Prevention and Control of Zebra Mussels; Proactive and Reactive Strategies

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Abstract

Most plant people would agree that having zebra mussels in any raw water system is not desirable. System blockage, loss of heat transfer and other associated safety hazards are not pleasant to deal with. Therefore most industries strive to minimise the effect of infestation. Opinions differ as to how to do this most efficiently and economically. Some facilities are committed to preventing the settlement of veligers in their piping systems and on some of the external structures they consider critical. This is the proactive approach. Others allow settlement and only treat the system or surface after fouling has occurred. This is the reactive approach. Which is the best and most economical treatment will depend on the individual facility and sometimes on the individual system.

The paper examines the different proactive and reactive strategies available to-date and how they are being used. It will also discuss some of the criteria for choosing a proactive vs. reactive approach and why the decision has to be made individually by each facility.

Introduction

The zebra mussels are small, byssate (meaning they have a holdfast) bivalves. They are native to the drainage basin of the Black, Caspian and Aral Seas. They were introduced into several European freshwater ports during the late 1700s, when industrial revolution resulted in canal building and much increased commerce throughout Europe. Within 150 years of its introduction, the zebra mussels were found throughout European inland waterways and eventually found their way to the British Isles.

Although the actual pathway of the mussel's introduction into North America is uncertain, it is believed that ships originating in an European freshwater port carried the mussel in the freshwater ballast which was then discharged in Lake St.Clair sometime in 1986. Lake St.Clair is part of the Great Lakes system, which is the world's largest body of fresh water. Unregulated ballast water discharge associated with commercial ship traffic in the Great Lakes has been implicated in the successful introduction of several other species during the 1980s. Species such as the spiny waterflea, river ruffe, the tube-nosed goby and the round goby.

The first confirmed sighting of zebra mussels in the western basin of Lake Erie was in July 1988. By August of 1989, mussels were found near Port Dover which is in the eastern basin of Lake Erie. By September 1991, the mussels were reported in all five of the Great Lakes and their connecting waterways, by 1993 they invaded the Hudson River and Mississippi drainage basins.

Although the mussels have not yet crossed the continental divide, all indications are that they will ultimately infest most areas of North America south of central Canada and north of the Florida Panhandle. This projection is based on the thermal tolerance limits currently observed in the Great Lakes Basin. It is possible that the observed genetic variation will allow greater extension of the range than anticipated, both to the north and to the south.

The reason for the phenomenal expansion of the zebra mussel range lies in the biology of the organism. During the life cycle, the first three to four weeks of life are spent as free living larvae called veligers. Female mussels can produce up to a million eggs in two years, therefore there tends to be high concentration of veligers in the water column during the breeding season. The free swimming stage allows for wide dispersal of the organism both through natural means, such as currents and through human assisted dispersal (bait buckets, live wells etc.)

Once the veliger settles, it attaches to the substrate by means of byssal threads and undergoes metamorphosis to an adult. The adult zebra mussels have a byssal bundle composed of up to 200 byssal threads. Each thread is terminated in a sticky pad with which they can cling to all firm substrates. However, the byssal threads can be broken and the adult mussel can translocate, almost at will. This allows for human assisted dispersal on hulls of boats and ships.

Impacts on Industry

Once the zebra mussels have reached a new area and provided the environmental factors are suitable, they rapidly impact both the ecosystem and the various users of water. The mussels will not thrive in areas where the pH is below about 7.2 and calcium levels are below 12mg/l. Also, up to now, the zebra mussels require temperature around 15C to release gametes and 48hours at temperatures above 32C will result in high mortality of adults. Otherwise, they can tolerate starvation for extended periods, highly variable dissolved oxygen levels, desiccation for several days and even some freezing.

For industries which use raw water from the lakes and rivers the zebra mussel infestation is particularly troublesome. The most obvious impact is the fouling of external surfaces exposed to raw lake water. Each year, new crop will settle on top of the established colony, sometimes resulting in layers many inches in depth. In the case of intake cribs or trash bars, this can present a serious problem as water supply can be cut off if infestation is allowed to proceed unchecked. On other structures such infestation can be regarded as merely a nuisance.

Internal Blockage of industrial piping occurs through two major processes. In one instance, the ready to settle veligers penetrate into the piping and if the flow in the pipe is less than 2m/s, they may settle. As zebra mussels grow very rapidly (up to 1mm per week), small diameter pipe may begin to loose flow quite soon after infestation. The other mechanism of blockage is when large clumps of mussels break off from the external surfaces and are transported into the piping system. The clump will move along till it reaches small diameter piping or a small orifice. There it may become wedged, block flow and increase accumulation of sediment. At this point it does not matter if the animals are alive or dead, the clump will become a permanent obstruction until physically removed.

As is the case with macrofouling bivalves in the marine environment, colonization of substrate by zebra mussels seems to lead to an increased potential for corrosion. Heavy accumulation of zebra mussel shells and the high organic content of the faeces and pseudofaeces they deposit may result in anaerobic conditions at the surface of the substrate. This may encourage growth of anaerobic bacteria, such as sulphate reducing bacteria, which have been implicated in Microbiologically Influenced Corrosion or MIC.

Even in the absence of these bacteria, lack of oxygen underneath the mussel colonies and at the points of attachment may set up a differential oxygen cells resulting in underdeposit localized corrosion.

MITIGATION

Having zebra mussels in any raw water system is not desirable and most industries strive to minimize the effect infestation. Opinions differ as to how to do this most efficiently and economically. Some facilities are committed to preventing the settlement of veligers in their piping systems and on some of the external structures they consider critical. This is the proactive approach. Others allow settlement and only treat the system or surface after fouling has occurred. This is the reactive approach. Which is the best and most economical treatment will depend on the individual facility.

The operators must ask themselves;

"can we operate with zebra mussels present in each of our raw water systems and on our external structures"?

To answer this properly, they need to examine all areas of the facility which are in contact with raw water and ask themselves the following questions;

* Can the raw water system tolerate zebra mussel shells without loosing flow?
* How much additional mechanical maintenance will be required if the shells are present on structures or in the system?
* Is there a safety issue? For example portions of the fire protection system such as nozzles and sprinklers can be easily plugged by just a few shells.
* Are there regulatory issues that would prohibit the presence of shells in some systems?

If zebra mussel shells that are likely to accumulate in one or two seasons pose no particular threat, than the facility is a good candidate for some form of reactive treatment. In other words, all that is required is a method of mitigation which kills established adult zebra mussels as quickly and efficiently as possible, with minimal negative impact on the facility or the environment. This seems to be the route used by most European facilities, primarily because the numbers of zebra mussels settling in one year are much lower than those observed settling in the Great Lakes. However, reactive treatments have also been used successfully in North America, provided that the targeted system can tolerate one season's worth of zebra mussel fouling and that the biomass and shells present can be removed from the system after the treatment.

Table 1 lists the most frequently used reactive treatment methods.

Methods for External Surfaces	Methods for Internal Piping
Thermal Shock (i.e.Steam sparging)	Thermal Shock (i.e. Flushing with hot water)
Mechanical Cleaning	Mechanical Cleaning (large diameter pipes only)
Dewatering and Desiccation	Dewatering and Desiccation

Dewatering and Freezing	Oxygen Deprivation
	Non-oxidizing chemicals
	Oxidizing Chemicals

If on the other hand it is clear that zebra mussel shells in some or all systems can't be tolerated or that they may result unacceptable mechanical maintenance burden, proactive method of treatment is required. The primary target in this case is the zebra mussel larvae (the veliger), but the treatment also has to prevent the settlement of translocating adults. This can be accomplished either by denying access (i.e. filtration) or by creating hostile environment where settlement is unlikely or if it occurs, life is not viable (chemical treatment).

Table 2 lists the most commonly used or proposed (marked with Asterisk) proactive methods.

Methods for External Surfaces	Methods for Internal Piping
	Sand/Media Filtration
Antifouling Coatings	Mechanical Small Pore Filters
Electrolytic Protection	Use of Low Pressure or Medium Pressure UV*
Acoustics*	Acoustics*
	Non-oxidizing chemicals*
	Oxidizing Chemicals

Having decided on a proactive or reactive approach or perhaps on a combination of approaches, one has to choose a specific method among those available. Only general descriptions of various methods are given as it is not within the scope of this paper to deal in detail with individual treatment strategies.

Chemical Treatment

The treatment of choice for internal system in most facilities tends to be based on chemical control. This has been the common practice in Europe and so far it has been the case in North America. This is likely to change as the environmental constraints on release of chemicals into natural water bodies continue to increase.

The advantage offered by most chemical treatments is that they can be engineered to protect most of the facility, sometimes from intake to discharge. The disadvantage is in limiting the discharge of toxic materials to the environment and meeting environmental regulations.

There are any number of chemicals which will cause mortality in a zebra mussel population. Even table salt, if applied in sufficiently high concentration, for long enough will be effective. The aim however is to choose chemicals that have minimal impact on the environment while achieving swift kill or preventing settlement of zebra mussels.
Chemicals used are basically grouped into two categories, oxidizing and non-oxidizing.

Oxidizing Chemicals

Oxidizing chemicals have been used in the water treatment industry for disinfection since the late 1800's. For the most part their effect on the environment is understood and documented. The primary chemicals used for zebra mussel control are chlorine (as gas, liquid sodium hypochlorite or powdered calcium hypochlorite), chlorine dioxide, chloramines, ozone, bromine and potassium permanganate. These chemicals all have a similar mode of action. For preventative treatment, they have to be added to the system throughout the breeding season at level ranging from 0.1 to 0.5ppm Total Residual Oxidant (TRO). This does not result in acute mortalities of zebra mussel veligers and translocator, but it does prevent settling. The exact method of action is much debated. Most likely scenario is that veligers sense the presence of a noxious substance, close their shells and either pass through the system or fall to the bottom of the pipe and die either through suffocation in the sediment or the long term toxic effect of the oxidant.

In a reactive mode, 0.5 to 1.0ppm TRO is required continuously for two to four weeks to eliminate established adult colonies. The exact level of oxidant and length of addition depends on ambient temperature, water chemistry and physiological state of the zebra mussels. For example, post spawning, the mussels tend to be more susceptible to treatment than prior to gamete discharge.

Although successful, to use oxidants in a reactive mode is probably not the best use of chemical control. The reason is that when zebra mussels are presented with acute adverse conditions, the animals will close their shell and remain closed for up to two weeks (depending on ambient conditions and physiological state) before having to reopen.

Chlorination is one of the most effective and popular methods of biofouling control. There are several ways that chlorine is used at Ontario Hydro to prevent infestation of systems. These range from proactive, a continuous application at 0.3ppm during the breeding season to reactive end of season treatment at 2ppm for two or three weeks. No matter which regime is used, all Ontario Hydro facilities using chlorine for zebra mussel control are subject to a limit of ≤ 10 μg/L (ppb) for their common discharge streams. This limit can usually be met by the dilution and the intrinsic chlorine demand of the unchlorinated condenser cooling water. Several of our multi unit facilities experienced difficulties meeting this goal when chlorinating continuously. We were able to resolve their problem by developing a semi-continuous chlorination regime. This consists of rapid on-off cycling of the chlorine addition, with a peak of 15 or 30 minutes duration (at 0.5 mg/L TRC), followed by an "off" period of 30, 45 or 90 minutes. The concept is based on an observed response where the mussels rapidly close their shell when exposed to chlorine, and only re-open the valves very slowly. While the animals have the shell closed, chlorine is not having any effect and could be used elsewhere. Multi-unit or multi-system facilities such as ours can re-direct the chlorine, following the initial addition, to another system and still mimic continuous chlorination. At the same time, the total residual oxidant loading is significantly reduced. Staggered semi-continuous chlorination at multi-unit stations can also reduce the peak TRC levels in the discharge by a factor of ≥2. This has allowed several of our sites to meet their environmental regulation.

Bromine acts much like chlorine, but it has been shown as a more effective oxidizing agent when water pH levels are greater than 8.0. Bromine has been used as a water treatment chemical by itself and in several proprietary compounds. Just like chlorine, it is acutely toxic to aquatic life and it forms toxic brominated compounds such as bromoform.

Chlorine dioxide is another popular water treatment and bleaching chemical. It has to be manufactured on site from precursors of sodium chlorite, sodium hypochlorite and hypochloric acid. It has been shown as an effective reactive control agent for zebra mussels. It has not been applied in a proactive manner at this time.

Chloramines are formed when free available chlorine reacts with nitrogen containing compounds such as ammonia and amino acids. Again, it is made on-site by co-injection of either ammonium gas or ammonium hydroxide and sodium hypochlorite. It is used in some water treatment plant applications as a proactive treatment strategy.

Ozone is a well known bactericidal agent in the sewage treatment and water treatment industry. Viruses and bacteria are completely removed within a thirty second contact time by a dissolved ozone residual of less than 0.5mg/L. Ozone also improves taste, odour and colour of drinking water. Ozone can also be used to prevent other forms of biofouling. Concentrations of 0.25 to 0.5 ppm have been reported to eliminate the blue mussel (Mytilus) in some European studies. In preliminary studies done for Ontario Hydro 0.5mg/L of dissolved ozone residual was required to achieve 94% mortality of adults in 24 hours at 20°C. In a study done by Niagara Mohawk on the effects of ozone on veligers, preliminary results indicate that 0.2mg/L of ozone resulted in 98% inactivation of the veligers.

Potassium Permanganate is another oxidizing chemical commonly used in municipal facilities for water purification. It has been used as a proactive zebra mussel treatment by several drinking water plants in the U.S.

Non-oxidizing Chemicals

There is a number of non-oxidizing chemicals, most of them proprietary formulations, that have been developed to control algae, bacteria and in some cases macrofoulers such as zebra mussels. Their mode of action does not rely on their ability to oxidize organic matter as is the case with oxidizing chemicals, the actual mode of action can be very diverse in this group and sometimes not well understood. In most instances, these chemicals are not recognized as noxious substances by the zebra mussels. This means that the animals keep their shell open and continue to filter. In a reactive treatment, this offers a great advantage as the kill can be accomplished sometime in hours as opposed to weeks. The most commonly used non-oxidizing chemicals are proprietary molluscicides (i.e. Clam-Trol from Betz, Bulab from Buckmann Laboratories, H130 and Veligon from Calgon and Mexel). Most of these product require detoxification prior to release. The exact amounts required vary from vendor to vendor and also depend on ambient temperature and health of the mussels. Todate, only Mexel has been used in a proactive treatments. Other non-oxidizing chemicals that have been tested on a small scale include ammonium nitrate and a variety of potassium salts.

Nonchemical Proactive Methods

Antifouling Coatings - In 1989, many coating manufacturers made claims on the abilities of their products to prevent zebra mussels from settling on critical surfaces. Most of these claims were made based on the performance of the coating in the marine environment, some were made based solely on hope. However, a small number of commercially available antifouling and foul-release coatings were found to resist zebra mussel fouling. Antifouling coatings prevent mussel attachment due to chemical properties of the coating surface (eg copper) while foul-release coatings prevent biofouling due to surface physical properties. Products that demonstrated the longest-term fouling resistance, durability, and cost-effectiveness are usually low surface tension silicones or copper rich coatings. These have been recommended for application to external structures that are susceptible to mussel fouling and amenable to coating, such as bar racks, pumpwells, and screenwells in generating stations.

Electrolytic Protection is another proactive method for control of zebra mussels on external surfaces (both concrete and steel). It involves a variation of cathodic protection normally applied to such surfaces as protection against corrosion. Electric current densities in the range of 15 to 20 mA/ft^2 are created on the surface to be protected. For steel, the surface to be protected becomes a cathode. Concrete surfaces to be protected are covered in a closely adhering titanium mesh, which when energized acts as an anode. It appears that zebra mussel do not settle within the electric field created. Electrolytic protection compares favourably to most coatings in price and it is thought to remain effective much longer. There are several pilot installations in place on the Great Lakes.

Acoustic control was investigated numerous times during the last decade. Experiments completed in the early 90's showed that exposure of juvenile zebra mussels (1 to 5 mm) to acoustic energy in an metallic structure could prevent attachment and result in mortality primarily by inducing structural vibrations at sonic frequencies (insonification),Kowalewski *et. al.* 1991. Larger sized mussels were found to be more resilient but there was evidence that their ability to migrate onto insonified structures was inhibited. Exposure to water-borne sound pressure appeared to affect smaller sized mussels by causing structural damage to their tissues.
There is proof of principle that shockwaves of sound or pressure could be used to protect both external surfaces and internal piping. There exist several pilot installations using variation of "acoustic" control.

Infiltration Galeries and Sand Filters - there are many examples of intakes that employ some type of prefiltration through granular media. Unfortunately most of these intakes are in Europe and very few designs if any could be retrofitted to existing intakes. For new installations, where the volume of water drawn in is not too great, this type of technology offers total protection from zebra mussels, other macrofoulers, debris as well as much improved quality of water coming in. There is increased interest in this technology in North America and we may see more intakes of this type in the future.

Mechanical Filtration - there are existing, commercially available filters with very fine screens (40 micron absolute) and self-cleaning capabilities. Several of these filters have been extremely

successful in removing all zebra mussel post-veligers as well as removing significant quantities of sediment from the raw water from small and medium sized systems (10 to 35cm pipes). Based on the relatively long-term testing of mechanical filters, it can be concluded that filtration is an excellent proactive method for controlling zebra mussels in raw water systems.
A significant advantage that has emerged by using filters is that both silt, algae and other organisms are also removed. This provides significant savings in downstream maintenance time (ie. coolers, bearings, seals, etc).
Further modifications aimed at improving the longevity and efficiency of the filters are desirable, but the bulk of future work will have to concentrate on developing/testing this type of filter on a large service water duct (70 to 80cm).

Ultraviolet (UV) Light - is commonly applied in a number of industries for sterilization of air or process water. UV has also become a popular disinfecting agent for potable water and recreational pools on a small scale. More recently, the ability of some of the equipment to treat large volumes of water have led to the promotion of UV disinfection at Municipal Water Treatment Plants. Over 500 systems are in place and UV has become accepted as a viable alternative technology to chlorination. Both low pressure and medium pressure UV lamps have been shown to prevent primary settlement. Potential exists that this method could immediately replace chlorine in some systems as many commercial UV units exist. One major drawback of this technology is that water quality can significantly limit the effectiveness of UV. Water that is loaded with particulate material is hard to penetrate by any wavelength of light, especially UV. Thus in turbid waters, stirred up by a storm for example, UV might not offer a reliable treatment unless powerful lamps are used.

Non-chemical Reactive Methods

Thermal Shock - thermal wash or flushing as well as steam cleaning of dewatered surface have been proven very effective in killing zebra mussels. So has the recirculation of hot water through piping. Periodic thermal backwash appears feasible for some facilities and systems as a reactive treatment. How much heat and for how long is a question of some debate. 32°C for forty eight hours has been recorded as lethal. So has 40°C for one hour. In between lies a grey area where the exact temperature and time to death is dependent on several factors. One is the acclimation temperature of the mussels, i.e. what is the ambient temperature of the water. The lower the acclimation temperature, the more susceptible the mussels are. Second factor is the rate of temperature increase. If the rate of increase is very gradual, the mussels will acclimate during the process and survive longer at higher temperature. The last factor is the possible genetic variation in local populations. It is possible that zebra mussels from one area may be more temperature tolerant than mussels in another area.
There are problems associated with using thermal shock. Regulations governing discharge of heated water have to be taken into account. Plants that do not possess the capability to recirculate hot water are not likely to be able to retrofit except for small systems. As plants have to be either taken off-line or production curtailed during thermal treatment, the cost of treatment tends to be quite high.

Desiccation - exposure to dry air can be a viable reactive method in some circumstances. This process would involve the draining of systems and subjecting the mussels to desiccation. Unless the process is speeded up by the use of hot, dry air circulating in the pipes, a prolonged shutdown may be required because mussels can survive for about two weeks in a cool, moist environment. However, at 22° C, zebra mussels survived only four days in relatively dry air.

Freezing - under low temperatures, mussels are quickly killed by freezing when systems are dewatered. At - 3°C, most mussels are killed in less than 10 hours. In northern climates this may be a more convenient and quicker reactive technique than desiccation, particularly for seasonally dewatered structures such as locks and canals.

Oxygen Deprivation - could be accomplished by adding an oxygen scavenging chemical into a closed system. This method would require a prolonged shutdown, as zebra mussels seem to be able to survive up to two weeks with shell closed when the ambient temperatures are low enough.

Mechanical Cleaning - a variety of mechanical methods, both underwater and above, can be used to remove zebra mussel populations from external surfaces and large diameter pipes. Scrapers and brushes of every description, some attached to vacuum hoses, have been used for cleaning. High and low volume water washes have also been used with varying success. Mechanical "pigs" or scrubbers have been deployed in large diameter piping systems. Whatever the method of removal, in most cases the shell debris has to be collected and disposed of, usually in a landfill site. Periodically there are concerns about zebra mussels bioaccumulating pollutants to such high levels that they will have to be disposed of in hazardous landfill sites. So far, although mussels do bioaccumulate a variety of substance, the levels found are low enough to allow disposal in regular landfill or composting at site.

Conclusion

Although the paper does not cover all of the methods that have been investigated to-date, it does represent those that may be used today or in the near future.

Generally, each control measure has some merit, but no one strategy is applicable to all systems or all locations at this time. To control zebra mussels, each user of raw water has to integrate the controls most applicable to their situation and implement a comprehensive plan which will minimize the impact of zebra mussels on their facility while protecting the natural environment from the effects of the control strategies.

At Ontario Hydro, chlorine still represents the best option for the majority of our systems. Some facilities are able to use hot water flushing to control zebra mussels in some systems. Coatings have now been identified that will help protect external structures from zebra mussels. Small pore filters are a promising technology for low and medium volume systems such as those found at hydraulic plants. Use of Ultraviolet radiation is likely to become popular provided the field trials are as successful as the small scale studies.