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Mussel beach: Lake Powell has 'trillions and trillions of these things'
By John Hollenhorst Jun 2, 2018, 2:00pm MDT

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Quagga mussels are pictured at the Glen Canyon Recreational Area on Wednesday, May 9, 2018. The shells of tiny quagga mussels are now so visible and dense on rock surface at Lake Powell that tourists will have trouble avoiding them. John Hollenhorst, Deseret News

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GLEN CANYON NATIONAL RECREATION AREA — As recreationists flock to Lake Powell this summer — as they always do — many of them are going to be shocked.

The shells of tiny quagga mussels — much like clamshells — are now so visible and so dense on rock surfaces that tourists will have trouble avoiding them.

They're usually out of sight; the invasion of quagga mussels has been building underwater for six years. But now, with water levels low, dead and dying shells are out of the water and clinging to rocks in astronomical numbers.

"Last spring was the first time that we noticed mussels in the north end of the lake at all," said Andre Delgalvis, of Grand Junction, Colorado, as he motored out of the harbor at Bullfrog Marina, the major boating facility on the northern portion of the vast man-made reservoir. The veteran boater pointed out that Lake Powell's famous white "bathtub ring" isn't so white this year.

"All this dark material that you're seeing on the side of the wall, it goes up maybe 15, 20 feet," Delgavis said. "These are all mussels that have just appeared within the last year."

He motored past mile after mile of tiny shells — the size of a fingernail or smaller — covering vast stretches of exposed rock.

"It's just mind-boggling that there could be such an outbreak and so many of these," Delgalvis said. "I mean, we're talking trillions and trillions of these things."

Officials of the National Park Service are quick to point out that it's not a new outbreak. It's actually more like the lowering of a curtain.

"In the years past, the water has been at a level that the average boater that comes and goes has not been able to see the mussels," said Colleen Allen, aquatic invasive species coordinator of the NPS-administered Glen Canyon National Recreation Area.

Last year the lake level went up vertically about 28 feet, allowing mussels to climb higher on the reservoir's rock walls. Now — after one of the driest winters on record — the lake is low again, leaving uncountable trillions, possibly quadrillions, of shells. Allen calls it "an opportunity to help folks to really understand what's below the water level."

Many boat owners already understand it. When boats are left in the water for long periods, their hulls, propellers and outboard motors become covered with shells. The mussels, which are native to the Black Sea region of Eurasia, are generally carried lake-to-lake on somebody's boat. Indeed, quagga mussels and their zebra mussel cousins are believed to have entered North America when a ship from the Black Sea entered the Great Lakes and emptied its ballast tanks.

On a smaller scale, that's apparently how quagga mussels got into Lake Powell — by hitching a ride on a boat that was hauled by trailer from a previously infested waterway.

"You get the people that don't care enough to wash their boats properly and this is what happens," boat owner Scott Lodder of Kaysville said as he gestured toward Lake Powell.

Federal and state agencies spent years in an aggressive campaign to educate boaters and to inspect and sometimes clean boats before they entered Lake Powell. After losing that battle, the agencies turned their strategy upside-down. Instead of trying to keep quagga mussels out, they're now trying to keep them in so they won't spread to other lakes and rivers. The focus is on boats leaving Lake Powell.

"You want to clean your boat, drain your boat and then let it dry," Allen said, emphasizing the main theme of the ongoing boater-education effort. Some boaters don't need additional persuasion.

"We watched Lake Mead get ruined" by quagga mussles, said Cedar City boat-owner Mike Sherratt. "Our support is 100 percent behind this effort to try and contain it."

At the Glen Canyon Dam, which created Lake Powell by plugging the Colorado River, the impacts from mussels so far are not great; they involve just a bit of extra cleaning.

"It has led to about eight more days worth of work for two people," said Shane Mower of the U.S. Bureau of Reclamation.

But the dam's problems might be just getting started. Quagga shells are turning up in nooks and crannies of the dam, and they've infested parts of the plumbing. A huge underwater control-gate that was recently removed for cleaning had a coat of shells 2 to 3 inches thick.

Next year, to protect the dam's cooling-water pipes and fire-suppression system, the bureau plans to install filters with ultraviolet light to kill the quaggas.

"And that's got a price tag of about $1.8 million," Mower said.

Last year, sampling of the lake suggested the possibility that the infestation might be leveling off in the lower end of the lake. But experts say it's too soon to say if that's a real trend.

With so much of the lake now infested it will take plenty of effort — by government agencies and especially boaters — to keep Lake Powell's mussels from spreading elsewhere.

"Well, a lot of people feel that it's a lost cause," said the Bureau of Reclamation's Robert Radtke. "But, you know, until you quit, the fight isn't over."

Costs for controlling dreissenid mussels affecting drinking water infrastructure: Case studies

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Costs for Controlling Dreissenid Mussels Affecting Drinking Water Infrastructure: Case Studies

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Dreissenid mussels—zebra mussels (*Dreissena polymorpha*) and quagga mussels (*Dreissena rostriformis bugensis*)—have infested various North American waters used for drinking water, causing clogging of water intakes and pipes and contributing to the formation of disinfection by-products. The management and control of mussels that have infested various treatment plant components (e.g., intake structure, pipes) is a priority for facility managers. Ten case studies of drinking water facilities contending with ongoing mussel infestations illustrate the capital costs and operations and maintenance (O&M) costs related to mussel control. The O&M-based unit costs of mussel control varied from $34.32/mil gal for 1-mgd capacity to $12.63/mil gal for 2,640-mgd capacity. The capital cost and O&M-based equivalent annual unit cost for treatment varied from $78.56/mil gal for 1-mgd capacity to $13.41/mil gal for 2,640-mgd capacity. Costs for larger water treatment plants (i.e., >10 mgd) varied between $1.00/mil gal and $13.00/mil gal.

Keywords: *capital cost, chemical treatment, Dreissena control, intake structure, operation and maintenance cost, water treatment plant*

Zebra mussels (*Dreissena polymorpha*) and quagga mussels (*Dreissena rostriformis bugensis*), referred to here as dreissenid mussels, are closely related, small-bodied bivalve species originally native to an area near the Caspian Sea (Mackie & Claudi 2010). The inadvertent introduction and subsequent spread of dreissenid mussels in source waters such as lakes, reservoirs, rivers, and other connected water systems throughout the United States present an economic and operational threat to water conveyance facilities (USGS 2015, Cary Institute of Ecosystem Studies 2011, TPWD 2012, Nalepa et al. 1995). Infestation of source water bodies by dreissenid mussels can negatively affect water supply, water quality, and food web ecology within these systems. Heavy mussel infestations occasionally create conditions that promote blue-green algae blooms and negatively affect recreational fisheries and water treatment facilities that depend on these source waters (Chakraborti et al. 2013; CH2M HILL 2009, 2007; Miller & Ignacio 1994; Ramcharan et al. 1992). Increased maintenance is also required in affected systems to dislodge mussels and remove dead shells (O'Neill 1993) from tanks, basins, and water treatment processes.

Maintenance of mussels in drinking water infrastructure is not only cumbersome and poses water quality threats but is also expensive. Although the literature includes numerous articles on such topics as the distribution of dreissenid mussels in water infrastructure and their water quality impacts (Chakraborti et al. 2013, 2010; Mackie & Claudi 2010; Nalepa et al. 1995; Miller & Ignacio 1994; Ramcharan et al. 1992), few studies report on the costs of maintaining and controlling mussels in drinking water infrastructure (Turner et al. 2011, Park & Hushak 1999). However, these studies do not explore costs for mussel control under variable environmental/site conditions that reflect the recent experience of various water infrastructure facilities that have been dealing with dreissenid mussel problems for many years. No recent study has explored the budgetary constraints for keeping treatment plant components functioning in the face of variable degrees of mussel infestation.

BACKGROUND

Mussel impacts and remediation methods. Among the various impacts of dreissenid mussels, the clogging of pipelines and water conveyance systems (including intake structures) poses severe problems to drinking water facilities. Various chemicals, in particular oxidizing chlorine-based chemicals, have been used to control dreissenid mussels in water infrastructure. Although these chemicals are effective in controlling mussel populations, they can adversely affect the water quality of receiving waters (Chakraborti et al. 2013). The formation of disinfection by-products (DBPs) is one of several drawbacks of using oxidizing chemicals such as chlorine. For example, an increase in total organic carbon (TOC) and harmful algal blooms (HABs) mediated by dreissenid mussel activity in source waters may exacerbate DBP levels in the treated water and increase potential complications in treatment processes to eliminate this toxicity. DBP formation depends on TOC levels, water temperature, chlorine, pH, bromide, and contact time. Increased TOC may require altering the water treatment processes in order to meet state and federal regulatory limits for finished water before distribution (Chakraborti et al. 2013).

As an alternative to oxidizing chemicals, nonoxidizing chemicals have been tested for controlling veligers (i.e., larval stages) and adult mussels in water systems. Unlike chemical oxidants, nonoxidizing chemicals do not promote the development of DBPs and are generally considered easier and safer to handle than oxidants such as chlorine (Chakraborti et al. 2010). In July 2014, a highly selective and environmentally compatible molluscicide[1] composed of dead cells of a naturally occurring microbe, *Psuedomonas flourescens,* was approved by the US Environmental Protection Agency for application in open water to combat invasive dreissenid mussels in lakes, rivers, recreation areas, and other open bodies of water. In general, the choice of specific mussel control methods, including chemical treatment, is highly system-specific because of the variability in opportunities and constraints presented at various sites and in the physicochemical and biological conditions of various raw water bodies (Chakraborti et al. 2002). Both fixed and moveable infrastructure components—ranging from fish screens, trash racks, and pump stations to pipes, aqueducts, valves, gates, cables, chains, and filters—are vulnerable to mussel infestations. Economic costs associated with the control and management of mussel infestations in these facilities can be considerable (Lovell et al. 2006).

Implications of mussel infestation. Potential economic and environmental impacts in the western United States could be greater than those in the eastern region of the country (CDFG 2011, California Science Advisory Panel 2007). Although no specific estimates are available for amounts spent directly on mussel control activities (e.g., control and prevention) or amounts lost indirectly (e.g., potential fishery decline) in the western United States, Turner and colleagues (2011) provided a list of expenditures for four federal agencies that were tasked with dealing with quagga mussel infestations. In 2008, the National Park Service spent \$5.0 million for inspection, the US Fish and Wildlife Service spent \$1.8 million for its aquatic invasive species program, and the US Geological Survey spent \$0.2 million for support to deal with dreissenids (Turner et al. 2011). From 2008 through 2010, the US Bureau of Reclamation spent \$12.6 million for research, prevention and control, early detection, and education (USBR 2012). The potential cost for upgrades to 13 hydropower facilities in the Colorado River Basin alone has been estimated to be \$23.6 million, with chemical costs estimated at another \$1.3 million per year. One study estimated that the Metropolitan Water District of Southern California alone would spend \$10 million to \$15 million annually in operations and maintenance (O&M) costs to address the quagga mussel infestation in its Colorado River Aqueduct and terminal reservoirs (De Leon 2008). The researchers estimated that about \$7.2 million of this total would be spent on design and installation of infrastructure to control mussels.

Approximately 1,200 water treatment plants (WTPs) operate in the western United States and rely on lakes and rivers for their raw water supply. Each one could potentially incur additional costs for facility improvements and annual maintenance to control dreissenid mussels (De Leon 2008). According to the US Fish and Wildlife Service (2012), the Massachusetts Department of Conservation and Recreation annually spends \$250,000 on staff, \$300,000 on equipment, and \$25,000 on publications related to zebra mussel prevention and control. The state will spend an additional \$71,000 over five months to install new boat ramp monitors for zebra mussels (USFWS 2012).

Control of new infestations of dreissenid mussels in existing WTPs often involves alterations to various physical–chemical water treatment methods (Connelly et al. 2007, Park & Hushak 1999). Control of mussels in the infested source water is typically not possible because of regulatory restrictions and potential impacts on the ecology and end uses of the system. Rather, mussel control measures are commonly implemented in the water treatment facility itself, typically at the intake structure, transmission pipe, and water treatment methods. The study described here was undertaken to provide an overview of capital and O&M costs for *Dreissena* control in source waters so that current experience of WTP personnel could help guide facility managers facing similar challenges.

STUDY DESIGN

This review provides case studies of direct and indirect costs associated with the implementation of specific measures to manage existing mussel infestations in water treatment facilities across North America. The authors present examples of mussel control costs at 10 drinking water treatment facilities in Canada and the eastern, midwestern, and western regions of the United States; these case studies were compiled from information provided by the WTP personnel and from online information.

The goal of the study was to present experiences from a variety of utilities dealing with mussel infestations in different ways. To ensure that study results could be used as an effective management tool for planning similar systems in other regions, case study facilities were selected to encompass a range of geographic locations, environmental conditions, source water quality characteristics, and degree of infestation by dreissenid mussels. The facility components surveyed included source waters with water intake structure, pipeline, and WTP operations.

Representatives from the drinking water infrastructure facilities were interviewed to determine

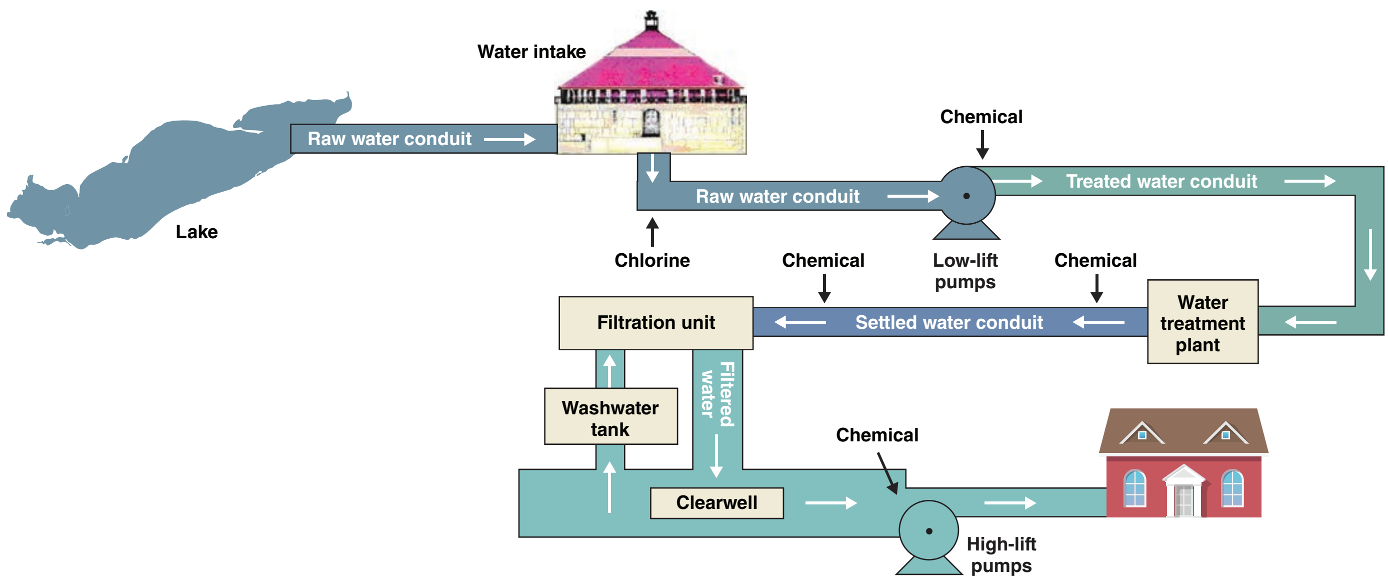
- the date when mussels first invaded the system,
- the manner in which mussels were first detected and the trend of mussel population fluctuations after detection,
- the types of control measures that were undertaken and found effective, and
- the capital and O&M costs for implementing the most suitable mussel control options.

The costs for mussel control presented here also included capital and O&M costs normalized to the plant's design treatment capacity.

OVERVIEW OF MUSSEL IMPACTS, CONTROL, AND COSTS

Drinking water infrastructure system and mussels. Figure 1 presents a simplified schematic of typical components of a drinking water distribution system. Core components include source water, intake structure, pump station, and conveyance pipelines of a conventional WTP. The water intake structure receives raw water from the source via a raw water pipeline. This raw water is pumped to the WTP after primary treatment with a chemical

FIGURE 1 Schematic of a typical drinking water distribution system



(chlorine in this depiction). The filtration unit receives water from the WTP units through a settled water pipeline. Typically chemicals are added to the settled water in the pipeline. In a broader sense, the WTP is referred to as a unit comprising the process components of a conventional drinking WTP, including coagulation/flocculation, sedimentation, filtration, disinfection, and conveyance pipes. Chemical doses and contact times are determined on the basis of the quality of influent raw water and to comply with regulatory limits of potable water. The lengths and size of pipes leading to the intake and in other parts of the distribution system can also vary depending on the quantity, quality, and proximity of the source water; the plant capacity; and design considerations.

Mussel veligers can be transported over considerable distances within the water treatment system before they settle and grow; as a result, various components of the system (including pumps) can be simultaneously infested. Although some of the chemicals used in water treatment systems are also effective for controlling mussels, once the source water is infested with adult and/or juvenile mussels, the treatment regimen must be optimized for mussel control in terms of chemical application locations, frequency, and quantity of dosing, and the types of chemicals used. Pipe material, size, pipeline geometry (e.g., number of bends, tees, constriction or expansion), and water velocity within the pipe are significant determinants of mussel infestation and govern design considerations for the chemical and/or physical control of these infestations. To cope with mussel population in the source water, WTPs often need to modify their system components, incorporate continuous monitoring into their O&M activities, and adjust chemical doses and contact times accordingly. Water infrastructure system components that are at the greatest risk of infestation by dreissenid mussels include intake structures and screens, pumps, small-diameter piping and valves, dead ends in the pipeline, areas with low water flow/velocity conditions or with stagnant water, and areas with abundant organic matter and oxygen (Table 1).

Control of dreissenid mussels. Once dreissenid mussels are established in source waters, the water intake structure becomes highly vulnerable to mussel infestation. Components of the intake structure at risk include log boom and piles, fish screens, chain and scrapers, pumps, pipes and valves, settling pond systems, control structures, adjustable weirs, and instrumentation. Buildup of mussels within intake pipes causes loss of flow—initially because of increased friction to flows and later because of volume restrictions. Dreissenid mussels generally will settle, attach to, and grow on surfaces where flows are approximately <6 ft/s (Boelman et al. 1997).

Physical and chemical methods, including antifouling materials and coatings, have been implemented to protect parts of the intake structure from mussel impacts (Chakraborti et al. 2013). Physical control measures such as scraping, oxygen deprivation, and desiccation can be effective control measures for protecting intake structures (Claudi & Mackie 1993). Mussel-infested pipes connected to the intake structure can also be protected using physical measures such as pigging, which involves forcing a flexible plug through pipelines to remove debris and mussels that accumulate on interior pipe surfaces. Manual cleaning—including hydroblasting, abrasive blasting, and wire brush cleaning—is also used to remove mussel infestations, particularly from small-diameter outfall diffuser nozzles. The installation of screens made of copper, brass, or nickel are effective because veligers avoid attaching to these surfaces (Wells & Sytsma 2009, Marsden & Lansky 2000). Hydraulic residence time of water in the transmission pipe and pumps is an important design consideration to allow for sufficient

TABLE 1 Water infrastructure system risks and vulnerabilities

Facility	Component	Potential Risks Caused by Dreissenid Mussels
Intake structure	Solid plates above/below screens	Operability[a]
	Intake screen rail system	Operability, sealing surfaces
	Air burst piping	Operability
	Chemical feed piping	None
	Bulkhead gate system	Operability, sealing surfaces
	Intake structure	Operability
	Intake channel	Secondary population[b]
	Wet well	Secondary population
	Pump	Hydraulics[c]
	Pump can	Blinding[d]
	Process piping, <12 in.	Hydraulics
	Blow-off piping	Hydraulics (at discharge)
	Valves	Operability
	Meters/instrumentation	Maintenance, reading error
	Pig launcher	None
Pipeline	Pipeline	Hydraulics, water quality, corrosion
	Air release	Operability
	Blow-off	Operability, vector transfer[e]
	Valves	Operability
Balancing reservoir	Pig catcher	Vector transfer
	Balancing reservoir	Secondary population
Booster pump station	Pig catcher	Vector transfer
	Forebay	Secondary population
	Pumps	Hydraulics
	Valves	Operability
	Process piping, <12 in.	Hydraulics
	Meters/instrumentation	Maintenance, reading error
	Pig launcher	None
Terminus	Outlet structure	Vector transfer
	Valves	Operability
	Meters/instrumentation	Maintenance, reading error
	Terminal reservoir	Vector transfer
	Pig catcher	Vector transfer

[a]Operability refers to the ability to operate machinery or equipment.
[b]Secondary population is the formation of a colony of species in a new location.
[c]Hydraulics refers to the restriction of flow caused by the presence of biofilm or invasive species.
[d]Blinding is a blockage of a particular component by a substantial accumulation of an invasive species.
[e]Vector transfer involves the transmission of a species from one location to another.

chemical contact time for mussel control. The small size of veligers (about 70 to 300 µm) requires that screening systems be appropriately designed in order to be effective. Sand filtration systems or, where practical, intakes buried in infiltration beds are effective at removing most mussel veligers from intakes (TPWD 2010), as are online filters of 40-µm mesh (Mackie & Claudi 2010).

Monitoring of veligers in source waters will indicate if the reproductive season is year-round or limited to warmer months. Chemical treatment can be conducted as a low-dose, continuous feed targeting veligers during the reproductive season or intermittently at higher doses to target the settled juveniles within the infrastructure. The chemical of choice depends on availability, cost, need for taste-and-odor control, need to avoid the production of DBPs, and other site-specific constraints. Some potential choices of chemicals include ozone in gaseous form, which is attractive from the perspective of effectiveness, simplicity, and treatment chemistry; potassium permanganate ($KMnO_4$), which can be effective against dreissenids, especially veligers; and chlorine compounds. Gaseous-source chemical feeds such as chlorine and ozone are normally constant-flow, variable-concentration designs. Changes in the amount of chemical applied at the intake will need to consider the response lag time, which is equal to the travel time from the chemical source to the intake. Liquid-source chemicals (e.g., hypochlorite) can be more easily applied at constant concentrations in variable-flow systems since response lag time will be minimal (Chakraborti et al. 2013).

Once viable populations of dreissenid mussels have been found in the water treatment facility, adjustments in coagulant dose, dose of disinfectants such as chlorine and/or ozone, and changes in the filtration process will be necessary. For example, adjustments in unit processes—such as powdered activated carbon (PAC)/granular activated carbon versus nanofiltration/ultraviolet/reverse osmosis—may be necessary if HABs are present in the source water (Alvarez et al. 2010). Obviously, any adjustments in unit processes requiring additional treatments and chemicals used will likely increase O&M costs.

Water treatment facilities typically will need to develop a multipronged strategy that includes public education and outreach; monitoring; assessment; and various control, containment, and management strategies as part of a comprehensive plan for managing and controlling mussel infestations in their source waters and facilities (Chakraborti et al. 2013). A multibarrier approach is often adopted for effective control of mussels in water systems, given that a single control method is often not optimal or may not provide the required redundancy for protecting complex water facilities. Life-cycle cost estimates and comparative analysis enable facility managers to select the control strategy that best fits their needs and is based on consideration of internal and external constraints and financial limitations. In addition, evaluations of any mussel control strategy will need to take into account the potential for unintended consequences (e.g., impacts on nontarget organisms, public health, and water quality) within the facility and the source water ecosystem.

Costs for mussel control at drinking water facilities. Economic costs for the management and control of dreissenid mussels will vary with the extent of mussel infestation in the source water and associated facility, the complexity of the WTP, its treatment goals (such as targeting adult mussels, or veligers, or both), the size of the WTP, and the designed unit processes of treatment. The following section provides case studies of capital costs and O&M costs incurred at various WTPs in Canada and in the eastern, midwestern, and western United States, whose source waters are infested by dreissenid mussels. For each case study, a brief description of the system components, O&M practices, and mussel control measures implemented is provided, and the costs (capital and O&M) of mussel control are described. Life-cycle cost analysis is provided for facilities that used chemical and physical methods for controlling mussels and includes the capital cost for installing tools and equipment as well as annual recurring O&M expenses that include costs for chemicals, equipment, power, and labor.

Unit cost per million gallons of water production for mussel treatment was computed from the annual O&M cost and respective design capacity of the WTPs. The equivalent annual cost (EAC) is the cost per year of owning and operating an asset over its entire lifespan. It is calculated by dividing the net present value (NPV) of a project by the present value of annuity factor (Jones & Smith 1982). The capital cost and O&M cost were used to determine the EAC per treatment capacity of the WTPs. For estimation purposes, a 6% rate of interest and 15-year lifespan of treatment technique were assumed. Table 2 summarizes the costs for controlling mussels at various water infrastructure facilities. A detailed description of each facility as determined from the survey is provided in the following section.

CANADIAN AND EASTERN US FACILITIES

Case study 1. Source water: Lake Erie, Ohio. *System components.* Raw water from Lake Erie enters the WTP through an intake structure located about 2.9 mi offshore under approximately 22 to 24 ft of water. The intake structure is concrete and has an outside diameter of 83 ft and an inside diameter of 43 ft, with 16 intake ports, each 10 ft^2. From the intake structure, raw water enters the lower pump station via a 15,470-ft (~3-mi) long, 108-in. diameter intake conduit, where it is subsequently screened and pumped to the plant for treatment. Two raw water force main pipes made of reinforced cement, each about 9 mi long with diameters of 78 and 60 in., connect the intake crib to the water filtration plant, which has a capacity of 120 mgd.

Mussel control. Initially, sodium hypochlorite (NaOCl) was used continuously for controlling mussel infestations at the intake structure. Because of the formation of DBPs, the WTP stopped adding chlorine at the raw water intake structure and switched to $KMnO_4$. NaOCl is less expensive than $KMnO_4$ on a per-unit basis and requires less chemical handling equipment. In order to maintain residual $KMnO_4$ concentrations of <0.2 mg/L in the water entering the WTP, $KMnO_4$ is added continuously at the intake crib at doses dependent on influent flow rates. For example, about 1 mg/L $KMnO_4$ is added at the intake at a 70-mgd-flow-rate plant. $KMnO_4$ is added not only for mussel control but also as a coagulant aid for water treatment processes.

No chemical for controlling mussels is added to the transmission pipes between the intake structure and the WTP. However, PAC slurry is added to the water flowing through the transmission pipes to avoid taste and odor problems attributable to blue-green algae. The contact time of chemicals ($KMnO_4$ and PAC) in the pipes varies between 4 and 6 h. A dose of 0.5 to 10 mg/L of PAC provides effective taste and odor control.

O&M. Lake Erie has experienced variable dreissenid mussel population dynamics over the years since the discovery of mussels in the late 1980s. Biologists found that zebra mussel densities were highest in the western basin of Lake Erie but mussels had declined after only two years of colonization (USFWS 2015). Routine O&M activities led to detection of zebra mussels in the raw water intake pipe, when their presence was first verified in August 1989 during underwater inspection of the surge well and intake piping. Hydraulic testing on Hazen–Williams *C*-factors was performed periodically to determine the effects of zebra mussels on flow restrictions (friction) through the raw water intake and the raw water transmission pipe. Roughness coefficient values indicated the extent of pipe clogging attributable to the presence of mussels, which provided information about reduced the volume of inflow to the plant.

Commercial divers periodically clean the raw water intake pipe with high-pressure water spray and remove mussels from the intake structure; this reduces the infestation load temporarily, but infestations quickly recur. In 2011, divers inspected 250 ft of the raw water intake pipe and found a 2- to 4-in.-thick layer of live mussels on the interior of the pipes. This finding led to regular cleaning of these big pipelines by divers as part of a routine maintenance schedule.

Cost. The cost in 2011 of chemicals for mussel control was as follows: $KMnO_4$ ($2.54/lb), chlorine ($0.17/lb), and PAC ($0.90/lb). Although chlorine is considerably less expensive than $KMnO_4$ for mussel treatment, DBP formation potential and possible source water pollution limited its use at the intake. Unit cost for mussel treatment was $9.23/mil gal in 2011 (Table 2). Total costs for control are dependent on the following factors: stage and extent of infestation (adult versus juvenile mussels), plant components, complexities in monitoring and using control measures, proximity of the treatment plant to source water, and regulatory compliance requirements.

Case study 2. Source water: small lake, N.Y. *System components.* The WTP (capacity of ~1 mgd) receives water from a small lake through an intake structure located 45 ft below water and 50 ft offshore. The small lake is 7.8 mi (12.6 km) in length with a surface area of 4,046 acres (16.37 km^2). Its average depth is 82 ft (25 m), with a maximum depth of 167 ft (51 m). The 14-in. cast-iron transmission pipe between the raw water intake and the WTP is approximately 4,300 ft long. The intake pipe was clogged by juvenile mussels that were present in the source water lake. Modification in the water infrastructure along with measures for juvenile mussel control were needed because if left unchecked, the juveniles mature into adult mussels, and eventually colonization could restrict flow through the pipes and affect water production.

Mussel control. In addition to pigging of the intake structure, the intake was modified to include pumping of $KMnO_4$ into the raw water transmission main at the water intake screen via a 2-in.-diameter solution feed line made of high-density polyethylene pipe. The feed line was installed by attaching it to the raw water transmission main extending from the WTP to the intake. With a baseline $KMnO_4$ residual of 0.25 mg/L to kill adult and juvenile mussels and a raw water $KMnO_4$ demand of 1 mg/L, the dosage required to effectively prevent the mussels from colonizing the raw water main was estimated as 1.25 mg/L. The design criteria for control of mussels with $KMnO_4$ determined

TABLE 2 Summary of cost for controlling dreissenid mussels at water infrastructure facilities

Case Study (Region of North America)	Source Water (Design Treatment Capacity)	Year[a] (Chemicals Used Primarily for Mussel Treatment)	Cost for Installation and Treatment (Year of Cost) *US$*	Unit Cost for Treatment: O&M Cost (Year of Cost) *US$/mil gal*	Unit Cost Based on EAC[b,c] *US$/mil gal*	Mussel Population Trends in Source Water (Increasing/Decreasing/Cyclic)	Status Update (as of Jan.1, 2014)
Case study 1 (East)	Lake Erie (120 mgd)	1980 ($KMnO_4$ and PAC)	O&M cost: 398,900/year (2011)	9.23 (2011)	—	Mussel population fluctuates but overall has decreased from initial infestation.	Environmental conditions suitable for mussel growth/reproduction led to heavy infestation in Lake Erie in the 1990s and early 2000. Quagga mussels have recently overtaken the population of zebra mussels. The western part of Lake Erie is shallow and more heavily infested than other parts. The mussel population has stabilized after initial fluctuation.
Case study 2 (East)	Small lake (1 mgd)	2008 ($KMnO_4$)	Capital cost: 154,670 (2013) O&M cost: 12,355/year (2013)	34.32 (2013)	78.56	With increasing mussel population, intake structure design must be modified.	An increasing trend was observed due to favorable environmental conditions and a good food source for dreissenid mussels.
Case study 3 (East)	Lake Ontario (730 mgd)	Early 1990s (chlorine)	Capital cost: 5 million O&M cost: 100,000/year (2011)	3.81 (2011)	2.34	Mussel population has fluctuated over the years but is currently steady.	Environmental and limnologic conditions are favorable for mussel populations, but infestation seems stabilized in recent years.
Case study 4 (Midwest)	Lake Erie (16 mgd)	Mid-1980 ($KMnO_4$)	Chemical costs 15,909/year (2011) 24,581/year (2010) 13,199/year (2009) 9,844/year (2008) 6,988/year (2007)	Chemical costs 5.12 (2011) 6.86 (2010) 4.11 (2009) 3.14 (2008) 2.26 (2007)	—	Mussel population has fluctuated over the years but is currently steady.	The western part of Lake Erie observed an initial fluctuation of zebra mussel populations. Recently, the quagga mussel population in the western basin appears to be stabilized.
Case study 5 (Midwest)	Lake Erie (165 mgd)	1988/1989 (physical cleaning)	Capital cost: 12,000/year (2011) O&M cost: 50,000/year for four plants combined (2011)	0.84 (2011)	0.86	Mussel population has fluctuated over the years, but currently mussel population is steady.	The central basin of Lake Erie has a smaller mussel population than the western basin. After ~20 years since the late 1980s, the mussel population has been stable followed by fluctuations in population.
Case study 6 (Midwest)	Lake Erie/ Lake Huron (400 mgd)	Late-1980s (chlorine)	O&M cost: 133,266/year on NaClO (2011)	0.93 (2011)	—	Mussel population is fluctuating but decreased from initial infestation and is currently stabilized.	Current design practice at the WTP is based on the current stable population of mussels in the source water.
Case study 7 (Midwest)	Lake Erie (18 mgd)	1989 (chlorine)	Total capital cost for feed lines, tanks, etc.: 367,268 (2006) O&M cost: 13,315/year (2011) 14,026/year (2010) 9,358/year (2009)	2.05 (2011)	7.89	Mussel population has remained steady over recent years; historically cyclic, it is decreasing overall from initial infestation.	Despite better control of the treatment method, there are some taste and odor problems that partially caused by blue-green algal blooms.
Case study 8 (Midwest)	Reservoir (6.5 mgd)	2007 (copper ionization)	Capital cost for copper ion treatment installation: 1.37 million design–build (2010) O&M cost: 30,000/year (2011)	12.82 (2011)	73.10	Mussel population fluctuates but currently is steady.	Reservoir has historically experienced fluctuations in mussel population because of seasonal water temperatures varying from more a favorable to a less favorable range for zebra mussels.
Case study 9 (West)	Lake Mead (900 mgd)	1997 (chlorine/ chloramines)	Capital cost: 6.0 million combined for three intake structures O&M cost: 219,000/year on NaClO and 131,400/ year on chloramine, totaling $350,400/ year for chemical treatment (2011)	1.08 (2011)	2.99	Mussel population has generally been cyclic, but it has decreased from initial infestation and is currently stabilized.	Lake Mead experienced a low to high to stable quagga mussel population over the last few years. Favorable physical–chemical and environmental factors have contributed to a stable mussel population. The WTP is experimenting with better control water treatment methods to deal with the mussel problem in the source water.
Case study 10 (West)	Lakes/ reservoirs (2,640 mgd)	Early 2007 (chlorine)	Capital cost: 7.2 million (2010) O&M cost: 10 million–15 million (2010)	12.63 (2010)	13.41	Lake mussel densities were less than $1/ft^2$ in February 2007, increased to $1,000/ft^2$ in January 2008.	Favorable physical–chemical environmental condition has contributed to high growth and reproduction of quagga mussels in reservoirs and water conveyance system.

EAC—equivalent annual cost, $KMnO_4$—potassium permanganate, O&M—operations and maintenance, NaClO—sodium hypochlorite, PAC—powdered activated carbon, WTP—water treatment plant

[a]Year infestation was first discovered
[b]Using capital cost and annual O&M cost
[c]Assuming a 6% rate of interest and 15-year lifespan for treatment

Dashes indicate EAC costs could not be derived because capital cost information was missing for these case studies.

that at a flow rate of 1 mgd, the exposure time to kill adult and juvenile mussels would be approximately 53 min through the length of the transmission main. Per design estimates, a minimum 30 min of contact time with $KMnO_4$ was assumed to be sufficient to kill adult mussels and veligers. In addition, special material made of a copper–nickel alloy was used to construct the intake screen as an effective surface for preventing mussel colonization. Although the $KMnO_4$ system was designed for continuous dosing, it was operated only when source water temperatures rose above 50°F, when adult mussels began to reproduce and veliger abundances increased.

O&M. The facility's O&M staff conducts an annual pigging of the raw water intake main to prevent the pipeline from clogging with mussels.

Cost. Table 3 shows a breakdown of this WTP's capital and O&M costs for mussel control assuming the system operates on a continuous basis. The construction cost includes construction of the new intake screen and removal of the existing screen. The capital cost also includes cost for components of chemical feed equipment and solution feed pipe.

The unit cost for mussel treatment was $34.32/mil gal in 2013; it is $78.56/mil gal based on EAC estimates (Table 2). The relatively higher cost for treatment at this WTP compared with other facilities is attributable to its smaller size and extensive modification of the facility.

Case study 3. Source water: Lake Ontario, Ont. *System components.* This potable water distribution system receives water from Lake Ontario through intake structures for four large-sized WTPs (design capacities of 251, 162, 211, and 106 mgd). Intake and transmission pipes (varying from 6 to 11 ft in diameter) are between 3,280 and 6,840 ft in length. Zebra mussels were found on the exterior of the raw water intakes in the early 1990s.

Mussel control. Typically 0.8 to 1 mg/L of free chlorine is added at the intake for controlling mussels as a part of prechlorination of the water treatment system operations and to kill zebra mussels. Intake and transmission pipes allow about 10 to 15 min of contact time for chlorine. Typically chlorine is added each year only during May–October when the mussel population is at its peak in the source water.

O&M. The use of chlorine to ward off zebra mussels from the water intake pipes required the extension of the prechlorination solution lines to the mouth of the intake pipes in the lake. All of the chlorine solution would then be drawn back into the treatment plant so that there would be no addition of chlorine to the lake environment. Levels of chlorine in the finished drinking water were continually monitored and regulated at the end of the water treatment process to ensure that chlorine levels in drinking water did not exceed permitted limits. No chemical was added to the transmission pipeline leading to the WTPs since the chlorine added at the intake crib seems to provide satisfactory control of the mussel infestation.

Cost. Although the unit cost of chlorine is inexpensive compared with other common chemicals used for mussel control, the total cost of control for such a large system (730 mgd, the combined design capacity for the four WTPs) is considerable. Under this treatment regime, the growth of mussel colonies was sporadic and did not affect water flows through the intakes and transmission pipes. Unit cost for mussel treatment was $3.81/mil gal in 2011; it is $2.34/mil gal based on EAC estimates (Table 2). The proximity of the WTPs to source water, the length of transmission pipe, and the complexities of the treatment systems influenced the total cost.

TABLE 3 Cost of installation and operations for mussel control in a 1-mgd WTP (case study 2)

Item	Cost—*US$*
Annual O&M Cost	
Granular $KMnO_4$	9,855
Power and pumping	1,500
Miscellaneous	1,500
Total annual O&M cost	12,355
Construction (Capital) Cost	
Intake screen	
New intake screen and removal of existing screen	18,000
Chemical feed equipment	
Chemical feed pump	2,500
Solution feed pump	2,300
Saturation equipment	7,800
Water softener	1,200
Miscellaneous (e.g., piping, valves, equipment)	4,000
Solution feed pipe	
Solution feed pipe (4,250 lin ft at $15/lin ft)	63,750
Band clamps (at 15-ft spacing)	4,250
Diver and assistant (80 h at $400/diver/h)	32,000
Directional drilling (222 lin ft at $85/lin ft)	18,870
Total construction (capital) cost	154,670

$KMnO_4$—potassium permanganate, O&M—operations and maintenance, WTP—water treatment plant

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Case study 4. Source water: Lake Erie, Ohio. *System components.* The WTP intake crib is located in the western basin of Lake Erie under 16 ft of water and about 1.5 mi offshore. The crib is totally submerged and connected to a low-pressure pumping station. Raw water is drawn from the lake via a 48-in. intake line and transported from the low-pressure pumping station to the WTP through 5 mi of 36-in.-diameter pipe. The WTP treats 16 mgd (667,000 gph) of water.

Mussel control. Since the onset of the zebra mussel infestation in Lake Erie, $KMnO_4$ is fed to limit mussel growth in the intake conduit year-round with doses varying from 0.2 mg/L (to kill predominantly small juveniles) to 1.5 mg/L (to kill adult mussels). The only chemical added in the 5-mi-long transmission pipeline between intake and WTP is liquid PAC at a 4% solution to control taste and odor caused by blue-green algae blooms.

O&M. As a part of regular maintenance of the water infrastructure facility, $KMnO_4$ is used to limit the growth in the intake conduit, the low-pressure force main, and the suction wells. Mussel infestation fluctuates but has demonstrated an increasing trend from its initial colonization. Cost of control per million gallons of production reflects the mussel population trend.

Cost. The O&M cost of $KMnO_4$ treatment is mainly the recurring annual cost of the chemical. The capital cost for installation was not available. The annual cost of $KMnO_4$ treatment varied with the degree of infestation in the source water, which generally increased from 2007 to 2011. Unit costs for mussel treatment for 2011, 2010, 2009, 2008, and 2007 were $5.12, $6.86, $4.11, $3.14, and $2.26 per mil gal, respectively (Table 2). The O&M cost clearly correlates with the extent of colonization of mussels. Additional annual O&M costs also included the costs to remove mussels from the screen.

Case study 5. Source water: Lake Erie, Ohio. ***System components.*** This facility comprises four WTPs and receives raw water from the Central Basin of Lake Erie. The intake crib is about 3 mi offshore. Two copper intake pipes (3-mi-long and 8 ft in diameter) and two other copper pipes (each 5-mi-long and 10 ft in diameter) draw water to the four WTPs, which collectively can provide capacities ranging from 92 to 165 mgd, depending on demand.

Mussel control. No chemicals are added for mussel control at the intake or transmission pipe supplying water to the four treatment plants. Physical control methods (e.g., scrubbing) for the copper intake pipes appear to work adequately in preventing the settlement of mussels within the pipe. Inspections of the intake tunnels showed that the mussels line approximately the first 1,500 ft of the intake tunnels, but after that the population declines substantially. The depth of mussels settled on the tunnel walls is approximately 1 to 2 in. When the mussels first colonized the pipe and intake structures, there was concern that continued buildup of mussels inside would interfere with water flow. Mussel colonization, however, appears to be adequately controlled with the efficient use of physical control methods at the intake structure. Pressure sensors at the intake structure trigger automatic flushing when pressure differential reaches a set point.

O&M. Divers scrape mussels off the intake structures twice a year, and mussel shells are vacuumed out of shore shafts once a year. Compared with the old concrete and brick-lined pipes, the copper intake pipes have been performing better in terms of decreasing mussel attachment and infestation. From time to time as determined by divers, the intake is flushed with water flowing horizontally to the face of the intake in order to wash away mussels after scraping.

Cost. Cost of mussel control includes the cost of divers and physical removal of mussels from intake and pipes. Unit cost for mussel treatment was $0.84/mil gal in 2011; it is $0.86/mil gal based on EAC estimates (Table 2).

Case study 6. Source water: Lake Erie, Mich., and Lake Huron, Mich. ***System components.*** A large water agency in the midwestern United States supplies high-quality drinking water to a large population, serving approximately 40% of the state's population. The drinking water supply system uses water drawn from three intakes. Two intakes are located in Lake Erie and a river, and the third is located in Lake Huron. Five WTPs supply potable water to the city. Four of the facilities treat water drawn from the river and Lake Erie intakes; the fifth uses water drawn from Lake Huron, where a large 16-ft-diameter, 10-mi-long tunnel is used to transfer water from the intake crib to the WTP. Total water production design capacity for the five treatment plants is 400 mgd.

Mussel control. In the fall season, chlorine is added at the mouth of the three intake structures as 15–17% NaOCl to produce 1.5 mg/L free chlorine to treat mussels during the two weeks of the year when mussel densities in the source water are at their peak. No chemical is added in the tunnel for mussel control.

O&M. These activities include continuous monitoring of intakes and the tunnel to detect mussel infestations (e.g., volume of mussels, adult or juveniles) and to monitor residual chlorine levels during the fall season after treatment.

Cost. In November 2011, the water agency used 237,979 lb (23,637 gal) of NaOCl. The annual O&M cost for zebra mussel control was $133,266. Unit cost for mussel treatment was $0.93/mil gal in 2011 (Table 2).

Case study 7. Source water: Lake Erie, Mich. ***System components.*** This facility draws water from Lake Erie. Two intakes (a 30-in. intake installed 6,000 ft offshore and a 42-in. intake installed 1,800 ft offshore) gravity-feed raw water to an onshore pumping station. Water is pumped from the pumping station through approximately 8 mi of 24-in. cast-iron transmission pipe to the WTP. The design capacity is 18 mgd, but average production is about 7 mgd.

Mussel control. Chlorine is injected at the mouth of the two intake structures and at the mouth of the transmission pipe from the wet well of the low service pump station (lift station). A relatively higher dose of chlorine was required because of the high concentration of blue-green algae and TOC in the source water. Approximately 5 to 6 mg/L of chlorine is added at the intake structure to control the mussel population and blue-green algae, with a target of 0.5 mg/L of free chlorine entering the WTP. Typically, contact time of chlorine in the transmission pipe is between 7 and 8 h.

O&M. A 2-in. chemical flow line runs through the transmission pipe and diffuses chlorine in front of the intake. Chlorine is added for two-week periods in May–June and October–November every year. This sporadic chlorine treatment minimizes the potential for DBP problems. Backflushing along with physical brushing at the intake once a year remove mussels from screens (using reverse water circulation). Divers also monitor intakes twice a year.

Cost. On the basis of the city's capital assets, the total costs associated with the feed lines, tanks, and related materials were determined to be $367,267 in 2006. Annual O&M costs for zebra mussel control at the intake structure, feed lines, transmission pipes, and tanks were $13,315, $14,026, and $9,358 for 2011, 2010, and 2009, respectively. Unit cost for mussel treatment was $2.05/mil gal in 2011; it is $7.89/mil gal based on EAC estimates (Table 2).

Case study 8. Source water: Reservoir, Kan. ***System components.*** The 6.5-mgd WTP receives water from a large reservoir through an intake structure. Water is transferred to the facility from the reservoir via 20 mi of transmission pipeline originating from the pump station. During the summer when water use is high, the plant operates at greater than 70% capacity, treating 6.0 mgd.

Mussel control. A copper ionization process[2] is used for mussel control (MacroTech 2016). The ozone process that was installed for taste-and-odor control also kills the mussels and protects the transmission pipeline. The zebra mussel population in the reservoir has decreased over time but currently has stabilized, requiring implementation of mussel control methods and continuous monitoring of the facilities for infestations.

O&M. A chlorine-based system to control mussel population was found to not be cost-effective. Over the years, mussel populations at the intake structure appear to be declining, an observation based on the decreasing trend of zebra mussel populations in the reservoir. Drought and reduced water levels in the reservoir along with food shortages may have contributed to the recent reduction of zebra mussel populations. The pump station is the first water treatment installation of the proprietary copper ionization process, which comprises two copper plates with an electrical charge that releases copper ions into the water (MacroTech 2016). The level of copper is enough to inhibit feeding, breeding, and settling of zebra mussels and to protect the intake structure, piping systems, and pump station. An auger system is used to remove dead mussels from the pipes and supporting utilities. However, the auger system apparently does not remove all of the dead mussels but rather grinds them into a powder or bypasses those that are too slippery to be removed. Facility staff have tried four or five different auger designs to resolve this problem.

Cost. The copper ion treatment was installed in the existing intake structure in 2010 at a capital cost of about $1.37 million. The process was selected on the basis of its lower NPV ($1.9 million), lower life-cycle cost, and fewer environmental risks. The current estimated construction cost for the copper ionization process is $1.6 million. The NaOCl system that was initially evaluated had a lower initial construction cost ($1.15 million) but an estimated annual operational cost of $75,000 and thus a higher NPV ($2.1 million). Unit cost for treatment using copper ions was $12.82/mil gal in 2011; it is $73.10/mil gal based on EAC estimates (Table 2). Recently, the electrode replacement cost for the proprietary copper ionization system was reported to be about $20,000 per year for an 80-mgd intake system.

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Case study 9. Source water: Lake Mead, Nev. *System components.* This treatment facility draws water from Lake Mead through two different intake structures that feed two separate WTPs. The intake for the 600-mgd WTP draws water at an elevation of 1,050 ft above sea level, and the intake for the 300-mgd WTP draws water at an elevation of 1,000 ft above sea level. Tunnels connecting the intakes to the WTPs are 12 ft in diameter and 1 mi in length. A raw water intake pumping station is also associated with each intake to convey water to each WTP.

Mussel control. The facility uses two approaches to treat quagga mussels at the intakes. Chlorine as liquid chlorine is added before the first pumping station that pumps water to the 600-mgd WTP. Chloramines are added at the mouth of the intake pipe (within the transmission tunnel) that transfers water to the 300-mgd WTP. The intake structures were not chlorinated because of the potential for DBP formation, which restricts the use of chlorine. To control mussels, the typical residual doses of chloramines and chlorine are 0.2 and 0.5 mg/L, respectively. The contact time of chemicals inside the tunnels is short (e.g., a few minutes) because the goal is not to kill quagga mussel veligers but rather to restrict them from attaching to surfaces.

O&M. Routine monitoring in 2007 determined quagga mussels were present at the intakes at densities up to 13,000 mussels/ft^2. During this time, veliger counts estimated that an average of 22×10^9 quagga mussel veligers entered the WTP on a daily basis. The maximum veliger count was approximately 98×10^9 per day. Veliger sampling between 2010 and 2012 indicated that the quagga mussel population was stable from year to year. Nutrient limitation and competition for food may have reached such a level that the mussel population is not flourishing. Because it is essentially an impounded canyon, Lake Mead has extremely steep shorelines and these limit the preferred habitat for the mussels.

Quagga mussel veligers are effectively removed in the water treatment process. Chlorine and chloramines are added throughout the year. Each intake has a coarse bar screen to help keep large debris from entering the intake structure. Mussels have been found on the screens, and divers have been deployed twice a year to examine the intake structures and remove any mussels that are found.

Cost. The cost for using chlorine for quagga control is approximately $1.01/mil gal of water delivered to the treatment plant in 2011, or $3.87/mil gal based on EAC estimates. The cost for using chloramine for quagga control is approximately $1.22/mil gal of water delivered to the treatment plant in 2011 or $6.94/mil gal based on EAC estimates. When costs of chlorine and chloramine treatment for the entire 900-mgd facility are combined, the unit cost is approximately $1.08/mil gal in 2011 or $2.99/mil gal based on EAC estimates (Table 2).

The O&M cost of chlorine for mussel control is $219,000 annually. Chloramines for quagga mussel control cost approximately $1.20/mil gal of water delivered to the 300-mgd WTP for an annual cost of chloramines of $131,400/year. Total cost of both chemicals for mussel treatment is $350,400 annually. The capital cost for the infrastructure needed for quagga control at three intakes is approximately $6 million. The complexity and size of the intake structure components affected mussel control costs.

Case study 10. Source water: lakes and reservoirs, Calif. ***System components.*** This large water storage and distribution system provides drinking water to more than 19 million customers in Los Angeles, Orange, San Diego, Riverside, San Bernardino, and Ventura Counties in Southern California. The system has lakes and nine reservoirs, three of which are infested with quagga mussels. The system includes 242 mi of water conveyance infrastructure that supplies water to five WTPs with a combined capacity of 2,640 mgd and also to Southern California at an average of 740,000 to 800,000 acre-ft of water annually. The water conveyance system consists of 65 mi of open canals, 92 mi of tunnels (27 tunnels), five pumping plants, 55 mi of cut-and-cover conduit, 30 mi of siphons (144 siphons), and five reservoirs. The system can deliver 1 bil gal of water daily and has an annual delivery capacity of 1,212,000 acre-ft of water.

Mussel control. Chlorine is applied at three locations within the system as part of the mussel management and control plan;

in addition, mobile chlorine units are used for application wherever and whenever required. The chlorine application locations are dispersed and at areas where maintaining water quality is essential. The chlorine dose ranges between 0.9 and 1.2 mg/L, with a free chlorine residual target between 0.3 and 0.5 mg/L. The residual is measured downstream of the injection point so it can be monitored and the dose adjusted if necessary. The free chlorine dissipates before it enters downstream lakes.

O&M. In July 2007, adult quagga mussels were found in the water intakes from routine O&M activities. Mussel infestations rapidly increased from densities of less than one mussel/ft^2 in February 2007 to 1,000 mussels/ft^2 in January 2008. In addition to chlorine treatments, some nonchemical techniques are applied to control mussel populations, depending on the severity and location of infestations. These techniques include periodic drying and wetting of reservoirs, the pumping out of water from reservoirs and cleaning the base of mussels, application of nonoxidizing molluscicides, desiccation, oxygen deprivation, and mechanical scraping. Monitoring also includes intermittent observation by divers of the water bed and sides of the water bodies.

Cost. To address quagga mussel infestations in its water system and terminal reservoirs, the facility incurs O&M costs of about \$10 million to \$15 million annually. The initial capital cost for design and installation of facilities for mussel control was \$7.2 million. Unit cost for mussel treatment was \$12.63/mil gal in 2010; it is \$13.41/mil gal based on EAC estimates (Table 2). The vast system components and long transmission pipe have resulted in high costs for this system.

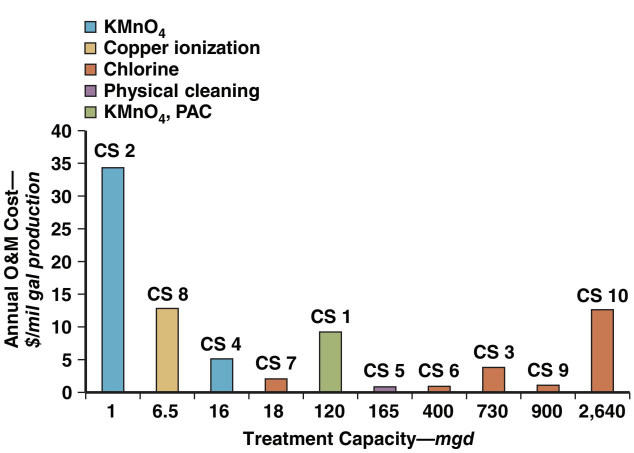
ECONOMIC COST SUMMARY

Figure 2 shows annual O&M costs by treatment capacity for the facilities profiled in case studies 1 through 10. As shown in the figure, unit O&M cost of treatment generally decreases with increasing capacity of the treatment facility. Unit O&M costs for small facilities (<10 mgd as in case studies 2 and 8) ranged from \$12.82/mil gal to \$34.32/mil gal, whereas costs for larger facilities (≥10 mgd as in all case studies except 2 and 8) ranged from \$0.84/mil gal to \$12.63/mil gal. Costs for the largest facility (case study 10) included O&M unit costs that are in the higher range of costs (more typical for smaller facilities) because they represent the cost of treatment of a vast conveyance system in addition to treatment at the intake.

In case studies where $KMnO_4$ is used for treatment, a decreasing trend in annual O&M cost per million gallons of production is evident as WTP design capacity moves from lower to higher production levels. When chlorine is the primary treatment chemical, the annual O&M cost ranges between about \$1.00/mil gal and \$4.00/mil gal (except for case study 10, where the majority of treatment is for maintenance of the conveyance system including channels, reservoirs, and lakes). The costs for mussel treatment presented in the case studies represent costs for upgrades to the existing facilities to include modifications and installations that are necessary for controlling and managing dreissenid mussels (Table 2).

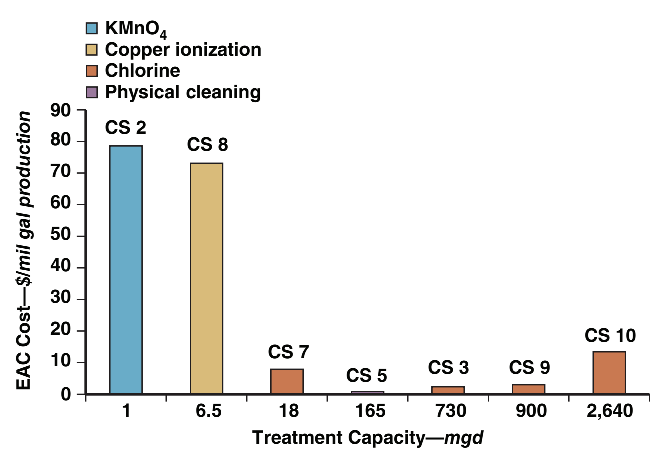
The EAC for mussel control was computed from the capital cost, O&M cost, annual rate of interest, and the expected lifespan of the treatment technique. Figure 3 shows the EAC per million gallons of water production as a function of treatment capacity for all case studies except 1, 4, and 6 (for which capital cost information was missing). For those facilities using $KMnO_4$ or chlorine as primary chemical for treatment of mussels, the EAC cost per $KMnO_4$ treatment is much higher than chlorine treatment for control of dreissenid mussels. Compared with larger facilities, the small WTPs (<10 mgd) have higher costs for mussel treatment. As noted previously, the largest facility (case study 10) has a very long conveyance system (comprising canals, ducts, and

FIGURE 2 Annual O&M cost per WTP production capacity



CS—case study, $KMnO_4$—potassium permanganate, O&M—operations and maintenance, PAC—powdered activated carbon, WTP—water treatment plant

FIGURE 3 EAC per WTP production capacity



CS—case study, EAC—equivalent annual cost, $KMnO_4$—potassium permanganate, WTP—water treatment plant

EAC costs could not be derived for case studies 1, 4, and 6 because capital cost information was missing for these case studies.

pipes of various sizes) that requires more special attention and extensive treatment for mussel control than is necessary in confined surroundings under controlled environments such as transmission pipes or WTPs. For the other case studies, costs for the most part reflect intake structure maintenance and treatment in the WTPs rather than costs for the conveyance system.

CONCLUSION

As the case studies profiled here demonstrate, maintaining transmission pipelines and intakes free of dreissenid mussels adds considerably to the capital and annual O&M costs for a drinking water treatment facility. Among these 10 case studies of costs of mussel control in WTPs, the majority of the facilities opted to apply chlorine or $KMnO_4$ to protect water intake structures, conveyance pipes, and pumps. Less common control methods included the use of chloramines and copper ion treatment. Physical methods such as periodic mechanical cleaning of accessible structures were also used in addition to chemical treatment. The case studies with Lake Erie as source water in the eastern United States and Lake Mead in the western region of the country (i.e., case studies 1 and 9) showed high costs of maintenance because of the extreme degree of mussel infestation. Handling of mussels from clogged structures and their removal added considerably to the total cost of mussel control. Management options for mussel infestations can be summarized as protection of intake structures, protection of outlet structures and transmission pipes, and preselection of multibarrier approaches to protect water intakes and transmission pipe.

The cost of mussel control is determined by various factors including the extent of infestation, stage of infestation (adult versus juvenile mussels), components and size of the WTP, complexities in monitoring and using control measures, facility proximity to source water, and regulatory compliance requirements. The cost of capital expenditure and O&M costs for mussel control vary according to the WTP's flexibility in upgrading the existing water treatment processes to effectively address the dreissenid mussel infestation, complexity of system components, age of the WTP, treatment method selected, location of intake structure, possibilities for relocation and modification of intake structure, and periodic monitoring opportunities.

The unit cost of treatment varies with WTP capacity. As plant capacity increases, economic costs decrease considerably. For treatment facilities with capacities >10 mgd (i.e., all case studies except 2 and 8), the unit cost of mussel treatment varied from about $1.00/mil gal to $13.00/mil gal. When a $1.00/mil gal cost for treatment for mussel control in a 100-mgd WTP is assumed, the total cost for mussel treatment is $100 per day. This estimate will depend on the specific site conditions, system components, extent of mussel infestation in the source water, and local jurisdictions. The objective of the current study was to provide an overview of mussel control methods used by various drinking water facilities and to present the related agglomerated costs on a lump sum basis. Future studies are planned to conduct individual cost analyses in terms of transmission pipes, veliger versus adult mussel control, periodic monitoring, and upgrades of components to incorporate changes in treatment method.

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ENDNOTES

[1]Zequanox®, Marrone Bio Innovations, Davis, Calif.
[2]MacroTech, Scarsdale, N.Y.

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PEER REVIEW

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Interior Releases Report on Fight Against Invasive Mussels

2/28/2018

Date: February 28, 2018
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WASHINGTON – The U.S. Department of the Interior today released a report highlighting the progress made in the fight against invasive zebra and quagga mussels, which can impair the delivery of water and power, diminish boating and fishing, and devastate ecosystem health.

The report comes after U.S. Secretary of the Interior Ryan Zinke announced in June a set of initiatives to protect western ecosystems and hydroelectric facilities from the destructive species through continued collaboration with western governors as well as federal, state, and tribal agencies.

“I am pleased to share progress made on honoring those commitments,” **said Secretary Zinke.** “There is more work to do, and Interior is committed to continuing our efforts. With the busy boating season approaching, it is imperative that we are vigilant in taking measures to prevent the spread of invasive mussels and other aquatic invasive species.”

In Fiscal Year 2017, Interior spent $8.6 million to address invasive mussels nationwide. This includes an additional $1 million for the Bureau of Reclamation to establish watercraft decontamination stations, provide educational materials, and continue monitoring efforts.

Interior is currently working on more than four dozen actions to address invasive mussels including preventing the spread of the species to uninfested waters, such as those in the Columbia River Basin in the Pacific Northwest, and containing and controlling them where they are established, such as in Lake Powell and the Lower Colorado River region.

Some highlights since June include:

- Convening federal, state, tribal, and nongovernmental groups to identify options to strengthen watercraft inspection and decontamination programs at infested waters, such as at Lake Havasu as well as Lake Mead, where the Bureau of Reclamation committed to spending another $150,000 this year to bolster efforts.
- In the Pacific Northwest, the U.S. Geological Survey, Pacific States Marine Fisheries Commission, and Columbia River Basin partners are mobilizing to improve regional coordination of monitoring efforts to ensure that they are strategic and effective.
- The U.S. Fish and Wildlife Service, National Marine Fisheries Service, and Pacific States Marine Fisheries Commission are leading planning efforts to expedite Endangered

Species Act Section 7 consultations to ensure a quick response if invasive mussels are detected.

- The Bureau of Reclamation launched a prize competition seeking innovation solutions to eradicate invasive mussels from large reservoirs, lakes, and rivers in a cost effective and environmentally sound manner.

This work builds on efforts and effective state-federal-tribal partnerships and initiatives in process for decades. Interior and WGA staff have communicated regularly on this initiative since its inception in the spring of 2017.

"Western Governors remain committed to the fight against invasive species on Western lands, including the threat that invasive mussels pose to Western waterbodies,” said the Western Governors’ Association (WGA). “Addressing a threat of this magnitude requires leadership, innovation, and coordination at all levels of government.”

The Department requested $11.9 million in Fiscal Year 2018, including an additional $3.4 million for the Bureau of Reclamation to expand on these and other efforts to prevent, contain, and control invasive mussels. Approximately $3.1 million is in the process of being released under the continuing resolution to support federal, state, and tribal activities such as the purchase and operation of watercraft inspection and decontamination stations in the Lower Colorado River basin, development of facility vulnerability assessments to determine risk for critical infrastructure in the Columbia River Basin, and increasing capacity for the Confederated Salish Kootenai Tribe at Flathead Lake for their Aquatic Invasive Species program.

First introduced to the Great Lakes in the 1980s, zebra and quagga mussels spread outward via recreational watercraft being transported to other regions of the country. Infestations clog power plant, industrial, and public water supply intakes and pipes, dramatically change aquatic ecosystems, and require substantial investments to control. They are among the many invasive species causing economic and ecological and harm to human health across the United States.

To help raise awareness about these and other invasive species, events are planned in Washington, D.C. and across the country this week during National Invasive Species Awareness Week (NISAW). More information about NISAW is available here.