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THE ZEBRA MUSSEL (DREISSENA POLYMORPHA): AN UNWELCOME NORTH AMERICAN INVADER

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INTRODUCTION

A new invader of North American fresh surface waters, *Dreissena polymorpha* (Pallas), commonly known as the "zebra mussel," has the potential to biofoul municipal, electric power generation and industrial water intake facilities; to disrupt food webs and ecosystem balances; and to interfere with sport and commercial fishing, navigation, recreational boating, beach use and agricultural irrigation throughout North American fresh surface waters.

ORIGIN OF THE ZEBRA MUSSEL IN THE GREAT LAKES

The zebra mussel, *Dreissena polymorpha*, native to the drainage basins of the Black, Caspian and Aral Seas, was introduced into several European freshwater ports during the late 1700s. Within 150 years of its introduction, the zebra mussel was found throughout European inland waterways.

Although the actual pathway of the mussel's introduction into North America is unknown, it is believed that ships originating from overseas freshwater ports where the mussel is found carried the mussel in freshwater ballast which was discharged into freshwater ports of the Great Lakes. Although adult mussels are capable of attaching to ships' hulls, their transoceanic transport in this manner is unlikely since the mussels cannot survive the high total salinity in open ocean saltwater for the time required for a transatlantic crossing.

The zebra mussel was first discovered in the Great Lakes Basin in Lake St. Clair in June 1988. Judging from shell size, it was theorized that the mussels were introduced into the lake sometime in 1986. The first confirmed sighting in the western basin of Lake Erie was in July 1988. Extensive colonies of up to 30,000 to 40,000 individuals per square meter were reported in the western basin of Lake Erie in the summer of 1989 by the Ontario Ministry of Natural Resources. By the end of 1989, specimens had been found in water treatment and industrial water systems in the Detroit River below Lake St. Clair, on beaches and in water treatment and industrial facilities along most of the north and south shores of Lake Erie. Adult mussels were first reported in Lake Ontario in Port Weller at the mouth of the Welland Canal in November 1989 and on a navigation buoy four miles off the Niagara Bar in December 1989.

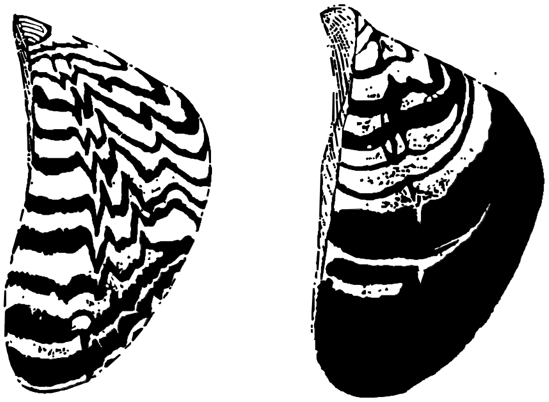
By September 1991, the mussel was found in all five of the Great Lakes; their connecting waterways; the St. Lawrence River; the western two-thirds of the Erie Canal; the eastern end of the Mohawk River; Cayuga and Seneca Lakes (in New York's Finger Lakes); the headwaters of the Susquehanna River in Johnson City, New York; the Hudson River between Albany and Red Hook, New York; the Illinois River; the Mississippi River between its confluence with the Illinois River and St. Louis, Missouri; the upper Mississippi River near La Crosse, Wisconsin; the Tennessee River near the Kentucky border; and the Ohio River near Mound City, Illinois.

Biologists believe that interbasin transport of the zebra mussel from the Great Lakes system into inland fresh surface waters is taking place via natural and human influenced dispersal vectors, and that the mussels will ultimately infest most areas of North America south of central Canada and north of the Florida Panhandle. This prediction seems to be borne out by sightings in the Illinois, Susquehanna, Mississippi, Tennessee, and Hudson Rivers. (See map for the zebra mussel's range in North America.)

Such dispersal will likely be greatly enhanced by interlake transport of veligers (larvae) in ship ballast and adult and juvenile mussels attached to ship and recreational boat hulls. The discovery of zebra mussels in Duluth Harbor (Lake Superior) may be evidence of such transport. There is concern that the range expansion of the zebra mussel will be further facilitated by transport of veligers by commercial bait transport, in anglers' bait bucket water and recreational boat engine cooling water, transport of juveniles and adults by waterfowl and by attachment to crayfish and turtles.

BIOLOGY OF THE ZEBRA MUSSEL

Zebra mussels are small (5 cm and smaller) bivalve mollusks (relatives of clams and oysters) with elongated shells typically marked by alternating light and dark bands (Fig. 1). As its scientific name *polymorpha* implies, the species shows considerable genetic and morphological plasticity, particularly in its marking and coloration patterns. Specimens with few markings, with a herringbone pattern, with stippled patterns or radial striping are quite common. Soviet studies suggest the presence of discrete morphological and physiological ecotypes or "phenes" (races) of *Dreissena* (Smirnova 1990). Early Soviet studies described at least five species (Andrussov, 1898).

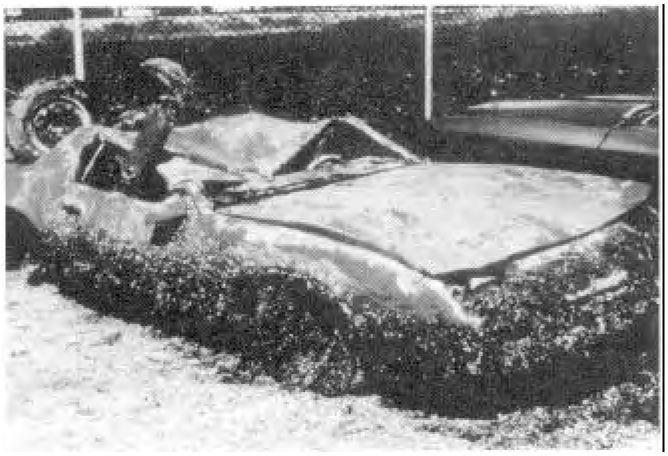


[From: Morton (1969)]

Figure 1. The origin of the name *polymorpha* can readily be seen in the variations in the light and dark banded markings on Zebra mussels.

Zebra mussels secrete durable elastic strands, called byssal fibers, by which they can securely attach to nearly any surface, forming barnacle-like encrustations (Fig. 2). Because of an affinity for water currents, zebra mussels extensively colonize water pipelines and canals, often severely reducing the flow of water and, upon death, imparting a foul taste to drinking water (serious impacts in Europe since the late 1800s).

Zebra mussels will colonize lakeshores and riverbanks where they attach to rock or gravel substrates, forming broad reef-like mats (Fig. 3). In some European lakes, colony densities exceeding 100,000 per square meter have been reported with 15 cm deep shell accumulations from dead mussels on the lake bottom within two years.



[Photo: Ontario Ministry of Environment]

Figure 2. Zebra mussels can attach to nearly any surface. This car, retrieved from the bottom of Erieau Harbor, Ontario, had mussels growing on every surface including sheet metal, tires, fiberglass, glass, even cloth seats.

The mussels are generally found within 2 to 7 meters of the water surface but may colonize to depths up to 50 meters (Walz, 1978). Colonization depths vary from lake to lake, but appear to be determined by light intensity, water temperature and availability of food. Zebra mussels can tolerate a fairly wide range of environmental conditions. They prefer water temperatures between 20° and 25°C (68° and 77°F) and water currents 0.15 to 0.5 meters per second for proper growth. While normally considered a freshwater species, the zebra mussel can adapt to and inhabit brackish areas ranging from 0.2 to 2.5 ppt (parts per thousand) total salinity in estuarine locales. European reports indicate occasional sightings of zebra mussels in total salinities exceeding 12 ppt (Benthem Jutting, 1943).

In Europe, mussel densities tend to be higher in large lakes (surface areas greater than 485 hectares) with depths exceeding 35 meters, which are not overly enriched but which have a high calcium content, generally greater than 12 ppm (parts per million). Conditions generally considered as unsuitable for growth are water temperatures below 7°C (45°F) or above 32°C (90°F), water currents greater than 2 meters per second or rapid water level fluctuations. Zebra mussels can withstand dessication for two to three days, depending upon atmospheric humidity.

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Figure 3 Zebra mussels attached to rock or gravel substrates can reach colony densities greater than 100,000 per square meter with shell accumulations reaching 15 cm or more on the lake bottom.

The zebra mussel has a reproductive strategy unique to freshwater mussels which is responsible for its rapid population expansion in Europe and the Great Lakes. Sexual maturity is typically reached at age two but may occur in the first year at a size of 3 to 5 mm. Zebra mussels are separately sexed, but some hermaphroditism has been reported. Mature female mussels can produce 30,000 to 40,000 eggs per year, as the water temperatures reach 12°C (54°F). At least one European study has indicated that a 30 mm female can produce, on average, up to 1 million eggs per year. Precocious young-of-the-year mussels as small as 3 mm may produce as many as 6,000 eggs per year (Walz, 1978). Egg production can occur in either asynchronous or synchronous batches enabling individuals to spawn several times during the spawning season. Spawning activity may extend throughout the year in warm, productive waters.

Although poorly understood, the reproductive cycle is apparently influenced by environmental cues such as water temperature, phytoplankton abundance and species composition, and mussel population density. Evidence from Lake Erie suggests that reproductive activity may be cued by such seasonal phytoplankton dynamics as blooms and algal species succession. Spawning patterns may show considerable year-to-year variations. Recent studies from Lake Erie suggest that cool water temperatures, storm events, elevated turbidity, and increased population densities can delay spawning, resulting in possible synchronous spawning activity. Spawning may also be induced by the presence of mussel gametes (sex products) in the water.

In Europe, fertilized eggs are 40 to 70 microns long and become planktonic larvae (veligers) in 2 to 3 days when water temperatures reach 14° to 16°C (57° to 61°F). In Lake Erie 11°C (52°F) is the norm, with the Ontario Ministry of Natural Resources reporting veligers in water as cold as 8.0°C (46°F). Veligers are capable of active swimming for 1 to 2 weeks, and are also transported by water currents, enabling them to disperse considerable distances from their parent colonies. Nocturnal vertical migrations of veligers have been reported in European lakes.

Within 3 weeks of hatching, the young mussels reach the "settling stage," where they can attach to bedrock, cobble, bottom debris or such manmade objects as boat hulls, breakwaters and water intake cribs. At this life-cycle phase, the settling larvae can experience mortalities exceeding 99%, primarily from hypoxia, temperature shock, and failure to locate a suitable attachment substrate (which could result in larvae sinking into bottom sediments or into deeper, colder water with lower productivity).

During the first year of life, young mussels are capable of active crawling along the substrate at speeds over 3.8 cm per hour until they find a suitable location to attach with small, temporary byssal fibers. With age, the mussels develop extensive byssal fibers and, for the most part, become sessile. Younger, overwintering mussels can detach from their temporary byssal fibers and migrate to deeper (warmer) waters to escape from cold temperatures and ice scour. During the first growing season, young zebra mussels may reach 5 to 10 mm in length.

The lifespan of a zebra mussel is highly variable depending on a number of environmental conditions. Lifespans average around 3.5 years but can reach 8 to 10 years in some less productive European systems.

Typically, when the zebra mussel is introduced outside its native range, the relocated population undergoes a rapid increase in number, often by a factor of 2 to 3, lasting for several years after the initial introduction, followed by a marked reduction in population size and subsequent population oscillations. However, in Sweden the population of zebra mussels has not yet crashed after more than 11 years. The zebra mussel population expansion in Lake Erie appears to be more aggressive than in Europe, most likely due to the lake's highly suitable chemical, biological and thermal regimes.

USE OF THE ZEBRA MUSSEL AS FOOD: NATURAL PREDATION

Although larval and adult zebra mussels (which offer a high nutritional value to predators) are regularly consumed in Europe by several species of fish, the overall impact upon mussel populations is believed to be insignificant in many instances. Veliger and post-veliger larvae are also preyed upon by young fish and zooplankton, but to what extent this predation contributes to mussel mortality is unknown, although some researchers estimate this loss can reach five percent (Piesek, 1974). In some European lakes, crayfish predation on mussels 1 to 5 mm long is considerable, with adult crayfish (90 mm) consuming over 100 mussels per day (about 6,000 mussels per summer). Crayfish, however, are believed to be ineffective predators in deeper lakes due to cooler water temperatures. Some studies indicate that over 90% of the diets of the roach, a Eurasian fish species, is composed of zebra mussels. In the Great Lakes, the role of coarse fish species such as carp, eels and sheepshead may become increasingly important as a biological control agent; sheepshead are already reportedly feeding extensively upon zebra mussels in inshore areas of Lake Erie.

In Europe, studies indicate that waterfowl predation rates on zebra mussel populations are variable, ranging from insignificant to as high as 32% during the summer months and greater than 90% during the winter in some lakes. In the littoral zone (water depths of 0 to 5 meters) waterfowl are considered to be the prime controller of zebra mussels. For example, Lake IJssel, in the Netherlands, supports a large population of diving ducks feeding on zebra mussels.

The value of zebra mussels as a human food source is doubtful. It appears that they may not be a viable human food because of their small size, a strong byssal attachment which would make them difficult to harvest, and a possible tendency to serve as a parasite vector (transmitter) to humans. Furthermore, the mussel's filter feeding process may cause bioaccumulation of toxic contaminants, making the mussels unfit for human consumption.

BIOLOGICAL IMPACTS

Using siphons and a ciliated gill system, zebra mussels filter small particles such as phytoplankton (microscopic plants and many forms of algae), small zooplankton (microscopic animals) such as rotifers, and detritus (bits of organic debris) out of water drawn into the mussel's mantle cavity. Laboratory studies indicate that the mussels can efficiently filter food particles down to 0.7 microns, but preferentially select those particles between 15 to 40 microns as food. Rotifers as large as 450 microns can be retained and eaten. Zebra mussels can also filter and consume their own veligers. Particles of unsuitable size or chemical composition that are not ingested are coalesced into a mucus bolus (pseudofeces) and subsequently discharged.

Filtration rates (volume of water filtered per unit of time) are determined by food particle concentration and sizes, water temperatures, hunger state and mussel body size. On average, a 25 mm long zebra mussel can filter 1 liter of water per day. Filtration rates up to 2 liters per day under optimal conditions have been observed. European studies indicate that the filtration ability of the mussels can dramatically increase lake water clarity. Since the introduction of zebra mussels into the western basin of Lake Erie, Canadian researchers have observed a two- to three-fold increase in water clarity and a significant reduction in chlorophyll a content (chlorophyll a analysis provides an index of the open water food chain production available for the aquatic plants and animals in a waterbody). The extent that changes in the lake's clarity and productivity can be attributed directly to zebra mussel filtration activity is unknown. It is suspected that the zebra mussel has played a role. Lake Erie has also experienced an effective phosphate abatement program, which may be responsible in part for these observed trends in increased water clarity and decreased chlorophyll a content.

Since phytoplankton and detritus are major food sources for pelagic (open water) lake and riverine food webs respectively, fisheries-related impacts could result from zebra mussel filtration activity. Excessive removal of phytoplankton and detritus from the water column could cause a decline in zooplankton species which feed upon those food particles. Small zooplankton are also eaten by zebra mussels. Larger zooplankton species and larval fish of all species preying on smaller zooplankton could face reduced survival as mussel populations expand, suggesting other potential food web impacts. In addition, extensive deposition of mussel pseudofeces on the lake bottom could favor the proliferation of benthic (bottom-dwelling) fish and invertebrate species, especially in littoral areas. The changes in water transparency and the selective survival of benthic algae in mussel pseudofeces could favor a shift towards increased importance of primary production of benthic algae in the Great Lakes.

Because zebra mussels settle on rock cobble as an attachment substrate, there is concern that extensive colonization of shoal areas could impair reproduction of species of fish (such as walleye and lake trout) which spawn only on rocky-bottomed areas. Some biologists are concerned that decomposing mussel pseudofeces could reduce water quality in and around fish egg masses on shoals, reducing egg survival. Data collected by the Ohio Department of Natural Resources in 1990-91, however, indicated good year classes of walleyes produced from mussel-encrusted shoals in western Lake Erie. Apparently, mussels were scoured from some spawning areas by ice prior to 1990 walleye spawning. Wave action also helped by sweeping shoal areas clear of mussel pseudofeces. Continued monitoring of spawning areas is necessary to quantify any future mussel impacts. Furthermore, increased water clarity may reduce the ability of larval fish to avoid predation. This also makes zooplankton more visible to fish predators.

In general, freshwater mollusks are important vectors of parasites (digenetic trematodes) in waterfowl, fish, wildlife, and, occasionally humans (in tropical areas). The typical life cycle of digenetic trematodes involves the development of the parasite within the bodies of mollusks, which serve as intermediate hosts. Although zebra mussels are not considered as common parasitic vectors in Europe, they could potentially increase the spread of certain parasites, particularly as the mussel colonizes rapidly throughout North America. Zebra mussels themselves show little effects from parasites.

Native mussel populations may be adversely impacted by competition for food and space by the sheer numbers of zebra mussel colonies reported in areas of the Great Lakes. There are already early signs that native unionid clam populations in Lake St. Clair are disappearing rapidly coincident with zebra mussel colonization. Numerous live and dead unionids have been observed covered with extensive growths of zebra mussels. Many unionids appear to die as zebra mussel colonies interfere with host shell movements or cause damage to the shell edges.

THE ZEBRA MUSSEL AS A BIOFOULER IN RAW WATER SUPPLIES

A major impact of zebra mussel infestations is the fouling of raw water intakes such as those at drinking water, electric generation and industrial facilities. Water intake structures (intake cribs, trash racks, pipelines and tunnels) serve as excellent habitat for mussel colonization. The continuous flow of water into intakes carries with it a continuous source of food and oxygen to the mussels and carries away wastes, while the structures themselves protect the mussels from predation and ice scour. This makes water intakes ideal mussel habitat.

The zebra mussel is capable of attaching to firm substrates at water flow velocities below 2.5 meters per second on horizontal surfaces or 2.0 meters per second on vertical surfaces. Researchers in the Netherlands have reported that flows of 1.0 to 1.5 meters per second are sufficient to preclude settling under some conditions (Jenner, 1989). The presence of zebra mussels in a raw water main is usually first detected by the discharge of shells into the facility's raw well or forebay, possibly accompanied by a noticeable decrease in head, as the mussels line the pipeline or tunnel, eliminating the laminar flow along the walls of the conduit. In some cases, layers up to 0.3 meters or more in thickness are formed in intake mains.

Once in a drinking water treatment facility, zebra mussels may colonize any surface within the distribution system up to the first oxidation or filtration stage, including intake mains, raw wells, screen house walls, traveling or stationary screens, strainers and settling tanks. The main impacts associated with colonization are: loss of intake head, obstruction of valves, putrefactive decay of highly proteinaceous mussel flesh, obnoxious methane gas production, and increased electrocorrosion of steel and cast iron pipelines.

A similar fouling problem can occur in power plants and industrial water systems which use an infested waterbody as their raw water supply. Condenser and heat exchanger tubing can become clogged, leading to loss of heat exchange efficiency and overheating. Service water (fire protection, bearing lubrication/cooling, transformer cooling, etc.) lines can also become clogged, resulting in potential damage to vital plant components and possible safety hazards if sprinkler systems fail to deliver sufficient fire fighting water.

The rate of overgrowth of zebra mussels from intake cribs and trash racks to internal distribution systems is dependent upon chemical and physical characteristics of the raw water supply, flow velocity within the system, the three-dimensional position of the surface of the overgrowth, and the surface structure of the substrate. One Great Lakes utility has reported mussel densities as high as 750,000 per square meter in its intake canal.

IMPACTS ON NAVIGATION AND RECREATIONAL BOATING

Zebra mussels can impact commercial navigation and recreational boating. As with any organism capable of attaching to hulls, zebra mussels increase the amount of drag, reduce a boat's speed, and increase fuel consumption. Growth of larval mussels drawn into a boat's engine cooling water intake may occlude the cooling system, leading to overheating and possible damage to the engine. If shells are drawn into the engine, abrasion of cooling system parts, especially impellers, could result.

Commercial and recreational navigation can also be impacted if marker buoys sink under the weight of mussel encrustations on the submerged portions of the navigation aids. There is concern that navigation canals can also be negatively impacted by mussel colonization in lock systems.

The zebra mussel can also negatively affect docks and piers. Large colonies can encrust pilings and ladders, making them difficult to tie up to and speeding corrosion as a result of the mussels' waste excretions. On floating dock systems, each square meter of adult mussels on the bottom and sides of floats can add as much as 20 to 30 pounds. Dock systems that are left in the water year-round could be destabilized or sunk by mussel colonization. Bubbler or flow developer systems which are used to prevent ice damage to dock systems could be colonized, decreasing the systems' ice minimization effectiveness.

IMPACTS ON RECREATION

Recreational use of beaches in infested areas may be impacted by colonization of cobble in shallow nearshore areas by the mussels and by littering of beaches by shells washed up from submerged colonies by storm waves. Bathers on some Great Lakes beaches are reportedly adopting the use of beach/bathing footgear to prevent cuts from zebra mussel shells. Obnoxious smells from the decomposition of mussels also detract from the enjoyment of shoreline recreational activities.

PHYSICAL AND MECHANICAL CONTROL ALTERNATIVES

The European and Soviet experiences indicate that it is best to eliminate the zebra mussel in water pipelines at the veliger stage or before the most rapidly growing post-veliger specimens are able to pass unhindered through the pipeline. Control can be continuous or periodic with the time schedule for elimination based upon the mussel's growth rate for the specific waterbody and the minimum openings in the pipeline through which dead or living specimens can pass.

The first, and most evident, method for controlling zebra mussel infestation of raw water use facilities is to prevent entry of the mussel into such water systems (exclusion). This is accomplished by the use of strainers and filters to prevent the entry of larval, juvenile and adult mussels. The effectiveness of exclusion depends upon the mesh size of traveling and stationary screens and the size of the mussel.

The common traveling screen mesh used in water supply systems is 9 to 13 mm. The effectiveness of screens can be increased by reducing the mesh size (some newer power plants use traveling screens with openings as small as 1 mm). This method is effective in excluding only those mussels which originate upstream of the screens or filters. Mussel colonization downstream of the screens (as a result of the passage of veligers through the screens) is not impacted. Additional service water strainers can exclude adult and juvenile mussels that were not excluded by the initial screening. Centrifugal separation debris filters or backflushable bag filters can be used to exclude most sizes of zebra mussels but may result in a loss of head in distribution lines.

Unfortunately, veligers pass easily through both screens and service water strainers and perhaps filters, as well, and need to be eliminated in some other manner before they have an opportunity to settle and colonize within the distribution system. The possibility does exist to use microstraining fabrics or filters with an aperture of 60-70 microns or smaller to keep veligers out of very sensitive portions of distribution systems. However, this is not practical on systems requiring large amounts or high velocities of water.

A different approach is filtration of intake water at the source, before the water enters the pipeline. This can be accomplished through the use of several different forms of buried intakes or sand filters. These types of filters are suitable for low flow requirements, up to a maximum of about 25,000-30,000 gallons per minute. These types of intake filters are either drilled vertically and laterally into a good sand and gravel aquifer near a lake or river (Ranney wells); consist of porous intake pipes laid in trenches excavated into the bed of a lake or river and backfilled with a graded sand and gravel media (infiltration galleries); or are comprised of a flowing water source entering a surface trench or basin filled with a graded sand/gravel media with the pumping conduit either beneath the trench/basin, in the center, or at the outflow end (surface sand filter). Some modified form of sand filtration may also be suitable for use in single family homes or cottages using raw lake or stream water.

Since zebra mussels do not attach in high velocity current areas, another control method is to maintain intake and distribution system flows exceeding the rates stated earlier in this paper. This may not be possible in existing facilities due to pipe and pump size, pipeline configuration, or other factors, but should be taken into consideration in the design of new facilities in infested areas. Anything that causes either a significant drop in flow velocity or an eddying effect (such as changes in pipe diameter, short radius bends, square wall intersections in pumping wells, etc.) which would allow for increased mussel settlement and subsequent colonization, should be avoided. Also, rough pipe walls caused by scale, pitting, or poor welds should be corrected, as these areas create turbulence which allows the mussels an improved chance of reaching conduit walls through the laminar layer and increasing rates of attachment.

Physically scraping mussels from water systems (removal) is also a viable method of control. The desirability and effectiveness of scraping depends upon the design and operational characteristics of the impacted system. Scraping is most effective in large conduits where mussels are found in high concentrations, where access for personnel and equipment is available, and where the conduit can be taken out of service for long enough periods of time that divers (or non-dive personnel, in the case of dewatered systems) can remove the accumulated mussels. This alternative is, however, very expensive in terms of labor and lost production.

In smaller pipes or in pipelines where the configuration does not allow for direct access by workers, scraping may be accomplished by "pigging." The effectiveness of this method depends upon the design of the system and the intensity of the infestation. Pigging is not effective in systems with sharp, short radius bends in the pipeline or where the infestation is so great that the large amount of dislodged mussels might obstruct the progress of the pig or cannot be effectively removed from the conduit. Pigging can be designed into new systems constructed in infested areas.

Attachment of zebra mussels on open surfaces (i.e. trash racks and gates) may be discouraged through the use of electrically charged surfaces using industrial-frequency currents. Care should be taken to ensure that humans cannot come in contact with the charged surfaces. Potential impact on fish, ducks and other animals should also be considered.

It may be possible to control veliger settling in pipelines by the use of electrostatic filters placed in a pipeline cross section. In this case, exposure time depends upon water flow rates. Soviet research indicates that veliger death can be achieved by exposure to high voltage for 0.1 second. For such short exposures, 225 to 250 volts per centimeter would be needed for specimens with open shell valves or 380 to 400 volts per centimeter for those with closed valves (Morton, 1969), making this alternative impractical for most situations. At higher temperatures and voltages, specimens die proportionately more quickly. It should be noted that preliminary testing in the U.S. indicates that even greater charges may be required to ensure 100% mortality.

A "last resort" mechanical control for extreme situations is the removal and replacement of clogged tubing.

AVOIDANCE CONTROL ALTERNATIVES

For facilities that place marker buoys to locate intake cribs, it would be advisable to keep the buoy anchors well away from the intake structures to prevent veligers from settling on the anchor cable and spreading down the cable to the cribs. Periodic scraping of the bottoms of buoys is advised to avoid possible sinking under the weight of attached mussels.

The use of acoustic vibrations (>20kHz) is also being researched as an avoidance methodology. Preliminary data indicate that certain frequencies and intensities may be effective in "deactivating" veligers, that is, rendering them unable to attach to available substrates. Ultraviolet B radiation may also prove to have some effectiveness at killing veligers entering low flow conduits.

OXYGEN DEPRIVATION CONTROL

Since zebra mussels "breathe" oxygen as they draw water over their gills, oxygen deprivation, accomplished by hermetically sealing water intakes and

WATER TEMP °C	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	CRITERIA STUDIED
17-18	7.5 0		0.7 0	0.03 0		0 90	0 100	D.O. (mg/l) % Dead
20-21	9.6 0	0.08 0	0 10.0		0 100			D.O. (mg/l) % Dead
23-24	7.1 0	0.33 0	0 48.0	0 100				D.O. (mg/l) % Dead

Table 1 Zebra mussel mortality rates at differing water temperatures and dissolved oxygen concentrations (Mikheev, 1968).

isolated internal distribution lines, can be used as a control method. Because the mussels utilize oxygen most efficiently at 20°C (68°F), oxygen deprivation tends to work best in summer. Two to three days exposure to anaerobic water at 23° to 24°C (73.5° to 75°F) will result in 100% mortality (Mikheev, 1968; see Table 1). Oxygen can be eliminated from a sealed conduit using sodium metabisulfite with cobalt chloride as a catalyst. Hydrogen sulfide gas may be added to increase the effectiveness of the treatment.

A relationship also exists between mussel size and susceptibility to oxygen deprivation. Small specimens die first because smaller mussels consume more oxygen than larger ones (Table 2). Unfortunately, however, since zebra mussels can survive several days of anaerobic conditions, any pipeline treated in this manner must be capable of being shut down and sealed for a number of days, a major drawback for most applications. It should be noted that many European water systems are designed with dual intakes, often quite short, to enable one to be shut down for cleaning while the other carries on the business of the facility.

Length (mm)	% Mortality
1.0-4.9	100
5.0-9.9	61
10.0-14.9	34
15.0-19.9	2
20.0-24.9	0

TABLE 2 Relationship of zebra mussel size and mortality under anaerobic conditions for 37 hours at 22° (Mikheev, 1968).

When eliminating zebra mussels through oxygen deprivation, it should be noted that mussels in closed vessels die more rapidly when dead specimens are already present. There are several explanations for this: the appearance of disintegration products in water, extensive development of bacterial flora, and the rapid uptake of any remaining oxygen for oxidation (decomposition) and bacterial respiration.

THERMAL CONTROL

Experience in Europe and the Soviet Union indicates that one of the most efficient, environmentally sound and cost effective methods of controlling zebra mussel encrustations is the systematic, periodic flushing of water systems with heated water. Water temperatures must exceed 37°C (98.6°F) for approximately 1 hour to ensure 100% mortality for mussels acclimated to 10°C (50°F) water temperatures (Ontario Hydro, 1990). Water temperatures in excess of 55°C (131°F) will result in rapid death of the most mussels of the widest size (life stage) range. In this temperature range, mussels tend to die with their shells slightly opened, promoting exposure and degeneration of byssal threads, followed by detachment of many specimens from the substrate (the smallest mussels, <7.0 mm, detach first). Lower temperatures, or thermal shocking applied to mussels acclimated to warmer water temperatures, will take longer periods of time to achieve 100% mortality (Figure 4). Mussels which remain attached must be mechanically scraped from the attachment areas or may be allowed to decompose. Treatments at temperatures greater than 60°C (140°F) result in immediate 100% mortality. However, many mussels may die with closed shells and may remain attached for several days.

When utilizing thermal control, it is often necessary to treat as many as three or more times annually to remove adults and to target the more vulnerable

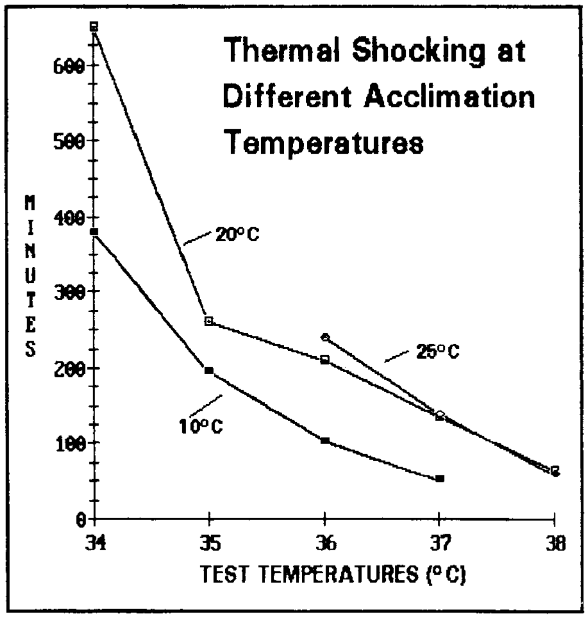

Figure 4 The time required to kill zebra mussels by thermal shocking varies dependent upon the temperature to which the mussels are acclimated and the temperature of the water used for the treatment.

early life stages of the mussel. The suggested annual treatment regime is early summer (June) to eliminate overwintered post-veliger specimens of the previous year, followed by second and third treatments in late summer (August) and fall (late October or November) to eliminate the current year's post-veligers. Each thermal treatment may have to be repeated several times during each of the three annual treatments to eliminate the greatest number of mussels. Mechanical scraping and cold-water flushing can be used after each hot water treatment to remove debris from major encrustations, much of which can be flushed from the system under high flow conditions. It should be noted that byssal threads will remain attached to substrate for considerable lengths of time, possibly disrupting laminar flow long after mussel shells have been removed.

CHEMICAL CONTROL ALTERNATIVES

Chemical control strategies generally fall into two categories: compounds which oxidize the mussels' organic material rather than acting in a toxic manner (e.g. chlorine, chlorine dioxide, ozone, potassium permanganate, hydrogen peroxide, chloramine) and chemicals which have a toxic effect on the mussels (e.g. molluscicides, copper sulfate, some metallic ions).

Chemical control strategies may be applied **once per year** at the end of the mussel spawning season (to kill all mussels of all ages which have been allowed to grow in a system since the end of the last spawning season); **periodically** throughout the spawning season (allowing some colonization but killing the mussels before densities get too great for efficient operation of the system; this allows less colonization than seasonal treatment); frequent **intermittent** treatment with relatively high concentrations of chemical (generally once or twice per day to purge the system of recently settled post-veligers, preventing growth to the more troublesome adult stage); and **continuously** with lower concentrations of chemical throughout the spawning season to prevent all settlement and colonization within the system.

Commercially available **molluscicides** lend themselves more to seasonal or periodic treatment of nonpotable water systems in which some colonization can be tolerated. **Oxidizing chemicals** may be used for short-term seasonal or periodic usage in systems with an immediate discharge to the environment. In potable water systems where little or no colonization can be tolerated because of potential human health impacts (mainly bacterial growth in rotting mussel flesh and taste and/or odor problems), oxidizing chemicals may be suitable for intermittent or continuous treatment.

Experiments in the Soviet Union have indicated that **electrolytically dissolved metal ions** in water may be used in low discharge pipelines and in underground and other inaccessible conduits to eliminate zebra mussels. When using metallic ions, larger mussels can be expected to exhibit a greater negative

ION	mg/l	% MORTALITY	TEST CONDITIONS
SILVER	2.5 5.0 7.5+	40.0 71.5 100	20°C 24 hour[1]
MERCURY	5.0	57.2	20°C, 24 hour[1]
ZINC*	5.0	4.8	20°C, 24 hour[1]
COPPER	4.0	100	20°C, 24 hour[1]
COPPER	3.9	8.0	10°C, 20 hour[2]
COPPER	3.9	93.0	20°-22°C, 20 hr[2]

Table 3 The effects of metal ions on zebra mussels. *Surviving mussels filter water but do not attach to substrate. [1] Static water test. [2] Flowing water test. (Dudnikov and Mikheev, 1968)

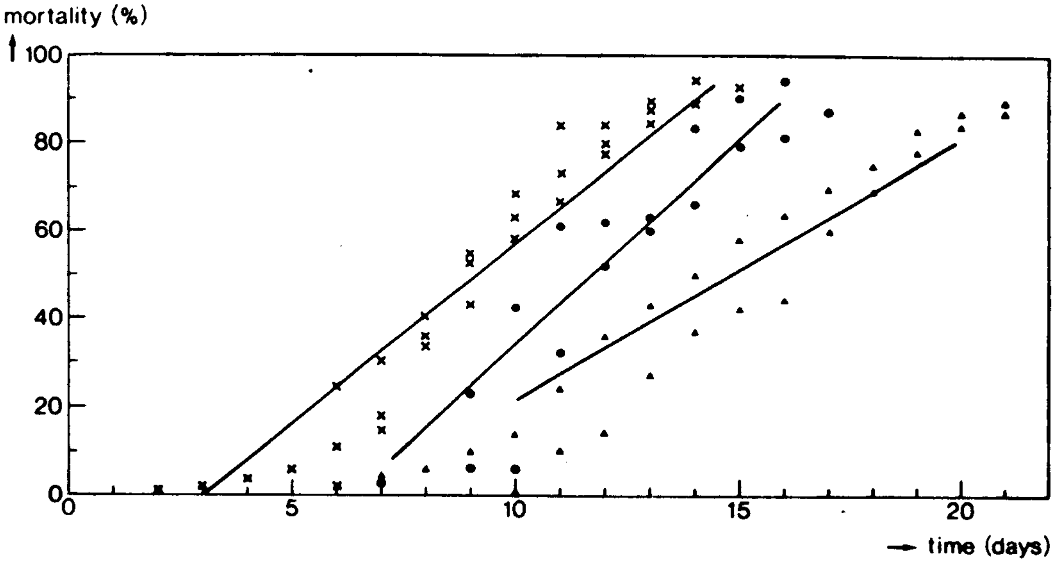

TABLE 4 Mortality rate of zebra mussels in laboratory experiments at varying chlorine concentrations. The lines represent linear correlations. Experiments were run at water temperatures of 12°-15°C.

x = 1.0 mg/l Total Residual Chlorine (TRC); 3 experiments in duplicate; r = 0.972
o = 0.5 mg/l Total Residual Chlorine (TRC); 2 experiments in duplicate; r = 0.988
▲ = 0.25 mg/l Total Residual Chlorine (TRC); 2 experiments in duplicate; r = 0.956

response due to incomplete hermetic sealing of their shells. While discharge of many of these metals into the natural environment (receiving waters) would not be permissible under state and federal regulations, some metallic ions might be applicable for use in closed water systems. Another factor which could limit use of metallic ions as a zebra mussel control measure is the potential corrosion of metal system components.

The use of copper sulfate has been shown in Soviet experiments to be an effective zebra mussel control. However, at temperatures below 22.5°C (72.5°F), lethal doses of copper sulfate are so high (i.e., 300 mg/l at 17.5°C for 5 hours results in 60% mortality [Lukanin, 1968]) as to be impractical, considering corrosion of metal pipes caused by the copper. At temperatures above 27.5°C (81.5°F), lethal concentrations decrease to more practical values (e.g., 11.0 mg/l at 27.5°C for 5 hours yields 88% mortality), perhaps making water pre-heating combined with copper sulfate a feasible control alternative in some situations.

Treatment at the point of raw water intake or within the system with various oxidizing chemicals has been proven in Europe, the Soviet Union, Canada, and the United States to be effective in controlling zebra mussels. Concentrations in the range of 0.25 mg/l to 1.0 mg/l total residual chlorine (TRC) for 2 to 3 weeks has been found to be effective in killing 95%-100% of zebra mussels (Jenner, 1989; see Table 4). Continuous treatment at concentrations of 0.25 mg/l to 0.5 mg/l during that period of the year when veligers and post-veligers are present in source waters has been shown to be effective in preventing settlement and growth of mussels in water treatment facility intakes. Chlorine treatment is more effective at warmer water temperatures than cold.

In power generation and industrial settings, continuous chlorination is feasible only for limited portions of water systems that are highly vulnerable to infestation and/or are part of safety-related systems. This is not a problem in water treatment facilities where oxidizing chemicals are commonly used during most, if not all, of the year for taste and odor control as well as disinfection purposes.

There is concern for negative effects of chlorine on nontarget species in discharge receiving waters. Therefore, dechlorination at the point of discharge is usually required.

There is also the risk that too high concentrations of chlorine may result in harm to the biological character of slow sand filters, thereby requiring dechlorination prior to filtration. In addition, an excessive rate of mussel killing can result in the putrefactive decay of the highly proteinaceous mussels, production of obnoxious or dangerous methane gas, and concentrated deposition of detached shells with a subsequent blockage of conduits when pipelines containing significant infestations are "shock treated."

Chlorination of organic-rich water at the intake end of pipes may cause the formation of trihalomethanes (THMs), suspected carcinogens, and may therefore not be practical for public water treatment facilities which already have THM production problems. In these situations, other oxidizing compounds (e.g., chlorine dioxide, ozone, potassium permanganate, hydrogen peroxide) may be alternatives to chlorine.

Molluscicides may also be effective in industrial and power plant applications. These are usually short-term applications used periodically throughout the year, similar to periodic thermal treatments.

Before using any chemical treatment method, readers are advised to check with local environmental regulatory agencies to determine legality of use for their situation.

COATINGS

Organometallic antibiofouling coatings such as tributyltin oxide (TBTO) may be effective in preventing zebra mussel attachment to pipes, boat hulls and buoys, but are relatively expensive, difficult to apply, must be reapplied frequently and may result in negative environmental impacts on nontarget species as the coatings ablate off the substrate into the surrounding waters. Many such compounds are currently banned for most uses in the Great Lakes. Since these coatings do ablate into the water, they are unsuitable for use in potable water systems. Other coatings, such as copper paints or epoxies or zinc galvanizing may be useful in minimizing zebra mussel attachment and growth without environmental consequences as great as those caused by TBTO. Silicone-based coatings may also prove to be effective.

SUMMARY AND CONCLUSIONS

The zebra mussel, *Dreissena polymorpha*, is now well established throughout the Great Lakes and their connecting channels, as well as in numerous inland river systems in North America. There is no way to eliminate the mollusk in these water bodies without harming other life forms, so we must assume that the mussel is here to stay and that it will eventually be found throughout most inland waterbodies throughout North America. The task now is to control its impacts on ecosystems and water uses.

The control methods cited above will give readers an introduction to the mussel and its control. Note that new control alternatives will most likely be developed as a result of the invasion of the zebra mussel into the Great Lakes. Readers should augment this fact sheet by referring to research reports available from Sea Grant, federal, state and provincial environmental management/regulatory agencies, and researchers.

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SIGHTINGS

North American Range of the Zebra Mussel

as of August, 2006

Compiled by New York Sea Grant with information from: Canadian Museum of Nature, Fisheries and Oceans Canada, Great Lakes Sea Grant Network, Illinois Natural History Survey, National Biological Survey, Ontario Federation of Anglers and Hunters, Ontario Hydro, Ontario Ministry of Natural Resources, Tennessee Valley Authority, US Army Corps of Engineers, US Fish & Wildlife Service, and Utilities and others throughout North America.

Sightings:

1. Hedges Lake, Cambridge, NY
2. Grand Lake O' the Cherokees, OK
   (confirmation of breeding population)
3. Oologah Lake, OK
4. Skiatook Lake, OK
5. Lake of the Ozarks, MO

North American Range of the Quagga Mussel

as of August, 2006

Sightings:

No new sightings