Monitoring for Invasive mussels, Zebra mussels (*Dreissena polymorpha*) and Quagga mussels (*Dreissena rostiformis bugensis*) at U.S. Army Corps of Engineers Projects in the Northeastern United States.

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Please note: Our intent is to minimize text within the body of the document where possible. Most details for physiologic parameters and dreissenid control measures along with associated literature citations occur in Tables 1 and 2. Although similar, zebra and quagga mussels do differ in some physiologic requirements. These differences are provided in instances where they are known to occur. Please be aware that more is currently known regarding the physiological requirements of zebra relative to quagga mussels thus the bulk of the parameters measured may be zebra mussel specific.

This is a "living document". Environmental parameters and mussel monitoring sites can be included in appendices with each section given to a specific project location. The monitoring process described here uses a risk-based approach. Prioritized (tiered) environmental measures are used to establish a relative probability that dreissenid mussels may occur within a given system. Such assessments can be used to prioritize areas for dreissenid mussel monitoring. It is important to note that the assessments are not perfect. Dreissenid mussels may occur in areas where environmental conditions suggest that they should not. Additional steps can be taken to reduce the risk of missing areas of potential dreissenid infestation. These steps are simple, prudent, and are described in this document. In general, the described assessment of environmental factors and monitoring for dreissenids does not require extensive specialized training. This document was developed for use by project and district staff so they can take a primary role in assessing dreissenid occurrence risks and in monitoring for the presence of dreissenid life stages at their projects. An example of a simple invasive mussel monitoring program that was established at Cowanesque Lake in PA in 2024 is provided in Appendices 1a and 1b. These appendices detail monitoring techniques and locations established and carried out by U.S. Army Corps of Engineers project and district staff.

Dreissenid mussels (zebra mussels, *Dreissena polymorpha* and quagga mussels, *Dreissena rostiformis bugensis*) are known to occur in water bodies with wide ranging characteristics. However, successful establishment of reproducing populations depends on several key limiting environmental factors listed in Table 1. The top tier factors most predictive for limiting zebra mussel establishment are calcium and related measurements (i.e., hardness, alkalinity), pH, and temperature. Second tier limiting factors that may be important in localized habitats or specific water bodies are water velocity/turbulence, dissolved oxygen, and salinity/conductivity. Third tier factors that have been considered but are unlikely to be limiting in most reservoir and lake systems are nitrogen (ammonia) and productivity.

Predictive studies on the occurrence and establishment of dreissenid mussels most often report mean measurements of water quality and water chemistry variables. Monitoring protocols should account for extreme values, as well as their timing and duration, to explain why mussel populations remain sparse or localized in "high risk" waterbodies or persist in those deemed "low risk". Additional examples of how extreme values may influence risk assessment can be found in Sepulveda et. al. (2025).

Example 1:

A water body with mean pH of 7.8 would be categorized as high risk (see Table 1). However, if the pH decreases below 7.0 for several days and at several time points, especially during the spawning and larval production season, the risk of successful reproduction may be minimal (See Table 1).

Example 2:

A water body with mean calcium concentration of 12 mg/L would be categorized as low risk (see Table 1); however, episodic rainfall or high-water inputs may produce intermittent increases in calcium concentrations. If this increase occurs during the reproductive period, usually summer, the shift may be enough to support veliger development to the juvenile stage (settlement).

In large waterbodies with a complexity of bays, channels and/or multiple inputs, it is important to characterize the variability in microhabitats to identify all potential areas of concern. Once the variability in water chemistry/quality is determined, it can inform selection and prioritization of sampling stations for invasive mussels.

The guidelines in Table 1 are based on a compilation of reports and publications that aim to predict dreissenid mussel distribution and to inform guidelines for monitoring their occurrence in waterbodies across North America.

In general, guidance for dreissenid monitoring programs has three basic considerations: life stage, location, and time. Monitoring may target one or multiple life stages. Locations for sampling can address multiple concerns ranging from threats to infrastructure (blockage), impairments to public use such as sharp-edge mussels cutting waders feet, downstream export of the invasive, and potential source areas providing for possible introductions. Spatial consideration must also include depth since the mussels are not likely to be restricted to a specific point within the water column. Time of sampling, the third sampling consideration, integrates life stages and spatial characteristics as both are likely to shift over the course of a year.

Monitoring Considerations for Dreissenid Mussels

Understanding of the general life cycle of dreissenid mussels will help guide the location and timing of monitoring efforts. Dreissenid mussels are broadcast spawners and release gametes (egg and sperm) into the water column. Spawning of zebra mussels most often begins at ~12 $^\circ$C (~54 $^\circ$F) and quagga mussels as low as 9 ◦C (48 ◦F). Spawning and veliger production will be tied to both temperature and phytoplankton production. Veligers will be present in the water column about 2-3 weeks after the first spawning. Mussels in temperate climates generally exhibit peak veliger production in mid to late July, followed by a lower pulse in August. However, spawning may continue throughout the year if water temperatures remain > 12 ◦C (>54 ◦F) but below 25-28 ◦C (77-82.4 ◦F) at which point conditions for reproduction are no longer favorable.

Juvenile Settlement: The planktonic veliger progresses through three planktonic stages—D-hinge (about 100 µm), umbo (approximately 200 µm), and pediveliger (ranging from 200 to 400 µm)—before settling on the benthos as a plantigrade or juvenile, measuring between 450 µm and 1 mm. Development of veligers to the settled juvenile stage occurs in 1 to 5 weeks, depending on water temperature. Veligers will accumulate in areas with reduced, slackened flow, warmer water, and high phytoplankton density. Wind and water currents can also displace settled juveniles. Settlement rates may decline during high discharge periods and significant differences may occur between dry and wet years. Settlement density and veliger density will generally be correlated. Macrophyte beds can be areas of significant veliger settlement, even when substrate is muck and mud. Juveniles can translocate from macrophyte beds to suitable substrates.

Dreissenid mussels most often reach sexual maturity at one year; however, in climates with early spring spawning, juveniles become mature in the same season.

Veliger monitoring provides evidence of the occurrence and movement of dreissenid planktonic stages in aquatic systems and can also be predictive of future increases or decreases in adult populations. The monitoring of dreissenid settlement and establishment on substrates provides evidence of sustained presence within these systems. The combined monitoring provides the most complete picture of dreissenid mussel occurrence. This complete picture, however, may not be required based on the management question to be addressed. The occurrence and location of settled dreissenid mussels, for example, may be the only concern. In this case monitoring could be limited to settlement and establishment only. If movement of dreissenid mussels into, through, and out of a lake is the only concern than veliger monitoring alone may suffice.

Adults

High risk: > 1 to 7 m depth; water temperature 12-25 ◦C (54-77 ◦F) for reproduction; high chlorophyll concentration, high dissolved oxygen, low discharge, limited wave action. Mussels prefer dark areas with crevices for protection from predators, excessive water flow, UV light, and desiccation. Mussels prefer hard substrate with texture. When native unionid mussels occur in a waterbody, dreissenids are commonly found colonizing their shells.

Low risk: < 0.5 m, > 7 m depth. Cooler water (< 12 ◦C (<54◦F)) (hypolimnion) and high temperature (>27 ◦C >81◦F), low dissolved oxygen, high discharge, turbulent flows and areas of high wave action. Mussels also avoid areas with high UV light penetration and soft sediments with no substrate.

Monitoring Methods

Monitoring guidance has been offered by multiple entities since dreissenid mussels were identified as a significant invasive threat. The Western Regional Panel on Aquatic Nuisance Species has produced guidance for dreissenid mussel monitoring in their publication "Zebra and Quagga Mussel Field

Sampling and Monitoring Protocol". This document was updated in September 2020, and a new update is forthcoming. The Panel provides guidance on both monitoring design and methods for surveys. Monitoring takes place for veligers and adult mussels. Veligers are to be sampled using vertical plankton tows that cover the area from near bottom to surface except in areas too shallow (see page 8 of Protocol for additional details). These are to take place at each of the water quality sampling locations. Surveys for adult mussels will focus on established water quality sampling sites, primary areas of concern as well as locations that could potentially provide refuge for the mussels during the winter months and thus serve as reservoirs for reintroduction. It is recommended that monitoring sites be sampled with settling structures located at multiple depths where possible. The use of plastic structures is recommended over cinderblock to reduce the weight that must be brought to the surface when checking settlement. The use of settlement samplers may also be considered. This will provide information on timing of this critical life stage event. These samplers are fragile and can only be used in areas with little current or turbulence. Timing of sampling is provided in the sampling and monitoring protocol. It's recommended that this guidance be adopted as written when local resources allow. The interval of sampling is flexible but should not exceed once every two weeks if possible. This interval will allow for the capture of recruitment and life stage conversion events.

Other factors to monitor and record:

Date of ice formation and ice out, ice thickness in littoral zone: Zebra mussel populations can be significantly reduced by winter ice scour. The degree of ice scour can be indicative of the expected level of recruitment the following summer. In mild winters with reduced ice cover and increased adult mussel survival, recruitment may also increase. In contrast, when ice cover is extensive, mussel mortality can be high in areas of ice cover and result in reduced recruitment the following summer.

Changes in water level: The magnitude and duration of reservoir drawdown can be an impactful factor in establishment of an invasive mussel population. In waterbodies that have suitable water chemistry and an introduced mussel population the magnitude of change in water surface elevation and duration of drawdown were most important for predicting whether mussels established (Yarnall et al., 2024). Drawdowns of 100 cm on average and with duration of 10-150 d were less likely to have established populations, even when there was a positive detection of quagga mussels. Shorter more frequent (< 5 d) drawdowns were not effective in preventing establishment (Yarnall et al, 2024) as mussels can survive emersion for up to 5 d, depending on air temperature and humidity. (McMahon et al. 1993; Ricciardi et al. 1995). Note that Yarnall et al. (2024) investigated reservoirs with quagga mussels. The ability of zebra mussels to tolerate these conditions has yet to be determined.

Sampling Frequency and sites

Frequency of monitoring depends on seasonal trends in the watershed and the characteristics of the waterbody. To start, sampling frequency would cover a length of time and types of weather that are common in the watershed with the occurrence of temperatures within the growing and reproductive period of the mussels (Table 1) being a good first criterion for bracketing the desired time period. Secondly, sampling sites would cover the spatial extent of the water body (e.g., upstream, downstream, at least one representative site in between, near stream inflows and ground water input). A consistent monitoring scheme is important for documenting long-term changes when feasible.

Calcium/Alkalinity/Hardness

Calcium levels can vary substantially in a water body, with location, depth or time. Water residence time or flushing and terrestrial processes – precipitation, runoff, air temperature, may be the most important determinants of annual variation in water chemistry. If previous monitoring data is available, it can indicate the variability in alkalinity over a season or annually and be used to determine how frequently and at what time periods (e.g., rainfall or high water) to sample. A sound starting point would be monthly sampling during the ice-free season, and once during ice cover. Measure Ca at several sampling points, upstream, downstream, mid-reservoir, near surface water and ground water inputs.

Other Water Quality Factors

pH, conductivity, DO, and water temperature will vary by depth, time of day, season, and site. Initially, to characterize the lake's extent of stratification and changes within the water column, take profile readings conjunction with calcium monitoring. Like Ca monitoring, select enough sampling sites to characterize pH (and other water quality values) upstream, downstream, mid-reservoir, near surface water and ground water inputs.

Awareness

The assessment of relevant environmental variables and the formal monitoring of dreissenid occurrence are central components to effective dreissenid risk-based management programs. Applying the tools, however, will not guarantee that these mussels will not find their way into project reservoirs. It is impossible to account for every contingency. It's always advisable to have supporting plans.

Project staff can be central to the execution of a dreissenid management program. Performing the prescriptive sampling required in the monitoring effort is one role. Equally important is informal monitoring performed by simply being aware of what's happening within those spaces that they visit on a regular basis. Keeping watch for dreissenids appearing in places like dam structures, buoys, or shoreline rocks requires a little extra effort but can provide early detections of dreissenids in areas where the formal monitoring is either absent or uninformative. Formal monitoring will not necessarily identify and contain all the high-risk areas for dreissenid invasion. Looking for the mussels even in unexpected places furthers familiarity with the project in general. Over time, inquisitive individuals can build a knowledge base as where to best look for the dreissenids and share this information expanding awareness both within and between projects. This information in term adds to the overall knowledge base required for adapting monitoring programs to improve overall management effectiveness. Engaged and aware project staff can make the defense against highly damaging dreissenid invasion a reality.

Dreissenid Control

Several methods have been developed for the control of zebra and quagga mussels (see Table 2). These methods can be situation dependent with some more appropriate for infrastructure than open water. This information is provided to create a sense of treatment possibilities for project staff and is in no way intended to be prescriptive. Execution of any treatment plan should be performed with the assistance of those knowledgeable in such actions and familiar with specific project needs.

Table 1. Environmental Parameters Relevant to Dreissenid Monitoring.

(Parameters relevant to zebra mussels with differences noted for quagga mussels where they are known; ZM Zebra Mussels, QM Quagga Mussels)

	Method of measurement	*Frequency of sampling*	*Relative risk of invasive mussel establishment*			*Comments/ considerations*
Factor			*Low risk*	*Medium risk*	*High risk*	
Tier 1						
Dissolved Calcium	Measure by EDTA titration (Method 215.2 USEPA 1983) or Calcium concentration can be determined from hardness, measured as $CaCO_3$ based on molecular weight Dissolved Calcium = Hardness ($CaCO_3$ mg/L) *0.04)	Collect water from representative sites to capture inputs and average concentration. Increase sampling during extreme events (drought, rain events).	ZM < 8 mg/L QM < 12 mg/L (Sepulveda et al., 2025)	ZM 8-20 mg/L QM 12-20 mg/L (Sepulveda et al., 2025) ZM Larval growth possible > 12 mg/L (Baker et al. 1993) QM Veligers able to grow and settle in 12 mg/L water (Davis et al 2015)	ZM > 20 mg/L QM > 20 mg/L (Sepulveda et al., 2025)	Calcium concentration can be impacted by events such as local input from mine drainage, precipitation events, extreme evaporation. Readings in low and medium category are unlikely to occur in the same water body but could occur in localized areas. Calcium concentrations in the low and moderate ranges are more sensitive to how data are summarized thus values such as minimum, maximum, and daily average across sites or time may not accurately reflect risk (Sepulveda et al. 2025). Risks of quagga mussel occurrence may be higher than anticipated when high levels of seston occur in low calcium water (Davis et al. 2015). Collect water from representative sites at multiple time points to capture inputs and average concentration.
pH	Probe and meter Recommend taking measurements directly in the field, not after transport to the lab.	pH can vary significantly diurnally and seasonally Measure pH a minimum of 3 per day (morning, midday, late day) and a depth profile (every 1	ZM < 7.0 or > 9.6 QM < 7.0 or > 9.6 (Sepulveda et al., 2025) ZM Veligers <7.2 (Claudi et al, 2012; Waller et al. 2021)	ZM 7.0–7.3 or 9.4-9.6 QM 7.0–7.3 or 9.4-9.6 (Sepulveda et al., 2025) ZM Juveniles only grow at pH >8.3 (Hincks and Mackie 1997)	ZM >7.3 - <9.6 QM >7.3 - <9.6 (Sepulveda et al., 2025) ZM Veliger settlement >7.3 to 9.4 (Claudi et al. 2012) Waller et al., 2021)	ZM Egg development requires optimal pH (Sprung 1987) Calcium uptake is limited to lower alkaline and lower pH water. pH > 8.5 and high Ca (>25 mg/L) could limit zebra mussels (Hincks and Mackie 1997)

		m) in areas with stratification. Expect higher pH above the thermocline; lower pH below the thermocline at depth where respiration is highest.			ZM Larval growth optimal 8.4-8.5 (Baker et al. 1993)	Consider changes in flows from inflow (e.g., nonpoint sources, mines) that can intermittently influence pH. Monitor these in more detail.
Calcium-pH as Calcite saturation	Saturation Index (SI) calcite can be calculated from calcium concentration (mg/L), water temperature (°C), total alkalinity (mg CaCO3/L), conductivity (µS/cm), and pH (APHA 2018).	Calculate whenever the required variables are measured	ZM <-0.9 (Prescott et al., 2014)	ZM 1.0 (Prescott et al., 2014)	ZM >1.0 (Prescott et al., 2014)	Pair calcium and pH values to account for situations when calcium is moderated by pH (i.e. at the extremes of the calcium and pH ranges). High pH (>7.8) which moderates the low calcium and makes the lake suitable for supporting zebra mussels (Claudi and Prescott 2011; Farr and Payne 2010; Prescott et al. 2014)
Temperature Lower temperature	Multifunction probe.	Measure in conjunction with pH and DO using a multi-probe meter to have a depth and diurnal profile. Use in conjunction with data logger to get time integrated data sets where possible	ZM: 0 ◦C (32 ◦F) lower limit for adult survival (Baker et al. 1993) Mortality occurs within 15 h at -1.5 ˚C (29.3 ◦F; Clarke 1993) Adults < 4 ˚C (39.2 ◦F), (Farr and Payne 2010) 6 ˚C (42.8 ◦F) is lower limit for adult growth (Bij de Vaate 1989). Lower limit for spawning and larval growth is 12 ◦C (53.6	ZM Mean summer temperature of 15 -16 ◦C (59-60.8 ◦F; Doll 1997; Sorba & Wiliamson 1997). Adults show moderate growth at 9 ˚C (48.2 ◦F; Claudi and Mackie 1993)	ZM Spawning begins 10-12 ˚C (50-53.6◦F) Peak spawning 18-25 ˚C (64.4-77 ◦F) Maximum adult growth 10-15 ˚C (50-59 ◦F) Larval growth 12-24◦C (53.6-75.2 ◦F; Baker et al., 1993)	Zebra mussels generally don’t occur below the thermocline (Mackie et al. 1989). Zebra mussel populations have shown temperature adaptation in southern regions and increased thermal tolerance (Morse 2009)

			◦F) for zebra mussels (Baker et al. 1993) and 9 ◦C (48.2 ◦F) for quagga (O'Neill 1996)			
Upper temperature			ZM: 28-32 ◦C (82.4-89.6 ◦F) can kill adults (McMahon 1996) Sustained summer water temperature of 28 ◦C (82.4 ◦F) or above increases risk Massive die-offs may occur above 30 ˚C (86 ◦F)	ZM 25-28 ˚C (77-82.4 ◦F) mussels live but reproduction is not favorable (Baker et al. 1993) though it could still occur at some point during the summer	ZM 18- 25 ˚C (64.4-77 ◦F) Mean summer temperature 16 ◦C (60.8 ◦F; Sorba & Williamson 1997) - Peak spawning 20-25 ˚C (68-77 ◦F) Larval growth < 24 ◦C (75.2 ◦F)	Studies using field conditions suggest that quagga mussels are more tolerant of extreme water temperatures than are zebra mussels (Thorp et al., 2002; Karatayev et al., 2011)
Alkalinity	Titration (APHA 2018)	Can be measured at the same frequency as hardness. Used to calculate calcite saturation index.	Same guidelines as above for Calcium			Correlated with calcium and hardness but also measures other components that contribute to buffering capacity. Alkalinity can buffer changes in pH. Waters with low pH often have low alkalinity.
Tier 2						
Dissolved oxygen	Probe and meter	Measure in conjunction with pH to develop a depth and diurnal profile.	ZM: At 18 ˚C (64.4 ◦F), 1.0 to 1.7 mg/L (Yu and Culver 1999); < 4 mg/L for veliger development (Sprung 1993).	ZM: 40-50% saturation; 4-8 mg/L depending on water temperature (Cohen and Weinstein 1998 a, b)	ZM 80-85% saturation. >8 mg/L (Cohen and Weinstein 1998 a, b)	Percent saturation may be more meaningful since dissolved oxygen threshold is temperature dependent. Lower temperature increases hypoxia threshold (Yu and Culver 1999; Sorba and Williamson 1997). Dissolved oxygen is not likely to limit mussel populations unless hypoxia is extended for weeks to months and the system is very eutrophic.

Water velocity and turbulence	Flow meter	Measure as needed to capture changes in flow patterns. It can be used to predict high risk areas for settlement and then prioritize monitoring sites. Can also be manipulated to limit larval settlement.				Hasler et al. reviewed the effects of hydrodynamics on a variety of dreissenid life history characteristics (2019). Although mostly qualitative, this review does provide a good perspective on the breadth of possible impacts
Conductivity	Probe and meter	Measure in conjunction with pH, DO, and temperature using a multi-probe meter. Conductivity can be used for calculation of salinity. Conductivity is used in calculation of calcite saturation index.	ZM: <22-36 µS/cm (Sorba and Williamson 1997)	ZM: 37-82 µS/cm (Sorba and Williamson 1997	ZM: ≥83 µS/cm (Sorba and Williamson 1997	Dreissenids are not tolerant of low conductivity water (low Ca, Mg, Na, K; Dietz et al. 1994)
Salinity	Can be measured or calculated from specific conductance as practical salinity units (PSU; ~ equal to ppt) PSU (ppt) = Conductivity (mS/cm)$^{1.0878}$) x 4665.	Same frequency as conductance measurements.	Adults ZM: > 5 ppt (Spidle and Miles 1995; McGarrity and McMahon 2024) Veligers >4 ppt (Wright et al., 1996)	ZM: 4-5 ppt adults (McGarrity and McMahon 2024)	ZM: < 2-4 ppt (McGarrity and McMahon 2024)	Salinity tolerance decreases with temperature (18-20 ◦C; 64.4-68 ◦F). Note that zebra mussels can acclimate to slowly changing salinities (Kilgour et al. 1994). Adults survived up to 12% salinity (Mackie & Schloesser 1996)
Tier 3						

Productivity as chlorophyll and/or Secchi disk	Chlorophyll a – measure by fluorometric methods (USEPEA 2013) Secchi depth is measured by taking the average of two readings.	Measurements will vary daily and diurnally. Secchi disk measures may be taken daily at multiple points of interest. Chlorophyll a measurement may be limited to weekly/biweekly at select locations on interest.	ZM 10-20 cm or 200-250 cm Secchi disk (Sorba and Williamson 1997)	ZM: 20-40 cm Secchi disk (Sorba and Williamson 1997)	ZM: 40-200 cm Secchi disk (Sorba and Williamson 1997)	Productivity is not expected to be limited in most systems with favorable water chemistry, temperature, and depth. Productivity measurement may be useful for explaining declines in zebra mussel population. Zebra mussels reduce phytoplankton stocks and as productivity declines, mussel population density can decline.
Ammonia (unionized ammonia)	Nitrogen-ammonia, Salicylate TNT method using spectrophotometer (Hach method DOC316.53.01079)	Concentrate sampling in areas of suspected organic inputs (agriculture, WWTP) and high organic decomposition. Measure weekly during summer peak water temperatures.	[a]Acute 96 h EC50s 1.5 to 8.0 mg N/L (Wang et al. 2017) 4 d < 6 mg N/L (Wang et al. 2017)	Chronic 1.9 mg N/L 1.67 mg N/L 28 d survival of juvenile mussels (Wang et al. 2017)	< 1.5 mg N/L Optimal <0.08 mg N/L (Wang et al. 2017)	[a]Threshold levels are derived in part from values reported for unionid mussels (Wang et al. 2017). Sources in water are agriculture inputs from fertilizers, industrial inputs, municipal effluent, decomposition of organic waste. Unionized ammonia, the more toxic form, becomes a higher fraction of total ammonia as pH increases. As pH and temperature increase mussels are more sensitive to ammonia.

Table 2. Dreissenid mussel control methods.

Control Group	Specific Control	Notes
Physical	pH	pH can be manipulated to prevent veliger settlement, cause mussel detachment, and kill adult mussels. Low pH: Phosphoric acid, acetic acid, citric acid, and Carbon dioxide can be used to reduce pH. Near or below a pH of 7 adult mortality is observed, settlement stops, and calcium is lost from shells (Claudi et al. 2012). Veliger settlement is prevented at pH ≤ 7.3 (Claudi et al. 2012a; Waller et al., 2021; Barbour et al., 2025). High pH: Sodium hydroxide or lime (calcium oxide) can be used to increase pH. Veliger settlement is prevented at pH 8.9 to 9.1. Adult mussels are more tolerant and require higher pH and long exposure duration (Claudi et al., 2012b). At pH 12, adult quagga mussels experienced 99% mortality after ~ 31 h (Barenberg and Moffitt 2018).
	Flow rates/Turbulence	Relatively high flow rates tend to negatively impact every aspect of dreissenid mussel life (Caludi et al. 2011; Horvath and Crane 2010). High turbulence can be used to reduce veliger settlement, but the rate is situation dependent. Veliger mortality is a function of size, and turbulence intensity and duration (Kozarek et al., 2018). Air bubble curtains can reduce biofouling of stationary structures (Scardino et al., 2009; Ibrahim et al., 2025)
	Electrified Fields	Pulsed direct current kills adult zebra mussels with mortality increasing with increased water temperature and duration of pulse application. The shell is a poor conductor of electricity. Use of electrified fields to kill adults is impractical in most situations (Luoma et al. 2017).
	Desiccation/Emersion	Water drawdowns combined with subfreezing temperatures resulted in a dreissenid mussel mass mortality event (Leuven et al. 2014; CPW 2023). Dewatering is most effective and rapid at air temperatures > 25 ◦C (77 ◦F) and < 0 ◦C (32 ◦F). Above 25 ◦C (77 ◦F), relative humidity has minimal effect on mortality; however, at cooler air temperatures the time to mortality increases significantly with greater relative humidity. Dreissenids do not tolerate air temperatures below freezing. Complete mortality can be achieved in 24 h at -3.0 ◦C (26.6 ◦F) and in 2 h at -10 ◦C (14 ◦F). Note that clustered mussels are more tolerant of freezing than individual mussels (McMahon et al., 1993).
	Ultraviolet Light	Larval quagga mussels are killed by Germicidal ultraviolet-C (Stewart-Malone et al. 2015) and Hydro-optic ultraviolet (HOD) light systems (Pucherelli et al. 2018). HOD UV systems are in use in Bureau of Reclamation hydropower facilities at Hoover Dam, Davis Dam, Parker Dam (Pucherelli et al., 2021) on cooling water systems to prevent veliger settlement. UV treatment also reduces biofouling by other organisms (e.g., bacteria, sponge). When complete veliger mortality is desired, higher UV doses are needed. Note that the effectiveness of UV decreases in turbid water and treatments should be tailored to the specific facility and water chemistry.

	Gas Impermeable Benthic Barrier	Prolonged (30 days or longer) placement of polyvinyl chloride barrier on lake bottom can eradicate localized bivalve populations (Kunze 2023; Conry et al. 2024; Wittman et al., 2012). The size of treatment areas treated with benthic mats ranges from 100 m^2 to 3900 m^2. The duration of benthic mat placement has ranged from 30 days to 5 months. The effectiveness of the treatment is dependent on sealing the mat to the substrate and preventing influx of freshwater underneath.
Chemical	Potassium Chloride	Potassium chloride is effective on all life stages of dreissenids. Potassium chloride (potash) will kill dreissenid veligers in 24 h at concentrations of 960 mg/L (Moffitt et al. 2016). Longer exposure (10 days) to 200 mg/L is lethal to juvenile mussels. Potash was applied at 100 mg/L to eradicate zebra mussels from a quarry (Fernald and Watson 2014) and in response to a new infestation in a northern lake (Lund et al., 2017). The toxicity of potassium chloride is reduced in high conductivity waters (Moffitt et al. 2016) and in cool water (10 ◦C; 50 ◦F) (Booth and Ayres 2024). Note, potassium chloride is relatively safe to many aquatic organisms, except for native mussels, but levels will remain high in a water body for an extended period after treatment. Potash is not a registered pesticide and requires a Section 18 Pesticide Emergency Exemption from the US Environmental Protection Agency. Efforts are underway to register potash as a molluscicide for dreissenid mussel control.
	Carbon Dioxide	Carbon dioxide can prevent veliger settlement, cause mussel detachment, and kill all mussel life stages. Carbon dioxide will prevent veliger settlement when applied at ~30 mg/L (equal to pH 7.0) (Barbour et al., 2025; Waller et al., 2021). Short term treatment (5-10 d) with 100 mg/L CO_2 (equal to ~ pH 6.5) at < 20 ◦C (68 ◦F) selectively kills adult zebra mussels while doing little harm to unionid mussels (Waller et al. 2020). Elevated CO_2 levels effective at reducing biofouling are tolerated by most freshwater benthic taxa but extended periods (10 weeks) of 100 mg/L CO_2 can alter the macroinvertebrate community structure and negatively impact juvenile native mussels (Waller et al. 2021). The efficacy of CO_2 is dependent on sodium concentration of the water source (Barbour et al 2024). In an open water application, CO_2 injected under a benthic barrier for 4-5 days killed >90% mortality of dreissenid mussels (Waller et al., 2025, in preparation and personal communication). Carbon dioxide is registered as Carbon Dioxide-Carp by the USEPA for use as a piscicide and fish deterrent and efforts are underway to extend the label to dreissenid mussels. CO_2 is currently used in open water with an experimental use exemption.
	Copper	Copper is the most common treatment for open water reduction of zebra mussels. Copper-based products registered for use as molluscicides include EarthTec QZ™ and Natrix™. The

		label allows maximum treatment of 1 mg/L as Cu+. EarthTec QZ is an acid-stabilized ionic formulation and Natrix is a chelated copper formulation. The choice of copper product will depend on water chemistry of the water body. At very low dose (µg/L as Cu+) copper products can prevent settlement in raw water lines (e.g., ACOE Gavins Point Hydropower facility, South Dakota). Low dose treatment of 50-80 µg/L in open water can reduce veliger populations and recruitment when applied during peak reproductive periods (Barbour et al., in press). Treatments targeting adults are effective at ≥ 250 µg/L when applied in mid-summer and/or at peak water temperature (Hammond and Ferris 2019). Quagga and zebra mussels exhibit differential sensitivity to copper with zebra mussels exhibiting relatively high resistance to toxic effects. (Claudi et al 2023). Copper is toxic to most aquatic organisms and can accumulate in sediment and non-target organisms. Nontarget mortality can be reduced by applying the minimum effective concentration and refining treatment levels for the chemistry of the water body (Dahlberg et al., in press; Dahlberg et al., 2025)
	Combination Treatment	The use of anti-molluscicides Clam-Trol CT-2 and niclosamide have synergistic effects potentially reducing the quantity of toxicant required to achieve effective control (Barbour et al. 2021)
Chemical/Physical Synergism	Hardness/ Specific Conductance & Temperature	Temperature impacts Earth Tec QZ® and potassium chloride treatment efficacy in high conductivity waters with mortality increased at higher temperatures (Booth and Ayres 2024). Generally, dreissenids are more sensitive and experience greater mortality when control agents are applied during periods of warmer water temperatures (e.g., mid-summer) (Luoma et al., Waller et al., 2020). Mussels may also be more sensitive after spawning (Barbour et al., in preparation). Chemical treatment applied when water temperature is <15 ◦C (59 ◦F) are less effective at causing adult dreissenid mortality.
Biological	*Pseudomonas fluorescens* strain CL145A (Zequanox)	Exposure to live or dead *Pseudomonas fluorescens* strain CL145A kills dreissenid mussels by causing lysis and necrosis of the digestive gland and disruption of the stomach epithelium (Malloy et al. 2013). This bacterial strain is the active ingredient in the molluscicide Zequanox® . The registration label allows maximum treatment at 200 mg/L as Zequanox for 8 hours. The active ingredient degrades within 24 h and does not persist in the environment. The active ingredient is relatively safe to other aquatic organisms (Waller et al., 2016, and others), with the exception of some fish species (Luoma et al., 2018; Waller and Luoma, 2017; Waller et al., 2016; Luoma et al., 2015)
	Predation	Fish species that consume dreissenids include redear sunfish (*Lepomis microlophus*)(Wong et al. 2013), freshwater drum (*Aplodinotus grunniens*), pumpkinseed (*Lepomis gibbosus*), yellow perch (*Perca flavescens*), rock bass (*Ambloplities rupestris*) (Watzin et al., 2008) and round goby (*Neogobius melanostomus*)(Naddafi and Rudstam 2014). Zebra mussels can comprise a significant part of the diet for pumpkinseed and

		freshwater drum (Watzin et al., 2008) as both species have pharyngeal teeth to crush the mussel shell. Round goby predation has maintained low quagga mussel densities in areas where control actions have occurred (Naddafi and Rudstam 2014; Bootsma personal communication)

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Appendices

Appendix 1a. Cowanesque Lake Monitoring Sites

Station	Description	Latitude	Longitude	Sample Types
COW10001	Tailwater (WQ)	41.988389	-77.147387	Water Quality[1], Adult on Rocks[4]
COW10010	Inflow (WQ)	41.976222	-77.250222	Water Quality[1], Adult on Rocks[4]
COW20002	Forebay (WQ)	41.982722	-77.154194	Water Quality[1], Veliger[2], Adult[3]
COW2002A	Dam Tower	41.983548	-77.150954	Water Quality[1], Veliger[2], Adult[3], Dam Tower[4]
COW2002B	Dam Shoreline	41.986859	-77.153483	Adult shoreline rocks[4]
COW2004A	Lawrence	41.97943	-77.174000	Water Quality[1], Veliger[2], Adult[3]
COW2005A	Tompkins Shoreline	41.98041	-77.18263	Water Quality[1], Adult[3,] Adult shoreline rocks[4]
COW2006A	Rt. 49 Bridge (WQ)	41.97023,	-77.19145	Water Quality[1], Veliger[2], Adult[3]
COW2007A	South Shore Shoreline	41.97476	-77.20001	Water Quality[1], Adult[3,] Adult shoreline rocks[4]
COW20009	(WQ)	41.974139	-77.223722	Water Quality[1], Adult[3]

[3]Quantitative defined area counts

[4]Qualitative presence/absence on structure (man-made or natural)

Appendix 1b. Cowanesque Lake Monitoring Locations