Zebra Mussels in Texas: Assessment of relative risks to fishery resources, recommendations for action, and expectations for the future.

Executive Summary

Zebra mussels have arrived in Texas. Unlike many invasive species' introductions, there is considerable information available regarding the biology, ecology, and effects of this invader. For nearly 20 years scientists, resource managers, and the public have witnessed the spread of zebra mussels across the United States. Research, experimentation, and practical experience are available to guide Texas' reaction to the discovery of zebra mussels in North Texas. This paper reports zebra mussel life history and environmental requirements and is an initial assessment of the relative risk to aquatic fishery resources. The paper concludes with recommendations that may serve to guide Division or agency response to the current situation.

Major conclusions of this assessment include the likelihood that zebra mussels will spread throughout much of Texas, as they have throughout other eastern and Midwestern states, because of their high fecundity, early age of reproductive maturity, free-floating larvae, and ease of transport by recreational vehicles or water transfer systems. Native mussels are at greater risk of catastrophic impact than are fish due to the propensity for zebra mussels to attach themselves to mussel shells and ability to outcompete native mussels for food. Reservoirs and wetlands are at greater risk of problematic infestation than are streams and rivers as zebra mussel settlement and colonization is inhibited by high flows, and planktonic food supplies are typically more abundant in standing water than flowing water. Nuisance rooted vegetation problems could be exacerbated by clearer water and increased nutrients cycling into substrates as a result of the zebra mussels' highly-efficient feeding and typically dense populations. Changes in sport fisheries will occur, but necessary fishery management tools are available to maintain recreational opportunities.

Recommendations for early agency responses include promotion and support of containment efforts that simultaneously slow or prevent the arrival of "new" invasive species (e.g., quagga mussels, silver carp) rather than focusing specifically on zebra mussel control. Elevating the priority of native mussel surveys within existing resource monitoring programs, grants programs, and other agency activities could yield guidance for future mitigation efforts relatively quickly and at relatively little additional cost. Developing policy and management plans outlining the Department's role in addressing nuisance infestations of zebra mussels on shorelines, recreational areas, and public or private piers, ramps, and other structures is warranted as public concern and inquiries will likely increase. The State Aquatic Vegetation Management Plan should be reviewed for adequacy in coping with increased nuisance vegetation infestations that may result from zebra mussel infestations.

Texas Parks and Wildlife Department – Inland Fisheries Division
Heart of the Hills Fisheries Science Center, January 2010

Zebra Mussels in Texas: Assessment of relative risks to fishery resources, recommendations for action, and expectations for the future.

Introduction and Purpose

The zebra mussel *Dreissena polymorpha* is a bivalve mollusk native to lacustrine systems of southeast Russia. However, the species has become an established invasive in Europe and continues to spread throughout North America. Since their discovery in Lake St. Clair, Michigan, in 1988 (Hebert et al. 1989), zebra mussels have invaded 29 US states and two Canadian provinces as of July 2009 (Figure 1; USGS 2009).

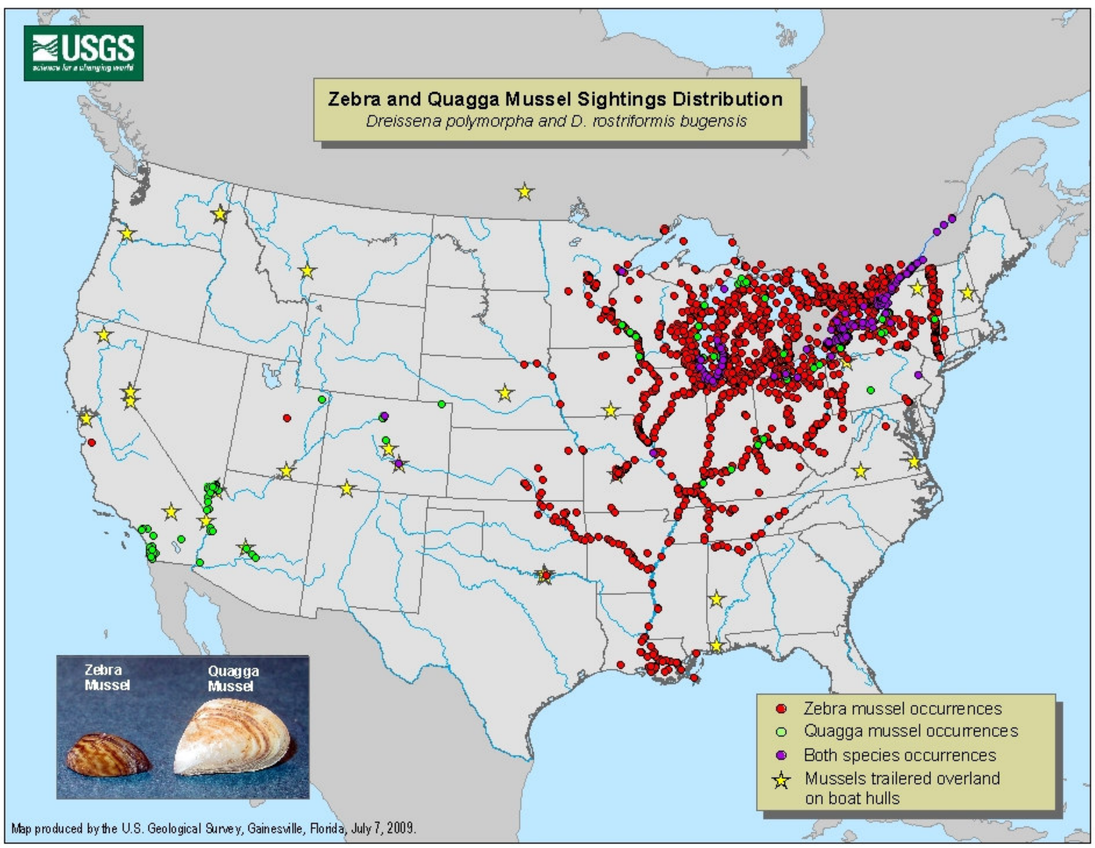

Figure 1. Dreissenid mussel distribution in the United States as of July 2009 (from USGS website).

Characteristic of invasive aquatic organisms, zebra mussels exhibit high fecundity, efficient mechanisms for dispersal, potential for rapid population growth, and negative effects on native biota. Recent discoveries of zebra mussels in Lakes Texoma and Lavon, Texas, and connecting waters prompted this preliminary investigation into the potential for establishment and likely impacts of zebra mussels in the state. This document provides information on life history and environmental requirements of zebra mussels, makes an initial assessment of the relative risk to aquatic fishery resources, and concludes with recommendations that may serve to guide Division or agency response to the current situation.

Life History

Gametogenesis in reproductively mature adult zebra mussels begins during fall and winter months at temperatures as low as 2 to 4 °C (35-39 °F; Borcherding 1991, Cohen 2005). Spawning begins in spring as temperatures reach approximately 10 °C (50 °F; Mackie et al. 1989; Sprung 1993; Mackie and Schloesser 1996; Nichols 1996; McMahon 1996). Spawning seasons are often prolonged and continue throughout late summer and early fall (Cohen 2005). Females are highly fecund, producing tens of thousands to millions of eggs per individual (Mackie et al. 1989; Sprung 1993; Mackie and Schloesser 1996; Nichols 1996; Cohen 2005). Gametes are released into the water column and fertilized externally.

The developing embryo/larva floats in the water column for up to one month; this serves as an efficient dispersal mechanism for the zebra mussel. There is a non-feeding phase of 2-9 days during which larvae develop digestive organs and initiate exogenous feeding. Veliger (i.e., free-floating larval) development continues for another 1-3 weeks, depending upon food availability and water temperature, before larvae settle and attach to bottom substrates (=become sessile) (Mackie et al. 1989; Sprung 1993; Ackerman et al. 1994; Mackie and Schloesser 1996). Throughout sessile life stages, zebra mussels filter feed at rates of 4 to 41 milliliters of water per milligram of body weight per hour, retaining nearly 100% of particles greater than 1 μm in size (Fanslow et al. 1995). Particles may be ingested as food and excreted as waste, or be deposited in the sediments undigested, thus transferring nutrients from the water column to the benthos (Fanslow et al. 1995).

Zebra mussels can become reproductively mature within the first year of life. Jantz and Neumann (1998) reported some 80% of Age 0 zebra mussels with shell lengths ≥9 mm were mature three months post-settlement in a European river. Growth rate of reproductively mature zebra mussels typically ranges from 1 to 1.5 cm/yr; maximum shell size is usually from 3.5 to 4 cm (Mackie et al. 1989; Mackie and Schloesser 1996). Longevity of the zebra mussel ranges from 3 to 5 years in Polish lakes, up to 5 years in British waters, and 6 to 9 years in Russian reservoirs (Mackie et al. 1989). North American populations of zebra mussels have been reported to have reduced longevity ranging from 1.5 to 2 years (Mackie 1991).

Expansion of zebra mussel populations occurs through the species' reproductive strategy and through unintentional transport associated with human activities. The free-floating larval stage provides an efficient means for population expansion by taking advantage of the natural movement of water through lentic and lotic environments. Human activity introduced the zebra mussel into North America and contributes to its ongoing spread. Larval and adult life stages can be transported to new waters by water pipelines, ship ballast water or boat livewells. Adults readily attach to recreational or commercial watercraft (and their trailers) and can be transported to new waters in that manner. Transfers of water for irrigation, industry or water supply can also spread zebra mussels.

Environmental requirements

Previous studies report that calcium and alkalinity are major factors controlling the growth and reproductive capacity of the zebra mussel (Heath 1993). Moderately hard-water lakes with calcium (Ca^{2+}) concentrations above 12 mg/L and alkalinity above 50 mg $CaCO^3$/L are required to establish significant populations; this is considerably higher than most other bivalves require (Heath 1993). Laboratory trials indicate that adult zebra mussels cannot persist when calcium concentrations are below 3.6 mg Ca^{2+}/L and alkalinity is below 4.7 mg $CaCO^3$/L. Larval veligers are more sensitive to these requirements than adults (Heath 1993).

Other environmental factors reported to affect colonization include water temperature, pH, salinity, and dissolved oxygen concentration. Adults can live in water temperatures ranging from about 0 °C (32°F) to about 31 °C (88°F; McMahon 1996). Water temperatures ranging from 3 to 25 °C (37-77 °F) represent the range of favorable conditions for survival and reproduction (Smirnova and Vinogradov 1990; Boelman et al. 1997; Cohen 2005). The lower limit of pH tolerance is approximately 5.2, with a preferred pH above 7.2 (Heath 1993). Values of pH above about 9.4 can be lethal (Hayward and Estevez 1997; Cohen 2005).

The effects of salinity on zebra mussel persistence depend upon both salt concentration and rate of change in concentration. Where salinity fluctuates rapidly, zebra mussels can tolerate only low levels of salinity. Where salinity is relatively stable, zebra mussels may persist at higher salinities. Research suggests confounding factors, including concentrations of divalent ions such as Ca^{2+} and Mg^{2+}, sulfate concentrations relative to those of the monovalent ions NA^{+} and Cl^{-}, chloride concentration (Strayer and Smith 1993), and water temperature (Baker et al. 1993) may affect the response of zebra mussels to salinity. Observed genetic variation among populations in different salinity levels suggests possible plasticity in salinity tolerance (Smirnova and Vinogradov 1990; Smirnova et al. 1993; Cohen 2005). Previous studies generally indicate zebra mussels can persist at salinities up to 12 to 14 ppt (Cohen 2005).

Zebra mussels will tolerate dissolved oxygen concentrations as low as 2 mg/L at 25 °C (77°F). In anoxic conditions, zebra mussels have survived for up to 6 d at 17-18 °C (62-64 °F) and for 3 d at 23-24 °C (73-75 °F; Baker et al. 1993). Boelman et al. (1997) reported zebra mussels are typically found where dissolved oxygen levels are greater than 90% saturation and become stressed below 50% saturation. Dissolved oxygen requirements vary directly with water temperature.

Zebra mussels originate from the lacustrine (lake) systems of Russia and typically do not inhabit waters where flow rates exceed 1.5 m/s (Claudi and Mackie 1994). Texas reservoirs and wetlands, with their relatively high plankton productivity and slow water flow, are at greater risk for problematic zebra mussel infestations than are the state's rivers and streams.

Zebra mussel infestations occur across a wide range of substrate types and levels of water turbidity. Density of zebra mussel populations is related to availability of hard substrates for the veligers to settle on and the highest densities can be expected in areas with an abundance of coarse, rocky substrates (Mellina and Rasmussen 1994). However, zebra mussels can also attach to aquatic vegetation, sand, hard clay, and each other. Although survival and density may be lower on soft substrates, and colonization slower, zebra mussels have developed extensive populations in soft substrates (Berkman *et al.* 1998). Early studies suggested high turbidity may limit zebra mussel distribution, through interference with feeding (Strayer & Smith 1993), but Doll (1997) noted zebra mussels are found in very turbid parts of the Mississippi River (> 80 NTU total suspended solids).

Effects on native biota

Zebra mussels have been reported to have both positive and negative effects on aquatic ecosystems. The high rate of filter feeding of zebra mussel populations, especially at high densities, typically results in increased water clarity (Lyakhnovich et al. 1988; MacIsaac 1996), allowing the penetration of sunlight and aquatic macrophyte growth to greater water depths. While this may increase habitat availability for structure-oriented fishes, excessive macrophyte growth may also hinder recreational opportunities due to beach fouling and unuseable shoreline areas.

Zebra mussels may also alter food web dynamics in aquatic ecosystems as a result of their filter feeding habits, removing phytoplankton, zooplankton, and nutrients from the water column and redistributing these energy sources to the benthos.

Decreases in seston, organic matter, primary productivity, phytoplankton and zooplankton have been reported (Karatayev et al. 1997) and changes in primary and secondary productivity have the potential to result in cascade effects throughout the aquatic food web. Previous study has suggested that this may negatively impact fishes that utilize pelagic food resources during their life cycle (MacIsaac 1996), but enhance food resources for benthivorous and molluscivorous species due to increases in macroinvertebrate densities (Zheltenskova 1949; Lyagina and Spanowskya 1963; Poddubnyi 1966; French and Burr 1993). Bird species have also been known to forage extensively on zebra mussels (Molloy et al. 1997).

Fish communities — Though limited in number, studies investigating impacts of zebra mussels on fish have reported few effects. MacIsaac (1996) suggested that reductions in zooplankton abundance may negatively affect the growth of fishes that feed on these organisms; this is particularly important for larval fishes, as zooplankton are a commonly preferred prey item (Hartmann et al. 1992; Wu and Culver 1992). However, Trometer and Busch (1999) compared age-0 growth rates and fall abundance of 11 fish species, representative of pelagic and benthic predator and forage species, before and after zebra mussel establishment in Lake Erie. No significant differences in growth or fall abundance were observed for 10 of the species – yellow perch *Perca flavescens* increased in abundance following zebra mussel establishment. The authors suggested that zooplankton abundance following zebra mussel colonization may still be sufficient to support age-0 fish growth and abundance.

Zebra mussels can serve as food for omnivorous and molluscivorous fishes. This has been documented for freshwater drum *Aplodinotus grunniens* in Lake Erie

(French and Bur 1996) and utilization of zebra mussels as food has resulted in increased growth rates of fish and productivity in some Eurasian systems (Zheltenkova 1949; Lyagina and Spankowski 1963; Poddubnyi 1966). Increased foraging opportunity for benthic fishes has been attributed to zebra mussels due to increased abundance of macroinvertebrates following zebra mussel establishment (Dermott and Munawar 1993; Griffiths 1993; Stewart and Haynes 1994; Karateyev and Burlakova 1995; Molloy et al 1997). Important sport fishes in Texas such as channel and blue catfish (*Ictalurus punctatus* and *I. furcatus*, respectively) are known to feed upon mussels (Graham 1999; Jackson 1999) and may utilize zebra mussels as an additional food resource.

Increased water clarity, resulting from filter-feeding by dense populations of zebra mussels, could be expected to alter dynamic processes such as fish predation and recruitment, thus favoring certain fish species over others. The extent of shifts in fish species composition will depend on the degree of change in water clarity.

It is unclear whether impacts of zebra mussels on fish communities in southern reservoirs will be as limited as those seen in more northern waters. Fish communities, food webs, and water clarity vary widely among Texas reservoirs. Water bodies with plankton-based food webs would be expected to undergo greater changes in fish community structure than water bodies currently dominated by aquatic vegetation.

Aquatic vegetation — Zebra mussel filter feeding can increase water clarity, allowing greater penetration of sunlight and the establishment of macrophytes at greater water depths. Lyakhnovitch et al. (1988) reported a 2.2-fold increase in water clarity in Lukomskoe Lake, Belarus, following zebra mussel establishment. Increased macrophytes coverage and biomass in waters infested with zebra mussels have been reported (Lyakhnovich et al. 1988; MacIsaac 1996). The euphotic zone of Lake St. Clair, Michigan, increased to include most of the lake following zebra mussel establishment, resulting in large areas of macrophyte growth (Griffiths 1993).

Filter feeding zebra mussels effectively transfer nutrients from the water column to the substrate, benthos, or sediments. Aquatic rooted macrophytes may benefit from this redistribution of nutrients. Infestations of nuisance aquatic vegetation are common to many Texas reservoirs; these problems may be exacerbated in water bodies colonized by zebra mussels.

Native freshwater mussels — The most notable negative impacts of zebra mussels occur to native unionid mussels, which directly compete for food resources and provide appropriate substrates for zebra mussel attachment. In North America, zebra mussels have nearly extirpated native unionids from heavily-infested systems by fouling their shells and outcompeting native species for food. Strayer (1999) provided evidence that zebra mussels reduced unionids' food availability below levels required to support reproduction and survival. Although native unionids are mobile, attachment of zebra mussels to their shells hinders movement and burrowing capabilities. Dense encrustations can inhibit feeding and closure of the valves, resulting in eventual death. Because zebra mussels typically do not inhabit waters where flow rates exceed 1.5 m/s (Claudi and Mackie 1994), native unionids in low gradient rivers and reservoirs are at greatest risk for competition and other impacts of zebra mussel colonization.

Native freshwater mussels reported in the Trinity River basin include ten species currently considered species of concern (Robert G. Howells, personal communication, August 2009), including the rock pocketbook *Arcidens confragosus*, Texas pigtoe

Fusconaia askewi, round pearlshell *Glebula rotundata*, sandbank pocketbook *Lampsilis satura*, white heelsplitter *Lasmigona complanata*, Louisiana pigtoe *Pleurobema riddellii*, Texas heelsplitter *Potamilus amphichaenus*, creeper *Strophitus undulatus*, fawnsfoot *Truncilla donaciformis* and little spectaclecase *Villosa lienosa*. These and other species could undergo significant declines in population size or even extirpation if dense infestations of zebra mussels occur.

Economic Impacts

Zebra mussels are considered the most problematic macro-fouling organism in North America. Zebra mussel fouling of infrastructure such as hydropower facilities and water intake pipes has resulted in billions of dollars in economic losses. In the United States, Congressional research estimated that the zebra mussel problem cost industry, businesses, and communities over $5 billion in economic impacts (New York Sea Grant 1994). Zebra mussels have increased maintenance costs for waterfront property owners, recreational boaters, and fishermen. Docks, seawalls, boat lifts, and similar structures provide appropriate substrates for zebra mussel attachment. Shorelines may also become fouled with windrows of dead and decaying mussels, resulting in noxious odors (US Army Corp of Engineers 1993). The shells of zebra mussels can hinder use of swimming beaches and reduce the utility of other waterfront areas for recreation.

Potential for Spread in Texas

The relatively wide range of environmental conditions tolerated by the zebra mussel suggests that much of Texas may be susceptible to zebra mussel infestation.

The lack of reliable predictive models for the eventual range of zebra mussels makes it impossible to know how widely they will spread in Texas. Strayer's (1991) model attempted to predict eventual distribution using air temperature, but within a few years the mussel was found outside the range predicted by that model. Drake and Bossenbeck (2004) published a predictive model that used several variables related to climate, geology, and topography to predict zebra mussel eventual distribution across the nation. This model predicts much of eastern and southern Texas susceptible to zebra mussel establishment (Figure 2).

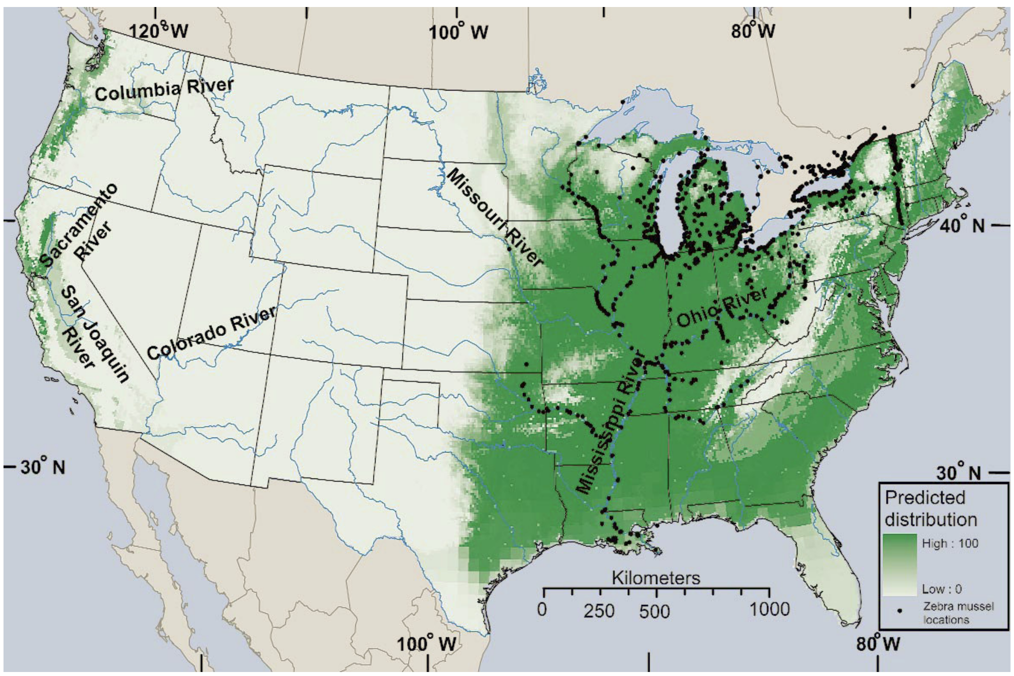

Figure 2. *Potential range of zebra mussels in the United States based on a full model including nine environmental and geological factors. Points on the map represent locations where zebra mussels have been observed as of 2003; shading represents the predicted likelihood of invasion. Figure from Drake and Bossenbeck 2004.*

However, Whittier et al. (2008) point out that this model poorly predicts recently-discovered infestations of quagga mussel (*Dreissena bugensis*), a closely related species that has followed zebra mussels into the Great Lakes, and now are found in reservoirs in Arizona, Nevada, and California. Using calcium concentrations, Whittier et al. (2008) developed an alternative model of eventual range for the genus *Dreissena* that predicts Texas' greatest infestations will occur throughout the western and central portions of the state (Figure 3).

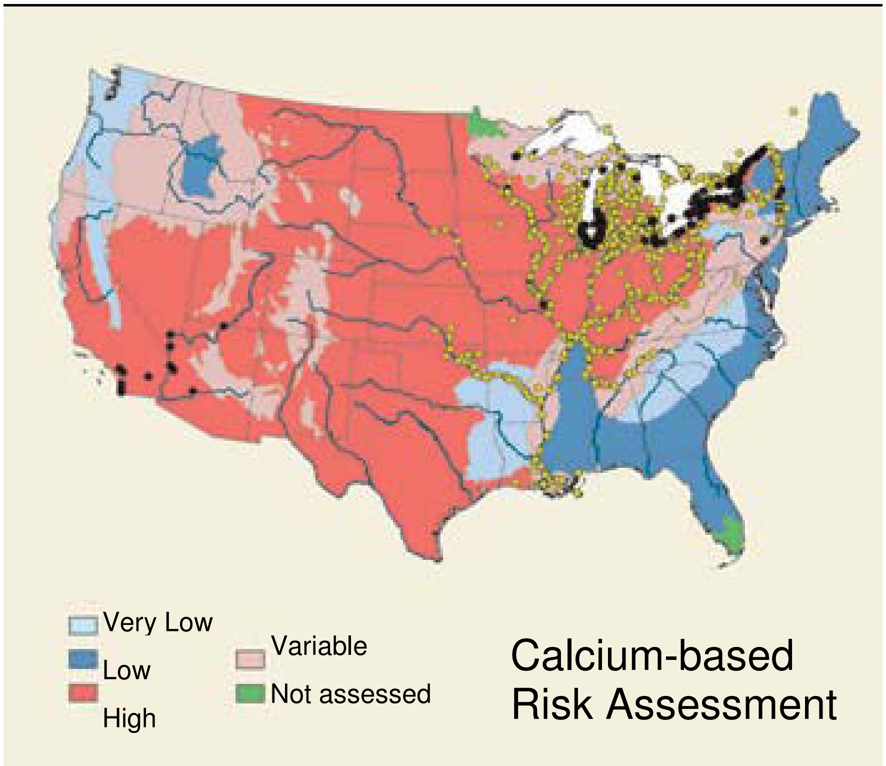

Figure 3. Predicted U. S. distribution of Dreissena mussels from Whittier et al. 2008 model based on calcium requirements.

While disparate predictions from these two models are problematic for deciding where to allocate resources, both models in fact predict establishment over vast areas of the state and both models predict establishment in at least portions of the Trinity and Red River basins.

The first confirmed occurrence of zebra mussels in Texas waters was in Lake Texoma in the Red River basin in April, 2009. Recent surveys have found zebra mussels at numerous sites in that reservoir. Zebra mussels have also been recently discovered in the Trinity River basin above Lake Lavon, Texas and are thought to have been transferred from Lake Texoma via an interbasin water transfer pipeline. Further surveys are ongoing to delineate the extent of zebra mussels in Texas.

A review of environmental and water quality data from the Trinity River basin suggests that conditions throughout the basin are favorable for zebra mussel establishment. While population expansion may be limited during the hottest part of the year, environmental conditions are suitable for colonization and expansion for most of the year, every year. Therefore, infestation of the Trinity River basin downstream of Lake Lavon is likely to continue.

Potential containment mechanisms

Although containment or eradication of zebra mussels may be possible in small water bodies (Heimowitz and Phillips 2006), eradication from large river systems and reservoirs is likely impossible. Biologists in the Great Lakes region have explored options for zebra mussel eradication for years without success. A reported successful eradication of zebra mussels in a 16-acre quarry lake (Millbrook Quarry, Virginia) used 174,000 gallons of potassium chloride at an approximate cost of $419,000 (Rupert 2006). Therefore, application of this technique, while successful, is likely only practical in small, closed systems.

Infestations of additional Texas drainages may occur through interbasin water transport or the transport of infested waters or recreational equipment by humans. Various strategies for minimizing this transfer risk are available dependent upon the particular mode of transfer. For water-based infrastructure, including water intake pipes and interbasin transfer lines, chemical controls can be effective if properly utilized. Chlorination is a commonly used control agent. Continuous exposure to concentrations at or above 0.5 mg/L will kill zebra mussels in 14 to 21 days. Alternatively, potassium permanganate can be applied for drinking water resources. Thermal shock can also be effective at killing zebra mussels. Water temperatures maintained at or above 32.5 °C for 3 hr results in 100% mortality and water temperatures at or above 40 °C results in instantaneous death. Lowering dissolved oxygen concentrations for an extended period of time using chemical agents such as sodium metabisulfate or hydrogen sulfide will reduce dissolve oxygen concentrations below required levels for zebra mussel survival. However, it should be noted that non-target organisms may also be eradicated. Screens or filters on raw water systems can be installed to remove juvenile and adult zebra mussels. However, the small size of larval zebra mussels (approximately 70 μm) requires appropriately designed screening systems that require continual maintenance to be effective. Sand filtration systems or intakes buried in infiltration beds are effective at excluding zebra mussels from water intakes.

Due to a high potential of incidental transfer by humans (via boat livewells, trailers, or other recreational equipment), public outreach and education can be expected to slow the spread of zebra mussels, but not prevent spread. Desiccation or chlorination of equipment upon removal from infected waters is an effective, environmentally sound technique for reducing transfer between systems. Exposure to hot, dry air for extended periods of time (e.g., up to several days) will cause mortality. Inspection of boat trailers and recreational equipment for adult zebra mussels can effectively reduce the risk of transfer between systems. There are a number of federal regulations, state laws, and TPWD regulations that provide authority for enforcement activity to limit the spread of exotic invasive species, including zebra mussels.

Recommendations

Passive downstream transport of free-floating veligers makes containment of zebra mussels extremely difficult in systems already infested. It should be more effective to direct control efforts toward preventing infestations in new basins or in headwater impoundments upstream of current infestations. Evaluation of potential control or containment measures should consider their ability to slow introduction of "new" invasive species. In this way, greater long-term benefits should be achievable.

Best Management Practices (e.g., Aquatic Nuisance Species Inspector programs, access point closures, statewide monitoring) have been developed by many states and other entities. These primarily focus on public awareness, monitoring of invasive species, and enforcement of regulations prohibiting transport of invasive species. These practices reduce the risk of spread, but none can be expected to be 100% effective. Practices range in cost, complexity, and practicality. Not all will be suitable for Texas. Some can be implemented quickly; others may take stakeholder or even legislative input. Reviewing these various management practices should be done carefully and with stakeholder involvement. Public support will be important, otherwise effectiveness can be compromised.

Development of a public outreach campaign to increase awareness of zebra mussels is considered an effective management practice for reducing incidental transport of this species by the public. Such communication strategies can be designed in a manner that makes them a useful template for responding to introduction of “new” invasive species in the future.

Additionally, the Texas Parks and Wildlife Department should adopt internal protocols to reduce the chance that Department activities, facilities, or operations contribute to further spread of zebra mussels. Similar protocols are in place to minimize the spread of golden algae and largemouth bass virus. The Department should also review its various permitting procedures and where feasible, integrate further consideration of invasive species spread.

The Department should also engage water authorities (especially regarding interbasin water transfers) and other stakeholders in efforts to prevent spread of all invasive species (to include zebra mussels). A database of existing and proposed water transfer infrastructure would be useful in this endeavor. Also, the Department should establish and maintain a reporting system and database for invasive species observations arising both from the public and from Department activities.

Zebra mussel infestations may create a substantial public nuisance – hindering public access, use, and enjoyment of some waters. Where dense infestations develop, the mussels may also exacerbate problems with nuisance aquatic vegetation. The Department should develop a policy and management plan outlining the agency and division roles in addressing nuisance infestations of mussels on shorelines, recreational areas, and public or private piers, ramps, and other structures. A review of the State Aquatic Vegetation Management Plan should also be conducted for adequacy in coping with increased nuisance vegetation infestations potentially resulting from zebra mussel infestations.

These recommended practices will not only aid in slowing the spread of zebra mussels in the state, but will further reduce the risks of other potential aquatic invasive species that may threaten Texas aquatic systems in the future.

LITERATURE CITED

Ackerman, J.D., B. Sim, S.J. Nichols, and R. Claudi. 1994. A review of the early life history of zebra mussels (*Dreissena polymorpha*): comparisons with marine bivalves. Canadian Journal of Zoology 72:1169-1179.

Baker, P. S. Baker, and R. Mann. 1993. Criteria for predicting zebra mussel invasions in the Mid-Atlantic region. College of William and Mary, Gloucester Point, Virginia.

Berkman, P. A., M. A. Haltuch, E. Tichich, D. W. Garton, G. W. Kennedy, J. E. Gannon, S. D. Mackey, J. A. Fuller, and D. L. Liebenthal. 1998. Zebra mussels invade Lake Erie muds. Nature 393: 27-28.

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

Borcherding, J. 1991. The annual reproductive cycle of the freshwater mussel *Dreissena polymorpha* Pallas in lakes. Oecologica 87:208-218.

Claudi, R., and G. Mackie. 1994. Practical manual for zebra mussel monitoring and control. Lewis Publishers, Boca Raton, FL.

Cohen, A. N. 2005. A review of zebra mussels' environmental requirements. California Department of Water Resources, Oakland.

Dermott, R., and M. Munawar. 1993. Invasion of Lake Erie offshore sediments by *Dreissena*, and its ecological implications. Canadian Journal of Fisheries and Aquatic Sciences 50:2298-2304.

Doll, B. 1997. *Zebra Mussel Colonization: North Carolina's Risks*. Sea Grant North Carolina, University of North Carolina, Raleigh, NC (UNC SG-97-01).

Drake, J. M., and J. M. Bossenbroek. 2004. The potential distribution of zebra mussels in the United States. Bioscience 54:931-941.

Fanslow, D. L., T. F. Napela, and G. A. Lang. 1995. Filtration rates of the zebra mussel (*Dreissena polymorpha*) on natural seston from Saginaw Bay, Lake Huron. Journal of Great Lakes Research 21:489-500.

French, J.R.P., III, and M. T. Bur. 1993. Predation of the zebra mussel (*Dreissena polymorpha*) by freshwater drum in western Lake Erie. *In* T. Nalepa and D. Schloesser, editors. Zebra mussels: biology, impacts, and control. Lewis Publishers, Ann Arbor, Michigan.

Graham, K. 1999. A review of the biology and management of blue catfish. Pages 37-49 *in* E. R. Irwin, W. A. Hubert, C. F. Rabeni, H. L. Schramm, Jr., and T. Coon, editors. Catfish 2000: proceedings of the international ictalurid symposium. American Fisheries Society, Symposium 24, Bethesda, Maryland.

Griffiths, R.W. 1993. Effects of zebra mussels (Dreissena polymorpha) on the benthic fauna of Lake St. Clair. *In* T. F. Nalepa and D. W. Schloesser, editors. Zebra mussels: Biology, impacts, and control. Lewis Publishers, Boca Raton, FL.

Hartman, K. J., B. Vondracek, D. L. Parrish, and K. M. Muth. 1992. Diets of emerald and spottail shiners and potential interactions with other western Lake Erie planktivorous fishes. Journal of Great Lakes Research 1843–50.

Hayward, D. and E. Estevez. 1997. Suitability of Florida waters to invasion by the zebra mussel, *Dreissena polymorpha*. Technical report 495, Florida Sea Grant College Program, Sarasota.

Heath, R. T. 1993. Zebra mussel migration to inland lakes and reservoirs: a guide for lake managers. Report FS-058, Ohio Sea Grant College Program, Kent.

Hebert, P. D. N., Muncaster, B. W., and Mackie, G. L. 1989. Ecological and genetic studies on *Dreissena polymorpha* (Pallas): a new mollusk in the Great Lakes. Canadian Journal of Fisheries and Aquatic Sciences 46:1587-1591.

Heimowitz, P, and S Phillips. 2006. Rapid response plan for zebra mussels in the Columbia River Basin: A comprehensive multi-agency strategy to expeditiously guide rapid response activities. Draft report, September 1, 2006.

Jackson, D. C. 1999. Flathead catfish: biology, fisheries, and management. Pages 23-35 *in* E. R. Irwin, W. A. Hubert, C. F. Rabeni, H. L. Schramm, Jr., and T. Coon, editors. Catfish 2000: proceedings of the international ictalurid symposium. American Fisheries Society, Symposium 24, Bethesda, Maryland.

Jantz, B. and D. Neumann. 1998. Growth and reproductive cycle of the zebra mussel in the River Rhine as studied in a river bypass. Oecologia 114:213-225.

Karatayev, A.Y., and L. E. Burlakova. 1995. The role of *Dreissena* in lake ecosystems. Russian Journal of Ecology 26:207-211.

Karateyev, A. Y., L. E. Burlakova, and D. K. Padilla. 1997. The effects of *Dreissena polymorpha* (Pallas) invasion on aquatic communities in Eastern Europe. Journal of Shellfish Research 16:187-203.

Lyakhovich, V. P., A. Y. Karatayev, P. A. Mitrakovich, L. V. Guryanova, and G. G. Veznovets. 1988. Productivity and prospects for utilizing the ecosystem of Lake Lukoml, thermoelectric station cooling reservoir. Soviet Journal of Ecology 18:255-259.

Lyagina, T.N., and V. D. Spanowskaya. 1963. Morphological peculiarities of some fish in the Uchinskoe water storage. Moscow State University, Moscow.

MacIsaac, H. J. 1996. Potential abiotic and biotic impacts of zebra mussels on the inland waters of North America. American Zoologist 36:287-299.

Mackie, G. L., W. N. Gibbons, B. W. Muncaster, and I. M. Gray. 1989. The zebra mussel, *Dreissena polymorpha*: A synthesis of European experiences and a preview for North America. Toronto, Ontario.

Mackie, G. L. 1991. Biology of the exotic zebra mussel, *Dreissena polymorpha*, in relation to native bivalves and its potential impact to Lake St. Clair. Pages 251-268 *in* M. Munawar and T. Edsall, editors. Envoronmental assessment and habitat evaluation of the upper Great Lakes connecting waters. Hydrobiologia, volume 219.

Mackie, G. L., and D. W. Schloesser. 1996. Comparative biology of zebra mussels in Europe and North America: an overview. American Zoologist 36:244-258.

McMahon, R. 1996. The physiological ecology of the zebra mussel, Dreissena polymorpha, in North America and Europe. American Zoologist 36:339-363.

Mellina, E. and J. B. Rasmussen. 1994. Patterns in the distribution and abundance of zebra mussel (*Dreissena polymorpha*) in rivers and lakes in relation to substrate and other physiochemical factors. Canadian Journal of Fisheries and Aquatic Sciences 51: 1024-1036

Molloy, D.P., A. Y. Karatayev, L. E. Burlakova, D. P. Kurandina, and F. Laruelle. 1997. Natural enemies of zebra mussels: Predators, parasites, and ecological competitors. Reviews in Fisheries Science 5:27-97.

New York Sea Grant. 1994. Policy issues. *Dreissena polymorpha* information review. State University of New York, Brockport, New York.

Nichols, S. 1996. Variations in the reproductive cycle of *Dreissena polymorpha* in Europe, Russia, and North America. American Zoologist 36:311-325.

Poddubnyi, A.G. 1966. A note on an adaptive response of a roach population to a change in environmental conditions. Tr. Inst. Biol. Vnutr. Vod. Akad. Nauk SSSR 10:131-138.

Rupert, M. 2006. Successful zebra mussel eradication in VA. Could be national model. Article published in The Examiner, Houston, Texas. Accessed 14 August 2009.

Smirnova, N. F., and G. A. Vinogradov. 1990. Biology and ecology of Dreissena polymorpha from the European USSR. Presentation at the US Environmental Protection Agency workshop: Zebra mussels and other introduced aquatic nuisance species. Saginaw, Michigan, September 26-28.

Smirnova, N.F., G.I. Biochino and G.A. Vinogradov. 1993. Some aspects of the zebra mussel (*Dreissena polymorpha*) in the former European USSR with morphological comparisons to Lake Erie. Pages 217-227 in Nalepa, T.F. and D.W. Schloesser (eds.), *Zebra Mussels: Biology, Impacts, and Control*, Lewis Publishers, Boca Raton, FL.

Sprung, M. 1993. The other life: an account of present knowledge of the larval phase of *Dreissena polymorpha*. In T. Nalepa and D. Schloesser, editors. Zebra mussels: biology, impacts, and control. Lewis Publishers, Ann Arbor, Michigan.

Stewart, T.W., and J. M. Haynes, J.M. Benthic macroinvertebrate communities of southwestern Lake Ontario following invasion of Dreissena. Journal of Great Lakes Research. 20:479-493.

Strayer D. L. 1991. Projected distribution of the zebra mussel, *Dreissena polymorpha*, in North America. *Canadian Journal of Fisheries and Aquatic Sciences* 48: 1389–95.

Strayer, D. L. 1999. Effects of alien species on freshwater mollusks in North America. Journal of North American Benthological Society 18:74-98.

Strayer, D. L., and L. Smith. 1993. Distribution of the zebra mussel in estuaries and brackish waters. *In* T. Nalepa and D. Schloesser, editors. Zebra mussels: biology, impacts, and control. Lewis Publishers, Ann Arbor, Michigan.

Trometer, E. S. and W-D. N. Busch. 1999. Changes in age-0 fish growth and abundance following the introduction of zebra mussels *Dreissena polymorpha* in the western basin of Lake Erie. North American Journal of Fisheries Management 19:604-609.

United States Geological Survey. 2009. Zebra and quagga mussel information resource page. http://nas.er.usgs.gov/taxgroup/mollusks/zebramussel/ Accessed Aug 4, 2009.

US Army Corps of Engineers. 1993. Zebra mussel research technical notes. Zebra mussel research program Technical note ZMR-4-04, Vicksburg, Mississippi.

Whittier, T. R., P. L. Ringold, A. T. Herlihy, S. M. Pierson. 2008. A calcium-based invasion risk assessment for zebra and quagga mussels (*Dreissena* spp). Frontiers in Ecology and the Environment, 6; doi: 10.1890/070073. Website: www.frontiersinecology, accessed August 9, 2009.

Wu, L. and D. A. Culver. 1992. Ontogenetic diet shift in Lake Erie age-0 yellow perch (*Perca flavescens*): a size-related response to zooplankton density. Canadian Journal of Fisheries and Aquatic Sciences 49:1932–1937.

Zheltenkova, M.V. 1949. Food and growth in genus *Rutilus*. *Zool. Zh.* 28:257-267.