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Literature Review and Synthesis of Invasive Mussel Control Techniques

Research and Development Office
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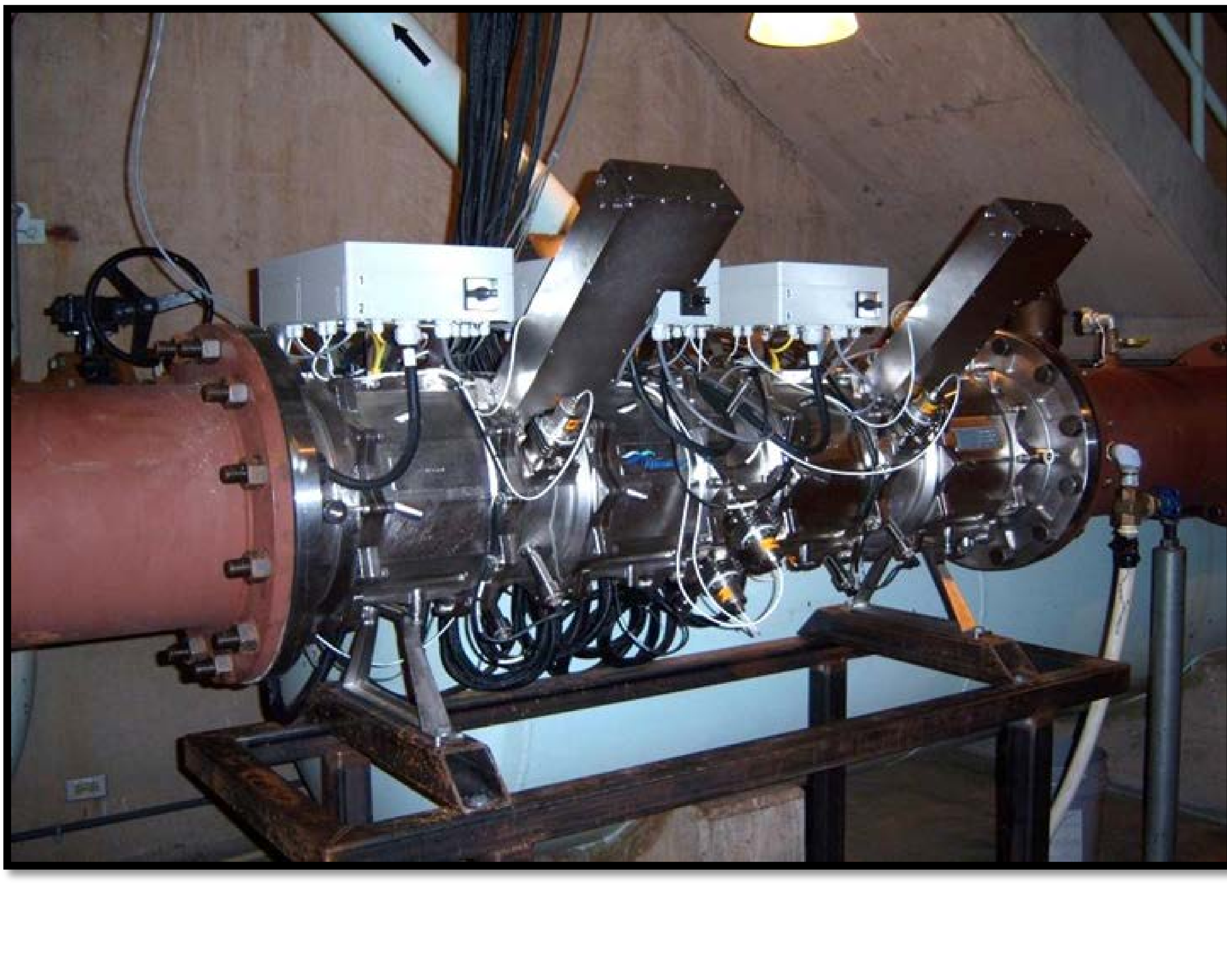

U.S. Department of the Interior
Bureau of Reclamation
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The Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities.

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Collection and review of literature related to the control of invasive dreissenid mussels was performed. Over 200 documents, including peer-reviewed publications, technical reports, theses, and presentation, were identified. These cover a range of studies on chemical controls, mechanical and other physical controls, and potential biological controls. This body of literature has been reviewed and summarized, and a bibliography of relevant literature has been generated.		
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Literature Review and Synthesis of Invasive Mussel Control

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Executive Summary

Over the thirty years since invasive zebra mussels were first detected in the Great Lakes, and the nearly twelve years since quagga mussels were discovered in Lake Mead, a large body of literature has accumulated on attempts to control these invaders. As research is ongoing on the development and use of control techniques, it is valuable to understand what has already been conducted so that future research can build upon the lessons from previous work. To this end, relevant literature on mussel control was identified, collected, and reviewed. This effort drew upon a variety of source materials, including peer-reviewed publications, technical reports, theses, and presentations. A broad range of tested techniques were identified, including chemical controls, and mechanical and other physical controls. Studies on potential biological controls, including predators, parasites, ecological competitors, and genetic manipulations, were also surveyed. The collected literature should serve as a guide for informing design of future research efforts to control invasive mussels.

Contents

Main Report

Methods

Literature on dreissenid mussel control was drawn from a wide variety of sources, including search engines, literature databases, and professional social networking tools, including Google Scholar (scholar.google.com), CiteSeerX (citeseer.ist.psu.edu), and ResearchGate (researchgate.net). Reports and theses were also obtained from institutional and academic websites and databases. Because a substantial portion of the research on mussel control has not been published in peer-reviewed journals or books, this study also incorporated technical reports, theses, conference proceedings, and presentations, to provide the broadest possible survey of relevant work.

This study focused on literature for which full-text PDFs could be obtained, so that methods and results could be directly evaluated. In the case of a few relevant older publications only the abstract could be obtained. All literature was organized using Zotero literature software (zotero.org), with citation items tagged with keywords and PDFs attached (where available).

For Bureau of Reclamation operations the quagga mussel (*Dreissena rostriformis bugensis*) is the primary species of concern. However, the majority of mussel control studies that have been conducted to date have focused of the zebra mussel (*Dreissena polymorpha*). Literature on both species was collected, and for the purposes of this study the two species were not distinguished in discussions of the literature. They are referred to collectively and “dreissenid mussels” or invasive mussels” in the following text.

Chemical controls

A variety of chemical compounds have been tested for control of dreissenid mussels (Glomski 2015), and the most appropriate choice of chemical will depend upon the specific circumstances under which treatments will be performed. An overview of chemical treatments and relevant literature regarding them is presented below.

Potassium salts

The toxicity of potassium salts to bivalves was first documented in native unionid mussels (Imlay 1973) and the invasive Asian clam *Corbicula* (Anderson 1976). Potassium salts was shown to have similar toxicity in zebra mussels shortly after their introduction to the United States (Fisher et al. 1991). Both potassium chloride (KCl), also known as potash, and potassium phosphate (KH_2PO_4) show comparable toxicity, destroying the gill epithelium and leading to asphyxiation (Fisher et al. 1991, Fisher 1994, O’Donnell et al. 1996, Wildridge et al. 1998). Potassium chloride has been shown to have significantly lower toxicity in fish than it does in mussels (Waller et al. 1993, Fisher 1994, Sykes 2009, Sykes et al. 2011, Crank and Barnes 2017), supporting its use as an environmentally benign treatment. However, native mussel populations may be susceptible to potassium chloride (Imlay 1973, Fisher et al. 1991), potential limiting its use in some waters.

Potassium chloride has been used to attempt open-water control of zebra mussels in several lakes in the Eastern United States and Canada (DFO 2014, Bloodsworth 2015, Butts 2016, Janusz 2016, Lund et al. 2018). Significantly, treatment with potassium chloride resulted in eradication of zebra mussels from Millbrook Quarry in Virginia (Fernald and Watson 2005, 2013, n.d.). To date this is the only documented case of successful open-water treatment and eradication of a dreissend population from an entire waterbody. Planning us currently underway to utilize potassium chloride for eradication of zebra mussels at the US Bureau of Reclamation’s San Justo Reservoir in California (Emerson 2015, O’Meara and Hosler 2016).

Copper

Copper compounds including cupric chloride (Rao and Khan 2000) and copper sulfate (Kennedy et al. 2006) have been shown to be toxic to zebra mussels. These compounds are not specific molluscicides, and can display toxicity in a wide variety of animals (Eisler 1998). Indeed, at least one effort to utilize in the copper sulfate to control zebra mussels in open-water resulted in significant fish mortality (URS Group, Inc. 2009). More recently, commercial copper-based formulation have been developed which are intended to more specifically target dreissenid mussels. These products, named EarthTec and EarthTec QZ, have been used in limited open-water applications, with high levels of mortality observed within treated areas (Bloodsworth 2015, Hammond 2016, Lund et al. 2018). However, such treatments have been limited to small portions of lakes, and have not resulted in full eradication of mussels from the whole lake (Dupuy 2015, Lund et al. 2018, Olson 2018). Copper ion generators have also been tested to directly introduce copper ions to control mussel veligers and limit settlement within water infrastructure such as power plant piping (Babinec 2003, Turcotte 2009). The success of such systems in unclear and they have not been widely adopted.

Chlorine

Chlorination, using a variety of chlorine containing compound (e.g. chlorine gas, hypochlorites, chloramine, chlorine dioxide) are effective at killing dreissenid mussels through oxidation (Klerks and Fraleigh 1991, Van Benschoten et al. 1995, Brady et al. 1996, Matisoff et al. 1996, Rajagopal et al. 2002). Chlorination is widely used for water treatment at it is largely in this context that it has been employed for control of dreissenid mussels. Because the action of chlorination is non-specific, this technique may not be appropriate for open-water use or treatments in power plants and other infrastructure where raw water is returned to the environment.

BioBullets

Microencapsulation of toxins has been pursued as a method to specifically target chemical treatments to invasive mussels. Because dreissenids are highly efficient filter feeders, their capture and ingestion of these particles are expected concentrate toxins in the target species. Termed “BioBullets” these synthetic particle have been shown in lab experiments to effectively kill zebra mussels when dosed with potassium chloride (Aldridge et al. 2006, Costa et al. 2008b, 2011, 2012). BioBullets have been reported to have been tested in a closed pipe irrigation system, with 100% mortality of fouling zebra mussels (BioBullets Ltd 2011, Latuszek 2013).

Zequanox

Zequanox is the trade name for a biopesticide (meaning is a pesticide derived from a living organism), which is specifically designed to target dreissenid mussels. Zequanox is derived from the a strain of the bacterium *Pseudomonas fluorescens*, a naturally occurring microbe which is found in soils and waters globally (Molloy and Mayer 2007, Molloy et al. 2013b). Zequanox appears to cause mortality by degrading the stomach and digestive gland of the mussel following ingestion of the bacteria (Molloy et al. 2013c). This is likely due to the production of a toxin by bacteria, rather than infection, as equivalent rates of mortality are observed following exposure to either live or dead bacteria (Molloy et al. 2013c). This is advantageous for application of the biopesticide as it allows preparation of a relatively stable formulation which need not contain viable bacterial cells.

Laboratory trials have generally found Zequanox/ *Pseudomonas fluorescens* to be highly specific in its toxicity, with low rates of mortality in a range of invertebrate and fish species (Molloy et al. 2013a, Meehan et al. 2014b, Waller et al. 2016). One recent study has reported significant latent morality in lake trout following exposure to Zequanox, suggesting additional testing of the impact on salmonid species may be warranted (Luoma et al. 2018b).

Laboratory trials of *Pseudomonas fluorescens* have found rates of mussel mortality up to, or in excess of, 90% (Molloy and Mayer 2007, Molloy et al. 2013c, Meehan 2014). Field test of Zequanox have shown a range of mortality rates from as low as 36% of adult mussels to as high as 100%, depending on the waters being treated (Link 2014, Meehan 2014, Meehan et al. 2014a, Lund et al. 2018). However, even at lower rates of adult mortality, reductions of up to 85% in juvenile settlement have been observed (Link 2014).

Considerations for chemical controls

As discussed above chemical treatments vary in their specificity, and so special attention must be payed to potential off-target effects. In addition, environmental conditions may impact the efficacy of chemical treatments. Variations in temperature have been shown to substantially effect the minimum lethal concentration or time to mortality for several treatments (Rao and Khan 2000, Costa et al. 2008a, O'Meara and Hosler 2016, Luoma et al. 2018a). In general higher temperatures are correlated with greater toxicity, and in some cases lower temperatures may limit the efficacy of chemical treatments. Other water quality parameters may also impact chemical controls. It has been shown that the efficacy of potassium chloride treatment appears to be inhibited in the presence of elevated dissolved solids, in particular the concentration of sodium (Moffitt et al. 2016, Stockton-Fiti and Moffitt 2017). Taken together, these results emphasize the importance of careful laboratory-scale testing of chemical treatments before any field-scale treatment as deployed. These laboratory-scale tests should mimic the physical, chemical, and biological conditions expected in the field as closely as possible to achieve representative results.

Physical and mechanical controls

Coatings

Dreissenid mussel metamorphosis from swimming veligers to sessile adults is associated with settlement on, and attachment to, hard substrates (Ackerman et al. 1994). This settlement on a variety of hard substrates represents the primary threat of dreissenid mussels to water infrastructure such as hydroelectric plants, as settled mussels or detached shells of dead mussels can significantly obstruct water flow, presenting risks to a variety of operations. For this reason significant effort has been focused on the development of materials and coating that will resist or repel the settlement and attachment of mussels (Wells and Sytsma 2009, Skaja 2010, 2015).

Traditionally anti-fouling coatings have relied on incorporation of metals, such as copper and zinc, which are leached from the surface and inhibit settlement and attachment of fouling organisms (Gross 1994, Race and Kelly 1994, Dormon et al. 1996, Kobak et al. 2002, Wells and Sytsma 2009, Skaja 2010, 2014a, 2015). A wide variety of naturally occurring and synthetic organic compounds have also been evaluated as biocides that could be incorporated into coatings to reduce fouling (Cope et al. 1997, Diers et al. 2006, Angarano 2007, Skaja 2011, Ram et al. 2012).

Another approach to coatings development is so called "foul-release" coatings. Rather than leaching biocides, these formulations have inherent surface characteristics which reduce the adhesion strength of fouling organisms, causing them to be dislodged by water flow over the surface or simplifying mechanical removal. A wide variety of foul-release coatings have been tested, with some showing promising results (Jones-Meehan et al. 1999, Tordonato 2011, Skaja 2012, 2014a, 2014b, Tordonato 2015). At present two major impediments to more widespread adoption of foul-release coating are durability of these materials (Mortensen 2013, Skaja 2015) and incompatibility with existing coal tar enamel coating present on many infrastructure surfaces (Tordonato 2011, Skaja 2015).

Emersion and desiccation

Because dreissenid mussels are aquatic organisms a number of studies have looked at the effects of air exposure as a potential method for mussel control (Payne 1992, McMahon et al. 1993, Ricciardi et al. 1995a, Ussery and McMahon 1995, 1995, Ussery et al. 1998). These studies have found that temperature extremes (either elevated above ambient air temperature or freezing temperatures below 0.0° Celsius) substantially decreased the time to mortality as compared with the physiologically normal temperature range of >0.0° Celsius to 25.0° Celsius (Payne 1992, Ricciardi et al. 1995a, Ussery et al. 1998). Relative humidity of the air in which mussels are emersed also plays an important role in the rate of mortality, with mussels in higher relative humidity environments showing substantially longer survival times in above freezing temperatures (McMahon et al. 1993).

Winter draw down of reservoirs of has been conducted in several locations as means of controlling mussels by exposing them to freezing temperatures (Grazio and Montz 2002, 100th Meridian 2008, Hargrave and Jensen 2012, Leuven et al. 2014). While temporary decreases in mussel populations have been observed, the populations have generally rebounded within a few years, seeded from populations in refugia within the rewatered reservoir or in inflowing rivers and streams. Dewatering are resultant desiccation or freezing may therefore provide a temporary control measure in some circumstances, but is unlikely to result in permanent eradication of an invasive mussel population.

Electric currents and electric fields

At least three distinct technologies employing electric currents or electric fields have been proposed for control of mussel settlement within facilities. These are electrical fields, pulse-power, and plasma pulse.

Alternating current and direct current electrical fields

Both alternating current (AC) direct current (DC) electrical fields have been tested for mussel control. These techniques have been shown to reduce settlement or increase mussel mortality (Fears and Mackie 1995, 1997, Luoma et al. 2017), although whether these approaches would reduce settlement downstream of the treatment remains unknown (Smythe and Miller 2003).

Pulse-power

Like AC and DC fields discussed above, pulse-power exposes water passing between electrodes to an electrical current. However, pulse-power cyclically produces higher energy fields than do either of comparatively low voltage techniques (Smythe and Dardeau 1999, Smythe and Miller 2003). The concept is that this high energy field will kill veligers or stun them for a sufficiently length of time that they will pass through infrastructure before they can recover and settle within a facility. Mortality in initial studies has generally been below 40% and the results in some cases were confounded by high rates of mortality in control treatments (Smythe and Miller 2003). However, decreases in settlement after pulse-power treatment have been reported (Smythe and Dardeau 1999).

Plasma pulse

Plasma pulse is generated from a plasma sparker has been proposed as another energetic method to control mussel growth within infrastructure. A plasma sparker operates through a rapid discharge of electrical energy, resulting in production of a shockwave, steam bubble production, and release of ultraviolet light (Miller 2000). This system is designed to control mussels by killing mussels, and preventing buildup of biofilm and settlement of mussels. Limited laboratory and field testing has shown that all three goals may be achieved through the use of plasma pulse technology (Mackie et al. 2000). How scalable and widely applicable this technology is has not been addressed, nor have potential structural impacts to infrastructure (Smythe and Dardeau 1999). This technology has been reported to have been installed by some utilities in the Eastern United States and Canada (Miller 2000), but its information regarding its performance in these installations is not available.

Laser-based pulsed pressure

Focused laser light power has been tested to create a shock wave and acoustic pulse to damage mussel veligers and reduce settlement (Kubitschek et al. 2017). Such a system was successfully developed and tested, but no physical impacts to veligers or reductions in settlement where measured (Kubitschek et al. 2017).

Turbulence

High pressure water jets have been tested to create turbulence within pipes, with the aim of physically damaging veligers and decreasing settlement (Mortensen and Pucherelli 2016). Test of this technique have shown that such in pipe generated turbulence can result in an increase in acute physical damage to veligers shells, although the results of some tests have been inconsistent (Mortensen and Pucherelli 2016). Whether such a treatment could reduce settlement remains unknown, as initial field testing has been hampered by technical challenges which have prevented consistent performance of experiments (Mortensen and Pucherelli 2016).

Centrifugal separation

Centrifugal separation has been tested in the laboratory and the field (Kubitschek and Pucherelli 2017). Both dreissenid veligers and adult shell debris are heavier than water, and centrifugal force could therefore could be used remove them from waters flowing through hydroelectric dams and other infrastructure. Lab tests found that a centrifugal separator was capable of removing 60-85% percent of adult shell debris (Kubitschek and Pucherelli 2017). However, in field test relatively few veligers were captured in the centrifugal separator and no decrease in mussel settlement was observed downstream of the treatment relative to controls (Kubitschek and Pucherelli 2017).

Acoustic and vibrational techniques

A number of acoustic and vibrational techniques have been tested for their ability induce mortality in dreissenids (Donskoy 1996). Ultrasonic cavitation has been shown to successfully cause mortality in veligers (Donskoy 1996). Whether such a system could be scaled for use facilities and how it might impact infrastructure has not been explored.

Ultraviolet irradiation

Ultraviolet (UV) irradiation has been tested for its ability to induce mortality and reduce settlement of dreissenid veligers. Lab scale tests have observed increased mortality days after exposure to UV irradiation (Delrose 2012, Stewart-Malone et al. 2015), time scales which are not applicable to flow-through facilities such as hydroelectric power plants where the residence time of veligers in the facility is on the scale of minutes. However, field tests have shown that inline UV treatment can reduce settlement in downstream bioboxes by as much as 99% (Pucherelli and Claudi 2017). Such effects have the potential to significantly reduce the impact of dreissenid mussel settlement on infrastructure, and such UV irradiation systems are beginning to be installed at a number of facilities (S. Pucherelli, personal communication).

Mechanical removal

Invasive dreissenid mussels colonize the intake trashracks of facilities in infested waters, requiring periodic cleaning (Wahl et al. 2008). Cleaning of these structures is generally accomplished with either mechanical rakes or high-pressure water jets (Heiner 2013). Integration of these two types of systems could increase the effectiveness and efficiency of trashrack cleaning, but technical challenges would need to be overcome for such a system to be implemented (Heiner 2013).

Manual removal

Manual removal of adult mussels by SCUBA divers was performed in Lake George, NY shortly after discovery of a colony of adult mussels (Wimbush et al. 2009). This treatment appears to have reduced numbers at the treated site, but additional colonies were subsequently identified at other locations in the lake. While such removal may temporarily reduce numbers of mussels in a targeted location, it seems unlikely to keep pace with population growth in a waterbody with conditions suitable to mussels, especially as many adult mussels may be missed by SCUBA divers even under ideal conditions.

Biological controls

A wide variety of organisms have been documented to prey on, parasitize, or potentially compete with dreissenid mussels. A thorough review of these interactions was previously published (Molloy et al. 1997). In the intervening two decades, numerous other predators and parasites have been documented, and an updated compendium of this information is forthcoming (Daniel Molloy, pers. comm.). A summary of current knowledge, and prospects for biological control of dreissenids, is presented below.

Predators

Predation on dreissenid mussels by a wide variety fish species has been observed both in the native ranges of zebra and quagga mussels, in Eastern Europe, and in novel habitats in Western Europe and North America where they have been introduced (Molloy et al. 1997, Kirk et al. 2001, Bartsch et al. 2005, Bowers and Szalay 2007, Karp and Thomas 2014). Fish predation may be target to either swimming veliger larvae or juveniles and adults attached to the substratum, depending on the fish species (Molloy et al. 1997). Predation by a wide variety of ducks, as well as by a variety of other diving and shore birds, has also been documented in both native and introduced habitats (Hamilton et al. 1994, Molloy et al. 1997). In North America a number of other organisms, including crayfish, blue crabs, and turtles, have also added invasive dreissenid mussels to their diets (MacIsaac 1994, Molloy et al. 1994, Perry et al. 1997, Lindeman 2006, Bulté and Blouin-Demers 2008, Carlsson et al. 2011).

Competitors

Populations of juvenile and adult mussels, which are attached to hard substratum, may be constrained though competition for space. Such competition with freshwater sponges has been documented to impact dreissenid populations in the Great Lakes, as well as in Italy (Ricciardi et al. 1995b, Early and Glonek 1999, Lauer and Spacie 2000, 2004, Gaino 2005).

Parasites

A wide variety of organisms have been found to live on or in dreissenid mussels. These include animals such as trematode, (Molloy et al. 1997, Peribáñez et al. 2006), nematodes (Karatayev et al. 2003), and an oligochaete (Conn et al. 1996), as well as single-celled eukaryotes including Haplosporidium (Molloy et al. 2012) and numerous ciliates (Laruelle et al. 1999, Karatayev et al. 2002, 2003, 2007, Molloy et al. 2005, Minguez et al. 2013). While many of these organisms have been referred to a parasites which harm the host, but some may be commensal, living on the host but not have a detrimental effect.

Prospects for biological control

A few studies have shown that predation pressure may decrease dreissenid mussel numbers in both the laboratory and the field (Molloy et al. 1994, Perry et al. 1997, Bartsch et al. 2005, Carlsson et al. 2011), however no evidence has been presented for long term reductions in mussel population sizes due to predation pressure. This, couple with the fact that most predators do not target a specific species, and will feed on other organisms depending upon preference and abundance, makes predation a poor choice for large scale biological control of mussels (Molloy 1998, 2002). Parasites provide a more promising route for development of biological controls, as they are very often species-specific in the hosts that they infect, and could therefore provide an environmentally-safe means of controlling mussel populations (Molloy 1998, 2002). To date no parasite has been identified which would be appropriate and effective for control of invasive dreissenid mussel populations, but research on this topic is ongoing (J. Keele, pers. comm.).

Recent work on biological control in other organisms has focused on using genetic tools to effect decreases in the population as a whole, even potentially leading to local extinction (Esvelt et al. 2014, Webber et al. 2015). Interest in such approaches has burgeoned the discovery that the bacterial CRISPR-Cas9 system can be employed to may targeted changes in the genomes of many species (Qi et al. 2013, Wang et al. 2013), and with the development of “gene drive” techniques to push deleterious mutations through a population (Burt 2003). Initial enthusiasm for using these techniques have been tempered by ethical and technical concerns (Webber et al. 2015, Champer et al. 2016, National Academies of Sciences and Medicine 2016, Esvelt and Gemmell 2017, Noble et al. 2017, Moro et al. 2018). Such tools may yet provide a valuable path towards the control or eradication of invasive dreissenid populations, but their development will need to be pursued with appropriate care and deliberation, including internal controls for technology.

Conclusions

Numerous chemical and physical means for controlling invasive dreissenid mussels have been tested with varying success and applicability. For the moment no “silver bullet” has been identified for eradication of mussels. In some specific conditions in small waterbodies it may be possible to effect eradication with chemical treatments, however this has only been accomplished once in a very small flooded quarry with no inflow or outflow. With regard to infrastructure and facilities the most effective and economical approach is likely to minimize impacts through a combination of physical and/or chemical treatments. What specific treatments are best suited will depend upon the specifics of the structure and waterbody, the goals of its manager, and any potential impacts of treatments to the environment or the infrastructure. Looking forward, biological controls may be the most promising path to potential eradication, but any such approach will entail significant research and judicious planning.

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Data Sets that Support the Final Report

A copy of the bibliographic references and source documents has been deposited in a US Bureau of Reclamation Technical Services Center shared drive to be archived and made accessible to Reclamation staff. File and access information is as follows:

- Share Drive folder name and path where data are stored:
  - Z:\DO\TSC\Jobs\DO_NonFeature\Science and Technology
- Point of Contact name, email, and phone:
  - Yale Passamaneck, ypassamaneck@usbr.gov, 303-445-2480
- Short description of the data:
  - Bibliographic library of literature identified in the project
  - Data is in the RIS file format
  - Data can be imported into Mendeley, Zotero, EndNote, ReadCube, and other reference management programs
  - Data may be provided in other file formats upon request.
- Keywords:
  - mussel control, quagga mussel, zebra mussel, dreissenid
- Approximate total size of all files:
  - 500 MB