Preparing for Invasive Mussels:

Vulnerability Assessment Guide for Raw Water Infrastructure

Okanagan Basin
WATER BOARD

RNT CONSULTING INC

Acknowledgements

This guide was produced by RNT Consulting and the Okanagan Basin Water Board.

- Primary information was provided by Renata Claudi, RNT Consulting.
- Editing and additional research was conducted by James Littley, Okanagan Basin Water Board.

Technical and editorial review was provided by:

- Anna Warwick Sears, Okanagan Basin Water Board
- Corinne Jackson, Okanagan Basin Water Board
- Heather Larratt, Larratt Aquatic Consultants
- Heidi McMaster, US Bureau of Reclamation
- Lisa DeBruyckere, Pacific States Marine Fisheries Commission
- Martina Beck, B.C. Ministry of Water, Land and Resource Stewardship
- Michael Stephenson, Idaho Power Company
- Nelson Jatel, Okanagan Basin Water Board
- Patti Meger, District of Lake Country
- Rod MacLean, City of Kelowna
- Sandra Schira, Okanagan Basin Water Board
- Stephen Phillips, Pacific States Marine Fisheries Commission
- Zee Marcolin, Regional District of North Okanagan

Graphic Design

- Karen Christensen

For more information or questions related to this guide, email info@obwb.ca.

How to use this guide

Anyone can use this guide!

All raw water infrastructure can be assessed using this guide, protecting water systems for drinking and agriculture, municipal and private, industrial facilities, small and large, simple and complex.

Invasive mussels usually begin to affect infrastructure within three to five years of introduction to a water body. Assessing the risks and understanding the costs of invasive mussels in advance can help in planning and preparing for anticipated increases in costs and maintenance.

This document is a step-by-step guide for facility managers to assess the vulnerability of their source water and facilities to invasive mussel infestation. The information presented here is likely more comprehensive than any one user needs. However, following the sections of this guide based on a user's specific situation before the mussels arrive will help mitigate potential costs through long-term capital planning rather than through emergency response measures.

The guide is organized into the following sections:

Section 1 provides a brief overview of invasive mussel biology and their effects on infrastructure.

Section 2 provides a table of water parameters to determine if your water is at risk. Use the table to compare against your raw water samples.

Section 3 provides a step-by-step guide for assessing your specific system, including:

- how to gather and review site data;
- how to conduct a facility walkthrough;
- how to analyze your risks; and
- planning and preparation from your findings.

Section 4 provides several options to mitigate risks to your system and to adapt your system to minimize impacts.

Section 5 provides options for prioritizing actions after you complete the vulnerability assessment, and a formula to calculate expected costs by facility type such as: water treatment plants, irrigation, and aquaculture facilities.

Use the following steps to complete your assessment:

Step 1 Read Section 1 to understand invasive mussel effects on infrastructure.

Step 2 Use Table 1 in Section 2 to determine if your source water is at risk. Assess all surface water sources in your systems.

Step 3 Gather and review site data as outlined in Section 3.

Step 4 Conduct a facility walkthrough using the information and checklist for each system or component in Section 3 that is relevant to your facility.

Step 5 Analyze the risks to your facility based on your walkthrough and the impacts provided in Section 3.

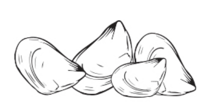
Step 6 Determine your options to mitigate risks and adapt using Section 4.

Step 7 Calculate the potential costs to your facility using the information in Table 2, Section 5.

Step 8 Develop a plan to incorporate mitigation and adaptation strategies into future retrofits and builds.

Zebra mussel shells (*Dreissena polymorpha*) line the shore of Lake Michigan, Wisconsin.
Photo credit: Wikimedia Commons, the free media repository

Table of Contents



Zebra Mussel (*Dreissena polymorpha*) shells on the shore of Lake Erie in Long Point, Norfolk County, Ontario, Canada.
Photo credit: Ryan Hodnet

Section 1: **Introduction to Invasive Dreissenid Mussels and their Effects on Infrastructure**

Impacts to Infrastructure

Invasive zebra and quagga (dreissenid) mussels are a significant threat to water infrastructure globally. “Dreissenid mussels grow on a variety of infrastructure, including water intake pipes for drinking water, irrigation, and power plants. They also attach to water navigation locks, and the face and interior of dams and canal systems, greatly increasing operation and maintenance costs. With continual attachment, the mussels can increase corrosion rates of steel and concrete, leaving equipment and infrastructure vulnerable to structural failure.”[1]

“Control of new infestations of dreissenid mussels in existing water treatment plants often involves alterations to various physical–chemical water treatment methods. Control of mussels in the infested source water is usually not possible because of regulatory restrictions and potential impacts on the ecology and end uses of the system. Rather, mussel control measures are commonly implemented in the water treatment facility itself, usually at the intake structure, transmission pipe, and as part of water treatment methods.”[2]

---

1 https://www.doi.gov/sites/doi.gov/files/uploads/isac_infrastructure_white_paper.pdf
2 Chakraborti, Madon and Kaur, 2016. 443

Specific risks and potential impacts that dressenids pose to a facility include:

Extreme changes in source water entering intakes, including:

- Increased cyanobacteria producing harmful algae blooms
- A drop in green algae
- An increase in water clarity
- An increase in aquatic weeds
- Decreased dissolved oxygen if bacteria are present
- Mussel attachment in pipes with slow water flows

Attachment in pipes causing:

- Increased friction and decreased head pressure
- Decreased water supply
- Obstruction of valves
- Loss of heat-exchange efficiency
- Increased bacteria
- Acidic compound production causing corrosion and pitting under the points of attachment

After shells are removed, up to 600 byssal threads per mussel (attachment points) remain on surfaces causing:

- Continued flow disturbance
- Increased corrosion at the points of attachment

Clumps of mussels may break off, fouling downstream intake structures, filters, pipes, etc.

The magnitude of impacts will depend on:

- The chemistry of your water source
- How the raw water gets into the facility
- Any processes to treat or transform (e.g. steam) the water for various facility applications
- The routing of piping branches, and location of components and equipment including construction materials
- The operating envelope of the various water systems (such as maximum and minimum flow rates, frequency of operation, temperature ranges)

Adapted from USBR 2009.

Infestation of Raw Water Systems

Larval mussels will settle in internal piping where the water flow is less than 1.5–2 m/sec (5-5.6 ft/sec), allowing them to attach easily. Dreissenids will attach to any non-toxic hard surface. They also attach to each other, which creates large clumping colonies. These clumps can break off and foul downstream intake structures, pipes, etc. When they first settle, dreissenids increase the coefficient of friction on surfaces, decreasing head pressure. Subsequent growth in place can reduce water supply to vital areas, obstruct valves, and lead to loss of heat exchange efficiency. If mussels infest a system and are then eliminated, a large number of byssal threads are left behind; up to 600 per mussel. These byssal threads continue to interfere with the flow of water through pipelines. Byssal threads can also affect iron and steel pipelines by increasing corrosion rates at areas of mussel attachment.

Bacteria thrive underneath the mussel colonies, and anaerobic respiration by these bacteria produces acidic compounds, that can accelerate corrosion and pitting of pipelines.

At the Hoover Dam, water enters through four separate penstocks, each with its own cylindrical intake tower, a segmented intake opening at each of two different water depths with gates for each segment opening, and trash racks set on 8 cm (3 in) centres. One of the intake towers was dewatered to inspect inside surfaces. Almost the entire internal concrete surface of the intake tower was colonized by quagga mussels. The highest density of mussels was in the upper 20 to 30 m (60 to 90 ft) of the tower. Settlement tapered off with increasing depth, until 60 m (200 ft) below lake level where there was no further settlement on the tower walls (Leonard Willett, US Bureau or Reclamation, pers. comm.). However, the 60 m (200 ft) deep penstocks had substantial mussel settlement on all the walls despite fast flow in the penstock. This is a result of water containing numerous larvae being drawn in from the 20m (60ft) depth. The larvae are able to attach to the penstock walls during the daily pause in operation. During this time the penstock remains full and the water is not flowing.

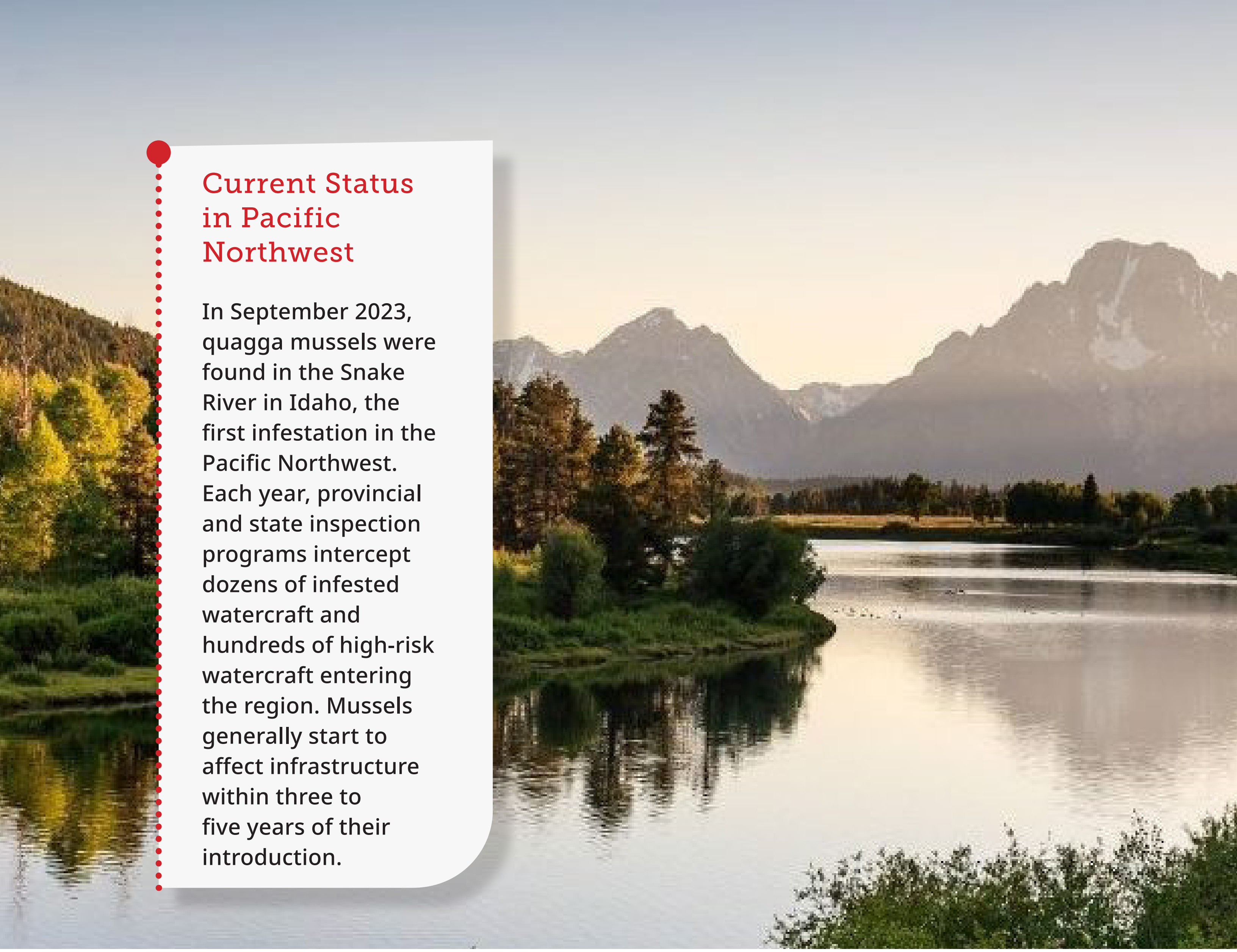
Alteration of Freshwater Ecosystems

Dreissenid mussels have wide-ranging and significant impacts on freshwater ecosystems. They can consume nearly all suspended organic material in the water, excreting feces and pseudofeces and creating extreme water clarity with organic buildup on the bottom.[3] The extreme water filtration by mussels removes organic particles from the water column and deposits them on the bottom, making nutrients available to benthic (bottom-dwelling) species and leaving less food material in the water column for planktonic species. The increased water clarity increases the amount of sunlight that reaches the euphotic zone. This in turn may stimulate the growth of rooted aquatic weeds in areas that were previously shaded. These changes in habitat can have severe impacts on many freshwater species, and on ceremonial, commercial and sport fisheries. “When pseudofeces accumulate, there is an increase in bottom feeding animals. If there is a substantial accumulation of pseudofeces, oxygen is used up due to presence of bacteria. When oxygen levels are reduced, the water pH at this interface also lowers. The mussels also bioaccumulate pollutants, which can be passed up the food chain, increasing wildlife exposure to organic and inorganic pollutants. The mussel shells are sharp, which forces people to wear shoes when walking on infested shores.”[4]

Dreissenid mussels will colonize all hard surfaces, including the shells of all species of unionid clams. In many cases the infestation is so great that unionids are unable to open their shells, and their locomotion and burrowing abilities are impaired. Dreissenid colonies threaten freshwater rare and endangered species of unionid clams.

3 Pseudofeces is created when a mussel coats a particle in mucus and expels it without it passing through the digestive tract.

4 https://www.doi.gov/sites/doi.gov/files/uploads/isac_infrastructure_white_paper.pdf (8)



Current Status in Pacific Northwest

In September 2023, quagga mussels were found in the Snake River in Idaho, the first infestation in the Pacific Northwest. Each year, provincial and state inspection programs intercept dozens of infested watercraft and hundreds of high-risk watercraft entering the region. Mussels generally start to affect infrastructure within three to five years of their introduction.

About Invasive Mussels

Zebra and quagga mussels are native to the Black and Caspian seas region in southeastern Europe, and are members of the dreissenid family of bivalves. These invasive mussels are an environmental and economic nuisance across North America and Europe. They are filter feeders that remove food and small particles from the water and expel waste. One important characteristic is their method of attachment using a byssus—a bundle of strong filaments secreted by the animal to attach themselves to surfaces (Figure 1). Mussels 2.5 cm (1 in) in length may have up to 600 threads holding them in place.

Figure 1 - Zebra mussel with byssus

Zebra mussels are named for the zebra-like stripe pattern on their shells with colours that can include albino, black and brown. Quagga mussels have an equally variable pattern to their shell, but the bottoms of their shells are more rounded than those of zebra mussels.

Figure 2 - Zebra mussel (left) and quagga mussel (right)

Most adult dreissenid shells average 1-2.5 cm (0.5–1 in) but may occasionally reach 4 cm (1.5 in). Their shells are designed to survive on hard surfaces. Their strong byssal attachment makes it difficult for predators to pry the mussels from surfaces.

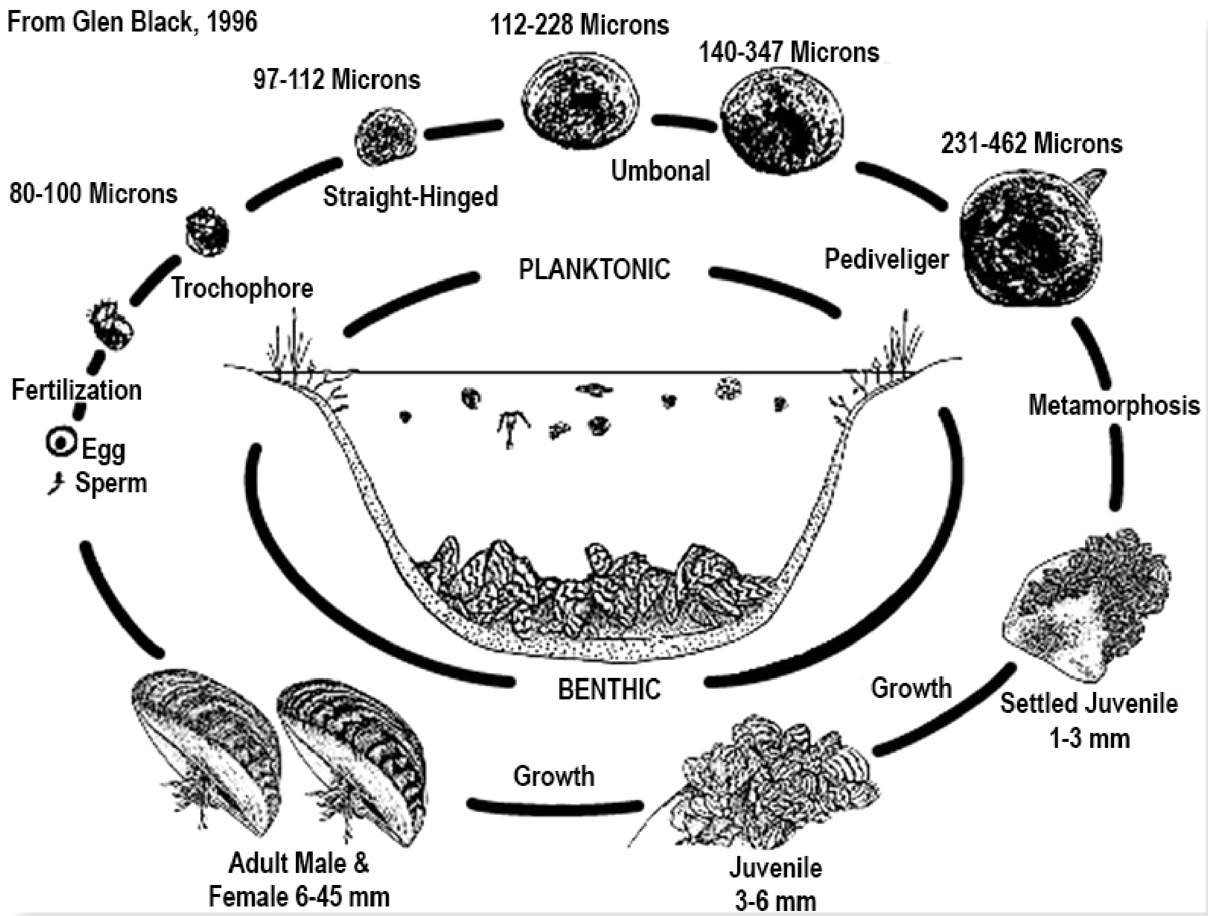


Figure 3 - Dreissenid life cycle

Dreissenids live on all types of solid substrates including rocks, floating logs, break-walls, pipelines, cooling water systems, wet wells, intake structures, hulls of boats, and large living invertebrates such as large unionid shells and crayfish.

The most numerous dreissenid populations are found in waters between 1-10 m (3-40 feet) deep, with densities up to 100,000/m^2 (9,290/ft^2), although quagga mussels have been found as deep as 120 m (400 ft) in Lake Ontario, and some studies have recorded densities up to 700,000/m2, or higher where young mussels attach to aquatic plants.

Invasive mussels quickly spread across much of North America after their discovery in 1988. They can spread by veligers (their free-floating larval form) carried by currents, or as adults attached to floating vegetation, wood or other objects. Their spread is primarily caused by human activities as they are unknowingly transported on the hulls and trailers of ships and boats, in ballast water or engine cooling reservoirs, or in the bait buckets of anglers.

Appendix B on page 71 provides more details on dreissenid mussel biology.

Section 2: **Assessing Source Waters for Invasive Mussel Vulnerability**

Although dreissenids have a distinct set of environmental preferences, they can survive in subpar conditions, enduring starvation, desiccation, and extreme variation in temperature and oxygen levels. They can survive in lakes and reservoirs, rivers, and in the fast currents of pipelines, in nutrient poor and nutrient rich conditions and can tolerate some pollution. They can survive for some time in brackish water, despite being a freshwater species. Under harsh conditions, a mussel can close its shell for up to 2 weeks before reopening, and some sources say they can live in damp, cool conditions out of water for up to 30 days.

At Risk, or Not at Risk?

1. Take water samples from multiple locations in your water body/stream as parameters may change from location to location, especially for large water bodies.

2. Take water samples seasonally as conditions may be suitable for mussel introduction during spring and fall, and not during summer and winter.

3. At risk: If your source water meets the “at risk” conditions for **all** parameters, then it is at risk for a mussel infestation.

4. Not at risk: If your source water does not meet **all** the “at risk” parameters, then it is not at risk. In other words, every parameter must be within the “at risk” range for the water at that sample site to be at risk.

Use Table 1 below[5] to determine whether your source water is at risk of infestation:

Parameter	At Risk
Calcium limits (mg/L)	> 12
pH range	7.0 – 9.5
Salinity (%)	< 10
Oxygen limit at 20°C (mg/L)	> 3
Temperature limit (°C)*	0 – 33
Breeding temperature (°C)*	12 – 24

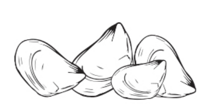
* If the whole of the water body goes below or above the temperature limit threshold, mussels will not survive. If the whole of the water body does not reach the breeding temperature, mussels will not reproduce.

At risk sources may experience different levels of infestation depending on local water chemistry. If your source is at risk given the criteria above, Mackie and Claudi (2010) and Karatayev and Burlakova (2022) provide more information on each of the parameters, how they affect infestation levels, and how they might affect juvenile vs adult mussel survival. These sources also provide more detailed information about specific ranges of each limiting factor.

Secondary factors which may limit risk or affect level of infestation include: chlorophyll a, phosphorus, nitrogen, potassium, secchi depth, conductivity, total dissolved solids, total suspended solids, and turbidity.

---

5 Table adapted from information provided in Karatayev and Burlakova (2022) and Macki and Claudi (2010)



Section 3 Contents

Section 3: **How to Assess Infrastructure Vulnerability for Dreissenids**

This section provides a description of impacts to each system component, followed by a checklist for each component. Once you have completed the walkthrough and taken notes, Section 4 provides options to mitigate risks and adapt.

Systems are best assessed by, or with the assistance of, a person who is familiar with them. Whether your asset is a small fish hatchery or a large pumping plant, it is important to know which components must be protected from either larval settlement, or entry of adult mussel shells. The checklist below can assist in conducting a vulnerability assessment under most circumstances, and for the most common assets.

Gather and Review Site Data

The first step is to obtain and review system schematics and layout drawings before your site visit. This is especially important if you are unfamiliar with the site. It will reduce the amount of time required from facility operators and allow you to determine data and information gaps. Review the information considering the following questions:

- Does the water quality indicate risk from dreissenids based on **the table on page 19**?

- What is the flow path of raw water entering the site?
- What equipment comes in contact with raw water?
- What are the construction materials? Concrete and stainless steel are more prone to fouling by dreissenids than are brass and copper.
- Are there any subsystems and splits from the main intake line?
- What are the positions of fixed grates, pumps, strainers, filters, coolers, heat exchangers, air-conditioning systems and any other equipment which either uses raw water for cooling, or raw water passes through?

Use the impact descriptions and checklists provided below as you review the drawings and make a list of the components that you must inspect. You are now ready to complete the facility walkthrough.

Facility Walkthrough

Using the impact descriptions and checklist sections for each system component below, and your drawings and notes from the system review, walk the facility from where the water enters, to where the water leaves. Make sure that the drawings are accurate, as sometimes modifications are made to the facility but not recorded, or systems are abandoned and decommissioned but still appear as functional on the drawings. If you are not familiar with the system, do the walkthrough with mechanical maintenance staff or an operator.

Systems that contain fixed grates with small gaps, narrow intake pipes already running at capacity, or small diameter pipes where raw water is chronically (or intermittently) moving at less than 2 m/sec, will be problem areas.

General Components Impacts

Construction Materials

Mussels will attach to almost any construction material, including concrete, carbon steel, and stainless steel, aluminum, wood, and plastics. When mussels are removed, the byssal threads almost always remain and can continue to cause corrosion pitting.

Copper and tin are toxic to mussels, although mussels will occasionally cover copper material. This usually occurs in areas of low flow where a biofilm has accumulated on the copper, and the mussels attach to the film. The mussels are usually easy to remove from the biofilm. However, to increase success with copper, it must be kept clean so that mussels are exposed to copper ions.

Mussels generally will not settle in silty areas as the silt can move, dislodging the mussel, or silt can cover the mussel, killing it.

Gates and Stop Logs

Isolation or emergency stop gate frames can become infested with mussels, making it difficult to seal the gate, or causing seal damage. C-shaped gate frame channels should be inspected for mussels frequently.

Penstocks

During full operating capacity, flow velocities in the penstock are generally too large for mussels to settle. However, mussel settlement can occur when the penstock water velocity is reduced, or if the penstock is not dewatered during short outages. During longer outages, especially in warm waters, the drop in dissolved oxygen in the water within the penstock may be sufficient to prevent settlement.

Infestation of the penstock by mussels increases hydraulic roughness, which translates to a loss of power production. In cold climates, the penstock may also be subject to frazil ice formation: loose, randomly oriented needle-like ice crystals that form in supercooled water as surface water loses heat to cooler air above.

Wet portions of penstock air vents can be mussel settlement locations as velocity flow is typically not high in the vent branch. Any assessment should consider the purpose of the air vent operation (for example: draining, filling, or emergency gate closure) and the consequences of a reduced capacity caused by invasive mussels.

Instrumentation and Control

The performance and health of all systems is monitored and adjusted by facility operators using the available instrumentation and control (I&C) systems. Level gauges, sight glasses, flow meters, pressure transmitters, and various types of control valves are all examples of equipment in the I&C systems. I&C piping and equipment are usually small compared to the systems they serve, making them particularly vulnerable to mussels. The pressure trap entrance may be especially vulnerable to mussels, even in systems with no flow in the instrument line or piping.

HVAC

Heating, ventilating and air-conditioning systems (HVAC) employ a variety of technologies, including some that use raw water for evaporative cooling, or as a medium for heat exchange within the system. HVAC systems may serve for personal comfort or may be needed for essential control equipment, usually electrical, that generates heat and requires uninterrupted cooling. These areas will need to be examined to make sure that any raw water is protected from mussels.

Fire Protection Systems

Fire systems and other safety systems frequently use treated city water making them safe from mussel fouling. However, if they draw water directly from a raw water source, they are as vulnerable as water systems for other services. Fire protection systems are designed to be filled with water and then maintained in a static pressurized state. If the system is used for other purposes (e.g. washing equipment, cleaning spills) or if the system is being tested and there is uptake of new water, the replacement water becomes an access point for invasive mussel larvae, and provides food and oxygen for the mussels. Larvae may fail to survive if the system is truly static or if there is rapid decay of oxygen in the system (through management, or natural processes). Adult mussels may be introduced if there are no strainers on the intake, but can be prevented by up-front strainers.

General Components Checklist

1. Note construction materials (if not previously noted, or different from the drawings).

2. Record duty cycles. These can often expose problems that may be otherwise overlooked, and can sometimes be used strategically to control mussel problems. Some duty cycles to note are:

   a. Critical systems that cannot risk failure or shutdown for other than scheduled inspection and maintenance (e.g. fire protection, cooling water, emergency gates, air vents, other safety systems). These are the highest priority systems to be protected.

   b. Systems that are always operational and always flowing. Record the flow velocity in the various parts of the system.

   c. Systems that are intermittently static and full. If they are static and full, how long do they remain static (i.e. water storage reservoirs)?

   d. Systems that are intermittently static and drained. Record the length of time the system is drained.

3. Note the presence of strainers on the discharge of the pumps. What kind of mesh size or gap do they have, and how often are they opened and inspected or cleaned?

4. Record the diameter of all pipes, especially the smallest pipe in the system.

5. Record the size of the smallest heat exchangers present.

6. Note if debris has ever been found in any part of the system that carries raw water. Describe the size and type of debris.

7. Is there adequate or excess cooling capacity in the heat exchangers?

8. Are there any visible signs of infestation by mollusks, such as Asiatic clams (Corbucula spp.), snails, or dreissenids, in exposed water areas, such as drains or open strainers?

Dam, Reservoir, and Aqueduct Impacts

This section includes structures that deliver water, provide inland waterways, regulate water levels, control flood flows, or provide water to industrial users. It also includes impoundments, holding ponds, recharge ponds, siphons, dikes, turnouts, and canals.

Dam inspectors and maintenance staff should be trained to identify invasive mussels during routine inspections and to understand the impact of mussels on various systems.

Trash racks and the upstream tunnels of dams must be considered carefully, as they are usually very difficult to drain and clean. The downstream tunnel is also at risk of mussel fouling, but usually is easier to access for cleaning. The pressure gates must also be considered, as well as any inter-chamber piping and vent lines.

Structures that rely on movable gates to regulate flow can be colonized by mussels, both on the outside and inside of submersed gates, increasing their weight—and potentially making the gates inoperable depending on their design. Mussels can also interfere with proper sealing around the gates, and clog small drains and weep holes.

Level gauging systems usually require small-diameter raw water lines that connect to sensor equipment and can become plugged, impairing the performance or response time of the gauges. If float-type measuring systems are used, mussel accumulation on the float will generate a level reading error. Dams may not be able to control water levels as required if they are impacted by mussels.

Reservoirs may be drained to reduce the level of mussel infestation, but any floating structures that are infested can reintroduce mussels to the reservoir if they are not removed or cleaned during draining.

In rare cases, dam drain tubes, which collect water that has passed the dam seal, can become settlement points for mussel larvae.

Uplift drainpipes and reservoir seepage passing through base material will not normally transport mussels or larvae, but it is important to ensure that these pipes do not come in contact with raw water.

Sumps can be ideal areas to check for mussels, which typically settle on external portions of submerged pump casings, and on the walls of the sump below the level of the shut-off switch.

Dam, Reservoir, and Aqueduct Checklist

1. Are there membranes, control joints, permeable construction media, drains, etc., that let raw water pass?

2. Are there any air vents?

3. Check if the spillway and appurtenances are always wet or dry, and record duration of dry period.

4. How much does the reservoir water surface elevation fluctuate?

5. Are all potential water seepage paths inspected on a regular basis?

Water Intake Structures Impacts

Deep Water Intakes

Intakes more than 30 m (90 ft) deep will generally experience the least amount of fouling by dreissenids for three reasons. First, greater depths contain water that is permanently cooler than shallower depths (below the thermocline), which means mussels will grow more slowly and free swimming larvae may not be able to survive if the oxygen is depleted below the thermocline through bacterial consumption. Second, low light will limit the growth of food sources such as green algae. Third, the number of viable larvae reaching the intake may be limited depending on the bottom profile of the lake or reservoir and on the circulation patterns which exist. Deep intakes should still be evaluated for vulnerability to mussels.

Mid-water Intakes

Small diameter water intakes—60 to 183 cm (24 to 72 in)—situated in the upper 30 m (90 ft) of water as well as very long intakes (several hundred metres/yards) are particularly vulnerable. The lake end of the intake usually terminates in a fixed grate or trash rack designed to exclude large debris, but is likely to be the most visible point of fouling. Mussels can easily close gaps in the grate and decrease the intake capacity.

Even before mussels reduce the amount of water an intake pipe can carry, they increase the friction and turbulence of flow by increasing the roughness of the pipe surface. This can happen within four weeks of a mussel introduction into a system. During intake design, the material roughness is used to determine the size of pipe required to satisfy discharge capacity. When the roughness increases due to mussel settlement, flow rates drop so that plants pumping water near their design capacity will have trouble meeting demand.

Shallow and Surface Water Intakes

For plants with very large diameter intakes, or which use a surface intake, often the mussel infestation only causes problems when the raw water reaches the pump house.

Fixed trash racks are frequently used to trap large floating debris before the entrance into the pump house and are often the first visible structure fouled by dreissenid mussels. At the Monroe, Michigan power plant for example, trash bars set at 8 cm (3 in) centres became badly fouled within one season. More than 75% of the straining surface was obstructed. Anywhere below the first 2 m (6.5 ft), the mussel layer spanned the 8 cm (3 in) gap between vertical slats, and also extended as much as 15 cm (6 in) past the downstream side of the rack. Similar findings have been recorded at other locations and for multiple types of infrastructure.

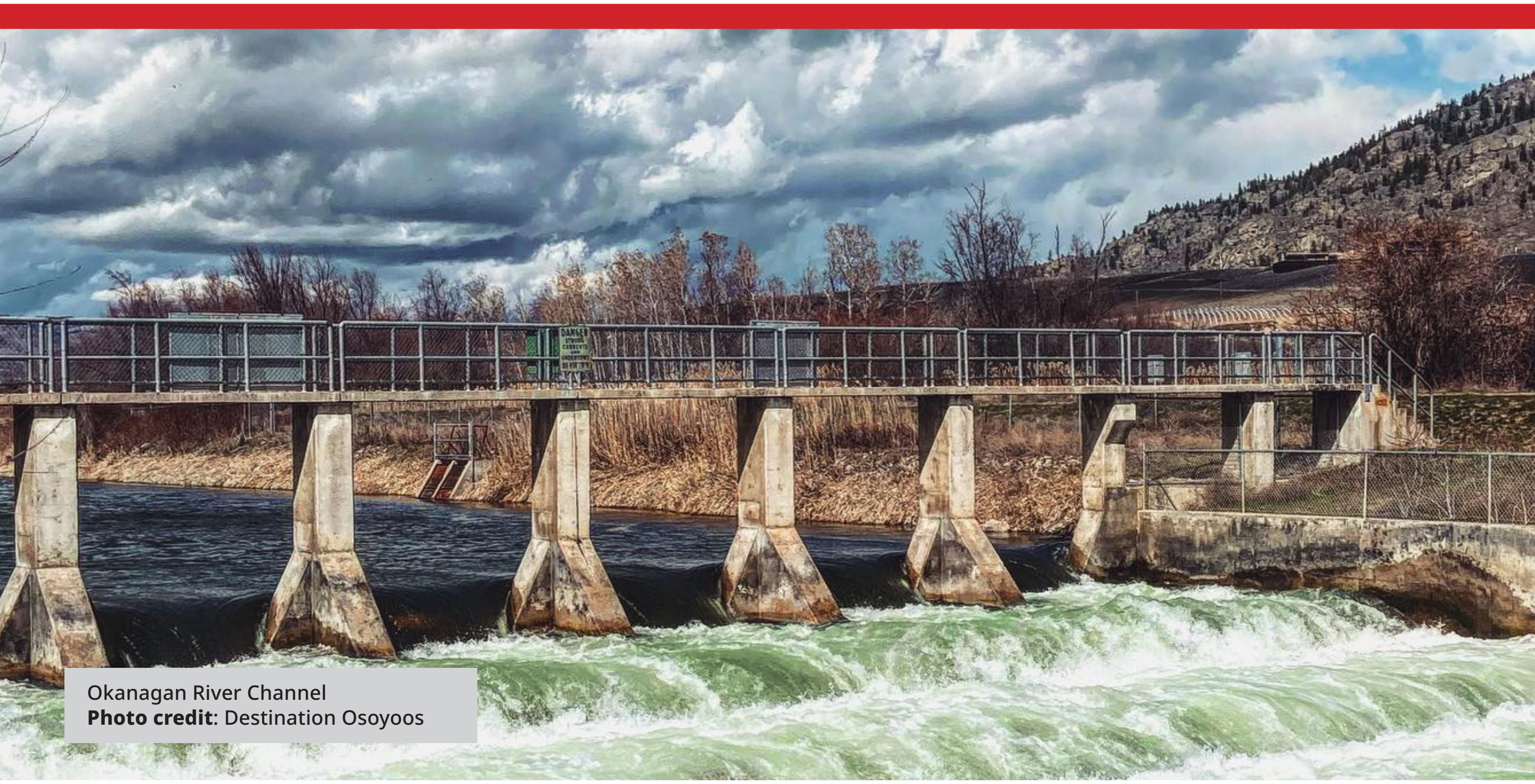
Floating barriers in front of an intake, including those with nets, can also be infested by mussels, weighing them down, and in some cases, causing them to sink.

Invasive mussels on shallow or surface intakes in cooler climates can create more frazil ice due to changes in flow and increased turbulence, potentially blocking the water intake. At the water works of Monroe, Michigan, zebra mussel populations in and around the inlet to the raw water intake contributed heavily to frazil ice formation, which interrupted raw water flow for more than 56 hours.

Water Intake Structures Checklist

Note the types of intake structures present (more than one may be present):

1. Open canal direct into facility (concrete).
2. Open canal direct into facility (other material-specify).
3. Forebay (specify lining material).
4. Tower (specify construction material).
5. Submerged tunnel or pipe intake (specify construction material).
6. Penstock intakes (specify construction material).
7. Fish Barriers (specify type and construction material).
8. Is the floor of any intake structure likely to be covered with silt or sediment?
9. Are any structures duplicated to provide a backup?
10. What is the flow velocity range in the structure?
11. Is the structure accessible for inspection or maintenance?
12. Are there any shutdowns to provide easy access and what is their frequency?
13. Are there scheduled maintenance cycles and how frequent are they?



Okanagan River Channel
Photo credit: Destination Osoyoos

Trash Racks and Screens Impacts

Most trash racks are at risk of mussel settlement making it important to determine their accessibility for cleaning. Facility protection and control strategies will depend on trash rack accessibility. Anti-fouling or foul-release coatings may be good control options for trash racks.

Rotating or traveling screens for fish exclusion and floating debris may have mesh sizes as small as 1 mm (3/64 in) or as large as 13 mm (1/2 in). Screens that move in and out of the water may not become infested, but their supporting structures are usually heavily infested, interfering with the operation of the screen. Adult mussels can form clusters, which can break off in high currents or with gravity, rolling along the bottom and frequently impinging travelling screens. The mussels may then become dislodged by the screen wash system, or may be carried over and fall into the pump well beyond the screen.

Fixed intake screens and grates often become infested and require periodic or continuous cleaning.

Trash Racks and Screens Checklist

1. Record spacing, size and material of trash rack bars.
2. Are trash racks fixed or easily removable for maintenance?
3. Is there a planned maintenance frequency for the trash racks and if so, what is the interval?
4. Is there a trash rake or other style of cleaning system?
5. Are the rake fingers sufficiently large to remove mussels from sides of trash rack bars?
6. Record the location, material, size, and grid spacing of any small intake grates.
7. Are grates fixed or removable for easy maintenance?
8. Check if grates at the bottom of pipes or channels get covered with silt or sediment.
9. Record location, material, size and grid spacing of any screens.
10. Are screens fixed or removable for easy maintenance?

Wells and Sumps Impacts

Drain piping and sumps are often overlooked, but can easily become colonized by mussels, creating an operational nuisance. Open drains and sumps can be good places to look for mussels as well as other species like clams and snails that indicate vulnerability to mussels.

Sump floats and pumps should be inspected regularly for mussel attachment or infestation. Floats may become weighed down by mussels, causing unreliable water level detection. Mussels typically settle on the external portions of submerged pump casings and on the walls of the sump at levels below the shut-off switch.

Concrete pumphouse wells are subject to heavy colonization by dreissenids. Mussels can attach to the walls and submersed pump bells, forming thick clumps of shells that can break off and flow into downstream systems which are not protected by up-front strainers. Fire protection pumps, frequently located in the pumphouse, are of particular concern.

Wells and Sumps Checklist

1. Note the construction material and location of wells.
2. Identify level fluctuations in pump wells.
3. Measure and note the distance of pump suction from the bottom of wells. Will the pump ingest shells that are transported along the floor into the well?
4. Note the location and construction materials of sumps.
5. Is there a float or other instrumentation in the sump that could become covered with mussels?
6. Record the frequency of sump inspection by plant staff.

Pumps and Turbines Impacts

At large pumping stations, the pump shaft seal water system is often only supplied during pump startup. The seal cavity may be exposed to small shell fragments under normal operating conditions, increasing wear. The seal cavity may also become a mussel settlement area. Check if the seal cavity has a procedure for inspection and cleaning provided by the seal manufacturer, and recommend inspections if seal cavity temperatures rise above acceptable operational levels.

Water cooled pump motors may be impacted by mussels when larvae pass through strainers and settle in areas not made of copper or copper alloys, or when shell fragments enter the system and increase the rate of wear on wear-rings and other components. Adult mussels should not pass through the strainers, but the seal cavity in mechanical seals, and the lantern ring cavity in stuffing boxes, may become settlement areas for larvae and must be inspected and cleaned if seal cavity temperatures rise above acceptable operational levels.

Air-cooled pump motors should not be impacted by mussels.

On turbines, guide and generator bearings may be oil-lubricated with water used to cool the oil. Oil coolers may be impacted by mussel shells. Turbine shaft seals with water passages for cooling may also become blocked with mussel shells, overheating and damaging seal components. Mussel larvae are small enough to pass through the gap between the shaft and seal, and drainpipes may also become blocked.

Pumps and Turbines Checklist

1. Is the pump motor or turbine generator water or air cooled? Water cooled motors are at risk.
2. Are the wear ring gaps large enough for mussels to get into them?
3. Does the pump have a mechanical seal?
4. How is the seal flushed during start-up?
5. How is the seal flushed during normal running?
6. Does the turbine or pump have a stuffing box?
7. Is there a stuffing box lantern ring or other cavity for cooling and flushing water?
8. How is the ring flushed during start-up?
9. How is the ring flushed during normal running?
10. Check if the motor bearings have water cooled lubrication.
11. Check if the pump has water cooled bearings.
12. Can mussel shells get into the water lubricated bearing passages?
13. Do seal or stuffing box cavities have a means of monitoring or inspection?
14. Can seals or stuffing boxes be cleaned without removing the motor?

Piping Impacts

Free-swimming mussel larvae are drawn into various systems along with water and can settle in piping. Carbon steel, stainless steel, aluminum, and concrete piping are all at risk of settlement and fouling, whereas copper piping or alloys with high copper content are at much less risk of fouling.

Most of the systems of concern are composed of small diameter (typically 200 mm (8 in) or less) piping in which the water velocities are less than 2 m/sec (6.5 ft/sec). Under such conditions, larvae may settle and begin to grow. The subsequent development of dense colonies decreases the amount of water available to the system. In some cases, areas with design flow rates high enough to preclude attachment have been observed full of juvenile mussels. In these cases, the mussel settlement may happen during partial or short-term outages when the flows are reduced.

Embedded small diameter piping is of particular concern because in most cases, the piping may not be accessible for cleanout. Cross connection piping between systems should be identified. When connections are closed, mussels can settle in the cross connect pipe and block flow when the cross connect is needed.

Surge tanks with large diameter pipes are at risk of mussel settlement in the wetted portion of the tank. If the inlet to the tank becomes partially plugged, then the piping is at increased risk of water hammer. If the tank also serves as a vent, then there may be an increased risk of pipe collapse unless the entrance to the tank is kept clear.

Piping Checklist

1. Identify construction materials for piping.
2. What is the flow velocity range in the piping?
3. How much time is velocity above 2 m/sec (6.5 ft/sec)?
4. How much time is velocity below 2 m/sec (6.5 ft/sec)?
5. Are there any offsets or changes in pipe diameter?

Instruments and Instrument Tubing Impacts

The inlet pipe of gauging stations and float wells could become colonized with mussels, impairing the accuracy of the gauging station where there are frequent or sudden changes in flow and levels. Locations with slow changes in flow rates and water levels may not be as prone to reduced accuracy, as a plugged pipe would still allow water to percolate to the stilling well. However, the floats could have sufficient mussels attached making level readings unreliable.

Mussels can settle in or on any instrument in contact with raw water. If the lines have no flow, such as pressure sensing lines, then the settlement is likely to occur near the tap end where oxygen and nutrients are available for the mussels. Any instruments in direct contact with raw water, such as level gauges or acoustic flow meters, are at high risk. Some float-based level sensing wells also have non-contact instruments for back-up. Facility operators should be advised that reading discrepancies may be due to mussels on floats.

The intake pipes for flow-through water sampling stations are particularly at-risk.

Instruments and Instrument Tubing Checklist

1. Identify any small diameter lines (5 cm (2 in) diameter or less) including construction material such as:
    a. Flow measurement taps;
    b. Piezometer taps;
    c. Pressure taps;
    d. Sample lines;
    e. Pressure balance lines;
    f. Other – Specify.

Heat Exchangers Impacts

All systems for power generating plants are vulnerable to mussels to some degree, including: cooling and heat transfer systems, make up steam systems, service systems for cleaning, air conditioning, fire protection and drinking water systems.

The inlet and outlet plenums of coolers are usually at risk of larval settlement unless these portions of the components are made from copper or copper alloy. Copper alloys may build up a biofilm that can reduce heat exchanger performance and create suitable conditions for mussel attachment. Mussels attached to the biofilm are easy to remove but can plug tubing if they are allowed to grow, and then break off, or are otherwise released.

In addition, the inlet plenum of a cooler is typically a catchment area for shell material that can gradually accumulate, blocking tubes and causing poor performance of the coolers. Inspect the heat exchanger for mussel fouling and clean it following the manufacturer's recommendations or existing operating procedures.

As a general guideline, if temperatures in the cooling water are below 32°C (90°F), water flow is less than 2 m/sec (6.5 ft/sec) and the tubes are non-copper, then the heat exchanger tubes could become settlement areas for mussels.

Heat Exchangers Checklist

1. Identify plenum construction material.
2. Identify tubing construction material.
3. What is the diameter of tubing?
4. What is the flow velocity range in tubing?

Valves Impacts

Dense colonies of mussels affect the proper operation of valves, especially valves that do not operate frequently. For example, at one facility, a 10 cm (4 in) butterfly valve failed to close because the disc was completely covered by mussels. Even if a valve is able to close, there may be leakage caused by trapped mussel shells. Inter-chamber cavities with vent lines and pressure balancing lines can be disabled by being plugged with mussels.

Valves Checklist

1. Identify all normally open (NO) valves.
2. Can NO valves fail to seal properly if valve seat or valve face becomes mussel coated?
3. Identify all normally closed (NC) valves.
4. Can NC valves fail to open if valve face becomes coated with mussels?
5. What is the throat diameter of the valve? Is it small/large enough to become plugged by mussel shells?

Dreissena polymorpha
Photo: F Lamiot Wikimedia.

Strainers and Filters Impacts

Large aggregates of mussels can block water at in-line strainers, limiting the flow to downstream systems. Self-cleaning strainers can also be at risk during duty cycle shutdowns, when mussels can begin to grow on the downstream side of the strainer and provide a source of mussel shells that the strainer would normally remove.

Strainers and Filters Checklist

1. Identify the style and construction material of the strainer, including the body and basket, and the size of the basket pores. Typical styles are:
    a. Fixed In-line strainer;
    b. Duplex strainer;
    c. Self-cleaning strainer;
    d. Wye (Y) strainer.
2. Identify the style and construction material of the filter, including the body and filter element, and the size of the filter pores. Typical styles are:
    a. Self-cleaning filter;
    b. Replaceable cartridge filter;
    c. Other type – specify.

Analysis of Risks

Following the walkthrough, consider your observations from your drawings and recorded in your notes.

1. Create a list of structures and systems likely to be impacted.
2. Once you have a complete list of at-risk structures and potential effects, use Section 4 to determine treatment or control options for each system.

Keep in mind that control in one system may mitigate the need for control in a subsequent system. Generally, systems that contain fixed grates with small gaps, narrow intake pipes already running at capacity, or small diameter pipes where raw water is chronically (or intermittently) moving at less than 2 m/sec (6.5 ft/sec) will be problem areas.

Section 4 Contents:

Section 4: **Options to Mitigate Risks and Adapt**

Use this section and the linked information to consider the best control options to mitigate risks or adapt your operations to control invasive mussels. This section includes options for both chemical and non-chemical mussel control.

Use of Chemicals for Mussel Control

A wide variety of chemical treatment strategies are available for controlling mussel populations. Chemical control is the usual treatment of choice in water delivery systems in both Europe and North America since it has proven to be convenient and effective for most systems. The major advantage of chemical treatments is that they can be engineered to protect almost the entire facility, from intake to discharge. **However, they must be used in accordance with local, provincial/state and federal regulations, to limit the discharge of toxic materials to the environment.** Even when using approved products, permits or authorizations may be required. A wider variety of chemical treatments can be used in closed systems or under static conditions, provided there is no release to the environment.

> "The major advantage of chemical treatments is that they can be engineered to protect almost the entire facility, from intake to discharge."

Appendix A – Types of Chemical Options Available includes more information on the following chemical options:

- Chlorine
- Chlorine Dioxide
- Chloramines
- Ozone
- Hydrogen Peroxide
- Potassium Permanganate
- Proprietary Molluscicides
    - Zequanox
- Copper Ions
- Potassium Salts (Potash)
- Sodium Metabisulfite
- pH Adjustment
- Chemical Cleaning

Proactive Options using Chemical Control

The following chemical treatments are designed to be used proactively to prevent the settlement of mussels in raw water systems.

Intermittent Treatment

Chemical dosing at frequent intervals is aimed at preventing infestations before they begin. When young mussels first settle, they are more susceptible to chemicals than adults. Chemicals may be applied at a lower concentration or a shorter duration to control mussels at this life stage. Most intermittent treatments will not eliminate adults already present in the system.

Effective treatments include:

- Chlorine as sodium hypochlorite used for 30 minutes every 12 hours, at 2 mg/L (2 ppm) prevents freshly settled mussels from developing. This strategy was used at a number of plants belonging to Ontario Power Generation for several years with good results.
- Ozone at 5–8 mg/L (5–8 ppm) for 5 minutes every 12 hours can prevent the development of mussel populations.
- Chlorine dioxide applied for 15 minutes every 6 hours at a concentration of 0.25 mg/L (0.25 ppm) and ambient temperature of 12.8˚C (55˚F), has been shown to achieve 95% reduction in new settlement.
- An intermittent strategy using the molluscicide Mexel was developed in Europe. An addition of 6 mg/L (6 ppm) of the Mexel chemical for 3 hours prevents infestation. More recently, the manufacturer suggested that a once-per-day 30-minute addition of Mexel at a level of 4–5 mg/L (4–5 ppm) will control freshly settled mussels and avoid infestation of the system.

Semi-Continuous Treatment

Mussels will stop filtering and close their shells for 15-30 minutes when exposed to a noxious substance (oxidizing chemical), allowing the treatment schedule to be adjusted to 15 minutes-on and 15 to 45 minutes-off. This is most beneficial to facilities with many systems to be treated. The chemical addition system will work continuously, but the chemical can be directed sequentially to the different systems to be treated.

This strategy results in complete control of all stages of zebra mussels in the piping, while using significantly less chemical than if applied continuously, and minimum discharge levels of the treatment chemical due to the large volume of water available for dilution.

This semi-continuous strategy has been further refined under the trademark Pulse-chlorination®. Using electrodes attached to shells of mussels within a specially constructed monitor, Pulse-chlorination® determines the precise timing for semi-continuous chlorine treatment by observing if the mussels in the monitor have their shell open or closed. The system only applies chlorine when the mussels have opened their shells and discontinues the addition when the shells are closed. This technique significantly reduces the amount of chlorine required (up to 50%) for an intermittent treatment, compared to a continuous application.

Continuous Treatment

The continuous treatment strategy is designed to eliminate any level of settlement in the system. The incoming veligers do not necessarily all die, but the presence of a noxious substance is enough to discourage settlement. Any adults present will either be killed by the treatment (if the low-level chemical addition is used for the entire reproductive season) or detach themselves and attempt to leave the system being treated. The concentration of chemical application can be quite low, but must be continuous.

Continuous treatment is often chosen for systems that cannot tolerate even the smallest degree of fouling. For example, fire protection and other safety related systems often use continuous treatment. This type of treatment has been attempted primarily with oxidizing chemicals such as chlorine or with a continuous feed of copper ions. Other chemical strategies, such as raising or lowering the pH or the continuous addition of flocculants, could be used as a continuous treatment.

Ozone for small fishery case study

A fish hatchery in New England currently uses an ozone treatment system. The facility is relatively small, using approximately 42 megalitres/day (11 million gallons/day) of raw water. The mussel-control regime involves continuous application of ozone at a concentration of 0.3 mg/L (0.3 ppm). The system is designed to treat a 760 m (2,500 ft) long pipeline, inactivating the zebra mussel larvae to limit infestation in the hatchery raceways. The ozone injection at the intake is followed by removal of ozone at the hatchery using ultraviolet light.

Reactive Options Using Chemical Control

Reactive chemical control strategies are used after adult mussels have become established in a raw water system. At this time, there are no reactive treatments using chemicals for fouled external structures.

Treatment at the End of Mussel Breeding Season

End-of-season treatment is performed after the mussel breeding season is complete. Sufficient oxidizing or non-oxidizing chemical is applied for a period long enough to kill all adults established in the system. The end-of-season treatment pre-supposes that the system in question can tolerate one season's worth of mussel fouling, and that the accumulated biomass and shells can be removed after the treatment. Adult mussels will release from the internal walls of systems during and after treatment. The system components must be able to tolerate the estimated mass of shell materials that are released, and maintenance staff must be on hand to remove the debris. Shells will release in large amounts early after the treatment, and may continue to release in smaller amounts for several weeks. Keep records to identify the patterns or trends in your system to predict amounts in future years.

When deciding on the timing for an end-of-season treatment, operating experience suggests that mussels are most vulnerable just after spawning. Therefore, adults may be most easily eliminated in the autumn at the end of the spawning cycle.

Periodic Treatment

Periodic treatment is a variation of end-of-season treatment that targets adults, but applies the chemical more often, eliminating fouling before mussel densities have a measurable disruption on flow. The chemical concentration and duration of application will be similar to an end-of-season treatment. The biomass that is removed after the application is proportionally smaller, but the system still must be capable of tolerating a high degree of fouling. Frequent periodic treatments will prevent the presence of large individual mussels in the system.

See Appendix A on page 63 for further information on oxidizing chemical, non-oxidizing chemical, and chemical cleaning options.

Non-Chemical Mussel Control

Proactive non-chemical mussel techniques are designed to prevent the introduction of mussels into a system. Reactive techniques treat or remove mussels after they are already introduced. Users should consider whether combining chemical and non-chemical techniques would be appropriate for their system..

Non-Chemical Proactive Techniques

Infiltration Galleries and Sand Filters

Infiltration galleries and sand filters can remove all stages of mussel fouling and protect downstream systems and components. An infiltration gallery can be described as a “built-in-place” rapid or slow sand filter. Those designed as rapid sand filters have flow rates of 7 to 15 L/min (2 to 4 gpm) per 0.1 m^2 (1 ft^2) of filter area. Others slow filter at a rate of 0.15 to 0.3 L/min (0.04 to 0.08 gpm) per 0.1 m^2 (1 ft^2). Given these projected flow rates, passage of large amounts of filtered water would require construction of a very large infiltration area. The installation of an infiltration gallery in or near a water body, may require shoreline alteration and regulatory approval. Engineering designs must also consider raw water quality, proximity to sources of high turbidity, hydraulic considerations, and cleaning method and frequency.

Although infiltration galleries and sand filters offer full system protection, they are usually not feasible for existing facilities using large volumes of water. The retrofit required would be very expensive, difficult to implement, and could cause an unacceptable pressure-drop to the system. An infiltration gallery can be a viable option for new intakes.

Mechanical Filtration

Mechanical filtration can remove all mussel life stages if an appropriate screen size and configuration is used. Most conventional industrial strainers have screen openings that will prevent some translocating mussels and most shell debris from fouling raw water systems. Strainers will generally protect against adult mussels but will not prevent the introduction of larvae without finer filtration. It is often not possible to retrofit existing strainers with finer screens because the performance tends to deteriorate. Backwash systems may not work as clogged screens may result in stretching and tearing of the material, and the pressure drop caused by the clogged strainer may be unacceptable.

Several organizations (including Ontario Power, US Bureau of Reclamation, and several U.S. utilities) have tested filters designed primarily for the removal of small particles for dreissenid larvae control. Wedge wire slot filters have difficulty excluding larvae as they are designed to remove inorganic matter such as quartz or metal shavings, not to stop organic matter from passing through the screen. Organic particles are flexible, helping them slip through the wedges of the screen. Ontario Power Generation obtained excellent results using a continuous backwash, pleated screen filter. The New York Power Authority successfully used a modified clean-in-place bag filter to eliminate dreissenid larvae from incoming water. While these methods are extremely effective, no filter can guarantee 100% larvae removal.

Hydro-cyclone or centrifugal separators were initially thought to be a mitigation option for facilities that already use this technology for silt removal. Studies have shown that centrifugal separators removed at most 50% of larvae present, and larvae that have passed through the centrifuge are likely still viable.

Many filters can remove all or most particles from the water stream, but most filters are not able to process large volumes of water efficiently. Filters that use stainless steel, square weave mesh and periodic backwash seem to have the best balance between particle removal efficiency and the volume of water they can filter.

Filter Mesh

Some manufacturers do not distinguish between nominal and absolute size of the pores in the mesh they offer. It is important to understand the difference. There are various test methods used to establish the absolute size of pores in woven wire cloths. One such method is the Bubble Point Test. The rating of absolute mesh size derived from this test corresponds to the diameter of the largest, hard spherical particle which can pass through the filter medium under steady flow conditions. Nominal value, on the other hand, is an arbitrary term that corresponds to the removal of 98% of all incident particles larger than the nominal value given. Various methods are used to determine the nominal rating, and there is poor reproducibility of the results when these methods are used. It is advisable to determine the quality and the absolute mesh size rating the filter manufacturer is offering.

Smythe et al. (1993) reports on the performance of the Kinney Strainer (equipped with a 40, 95, or 142 µm mesh) and the Bromm Filter (nominal mesh size 60 µm and 100 µm). Although the Kinney Strainer (40 nominal µm mesh) and the Bromm Filter (60 µm nominal mesh) reduced the densities of ready-to-settle larvae (>250 µm) in the filtrate by up to 97%, they did not totally exclude all individuals from the system. Examination of the mesh used in each case revealed that the nominal micron ratings were not reliable indicators of the largest opening found in the mesh.

Even high-quality wire weave mesh will allow some organic particles greater than the absolute micron size to pass through. This is because the test protocol uses hard spherical particles. Soft or flexible particles of size greater than the absolute mesh pore-rating can pass through. During recent filter trials, a 120 µm absolute mesh allowed passage of larvae of up to 200 µm. A 57 µm absolute screen passed some larvae up to 100 µm in size.

Mesh wires tend to be very thin to have as much open area as possible in the mesh. Unless the mesh is properly supported, individual pores may be distorted by pressure, and the cloth may be torn by the backwash system. Strong support for the screen is essential to prevent distortion and tearing. Three to four sandwiched layers of screen is recommended. The layers should be sintered together for best support and performance.

Backwash System

The more water a filter uses for its backwash, the less there is available to use in the primary application. Under normal conditions, 1% to 3% of the total filtered flow is required for backwash. This percentage increases as the total suspended solid (TSS) load increases. The filter should be capable of backwash cycles that are based both on time elapsed, and differential pressure across the screen. The greater the differential pressure across the screen, the more likely it is that soft organic material will pass. A differential of no more than 3 to 5 psi is generally recommended.

In addition to removing all larval stages of mussels, filters remove substantial portions of particulate matter such as sediment. How much they remove depends on mesh size and size distribution of the particulate matter in the water column. Self-cleaning filters installed on a system carrying 4,000 L/min (1,057 gpm) of water removed over 10,000 kg (22,000 lb) of silt each year. Sediment removal improves performance and decreases maintenance for most industrial systems.

Filtration systems are not appropriate for water streams with continuously high sediment load like those of some rivers. Under such conditions, the backwash system may not be able to remove the sediment cake that builds up on the screen. Very efficient backwash systems are capable of coping with higher sediment loads. BallastSafe® reported that a filter using a 40 μm screen continued to perform even when incoming water had 250 ppm of TSS. The filter flushed continuously, with the backwash consuming between 8% and 12% of the total flow water. Since the amount of TSS a filter can handle is related to the particle size distribution in the incoming water, a small-scale, site-specific trial with the filter under consideration is recommended.

Field Installation

If filtration is being considered for critical applications, it is important to include a backup system, such as a parallel arrangement of multiple units. Using two filters that are each capable of filtering 100% of the flow would ensure that only filtered water reached downstream systems. If some ingress of unfiltered water can be tolerated, a system by-pass may be installed to guarantee uninterrupted water supply in case the filter is moved out of place.

At least one manufacturer suggests installing a small, fixed filter screen downstream of the self-cleaning filter to monitor the performance of the filter. The fixed screen should be the same, or a slightly larger pore size, than that used in the self-cleaning filter. A plugged fixed screen is an alert that the self-cleaning filter is passing particles larger than its rating.

The State of Vermont has successfully used a series of Amiad® automatic backwashing filters for zebra mussel control at the Edgar Weed Fish Culture Station facility since 1996. At this installation, the filter had to be located downstream from the pump due to the line pressure required by the filtration unit. This requirement means that the intake piping must periodically be mechanically cleaned using a “pigging” unit, and that the pump itself must be allowed to dry out biannually to allow for mussel desiccation and elimination.

Several manufacturers now design filters capable of removing all particles greater than 25 μm from relatively large water streams. Zebra mussel larvae are 80-100 μm in their earliest stages of development. Several of these filters are currently being tested as part of ballast water treatment systems to remove all particles. Should these tests prove successful, the same filters could be used for larvae.

Note on filter construction for mussel exclusion:

The shape of mussels is almost like a flat disc. At the life stage when they are ready to settle, their shell has some flexibility allowing them to be temporarily flattened beyond their normal thickness without harm. Therefore, wedge wire filters are not effective at excluding mussels. The recommended filter basket material is woven wire square mesh designs. The diagram below depicts a suitable commercial mesh.

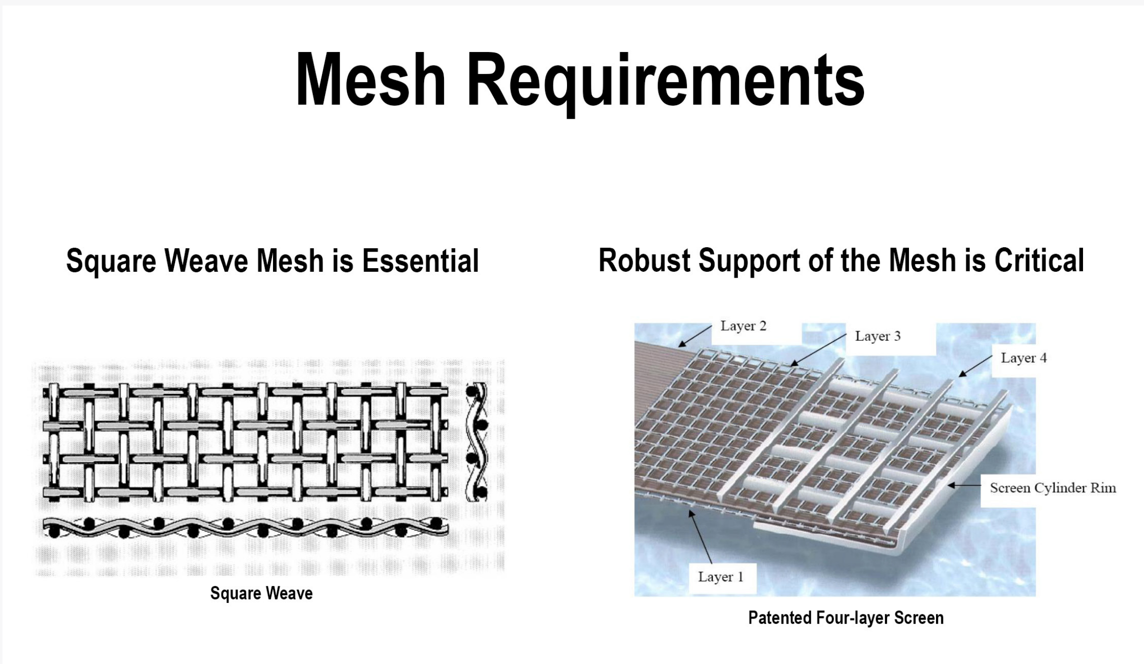


Figure 4: Recommended filter screen construction for mussel exclusion

Ultraviolet Light

Ultraviolet (UV) radiation is appropriate for larval stages of mussels that have transparent or semi-transparent shells. The UV light ranges between 190-400 nm and is subdivided into UVA, UVB, and UVC. Based on work by numerous authors, UVB and UVC wavelengths are the most effective for dreissenid larvae control.[6] The UV light is thought to impact the essential functions of the larva, inactivating the organism, and preventing attachment. Numerous experiments were conducted to determine the most effective wavelength and radiation dose (Dose = intensity x residence time) that the larva must receive to experience either immediate or latent mortality.

Waite et al. (2003) attempted to determine an effective treatment regime for ballast water systems.[7] They found that post filtration, any remaining organisms could be eliminated by a UV dose of 200 mW/cm^2/sec applied at a flow rate of 63 L/sec (1000 gpm).

The effectiveness of a UV system depends on the characteristics of the raw water being treated. Factors such as water transmittance, presence and size of suspended solids, iron, hardness, and temperature influence the effectiveness of the UV system. Treatment systems must be designed for worst-case scenarios. This means designing for peak flows, end of lamp life intensity (as the lamp may dim over time), minimum transmittance, and maximum suspended solids at the installation location. The aim of the system is to achieve 100% immediate or latent mortality in all ready-to-settle larvae. Because UV-based systems have no residual toxicity, if an adequate dose is not delivered, downstream settlement will impact areas outside the influence of the lamps.

The Atlantium Technologies® medium pressure UV system was evaluated as preventative treatment for the settlement of quagga mussel larvae in 2021. This study was carried out on the Lower Colorado River in four separate experiments, each with a UV dose level between 80 and 20 mW/cm^2/sec. Each level provided settlement inhibition greater than 95% (Figure 5).[8]

6 Claudi and Prescott, 2013 “References” section lists numerous UV studies.
7 Waite, T.D., et al. 2003.
8 Pucherelli and Claudi, 2017.

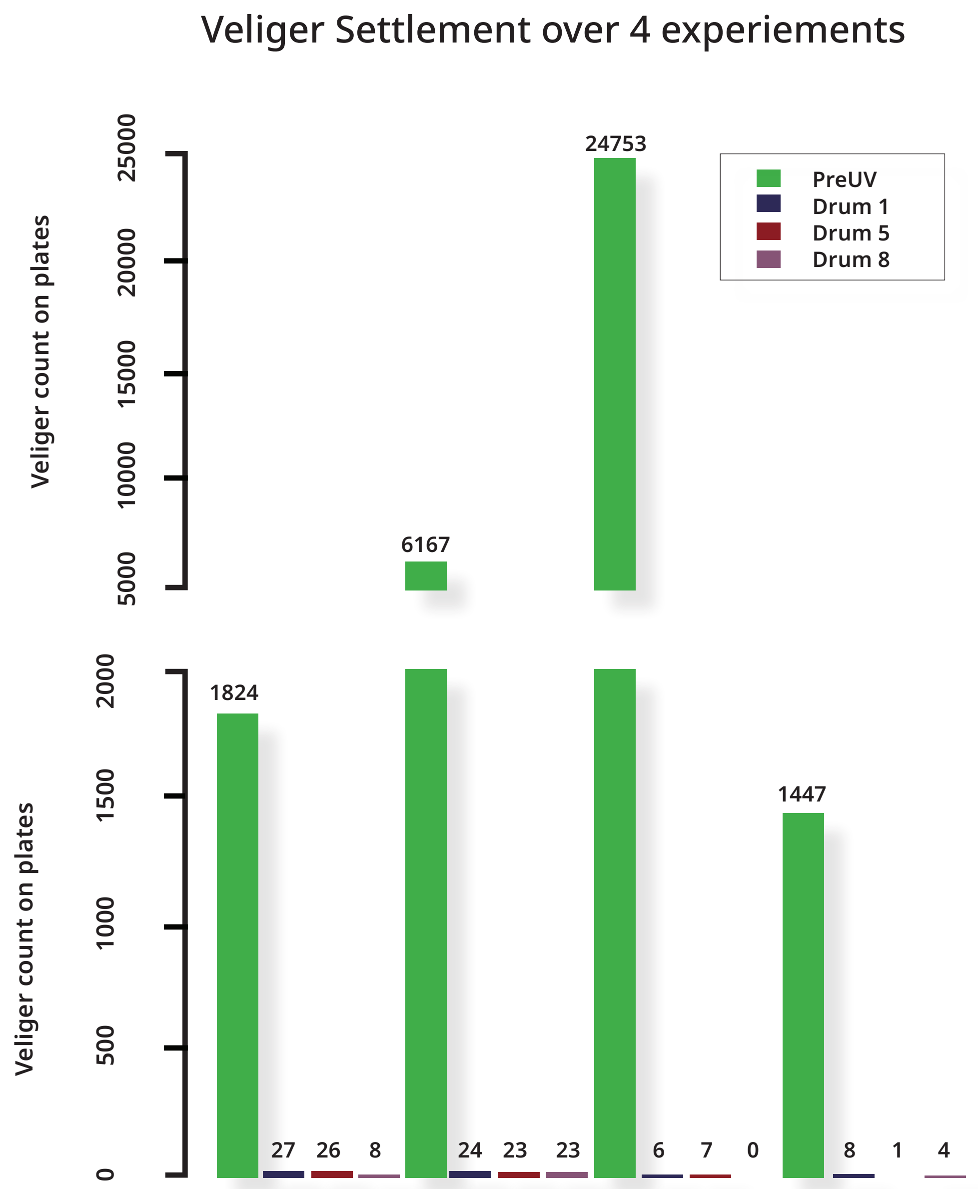


Figure 5: Overview of veliger settlement before and after UV treatments of varying strengths

Davis Dam installed a full-sized medium pressure UV system from Atlantium Technologies to protect all the cooling water (total flow of 224 L/sec or 3,550 gpm) on a power generating unit in 2013. Dam managers allowed the UV system to be adjusted to deliver various levels of UV irradiation. This in turn allowed for second evaluation of downstream quagga veliger settlement after exposure to different UV doses using an actual industrial installation.

Table 1. Total settlement of mussels per square foot, including percent reductions.

Cycle	UV Dose	Settlers	% Reduction	
		Control	Test (after UV)	Box 1 to 2
1	50	160	8	95%
2	40	386	8	98%
3	20	223	26	90%
4	40	1445	18	99%
5	40	810	76	91%

For complete elimination of all settlement UV doses between 100–120 mW/cm^2/sec are recommended.[9]

Anti-Fouling and Foul Release Coatings

Historically, development of anti-fouling paints and coatings focused on preventing barnacle growth on ships. Anti-fouling coatings used in freshwater prevent mussel attachment to structures exposed to raw water. Coatings do not offer any protection to the rest of a facility and therefore must be combined with other mitigation strategies. Appropriate selection of construction materials may minimize the need for coatings in new facilities.

9 Pucherelli and Claudi, 2017.

General Substrate Preference by Mussels on Settling Plates

Most preferred by mussels	Stainless Steel
	Asbestos
	Polypropylene
	Pine
	Black Steel
	Pressure Treated Wood
	Vinyl
	Teflon
	PVS
	Acrylic
	Aluminum
	Galvanized Iron
Least preferred by mussels	Copper

General Material Preference by Mussels in Pipes

Most preferred by mussels	ABS
	PVC
	Polyethylene
	Black Steel
	Acrylic
	Aluminum
	Galvanized Iron
	Brass
Least preferred by mussels	Copper

Horizontally oriented pipes had significantly greater mussel settlement than vertical pipes, and rough surfaces were more heavily colonized than smooth surfaces. Zebra mussel strength of attachment also varies with substrates. Their strength of attachment increases with surface roughness of the substrate. Strongest attachment is to limestone and mild steel. Attachment strength is intermediate on marine concrete, polyvinyl chloride, stainless steel, and coal tar epoxy-coated mild steel. Smooth polytetrafluoroethylene, polymethylmethacrylate, and aluminum have the weakest attachment. Most facilities must deal with existing structures, therefore coating selection presents one of the best methods for minimizing the fouling on external surfaces.

The overall trend is toward the use of environmentally benign foul-release coatings that form a physical barrier to attachment. The current most promising coatings are nontoxic silicone-based paints that prevent or greatly decrease the strength of attachment. Silicone-based coatings applied to the pump well wall at a nuclear power plant were effective at minimizing mussel settlement for almost 10 years. The silicone-based coatings usually require several different layers to be applied to a perfectly clean, white metal surface or very clean, almost dry (10% or less moisture level) concrete. This tends to make them very costly ($80–$100/m^2 or $7–$9/ft^2). Foul-release coatings tend to perform better in areas of high or moderate flow, rather than in slower flow areas.

The U.S. Bureau of Reclamation (USBR) has a coatings research program that has evaluated many of the same coatings and has published a report titled: *Coatings for Mussel Control - Results from Six Years of Field Testing.*

The choice of coating to protect external structures should factor in the cost of coatings, and the problems associated with the application (e.g. sandblasting surfaces, exposure to toxic fumes, keeping large areas dewatered, etc.), and compare to the cost of mechanical cleaning and the disposal of mussel debris on a regular basis. If coating is still the appropriate strategy after this evaluation, carefully examine the data provided by the coatings vendor. Ensure that the coating has been successfully used in an industrial environment for at least three years and has been shown to prevent mussel settlement. Also ensure that no toxic substances are likely to leach from this coating, or be released into the environment when the topcoat of the coating is "reactivated" (i.e. abraded to expose fresh coating). Check with local, provincial/state and federal regulatory agencies for possible constraints on the use of any product.

Speed of Flow

When the speed of flow in a raw water system exceeds 1.5 m/sec (4.9 ft/sec), there is minimal, if any, larval settlement observed. However, very few systems are designed for such fast flow rates, and it would involve a major expense to redesign systems. Intake structures are frequently designed to maintain as slow a rate of flow as possible to prevent entrainment of fish.

Non-Chemical Reactive Techniques

Thermal Shock

Hot water is very effective at killing mussels (Table 2) and most regulatory authorities regard heat treatment as a more environmentally safe and benign method than chemical treatment. Thermal backwash seems feasible for some facilities and systems as an end-of-season or periodic treatment. The temperature and duration of the treatment can be combined in different ways. A temperature of 32°C (89.6°F) for 48 hours has caused 100% mortality in dreissenids, as has 40°C (104°F) for one hour. Between these temperatures, time to death depends on several factors including the acclimation temperature of the mussels to the ambient temperature of the water. The lower the acclimation temperature, the more susceptible the mussels are to thermal shock. A second factor is the rate of temperature increase. If the rate of increase is very gradual, the mussels may acclimate during the process and survive for longer than anticipated. Another factor is genetic variation in local populations. Zebra mussels from a particular geographic area may be more tolerant to high or low temperatures, or temperature variation, than mussels locally adapted to other areas.

Table 2. Resistance time (in minutes) for 100% mussel mortality in relation to temperature.

Test Temperature	Acclimation Temperature			
	5°C/41°F	10°C/50°F	20°C/68°F	25°C/77°F
34°C/93.2°F	419	396	687	-
35°C/95°F	243	231	271	525
36°C/96.8°F	209	107	202	261
37°C/98.6°F	116	52	126	153
38°C/100.4°F	-	-	66	78

There are problems associated with using thermal shock for mussel control.

- There may be regulations governing discharge of heated water.
- It may be difficult to retrofit plants that do not already possess the capability to recirculate hot water, so those plants will only be able to apply thermal shock in small systems using an external heat source, such as a steam generator.
- The cost of treatment can be quite high when plants are either taken off-line or have curtailed production during thermal treatment.
- Manual cleaning of components may be required after a thermal treatment to clear away accumulated dead mussels and shells.

Despite these problems, several facilities have used this method of treatment and achieved very good results. Commonwealth Edison (in the Great Lakes) heat-treated one of its plants by raising the water temperature from 31.6°C to 37.2°C (89°F to 99°F) in 10 hours. They then maintained this temperature for six hours, resulting in 100% mussel mortality. Plants in Italy, France, and Spain have also used thermal treatments for mussel control. It is worth considering a periodic or an end-of-season heat treatment as an alternative to chemical treatment.

Desiccation

Desiccation involves the draining of systems and subjecting the mussels to drying. Unless the process is accelerated using hot air circulating in the pipes, a prolonged shutdown may be required. Adult dreissenid mussels can survive more than 10 days in a cool (below 15°C or 59°F), moist environment. On the other hand, at 25°C (77°F), zebra mussels survive for less than 150 hours regardless of relative humidity. At 35°C (95°F), death occurs in less than 40 hours, particularly at high relative humidity. Rather than actual loss of water from their tissues, mussel mortality is due to their inability to cool their tissues through evaporation when it is both hot and humid.

Oxygen Deprivation

Oxygen deprivation could be accomplished by adding an oxygen-scavenging chemical into a closed system or by keeping a system such as a pipeline static for a sufficient time. Mortality due to lack of oxygen occurs faster at higher temperatures (Table 3).

Table 3. Approximate number of days to 100% mortality for zebra mussels at different oxygen and temperature levels.

O_2 Partial Pressure (Torr)	O_2 % Saturation (%)	Temperature (°C)		
		5°C	15°C	25°C
7.9	5	*x	70	12
11.9	7.5		x	15
15.9	10		x	19
23.8	15	x	x	x
*x = mortality was observed but 100% mortality was not reached in the experimental time frame.				

Oxygen deprivation could be an efficient method of control in facilities that have two intakes, but only need to use one at a time. One intake is capped until the other one becomes fouled by mussels, and then the two are switched. The treatment would work best at high ambient water temperatures. A word of caution: lack of oxygen frequently results in a dramatic increase of sulphate-reducing bacteria, which in turn may cause some microbially-induced corrosion (MIC). Thus, limiting the amount of oxygen in a system may exacerbate corrosion problems.

Mechanical Cleaning

Accumulated mussel populations can be removed from all external structures and some large diameter piping by a variety of manual methods, primarily scraping or water-blasting. This provides a short-term solution that must be repeated at regular intervals.

To date, mussels removed by all types of mechanical cleaning have been disposed of in regular landfill sites or composted at site. Several tests done on these mussels did not find high concentrations of toxic materials, which would force disposal at a hazardous waste site.

Mechanical Cleaning of Large Diameter Pipes

Mechanical “pigs” or scrubbers have been used effectively to knock and scrape mussels and other debris from large-bore pipelines. Pigs are available in a wide variety of designs, and they are manufactured to clean pipes up to 180 cm (70 in) in diameter. The pipeline is unavailable for its primary function during cleaning, and the disposal of dislodged mussels can cause problems.

Drinking water plant intakes are particularly suitable for this method. However, several operators have expressed concern that their structures may not be able to withstand the pressure generated by the mechanical pig on the pipeline.

Underwater Cleaning Using Divers

Ontario Power Generation has developed efficient, economical strategies for underwater cleaning to meet operational requirements. Several diver-operated tools and techniques were tested during the summer and fall of 1990 on a variety of infested surfaces. A continuous flow, 15 cm (6 in) hydraulic pump reduced to 8 cm (3 in) at 38L/sec (600 gpm), equipped with two scraper assemblies (two diver operation) was found to be the best available option for cleaning vertical walls. Power washing was used on the pump bells with some success, but a more efficient technique is needed.

New diver-operated tools and remotely operated tools currently under development could make mechanical cleaning a viable option for pipelines and external structures.

High-and Low-Pressure Water Cleaning

Hydro-blasting, or hydro-lasing, is used to remove corrosion products, unwanted coatings, and biofouling. The area to be cleaned is dewatered and then cleaned with a jet of water. It is advisable to proceed with cleaning as soon as the structure is dewatered so that crews can avoid odors and other possible hazards caused by decomposing mussels. At Detroit Edison, a jet at 20,700 kPa (3000 psi) was adequate to remove a thick build-up of mussels on the concrete wall of the pump well. A variety of nozzle and hose configurations are possible, as is a combination of pressure and volume. The choice will depend on worker preference but the integrity of the surface being cleaned must be preserved. It is preferable to remove as much of the byssal thread and byssal pad as possible. In 2008, the U.S. Bureau of Reclamation initiated a demonstration project on the use of water jetting to remove mussels from an underwater intake pipeline. A water jetting nozzle delivering a water stream at 69,000 kPa (10,000 psi), was inserted into a 25 cm (10 in) diameter pipe, which was over 30 m (100 ft) in length. The pipe was heavily fouled by adult quagga mussels. The water jet was able to remove the majority of the fouling and restore the pipe to full operation.

Design Changes

Occasionally, a system design change may be the most expeditious way to cope with mussels. If well water or municipal water is available, the fire suppression system may be connected to these mussel-free water sources. Old equipment that is being upgraded, such as air compressors, electricity transformers, or HVAC units, may be replaced with air-cooled models rather than models that are cooled with raw water. If trash racks are being replaced, consider designs that are easy to remove for cleaning and painting.

Section 5: **Prioritizing Actions for Mitigation and Adaptation**

Once you have completed your system assessment and selected options to protect your systems and operations, consider how your findings can be integrated into your planning and budgeting processes.

There are three potential timelines to consider for planning:

1. Immediate: What changes can we make immediately to our existing systems to mitigate vulnerability to invasive mussels?

2. Changes Over Time: How can we mitigate risk to our systems as we conduct future retrofits, new builds, and operational changes?

3. Last Resort: If invasive mussels arrive, how can we respond rapidly to protect our systems?

If water in your region is at risk, (see Section 2), a mussel infestation may happen at any time or may be delayed for years. Facility managers should understand the costs and benefits associated with each of the three timelines above, and at minimum, should prepare a contingency reserve-fund sufficient for the last resort scenario.

The following are some considerations for future planning:

1. Create a policy that all future infrastructure builds, retrofits, upgrades etc., incorporate invasive mussel mitigation/prevention measures during the planning phase.

2. Reconsider any existing plans using the assessment and mitigation options provided in this document.

3. Create a response plan which can be implemented as soon as invasive mussels are detected in your region, that accounts for any necessary mitigation and control options. Make sure this plan is updated with each new infrastructure change.

Communicating the plan internally and externally will be critical to ensuring resources are in place.

Expected Costs by Facility Type

This section outlines the expected additional cost of a mussel invasion by facility type. Information for this section was adapted from the May 2023 report, "Potential Economic Impact of Zebra and Quagga Mussels in B.C." The report includes detailed methods for each projected cost type.

Use Table 4 to calculate expected annual high and low range costs to your facility type.

Table 4. Expected range of costs by facility type (2023 Canadian Dollars).

Facility type	**Low cost/ML treated**	**High Cost/ML treated**
Water Treatment Facilities (size is based on capacity)		
Small Facility < 3.8 ML/Day	$26.40 (benchmark cost rather than range)	
Medium Facility 3.8 – 38 ML/Day	$2.60	$24.10
Large Facility > 38 ML/Day	$0.30	$4.70
Irrigation – Ag and Golf	$3.30	$6.80
Aquaculture	$4.40	$40.80
Annual ML treated X low cost = lowest expected cost		
Annual ML treated X high range = highest expected cost		

References

Chakraborti, R.K., Madon, S. and Kaur, J. (2016), *Costs for Controlling Dreissenid Mussels Affecting Drinking Water Infrastructure: Case Studies.* Journal - American Water Works Association, 108: E442-E453. https://doi.org/10.5942/jawwa.2016.108.0104

Claudi, R and P. Prescott. *Evaluation of UV Technology at Hoover Dam as Means of Eliminating Downstream Settlement of Dreissenid Mussel Veligers.* February 2013. Prepared for U.S. Bureau of Reclamation. https://www.rntconsulting.net/Publications/Articles/RNT2013Hoover.pdf

Connelly, N.A., O'Neill, C.R., Knuth, B.A. et al. *Economic Impacts of Zebra Mussels on Drinking Water Treatment and Electric Power Generation Facilities. Environmental Management* 40, 105–112 (2007). https://doi.org/10.1007/s00267-006-0296-5

Kachanova, A. A., 1963. *About growth of* Dreissena polymorpha *Pallas in the Uchinskoe Reservoir and in the channels of Moswater-supply.* In Sokolova, N. Y. (ed), Uchinskoe and Mozhaiskoe Reservoirs Moscow University Press, Moscow: 226–234. (in Russian).

Karatayev, Alexander and Lyubov E. Burlakova. *What we know and don't know about invasive zebra* (Dressena polymorpha) *and quagga* (Dreissena rostiformis bugensis*) mussels. Hydrobiologia*. October, 2022. https://doi.org/10.1007/s10750-022-04950-5

Mackie, Gerald L., and Renata Claudi. *Monitoring and control of macrofouling mollusks in fresh water systems.* CRC Press, 2009.

Province of B.C., Ministry of Water, Land and Resource Stewardship. *Potential Economic Impact of Zebra and Quagga Mussels in B.C.* May 2023. https://www2.gov.bc.ca/assets/gov/environment/plants-animals-and-ecosystems/invasive-species/invasive-mussels/zqm_economic_report_2023_05_26_final.pdf

Pucherelli, Sherri and Renata Claudi. *Evaluation of the effects of ultra-violet light treatment on quagga mussel settlement and veliger survival at Davis Dam.* Management of Biological Invasions. Volume 8, Issue 3: 301-310. 2017. https://www.reabic.net/journals/mbi/2017/3/MBI_2017_Pucherelli_Claudi.pdf

Scribner, McKoy, *Researchers find relationship between invasive zebra mussels, toxic algae.* Great Lakes Echo, July 8, 2021. https://greatlakesecho.org/2021/07/08/researchers-find-relationship-between-invasive-zebra-mussels-toxic-algae/

Skaja, A.. (2010). *Testing coatings for zebra and quagga mussel control.* Journal of Protective Coatings and Linings. 27. 57-65.

Smythe, A. Garry, et al. "*Efficiency Evaluations for Inline Automatic Backwash Filters in Controlling Zebra Mussel Veligers.*" Proc. 1993 Electric Power Res. Inst. Third International Zebra Mussel Conf., Toronto, Ont. 1993.

Sprung, M., 1991. *Costs of reproduction: a study on metabolic requirements of the gonads and fecundity of the bivalve* Dreissena polymorpha. Malacologia 33: 63–70.

USBR, Prepared by RNT Consulting Inc. *Facility Vulnerability Template: Invasive Quagga and Zebra Mussels.* May 2009. https://www.usbr.gov/mussels/research/docs/facilitytemplate/Facility%20Vulnerability%20Assessment%20Template.pdf

U.S. Department of the Interior, *Invasive Species Advisory Committee. Invasive Species Impacts on Infrastructure.* Dec 6, 2016. https://www.doi.gov/sites/doi.gov/files/uploads/isac_infrastructure_white_paper.pdf

Waite, T.D., *et al. Removal of natural populations of marine plankton by a large-scale ballast water treatment system.* Marine Ecology Progress Series, Vol.258: 51-63, 2003. https://www.int-res.com/abstracts/meps/v258/p51-63/

Walker, G.K., M G. Black, and C.A. Edwards. 1996. *Comparative morphology of zebra (Dreissena polymorpha) and quagga (Dreissena bugensis) mussel sperm: light and electrom microscopy.* Canadian Journal of Zoology 74:809-815.

Appendix A – Types of Chemical Options Available

Although various chemical treatment options are available for invasive mussels, each comes with its own advantages and challenges.[10] It's crucial to consider each method's environmental, economic, and regulatory requirements (local, provincial/state and federal) before implementation. In Canada, products must be registered by Health Canada's Pesticide Management Regulatory Agency (PMRA) to control for zebra and quagga mussels. Products that are currently registered in Canada to control invasive mussels include potash for use in open waters, and chlorine to control mussels in closed systems. One ozone generating device and a partial label for Zequanox are also approved by PMRA. Special authorization by PMRA will be required to use products that are not currently registered for invasive mussel control. Provincial permits such as a Pesticide Use Permit under the Pest Management Act (B.C.) may also be required. The facility's specific conditions and the surrounding ecosystem should also be considered when choosing a treatment strategy.

Oxidizing Chemicals

Oxidizing chemicals have been used as disinfecting agents in water supply systems for over 100 years. In most cases, their effect on the environment is understood and well documented. Treatment with oxidizing chemicals (primarily chlorine) has been the most frequently used proactive chemical treatment for invasive mussels to date and can also be used in periodic and end-of-season treatments by a number of different industries.

Chlorine

Chlorination is one of the most effective and popular methods of mussel control, whether added as diatomic chlorine gas, liquid sodium hypochlorite, or solid calcium hypochlorite. Chlorine treatment strategies and concentrations used to control zebra mussels also successfully control quagga mussels.

One strategy for mussel control is to move chlorinators to the raw water intake point, ensuring that viable mussels cannot enter the system. Many regulatory agencies permit the use of chlorine in flow-through systems, but have stringent limitations on the level of total residual chlorine in the discharge water as it may combine with organic compounds to form carcinogenic trihalomethanes (THMs). As with all chemical strategies, check with your local regulator.

10 The list includes some chemicals that are not considered effective options, but are used for informational purposes to allow facility managers to make informed choices.

Chlorine Dioxide

Chlorine dioxide (ClO_2) does not react with ammonia and therefore does not form chloramines or trihalomethane biproducts. It is effective for controlling mussels at all pH levels. The biproducts generated in the breakdown of ClO_2 in aqueous solution are primarily sodium chlorite, chlorate, and chloride, all considered to be acceptable at low levels by regulatory bodies. However, the United States Environmental Protection Agency (EPA) found that bromate and aldehyde biproducts can be formed when chlorine dioxide is added to water and this treatment has not been approved by PMRA for use in Canada. The biproducts include the propanal to decanal series, benzaldehyde, methyl glyoxal, and glyoxal which may be of some interest depending on specific facility concerns.

Chlorine dioxide can be manufactured on-site from sodium chlorite and hydrochloric acid; sodium chlorite and chlorine gas; sodium chlorite and sodium hypochlorite; and hydrochloric acid or sodium chlorate; and hydrogen peroxide and sulphuric acid. The manufacture of chlorine dioxide requires specialized equipment, and there have been past concerns regarding worker safety.

Recently, manufacturers have started producing 3,000 mg/L (3000 ppm) solutions of chlorine dioxide off-site and delivering these solutions to the client. Although an aqueous solution of 3,000 mg/L (3000 ppm) chlorine dioxide is not classified as a hazardous substance, at room temperature it will sublimate into a poisonous gaseous phase. This can lead to health and safety concerns if the equipment is not airtight and carefully controlled. For this reason, on-site generation with state-of-the-art equipment is recommended.

Chloramines

Chloramines are formed when free available chlorine (HOCl and OCl) reacts with nitrogen containing compounds, such as ammonium and amino acids. Monochloramine (NH_2Cl) has been used as a disinfectant in drinking water, and it was also found effective in controlling larvae of the invasive clam (*Corbicula fluminea*). At two French power plants, monochloramine is produced on-site by mixing sodium hypochlorite and ammonium chloride, and it is used to control zebra mussels as well as bryozoans (Plumatella sp). Chloramines may be a better option over chlorine for some facilities if the formation of trihalomethanes is a concern.

Chloramines are formed naturally when chlorine or sodium hypochlorite is added to raw water. The more ammonium present, the higher the level of chloramines formed. Chloramines can be generated in bulk by co-injection of ammonium as either ammonium gas or ammonium hydroxide, and sodium hypochlorite. Although chloramines are a less powerful oxidant than hypochlorous acid, they have been used as disinfectants in various applications.

Ozone

Ozone is a well-known and popular bactericide in sewage water treatment. In practical applications at the Lennox power generating station on Lake Ontario, ozone has performed remarkably well in controlling dreissenid infestations in concentrations of 0.3 to 0.5 mg/L (0.3 to 0.5 ppm) continuously or periodically during the mussel breeding season. Viruses and bacteria are eliminated within 30 seconds by a dissolved ozone residual of less than 0.5 mg/L (0.5 ppm). Significant mortality of adult mussels was observed after 20 days of exposure, with complete mortality achieved in 48 days.

Ozone outperforms other oxidizing chemicals in contact time at comparable residual levels while improving taste, odor, and color of drinking water, and can also be used to prevent various other forms of biofouling. Ozone has also been shown to have very little environmental effect and breaks down quickly under UV exposure. However, ozone systems have a high initial equipment cost, and can be difficult to maintain. Ozone also dissipates quickly in water depending on factors like temperature, pH, and organic matter concentration.

Hydrogen Peroxide

Several trials on both adult zebra mussels and larvae have shown that relatively high doses of hydrogen peroxide are required to induce mortality. A concentration of 12 mg/L (12 ppm) was required for adults and 6 mg/L (6 ppm) for larvae. At 5.4 mg/L (5.4 ppm), 90% mortality of adults occurred in 21 days. The duration of the treatment decreased with increasing hydrogen peroxide concentration. As hydrogen peroxide is quite expensive compared to sodium hypochlorite, it is not economically practical to treat large volume, flow-through systems using this chemical.

Potassium Permanganate

Potassium permanganate is another oxidizing chemical commonly used in municipal facilities for water purification. It is widely used to protect against oxidation of iron and manganese, and for control of taste and odor problems. Effective control of adults has been achieved at a concentration of 2.0 mg/L (2.0 ppm) and larval settlement was prevented using a concentration of 1.0 mg/L (1.0 ppm). These results suggest that potassium permanganate may prevent the settlement of mussels, but that it is not acutely toxic to either larvae or adults. Potassium permanganate can be used in potable water treatment facilities as a mitigation strategy, as many may already use it for sanitation purposes or to eliminate trihalomethanes already in solution.

Table 5. Summary of oxidizing chemical treatments.

Treatment Option	Pros	Cons	Concentration
Chlorine	‣ Effective and popular method. ‣ Effective against both zebra and quagga mussels. ‣ Currently registered for use in closed systems	‣ Forms carcinogenic THMs. ‣ Requires regulatory checks.	
Chlorine Dioxide	‣ Doesn't form chloramines or THMs. ‣ Effective across all pH levels.	‣ Requires specialized equipment. ‣ Can sublimate into poisonous gas.	
Chloramines	‣ A better option if THM formation is a concern.	‣ Less powerful oxidant than hypochlorous acid.	
Ozone	‣ Effective bactericidal agent. ‣ Minimal environmental impact.	‣ High initial cost. ‣ Maintenance challenges.	0.3–0.5 mg/L (0.3–0.5 ppm) achieve complete adult mortality in 48 days.
Hydrogen Peroxide	‣ Effective against adult zebra mussels and larvae at certain concentrations.	‣ Requires high doses. ‣ Economically impractical for large systems.	10 mg/L (10 ppm) kills zebra mussels in 7.8 days; 20 mg/L (20 ppm) kills zebra mussels in 4.8 days; 30 mg/L (30 ppm) kills zebra mussels in 3.0 days;
Potassium Permanganate	‣ Commonly used in municipal facilities. ‣ Effective in preventing mussel settlement.	‣ Not acutely toxic to larvae or adults.	2.0 mg/L (2.0 ppm) controls adults, 1.0 mg/L (1.0 ppm) prevents larval settlement.

Non-oxidizing Chemicals

Several non-oxidizing chemicals have been developed for bacterial disinfection, algae control, and as molluscicides, some having regulatory registration for use in once-through cooling systems. With few exceptions, these products require detoxification upon discharge to the environment and would be most useful for end-of-season or periodic treatments.

Proprietary Molluscicides

The term molluscicide is somewhat of a misnomer, as generally these formulations are toxic to a wide variety of species and not just molluscs. Mussels do not detect these chemicals as noxious compounds, so they continue filtering them, causing quick mortality in 4 to 24 hours depending on concentration and ambient water temperature. Many of these proprietary formulations are based either on quaternary amines (Betz-Clamtrol) or on isothiazolones (Buckman-Bulab 6002) or on other organic compounds (Bayer-Baylucide).

Non-oxidizing chemicals have been used with good results in several facilities in North America, primarily as an end-of-season or periodic treatment. In some of these applications, operators have been able to set up closed loop systems where the same chemical was recirculated for the required period of time. This type of application significantly decreases the volume of chemical required, with both environmental and economic benefits.

These products can be used easily in closed systems, but in flow-through applications most of the products must be detoxified by adding a bentonite clay slurry. The bentonite clay can slowly accumulate over many years, carrying the active product to the bottom, bonded to the clay. Some of these complex products can be quite persistent and their fate is not well documented.

Most of these products also require relatively warm ambient temperatures to work quickly. In temperate zones, this may mean a treatment well before the end of spawning, leaving a large population of dreissenids in the system to grow over the winter.

Zequanox

Zequanox is a proprietary biocontrol from Marrone Bio Innovations, California. While the product is currently very expensive, it could potentially offer a significant alternative to all forms of chemical control. Zequanox is currently registered for use in Canada.

A team from New York State Museum led by Dr. Dan Molloy studied the use of a common soil bacterium as a specific control agent for dreissenids. The team found that the bacterial species *Pseudomonas fluorescens*, strain CL145A, causes mortality in adult mussels. When dreissenid mussels ingest artificially high densities of the bacteria (living or dead), a toxin within the bacterial cell destroys the mussels’ digestive system. To date, no other aquatic species that has been tested has demonstrated any susceptibility to this bacterium.

Copper Ions

A continuous dose of 0.02 mg/L (20 ppb) of copper ions appears to limit larval settlement in systems using electrolysis to dissolve copper and aluminum anodes. This technology is trademarked as MacroTech Copper Ion generator and is used by the Wisconsin Energy Corporation to control dreissenid mussel infestations in its Oak Creek Power Plant service water system in west Lake Michigan. The copper ion generator does not eliminate all mussel fouling in the service water system, but the level of infestation is acceptable to the plant personnel. The copper ion generator equipment has significant shortcomings for use in industrial setting such as uneven release of copper ions, no built-in feedback loop, and no alarm system for low levels of copper. The discharge of copper ions into the aquatic ecosystem may not be permitted in all jurisdictions. This treatment is currently not approved for use in Canada.

Copper sulphate and the copper rich algaecide, Cutrine-Ultra® and EarthTec, have been reported to eliminate adult mussels while being used for algal control in various systems at levels of 30 to 50 ppb applied for a number of days (Table 6). This treatment is not currently approved for use on mussels in Canada.

Table 6. Mortality of adult zebra mussels when exposed to various levels of EarthTec under flow-through conditions.

Dose as EarchTec	Dose as Element	Mortality After:				
		6 days	11 days	12 days	19 days	25 days
3 ppm	150 ppb	100%				
2 ppm	100 ppb	100%				
1 ppm	50 ppb	50%	100%			
0.6 ppm	30 ppb	15%	55%	70%	80%	pending

Potassium Salts (Potash)

Potassium compounds are toxic to most bivalves, including dreissenids and corbiculids. A concentration of 100 mg/L (100 ppm) for two days at an ambient temperature of 15°C (59°F) resulted in 100% mortality of dreissenid adult mussels. The length of treatment increased with decreasing temperatures.

Although potassium compounds are nontoxic to higher organisms such as fish, the toxicity to native bivalves makes it unlikely to get approval for use of potassium salts in once-through systems. In closed-loop systems, however, the use of potassium salts is a good option. Potash has also been used in a few small open-water applications, either in a single quarry or a screened-off harbour with good results.

In larger open water bodies, such as Lake Winnipeg, Manitoba, treatment was not successful beyond the local harbours which were curtained off to contain the application. Invasive mussels had already surpassed the containment area before the treatment began. The treatment is also expensive and can act as a fertilizer for algae. It is unlikely to be successful in any large water body.

Sodium Metabisulfite

Sodium metabisulfite is not highly toxic to zebra mussels, requiring minimum concentrations of about 177 mg/L (177 ppm) to kill adult mussels in a closed system. However, anoxia caused by the addition of sodium metabisulfite, an oxygen stripper, contributes to mussel mortality on prolonged exposure. Depending on facility-specific conditions, anoxic conditions combined with higher water temperatures will increase dreissenid mortality more than the effects of either alone.

Sodium metabisulfite is not feasible in pipelines or conduits because enormous amounts of the compound are required for treatment where water is renewed continuously. However, it may be practical for use in closed systems, such as fire protection systems, which hold water for long periods of time. The potential for unacceptable growth of sulphate-reducing bacteria should be evaluated before using this method as the bacteria can cause serious corrosion problems in the system.

Dreissenid mussels are relatively intolerant of low dissolved oxygen concentrations. Systems with dissolved oxygen concentrations above 50% saturation are required for sustained, healthy populations. Systems with less than 3 mg/L (3 ppm) at 20°C (68°F) would have little chance of mussel survival. Depressing the dissolved oxygen level in a system infested by dreissenids could be a form of end-of-season treatment. Adding either chlorine or sodium bisulphite to an intake before capping, followed by a four to 10 week period in a static state will kill all zebra mussels.

pH Adjustment

Dreissenid mussel larvae require a pH of 7.0 – 9.5 to settle and survive. For adults, a pH below 3 or above 12 will cause mortality in 140 hours. If practical, pH adjustment would act as a continuous chemical treatment preventing all settlement and growth. Lowering pH can be particularly useful for drinking water facilities which adjust the pH of the incoming water before processing it. If the point of pH adjustment could be moved to the intake of a facility, it would protect all subsequent structures and systems.

Increasing the pH to 9.6 will not only prevent mussel settlement but it may also inhibit bio-film formation in the treated system. However, if the raw water has a high calcium saturation index, precipitation of calcium carbonate may occur when pH is increased. In such water bodies, high pH treatment will not be a viable option.

Chemical Cleaning

Chemical cleaning may be required in small diameter piping or heat exchangers that become plugged and where mechanical cleaning is not viable. Several products, mostly proprietary inorganic acid mixtures (e.g. phosphoric acid mixtures), will rapidly dissolve mussel shells and will often remove accumulated corrosion products as well. Pipe material must be considered before circulating the chemical cleaner through the pipes in a closed loop for three to four hours before removal for recycling. The system is then flushed and returned to service. This is an expedient remedy for small, neglected systems but is not appropriate for large volume systems. Check with the product vendor for specific instructions and process support.

Table 7. Summary of non-oxidizing chemical treatments.

Treatment Option	Pros	Cons	Concentration
Zequanox	▸ Specific control agent for dreissenids. ▸ No other aquatic species have shown susceptibility.	▸ Currently very expensive.	
Copper Ions	▸ Limits larval settlement.	▸ Equipment has significant shortcomings. ▸ Discharge of copper ions may not be permitted and is not currently registered for use in Canada.	A continuous dose of 0.02 mg/L (20 ppb) of copper ions appears to limit larval settlement in systems using dissolving copper anodes by electrolysis or liquid copper molluscicide.
Potassium Salts (Potash)	▸ Toxic to most bivalves.	▸ Toxicity to native bivalves may prevent its use in once-through systems.	100 mg/L (100 ppm) for two days at an ambient temperature of 15°C (59°F) resulted in 100% mortality of dreissenid adult mussels. The length of treatment increased with decreasing temperatures.
Sodium Metabisulfite	▸ Causes anoxia, contributing to mussel mortality.	▸ Not feasible in pipelines or conduits. ▸ Potential for bacterial growth causing corrosion.	177 mg/L (177 ppm) required to kill adult mussels in a closed system.
pH Adjustment	▸ Prevents mussel settlement and growth. ▸ Can inhibit biofilm formation.	▸ May cause precipitation of calcium carbonate in waters with a high calcium saturation index.	Dreissenid mussel larvae require a pH of 7.0 – 9.5 to settle and survive. For adults, a pH below 3 or above 12 will cause mortality in 140 hours.

Appendix B – Overview of Dreissenid Mussel Biology

Zebra and quagga mussels are members of the dreissenid family and are native to the Black and Caspian seas region in southeastern Europe. These invasive mussels are an environmental and economic nuisance across North America and Europe.

Dreissenid mussels are bivalve mollusks – invertebrates that have shells. Typically, bivalves have:

- Two equal sized shells, also referred to as valves.
- Unequal adductor muscles - the main muscular system in bivalve mollusks. Bivalve mollusks generally have either one or two adductor muscles. The muscles are strong enough to enable the animal to close its valves tightly when necessary, such as when the bivalve is exposed to the air by low water levels, when attacked by a predator, or exposed to a noxious chemical. Most bivalve mollusk species have two adductor muscles, which are located on the anterior and posterior sides of the body.
- They are filter feeders, using an inhalant siphon to bring in food, sieving small particles from the water and exhaling the sieved water and waste through the exhalant siphon.

There are four main species of freshwater bivalves:

Native Bivalves

- **The Sphaeriidae**, or Fingernail Clams (named for their shape)
- **The Unionidae**, or Pearly Mussels (named for the mother-of-pearl layer on the interior of their shell)

Introduced/Exotic Bivalves

- **The Corbicula fluminea**, (invasive clam)
- **The Dreissenidae**, zebra and quagga mussels (named for the zebra-stripe pattern on their shells), and Conrad's false mussel, are the only freshwater mussels in North America which possess a byssus - a bundle of strong filaments secreted by the animal to attach themselves to surfaces.

Figure 5 - Zebra mussel with byssus

External Biology

The shell of the zebra mussel is distinct, taking its name from its zebra-like stripes on the exterior of its shell. Its scientific name (*Dreissena polymorpha*) refers to the many variances (or morphs) that occur in the shell's color pattern, which can include albino, black and brown. Quagga mussels (*Dreissena rostriformis bugensis*) have an equally variable pattern to their shell, but the bottoms of their shells are more rounded than those of zebra mussels. Usually, the way to tell zebra and quagga mussels apart is to place each shell on its ventral side; the quagga mussel will topple over due to its rounded bottom surface, while the zebra mussel will remain upright (Figure 6).

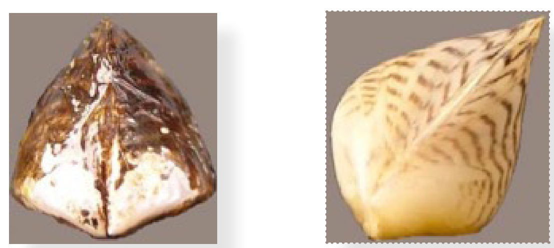


Figure 6 - Zebra mussel left and quagga mussel right

Another distinguishing feature is found when looking at the ventral side of the mussels. Zebra mussel shells come together in a straight symmetrical line while quagga mussels do not (Figure 7).

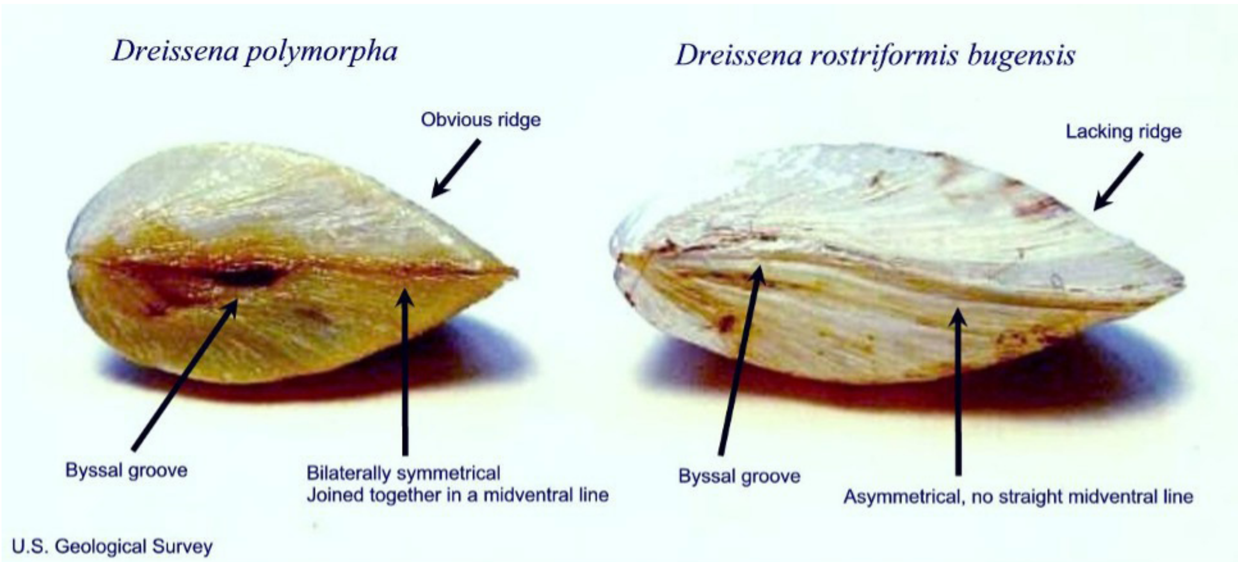


Figure 7 - Ventral side of zebra and quagga mussel

Occasionally, zebra and quagga mussels are confused with a third species – *Mytilopsis leucophaeta*, Conrad's false mussel. This species is distinct in that it has unique structure on the inside of the shell (an interior apophysis or septum), which is absent in zebra and quagga mussels, and generally the shell is uniformly dark and not striped. It is found primarily in brackish waters near the coast.

Most adult dreissenid shells average 1–2.5 cm (0.5–1 in) but may reach 4 cm (1.5 in) on occasion. Their shells are designed to survive on hard surfaces. Their strong byssal attachment makes it difficult for predators to pry the mussels from surfaces. If cross-sectioned, the shells are tent shaped.

Interior Biology

The shells hinge open and closed using a ligament, which is internal and anterior. The pointed end of the shell has an apical septum, or myophore plate which attaches the small anterior adductor muscle – one of two that help to close the two valves. The broad, round posterior end of the shell houses the large posterior adductor muscle scar – each of these posterior and anterior adductor muscles serve to close the valves. The ligament serves to open the valves when the adductors relax.

A thin tissue called the mantle envelops the internal body of the mussel. The mantle (also known by the Latin word pallium meaning mantle, robe or cloak) is a significant part of the anatomy of mollusks: it is the dorsal body wall which covers the visceral mass and usually protrudes in the form of flaps well beyond the visceral mass itself. In dreissenids the epidermis of the mantle secretes calcium carbonate to create the shell.

The mantle has two openings for the inhalant siphon and exhalent siphon. Siphons are tube-like structures in which water flows in and out. The water flow is used for feeding, respiration, and elimination of waste. The siphons are part of the mantle.

The inhalant siphon is the larger opening and is ringed with 80 to 100 tentacles, which assist in selecting food particles. The exhalent siphon is cone-shaped, has no tentacles and is dorsal to the inhalant siphon. The only opening of the shell is the pedal gape, which allows for the extrusion of the large byssus. Dreissenids have a large muscular foot, which is used to pull the animal over the substrate (typically rock, sand or gravel). It does this by repeatedly advancing the foot, expanding the end so it serves as an anchor, and then pulling the rest of the animal forward. It also serves as a fleshy anchor when the animal is stationary.

The byssal glands are housed adjacent to the foot, and are responsible for secreting byssal threads, which allow mussels to adhere to objects. The threads are formed one at a time, branching from a central stem. In order to detach itself from an object, enzymes are secreted at the base of the byssal mass and the entire mass of byssal threads are released – the mussel then secretes new threads. Mussels 2.5 cm in length may have up to 600 threads holding it in place.

On each side of the body of dreissenid mussels are gills, which are divided into a series of water tubes by septa or filaments – these filaments make up sheets or lamellae (thin plate-like structures with space in between). Lake water circulates through the small openings in the lamellae.

Dreissenid mussels' gills are covered in small cilia, which create currents that aids in pulling water through the inhalant siphon, into the mantle cavity and over the gills. As digestible particles pass over the gills, they are removed by the cilia, and directed towards the mouth for digestion. Inedible particles are wrapped in mucous and rejected as pseudofeces.

The mouth is comprised of a pair of flaps called labial palps and is located at the anterior end of the body. The labial palps assist in guiding and selecting digestible food into the mouth, through a short esophagus and into a large, thin-walled stomach. Undigested food is passed by cilia from the stomach to eventually be expelled at an anal papilla located within the exhalant siphon.

Reproduction and Life Cycle

Zebra and quagga mussels have separate sexes. Eggs and sperm begin maturing when the water temperature reaches about 12°C (54°F), but their numbers don't peak until the water temperatures near 15–17°C (59°F–63°F). After eggs and sperm are released by the adults, fertilization occurs externally in the water. Sprung (1991) estimated that a single large (mature) female mussel can produce up to one million eggs given the right environmental, food, and temperature conditions. Kachanova (1961) found that smaller mussels could produce 30,000 - 40,000 eggs at a stable rate even under varying environmental conditions.

In the Great Lakes the peak reproductive season is in June/July, but the veligers that are born in the spring can reach sexual maturity (at length of 8–10 mm or 0.3–0.4 in) by mid-summer and contribute to the production of new veligers by the fall. Spawning may last three to five months though it can last longer in warmer climates. The development from fertilized egg to ready-to-settle veligers requires three to five weeks depending on the ambient temperature of the water.

Larval Life Cycle

The larval life cycle has three stages:

- Veliger Stage: After fertilization the embryo develops into free-swimming larvae in 6–20 hours. Several days after fertilization the veliger secretes its first larval shell and continues to grow for the next three to five weeks. The next stage is D-shaped or straight hinge shape, followed by a clam shape. Up to this point all the larval stages are capable of limited "swimming" using an apparatus called the velum. This ability makes it possible for them to maintain their position in the water column. It is not possible for them to swim against any current. Eventually the larvae lose their velum and acquire a foot. At this stage they are called pediveligers. Unless carried by current, they fall to the bottom seeking a place to attach.
- The pediveliger uses its foot for crawling on surfaces. It seeks out appropriate surfaces, secretes its byssal thread and undergoes metamorphosis to become a plantigrade (a stage between pediveliger and an adult shape).
- The plantigrade continues to grow, acquiring the adult triangular shape. It is now called a juvenile, and with time, further growth, and sexual maturity, an adult. Mussels can grow incredibly fast, as much as 0.5 - 1 mm/day. Typically, adults grow 1.5–2 cm (0.6 – 0.8 in) per year, with average daily growth rates in summer at about 0.10 mm – 0.15 mm/day. Depending on water temperature and food supply, mussels can reach sexual maturity in as little as eight weeks. In the Great Lakes the maximum lifespan of the adult mussels appears to be two to three years.

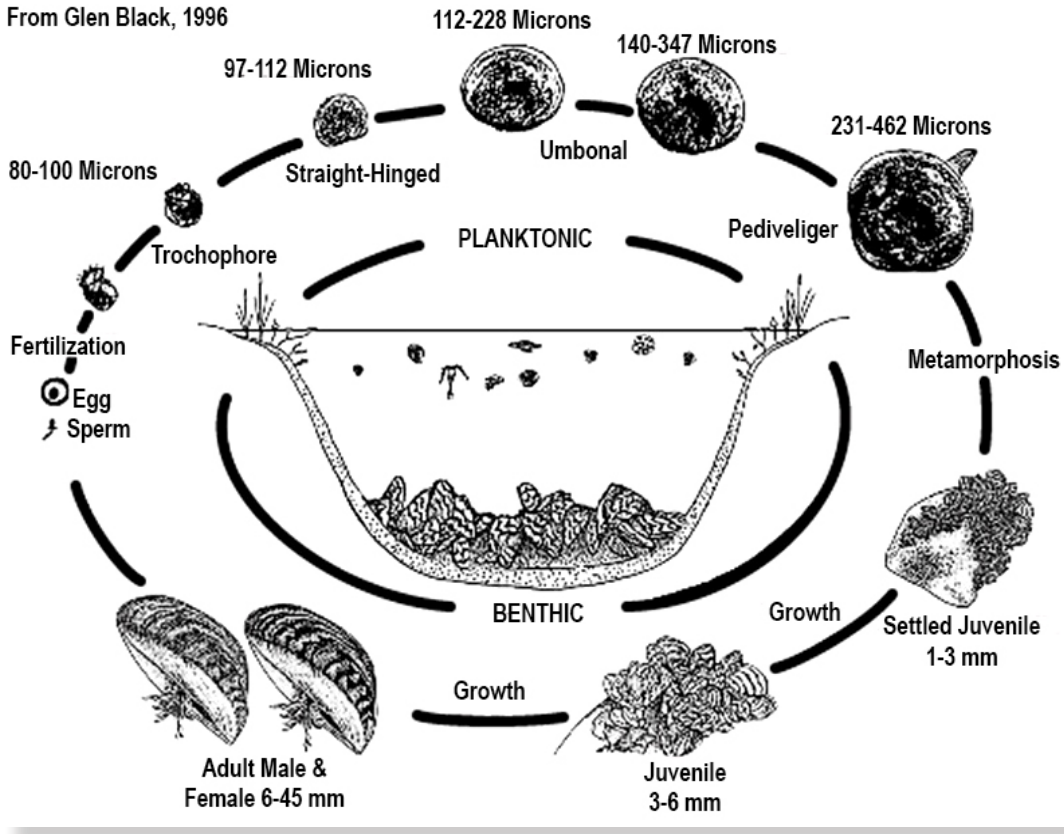


Figure 8 - Dreissenid life cycle

Habitat

Dreissenids are epifaunal, meaning they live upon, or on top of, all types of solid floating logs, break-walls, pipelines, cooling water systems, wet wells, intake structures, hulls of boats and large living invertebrates such as large unionid shells and crayfish.

All other freshwater bivalves are infaunal, meaning they live partially or completely buried in sediments.

Dreissenids are found at varying depths. Quagga mussels have been found as deep as 120 m in Lake Ontario. They tend to be most numerous in the zone below ice formation and above the thermocline (1 to 10 m, or 3 to 33 ft). Densities of up to 100,000/m^2 (9,290/ft^2) have been recorded in many infested areas.

In most areas dreissenids extend their range at a rate of approximately 250 km (155 mi) per year. This may be accomplished by veligers being carried by currents or by adults attached to floating vegetation or wood. The primary way that dreissenid mussels reach unconnected bodies of water is with human assistance. They can be unknowingly transported on the hulls of ships and boats, in ballast water or bait buckets of anglers.

Okanagan Basin
WATER BOARD

RNT CONSULTING INC