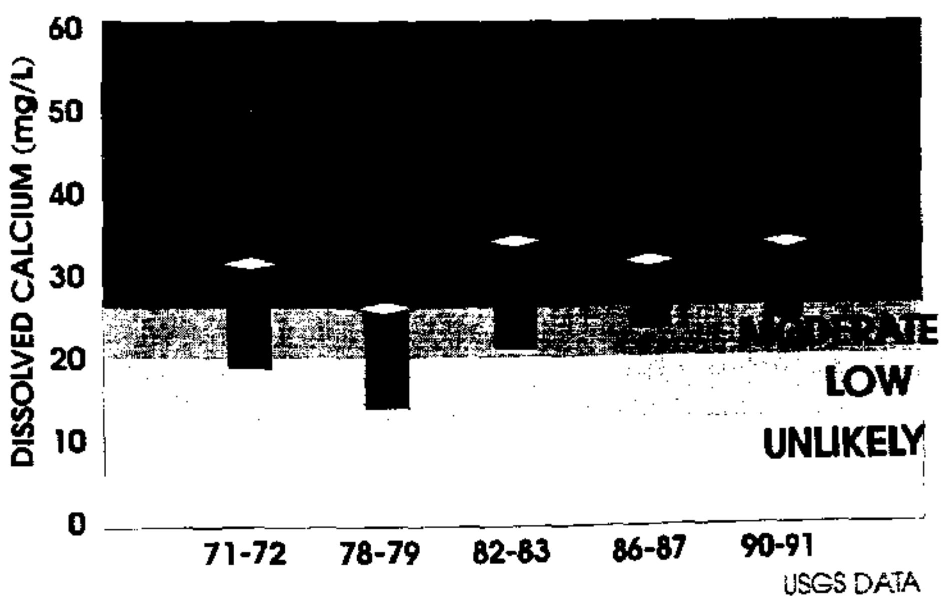

Figure 6. ***Probability of Zebra Mussel Survival, Potomac River (at Chain Bridge near Washington, D.C.).*** *Probability of zebra mussel survival in the Potomac River based on Ca levels from 1971-1991. Diamond symbol = median and black bar = range.*

the Potomac River and Baltimore Harbor. Another likely entry route is the Youghiogheny River, a tributary of the Ohio River. Zebra mussels are present in the Ohio River, near Wheeling, West Virginia, just seventy-five miles downstream from Maryland's portion of the Youghiogheny River. The overland distance from the headwaters of the Youghiogheny River to the headwaters of the Potomac River is less than one mile in some places.

According to the 1978-1991 United States Geological Survey data for the Susquehanna River at Conowingo, Maryland, calcium levels ranged from 7 to 35 ppm (Figure 5). The median calcium levels predict a moderate probability for zebra mussel survival. The Potomac River at Chain Bridge near Washington, D.C., has considerably higher calcium levels, ranging from 14 to 58 ppm between 1971 and 1991 (Figure 6). The median calcium values were well within the high probability range for zebra mussel survival. Calcium data for Baltimore Harbor are being compiled, but salinity is much more likely to be a limiting factor in this area.

In Baltimore Harbor, which could potentially receive zebra mussel larvae from both the Susquehanna River and ship ballast water, salinity values were quite variable, varied from 3.4 to 17.2 ppt in 1991 (Figure 7). However, the seasonal means were quite high, ranging from 10.7 to 12.3 ppt and indicating an unlikely probability of zebra mussel survival. However, 1991 was a year of low summer rainfall, and wetter years may provide more favorable conditions.

ZEBRA MUSSEL MANAGEMENT AND REGULATION IN MARYLAND

Although zebra mussels have not yet been found in Maryland, the city of Baltimore has implemented efforts to prevent the immediate spread from nearby populations to their water supply reservoirs, which are located near the Susquehanna River. Pretty Boy, Liberty, and Loch Raven reservoirs were closed in 1992 to recreational fishing boats without permanent moorings. In early 1993, these three reservoirs were reopened, but proposed restrictions prohibit the use of live aquatic bait or gasoline motors. Fishermen bringing in boats must sign an affidavit that these boats will only be used in these three reservoirs.

In 1991, fearing accidental releases, the Maryland DNR issued an emergency regulation that prohibited the importation of zebra mussels for any purpose, including scientific investigations. The Living Resources Subcommittee of the Chesapeake Bay Program formed an Exotic Species Work Group in early 1992 to formulate policies for addressing introduced species and formulating risk assessment procedures. Within this Work Group, policies, controls, proposed research protocols, and standardized monitoring and water quality procedures are being drafted. Currently, limited scientific research on zebra mussels is being allowed in Maryland but only with strict adherence to established research protocols (Research Task Group, 1993) and the issuance of a conditional permit by Maryland DNR. Maryland DNR is formulating a state management plan in accordance with guidelines stipulated by the Non-Indigenous Aquatic Nuisance Prevention and Control Act of 1990.

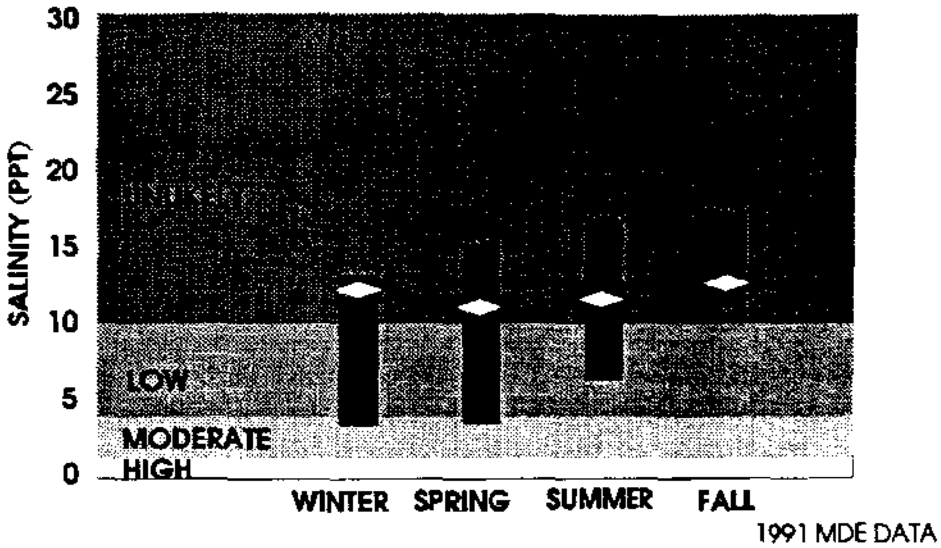

Figure 7. Probability of Zebra Mussel Survival, Baltimore Harbor. *Probability of zebra mussel survival in Baltimore Harbor in 1991 based on mean seasonal salinities in 1991. Diamond symbol = mean and black bar = range.*

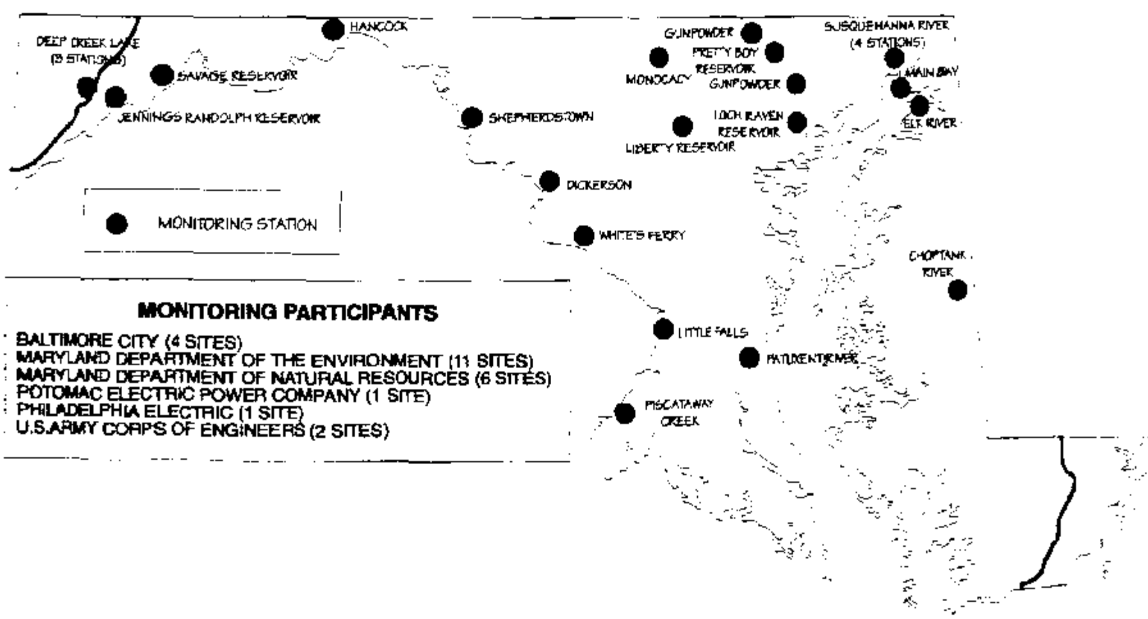

Figure 8. Zebra Mussel Monitoring Sites in Maryland in 1992.

ZEBRA MUSSEL MONITORING EFFORTS IN MARYLAND

Statewide monitoring was begun in 1992 by a variety of organizations, including the Department of the Environment, the Department of Natural Resources, Baltimore City, the Army Corps of Engineers, and the power generating facilities of Potomac Electric Power Company and Philadelphia Electric. A total of 25 sites were sampled for settled juvenile zebra mussels using artificial substrate samplers (Figure 8). Philadelphia Electric and the Department of the Environment utilized side-stream and pump sampling, respectively, for veliger monitoring. Bi-weekly sampling began when water temperatures exceeded 8° C and continued until temperatures fell below 8° C. In 1992, the monitoring period was from April 1 to December 12.

Most fresh water bivalves in Maryland, including several species of the family Unionidae, have glochidial larval stages. These larval stages make identification easier when planktonic sampling methods are used. The only freshwater bivalves in Maryland that produce free-swimming veligers that could be found in planktonic samples are the dark false mussel, *Mytilopsis leucophaeata*, and the Asiatic clam, *Corbicula fluminea*. While zebra mussels have not been reported so far in Maryland — either from monitoring sites or anecdotal information — monitoring will continue as control and mitigation policies and methods are being formulated.

SUMMARY

Even if zebra mussels are successful in colonizing tidal freshwater and oligohaline portions of the Bay, it appear — based on current research data — that only marginal populations of zebra mussels could survive in waters with salinities greater than 5 ppt that are inhabited by commercially-important populations of soft shell clams and oysters. The potential for competition by invading bivalves with native species is of great interest in Maryland.

Although zebra mussels have not yet been discovered in Maryland, coordinated monitoring, research, education, and prevention efforts have been initiated by both the public and private sectors. In addition to ongoing monitoring and education activities, the following efforts are underway:

- Develop a composite GIS map incorporating calcium, pH, and salinity data obtained from existing data sets.
- Develop seasonal salinity maps for tidal waters.
- Obtain necessary water quality data (i.e., calcium, pH, salinity) for those areas where it is lacking.
- Develop a Dispersal Probability Index for the major freshwater impoundments in Maryland based on water quality and dispersal vector criteria.
- Organize a citizen monitoring program for freshwater impoundments.

- Expand public education and information dissemination efforts.

- Adopt research protocols for *Dreissena* sp. mussels to be used in an interim permit process administered by Maryland DNR to regulate importation of live zebra mussels for research purposes.

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New Jersey Zebra Mussel State Report

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Scientists believe that nearly every waterway in North America could be infested with zebra mussels (*Dreissena polymorpha*) within the next twenty years. With a *Dreissena* population located in the Hudson River (just north of the Tappan Zee Bridge) and a sighting in the Susquehanna River (just north of the Pennsylvania border) Zebra mussels are rapidly approaching New Jersey's borders and posing a real threat to the state's estuarine and fresh waters. New Jersey, the most densely populated state and a key industrial center, is situated between the Hudson River estuary (eastern border) and the Delaware River estuary (western border); both have been designated as "National Estuaries" by the USEPA. These "National Estuaries" are not only important marine transportation and industrial centers, they provide habitat to valuable wildlife species, recreational opportunities to millions of boaters and fishermen and a source of water for drinking and industrial purposes.

THE DELAWARE RIVER ESTUARY

The Delaware River is tidally influenced from Trenton, New Jersey, to its mouth. Salinity in the river is determined primarily by the rate of freshwater discharge. During times of low freshwater discharge, salt water in trace amounts will intrude as far north as Philadelphia. During normal flow rates, the Delaware River is considered freshwater as far south as Chester, Pennsylvania. At the mouth of Delaware Bay, salinity levels approach those of ocean water. Zebra mussels are primarily a freshwater mollusks, but they can tolerate salinity levels between zero to about 10 ppt. Therefore, zebra mussels could potentially inhabit the entire Delaware River proper and northern stretches of Delaware Bay and, depending on river flow rates, extend into more southern regions of Delaware Bay.

THE HUDSON RIVER ESTUARY

The Hackensack and Passaic Rivers parallel the Hudson River as they flow southward into Newark Bay. Depending on water flow, zebra mussels could potentially inhabit the

Hackensack River to its mouth, but infestation is more likely upstream. The Passaic River is freshwater from the headwaters to the Dundee Dam and then becomes tidal and brackish to its mouth. Zebra mussels could probably infest the Passaic River to Newark Bay. Since salinity levels are higher in Newark Bay than in the river, there is a low probability of zebra mussel infestation in the Bay.

The Arthur Kill flows between Newark and Raritan Bays. Salinity levels are high throughout the Arthur Kill and even higher in Raritan Bay. Therefore, the probability of zebra mussel infestation in these waterways is low.

OTHER BODIES OF WATER

New Jersey has approximately 1200 lakes and ponds comprising approximately 51,000 acres. Three hundred and eighty-one of these lakes and ponds (24,000 acres) are public bodies of water. In addition, there are approximately 6,450 miles of streams and rivers throughout the state.

Many of these lakes and ponds, including several reservoirs in the northern and central regions of the state, have the proper conditions to sustain zebra mussel populations. However, as one reaches the pinelands section of south Jersey, many of the waterways have low calcium and pH levels. Hence, many of these waterways are at low risk of invasion by zebra mussels. Salinity levels are high in most of the bays along the Jersey coast. Therefore, these regions have a low probability of zebra mussel infestation.

POTENTIAL IMPACTS

Zebra mussels could invade power generating facilities, municipal water authorities, petrochemical and pharmaceutical firms and other industries in New Jersey. In addition, many agribusinesses, golf courses, marinas, boaters and even homeowners could also be affected.

Over 1.5 million marine and freshwater recreational fishermen use New Jersey's waterways. Approximately one million are state residents. Based on the sale of freshwater licenses, a total of 265,000 of these anglers fish in New Jersey's freshwater lakes, ponds, rivers and streams. The Delaware River supports important recreational fisheries for shad, trout, muskie, stripers and largemouth and smallmouth bass. In the spring and fall, there is a put and take trout fishery in most of the state's fishable freshwater lakes, ponds, rivers and streams. Some streams in the northern part of the state support wild trout populations. Throughout the spring, summer and fall, anglers fish for largemouth bass, other centrachids and pickerel in most waterways. In the winter, ice fishing is popular in the northern lakes and ponds.

POTENTIAL VECTORS

Researchers have shown that the primary vectors for spreading zebra mussels are natural dispersion, barge traffic and recreational anglers/boaters. Many New Jersey boaters traveling to the Great Lakes, Hudson River, Finger Lakes and other infested waterways for pleasure boating and fishing could introduce the zebra mussel to New Jersey waters. Even anglers fishing from banks and wading in zebra mussel infested streams, rivers and lakes could introduce the zebra mussel to New Jersey. Larvae can be carried in bait bucket water. When anglers transport their bait buckets full of water from one fishing area to another and then dump it into the last waters fished, they could be introducing zebra mussels. Many bass tournaments are held throughout the state and participants could spread the zebra mussel. Bait dealers located throughout New Jersey purchase bait such as minnows from other states. The bait could be shipped in water containing zebra mussel larvae that is then unintentionally dumped into a local waterway.

Commercial ships, especially barges, can be a major vector for spreading zebra mussels. However, the majority of New Jersey's waterways are not used for shipping. Zebra mussels could be introduced into the Delaware River by these vessels traveling as far north as the Philadelphia/ Camden area. Ships also travel in Raritan Bay, the Arthur Kill and Newark Bay, but the salinity is probably too high for zebra mussels.

Once the zebra mussel invades New Jersey, it will be able to travel from one body of water to another via the old canal systems (i.e. Raritan canal). This natural dispersion mechanism could spread the mussel throughout much of New Jersey.

NEW JERSEY ZEBRA MUSSEL OUTREACH PROGRAM

The New Jersey Sea Grant Marine Advisory Service (NJSGMAS) zebra mussel outreach program works closely with the Great Lakes and Mid-Atlantic Sea Grant Zebra Mussel Networks. The primary goal of the program is to educate potentially affected industries; state, county and local governments; natural resource managers, environmentalists and the public (especially natural resource users) by providing them with current information on the ecology, identification, monitoring and control of the zebra mussel.

The NJSGMAS program utilizes various methods to accomplish it's outreach efforts. Two fact sheets that target recreational boaters in the region are being produced. One fact sheet will educate recreational boaters\fishermen about the zebra mussel and ways to prevent it's spread. The other fact sheet will discuss boat bottom treatment laws and regulations in the Mid-Atlantic region. A GIS map identifying potential areas of zebra mussel infestation in the Mid-Atlantic region (New Jersey to North Carolina) is being produced.

The NJSGMAS has conducted conferences and meetings, given presentations, published articles in various magazines and newspapers and produced a series of radio scripts and identification cards about the zebra mussel. These programs are targeting power generating facilities, municipal water authorities, agribusinesses, golf courses, marinas, boaters, fishermen, government agencies, natural resource managers, environmentalists and the general public.

CONCLUSION

Many of New Jersey's waterways have a high probability of infestation by the zebra mussel. Natural dispersion, commercial ships and recreational boaters/fishermen are some of the potential vectors for spreading the zebra mussel in New Jersey. The main goal of the NJSGMAS zebra mussel outreach program is to educate New Jersey residents and industries about the zebra mussel. Through these educational efforts, we hope to slow the spread of zebra mussels within the state and assist potentially affected industries to minimize the impacts of the zebra mussel.

Delaware: Criteria for Determining Areas At Risk

Jim Falk
Delaware Sea Grant

INTRODUCTION

Delaware is a small state comprised of only three counties (New Castle, Kent, Sussex). It is surrounded by mostly saline and brackish water (Delaware Bay, Atlantic Ocean, and portions of the Delaware River). Numerous streams, ponds, lakes, and a major inland bay system also add to the total surface water within the state. From an initial examination of the major watersheds in the state, we have conducted the following risk assessment.

DETERMINING AREAS AT RISK

The state Department of Natural Resources and Environmental Control (DNREC) selects stream basins or watersheds for planning, monitoring and control. There are 36 identified systems throughout the state. Six of the watersheds have been designated as protected use for public (drinking) water supply and should be monitored. These six watersheds are in the northernmost county of New Castle.

All of the watersheds except two (Army Creek in New Castle County and Bunting's Branch in Sussex County) are "protected for industrial water supply." Two important systems that should also be closely monitored include the Chesapeake and Delaware Canal (New Castle County) and the Nanticoke Watershed in Sussex County.

There are 60 lakes and ponds scattered throughout the state. Most of the large water bodies are state-owned and used for recreation. DNREC, Division of Fish and Wildlife, owns and manages 23 of them for fishing. Numerous smaller ponds are also used for farm purposes, especially irrigation of crops, and more recently for aquaculture purposes. All of Delaware's lakes and ponds are small in size (less than 5,000 acres), and most are located in Kent and Sussex counties. Many of these small water bodies could be infested with zebra mussels by small boats traveling from an infested waterway. Monitoring of these systems is a must.

The portion of the Delaware River that touches northern Delaware and is used by various water users (water supply and industrial uses) is not included as a separate watershed; however, it, too, should be monitored for any signs of zebra mussel infestation.

MAJOR WATER USERS

Major water users in the state have been identified as those industries or agencies possessing either water discharge (NPDES) or water withdrawal permits from the state DNREC. With the help of DNREC staff, we have been able to obtain addresses of these water users to begin educating and informing them of the potential threat of the zebra mussel.

There are 95 permit holders in the state: 54% from New Castle County, 31% from Sussex County, 11% from Kent County, 5% other. Permit holders include major chemical companies such as DuPont, ICI, and Hercules, poultry processing plants such as Townsend's and Perdue, power generating companies, municipal wastewater operations, and drinking water suppliers. A majority of these water users who have responded to a brief survey are using fresh water, and most monitor these common parameters: pH, dissolved oxygen, and temperature. Very few measure calcium, a necessary chemical for zebra mussel growth.

As we receive additional responses from the water users and begin to better characterize the physical makeup and composition of our major water bodies in the state, we should be able to more accurately respond to the needs of the state's water users. Our primary goal is to be able to tell each surface water user in the state how likely they are to be faced with the threat of zebra mussel infestation — based on the parameters identified as critical to zebra mussel reproduction and growth.

EDUCATION AND AWARENESS

The Sea Grant Marine Advisory Service and Sea Grant Communication Staffs in Delaware are committed to providing zebra mussel education and awareness. A first task was to identify major water users throughout the state, maintain mailing lists of these municipalities and industries and identify the major state agency offices who have oversight for water quality and permitting water uses.

Information is being shared with cooperative extension colleagues and other scientists at the university in order to acquaint a large network of educators about the zebra mussel and the potential impacts that it could have. Newsletter articles, radio public service announcements, and distribution of zebra mussel identification cards also spread the word to statewide audiences. These cards, adapted from cards developed for the Great Lakes states, carry a local telephone number for people to call if they have questions about zebra mussels. A stick-on decal will caution recreational boaters in Delaware and throughout the region about the transfer of mussels from one area to another after boating in an infested area.

Once conditions for *Dreissena* growth and reproduction are known, the Delaware Sea Grant will identify water bodies in the state that are at high, moderate, or low risk for invasion by the organism. The Scientific and Technical Committee meeting of the Inland Bays Estuary Program and the Delaware Estuary Program will include discussion of the potential for zebra mussel infestation in the near future.

ZEBRA MUSSEL ANECDOTE

Last November, a call came in from an individual at a chemical company along the Delaware River about a possible infestation of zebra mussels. He had noticed some hard-shelled organisms growing on pH probes in his water-cooling intake system. Everything he had heard and seen about zebra mussels made him think that an invasion along the Delaware River had started.

He sent a sample to the Zebra Mussel Clearinghouse, sponsored by the New York Sea Grant. At that time, there had been no sightings of zebra mussels in the Delaware River. Fortunately, the organisms were identified as a species of snail.

As time goes on and as more locations install monitoring systems, more hard-shelled organisms will have to be identified. Next time we may not be as lucky, and the ball game will change dramatically.

The Zebra Mussel Information Clearinghouse

New York Sea Grant Extension

Since its discovery in Lake St. Clair (June, 1988), the zebra mussel (*Dreissena polymorpha*) has spread throughout the Great Lakes; the Arkansas, Hudson, Illinois, Mississippi, Mohawk, Ohio, St. Lawrence, and Tennessee Rivers; and other waters of southern Canada and eastern United States. Zebra mussels foul the intakes of municipal drinking water, electric power generation, and industrial facilities and affect aquatic food webs, ecosystems, navigation, and beach use. Electric utilities, industries, municipal water authorities, natural resource management agencies, and government officials need information on the mussel.

ZEBRA MUSSEL INFORMATION CLEARINGHOUSE

This special project of the New York Sea Grant Extension Program, was established in 1990 to:

- serve as a national focal point for zebra mussel information
- provide easy access to the most current research, technological, and policy information available on the biology, spread, impact, and control of the mussel
- facilitate and coordinate zebra mussel information sharing throughout North America
- provide timely dissemination of research findings

The Clearinghouse works in conjunction with Sea Grant programs in the Great Lakes, New England, Mid-Atlantic, Southeast, and Gulf regions, as well as universities, government agencies, industries and others involved in zebra mussel information and research throughout the United States and Canada. The Federal Aquatic Nuisance Species Task Force and the U.S. Army Corps of Engineers use the Clearinghouse to report on federal initiatives regarding zebra mussel research and policy issues.

The Clearinghouse is funded by grants from electric utilities, public water authorities, industry, and the National Sea Grant College Program.

CLEARINGHOUSE SERVICES

Technical Library Collection: The Clearinghouse maintains North America's largest, most comprehensive library of research and other relevant information on the zebra mussel and related biological macrofoulers, available from the Clearinghouse on interlibrary loan.

Bibliography: A 90-page Technical Collection bibliography is available for $3.00 (U.S.)

The *Dreissena polymorpha* Information Review: A bimonthly research-based periodical, addressing all facets of zebra mussel biology, spread, monitoring, impacts, control research, and public policy. The ***Dp*IR** is available for a $60 (U.S.) annual subscription fee.

Electronic Databases: Annotated versions of the Technical Collection Bibliography that can be searched by keywords are available on the INTERNET and EPRINET computer networks; interlibrary loan copies can be ordered by electronic mail. Call for information.

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Mid-Atlantic Zebra Mussel Conference

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