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The Costly Impact of Zebra and Quagga Mussels in United States Waterways:

Hydropower, Navigation, and other Industries

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SUMMARY

Zebra Mussels (ZM) and Quagga Mussels (QM) (Dreissenidae) are invasive mussels in North American waterways. Due to their high rates of reproduction and behavior of attaching to substrates such as pipes and water intakes, they are problematic for industries and recreation that utilize the rivers they inhabit. Examples of affected business lines include but are not limited to hydropower, municipalities, water treatment facilities, fish hatcheries, navigation, and commercial and recreational boating. There are numerous ongoing efforts to eliminate and prevent infestations of ZM/QM. These include completing vulnerability assessments of U.S. Army Corps of Engineers (USACE) facilities, regular sampling for juveniles, treatment of water using ultraviolet light and copper ions, development of new coatings for structures that mussels cannot attach to, and modification of flows to prevent attachment of mussels.

INTRODUCTION

Zebra Mussels (*Dreissena polymorpha*) and Quagga Mussels (*Dreissena rostraformis bugensis*) are two species belonging to the family Dreissenidae and are collectively referred to as dreissenids. Zebra Mussels (Figure 1) are native to the Black, Caspian, and Azov Seas of southern and eastern Europe, and became widespread in western Europe during the early to mid-1800s (Benson et al. 2021; USGS 1994). They were first discovered in North America in Lake St. Clair in June 1988 and are presumed to be an unintentional consequence of transcontinental commercial navigation from Black Sea ports during the mid-1980s, possibly from ballast water exchange (McMahon 1996). Due to their characteristics and behavior, ZM have become widespread throughout the eastern and central United States and south-central portion of Canada, with sightings reported for 32 states (Figure 2). Quagga Mussels (Figure 1), native to the Dneiper River basin of Ukraine and Ponto-Caspian Sea, were first discovered in North America in Lake Erie in 1991, also presumably introduced through ballast water exchange from the transcontinental commercial navigation industry. Though discovered in the United States later than ZM, there is evidence that QM were introduced prior to ZM. Like ZM, QM have become widespread in distribution in the United States, with sightings reported in 17 states (Figure 3).

The life history and reproductive behavior of dreissenids differ substantially from native mussels in the United States and have promoted their prolific spread. While most native mussels require an intermediate host (e.g., fish) to complete larval development, larval dreissenids (called veligers) are free-living and are carried by water current as they develop into juveniles, which rapidly colonize substrates using proteinaceous byssal threads. Any suitable substrate, including rock, rope, metal, plants, native mussel shells, etc., can be colonized, and colonies (called druses) can be comprised of thousands of dreissenids per square meter. These accumulations are responsible for the notorious biofouling (accumulation of animal or plant material on an unintended surface) of water supply lines, significantly impacting industry and municipalities. Colonization of dreissenids on in-stream structures and commercial and recreational vessels has led to deterioration and collapse of pilings and buoys and affects the movement and speed of vessels through the water.

Like all organisms, dreissenids have specific environmental and habitat constraints in which they can survive and become established. Though there are similarities between the two species, there are also physiological differences that allow for colonization and infestation of different habitats. For example, ZM rapidly colonize hard substrates while QM can colonize both hard and soft substrata. There are also differences in colonization rates, and the two can occur at different depths based on water quality and water chemistry. One of the tools used to predict the ability of ZM and QM to infest industrial facilities is found in Table 1.

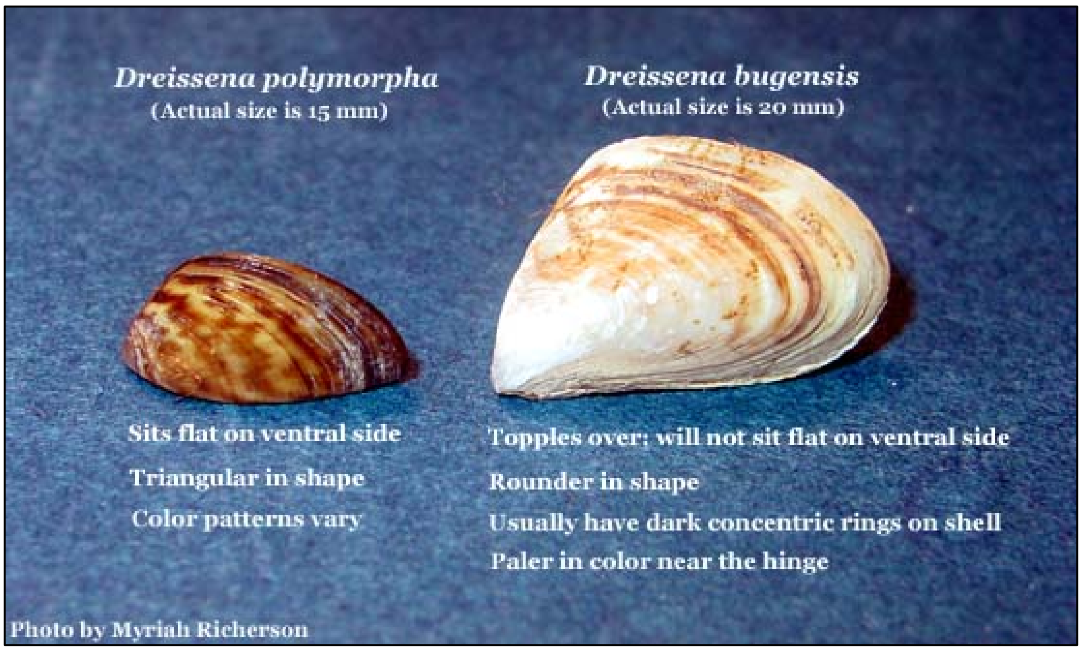

Figure 1. Zebra Mussel (*Dreissena polymorpha*). Photo by Amy Benson (USGS).

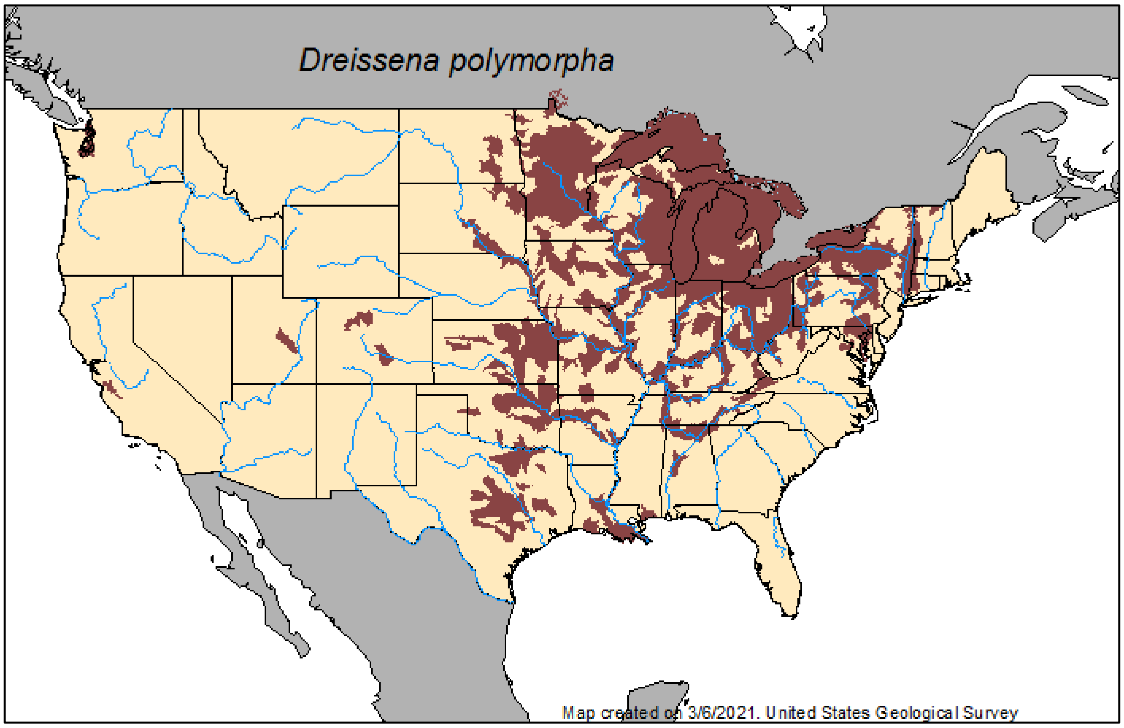

Figure 2. Current distribution of Zebra Mussels (*Dreissena polymorpha*) in the Continental United States.

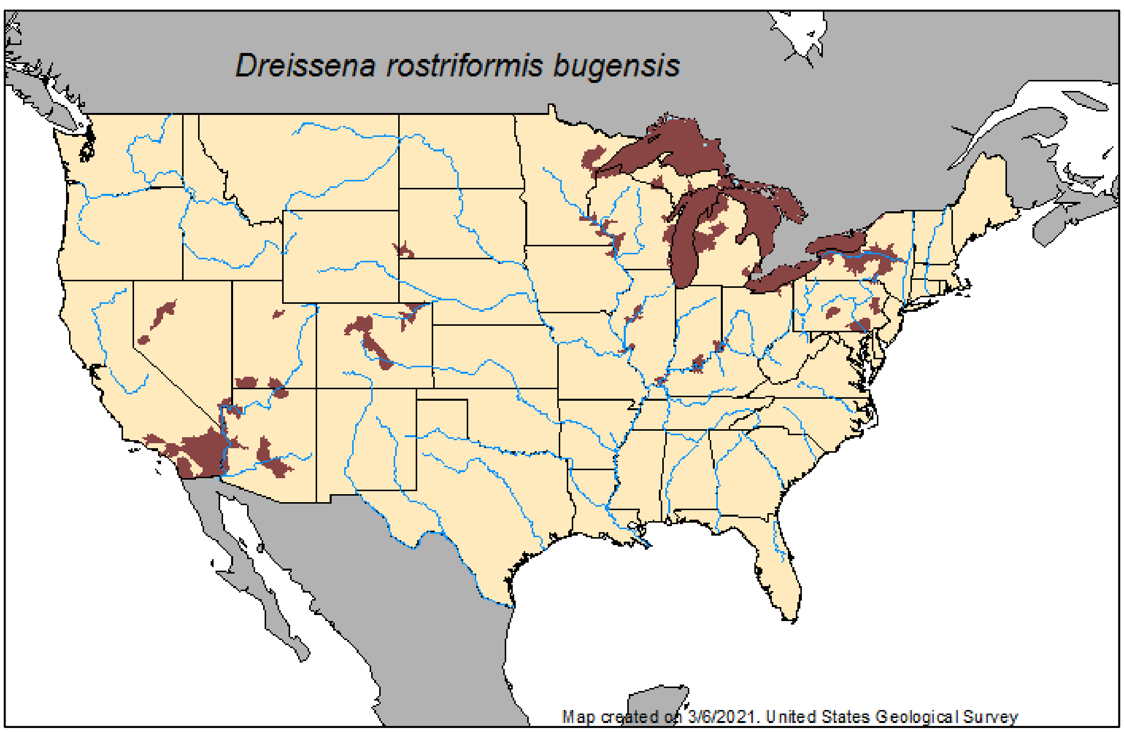

Figure 3. Current distribution of Quagga Mussels (*Dreissena rostriformis bugensis*) in the Continental United States.

Table 1. Presumptive infestation-level suitability criteria for invasive mussels. Abbreviations: QM = Quagga Mussels (*Dreissena rostriformis bugensis*); ZM = Zebra Mussels (*Dreissena polymorpha*). *From Bureau of Reclamation Facility Vulnerability Assessments.*

Parameter	Low Probability of Survival	**Infestation Levels**		
		Low	Moderate	High
Calcium (mg/L)	<10 (QM) <8 (ZM)	10-12 (QM) 8-15 (ZM)	12-30 (QM) 15-30 (ZM)	>30
Alkalinity/Total Hardness (mg $CaCO_3$/L)	<35 (QM) <30 (ZM)	35-42 (QM) 30-55 (ZM)	42-100 (QM) 55-100 (ZM)	>100
pH	<7.0 >9.5	7.0-7.8 9.0-9.5	7.8-8.2 8.8-9.0	8.2-8.8
Dissolved Oxygen (mg/L)	<3	5-7	7-8	>8
Dissolved Oxygen (% saturation)	<25%	25-50%	50-75%	>75%
Mean Summer Temperature (°F)	<64 >86	64-68 83-86	68-72 77-83	72-75
Conductivity (µS/cm)	<30	30-60	60-110	>110
Salinity (g/L)	>10	8-10	5-8	<5
Secchi depth (m)	<1 >8	1-2 6-8	4-6	2-4
Chlorophyll a (µg/L)	<2.0 >25	2.0-2.5 20-25	8-20	2.5-8
Total phosphorous (µg/L)	<5 >50	5-10 35-50	10-25	25-35

IMPACTS

Zebra and Quagga Mussels present a challenge to the management and stewardship of United States waterways. They impact the environment, recreation, municipalities, industry and the ability to generate hydroelectric power at USACE facilities. For example, a 2019 cost estimate of invasive species damages to the hydropower program was $7M/year. As invasive species, ZM/QM have few natural predators in U.S. waterways to keep their populations in check, and without a proper management procedure in place, they can colonize an entire body of water (such as a reservoir) and negatively impact its associated infrastructure such as piers, pump stations and hydroelectric powerhouses. These impacts occur rapidly and may go unnoticed until failure of operations and infrastructure occurs. ZM/QM infestations also pose a threat to human safety, as fire suppression systems are vulnerable to colonization and infestation.

Hydropower

With ideal environmental conditions (e.g., calcium concentration, water temperature, etc.), ZM/QM are able attach to almost any wetted surface within or around a hydroelectric powerhouse, and can attach to both concrete and metallic structures. From a risk assessment standpoint, any surface within or outside of a hydroelectric powerhouse that regularly makes contact with non-treated water is at risk of becoming a site for ZM/QM colonization. Potentially affected structures, surfaces and equipment include but are not limited to:

1. Exterior concrete structures, such as intake or tailrace structures (Figure 4a).
2. Gates that help regulate the flow of water in and out of the powerhouse (Figure 4b).
3. Grates, filters and strainers that help keep unwanted particles out of the water stream (Figure 4c).
4. Sensors, seals and valves that help to monitor, contain and adjust the flow of water in the powerhouse raw water system.
5. Piping that carries raw water to vital pieces of equipment throughout the powerhouse.
6. Raw water coolers, including air coolers and thrust bearing oil coolers for the hydroelectric generators.
7. Station service equipment that utilizes raw water such as air compressors, air conditioning equipment and heat pumps.
8. Drainage and unwatering facilities such as sumps, sump level sensors and sump pumps.
9. Ice prevention equipment such as bubblers for intake structures and surge tanks.
10. Fire suppression systems that utilize raw water to protect plant staff and equipment.

Figure 4. Zebra Mussel biofouling of water intake gate (a), spillway stop (b), and raw water booster pump strainer (c).

Regarding systems and equipment, the most vulnerable items from an impact standpoint are those contained within the powerhouse raw water system. Generator air coolers, thrust bearing oil coolers, and strainers are vital to the continued production of hydroelectric power. ZM/QM can colonize these areas and their shells can become lodged in equipment (Figures 5-6), resulting in low cooling water flows to the generator. When cooling water flows are not adequate, the generator can overheat, which can lead to long and expensive repairs such as generator rewinds and the replacement of thrust bearing shoes. To prevent the generator from overheating, generators are typically brought offline when ZM/QM debris block the flow of cooling water to the generator. This loss of production is costly.

Figure 5. Clean generator air cooling tubes (left) versus generator air cooling tubes affected by Zebra Mussel biofouling.

Figure 6. Air cooler tube plugged with ZM shells.

In addition to loss of production, when ZM/QM colonize a hydroelectric powerhouse and begin to infest its raw water systems, powerhouses see a sharp increase in labor to remove mussel debris from coolers, piping, strainers, and other raw water equipment (Figure 6). Powerhouses that clean generator coolers once every 2-3 years may need to clean coolers 3-4 times per year after ZM/QM infestation. Increased cleaning of affected equipment is necessary to keep the generator operational and cannot be deferred unless the generator is taken out of service. Corrective action to remove ZM/QM debris is therefore disruptive to normal powerhouse operation and maintenance procedures and can lead to other critical work being delayed. In addition to increased expenditure due to the labor required to remove debris, powerhouses see a decrease in total generating revenue after the onset of a ZM/QM infestation within the powerhouse. Additionally, since it is difficult to predict when a generator will need to be taken offline for cleaning, the flexibility of a powerhouse to help meet the demands of a local power grid is reduced.

The precise cost of ZM biofouling in hydropower facilities is difficult to determine due to the nature of ZM settlement and treatment at each powerhouse. Maintenance to remove ZM debris may coincide with normally planned outages or operational work, or it may require specific unplanned outages and additional work depending on the powerhouse and time of year. At one USACE powerhouse that has been experiencing aggressive biofouling from ZM since at least 2018, it was calculated that additional labor throughout the year to remove ZM debris from generator coolers amounted to approximately $145,000. Furthermore, the lost revenue from power generation was estimated at nearly $620,000 for one year due to the amount of time that the powerhouse could not generate power due to zebra mussel biofouling. The powerhouse in question consists of three generating units with a total installed power generation capacity of 132 MW. For powerhouses that generate more power, unit outages will be more costly and labor costs will increase since more units will need to be taken offline for cleaning.

Impacts to Other Business Lines and Environmental Impacts

Other business lines impacted by ZM/QM biofouling include any industries that utilize raw water for cooling (e.g., nuclear power plants, manufacturing), water treatment facilities, and municipalities that utilize river water for drinking (Benson et al. 2021; Lovell and Stone 2005). Most of the expenses related to ZM/QM biofouling relate to facility redesign, increased maintenance, and downtime. A 2005 report released by the US EPA listed individual facility costs related to ZM were up to $800K and an average industry expenditure of >$200K per facility (Lovell and Stone 2005). Not only are ZM/QM responsible for disruptions to the physical infrastructure of intake facilities, they have also been linked to changes in the taste and odor of drinking water (Vogel et al. 1997). Taste and odor complaints are filed each year in cities surrounding Lake Michigan and the Austin, Texas area. Infestations on commercial shipping equipment and barges can cause increased drag and decrease towing speed, which increase cost.

Environmental impacts of ZM/QM are also significant and costly. Like water intake structures subject to biofouling, so are underwater hard surfaces in rivers and lakes, including piers, rocks, native mussel shells. These accumulations affect the structural integrity of underwater structures and cause competition with native mussels, other invertebrates, and fishes for both habitat and food (Benson et al. 2021). Dreissenids feed by filtering suspended material from the water column, including phytoplankton and other microscopic organisms. Large infestations of ZM/QM reduce the availability of these food items to native organisms such as native pearly mussels and planktonic fishes. Water quality changes, such as reduced biomass and increased water clarity disrupt natural ecosystem processes and alter food webs. Increased light availability results in increased growth of submerged aquatic plants, or macrophytes, which alters communities (Benson et al. 2021).

Current Operations

The USACE Hydroelectric Design Center (HDC) has worked with individuals and powerhouses within the Omaha District as well as scientists and researchers at the Engineer Research & Development Center (ERDC) to collect information regarding ZM/QM biofouling and the threat that ZM/QM pose to the generation of hydropower at USACE facilities. HDC has also established working relationships with non-USACE entities such as the United States Bureau of Reclamation's Technical Service Center in Denver, Colorado. and representatives in industry involved in ZM/QM research and mitigation. Through these partnerships, several control techniques have been identified to help prevent ZM/QM colonization in hydroelectric powerhouses. These include experimental methodologies that are currently being investigated and developed as well as commercially available products that have been used in the industry to treat ZM/QM biofouling in raw water facilities. The following methods of ZM/QM control are considered highly promising based on success in industry and ease of procurement and application in the field:

1. The treatment of raw water with ultraviolet light.
2. The treatment of raw water with ionic copper solutions or copper ion generation.
3. The redesign of raw water systems and equipment for emphasis on ease of maintenance for cleaning.

Ultraviolet light therapy was researched extensively by the U.S. Bureau of Reclamation (USBR) at hydropower facilities in the Southwest and was found to be very effective at preventing new mussel settlement in powerhouse raw water piping. Ultraviolet light therapy is attractive due to its simplicity with regards to environmental permitting, although it may not be practicable at all powerhouses. Copper ion therapy involves treating the raw water stream with ionized copper as it enters the powerhouse. Copper ion therapy has the advantage of protecting equipment downstream of the treatment point while preventing new mussel settlement and eradicating existing colonies within the powerhouse. At some locations, the use of copper ion therapy may not be possible due to increased environmental sensitivity and raw water discharge regulations. Other ZM/QM mitigation techniques such as microfiltration, the application of custom biocides and the use of special foul release coatings could also prove effective in the future, but more testing and development is required for these and other experimental control techniques to be fully vetted for use in USACE hydropower facilities. USACE is in the process of evaluating commercially available paint and coating systems that prevent ZM/QM settlement or make ZM/QM easier to remove. Although USACE has not formally approved of any of the commercially available coating systems to date, new technologies are being developed both in private industry and within government agencies like the USBR that should be evaluated for use at USACE facilities in the future.

As a preventative measure in key regions, USACE facilities in collaboration with the US Bureau of Reclamation have undertaken vulnerability assessments to determine potential impacts to operations. While ZM/QM have not yet been detected near these structures, substantial disruption to operations would be expected at each lock and dam. In an abundance of caution and damage prevention, vulnerability assessments for hydropower facilities in the Columbia River Basin (CRB) have been completed. Facility inspections followed by vulnerability assessment reports for each structure detail precautionary steps recommended for early detection of ZM/QM, including regular planktonic sampling for veligers. Water quality analyses have also been performed to assess the infestation risk at different reaches of Columbia Basin rivers. These risks are based on the suitability criteria for ZM/QM establishment developed from habitat studies (Table 1).

The USACE has implemented education and outreach programs aimed at informing and educating the public about the threat of ZM/QM to waterways. In the CRB, one of the last major U.S. watersheds without ZM/QM invasions, Watercraft Inspection Stations have been established in six states. The aim of these efforts is to prevent the spread of aquatic nuisance species through inspection, removal, and cleaning of watercraft after use.

Conclusion

The focus of the USACE will remain on identifying and implementing measures to prevent spread of ZM/QM as well as developing innovative ways to combat current and future infestations in USACE facilities. New technologies to aid in the prevention and release of attached dreissenids are currently in development, as well as new water treatment methodologies focused on pre-treating raw water to kill any ZM/QM veligers prior to attachment.

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