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14. ABSTRACT
Protection of hydropower systems susceptible to mussel fouling requires development of site-specific control methods and Reclamation has focused on identifying, developing, and implementing environmentally compliant control strategies. Reclamation's Science and Technology Program managed by the Research and Development Office has made mussel research activities a priority since 2008. The Research Office, Technical Service Center, and contract researchers have worked closely with the Lower Colorado Dam's Office to develop and test a variety of control methods. The purpose of this document is to compile and summarize the research that Reclamation has conducted, up to this point, for the control of invasive mussels at hydropower facilities.

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prepared by

Technical Service Center

Hydraulic Investigations and Lab Services

Sherri Pucherelli, Biologist

Peer Review Signature Page

Peer Review

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SHERRI PUCHERELLI Digitally signed by SHERRI PUCHERELLI Date: 2020.02.24 09:53:38 -07'00'

Prepared by: Sherri Pucherelli
Biologist, Hydraulic Investigations and Lab Services, TSC

JOSEPH KUBITSCHEK Digitally signed by JOSEPH KUBITSCHEK Date: 2020.02.24 10:06:37 -07'00'

Peer Review by: Joseph Kubitschek, P.E.
Hydraulic Engineer, Hydraulic Investigations and Lab Services, TSC

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Executive Summary

Invasive dreissenid mussels (quagga and zebra mussels) are prolific breeders and are capable of settling on any hard surface they encounter. This behavior is problematic for hydropower facilities because the mussels settle on submerged surfaces like water intakes, trashracks, pipes, and other hydraulic equipment that are utilized for water delivery and hydropower production. When mussel populations are dense, mussels will begin to settle on top of each other which can restrict flow in critical systems leading to increased maintenance and unplanned outages.

The impact of invasive mussels to Reclamation hydropower facility operation and maintenance has been a concern since the first western discovery of quagga mussels (*Dreissena rostriformis bugensis*) in 2007 at reservoirs along the lower Colorado River. Four major Reclamation facilities including Glen Canyon, Hoover, Davis, and Parker Dams and Powerplants are currently impacted. Quagga mussel populations at these locations are dense and pose serious potential for interrupted water delivery and power generation and increased operations and maintenance costs.

Reclamation has focused on developing and implementing environmentally compliant control strategies. Reclamation's Science and Technology (S&T) Program, managed by Reclamation's Research and Development (R&D) Office has made mussel research activities a priority since 2008. The Research Office, Technical Service Center, and contract researchers have worked closely with the Lower Colorado Dam's Office to develop and test a variety of control methods. The purpose of this document is to compile and summarize the research that Reclamation has conducted, up to this point, for the control of invasive mussels at hydropower facilities.

Reclamation researchers and contractors have developed and tested a variety of mussel control methods along with site-specific testing of commercially available products. This research has focused primarily on methods and technologies for mussel settlement prevention and shell debris mitigation. Reclamation has examined or is in the process of examining the following list of control methods which are summarized in this report.

Self-Cleaning Microfiltration
Antifouling and Foul Release Coatings
Ultraviolet (UV) Treatment
Zequanox
Turbulence
pH Manipulation
Endothall
Copper Ion Generator
Conductivity Manipulation
Laser-Generated Pulsed Pressure
Centrifugal Separator
Carbon Dioxide
Ultrasound
Electrical
Self-Cleaning Strainers

Contents

Introduction

Invasive dreissenid mussels (quagga and zebra mussels) are prolific breeders and are capable of settling on any hard surface they encounter. This behavior is problematic for hydropower facilities because the mussels settle on submerged surfaces like water intakes, trashracks, pipes, and other hydraulic equipment that are utilized for water delivery and hydropower production. When mussel populations are dense, mussels will begin to settle on top of each other which can restrict flow in critical systems leading to increased maintenance and unplanned outages. Along with the impact to hydropower facilities, mussels also negatively impact the ecosystem. As filter feeders, mussels can cause shifts in the natural ecosystem by disrupting the food chain, concentrating toxic substances, and degrading critical habitat which can all lead to the decline of native species and potentially the proliferation of disadvantageous species such as weeds or toxic algae.

The impact of invasive mussels to Reclamation hydropower facility operation and maintenance has been a concern since the first western discovery of quagga mussels (*Dreissena rostriformis bugensis*) in 2007 at reservoirs along the lower Colorado River. Four major Reclamation facilities including Glen Canyon, Hoover, Davis, and Parker Dams and Powerplants are currently impacted. Quagga mussel populations at these locations are dense and pose serious potential for interrupted water delivery and power generation and increased operations and maintenance costs. Unlike northern mussel populations, quagga mussels are able to reproduce year-round due to warm water temperatures in the lower reaches of the Colorado River. This has allowed for mussel populations to become particularly dense, requiring near year-round control at hydropower facilities.

Quagga mussels have had negative impacts at Reclamation hydropower facilities, but it has been difficult to track the increased costs associated with mussel fouling. Depending on levels of infestation and facility operating conditions, mussel-related impacts can generally range from fouling of intake structures including trashracks, grates, and screens by live mussel attachment, to clogging of small-diameter piped systems (generally less than about 6 inches) due to live mussel attachment and mussel shell debris that can be drawn into systems. Some of the impacts include increased maintenance requirements and outages associated with shell debris and mussel settlement in smaller flow passages of cooling water systems and turbine packing boxes. At one facility, there is increased maintenance cost associated with seasonal removal of weeds from the trashracks. Mussel feeding has increased the clarity of the water allowing weeds to proliferate and accumulate on the trashracks.

While there are similarities among hydropower facilities across Reclamation, it is recognized that site-specific or as-built conditions including equipment and associated arrangements can vary significantly. The degree of impacts will depend largely on design, operating principles of particular equipment, operating conditions, and levels of infestation. The following systems and equipment specific to most hydropower facilities have the potential to be adversely impacted by invasive mussels:

- Intakes and penstocks
- Gates and valves
- Bypasses and air vents

- Cooling water systems
- Raw water fire protection systems
- Service and domestic water systems
- Instrumentation
- Drainage and unwatering systems

Other features associated with power facilities that may also be susceptible to mussel related impacts include:

- Spillways and appurtenances
- Outlet works and appurtenances
- Water diversion and conveyance facilities
- Fish screening and passage facilities
- Structural drainage systems (formed drains, under drains, and toe drains with potential for back flooding)

Methods for the eradication of established mussel populations in reservoirs and lakes have yet to be developed. Open-water control is complex, and it has been difficult to find methods that are species specific, economically feasible, scalable to large water bodies, and do not harm nontarget species or the native ecosystem. Therefore, protection of hydropower systems susceptible to mussel fouling requires development of site-specific systems-level control methods. Surveys of water management agencies throughout the United States who have mussel infestations suggest that chemical control and physical removal are some of the most common methods for managing mussel fouling (O'Neil 1997; Park and Hushak 1999; Connelly et al. 2007). Several chemical methods have been found to successfully control mussels including chlorine, ammonia, bromine, potassium permanganate, quaternary and polyquaternary ammonium compounds, aromatic hydrocarbons, copper ions, and potassium compounds. Information about the use of chemicals for mussel control can be found in the United States Army Corps of Engineers Zebra Mussel Chemical Control Guide (Glomski 2015).

Although chemicals are effective for mussel control, the use of chemicals requires knowledge of permitting, labeling, and chemical specific application regulations. The Clean Water Act requires all molluscicides and biocides discharged to waters of the United States be regulated. Due to environmental concerns with the use of conventional chemicals, Reclamation has focused on developing and implementing environmentally benign control strategies.

Reclamation's Science and Technology (S&T) Program, managed by Reclamation's Research and Development (R&D) Office has made mussel research activities a priority since 2008. The Research Office, Technical Service Center, and contract researchers have worked closely with the Lower Colorado Dam's Office to develop and test a variety of control methods. The purpose of this document is to compile and summarize the research that Reclamation has conducted, up to this point, for the control of invasive mussels at hydropower facilities.

Completed Research

Reclamation researchers and contractors have developed and tested a variety of mussel control methods along with conducting site-specific testing of commercially available products. Site-specific testing is important for many control methods because water quality and powerplant design can significantly impact the efficacy of many treatments. The focus of this research has included mussel settlement prevention and shell debris mitigation. Critical systems that need to be protected include intake structures, cooling water systems, water conveyance piping, and other small piped systems. Mussel larvae (veligers) are microscopic, freely dispersed in the water column and are easily transported into hydropower facilities. Many of the younger mussel veligers will pass through the facility without causing any issues. The target life stage for settlement control is the pediveliger, which is the life stage that is able to settle out of the water column and attach to a surface.

Pediveligers are the first larval stage that have a foot, which they can use to move across a surface and locate an appropriate site for settlement. The pediveliger will then secrete a byssal thread and begin growing and developing in place until they become an adult. Control methods that kill or deter the pediveliger life stage before or soon after settlement are often the most effective. Adult mussels settled on or around intake structures can also be problematic because as they die their shells become dislodged, enter the facility and can buildup, clogging strainers, screens, piping, small flow passages, and other critical points within the system.

Once a control method is selected for study there are a few common methods used to evaluate its effectiveness for mussel control. The prevention of mussel settlement is commonly evaluated using bioboxes which are plumbed into the cooling water system, or on settlement plates hung in the forebay upstream of the facility (Mackie and Claudi 2010). Bioboxes allow veliger laden water to flow through at a rate that allows enough time for mussels to settle on plates placed in the bioboxes. These plates allow for easy analysis and comparison of settlement between bioboxes receiving treated water and those receiving un-treated water. The impact of a treatment on veliger and adult survival can also be assessed by observing exposed mussels immediately and for several days after treatment.

Table 1 and Table 2 list all past and current Reclamation funded and supported invasive mussel control research projects that were designed for protection of specific structures and systems within hydropower facilities. Table 1 includes information about where, when, and for what purpose research was conducted and if the method has potential, has been implemented, or factors that have prevented implementation. Table 2 includes researcher contact information and a list of research reports and their location (links to reports are included where possible). The tables are followed by a summary of each project including a list of referenced reports, description, study design, results, and conclusions.

For more information about the research included in this compendium, or other invasive mussel research conducted by Reclamation please contact the Invasive Species Research Coordinator (currently, Sherri Pucherelli, spucherelli@usbr.gov (303)-445-2015) or the Reclamation Research and Development Office at Sha-DRO-reserach@usbr.gov. For more information about Reclamation's Invasive Mussel Program please visit, https://www.usbr.gov/mussels/. More information about Reclamation's Research and Development Office, Science and Technology Program can also be found at, https://www.usbr.gov/research/.

Table 1 List of mussel control methods, for hydropower facilities tested (and in progress) by Reclamation, year/s research was conducted, study location, target result, potential for use, and if methods were implemented, or reasons implementation has not occurred at Reclamation facilities.

Method	Year/s Research Conducted	Study Location	Target Result	Potential for Use	Implemented	Reason Not Implemented
Self-Cleaning Microfiltration	2008	Parker Dam	Settlement reduction in piped systems	Yes	No	Maintenance
Antifouling and Foul Release Coatings	2008-Present	Parker Dam	Settlement reduction on intake structures	Yes	Limited	Durability and Cost
Ultraviolet Light	2008-2018	Hoover, Davis and Parker Dams	Settlement reduction in piped systems	Yes	Yes, Hoover, Davis, Parker and Glen Canyon	–
Zequanox	2011 and 2013	Davis Dam, Hoover Dam	Settlement reduction in piped systems	Yes	No	Cost
Turbulence	2011-2016	Davis Dam	Settlement reduction in piped systems	No	No	Efficacy
pH Manipulation	2011	Lake Havasu, San Justo Reservoir	Settlement reduction in piped systems	Yes	No	Location for install not identified

Method	Year/s Research Conducted	Study Location	Target Result	Potential for Use	Implemented	Reason Not Implemented
Endothall	2012	Mohave and San Justo Reservoirs	Settlement reduction in piped systems	Yes	No	Discharge permitting
Copper Ion Generator	2013- 2014	Davis Dam	Settlement reduction in piped systems	Yes	No	Maintenance
Conductivity Manipulation	2015	Davis Dam	Settlement reduction in piped systems	No	No	Efficacy
Laser-Generated Pulsed Pressure	2017	Davis Dam	Settlement reduction in piped systems	No	No	Efficacy
Centrifugal Separator	2017	Davis Dam	Shell removal/ settlement reduction in piped systems	Yes	No	Location for install not identified
Carbon Dioxide	In progress, started 2018	Not yet field tested	Settlement reduction in piped systems	–	–	–

Method	Year/s Research Conducted	Study Location	Target Result	Potential for Use	Implemented	Reason Not Implemented
Ultrasound	In progress, started 2020	Planned at Glen Canyon Dam	Settlement reduction on intake structures	–	–	–
Electrical	In progress, started 2019	Not yet field tested	Settlement reduction in piped systems	–	–	–
Self-Cleaning Strainers	In progress, started 2018	Not yet field tested	Shell removal in piped systems	–	–	–

Table 2 List of mussel control methods tested (and in progress) by Reclamation, lead researcher/s, researcher/s contact information, and links to reports (where possible).

Method	Researcher/s	Contact Information	Report Locations
Self-Cleaning Microfiltration	RNT Consulting Inc. Reclamation: Denise Hosler, Fred Nibling	RNT Consulting Inc. (613)476-7994 rnt@idirect.com	Claudi et al. 2008
Antifouling and Foul Release Coatings	Reclamation: Allen Skaja, David Tordonato, Bobbie Jo Merten, Brian Baumgarten, Carter Gulsvig	Allen Skaja (303)445-2396 askaja@usbr.gov	Skaja 2018 Skaja 2016 Skaja 2015 Skaja 2014 Merten 2013 Skaja 2011 Tordonato 2011 Baumgarten and Tordonato 2011 Skaja 2011

Method	Researcher/s	Contact Information	Report Locations
Ultraviolet Light	RNT Consulting Inc. Reclamation: Sherri Pucherelli, Fred Nibling	RNT Consulting Inc. (613)476-7994 rnt@idirect.com Reclamation: Sherri Pucherelli (303)445-2015 spucherelli@usbr.gov	Pucherelli et al. 2018 Pucherelli 2018 Pucherelli and Claudi, 2017 Pucherelli 2014 (contact author) Claudi et al. 2014 Claudi and Prescott 2013 Pucherelli et al. 2012 (contact author)
Zequanox	Marrone Bio Innovations Inc. (MBI) Reclamation: Fred Nibling, Scott O'Meara, Denise Hosler	Marrone Bio Innovations Inc. (530)750-2800	Link 2014 Link 2011
Turbulence	Reclamation: Josh Mortensen and Sherri Pucherelli	Josh Mortensen (303)445-2156 jmortensen@usbr.gov	Mortensen and Pucherelli, 2012, 2013, 2014, and 2016 (contact author) Mortensen 2011 (contact author)

Method	**Researcher/s**	**Contact Information**	**Report Locations**
pH Manipulation	RNT Consulting Inc.	RNT Consulting Inc. (613)476-7994 rnt@idirect.com	Claudi et al. 2012
Endothall	RNT Consulting Inc.	RNT Consulting Inc. (613)476-7994 rnt@idirect.com	Claudi et al. 2013
Copper Ion Generator	RNT Consulting Inc.	RNT Consulting Inc. (613)476-7994 rnt@idirect.com	Claudi and Prescott 2014 (contact author)
Conductivity Manipulation	Reclamation: Sherri Pucherelli and Scott O'Meara	Sherri Pucherelli (303)445-2015 spucherelli@usbr.gov	Pucherelli et al. 2016
Laser-Generated Pulsed Pressure	Reclamation: Joe Kubitscheck and Sherri Pucherelli National Institute of Standards and Technology (NIST): Matthew Spidell and Paul Williams	Joe Kubitscheck (303)445-2148 jkubitscheck@usbr.gov	Kubitscheck et al. 2017 (contact author)
Centrifugal Separator	Reclamation: Joe Kubitscheck, Bryan Heiner, and Sherri Pucherelli	Joe Kubitscheck (303)445-2148 jkubitscheck@usbr.gov	Kubitscheck and Pucherelli, 2017
Carbon Dioxide	Reclamation: Kevin Kelly	Kevin Kelly (720)663-7944 kkelly@usbr.gov	In progress
Ultrasound	Reclamation: Shane Mower	Shane Mower (928)645-0468 cmower@usbr.gov	In progress

Method	Researcher/s	Contact Information	Report Locations
Electrical	Reclamation: Kevin Kelly	Kevin Kelly (720)663-7944 kkelly@usbr.gov	In progress
Self-Cleaning Strainers	Reclamation: Bryan Heiner	Bryan Heiner (303)445-2140 bheiner@usbr.gov	In progress

Self-Cleaning Microfiltration

Report

Claudi R., T. Prescott, C. Taraborelli. 2008. Assessment of the Ballast Safe Filter Performance in Removing Quagga Mussel Veligers from the Raw Water of Lake Havasu. RNT Consulting Inc.

Description

Self-cleaning small pore filtration (microfiltration) is a well-documented technology for mussel control. The technology has been available for several decades and more recently, several manufactures have improved the technology for use in invasive species removal from ballast water. When a self-cleaning small pore filter is installed downstream of a strainer, it should protect downstream piping from ingress of adult shells, shell debris and ready to settle veligers.
The filter installed for testing at Parker Dam in 2008 was a BallastSafe™ filter (Sigma Design Company; Figure 1). The attributes of this filtration system that made it appealing to Reclamation was that the system is self-cleaning, the four-layer weave wire filter has been proven to be highly effective for removal of organic matter, and the filtration process only produces a small pressure drop on the system.

The filter selected for testing at Parker Dam was sized to accommodate 450 gallons per minute (GPM) flow, was installed on an eight-inch domestic water line and was equipped with two interchangeable screens with 40-micrometer (µm) (57- µm absolute) and 80-µm (120-µm absolute) pore size. The BallastSafe™ filter was installed downstream of a course, self-cleaning Hayward strainer (3/16-inch pore size). The online backwash is achieved by small nozzles that float on the inside surface of the filter mesh.

The goal of this research study was to test the filtration system under difficult circumstances, i.e. a raw water system with large amounts of debris and high veliger concentrations, in order to determine if an 80-µm screen was adequate to exclude mussel shell debris and settlement size veligers from the cooling water piping, or if a smaller 40-µm screen was required. The study was performed by RNT Consulting Inc. with assistance from Reclamation TSC employees and Parker Dam staff.

Figure 1. BallastSafe™ filter installed at Parker Dam to test veliger exclusion effectiveness.

Study Design

Ten, 1,000-L samples were collected from sample ports installed upstream and downstream of the filtration unit. Samples were concentrated in 20-µm plankton tow nets, observed under a microscope, and the number and size of veligers was recorded. Samples were collected for both 80 and 40-µm filters.

Results

The 40-µm mesh removed all veligers greater than 100-µm microns in size and achieved 89% removal of veligers up to 100-µm. The 80-µm filter removed 69% of the 100-200-µm sized veligers and removed nearly all veligers that were 200-300-µm in size. Both the 40- and 80-µm filters allowed passage of veligers that were larger than the absolute openings in the mesh weave. The absolute mesh size was determined by use of glass spheres, which are not flexible. Veliger shells are flexible and can be pushed through openings smaller than their undeformed shape. Both the 40- and 80-µm meshes excluded all near settlement veliger life stages.

Conclusions

Additional research to confirm the findings of this study is suggested because of the low number of settlement-sized veligers (pediveligers) present during the study. Furthermore, the performance of the filter could not be evaluated under high total suspended solid (TSS) conditions because of the high clarity of the raw water at Parker Dam. Further research into the filters ability to exclude veligers in high TSS conditions, including the ability of the backwash to remove sediment at the different sized mesh would be worthwhile to determine if there is additional benefit of sediment removal using the finer mesh. Reclamation has not installed self-cleaning microfiltration for the control of invasive mussels at any of its facilities.

Antifouling and Foul Release Coatings

Reports

Skaja A. 2011. Adhesion Mechanism of Zebra and Quagga Mussels. MERL-2011-21

Baumgarten B.A. and D.S. Tordonato. 2011. Investigation of Molybdenum and Tungsten Disulfide for Mussel Control. MERL-2011-37

Tordonato D. 2011. Investigation of Overcoating Coal Tar Enamel with Foul Release Coatings. MERL-2011-41

Skaja A. 2011. Natural biocides for zebra and quagga mussel control 2011 MERL-2011-46

Merten B.J.E. 2013. Review of Mussel Adhesion Mechanism and Scoping Study. MERL-2013-43

Skaja A. 2014. Durable Foul Release Coatings Final Report 2012-2013. MERL-2014-57

Skaja A. 2015. Coatings for Invasive Mussel Control-Final Report. Research and Development Office, Science and Technology Program. ST- 2015-7095-01

Tordonato D.S. 2015. Foul-Release Coatings Scale-Up Testing– Parker Dam Trashrack. Research and Development Office, Science and Technology Program. ST-2015-5270-1

Skaja A. 2016. Durable Silicone Foul Release Coatings CRADA. Research and Development Office, Science and Technology Program. Final Report: ST-2016-0809-01/8540-2016-02

Skaja A. 2018. Continuation of Field Evaluations on Advanced Coatings for Mussel Control. Research and Development Office, Science and Technology Program. Final Report: ST-2018-7089-01

Description

Reclamation's Materials and Corrosion Laboratory has been conducting research on antifouling and foul release coatings for use at Reclamation facilities since 2008. The commercial products tested thus far have been marketed for fouling control in the shipping industry. However, the service environment at Reclamation facilities presents some unique challenges that must be considered when evaluating a fouling control coating. They include highly variable water quality and numerous water-borne substances that affect durability, including sediment loads, woody debris, vegetation, ice, and other debris. Therefore, these commercially available products have been evaluated to determine if they can meet Reclamation's service life requirements.

Reclamation has worked with manufacturers to evaluate the performance of a variety of commercially available coatings to reduce biofouling by mussels. In the first three years of this research, Reclamation evaluated over 50 coatings and metal alloys in six broad categories: conventional epoxies, antifouling coatings (which use a biocide to prevent mussel settlement), foul release coatings (which rely on hydrophobic properties to make it difficult for mussels to strongly attach), fluorinated powder coatings, metallic coatings, and metal alloys. Since this initial research effort, Reclamation has tested over 100 materials and coatings, studied the mussel adhesion mechanism and worked closely with industry partners to develop coatings for mussel settlement prevention.

Study Design

Coatings have been tested in still and flowing waters at Reclamation's Parker Dam on the Colorado River, where mussels reproduce year-round (Figure 2). For each coating system tested, three 1-foot-square steel plates were tied off by a nylon rope and lowered into the water to approximately 50 feet (ft) depth in a low-velocity zone near the face of the dam. For the dynamic conditions, one 18-inch by 24-inch coated floor grate with 1-inch spacings was tied off with two nylon ropes to prevent twisting and lowered to a depth of 40 ft below the water surface. The grates in this case were hung in flowing water just downstream from the forebay trashrack structure. After immersion in the reservoir for several months, the coated metal grates were examined to determine the extent of mussel fouling. Testing also included measuring the force required to remove the attached mussels.

Other coatings research includes development and testing of fluorinated polyurethane elastomer and elastomeric polyurethane coatings. Unfortunately, mussels were found to attach to several formulations tested in the field. Other work to develop durable foul release coating systems was pursued via a Cooperative Research and Development Agreement (CRADA) between Reclamation and Fujifilm Hunt Smart Surfaces, LLC (Fuji), which investigated the thickness of silicone topcoat required to prevent fouling.

Figure 2. Aerial photo of Parker Dam where coatings are field tested. The red line just to the right of the spillway gates indicates the location where panels were placed, and the yellow line indicates where grates were placed.

Results

Reclamation's Materials and Corrosion Laboratory has evaluated over 100 materials and coatings under field conditions to determine the types of materials/coatings that prevent mussels from adhering to surfaces. The results of this research can be found in the ten reports listed above and in Table 2. Some of the main findings of this research are listed below.

1. Mussel fouling occurs at a faster rate under flowing water conditions.
2. Foul release coatings appeared to be the best option for controlling mussel fouling.
3. Copper and copper alloys can work for antifouling, but efficacy depends upon water chemistry, flow rates, and the corrosion rate of the alloy. Performance of copper alloys may vary between facilities, so it is important to fully evaluate site specific conditions prior to deciding whether to use a copper alloy.
4. Antifouling coatings performed well in low velocity and intermittent flow conditions, but not in constantly flowing water.
5. Durable, hard hybrid coatings (Jotun Sealion Resilient and North Dakota State University formulations) showed promise.

6. Silicone foul release coatings were found to be one of the best options for mitigation in both static (non-flowing) and dynamic (flowing) conditions. However, these commercially available coatings lack durability.
7. Scaleup study: Three commercially available silicone foul release coatings and one hard epoxy silicone hybrid were evaluated for 18 months on a trashrack panel.
    a. The three silicone foul release systems had less damage than the hard silicone epoxy hybrid.
    b. The three silicone foul release systems had minimal algae on the surface with no attached mussels.
    c. The hard silicone epoxy hybrid had heavier fouling than the silicone foul release systems.

Conclusions

The results of 10 years of coatings research has provided significant insight into the effectiveness (or lack thereof) of coatings for use in mussel settlement prevention at Reclamation facilities. Despite the success of this research effort, coatings for mussel settlement prevention have been used sparsely at Reclamation facilities due to cost and durability. Field testing needs to continue in order to advance new technologies. Reclamation plans to continue testing new coating technologies including coatings developed by the Pacific Northwest National Laboratory as well as other partners. The Army Corps of Engineers is also planning to work with Reclamation to further study the mussels' adhesion mechanism and to perform large scale testing of foul release coatings previously evaluated by Reclamation to determine if they are durable enough for their specific service conditions.

Ultraviolet Light

Reports

Pucherelli S.F. 2018. Control of Biofouling in Hydropower Cooling Systems using HOD Ultraviolet Light. Research and Development Office, Final Report ST-2018-1712-01.

Pucherelli S.F. 2014. Evaluation of the Effects of Ultra-Violet Light Treatment on Quagga Mussel Veligers at Davis Dam. Research and Development Office, Final Report 2014-01-0891.

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Claudi R.M., T.H. Prescott. 2013. Evaluation of UV Technology at Hoover Dam as Means of Eliminating Downstream Settlement of Dreissenid Mussel Veligers. RNT Consulting Inc. report prepared for Bureau of Reclamation. Task Order: R12PD80180, IDIQ Contract: R10PC80264.

Pucherelli S.P., D. Hosler, F. Nibling. 2012. Evaluation of Ultra-Violet Light Treatment for the Prevention of Quagga Mussel Settlement in Hoover Dam Cooling Water. Reclamation Research and Development Office. Technical Memorandum No. 86-68220-12-07.

Journal Articles

Pucherelli, S.F., R. Claudi, and T. Prescott. 2018. Control of Biofouling in Hydropower Cooling Systems using HOD Ultraviolet Light. Management of Biological Invasions 9(4): 451-461.

Pucherelli, S.F. and R. Claudi. 2017. Evaluation of the effects of ultra-violet light treatment on quagga mussel settlement and veliger survival at Davis Dam. Management of Biological Invasions 8(3): 301-310.

Description

Several studies carried out in the 1990's have shown that flow-through ultraviolet (UV) light treatment systems have the ability to prevent attachment of dreissenid veligers on downstream surfaces in piped systems (Lewis and Whitby 1993, Chalker-Scott et al. 1993, Chalker-Scott et al. 1994, Evans et al. 1995, Lewis and Whitby 1996, Lewis and Cairns 1998, Pickles 2000). UV light treatment within the UVB and UVC range of the electromagnetic spectrum (<320 nm) are thought to be the most effective at disabling mussels and preventing attachment (Mackie and Claudi 2010). The effectiveness of UV treatment is dependent on site-specific characteristics such as water clarity which affects transmittance, presence of suspended solids, and flow conditions. Effectiveness also depends on achieving the correct UV dose (defined as intensity × exposure time). Reclamation and RNT Consulting Inc. tested the effectiveness of UV for mussel settlement prevention at Hoover, Davis and Parker Dams between 2010 and 2018.

Study Design

A medium pressure UV light unit, designed to deliver a dose of 100 millijoules per square centimeter (mJ/cm^2), was installed on a cooling water system at Hoover Dam in 2009. The performance of the UV unit in the hydropower plant and its impact on mussel settlement were monitored. The system was overhauled at the end of 2011 and two additional UV lamps were installed in order to deliver a higher dose. RNT Consulting Inc. evaluated the performance of the upgraded UV unit.

A full-sized medium pressure UV hydro-optic disinfection (HOD) system from Atlantium Technologies Ltd. was installed on a cooling water line (25.4 cm) at Davis Dam (Figure 3). The unit treated approximately 3,500 GPM and contained six medium pressure UV lamps with a maximum power of 4.2 kilowatts (kW) each. The UV dose was controlled by automatic modulation of lamp output based on in-line sensors measurements of water flow rate, ultraviolet transmittance (UVT), and incoming water temperature in order to achieve the selected UV dose. Real-time readings of the set dose, actual dose, UVT, flow rate, water temperature, lamp power, and lamp age were monitored and recorded during testing using the integrated control panel on the UV unit.

Power usage of the UV unit was measured with an EKM omnimeter power use data logger. Mussel settlement was evaluated in bioboxes at four UV doses (20, 40, 50 and 100 mJ/cm^2). The impact of UV treatment on veligers was also monitored by evaluating veliger mortality after UV exposure. The effect of each UV dose on the mortality of three veliger life stages (straight-hinged, umbonal, and pediveligers) was determined by observing a sample of quagga mussel veligers immediately after exposure, and every 24 hours thereafter for a total of 120 hours post exposure.

After completion of the research at Davis Dam, medium pressure, HOD UV light systems with a 100 mJ/cm^2 target dose were installed on four main turbine cooling water lines and a raw water supply for the onsite water treatment facility at Parker Dam to mitigate mussel and other site-specific biofouling including, colonial hydroid, bacteria, and sponge. The impact of HOD UV on biofouling over a two-year period was subsequently monitored.

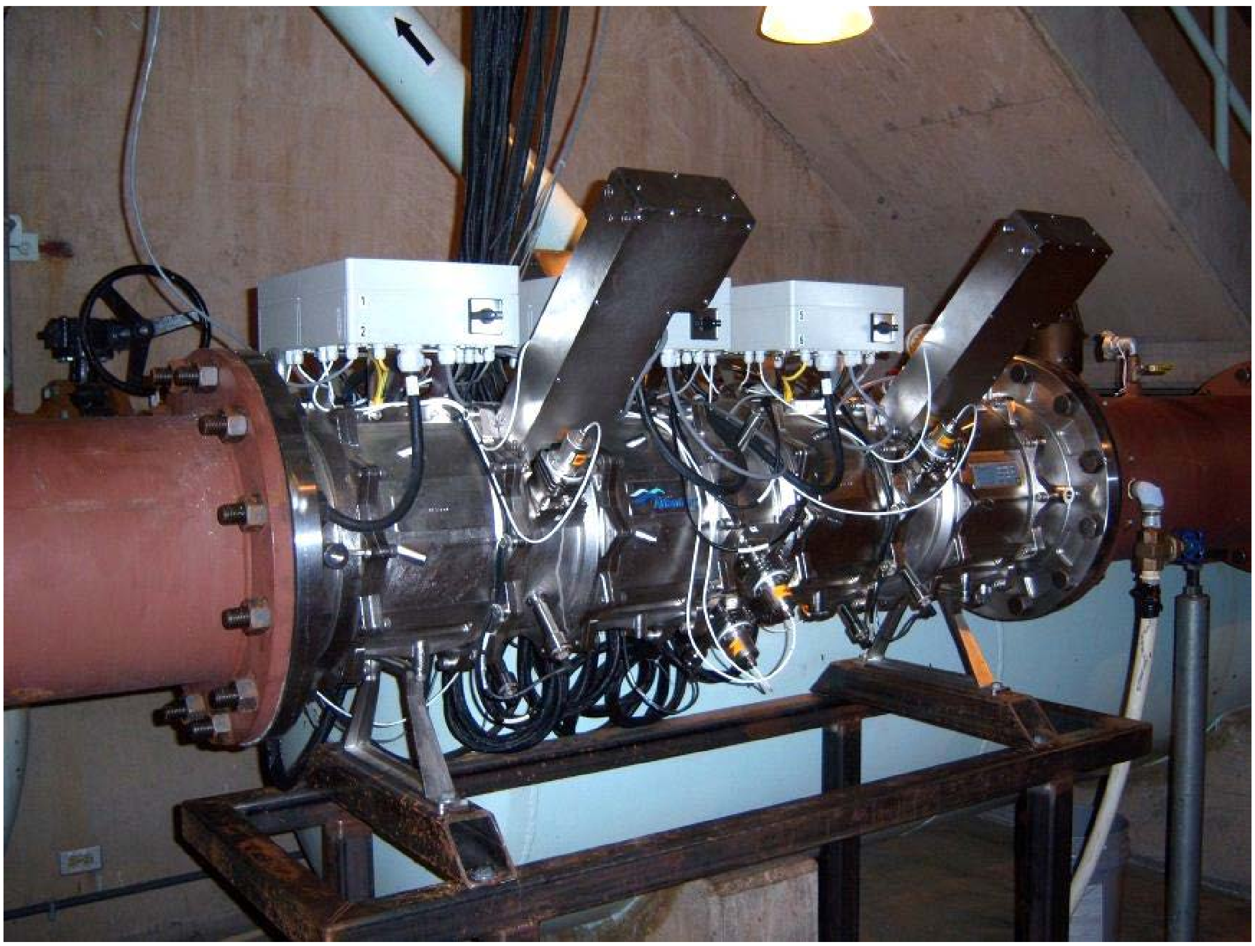

Figure 3. UV unit installed at Davis Dam to test the effectiveness of UV for mussel settlement prevention.

Results

Initial evaluation of the UV unit installed at Hoover Dam indicated the unit required upgrading to improve the ability of the unit to achieve the desired dose. The UV unit was not automated, and researchers were not able to measure the operational dose. Additionally, the wiper system, designed to clean the quartz sleeves protecting the lamps was not robust enough to handle the debris in the raw cooling water. Settlement testing after the unit was overhauled, indicated that an average dose of 100 mJ/cm^2 prevented all downstream settlement. However, settlement in the control biobox and the number of veligers entering the bioboxes was found to be less than expected. The cause was thought to be due to the fact that the UV unit received water pumped from the tail-race, which may have reduced the number of veligers entering the system.

The HOD UV system installed at Davis Dam effectively reduced quagga mussel settlement at all doses tested. Mussel settlement was reduced by 88% at the lowest dose (20 mJ/cm^2) and a 99% reduction was observed at the highest dose (100 mJ/cm^2). Veligers exposed to UV experienced delayed mortality, and mortality rates were variable based on UV dose, monthly environmental conditions, and veliger size. The annual cost to power the UV unit installed at Davis Dam at a dose of 40 mJ/cm^2 was found to be between $3,150 and $4,350. The annual cost to power the unit at 20 mJ/cm^2 was found to be approximately $1,950.

Comparison of biofouling dry weight from settlement plates exposed to HOD UV-treated and untreated water at Parker Dam indicate a significant reduction in total biofouling after UV exposure. Mussel settlement and bacterial sludge formation were consistently reduced in bioboxes despite lower than expected average UV dose. Hydroid settlement reduction data after UV treatment were inconclusive. The Parker Dam facility manager confirmed that biofouling-related maintenance of the coolers was reduced by about 75 percent after the first year of HOD UV operation and eliminated in the second and third years after implementation.

Conclusions

The results of this research indicate that treatment with the Atlantium medium pressure UV is effective in preventing quagga mussel settlement in hydropower cooling water systems. Site specific water quality is a critical consideration for UV treatment mussel settlement prevention effectiveness. Increased levels of turbidity (decreased UVT readings) limit UV penetration and greatly impacts the effectiveness of this control strategy against veligers. It is suggested that self-cleaning strainers are installed upstream of the UV units to remove large debris which can impact the function of the UV unit. It is possible that self-cleaning strainers will not be able to handle the debris loads experienced at some sites, therefore installation location should be carefully considered.

UV units were installed on each of the four cooling water systems at Parker Dam in 2015. Prior to UV installation, all heat exchangers required cleaning and maintenance as a result of mussel fouling and overheating. The increased maintenance required approximately 640 staff hours, annually. After UV installation the heat exchangers have not required maintenance, saving approximately $80,000 per year in labor. UV treatment was also found to reduce bacteria and sponge biofouling. UV installation is currently in progress at Hoover Dam and Glen Canyon Dam.

The cost of UV treatment installation and its effectiveness for mussel settlement prevention is dependent on-site specific conditions including installation location, pipe size, flow rate, water clarity, and water temperature. The cost of the UV units range between $62,500 and $92,500 each. Service contracts are approximately $3,600 per unit annually. The total cost of purchasing and installing 5 UV units at Parker Dam was approximately $995,000 and the cost of purchasing and installing 16 UV units at Hoover Dam was approximately 2.5 million.

An additional finding from the research at Hoover was that the use of cooling water supplied from the tailrace rather than the penstock resulted in a reduction of mussel settlement. The benefits of using tailrace water also include the reduction of the entrainment of mussel shell debris from the penstock and a reduction in power plant noise levels, as the centrifugal pumps emit lower decibel levels than the high-pressure water eductors.

Zequanox

Reports

Link C. 2014. Demonstration of Biweekly Zequanox Treatments to Control Invasive Mussel Populations at Hoover Dam. Report by Marrone Bio Innovations.

Link C. J. Waller, B. Tu, C. Bagley, B. Hohner, S. Rackl. 2011. Davis Dam 2011 Zequanox Facility Treatments Report.

Description

Pseudomonas fluorescens (Pf) is a bacterium commonly found in soil and water. Researchers at New York State Museum discovered a specific strain of Pf deteriorates the digestive lining of invasive zebra and quagga mussels following ingestion and has the potential to kill both adult and larval life stages. Marrone Bio Innovations, Inc. (MBI), via a license agreement with New York State Museum, commercially developed a product derived from dead Pf under the trade name Zequanox®. MBI began testing Zequanox formulations at Davis Dam in early 2009. In 2011, under an EPA Section 18 emergency use exemption permit, Davis Dam became the first United States facility to be treated using Zequanox for an infestation of quagga mussels. The objective of the project was to evaluate the efficacy of Zequanox in cooling water systems.

Another Zequanox demonstration was conducted at Hoover Dam in 2013. Zequanox was applied biweekly for 4 months in an attempt to minimize the size of equipment and the amount of product used in order to minimize the impact to facility operations and the overall cost of the treatment.

Study Design

MBI first applied Zequanox to the infested cooling water system a Davis Dam and monitored mussel mortality in the system after the treatment, to determine efficacy. A linear correlation with turbidity was used to monitor the concentration of Zequanox in the water during treatments. An injection system was designed to deliver Zequanox into the cooling water system to achieve desired concentrations for an estimated cooling water flow rate of 1,300–1,700 GPM. The efficacy of Zequanox applications was determined by monitoring the mortality of a sample population of adult mussels in bioboxes receiving water from the treated cooling system. Mortality of the treated mussels was compared with that of untreated mussels held in bioboxes receiving untreated water. Calculations completed for the NEPA Environmental Assessment (DOI 2011) indicated the dilution downstream of the dam would result in Zequanox concentrations of 0.06–0.29 mg/L. These low levels were considered unlikely to have a negative impact on water quality, and monitoring was completed to identify any unexpected increases in concentration. During treatments, turbidity was monitored with onsite equipment, and samples were collected for biological oxygen demand (BOD) and total organic carbon (TOC).

At Hoover Dam, Zequanox was injected into the cooling water system (approximate flow rate of 1,100 GPM) at 15 milligrams active ingredient per liter (mg a.i./L) for approximately 3.5 hours over 14-day intervals for a total of 8 treatments. The treatments were monitored to determine the effectiveness by comparing mussel settlement density and mortality, in bioboxes, at both treated and untreated points within the system.

Results

At Davis Dam the concentration during the first trial was 3 times less (55 mg active ingredient per liter of water (a.i./L)) than designed (175-185 mg a.i./L) due to higher than expected flow rates (5,000 GPM) in the cooling system. Mussel mortality was found to be 43%. The same mussels were exposed to three additional treatments at 25, 25, and 85 mg a.i./L, and the final mortality rate reached was 75.6%.

The concentration of Zequanox during the second treatment was 85 mg a.i./L and a mortality rate of 77% was achieved. The mussel mortality during this treatment was 19% higher than previous tests but may have resulted from natural end of summer physiologic weakening. The Zequanox concentration during the third treatment was 100 mg a.i./L with a mortality of 43.5%. During this treatment, an unusually extensive algae bloom of Microcystis was occurring throughout the lower reaches of the Colorado River. It is possible that the algae bloom resulted in reduced mussel mortality during this treatment. The complete impact of the algae on Zequanox efficacy and on mussel filtration is still unknown.

Monitoring of downstream water quality, conducted during the three treatments in 2011, showed little-to-no impact on the Colorado River. No detectable difference was observed between locations upstream of treatment and downstream of treatment for measured parameters including turbidity, environmental *Pseudomonas* concentration, and TOC.

All treatments at Hoover Dam were at target turbidity concentrations of approximately 15 mg a.i./L and lasted approximately 3.5 hours. The level of control, indicated by the percent reduction (calculated as [untreated density - treated density]/untreated density) in the settled mussel population, increased during the first four treatments, and then maintained a level of control of approximately 85% for the remaining treatments. The adult mussel population within the Hoover cooling water system experienced 36% mortality during the course of the demonstration.

Conclusions

The mortality results (43.3%, 77.0%, and 43.5% for the June, September, and November treatments, respectively) indicate that application of Zequanox can achieve high mussel mortality in cooling water systems. Applying lower concentration, monthly treatments is a strategy that can be used for mussel management as the cumulative effects of successive treatments were found to increate mortality rates. The higher mortality rate of control mussels in the second treatment was likely due to annual end-of-summer senescence of the mussel population. The weaker physiologic state of mussels is often part of the motivation for all types of end-of-season treatment planning, inclusive of chemical treatments. Despite the success of the Zequanox treatment testing, Reclamation has not implemented this method for control of mussels due to cost.

Turbulence

Reports

Mortensen J.D., S.F. Pucherelli. 2016. Invasive Mussel Control in Pipelines using Turbulence. Research and Development Office, Science and technology Program. Final Report: ST-2016-4183-1.

Mortensen J.D., S.F. Pucherelli. 2014. Invasive Mussel Control in Pipelines using Turbulence. Research and Development Office, Progress Report, Project ID: 4183.

Mortensen J.D., S.F. Pucherelli. 2013. Invasive Mussel Control in Pipelines using Turbulence. Research and Development Office, Project ID: 7169, Document ID: 1070. FOUO PAP-1103

Mortensen J.D., S.F. Pucherelli. 2012. Invasive Mussel Control in Pipelines using Turbulence. Research and Development Office, Project ID: 9829 Document ID: 718. FOUO PAP-1077

Mortensen J.D. 2011. Creating Turbulence to Prevent Invasive Mussel Colonization within Pipelines. Research and Development Office, project ID: 9829, Document ID: 716. FOUO HL-2013-02

Background

Laboratory and field testing were conducted from 2011 through 2016 to determine if increased turbulence intensity can be used to mitigate invasive mussel colonization in piping systems. The theoretical approach was to generate high-intensity turbulent eddies that are smaller than veliger shell size (approximately 200 μm) to expose them to turbulent shear forces and physical damage. A test system was developed using high-pressure water jets to expose mussel veligers to intense turbulence as they flow through the pipe. A variety of jet configurations were tested in order to alter the hydrodynamics of the flow field to produce different shear forces in an attempt to damage the majority of mussel pediveligers.

Study Design

Initial laboratory testing to develop a turbulence generation system was performed in 2011 at Reclamation's Hydraulics Laboratory in Denver, CO. The turbulence treatment was generated using jet nozzles housed in a pipe spool fitting supplied by high pressure pumps. Following initial laboratory development, this turbulence system was installed on a 4-inch pipe of the cooling water subsystem at the Davis Powerplant, where multiple jet nozzle configurations were tested to determine their impact on mussel settlement reduction.

Mussel settlement was evaluated on settlement plates in bioboxes installed upstream and downstream of the turbulence system. Veliger shell damage was examined immediately after turbulence exposure and the amount of veligers in each size class with damage was enumerated. Veliger samples were also collected to determine if the turbulence treatment caused any veliger life stage to exhibit unusual behavior that might prevent settlement.

Results

Turbulence did cause acute physical damage to mussel veliger shells and a correlation was identified between veliger damage and hydrodynamics of the flow field (percentage of damaged veligers increased with average pipe velocity in the turbulent zone). Results showed that turbulence intensity was more important than time of exposure to the turbulent environment. However, results were insufficient to determine the correlation between veliger damage and settlement reduction. Although damage results were variable, turbulence does tend to preferentially damage pediveligers which is consistent with the theory of exposure to turbulent shear forces based on eddy size.

Veliger damage results varied significantly even with consistent operation and hydraulic performance of the turbulence generation system. The reason for inconsistent damage results is unknown. Settlement results obtained from this study were limited and inconsistent, and it was not possible to determine if turbulence treatment significantly reduces mussel settlement in hydropower facilities. Turbulence does not appear to impact mussel behavior, suggesting that settlement would not be reduced as a result of behavioral disturbance.

Key maintenance needs were identified for the turbulence system during long-term field testing. When using raw reservoir water, flow must be filtered to less than 1/16-inch before entering the high-pressure pumps to prevent damage to the pump and/or clogging the jet nozzles. High-pressure hoses must be protected from wear and rubbing due to vibration. Corrosion occurred inside the jet nozzle housing (steel pipe spool). However, no signs of cavitation pitting or erosion were found.

Conclusions

Despite resolving issues that made obtaining consistent results possible, significant settlement reduction was not observed in any of the turbulence configurations tested.

pH Manipulation

Report

Claudi R., T.H. Prescott, K. Prescott, S. Mastitsky, D. Evans, and A.C. Taraborelli. 2012. Evaluating High pH for Control of Dreissenid Mussels. Task order R10PD80829, IDIQ Contract R10PC80264

Description

Dreissenid mussels have a relatively narrow range of pH tolerance, with the optimum range being pH 7.5 to 9.3. It was hypothesized that increasing the pH level may allow for control of growth, settlement, and survival of dreissenids in raw water systems. The purpose of this study was to carry out a "proof of principle" experiment to determine the upper pH at which quagga and zebra mussel veligers will not settle even with adequate calcium levels, and to assess the impact of this elevated pH has on adult mussels. This study also examined the existing regulations regarding the use of sodium hydroxide as a pesticide to determine its potential for mussel control.

Study Design

Two field experiments were carried out using a custom-built flow-through laboratory to test the effect of elevated pH on dreissenid mussels. The first experiment involved quagga mussels at Lake Havasu, Arizona and the second was performed on zebra mussels using water from San Justo Reservoir in San Benito County, California. Both experiments tested the ability of dreissenid pediveligers to settle under conditions of elevated pH, the long-term survival of the adult dreissenids under the same conditions, and the influence on experimental conditions on corrosion rates for carbon steel, stainless steel, and copper.

Raw water containing dreissenid veligers was drawn into the field laboratory and the water was split into four streams which entered 160-L mixing tanks (Figure 4). Three tanks had pH individually increased by the addition of sodium hydroxide solution, the fourth stream acted as control at background pH. On exiting the mixing tanks, each water stream was further subdivided into three streams which flowed into individual settling tanks. Live adult dreissenid mussels were placed in mesh bags in each settling tank, along with a rack containing four settlement plates and six corrosion coupons of carbon steel, stainless steel, and copper. Average corrosion penetration rates were determined gravimetrically.

All tanks were monitored continuously for pH and temperature using electronic probes connected to a programmable logic controller. The controller adjusted the pH by adding a concentrated solution of sodium hydroxide via the metering pumps. All tanks were monitored weekly for settlement.

Figure 4. Flow-through laboratory used to test the effectiveness of increased pH for the control of invasive mussels at Lake Havasu and San Justo Reservoir.

Results

The experiment at Lake Havasu could not be carried out at the desired pH due to the unexpected formation of a calcium carbonate (calcite) precipitate. At the target pH levels there was unmanageable precipitate and the pH test levels had to be decreased for the experiment to continue. Settlement of dreissenid pediveligers at Lake Havasu was inhibited with increasing pH. At the maximum achieved pH of 9.1 there was approximately 90% reduction in the maximum settlement observed in comparison with the controls. However, settlement was almost as low with pH 8.9 as at pH 9.1 (85% reduction in settlement). These results suggest that perhaps the inhibition in settlement was due to the presence of the precipitate rather than the increase in background pH. No mortality of adults was observed at the experimental pH levels. The shell length to total dry weight relationship did not vary between treatments and control suggesting that the adult mussels at the lower Colorado River were not under any growth limiting stress.

The results from the experiment on zebra mussels at San Justo Reservoir are similar to those for Lake Havasu, without the formation of a precipitate. Settlement decreased with increasing pH; at the highest pH tested (pH 9.6) new settlement by zebra mussels was almost entirely absent. The observed mortality of adult zebra mussels was low, but did tend to increase with increasing pH. As with the quagga mussels at Lake Havasu, the shell length to total dry weight relationship did not vary between treatments and control suggesting that the adult mussels were not under any growth limiting stress.

A small sample of adult zebra mussels was exposed to pH of 10, 11, and 12 at San Justo Reservoir. After 12 hours, 90% mortality of adults was recorded at pH 12. Due to the small sample size and possible poor physical condition of the adults in San Justo Reservoir in the spring, the experiment was repeated in October 2011 during which 90% mortality of adults at pH 12 was reached after 120 hours. At the same time, significant mortalities were observed both at pH 10 and pH 11.

In the Lake Havasu experiment, elevated pH had little effect on the corrosion rates for carbon steel and copper, but there was a significant increase in the corrosion penetration for stainless steel. However, the corrosion rates for stainless steel were quite low in absolute terms in all treatments. At San Justo Reservoir, the corrosion coupons showed decreased corrosion rates, compared to the control, for all three alloys.

Conclusions

The results of this study indicate that pH elevation could be used both as a preventative treatment to eliminate settlement by dreissenid mussels and as an end of season treatment to eliminate adults provided the source water does not have a high calcite saturation index. The high pH treatment would have to be tailored to the site water quality. Particularly, if high pH was to be used as end of season treatment, longer treatment at lower pH (10) may be preferable to shorter treatment at higher pH (11 or 12) if the calcite saturation index for the source water is high. Sodium hydroxide is currently registered by the US EPA as a pesticide and is primarily used as an herbicide, fungicide, algaecide, and indoor disinfectant. An application for an amendment to the registration of sodium hydroxide would be required prior to its use for mussel control.

Endothall

Report

Claudi R., C. Taraborelli, T.H. Prescott. 2013. Efficacy of Endothall for Control of Adult Quagga and Zebra Mussels. Prepared for Bureau of Reclamation, by RNT Consulting Inc. Task Order: R11PD81448, IDIQ Contract: R10PC80264.

Description

Various endothall formulations, under different labels, have been used to control aquatic weeds and algae for a number of years. Currently, the di-potassium salt of endothall under trade name, Cascade® is labeled for aquatic plant control in irrigation waters and canal treatments. The effects of this particular endothall formulation on invasive mussels are not known. The amine salt of endothall is currently used for the control of algae and aquatic plants under the trade name of Teton®. The use is restricted to applications in irrigation canals and other bodies of water which do not support fish.

At this time, a formulation of the amine salt of endothall is approved for control of dreissenid mussels in closed systems under the trade name of EVAC®.

The main purpose of the study was to evaluate if endothall based herbicides would impact dreissenid mussels while in use for the treatment algae or aquatic weeds in irrigation channels. But the research also provided insight into the effectiveness of endothall for use in closed pipe systems at hydropower facilities. This research was conducted by RNT Consulting Inc. for the Bureau of Reclamation.

Study Design

Two formulations of the endothall chemical (Cascade® and Teton®) were tested to determine mussel dose/exposure response curves. Adult mussels were exposed to different concentrations of both formulations at 20º C and 25º C water temperatures for 96, 12, 8, and 4 hours. Mortalities were recorded every 12 hours. The experiments were carried out in mobile flow through laboratories (Figure 5). One laboratory was at Davis Dam on the Colorado River to test the effects on quagga mussels, and the second laboratory was situated at San Justo Reservoir in CA to test the response of zebra mussels.

Figure 5. Test facility designed to test the effectiveness of endothall for the control of invasive mussels.

Results

Very low quagga and zebra mussel mortalities were observed after exposure to all concentrations of Cascade®. Maximum quagga mussel mortality (5%) was observed at the highest concentration of Cascade® tested (5 ppm) at 20º C. At 25º C, a maximum mortality of 2.5% was found. No mortalities of zebra mussels were observed at any concentration of the Cascade® formulation at either of the temperature regimes tested.

Quagga mussel mortality was near 100% after exposure to Teton® for 36 hours at 1 ppm, 24 hours at 2 ppm, and 12 hours at 3 ppm in 25º C temperature water. Only 2% mussel mortality was observed in 20º C temperature water after 96 hours of exposure at 1 ppm. Near 100% mortality was reached at the 20º C temperature with 2 ppm for 84 hours and 3 ppm for 24 hours.

Although zebra mussels were less susceptible to Teton® than quagga mussels, they too exhibited increased mortality at warmer water temperature. At 20º C, 34% mortality was reached after 96 hours, while mortality at 25º C reached 75% after 96-hours of exposure.

Conclusions

The results of this study indicate that quagga mussels are more susceptible to Teton® than zebra mussels. However, the water quality is very different between the two test sites and may have been a factor in the effectiveness of the products tested. Equally, the difference may have been species specific. The only definitive answer to the apparently greater impact on quagga mussels would be to conduct side-by-side experiments using both species in the same source water.

The work carried out in this report is also applicable to the potential use of EVAC®, which has the same active ingredient found in Teton®. EVAC® is approved for use in re-circulating and once through cooling water systems. The use label suggests application of 0.3 ppm to 3 ppm as active endothall for 6 to 144 hours of exposure. The label states that more product may be needed if there is a heavy population or if the application temperature is below 21.1 ºC. The product relies on dilution to meet the regulatory discharge limit as degradation is strictly microbial and may be lengthy.

The results of this research indicate EVAC® could be a very successful treatment for quagga mussels but may not be as useful for zebra mussel control. A minimum dose of 1 ppm of active product for 36 hours would be required to kill the majority of quagga mussels from a cooling system at temperatures near 25 ºC. For zebra mussel it would appear that a minimum of 3 ppm would be required for 96 hours.

The use and discharge of EVAC® is regulated by the requirements of the National Pollutant Discharge Elimination System (NPDES) permit. As this product is toxic to fish, effluent containing this active ingredient into lakes, streams, ponds, estuaries, oceans or other waters is prohibited unless in accordance with the requirements of the NPDES permit. The permitting authority has to be notified in writing prior to discharge. Discharge of effluent containing this product to sewer systems is not allowed without previously notifying the local sewage treatment plant authority. NPDES permit requirements vary by application and region and the Regional Office of the EPA would have to be contacted prior to any industrial application.

Copper Ion Generator

Report

Claudi R. and T.H. Prescott. 2014. Evaluation of Copper Ion Generator for Effects on Settlement of Veligers and Impact on Adult Quagga Mussels. Prepared by RNT Consulting Inc. for the Bureau of Reclamation. Task Order: R13PD80252, IDIQ: R10PC80264.

Description

Copper is a known toxicant to mussels. Exposure to elevated levels of copper can result in decreased growth rate, reproductive impairment, enzyme inhibition, reductions or alterations in protein synthesis, and disruptions of ATP synthesis and Ca^{2+} homeostasis (Clayton et al. 2000). Copper ion generators have been promoted as an inexpensive invasive mussel control technology, despite limited available literature on efficacy. A study by Blume et al. (1994) suggested that a dose of 10 ppb above background prevented zebra mussel veliger settlement. A ZM01 copper ion generator from MacroTech Inc. was installed on a side stream of the cooling water supply at Davis Dam in 2013 to test the impact on mussel larvae settlement and adult mussel mortality. The technology was also evaluated for ease of use and reliability. This research was conducted by RNT Consulting Inc., in collaboration with the Reclamation Lower Colorado Dam's Office.

Study Design

Mussel settlement was observed on settlement plates placed in bioboxes that received a consistent flow of water. One biobox received input from the copper ion generator, while another biobox received untreated raw water and acted as a control. In addition to settlement evaluation, captive adult quagga mussels were placed in both bioboxes to evaluate the effect of continuous low dosage of copper ions on adult quagga mussels. The flow into each biobox was measured with a totalizer which allowed verification that both streams were delivering the same amount of water.
Raw water flowed through the generator at 13 GPM and the current was set to 1 ampere. A peristaltic pump was used to extract a constant quantity of copper ion solution from the generator discharge and to inject the known quantity into the test biobox (Figure 6). A variety of copper concentrations were tested in an attempt to produce a dose-response curve. Copper concentrations were measured in control and treated samples using a Hach DR900 colorimeter and additional samples were sent for laboratory analysis.

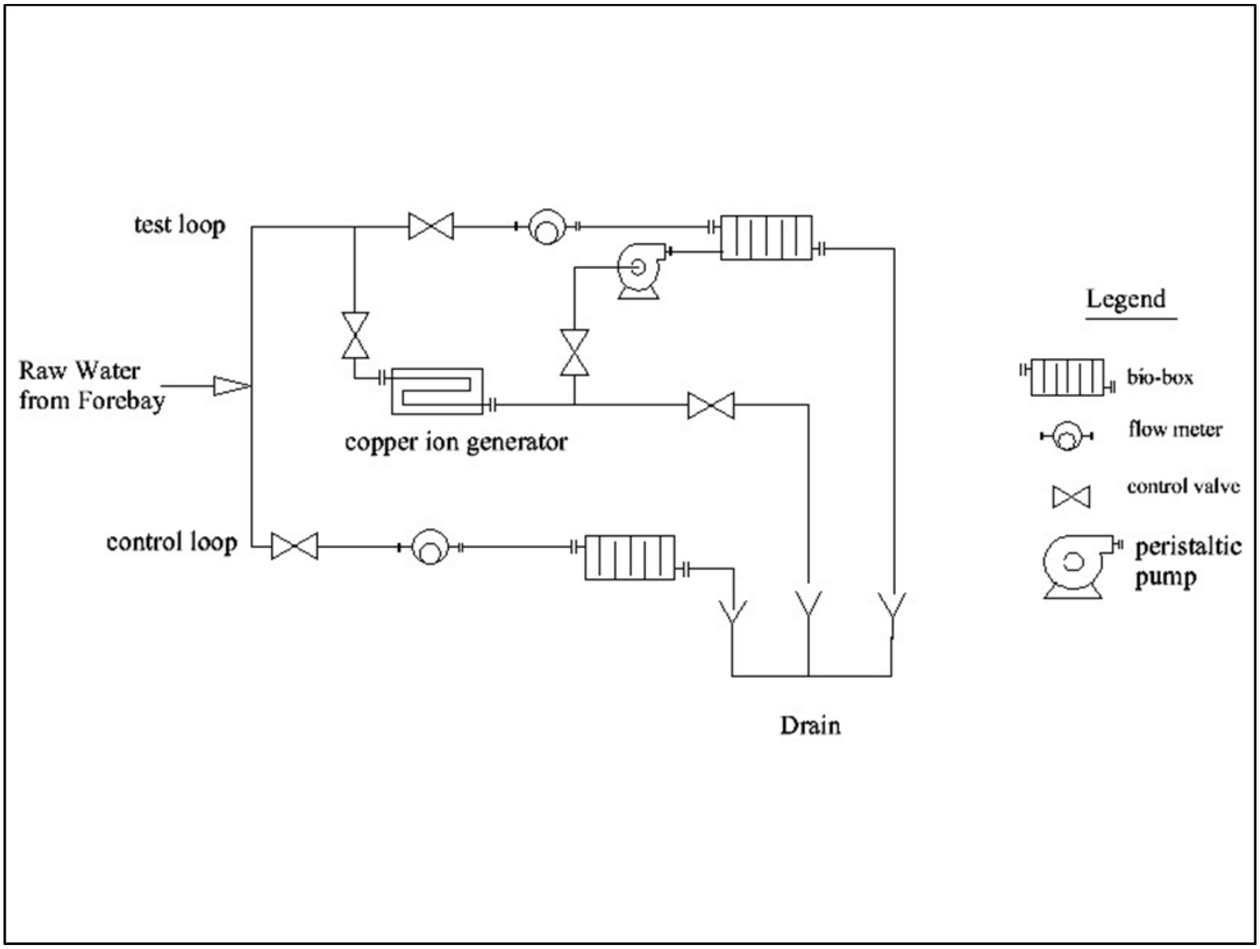

Figure 6. Experimental set up designed to test a copper ion generator at Davis Dam.

Results

The copper ion concentration being produced by the generator was found to be erratic and at lower levels than expected. The ZM01 unit manufacturers manual indicated that the unit would be capable of treating 2,000 GPM, but the levels of copper ion detected indicate that the unit would only be capable of treating a total flow stream of approximately 200 GPM. During the study the flow and impressed current were always within the manufacturers recommended settings. At the conclusion of the study it was discovered that the copper electrodes were coated with deposits and a significant amount of scale was being shed from the electrodes. The reduced and erratic copper ion production was likely due to unwanted side reactions. The light blue color of the scale suggests that copper carbonate was being formed, likely a result of the high alkalinity (130 mg/L $CaCO_3$) of the Colorado River water. Water chemistry has a significant influence on the toxicity of the copper ion; therefore, the results of this study are only applicable to the site-specific water chemistry at Davis Dam. The response of quagga mussels to the same copper ion levels would likely differ in other water chemistries.

In all six tests, settlement was observed in both the control and in the treated bioboxes. There was approximately 75% reduction of settlement in the treated bioboxes with treatments that had greater than 15 ppb copper concentration. Reduction of settlement dropped to 38% when treatment concentrations were lower than 15 ppb. However, when the copper ion concentration was in the 15 to 20 ppb range, the settlers observed in the treated bioboxes were smaller (0.5 mm to 1 mm) than those observed in the control biobox (0.5 mm to 5 mm). This finding suggests that the copper limited growth after settlement. Complete adult mussel mortality was not observed at any concentration and was variable based on copper ion concentration, length of exposure, and ambient water temperature.

Overall the results of this study indicate that copper ion levels between 10 and 40 ppb above background do not prevent settlement of quagga mussel veligers in Colorado River water. The toxic effect of the copper appears to occur after mussel settlement, limiting growth and leading to mortality. Copper ion levels remained consistent in the water stream for at least 20 minutes. Therefore, in a typical hydraulic power plant or pumping station where the residence time of the cooling water is 20 minutes or less, all of the cooling water piping downstream of the copper injection point should be protected. Given the observed mechanism of action, a continuous treatment at 20–25 ppb would likely prevent infestation from developing and eventually eliminate any adults which may be present. Equally, a periodic treatment at 40 to 50 ppb for four weeks is likely to eliminate all juveniles and adults present in the system in four weeks, particularly during warmer weather.

Conclusions

RNT Consulting Inc. recommends repeating this copper toxicity evaluation using an alternative source of copper ions to verify the dose findings in this evaluation. In an industrial setting, it would be easier to add a precise amount of copper to the treated stream using a liquid source of copper ions with stable copper concentration, thereby avoiding the instability issues observed with the ion generator method. Additional testing to confirm the treatments effectiveness on zebra mussels and on mussels in different water chemistries is also recommended. Any copper ion generator being proposed for commercial or industrial use should include provision for the following:

- An automatic on-board method to alarm when electrodes are deteriorated and easy access to the ion chamber for inspection and maintenance.
- A method of cleaning the electrodes of deposits without opening the generator such as a clean in place (CIP) circuit, mechanical wipers or water softener that is used in the ion generator.
- Automated current regulation.

Conductivity Manipulation

Report

Pucherelli, S.F., S. O'Meara. K. Bloom, J. Kirsch. 2016. Habitat Suitability Parameters for Quagga Mussels in the Lower Colorado River System and at Reclamation Managed Facilities. Research and Development Office, Science and Technology Program. Final Report ST-2015-754F-01

Description

Quagga mussel settlement downstream of Parker Dam, near Imperial Dam is less dense than locations upstream in the Colorado River. Although it is the same water source, the water quality is slightly different at downstream locations. The water quality parameters showing the greatest difference are conductivity, total suspended solids, and temperature. All of these water quality parameters are known to impact the survivability of mussels. It was hypothesized that a slight manipulation of conductivity may provide control of the growth, settlement, and survival of dreissenids in raw water systems at hydropower facilities. Conductivity was selected for examination because a single point addition of salts appeared to be a more practical treatment for a hydropower facility since temperature increases or addition of total suspended solids would negatively impact the function of cooling water systems. In January and April 2015, biobox studies were set up at Davis Dam to determine the impact of increased conductivity on quagga mussel settlement and adult survival.

Study Design

The tests were conducted using two existing, flow-through, bioboxes installed on a cooling line. The arrangement was retrofit with a flowmeter and conductivity loggers (Figure 7). Each biobox received cooling water, containing mussel larvae from the cooling water system. The water flow rate into the bioboxes was set to 2 gallons/min and was logged hourly, along with conductivity and temperature. The control biobox received untreated water. The treated biobox received a continuous drip of concentrated salt solution to increase conductivity to downstream levels. The concentrated salt solution consisted of 446.27 grams of magnesium sulfate ($MgSO_4$) and 472.21 grams of sodium chloride (NaCl) per gallon of water. A peristaltic pump was used to pump the concentrated salt solution from a holding tank into the biobox at 5 ml/ min (Figure 7).

Ten PVC settlement plates were placed in each biobox to monitor settlement. The duration of each test was one month. At the end of a test, settlement plates were scraped, and the collected sample was observed under a microscope to determine the total number of mussels collected from the plate. The water quality in each biobox was monitored weekly using a YSI multi-probe, and additional water samples were collected from each box and sent to a laboratory for analysis of conductivity, pH, TDS, cations and anions.

The effect of increased conductivity on adult mussels was also observed. Adult mussels from the Davis Dam forebay were collected and placed in mesh bags. Two bags, each containing 10 mussels, were placed in each bio-box. At the end of the one-month long exposure, adult mussels were examined for mortality.

Figure 7. Bioboxes installed at Davis Dam, where concentrated salt solution was added to increase the conductivity to mimic downstream water quality where mussel settlement is less.

Results

Dripping a salt solution into a biobox at Davis Dam increased the conductivity to 1.178 milliSiemens per centimeter (mS/cm) during test 1 and 1.200 mS/cm during test 2. The conductivity levels achieved during these two tests were comparable to conductivity observed in Colorado River water near Imperial Dam. Average conductivity in the control biobox during test 1 was 0.992 mS/cm and 1.002 mS/cm during test 2. Other water quality parameters stayed consistent between the control and treated bioboxes throughout the duration of the study. Mussel settlement was reduced by 22% in the first test and 30% in the second test. No adult mortality was observed in either control or treated biobox at the end of each month-long test.

Conclusions

Although the slight increase in conductivity did appear to reduce settlement, settlement reduction was not significant enough to pursue additional research. But it is possible that conductivity manipulation may be more effective for small scale application at sites with different background conductivity levels.

Laser-Generated Pulsed Pressure

Report

Kubitscheck J., S.F. Pucherelli, M. Spidell, and P. Williams. 2017. Pulsed Pressure Technology Development and Testing for Invasive Mussel Control. Research and Development Office, Science and Technology Program. Final Report ST-2017-1612-01.

Description

Pulsed pressure technologies can be classified as mechanical, electrical, or optical. The efficacy of these technologies for mussel control depends on being able to produce sound pressure levels (SPLs) that either damage, kill or elicit a response that prevents mussels from settling. This threshold is estimated to be approximately 0.04 megapascal (MPa) (212 decibel (dB) ref 1 μPa) based on a single available literature source (Schafer et al. 2010). Each of the technologies is capable of producing comparable SPLs, with some differences in pulse duration and spectral content. However, optical (laser) technology has the advantages of requiring less energy with much faster pulse rate capability. By comparison, mechanical technologies are limited to open water applications by size of equipment (cumbersome to deploy), relatively low pulse rates (>5 seconds per pulse), and lack of automation. Electrical sparkers are less cumbersome to deploy, but require more energy, have even slower pulse rates (>30 seconds per pulse) owing to capacitor charge time, and suffer from limited electrode service life.

Based on the above considerations, optical pulsed pressure technology was selected for evaluation. Optical pulsed pressure generation utilizes lasers to focus light energy into a very small volume to create a rapidly expanding and contracting vapor bubble in the production of a shock wave and associated high-intensity acoustic pulse (Lauterborn & Vogel 2013). The concept for mussel control applications involves exposing mussel larvae to high intensity pressure pulses as they pass by the laser cavitation site (treatment) while being transported in a piped system (e.g., a cooling water supply pipe). The hypothesis being that exposure to large changes in pressure over a short duration (pulsed pressure waves) will either damage veligers or elicit a response such that veliger settlement does not occur in downstream portions of the piped system.

The objectives of this project were to assess the potential for optical pulsed pressure lasers to induce high intensity SPLs and, if feasible, develop a field deployable prototype for testing to evaluate the potential for controlling mussel settlement in hydropower cooling water systems. The project was a collaborative effort between Reclamation and the National Institute of Standards and Technology (NIST) Physical Measurements Laboratory in Boulder, CO.

Study Design

Development and testing of the laser pulsed pressure technology was conducted in two phases. The first phase involved initial proof-of-concept to demonstrate the capability of lasers to generate sufficiently large SPLs (Figure 8). The second phase included follow-on development and testing of a field deployable prototype that was installed on a branch of the cooling water system at Reclamation's Davis Powerplant. Field testing included prototype functional performance and biological evaluations. The biological evaluations involved several one-month exposure tests to assess the effects of pulsed pressure treatment on mussel damage and settlement reduction. Mussel settlement before and after exposure to the laser treatment was examined on settlement plates in bioboxes. Veliger samples were collected from upstream and downstream of the laser and examined under a microscope to determine if the laser caused visible physical damage to the veliger shell. Additionally, a TUNEL (terminal deoxynucleotidyl transferase dUTP nick end labeling) assay was used to detect DNA breakage.

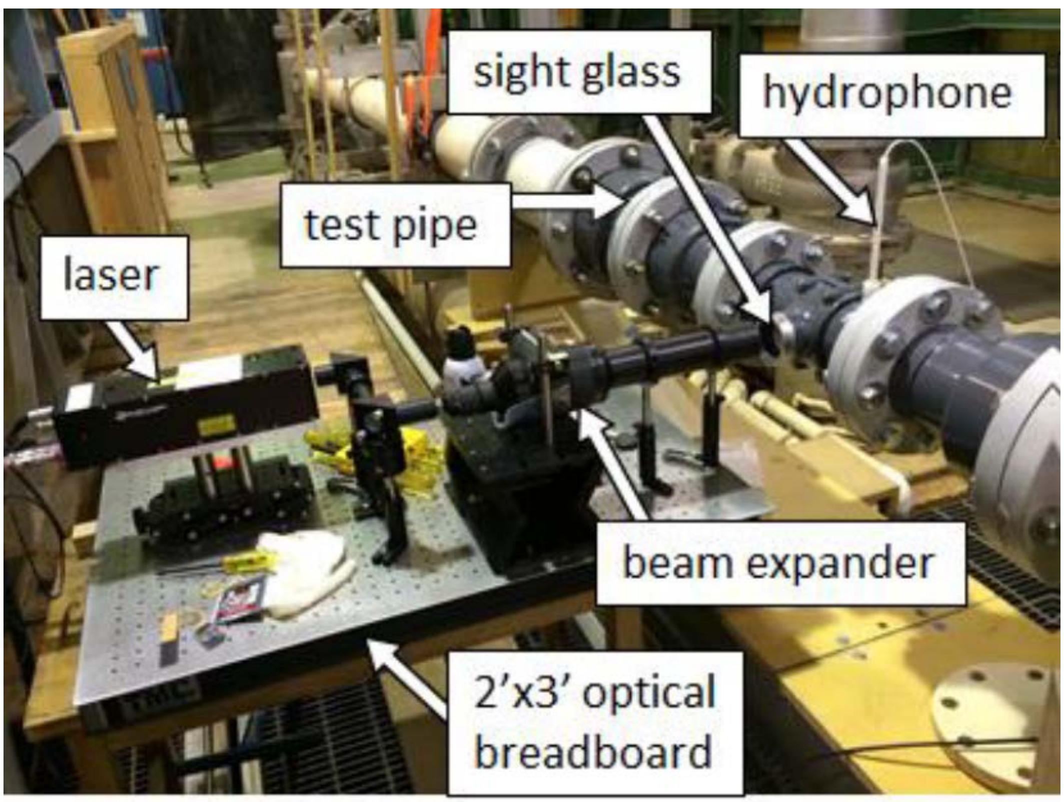

Figure 8. Laser pulsed pressure test setup at Reclamation's Hydraulic Laboratories in Denver, Co

Results

Although a functional laser-based pulsed pressure prototype was successfully developed (demonstrated to be capable of producing high intensity sound pressure levels), field testing indicated the treatment had no effects on mussel settlement and damage. The following conclusions are summarized as

- Optical laser technology is capable of producing sound pressure levels in water up to 0.24 MPa (227 dB ref 1 µPa) with an Nd:Yag laser power of 400 mJ at pulse rates up to 20 Hz.
- Although mussels were exposed to SPLs considerably above the assumed settlement threshold 0.04 MPa (212 dB ref 1 µPa) and at much higher pulse rates than that reported in the literature, the effects of pulsed pressures on mussel damage and settlement were found to be negligible.
- The optical laser technology did not reduce mussel settlement and exposed veligers did not exhibit shell or cellular damage.

Conclusions

Based on the findings of this study it is concluded that pulsed pressure technology has little promise for controlling mussel settlement in hydropower cooling water systems.

Centrifugal Separator

Report

Kubitschek J. and S.F. Pucherelli. 2017. Centrifugal Separator Evaluation for Mussel Shell Debris Removal and Settlement Reduction. Research and Development Office, Science and Technology Program. Final Report ST-2017-8169-01.

Description

The centrifugal separation concept has been in use for many decades, to separate components of different densities in a heterogeneous mixture. The physical processes involve an imposed inertial force (often referred to as centrifugal force) that is directed radially away from an axis of rotation in a multi-constituent fluid. More recently, centrifugal separators (sometimes referred to as cyclone separators) have been used in water treatment processes for solids removal. The concept for such an application involves passing water through an upright or inclined cylinder containing an internal annulus and baffling components in such a manner as to create swirl. The swirling motion generates radial inertial forces by which particulates of larger density are separated from the primary flow and settle to the bottom of the cylinder for periodic purging. Recognizing that mussel shell debris has a larger density than water, it was postulated that such a system may be capable of shell debris removal without the need for system shutdown for manual cleanout. Although various manufacturers of centrifugal separators exist, the Lakos (Lindsey Corp) system was selected for purchase and testing primarily due to cost and availability.

The primary objective of this study was to evaluate the effectiveness of centrifugal separation for removal of mussel shell debris and reduction of mussel settlement in hydropower cooling water systems. Laboratory testing was performed using a test facility constructed at Reclamation's Hydraulics Laboratory in Denver, Colorado to evaluate operational characteristics and shell debris removal performance. Subsequent field testing was conducted at Reclamation's Davis Dam to evaluate settlement reduction performance on a hydropower cooling water subsystem.

Study Design

In the laboratory, flow to the separator was supplied from the laboratory pump system to a head tank. Water was then drawn from the tank using a 3 HP centrifugal pump which charged the separator at the required operational flowrate (Figure 9). Treated water from the separator was discharged to a settling tank with an overflow weir to capture solids that were not removed by the separator. The setup included an automatic purge value at the bottom of the separator to purge separated debris. The flowrate for all tests was set at 0.40 ft^3/s (approximately 180 GPM) within the separator design range of 130-225 GPM. Preserved dead mussel shell debris obtained from Lake Mohave, AZ was passed through the separator. Mesh bags were attached to the discharge side of the separator and on the discharge end of the purge system to capture debris. The total wet weight of debris collected from the discharge of the separator (not separated) and the purge (separated) were compared with the total wet weight of debris introduced to obtain separation efficiency.

Following laboratory testing, the centrifugal separator was shipped to Davis Dam for installation on a test branch of a turbine packing and runner seals cooling water supply piping. Flow through the separator was approximately 175 GPM. A bag filter housing with 800-micron filter media was installed on the purge line for collection of shell debris that was removed by the separator. Purged debris was collected from the bag filter housing monthly and dried in a 105°C oven for 24 hours to obtain a dry weight. Finally, bioboxes were installed upstream and downstream of the separator for the control and treatment settlement evaluation.

Quagga mussel settlement was analyzed on settlement plates in bioboxes pre and post separation to determine if the separator was capable of removing pediveligers from the cooling water. At the end of each one-month test the mussels which settled on both sides of each plate were collected and enumerated using cross polarized light microscopy. Veliger samples were collected from sample ports located upstream and downstream of the separator using a 64-µm plankton tow net to determine if the separator was capable of removing significant numbers of veligers of different size classes. Additional veliger samples were collected to determine if any veligers were purged.

Figure 9. Laboratory setup for preliminary centrifugal separator testing

Results

The laboratory testing results suggest that a centrifugal separator comparable to the Lakos design is capable of removing significant percentages (65-80%) of shell debris. It was observed that most of the weight collected on the outlet (not separated) consisted of mussel tissue with very few shells passing through the separator. Mussel settlement was not reduced downstream of the separator during field testing indicating low separation efficiencies for mussel larvae. Only a small proportion of veligers from each size class were purged by the separator which is consistent with the lack of settlement reduction. All samples collected from the bag filter housing contained mussel shells indicating the separator, as installed, is capable of removing mussel shell debris in the relatively low-flow cooling water subsystem supply at Davis Dam.

Conclusions

Although the performance of the separator for settlement reduction does not appear effective, performance regarding shell debris removal does appear promising. During the course of field testing, the separator operated continuously for the entire six months without requiring any maintenance. This operational characteristic, combined with shell debris removal, represents good potential as a low maintenance technology for mussel shell mitigation.

Typical cooling water systems are protected from debris using conventional strainers installed just downstream of supply piping takeoffs from penstocks or scroll cases. However, given typical cooling water system flowrate requirements (on the order of thousands of GPM), strainer media size is limited to about 1/8-in perforations. While this size removes a large portion of shell debris, it is too large to prevent smaller shell debris from passing and impacting downstream systems. The use of centrifugal separation downstream of existing strainers may relax the 1/8-in strainer medial requirement such that improved (lower maintenance) shell debris removal could be possible with conventional 1/4-in media (i.e., without the need to reduce strainer media size as is commonly recommended for cooling water systems exposed to mussels).

Research Projects in Progress (2020)

Carbon Dioxide

Preliminary research into the use of carbon dioxide for invasive mussel control is promising (Waller and Bartsch 2018). The addition of carbon dioxide to water reduces the pH and also reduces the bioavailability of calcium. Mussels are very sensitive to changes in pH and calcium availability which can inhibit shell growth. Additionally carbon dioxide is a natural chemical that does not require a separate or specialized production, is already produced in large quantities, is recycled from initial combustion waste streams for good environmental stewardship, has an indefinite shelf life, nonflammable, is easy to handle and store, does not require electrical or mechanical power to deliver, and can be distributed easily and evenly in water, including hard-to-reach confined water. Once treated, water is freely exposed to the air at the outlet, purged, or the carbon dioxide is stripped and reused, equilibrium is quickly re-established and goes back to ambient pressure, so that it will not affect the downstream water ecology. The goal of this research is to develop an effective delivery method for carbon dioxide to treat flowing water in pressurized piped systems. Additional research will be conducted to determine the lowest dose needed to prevent mussel settlement in typical cooling systems.

Ultrasound

The goal of this research project is to test the effectiveness of ultrasonic waves for the prevention of invasive mussel settlement on critical water facility infrastructure (e.g., intakes trashracks). Ultrasonic transducers have been designed and are currently being used to control algal blooms. While studying the impact of ultrasonic waves on algae, researchers also noticed a reduction in overall biofouling, including native mussel settlement at some locations. The impact of ultrasound waves on invasive dreissenid mussel settlement has not been studied, but it is theorized that ultrasonic waves prevent the growth of biofilm and potentially limit food availability for settled mussels preventing their growth and survival after settlement. A field study is being designed to quantify mussel settlement reduction and biofilm accumulation. The field study will occur at Lake Powell, AZ, where a dense quagga mussel population will allow for settlement analysis. Reclamation is pursuing a Material Transfer Agreement with AlgaeControl.US, LLC to obtain two ultrasonic treatment units for field testing.

Electrical

Electricity has been shown to impact mussel behavior, including mortality and a reduction in the rate of byssogenesis (byssus attachment). Methods include electrified fields which inhibited passage of live veligers (larval life stage) and electrical currents which prevented attachments on metallic surfaces. This project proposes to carry out well established electrical testing procedures to investigate the effectiveness of electrical control methods under field conditions similar to those found in Reclamation facilities. The goals of this project are to determine and compare the electrical dosage and electrical power consumption of AC and DC applied at different waveforms (sinusoidal AC, squared DC, cycle rates, etc.) to induce quagga mussel mortality and inhibition of byssogenesis with raw water parameters typically found in Reclamation facilities on the Colorado River. These key electrical parameters will be correlated with the observed behavior of quagga mussels at different life stages.

The survival and attachment of quagga mussels will be compared between exposed and unexposed groups at each set of conditions by using parallel chambers receiving the same raw water at the same flow rate. Some of the key water parameters to be monitored includes water chemistry, physical parameters, temperature, construction materials, and flow rates. Electrical control in a small metallic pipe such as a raw water-cooling line would not be the same as electrical control on a very large radial gate. Construction materials and size must be considered during testing. Isolation of the applied electrical field to prevent adverse impact on neighboring infrastructure are routinely designed by electrical engineers. Grounding, nonconductive spacers for separation, or treatment of confined water are a few examples that have been used to prevent the propagation of electrical fields to neighboring non-target infrastructure. Materials to be used for electrodes will be chosen from commercially available sources that do not cause a change in pH in the water and do not cause corrosion of nearby metallic surfaces.

Self-Cleaning Strainers

The goal of this research is to determine if self-cleaning strainers and filters can be used to more effectively manage mussel shell debris impacts with reduced maintenance at Reclamation facilities. Research will include analyzing commercially available products to select those that have the greatest potential and likelihood of success. Equipment will be purchased and tested at the Reclamation's Hydraulics Laboratory, prior to installation at a Reclamation hydropower facility (to be determined) where mussels are present. The ease of operation, maintenance requirements, and ability of the strainer(s) to successfully remove mussel debris will be assessed.

Conclusions

Invasive mussel fouling is a significant issue for Reclamation and its hydropower facilities. The research summarized in this report is unique because much of the testing was conducted on-site and provides useful insight into how the treatments work in true conditions and on actual systems they were designed to protect. The efficacy and suitability of many mussel control treatments are site-specific, as they are impacted by installation location, water quality, and other unique variables at the site. Conducting research in hydropower facilities can be difficult and may provide inconclusive results. The design and timing of projects must be scheduled around plant operation and oftentimes unforeseen events impact the research timeline. Analysis of mussel settlement requires undisturbed water flow through bioboxes for at least one months' time, and interruption of the flow into the biobox requires restart.

While most of the treatments summarized in this report have not been implemented, many do show promise and may be suitable for locations other than where they were tested. Some treatments were not implemented because testing did not significantly impact mussel settlement, others were not implemented despite positive results. The common reasons that treatments were not implemented or further pursued, despite positive results, include increased maintenance requirements, cost, durability, discharge permitting requirements, and inability to identify a good location for installation. Most of the time the decision to move forward with implementation is subjective and complicated by site specific factors. Currently very few Reclamation facilities are impacted by invasive mussels, as mussels are not currently widely distributed in the western United States. The research presented in this report, along with methods developed and tested by others will provide newly impacted facilities with treatment options. Reclamation will continue to research new methods for mussel control because a variety of methods are needed to protect hydropower facilities with unique designs, operation, and water quality.

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