Costs Associated with Invasive Mussels Impacts and Management

Science and Technology Program
Research and Development Office
Final Report No. ST-2021-8142-01

U.S. Department of the Interior

August 2021

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Cover Photo: Mussel fouled wheel gate at Glen Canyon Dam. (Reclamation/C. Shane Mower)

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Bureau of Reclamation
Research and Development Office
Science and Technology Program

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
08-10-2021	Research	October 1, 2018 – August 10, 2021

4. TITLE AND SUBTITLE
Costs associated with invasive mussels impacts and management

5a. CONTRACT NUMBER
RY.15412018.ZQ38142/ FA732

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
1541 (S&T)

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5d. PROJECT NUMBER
Final Report ST-2021-8142-01

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Bureau of Reclamation
Denver Federal Center, PO Box 25007, Denver, CO 80225

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Science and Technology Program
Research and Development Office
Bureau of Reclamation
U.S. Department of the Interior
Denver Federal Center
PO Box 25007, Denver, CO 80225-0007

10. SPONSOR/MONITOR'S ACRONYM(S)
Reclamation

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
Final Report ST-2021-8142-01

12. DISTRIBUTION/AVAILABILITY STATEMENT
Final Report may be downloaded from https://www.usbr.gov/research/projects/index.html

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This study explores the impacts of mussels through an evaluation of costs associated with mussel prevention strategies, ecological proxies, and costs of capital investments and operations and maintenance (O&M) expenditures to mitigate mussel-related damages at hydropower facilities. Watercraft inspection and decontamination (WID) stations are the primary strategy used to prevent the spread and introduction of dreissenid mussels throughout the West. The 2019 average annual WID budget was approximately $1,605,900. Control cost data collected through a survey from S&T Project 1876 showed that surveyed hydropower facilities experienced negative economic impacts related to control or mitigation of mussel-related damages. Facilities surveyed have spent approximately $10 million in total on preventative control measures since mussel inception. Facilities surveyed spend approximately $464,000 annually on increased maintenance. Total reoccurring maintenance costs for facilities surveyed were $650,000 per occurrence. Facilities surveyed spend approximately $88,000 in total annually on monitoring. Mussel infestation can have a variety of ecological impacts which can result in negative economic impacts. This analysis did not attempt to quantify lost ecosystem benefits, but rather it relied on existing studies to estimate a range of values for lost ecosystem or social benefits. This study provides evidence that mussels management strategies provide considerable value to the nation.

15. SUBJECT TERMS
Invasive mussels, quagga mussels, zebra mussels, mussel impacts to hydropower, mussel costs, watercraft inspection and decontamination, prevention of mussels, ecological impacts of mussels

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	THIS PAGE			Nicholas Rumzie
U	U	U			19b. TELEPHONE NUMBER *(Include area code)* 303-445-2729

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Science and Technology Program
Research and Development Office
Final Report No. ST-2021-8142-01

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Executive Summary

This study explores the impacts of mussels on infrastructure, ecosystems, and economies through a literature review and investigation techniques and evaluates costs associated with mussel prevention strategies and avoided costs of future increased capital investments and operations and maintenance (O&M) expenditures to control or mitigate mussel-related damages at hydropower facilities. The dreissenid invasion of North America has posed both ecological and economical risks to the nation. Watercraft inspection and decontamination (WID) stations, a tool of an AIS Program, are the primary strategy used to prevent the spread and introduction of dreissenid mussels throughout the Western States. By implementing consistent and effective protocols, managers have realized success in identifying watercraft and other equipment that pose a risk. In 2021 nine western states: California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, and Wyoming had webpages that discussed their AIS Program and WID station locations. A total of 422 stations were in the states mentioned above. The 2019 average annual WID budget was approximately $1,605,900. For this study, control is focused on mitigating the damages to hydropower facilities that are affected by a mussel infestation. Control cost data was collected through a literature review and a survey from S&T Project 1876 and was gathered to understand the potential costs of increased capital investments and O&M expenditures to control or mitigate mussel-related damages to hydropower facilities. Data collected from the survey highlighted four categories of increased costs due to mussel infestation: preventative control, increased O&M, monitoring, and unplanned outages. Facilities surveyed have spent approximately $10 million in total on preventative control measures since mussel inception. Nine out of thirteen facilities surveyed spend approximately $464,000 annually on increased maintenance. Four out of thirteen facilities surveyed do not have annual maintenance but rather maintenance that is reoccurring on an intermittent basis. Total reoccurring maintenance costs for facilities surveyed were $650,000 per occurrence. Facilities surveyed spend approximately $88,000 in total annually on monitoring. Cost data collected from the survey does not represent all costs a facility may incur if invasive mussels are detected. To fully compare and complete an economic benefit-cost (B/C) analysis of measures to prevent the spread of invasive mussels versus measures to control post-invasion impacts to water and power delivery facilities, this study would also need to include the value of lost ecosystem benefits due to a mussel infestation. Additional research is needed to identify and quantify the impact of invasive mussels on ecosystem services, such as impacts to water deliveries, power generation, fisheries, recreational values, and property values.

Background

The zebra mussel (*Dreissena polymorpha)* and quagga mussel (*Dreissena rostriformis bugensis)*, are species of freshwater mussels that are invasive to the United States. Zebra mussels are native to drainage basins in the Black, Caspian and Aral Seas in Eastern Europe and Western Asia (O'Neill and Dextrase 1994). Through the 1700s and 1800s zebra mussels migrated inland and currently inhabit most European waterways. The quagga mussel is a close relative to the zebra mussel and is indigenous to Ukraine (Wozniczka et al. 2016).

Both zebra and quagga mussels were discovered in in the Great Lakes Region of the United States in the mid to late 1980s. The mechanism of introduction is not definitively known but hypothesized to be a result of ballast water discharge from oceanic cargo ships (O'Neill and Dextrase 1994). Since their introduction, invasive dreissenids have spread rapidly across the U.S. due to favorable habitats, high fecundity, and dispersal via connected water systems and other vectors such as boats and trailers (O'Neill and Dextrase 1994). Species in the genus *Dreissena* are also known to be highly polymorphic and prolific, with great potential for rapid adaptation (Mills et al. 1996). The dreissenid invasion of North America has already had substantial effects, both ecologically (Higgins et al. 2010, Barbiero et al. 2006, McCabe et al. 2006, Noonburg et al. 2003, Ricciardi et al. 1998, Schloesser et al. 1998), and economically (WRP 2010).

This research project explores the impacts of mussels on infrastructure, ecosystems, and economies through a literature review and investigation techniques to evaluate costs associated with mussel prevention strategies and control technologies and practices post infestation.

In order to fully compare and complete an economic benefit-cost (B/C) analysis of measures to prevent the spread of invasive mussels versus measures to control post-invasion impacts to water and power delivery facilities, it was determined that this study would also need to include the value of lost ecosystem benefits due to a mussel infestation. However, because of limited literature pertaining to the various ecological impacts on western waters, specifically regarding deep, artificial water bodies, typical of most Reclamation reservoirs, the focus of this study shifted to the collection and comparison of financial costs related to increased investment and O&M activities related to prevention and control of invasive mussels. Consequently, this analysis did not attempt to quantify lost ecosystem benefits, but rather relies on existing studies to estimate a range of values for lost ecosystem or social benefits.

Impacts of Invasive Mussels

Impacts from dreissenids are currently taking place across the nation and are likely to increase through ever increasing population connectivity and climate change. Quagga and zebra mussels can completely alter aquatic systems; threatening the diversity and abundance of native species; and damage industrial, agricultural, and recreational activities dependent on surface waters. To characterize the significant ecological and socio-economic problems for water users across the United States, a detailed literature review was conducted, and results are outlined below.

Hydropower Infrastructure

Invasive mussels pose serious threats to water resources hydropower infrastructure and operations. Of major significance to facilities is the ability of mussels to rapidly colonize hard surfaces at densities of tens of thousands of mussels per square meter, as well as generate a significant volume of shell debris that may be transported from upstream colonies. Invasive dreissenids can affect all components regularly exposed to raw water, including conduits, canals, intake orifices and trashracks, gates and valves, drains, pumps, air valves, fish screens and diffuser gratings, hydropower cooling and fire suppression systems, gauging stations, weirs, and instrumentation (Prescott et al. 2014). Flow restriction is typically the foremost concern, as it can threaten water delivery to critical systems and reduce pumping and conveyance capacities, often requiring costly modification to operations and/or additional maintenance. Mussel colonization can cause flow obstructions in water intakes and conveyances (primarily pipe systems). Accumulation of settled mussels or influxes of shell debris can lead to roughening of surfaces (increased frictional coefficients and head-loss) or complete blockage. Chemical degradation (corrosion) of infrastructure can also be accelerated as a result of mussel fouling of metallic structures and equipment (Prescott et al. 2014).

Ecological

The full ecological impact of a dreissenid mussel invasion depends on the initial conditions of the waterbody and the size of the resulting mussel population (Nalepa 2010). Many lakes, reservoirs, and rivers are degraded by anthropogenic modification, pollution, or climate change, leaving them vulnerable to invasion. However, environmental characteristics of some waterbodies may not allow them to sustain large populations. Dreissenids survive within a limited range of environmental tolerances for factors such as calcium, salinity, and temperature, and values outside these ranges may protect some waterbodies from large scale invasion (Mackie & Claudi 2010). However, quagga mussels survive and reproduce in a wider range of temperature, depth, and food resource conditions than zebra mussels (Baldwin et al. 2002), expanding the suite of threatened waters in the western United States.

Energy and Nutrients

Mussels filter large amounts of water and deposit processed organic matter, in effect transferring energy from the open water to near shore and bottom regions (Higgins & Vander Zanden 2010, Miehls et al. 2009). This shift of energy areas changes food webs and functional relationships between trophic levels (Miehls et al. 2009), potentially causing cascading effects across traditional trophic boundaries. In addition, this "benthification" of the waterbody may reduce eutrophication caused by anthropogenic activities and restore clarity and benthic biomass to pre-human influenced levels (Mayer et al. 2014).

Dreissenid mussels filter and break down particles in the water, which separates particle bound nutrients and increases the availability of soluble nutrients, particularly phosphorus (Higgins & Vander Zanden 2010). Several studies have shown fluctuations in soluble phosphorus, ammonium-nitrogen, silica, chloride, and chlorophyll a as a result of mussel infestation (Cha et al. 2013, Higgins and Vander Zanden 2010, Holland et al. 1995, Nalepa et al. 2008). The observed trend and magnitude of these changes has been site-specific and may be strongly related to mixing/stratification and seasonality, especially at high-altitude lakes in the western US. In instances where the bioavailability of total phosphorus increases there is greater potential for cyanobacteria or algal blooms.

Climate

There is some evidence that a large infestation of mussels changes the carbon dioxide dynamics of waterbodies. In a study of the Great Lakes, increases in overall CO_2 emissions were observed in comparison with pre-invasion (1983-2006) levels, with fluxes three to four times higher in Lakes Michigan and Huron, causing the Great Lakes to become a significant atmospheric CO_2 source (Lin and Guo 2016). The study hypothesized that quagga mussels altered CO_2 dynamics by decreasing primary production, increasing water clarity and photo-degradation of organic matter, and by the metabolic processes of the mussel population.

It is not clear that mussels are fully responsible for observed increases in CO_2 fluxes, and additional data are necessary to develop a complete model of the relationship between mussels and emissions. As dreissenid populations expand, ecosystems become homogenized and biodiversity is lowered or lost. This can create situations where it may require significantly longer periods of time to recover from extreme climate events, particularly in degraded ecosystems (McDowell et al. 2017).

Water Clarity

Dreissenid mussels filter large amounts of water and remove suspended particulate matter, which can significantly improve water transparency (Higgins & Vander Zanden 2010, Holland 1993, Zhu et al. 2006). Zebra mussels have been found to increase water transparency 1.3 to 2.4 times, reducing seston by a factor of 2.3 to 6.9, and increasing the average depth receiving 1% light by up to 1 meter (Karatayev et al. 1997, Zhu et al. 2006).

Higher water transparency and increased light penetration may reduce available habitat for deep-water fish that prefer low-light, as well as expand macrophyte coverage (see Plants & Algae section below). In systems with high suspended solids caused by environmental degradation, mussels may improve conditions and ecosystem function (Bilotta & Brazier 2008). Water clarification also has implications for heat budgets, mixing depth, nutrient regeneration, and deep-water fish habitat (Higgins & Vander Zanden 2010).

Plants & Algae

Because mussels increase water transparency and depth of light penetration, the area available for macrophyte colonization increases. Biodeposition of feces and pseudofeces also enriches sediment, providing resources for expanded plant life (Minchin & Boelens 2011). Lakes with mussels have been observed to have substantial increases in the coverage, distribution, and depth of submerged macrophyses (Bailey et al. 1999, Chu et al. 2004, Higgins and Vander Zanden 2010, Skubinna et al. 1995). The low slope of many lakes allows a ~1 meter increase in light penetration to expand macrophyte area significantly. However, many reservoirs in the western US are artificially created in steep-sided canyons, which will limit the extent of benthos that will receive additional light when water clarity improves.

As suitable plant habitat increases, there is no guarantee that native or beneficial vegetation will fill the newly created space. Significant changes in macrophyte community composition after dreissenid invasion have been documented (Minchin and Boelens 2011, Zhu et al, 2006). Many of the reservoirs in the western US are less than 100 years old, and their aquatic ecosystems may still be acquiring equilibrium. This potential instability leaves them open to invasion by non-native macrophytes, or rapid population expansion by existing macrophytes.

Water clarity improvements and the complex substrate created by mussel beds also facilitate the expansion of algae species. Because mussel eradication currently is not generally feasible in large open water areas, controlling algae requires additional phosphorus load reductions, imposing an economic burden on surrounding communities (Auer et al. 2010). Both macrophytes and algae pose substantial challenges for dams and other water infrastructure, accumulating on intakes, screens and trash racks that impede flow and potentially causing shutdowns (Auer et al. 2010).

Phytoplankton & Zooplankton

Phytoplankton and zooplankton are critical components of freshwater food webs. Waters infested with dreissenid mussels have been documented to experience significant reductions (up to 87%) in planktonic biomass (Fahnenstiel et al. 2010, Higgins and Vander Zanden 2010, Rowe et al. 2017) as well as alterations to their spatial and temporal distributions (Rowe et al. 2017). Impacts to plankton have been related to direct predation by mussels (Thorp & Casper 2003) and indirectly due to competitive advantages resulting in reductions in prey size and abundance (Lozna et al. 2001, Nalepa et al. 2009, Rowe et al. 2017, Turkett 2016). The reduction in plankton negatively impacts a primary source of food for higher-order organisms such as alewife, lake whitefish, and sculpin (Alepa et al. 2009, Nalepa et al. 2009).

Zoobenthos

Zoobenthos includes the biodiversity rich community of macroinvertebrates that inhabits the substrate of lakes and rivers. In addition to changing water quality and macrophyte coverage, mussels also physically alter the substrate and reallocate resources. Mussel beds increase habitat complexity and heterogeneity, creating refuges for small invertebrates and islands of hard substrate in otherwise sandy bottoms (Karatayev et al 1997, Nalepa et al 2008). The deposition of pseudofeces transfers nutrients from the water column to the benthos (Izvekova & Lvova-Katchanova 1972), increasing food availability for many organisms. As mussel colonies spread throughout a waterbody, the substrate will eventually approach homogenizations (Ozersky et al 2011); final community structure will depend on what species are present and how well they adapt to a changing environment.

The presence of dreissenid mussels has been positively correlated with increased benthic macroinvertebrate density and taxonomic richness, and decreased community evenness (Karatayev et al. 1997, Higgins and Vander Zanden 2010, Horvath et al. 1999, Ward & Ricciardi 2007). Increases in total macroinvertebrate abundance appear to persist long after the initial invasion

(Ozersky et al. 2011). Leeches, flatworms, and small gastropods successfully colonize mussel beds, and benefit from additional spawning and refuge habitat and food resources, and have been observed increasing overall abundance in mussel infested areas (, Griffiths 1993, Higgins & Vander Zanden 2010, Ward & Ricciardi 2007, Stewart & Haynes 1994). Detritivores also readily assimilate the nutrients contained in pseudofeces deposited near mussel colonies (Izvekova & Lvova-Katchanova 1972).

Other zoobenthos species including amphipods, dipteran flies, oligochaetes, caddisflies, ostracods, and nematodes do not appear to be significantly impacted by mussel infestation (Ward & Ricciardi 2007). Large gastropods can be negatively impacted by biofouling from mussels, leading to reduced mobility and burrowing ability, as well as inhibited growth (Van Appledorn et al. 2007, Van Appledorn & Bach 2007). If large gastropods experience reduced fitness, they may begin to select for smaller sizes, and change the aquatic ecosystem.

Most literature reporting impacts of dreissenids on other invertebrates is focused on the Great Lakes and zebra mussels (Karatayev et al. 2012). As of this writing, no studies reporting the long-term ecological effects of quagga mussels in the western U.S. appear to have been published.

Native Bivalves

Unlike other macroinvertebrates, native bivalves are often decimated following an invasion by dreissenids. Rapid declines in native mussel populations were observed in the eastern U.S. in the early stages of dreissenid colonization (Lauer & McComish 2001, Nalepa et al. 1991, Nalepa et al. 2001, Ricciardi et al 1998, Strayer & Malcom 2018, Schloesser et al. 1998). Zebra and quagga mussels affect native mussels directly through biofouling, and indirectly by competing for food (Burlakova et al. 2014, Karatayev et al. 1997, Lucy et al. 2014, Strayer & Malcom 2018, Ward & Ricciardi 2007). Native species then suffer from starvation, resulting in reduced fitness, and eventually causing death (Baker & Hornbach 1997, Strayer & Malcom 2018).

Although rapid unionid population declines have been documented postinvasion, native species were often highly stressed prior to the appearance of dreissenid mussels, suggesting they may have simply been one stressor too many as opposed to the primary driver of unionid decline. And though native losses have been dramatic, refuge populations have been documented to persist in shallow embayments, river mouths, and coastal wetlands with soft substrates (Crail et al 2011, Zanatta et al. 2015). As a steady state ecosystem develops, native species may be able to disperse from refugia and return to preinvasion densities and juvenile recovered substantially, although studies have shown adults are rare and not all species have similar recoveries (Strayer & Malcom 2018).

In the western U.S., native bivalves have been negatively impacted by anthropogenic modification of rivers and a changing climate (Blevins et al 2017). However, western species may avoid the worst biofouling effects because quagga mussels have established before zebra mussels. Quagga mussels have demonstrated a weaker ability to attach to unionid shells, decreasing the potential impact on native species (Burlakova et al. 2014, Peyer et al. 2009).

Fish

The impact of dreissenid mussels on fish populations depends greatly on the adaptability of different fish species and the resiliency of the overall food web (Nienhuis et al. 2014). Because mussels reduce the amount of plankton in a waterbody and shift energy resources to the littoral zone, obligate planktivore and deep-water benthivore species are likely to be negatively impacted (Higgins & Vander Zanden 2010, Hoyle et al 2008, Pothoven et al. 2001, Strayer et al. 2004). Other species that can use a variety of resources and forage in the littoral zones are less impacted, and have a greater ability to maintain population sizes, or potentially expand (Fera et al 2017).

Herbivorous fish and species that make use of aquatic vegetation for cover may benefit from the indirect effects of mussels to increase submerged aquatic plant biomass (Mayer et al. 2000, Vanderploeg 2003) and algae colonies (Madenjian et al. 2015). Alternatively, fish species that prefer low light may decline (Holdren & Turner 2010, Vanderploeg 2003).

Some will shift to a diet of lower energy value, including mussels, in response to changes in the food web (Hoyle et al. 2008, Karp & Thomas 2014, Madenjian et al. 2010, Pothoven et al. 2001). Although some fish utilize mussels as a food source, without a concurrent increase in overall waterbody productivity, shifting to a lower energy diet will likely result in smaller fish. (Madenjian et al 2006, Raikow 2004)

Harmful Algal Blooms

Harmful algal blooms (HAB) have serious impacts on local economies, fish populations, and human health. Many HABs are caused by cyanobacteria such as *Microcystis aeruginosa*, which produce toxins that are harmful to organisms living in or in contact with the affected water. Lakes with dreissenid mussels tend to see an increase in the biomass of cyanobacteria species (Higgins & Vander Zanden 2010, Knoll et al. 2008) Although cyanobacteria ingested during filter feeding, dreissenids will selectively reject cyanobacteria and other pollutants as pseudofeces. Since other phytoplankton and small algae species are consumed, the rejection of cyanobacteria increases the relative abundance of toxic species in a waterbody, leading to harmful blooms (Vanderploeg et al 2001). Harmful algal blooms cause significant economic costs to human health, commercial fisheries, tourism, and resource management programs (Sanseverino et al. 2016).

Bacteria

Benthic bacterial communities change in both structure and metabolic function in the presence of dreissenids (Lohner et al 2007). Mussels deposit large amounts of resources in the form of feces and pseudofeces, opening new niches for bacteria to colonize. Lohner et al. (2007) showed that mussel clusters changed what bacteria was present, increased bacterial density 10-fold, and modified metabolic activity by providing new resources. Lee et al (2015) also documented increases in bacterial diversity, particularly when mussels were complimented by the presence of algae. The most significant changes were observed in nitrifying bacteria that were able to take advantage of an increase in mussel-excreted ammonium. Responses across bacteria genera were inconsistent, with both positive and negative changes to abundance.

Arthropods

Zebra mussels attach to the larvae of dragonflies (*Macromia illinoiensis*), impeding their ability to burrow, forage, and emerge from the water to molt (Fincke & Tylczak 2011). In addition, mussel beds provide complex substrate that insect larvae, such as mayflies, use as preferred habitat (Fincke & Tylczak 2011). Because dragonflies prey upon both larval and adult mosquitoes, as well as other small insects (Corbet 1999), losses in dragonfly populations can significantly change the entomological community near the waterbody.

Crayfish

The ultimate effect of dreissenids on crayfish populations is uncertain, but both positive and negative changes have been observed. Hard-bodied aquatic organisms are vulnerable to dreissenid colonization; the carapace and hard appendages of crayfish are ideal attachment points (Brazner & Jensen 2000, Ďuriš et al. 2007). Because crayfish molt as they grow, the effects of mussels will vary seasonally, with the largest impact in spring and early summer (Ďuriš et al 2007). The additional weight imposed by mussel biomass will likely impose energetic costs on affected crayfish, reducing their fitness and potentially causing death (Brazner & Jensen 2000). These impacts may be mitigated by enhanced hunting success, facilitated by increased water clarity, and by added refuges in complex mussel beds.

Waterfowl

In addition to providing a low-energy replacement resource for some fish species (Madenjian et al, 2010), various waterfowl species utilize mussels as a food source. After dreissenids established in the Great Lakes, migratory patterns of greater scaup (Aythya affinis), lesser scaup (A. marila), and buffleheads (Bucephala albeola) changed to take advantage of the new food source (Luukkonen et al 2014, Vanderploeg et al. 2002). During winter months, diving ducks are still able to remove mussels through holes in the ice (Mitchell et al. 2000).). In addition to serving as a food source, changes induced by mussels improve habitat for waterfowl. Submerged macrophytes become more abundant with improvements to water clarity, and canvasback ducks expand their foraging area to deeper water in response (Luukkonen et al 2014). The biomass of other plant foods that prefer clear water, such as Vallisneria and Chara, also increases, supporting larger populations of dabbling ducks (Vanderploeg et al. 2002). However, the long-term effects of mussel consumption by waterfowl are still uncertain, as contaminants that accumulate in dreissenid tissues could negatively impact waterfowl reproductive success (Petrie & Knapton 1999)

Conclusion

Although some waterbodies have shown signs of recovery from ecological changes caused by *Dreissena* invasion (Karatayev et al. 1997, Strayer & Malcom 2018), the subtropical climate and naïve communities of western waters (Holdren & Turner 2010) could make them particularly susceptible to ecosystem collapse. It is difficult, however, to predict how deep, artificial reservoirs will be affected by the quagga mussel invasion. Many Reclamation reservoirs have low productivity, and a significant change could cascade across trophic levels. Likely shifts include:

- Increases in benthic macroinvertebrates.
- Expansions of aquatic plant habitats and biomass.
- Changes to fish communities.
- Increases in harmful algal bloom frequencies.

Management of Invasive Mussels

There are seven strategies currently in use to address the invasion of zebra and quagga mussels in the West: Increasing Capacity to Address Invasive Mussels; Prevention; Early-Detection Monitoring; Rapid Response; Containment and Control; Outreach and Education; and Research (QZAP, 2010).

The level at which prevention activities occur varies greatly among the Western States. Current prevention is typically coordinated through an aquatic invasive species (AIS) program. The programs activities include outreach and education, law enforcement, watercraft inspection and decontamination (WID) and impoundment, watercraft exclusion, management of overland boat movement, permitting for movement of large water-based materials and equipment, and development of risk management/assessment plans.

A common strategy employed, by AIS programs, is the implementation of watercraft inspection and decontamination (WID) stations used to prevent the spread and introduction of dreissenid mussels throughout the Western States. By implementing consistent and effective protocols, managers have realized success in identifying watercraft and other equipment that pose a risk.

Controlling mussel infestations in water distribution systems for municipal, agricultural and industrial supply maintains facility operation, reduces populations, and reduces the likelihood of infestation spreading to new areas. A variety of management techniques are possible, including settlement prevention, desiccation, mechanical removal, oxidizing biocides, thermal, and biological control. Most containment and control technologies were developed for closed-water systems. Additionally, containment can be difficult if the volume of water to be treated is large, the environmental impacts of the treatment must be acceptable, and the costs must not be prohibitive.

Prevention for this study is defined as implementing measures to reduce the probability of the spread of mussels from infested waterways to un-infested waterways. In this study control refers primarily to mitigating damages at hydropower plants, not other water delivery facilities.

Prevention

Aquatic invasive species (AIS) programs are the main tool for preventing the spread of invasive species. AIS program coordinators are located throughout the U.S. and work closely with public and private sectors to develop and implement AIS projects. An AIS program provides species monitoring, prevention techniques and education and outreach to reduce the threat and spread of AIS. 15 western states have implemented an AIS program: Arizona, California, Colorado, Idaho, Kansas, Montana, Nebraska, Nevada, New Mexico, North Dakota, Oregon, South Dakota, Utah, Washington, and Wyoming. These states utilize watercraft inspection and decontamination (WID) stations as a primary component of their AIS program. North Dakota and Kansas currently do not require boaters to visit WID stations and are focusing their resources on educating water users and enforcing current regulations.

WID Stations

Prevention is based on stopping the spread of invasive mussels to waters that do not already have invasive mussel populations. The primary prevention tactic employed by western states AIS programs are WID stations. A WID station is tasked with inspecting boats and other water based recreational equipment for any biological material. If biological material is found, the item will be decontaminated before it can enter the waterway. States utilize different locations when operating inspection stations, typically roadside or at a waterbody. Across the west states are encouraged to follow the Uniform Minimum Protocols and Standards for Watercraft Inspection and Decontamination (Elwell LC and S Phillips 2016) for the best standards, practical science and technology currently available for WID station consistency. Many Western states instituted watercraft inspection and decontamination programs after the discovery of invasive mussels in Lake Mead in 2007 (Zook and Phillips 2015). There is no universal requirement for WID stations and WID stations have been adopted by state and private waterways.

Examples of WID Stations

Idaho Inspection Program (State Level)

Idaho has adopted a primarily roadside inspection program; this program has inspection stations centered around the main access points into Idaho. The law in Idaho is that any boats coming from out of state must stop and be inspected for invasive species. Failure to do so can result in monetary fines. A brief excerpt from Invasive Species of Idaho website provides insight on what a boat inspection entails.

> High-risk inspections are intense and include a thorough inspection of the exterior and interior parts of the boat. The inspection includes a thorough and complete visual and tactile inspection of all portions of the boat, including compartments, bilge, trailer and any equipment, gear, ropes or anchors. If any biological material is found on the boat or equipment, the inspectors conduct a roadside "hotwash" of the watercraft.

The "hotwash" is a standard procedure for decontamination stations and entails the watercraft/equipment of boats harboring mussels to be decontaminated with hot pressure washers. Along with the roadside inspection stations, Idaho has a variety of roving stations that circulate around the state during the boating season. The state government of Idaho had 25 inspection stations during the 2020 season. The program conducted 135,000 boat inspections during the 2020 season and performed a "hotwash" on 5,700 watercraft (Invasive Species of Idaho).

Standley Lake Colorado (Private Level)

Standley Lake is a small reservoir located in the City of Westminster, Colorado; it is home to one of the most stringent prevention programs in the United States. The City of Westminster has recently prohibited trailered boating on Standley Lake to prevent the risk of a mussel infestation.
Standley Lake does not allow any type of watercraft including paddle boards, canoes, kayaks, inflatable rafts, or tubes to enter the lake at any entrance point except the main park entrance. All paddle craft must be decontaminated in accordance with Aquatic Nuisance Species regulations prior to launching. The city's main priority is to provide reliable, healthy drinking water, to which Standley Lake is the source for over 300,000 people living in the City of Westminster. It was estimated to cost Westminster $10 million in capital expenses and $3 million in annual operating costs if mussels enter

Standley Lake, significantly increasing the cost to deliver water. The establishment of invasive mussels would permanently change the ecology of Standley Lake, resulting in taste and odor issues and a reduction in water quality (City of Westminster).

WID in Western States

In 2021 nine western states had webpages that discussed their WID program and station locations: California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, and Wyoming. Arizona, Nebraska, South Dakota, and Washington have WID stations but information regarding number of stations and locations was not available. Wyoming, California, and Colorado had the greatest number of WID stations with 102, 91, and 72 stations, respectively, located throughout each state. Total number of WID stations by western state are shown in Table 1. WID station data was collected from State sponsored websites.

Table 1: Total number of WID stations by western state

State	Number of WID Stations	Source
California	91	California Department of Parks and Recreation
Colorado	72	Colorado Parks and Wildlife
Idaho	31	Invasive Species of Idaho
Montana	43	Montana Fish, Wildlife, and Parks
Nevada	17	Nevada Department of Wildlife
New Mexico	18	New Mexico Department of Game and Fish
Oregon	6	Oregon Department of Fish and Wildlife
Utah	42	Utah Division of Wildlife Resources
Wyoming	102	Wyoming Game and Fish Department

WID Station Costs

The cost to develop and operate WID stations, within an AIS program, varies due to several factors. Some factors include station schedule, employment numbers, and wage rates. Cost data for 2019 state operated WID stations was gathered and shared with Reclamation by the Western Invasive Species Coordinating Effort. WID budgets were provided for the western member states. Annual WID budgets ranged from $18,000 to $4,500,000 per year. The average 2019 WID Budget for western member states is approximately $1,605,900. Montana and Colorado had the largest 2019 WID budgets at $4,500,000 and $4,100,000, respectively. A full breakdown of the 2019 WID budget by state is shown in Table 2.

Table 2: 2019 WID Station Budget by State

State	WID Budget
California	$3,275,000
Colorado	$4,100,000
Idaho	$3,700,000
Montana	$4,500,000
Nebraska	$262,000
Nevada	$900,000
New Mexico	$149,000
Oregon	$18,000
South Dakota	$90,300
Utah	$2,550,000
Washington	$232,000
Wyoming	$1,100,000

Synthesis of WID Costs

As of 2021, WID stations were present in 9 western states: California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, and Wyoming. There is a total of 422 WID stations operated in the Western United States. The 2019 average annual WID budget was approximately $1,605,900.

WID Cost Tool

As part of this study, to assist decision makers in development of basic startup and operation costs the authors created a tool in Microsoft Excel Visual Basic for Applications (VBA). The features of the tool and how it works are discussed here.

Parameters

When constructed, WID stations, can have three station types, four different seasons (the traditional 4 seasons in a calendar year), and two employee types, supervisor and inspector, with different wage rates. Each season can have different hours of operation for the inspection stations. The first required model input is the type of station and the quantity of stations operated. Station types are broken into three categories: minimum, medium, and mega. Each station type has a different number of employees available during the station's operating hours. After the station type and quantity are chosen, the user is required to enter the season type. In most cases, WID stations operate with different hours of operation depending on the time of year. During the offseason, stations have limited hours of operation. Each season entered by the user requires a start and end date, as well as the hours operated per day. The hours of operation can be changed on weekends due to increased visitation. Finally, the wage rate of employees is required. These are the main model inputs that the user must enter for the tool to run. There are secondary model inputs that can be manipulated by the user for a more accurate cost estimate, but those model inputs are not mandatory. A snapshot of the main model inputs page of the cost tool can be seen in Figure 1.

Inputs													
Station Types:	Qty:		Season:	Start Date:	End Date:	Hours Operated per Day:	Operation Hours Different on Weekend?:	Hours off Operation on Weekend:		Wage Rate:			
										Inspector			
										Supervisor			
Results													

Figure 1: WID Cost Tool Main Model Inputs.

Control at Hydropower Facilities

For this study, control is focused on mitigating the damages to hydropower facilities that are affected by a mussel infestation. Control cost data was collected through a literature review and a survey from S&T Project 1876.

The survey from S&T Project 1876 was conducted by Reclamation in collaboration with RNT Consulting Inc. A total of thirteen hydropower plants were selected to be interviewed. A variety of different size, designed, and operated plants were selected to represent a variety of different scenarios. Additionally, sites were selected that had been experiencing mussel infestations for different time frames. Four of the 13 plants interviewed are operated by the Bureau of Reclamation, 6 plants are located in Canada, and 3 are operated by other agencies in the United States. The contact at each plant was provided the list of questions in advance of the scheduled interview. The survey list is shown in Table 3.

Table 3: Hydropower Facilities Surveyed

Hydropower Plant	Location	Water Body	Operating Agency	Date Mussel Issues Began
Hoover Dam	USA, Arizona/ Nevada	Colorado River, Lake Mead	Bureau of Reclamation	2010
Davis Dam	USA, Arizona/ Nevada	Colorado River, Lake Mohave	Bureau of Reclamation	2008
Parker Dam	USA, Arizona, California	Colorado River, Lake Havasu	Bureau of Reclamation	2008
Glen Canyon Dam	USA, Arizona	Colorado River, Lake Powell	Bureau of Reclamation	2013
Beauharnois Generating Station	Canada, Québec	St. Lawrence River, Lake St. Francis	Hydro Québec	1995
Jenpeg Generating Station	Canada, Manitoba	Nelson River	Manitoba Hydro	2020
Lewiston Pump Generating Station	USA, New York	Niagara River	New York Power Authority	1990
Sir Adam Beck #1	Canada, Ontario	Niagara River	Ontario Power Generation	1990
Sir Adam Beck #2	Canada, Ontario	Niagara River	Ontario Power Generation	1990
DeCew NF23	Canada, Ontario	Lake Gibson, Welland Canal	Ontario Power Generation	1990
Pump Generating Station	Canada, Ontario	Niagara River	Ontario Power Generation	1998
Wilson Hydropower Plant	USA, Alabama	Tennessee River	Tennessee Valley Authority	Early 1990's
Gavins Point	USA, South Dakota	Missouri River, Lewis and Clark Lake	US Army Corps of Engineers	2018

Literature Review

A study conducted from 1994-1995 surveyed power plants, water companies, golf courses, and other industries about their annual costs of zebra mussel monitoring, control, and research to reduce zebra mussel costs. The survey received 584 responses (a response rate of 50%). The survey concluded that from 1992 to 1994, average annual zebra mussel costs were estimated at about $30 million for facilities surveyed (Park & Hushak 1999).

Another study conducted in 2004 surveyed electric generation and drinking water treatment companies which use surface water in U.S. states and Canadian provinces within the range where zebra mussels were known to be present (Connelly et al. 2007). The survey results were used to estimate total economic impacts caused by zebra mussels from 1989–2004. Control costs were estimated to be $191,883 per facility and $89,801,244 for the study area from 1989-2004. Increased maintenance costs were estimated to be $32,698 per facility and $15,302,664 for the study area, and lost power production revenue was estimated to be $124,110 per facility and $58,083,480 for the study area (Connelly et al. 2007).

Other studies have focused on costs of controlling dreissenid mussels affecting drinking water infrastructure. Chakraborti et al. (2016) for instance analyzed case studies of capital and O&M costs incurred at various water treatment plants (WTP) in Canada and in the eastern, midwestern, and western United States. Capital and O&M costs were provided for 10 case studies which can be found in Table 4.

Table 4: Impact to WTP

Case Study	Impact
1	O&M cost: $398,900 per year (2011)
2	Capital cost: $154,670 (2013); O&M cost: $12,355 per year (2013)
3	Capital cost: $5,000,000; O&M cost: 100,000 per year (2011)
4	Chemical costs: $15,909 per year (2011); $24,581 per year (2010); $13,199 per year (2009); $9,844 per year (2008); $6,988 per year (2007)
5	Capital cost: 12,000 per year (2011); O&M cost: 50,000 per year for four plants combined (2011)
6	Chemical cost: 133,266 per year on NaClO (2011)
7	Capital cost: $367,268 (2006); O&M cost: $13,315 per year (2011); $14,026 per year (2010); $9,358 per year (2009)
8	Capital cost $1,370,000 (2010); O&M cost: 30,000 per year (2011)
9	Capital cost: $6,000,000; O&M cost: $350,400 per year for chemical treatment (2011)
10	Capital cost: $7,200,000 million (2010); O&M cost: $10,000,000 - $15,000,000(2010)

A 2010 study conducted for the Northwest Power and Conservation Council, analyzed the economic risk associated with the potential establishment of mussels in the Columbia River Basin (Independent Economic Analysis Board 2010). A scenario was created to estimate economic impacts; the scenario assumed "an accidental introduction in the upper Snake River basin would enable veligers to drift downriver and colonize suitable areas into the lower Snake River with some establishment in the mainstem Columbia" (Independent Economic Analysis Board 2016). An excerpt from the study's findings can be found in Table 5.

Table 5: Economic Impacts of Invasive Mussels, Snake River Infection Scenario

Type of Cost	Annualized Cost Per Year
Hydropower main cooling system, trashracks, intakes, other water supply	$16,000,000 (Snake River and downstream FCRPS). $5,000,000 others
Hydropower spillway gates, piers, apron, stilling basins	$3,000,000 - $10,000,000 (FCRPS only)
Fish passage facilities, bypass screens, fish ladders, gatewells	$1,100,000 Ladders, $1,950,000 Screens, $1,000,000 gatewells
Hatcheries	$3,000,000 (20 facilities). $1,000,000 annual monitoring and cleaning (system-wide)
Impacts to recreation and other facilities, including water supply, navigation, boats and marinas	Max potential unknown, estimated $50,000,000 annually

Source: Independent Economic Analysis Board (2010).

Survey Results from S&T Project 1876 included in this Study

Data collected from the survey highlighted four categories of increased costs due to mussel infestation: preventative control, increased O&M, monitoring, and unplanned outages. Preventative control is defined as treatments that reduce or eliminate mussel fouling before it occurs by deactivating or interfering with the mussel's ability to attach, grow and cause clogging (UV, Chemical, etc.). Cost data collected from Canadian facilities was converted to U.S. dollars using the average exchange rate over the last 35 years. The appropriate yearly exchange rate could not be determined since this report does not know the date costs occurred at the Canadian facilities. Exchange rate data was collected by the Organization for Economic Co-operation and Development. The average exchange rate over the last 35 years is $1 U.S. Dollar ~ CAN$ 1.27. The rest are costs due to increased maintenance, monitoring, and unplanned outages. Cost data for each facility surveyed can be found in Table 6.

Preventative Control Costs

Preventative control measures were implemented at all the 13 facilities surveyed. Preventative measures implemented at all facilities had an estimated capital cost that ranges from $72,000 - $2,600,000. Facilities also incur O&M costs related to preventative control investments at an estimated range of $4,000 – $141,700 per year. Of the 13 facilities surveyed, 5 implemented Hydro-optic Disinfection Ultraviolet Light treatment (HOD UV) with an estimated capital cost range of $1,000,000 - $2,100,000. HOD UV typically requires an annual O&M service cost at an estimated range of $18,000 - $32,000 per year. Chlorine injection treatment was installed at seven facilities with an estimated capital cost range of $100,000 – 1,020,000. Annual chlorine injection treatments have an estimated O&M cost range of $5,000 - $ 141,700. The cost of HOD UV and chlorine can range significantly and is dependent on-site specific characteristics including the design and number of raw water systems being protected.

Increased Operation and Maintenance

Increased maintenance costs were experienced at all the 13 facilities surveyed, but most of the facilities do not track and record all costs associated with mussel fouling, therefore the estimates provided are not representative of actual total costs. Total increased maintenance costs for facilities were estimated to be within $22,000 - $505,000. The annual increased maintenance costs of the facilities are at an estimated range of $26,000 - $112,000 per year. Some of the facilities do not incur annual O&M costs but rather a periodic maintenance event every few years. This was estimated to be within $22,000 - $505,000 per occurrence.

Monitoring

Monitoring costs were provided by seven facilities surveyed. Monitoring expenses have an annual estimated cost range of $1,970 - $ 47,245 per year.

Table 6: Costs Incurred by Facility

Facility	Preventative Control	Increased Maintenance	Monitoring	Unplanned Outages
Hoover	$2.6 million total	$122,630 (reoccurring)	N/A	$44,000-$80,000 (reoccurring)
Davis Dam	N/A	$26,000 per year	N/A	N/A
Parker Dam	$1 million total; $18,000 per year	$48,000 per year	N/A	N/A
Glen Canyon Dam	$1.9 million (planned) total; $4,000 per year	$59,820 per year	N/A	N/A
Beauharnois Generating Station	$1,020,000 (CAN$ 1.3 million) total	$9,840 (CAN$ 12,500) per year	$47,245 (CAN$ 60,000) per year	N/A
Jenpeg Generating Station	$141,700 (CAN$ 180,000) per year	N/A	$1,970 (CAN$ 2,500) per year	N/A
Lewiston Pump Generating Station	$40,000 per year	$22,000 reoccurring	$15,000 per year	N/A
Sir Adam Beck #1	$393,700 (CAN$ 500,000) total; $2,360 (CAN$ 3,000) per year, $6,300 (CAN$ 8,000) reoccurring	$48,230 (CAN$ 61,250) per year	$5,905 (CAN$ 7,500) per year	N/A
Sir Adam Beck #2	$1,020,000 (CAN$ 1.3 million) total; $6,300 (CAN$ 8,000) per year, $12,600 (CAN$ 16,000) reoccurring	$63,976 (CAN$ 81,250) per year	$5,905 (CAN$ 7,500) per year	N/A
DeCew NF23	$197,000 (CAN$ 250,000) total; (CAN$ 2,000) per year, (CAN$ 5,000) reoccurring	$48,230 (CAN$ 61,250) per year	$5,905 (CAN$ 7,500) per year	N/A
Pump Generating Station	$566,900 (CAN$ 720,000) total; $2,360 (CAN$ 3,000) per year, $3,937(CAN$ 5,000) reoccurring	$48,230 (CAN$ 61,250) per year	$5,905 (CAN$ 7,500) per year	N/A
Wilson Hydropower Plant	$72,000 total	$505,000 reoccurring	N/A	N/A
Gavins Point Hydropower Plant	$1.012 million total; $46,580 per year	$111,240 per year; $1,000 reoccurring	N/A	$848,925 total

Note: N/A is used to represent costs that were not provided by the facility.

Unplanned Outages

Unplanned outages were experienced by five of the thirteen facilities interviewed. The cost of unplanned outages was only provided by two facilities; One facility has reoccurring outages at an estimated cost of $44,000 - $80,000 per outage. The other facility provided total costs due to outages since mussel invasion in 2014, this was estimated to be $849,000. Unplanned outages pose a serious threat to hydropower facilities. As infestation occurs and intensifies, hydropower facilities may experience an increased risk of unplanned outages. The likelihood of an outage occurring because of mussel fouling is related to the design and operation of the plant and the mussel population numbers. Power generation is decreased when an outage occurs resulting in lost power generation revenue. Currently, four Reclamation facilities are infested with mussels, two of which have experienced unplanned outages. Average lost power generation revenue per unit per day was derived for Hoover, Parker, Davis, and Glen Canyon Dam. If an unplanned outage occurs at Hoover, lost power generation revenue is estimated to be $18,211-$24,544 per unit per day. For Parker, Davis, and Glen Canyon Dams lost power generation revenue is estimated to be $9,934-$13,249, $19,552-$26,236, and $45,278-$61,465 per unit per day, respectively. Average lost power generation revenue estimates can be found in Table 7. Cost data per MWh was collected from the U.S. Energy Information and Administration; plant generation data was collected from the Reclamation Power Resource Office.

Table 7: Average lost power generation revenue per unit per day

Hoover Dam	Parker Dam	Davis Dam	Glen Canyon Dam
$18,211-$24,544	$9,934-$13,249	$19,552-$26,236	$45,278-$61,465

Summary of Control Costs at Surveyed Hydropower Facilities

All facilities implemented preventative control measures and experienced increased maintenance costs. Monitoring costs were provided by seven facilities; only two facilities provided costs associated with unplanned outages. A breakdown of costs is shown in Table 8.

Table 8: Facility Control Costs

Category	Cost Range
Preventative Control Capital Costs	$100,000 - $2,000,000
Preventative Control Annual Costs	$4,000 – $141,700
Increased Maintenance Reoccurring Costs	$22,000 - $505,000
Increased Maintenance Annual Costs	$26,000 - $112,000
Monitoring Annual Costs	$1,970 - $ 47,245
Unplanned Outages Cost per Occurrence	$44,000 - $80,000
Unplanned Outages Total Cost	$849,000

Additional Costs Associated with Invasive Mussels Infestations

Mussel infestation can have a variety of ecological impacts which can result in negative economic impacts. Research indicates there will likely be significant changes to aquatic ecosystems, including: (1) transfers of energy to littoral areas, with concurrent increases in benthic biomass, (2) increased water clarity leading to expanded aquatic plant coverage, (3) changes to food webs and fish communities, and (4) an increased likelihood of harmful algal blooms. Other organisms, including native mussels, crayfish, waterfowl, and insects may experience population changes as well.

As mentioned, a mussel infestation can lead to increased water clarity and increased likelihood of harmful algal blooms which can have a negative economic impact (Higgins and Vander Zanden 2010). Mussels selectively reject cyanobacteria, commonly referred to as blue-green algae, causing an increase in overall bacteria blooms. If a lake were to become infested with invasive mussels, there is a possibility for increased occurrences of harmful algae blooms. Cyanobacteria masses increase in lakes that are infested with invasive mussels and these lakes can have 3.6 times more cyanobacteria masses than those without mussels. Cyanobacteria masses contribute to the death of fish species resulting in an overall decline of fish in the lake (Knoll et al. 2008). Cyanobacteria can have significant economic implications as seen in Florida and Texas.

In May 2016, there was a large harmful algae bloom in Lake Okeechobee, Florida. The bloom lasted over 2 months as it did not start to dissipate until the end of July. Algal-laden water from the lake was transported through a series of canals and rivers to coastal areas due to high water levels during that time. This resulted in several beach closures throughout Florida (USGS). There can be an expected negative impact to recreation and tourism when beaches are closed due to harmful algae blooms. A golden algae bloom, caused by cyanobacteria, devastated Lake Texoma in 2004. This event killed 25-30 thousand fish and endangered their $40 million per year fishing industry (Linkov et al. 2008). A 2014 cyanobacteria algae bloom in Lake Erie resulted in $65 million in lost revenue (Bingham et al. 2015). The $65 million in lost revenue was broken down into lost revenue of tourism ($43 million), decease in property value ($18 million), and treatment of drinking water ($4 million).

A 2009 study of Lake Tahoe, California, by the Army Corp of Engineers estimated a $22 million annual loss to the region if mussels were to infest Lake Tahoe. The study "details potential damage to tourism, reduced property values, and increased maintenance costs" (Hoddle). Large accumulations of the algae *Cladophora,* clogged cooling water intake systems which caused nuclear power plants to shut down (Auer et al. 2010). The US Army Corps of Engineers reported that spending in fiscal year 2004 was over $4 million at 12 Civil Works projects on aquatic plant control (Cole et al. 2010). Management of aquatic plants was estimated to cost $5 million from 1985 to 2001 at Lake George, NY (Boylen et al. 2001).

Expanded aquatic plant coverage, as a result of increased water clarity, can have negative economic impacts. Aquatic plant biomass can have a negative impact on lakefront property values. In King County, WA, lakefront homes with milfoil infestations saw a 19% decrease in mean property value (Olden & Tamayo 2014), and in Vermont property values were negatively impacted by 1 to 16% (Zhang & Boyle 2010). The Truckee River watershed estimated a 1% decline in recreation values due to milfoil at $500,000 annually (Eiswerth et al. 2000).

Aquatic plant coverage can decrease the quantity and quality of recreational activities. Activities such as angling, boating, and swimming can be negatively impacted (Newroth 1985). For example, Eurasian watermilfoil an invasive aquatic plant, can cause a decline in sport fish populations and diversity which can negatively impact recreational angling (Eiswerth et al. 2000). Walleye in Lake St. Clair decreased by 50-75 percent due to increased light penetration, which can be attributed to a mussel infestation (Vanderploeg 2003). Lake Huron had a decline in salmon and alewife populations after the infestation of mussels (Michigan DMR 2010). In a 2017 study of Lake Powell, researchers predicted a decline in striped bass and threadfin shad populations due to a mussel infestation (Verde 2017).

Economic data for recreational angling by State Congressional District, has been estimated by the American Sportfishing Association. Congressional districts have been selected due to their proximity to the reservoirs associated with Hoover, Parker, Davis, and Glen Canyon Dams. Table 9 shows fishing related purchases by congressional district and the resulting statewide economic contribution from recreational angling within each congressional district. Increasing invasive mussel infestations would likely cause a decrease to recreational activity. Statewide economic contributions, as a result of recreational angling, shown in Table 9, could be negatively impacted.

Table 9: 2018 Economic impact of anglers by state congressional district

State	Congressional District	Number of Anglers by Congressional District	Fishing-related purchases in State by Congressional District Anglers	Statewide Contributions by Congressional District Anglers
Arizona	District 5	104,400	$153,400,000	$251,100,000
Arizona	District 7	56,400	$82,900,000	$135,700,000
California	District 8	45,100	$69,500,000	$127,300,000
Nevada	District 1	34,600	$30,400,000	$46,400,000
Nevada	District 3	50,600	$44,500,000	$67,900,000

The potential costs to fisheries, hatcheries, and spawning runs due to a mussel invasion are severe. In Lake Huron, salmon and alewife populations have declined, causing a $19 million/year decrease in sport fishing revenues (Michigan DNR 2010). An infestation in the Columbia River Basin or Snake River could cost hundreds of millions of dollars annually, and counter recent investments to restore fish runs in the area (Mann 2010, IEAB 2013). In addition to the cost of damaged habitat and the threat posed to other species, reduced populations of keystone species such as salmon would be economically damaging.

Summary of Other Costs Associated with Invasive Mussels

Mussel infestation can have a variety of ecological impacts which can result in negative economic impacts. This analysis did not attempt to quantify lost ecosystem benefits, but rather it relied on existing studies to estimate a range of values for lost ecosystem or social benefits. Other costs associated with invasive mussels are shown in Table 10.

Table 10: Other Costs Associated with Invasive Mussels

Category	Impact	Study
Algae bloom (Lake Texoma, 2004)	Endangered $40 million/ per year fishing industry	Linkov et al. 2008
Algae bloom (Lake Erie, 2014)	$65 million lost revenue	Bingham et al. 2015
Milfoil (King County, WA)	a 19% decrease in mean lakefront property value	Olden & Tamayo 2014
Aquatic plant biomass (Vermont)	1 to 16% decrease in property values	Zhang & Boyle 2010
Aquatic plant control (Army Corp FY 2004)	$4 million at 12 Civil Works projects	Cole et al. 2010
Aquatic plant control (Lake George, NY 1985-2001)	$5 million	Boylen et al. 2001
Milfoil (Truckee River Watershed)	1% decline in recreation at $500,000 annually	Eiswerth et al. 2000
Increased Light Penetration (Lake St. Clair)	Walleye populations decreased by 50-75%	Vanderploeg 2003

Discussion

The introduction of invasive mussels into a particular body of water can occur as the result of transportation, via watercraft, from one water body to another, as well as from stream flows from upstream infested water bodies. Consequently, an AIS program, in and of itself, cannot provide absolute protection against the introduction of invasive mussel species into a particular water body. However, a comprehensive, well-managed AIS program can make a valuable contribution in preventing, or significantly delaying, the spread of invasive mussels and other invasive aquatic species, to additional water systems in the western U.S. For example, in Colorado, there are no waters positive for zebra or quagga; all waters have been de-listed following five years of no detections per Western Regional Panel standards (Colorado Parks and Wildlife 2021). Colorado's success can be partially attributed to the implementation of WID stations. Colorado had the second largest expenditure on WID stations, 231% larger than the average 2019 western state WID budget. Montana has also experienced success with AIS programs. In 2016, the Early Detection and Monitoring Program detected invasive mussel larvae in Tiber Reservoir and had a suspect detection in Canyon Ferry Lake (Montana Fish, Wildlife, and Parks 2021). In 2020, Canyon Ferry Reservoir was delisted as a suspect waterbody after three years of monitoring with no detections of invasive mussels or larvae. Tiber Reservoir will continue to be listed and have boating restrictions, including mandatory inspection and decontamination for all vessels and equipment leaving the reservoir to prevent spread to other locations in Montana (Montana Fish, Wildlife, and Parks 2021).

States with low annual WID budgets have seen increased growth in the spread of invasive mussels. For example, in Texas twenty-four lakes can be classified as fully infested with zebra mussels, meaning the water body has an established, reproducing population (Texas Parks and Wildlife 2021). Texas does have an AIS program but does not have a budget allocated to statewide WID stations. Texas has adopted state regulations that only require draining of water from boats and onboard receptacles when leaving or approaching public fresh waters (Texas Parks and Wildlife 2021).

Data gathered shows all surveyed hydropower facilities experienced negative economic impacts related to control or mitigation of mussel-related damages. Facilities surveyed have spent approximately $10 million in total on preventative control measures since mussel inception. Facilities surveyed spend approximately $464,000 annually on increased maintenance. Some facilities do not have annual maintenance but rather maintenance that is reoccurring; these maintenance costs are not incurred annually. Total reoccurring maintenance costs for facilities surveyed were $650,000 per occurrence. Facilities surveyed spend approximately $88,000 in total annually on monitoring.

Cost data collected from the survey does not represent all costs a facility may incur if invasive mussels are detected. Control costs can be heavily dependent on design and operation of an individual facility. Control methods may also be influenced by environmental regulation. For example, chemical injection treatments may not be feasible depending on the vulnerability of the surrounding ecosystem. It is important to note some of the facilities have incurred large capital costs to reduce annual costs. Capital costs can range from 100,000 to $2,100,000. Some facilities also experience reoccurring maintenance costs. These maintenance costs range from $22,000 to $505,000 per occurrence.

Even though economic impacts experienced at individual facilities can be low compared to statewide program spending, if a state experiences a large number of facility infestations, the total economic burden experienced by all facilities in state has the potential to greatly outweigh the statewide AIS program spending. As mentioned, ecological impacts associated with mussels are difficult to estimate but including these values is critical to understanding the full economic picture associated with mussel management in the west and AIS spending should be considered within the full realm of economic impacts experienced at facilities and the potential ecological/economic damages to waterbodies.

Limitations

As indicated earlier, the scope of this study did not include a full benefit-cost analysis of prevention activities, such as state-wide or regional AIS programs. Additionally, the study does not attempt to provide a thorough comparison of prevention costs with control costs related to invasive mussels. Both of these efforts require the quantification and monetization of the ecological impacts caused by invasive mussels described earlier in this report. Evaluating the economic impacts of mussel invasion requires the estimate of a number of variables, including the rate at which invasive mussels spread within and between water systems, the success rate of prevention activities in preventing or delaying the spread of invasive mussels, and the rate and extent to which invasive mussels impact the initial conditions of a water body and, consequently, the vitality of native species, as well as property values, recreation, cultural values, and health and safety concerns.

An analysis to compare costs of prevention (which are generally provided on a larger geographical scale, such as a river basin or state) with control costs (which are generally provided on a much smaller scale, such as a reservoir or even a single facility) must include the addition of ecosystem impact costs to control costs so a proper comparison with prevention costs can be made. Since prevention costs, by definition, are assumed to prevent all impacts that would occur as a result of mussel invasion (not just facility-related control costs), it would be incorrect to simply compare facility-related control costs to prevention costs. Therefore, the costs of all mussel-related impacts to the ecosystem must be combined with facility-related control costs before they can be compared to prevention costs. Additionally, the combined costs of all affected water and power facilities within a watershed should be aggregated to the same level as the corresponding prevention costs. Failure to properly account for all appropriate costs at the same geographic scale will result in incorrect results.

One of the primary obstacles encountered in attempting to compare the costs of prevention measures to control costs was the inability to identify a direct cause-and-effect relationship between mussel infestation and a large number of O&M activities. In cases where control systems, such as HOD UV lights, were installed or additional chemical treatments, such as chlorine, were used specifically to control mussels at a facility, the cost of mussel infestation was relatively easy to determine. However, we found that many increases in O&M activities related to mussel infestation at various facilities were typically not identified as being mussel related. As a result, estimates of increased labor and materials costs due to mussels were generally based on the professional judgement of facility operators rather than actual accounting data.

Another issue with attempting to compare the costs of prevention versus control measures is related to a difference in how prevention and control costs are measured and tracked. This issue is primarily an issue of geographic scope but is also affected by the fact that both control and prevention costs are sometimes applicable to more than one particular species or operational function. For example, the majority of AIS program costs are reported on a state-wide or regional basis, while most control costs are reported by specific facility Additionally, while WID activities are perceived to be focused primarily on invasive mussels, the program also prevents the spread of other invasive aquatic species to additional water bodies. Similarly, a number of O&M activities required to keep water and power facilities operating normally are also used to controlling the effects of mussel invasion. The only difference is that the frequency of such O&M activities increases as a result of mussel infestation, however, it is difficult to quantify the increase due to invasive mussels.

The ecological impacts associated with mussels are wide reaching and vary considerably, however, the ability to assign appropriate economic costs to these ecological impacts is critical to understanding the full economic picture associated with mussel management in the west. Ecological costs are indirect costs associated with a mussel infestation, and though difficult to quantify are relevant to the discussion of accurate control costs. Natural resource managers at all levels of government are responsible for accountable stewardship and need to consider the full range of impacts when determining the appropriate course of action for mussel management.

Recommendations

This synthesis of costs associated with prevention activities, including WID stations and activities versus post-infestation control measures, provides evidence that these mussels management strategies provide considerable value to the nation. Efforts to identify the most relevant factors for preventing future mussel invasions, as well as measuring the economic impacts of mussels on the ecosystems they invade, as well as water delivery and power generation facilities, will help provide water resource managers with critical data to develop and fund adequate prevention, containment, and eradication programs.

As a result of the data collected and analysis performed to prepare this report, we propose the following list of recommendations.

1. Improve accounting measures to more accurately identify increased costs related to invasive mussels. Such improvement needs to categorize and assign both prevention and control costs to allow for both incremental and aggregated economic/financial analyses can be performed. For example, identifying specific costs or activities that have occurred as a result of invasive mussels rather than routine maintenance activities.

2. Additional research to identify and quantify the impact of invasive mussels on ecosystem services, such as impacts to water deliveries, power generation, fisheries, recreational values, and property values. This is similar to the above recommendation in that better data allows for better analyses. However, while data for some of the above areas are routinely collected and maintained for specific operational purposes, others are not – and even for those that are, such as water deliveries and power generation, the data is not available to determine if causality can be linked to invasive species.

3. Additional research to identify the most prevalent means by which invasive mussels spread and infest new water systems. This information is one of the variables needed to be able to determine the effectiveness of various prevention activities, such as WID stations.

4. Additional research to identify and quantify the success of WID stations to minimize the rate of mussel invasions into additional water systems. This information is needed for water resources managers to be able to prioritize how to spend limited budgets in the effort to minimize economic and financial impacts of invasive mussels. While the focus of this paper is invasive mussels, this recommendation should not be limited to invasive mussels but also evaluate the success of AIS programs in preventing the spread of other aquatic invasive species.

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