Case Studies: Impact and Control of Invasive Mussels at Hydropower Plants

Science and Technology Program
Research and Development Office
Final Report No. ST-2020-1876-01
EcoLab-FA807-2021-01

U.S. Department of the Interior March 2021

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
03-31-2021	Research	2/28/18- 3/31/21

4. TITLE AND SUBTITLE
Case Studies: Impact and Control of Invasive Mussels at Hydropower Plants

"Impact and Control of Mussels at Hydropower Plants"

5a. CONTRACT NUMBER
RY.15412018.ZQ21876/FA808

5b. GRANT NUMBER

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

6. AUTHOR(S)
Sherri Pucherelli, Biologist[1]
Renata Claudi[2]
Thomas Prescott[2]
Leonard Willett[2]
Tony Van Oostrom[2]

5d. PROJECT NUMBER
Final Report ST-2020-1876-01

5e. TASK NUMBER

5f. WORK UNIT NUMBER

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

[2]RNT Consulting INC.
823 County Road 35, RR#2, Piston, Ontario KOK 2T0, Canada

8. PERFORMING ORGANIZATION REPORT NUMBER

EcoLab-FA807-2021-01

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-2020-1876-01

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

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Thirteen hydropower plants with invasive quagga or zebra mussel fouling were interviewed about their experience. Information was gathered about the size and operation of the facility, the mussel infestation timeline, the systems, and structures experiencing mussel fouling, the implemented control and mitigation methods, and the expenses associated with mussel management. The severity of mussel impacts was dependent on the design of the power plant and raw water usage. The size and number of generators was not indicative of the severity of impacts. The majority of plants interviewed do not completely track mussel specific maintenance and costs, therefore the estimates do not provide a complete picture of the costs associated with mussel infestations at hydropower plants. These case studies provide valuable information to managers at plants preparing for the potential arrival of dreissenid mussels.

15. SUBJECT TERMS
Invasive mussels, quagga mussels, zebra mussels, mussel fouling, mussel impacts, mussel costs

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	THIS PAGE		68	Sherri Pucherelli
U	U	U			19b. TELEPHONE NUMBER *(Include area code)* (303) 445-2015

Mission Statements

The Department of the Interior (DOI) conserves and manages the Nation's natural resources and cultural heritage for the benefit and enjoyment of the American people, provides scientific and other information about natural resources and natural hazards to address societal challenges and create opportunities for the American people, and honors the Nation's trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities to help them prosper.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Disclaimer

Information in this report may not be used for advertising or promotional purposes. The data and findings should not be construed as an endorsement of any product or firm by the Bureau of Reclamation, Department of Interior, or Federal Government. The products evaluated in the report were evaluated for purposes specific to the Bureau of Reclamation mission. Reclamation gives no warranties or guarantees, expressed or implied, for the products evaluated in this report, including merchantability or fitness for a particular purpose.

Acknowledgements

The Science and Technology Program, Bureau of Reclamation, sponsored this research. This project was a commitment to the Department of the Interior's Safeguarding the West Initiative. A special thank you to those who took the time to provide detailed information about the impact of mussels at their hydropower plants. Thank you to the reviewers of this document.

Case Studies: Impact and Control of Invasive Mussels at Hydropower Plants

Final Report No. ST-2020-1876-01
EcoLab-FA807-2021-01

prepared by

Technical Service Center

Hydraulic Investigations and Lab Services
Sherri Pucherelli

RNT Consulting Inc.

Renata Claudi
Thomas Prescott
Leonard Willett
Tony Van Oostrom

Peer Review

Bureau of Reclamation
Research and Development Office
Science and Technology Program

Final Report ST-2020-1876-01

Case Studies: Impact and Control of Invasive Mussels at Hydropower Plants

SHERRI PUCHERELLI
Digitally signed by SHERRI PUCHERELLI
Date: 2021.04.08 08:17:28 -06'00'

Prepared by Sherri Pucherelli
Biologist, Technical Service Center

JOSEPH KUBITSCHEK
Digitally signed by JOSEPH KUBITSCHEK
Date: 2021.04.13 09:54:47 -06'00'

Peer Review by Joseph Kubitschek
Hydraulic Engineer, Technical Service Center

"This information is distributed solely for the purpose of pre-dissemination peer review under applicable information quality guidelines. It has not been formally disseminated by the Bureau of Reclamation. It does not represent and should not be construed to represent Reclamation's determination or policy."

Contents

Page

Executive Summary

Invasive mussels became an issue for Reclamation in 2007 after quagga mussels were detected in reservoirs along the lower reaches of the Colorado River in AZ and NV. Several large hydropower facilities have been impacted and Reclamation is anticipating that mussels will impact other locations in the future. The purpose of this study was to meet with hydropower facilities across multiple agencies throughout the United States and Canada who currently have invasive mussel infestations to learn more about how mussels are impacting operation and maintenance and the types of control methods that have been implemented. When possible, information about the cost of mussel control and maintenance was gathered. These case studies can be used by Reclamation facility managers and others throughout the United States and Canada that are preparing for a potential mussel invasion or those that are re-evaluating their current treatment approach.

Reclamation and RNT Consulting Inc. selected thirteen hydropower plants to be interviewed. Questions were designed to develop a comprehensive understanding of the plants experience with mussels. Four of the thirteen plants interviewed are operated by Reclamation, six plants are located in Canada, and three are operated by other agencies in the United States. The case studies include hydropower plants with two (144 MW total) to thirty-six (1899 MW total) generator units, a range of raw water system designs and usage in the plants, and 1 to 31 years of experience with mussel fouling.

Two of the plants consider mussel impacts to be significant, eight consider the impacts to be moderate, and three plants experience little to no impact. This study confirms that mussel impacts are primarily dependent on the design configurations of hydropower plants and how they utilize raw water. The size or number of generators at a plant does not usually correlate to the severity of impacts or expenditures. Mussel population size and dynamics also influence the impacts experienced.

Eight plants have implemented treatments to prevent mussel fouling. Preventative control treatments include those that reduce or eliminate mussel fouling before it occurs by deactivating or interfering with the mussel's ability to attach, grow and cause clogging. The most common preventative control treatments utilized by the plants in this study were chlorine and HOD UV. While these treatments are effective at mitigating mussel fouling, they will not always be appropriate for every hydropower plant due to site specific limitations including discharge permitting requirements and water quality parameters.

Expenses associated with mussel fouling and maintenance were not recorded at the majority of plants interviewed. Five of the thirteen sites have experienced or are currently experiencing unplanned outages as a result of mussel fouling in the generator cooling systems. Cost estimates associated with preventative control measures, increased maintenance, unplanned outages, and monitoring are provided in this report, but it is difficult to provide exact costs associated with an infestation because all expenses are not usually recorded and tracked.

Best practices such as, mussel monitoring, facility vulnerability assessments and formulation of response plans can help facilities prepare for and mitigate significant operational impacts at plants. Seven of the thirteen plants interviewed in this study had prepared for a mussel infestation by conducting a facility vulnerability assessment or developing a response plan. All of the plants that had prepared indicated that the assessment or plan was useful for detecting mussels sooner and implementing control methods before fouling became unmanageable. Mussel vulnerability assessments and the information provided by these case studies can be utilized by hydropower plant managers that are preparing for a mussel infestation.

Introduction

Invasive dreissenid mussels, quagga (*Dreissena rostriformis bugensis*) and zebra (*Dreissena polymorpha*) mussels, were first introduced to the Great Lakes and have since spread across much of the United States. Adult mussels and mussel larvae (veligers) are most commonly transported from one water body to another on recreational boats. A water body must have appropriate habitat suitability for a mussel population to establish and for the population to grow. A few of the important habitat factors that must be within the mussel's range of suitability include calcium, pH, temperature, and dissolved oxygen. Calcium and pH are important in order for the mussels to develop their shells.

Once established, invasive mussels are prolific breeders and the pediveliger life stage of the mussel is capable of settling on any hard surface they encounter. This behavior is problematic for hydropower plants because the mussels settle on submerged surfaces and in pipelines and systems that convey and utilize raw water. Additionally, shell debris from dead adult mussels that were settled upstream can enter hydropower plant systems and accumulate in strainers and other locations. When mussel populations are dense, mussels will begin to settle on top of each other, creating thick mats which can restrict flow in critical systems leading to overheating of critical systems, unplanned outages, and increased maintenance.

The degree of impact mussels will have at a hydropower plant is dependent upon the level of infestation, the yearly reproduction frequency at the location, and the specific facility operating conditions and design. While there are similarities among hydropower facilities, it is recognized that site-specific or as-built conditions including equipment and associated arrangements can vary significantly. Mussel fouling is common on submerged structures and in areas where raw water is used, particularly in complex components like small diameter pipe networks (less than 6 inches) with low velocity (4.5 feet per second or less). The following systems and equipment specific to most hydropower facilities have the potential to be adversely impacted by invasive mussels (Prescott et al. 2014):

- Intakes and penstocks
- Gates and valves
- Bypasses and air vents
- Cooling water systems
- Raw water fire protection systems
- Service and domestic water systems
- HVAC systems
- Instrumentation
- Strainers and filters
- Pumps, turbines, and generators
- Drainage and unwatering systems
- Spillways and appurtenances
- Outlet works and appurtenances

- Water diversion and conveyance facilities
- Fish screening and passage facilities
- Structural drainage systems

Along with the impact to hydropower facilities, mussels also negatively impact the ecosystem. As filter feeders, mussels can cause shifts in the natural ecosystem by disrupting the food chain, concentrating toxic substances, and degrading critical habitat which can lead to the decline of native species and potentially the proliferation of disadvantageous species such as weeds or toxic algae, which in turn can also become a problem at some power plants.

In order to prepare for a potential mussel infestation hydropower plants can complete a facility vulnerability assessment where an expert will identify critical systems and structures at the plant that are most at risk for mussel fouling. Monitoring for mussel presence can also provide advanced warning and allows time to implement preventative control measures. Monitoring efforts can include collecting plankton tow net samples from the upstream water body to detect mussel larvae, installing settlement plates in the upstream water body to identify adult mussels, or installation of bioboxes on critical systems to monitor for mussel settlement in the plant. Bioboxes are flow-through aquariums that have settlement plates for easy monitoring. The flow of water into the biobox is slow enough to allow pediveligers to settle and grow. Following completion of a vulnerability assessment, developing a response plan prior to mussel establishment can help reduce the impacts after mussels are initially detected.

Invasive mussels became an issue for Reclamation in 2007 after quagga mussels were detected in reservoirs along the lower reaches of the Colorado River in AZ and NV. Several large hydropower facilities have been impacted and Reclamation is anticipating that mussels will impact other locations in the future. The purpose of this study was to meet with several hydropower facilities across multiple agencies throughout the United States and Canada who currently have invasive mussel infestations and to document their experiences. Interviews focused on how mussels are impacting operation and maintenance and the types of control methods that have been implemented. When possible, information about the cost of mussel control and maintenance was also gathered for reference.

The information gathered from these case studies can be used by Reclamation facility managers and others throughout the United States and Canada that are preparing for a potential mussel invasion or are considering changes to their existing treatment. This study also fulfills Reclamation's commitment to the Department of Interior's Safeguarding the West Initiative to compile best practices, strategies and technologies used at infested facilities to help minimize risks and impacts at other sites. The case studies provide insight into the specific systems and structures that are impacted for differently designed and operated plants and the types of control methods found to be most useful. Although mussel control and mitigation techniques are site specific and dependent upon facility design and operation, these case studies can be used as a reference alongside mussel facility vulnerability assessments for planning and mitigation purposes.

Literature Review

It has been estimated that impacts associated with damage and control of invasive mussels' costs $1 billion per year in the United States (Pimentel et al. 2005). Several surveys were identified in the literature that investigated the expenditures associated with mussel control and monitoring at a variety of water management facilities in the United States.

A survey by O'Neil (1997) investigated the expenditures associated with invasive mussel infestation at a variety of facilities including golf courses, marinas, reservoirs, hatcheries, navigation locks, water treatment facilities and electric power generation facilities. The survey was mailed to 766 infrastructure owners and operators in 35 states and 3 Canadian provinces. Of the 436 responses, 339 facilities reported expenses associated with invasive mussels, with a mean expenditure of $205,570 per facility. Of the different types of facilities surveyed, nuclear power plants were found to spend the most, with a mean expenditure of $786,670 per facility. Electric generation plants had a mean expenditure of $145,620. Hydropower facilities spent the greatest amount on chemical control methods, followed by, prevention, monitoring, retrofitting, nonchemical treatment, training, mechanical removal of mussels, and research.

Park and Hushak (1999) surveyed 1,490 powerplants, water companies, golf courses, and other industries about their annual costs of zebra mussel monitoring, control, and research. They received 584 responses and found that only 44% of infested facilities had taken preventive actions prior to infestation. Total monitoring and control costs (between 1989 and 1994) were $120 million and average annual monitoring and control costs (between 1992 and 1994) were $30 million. The costs associated with control included retrofitting, physical removal or mechanical exclusion, chemical treatment, and other treatments. Of the utility and industrial plants surveyed, 39 of 66 were using at least one chemical treatment method (59% using chlorine, 23% were using molluscicides, 18% were using bromine and 18% sodium bisulfate), but there were some sites using exclusively physical removal.

Connelly et al. (2007) investigated the economic impacts of zebra mussels on drinking water treatment and electric power generation facilities. They attempted to survey all identifiable electric generation and drinking water treatment companies that used surface water in the US and Canada in the range that mussels were present. A total of 708 electric generation companies and 876 drinking water treatment providers were identified and contacted, of which 81 electric generation companies and 321 water treatment companies responded. The study found a cumulative economic impact to facilities in North America of $267 million between 1989 and 2004, and an average cost per facility of $30,000 per year. A significant contribution to the overall estimate of impacts associated with mussel fouling were the costs associated with prevention efforts, and lost production and revenues.

Phillips et al. (2005) estimated costs to the Federal Columbia River Power System hydroelectric projects in the event of invasive mussel infestation. The estimated cost to implement a sodium hypochlorite (NaOCl) injection system and anti-fouling paint could range from hundreds of thousands of dollars to over a million dollars per facility. The estimated cost to implement the control measures at 13 hydroelectric projects was $23,621,000. A survey of zebra mussel mitigation costs at other hydropower generation facilities in North America indicated that most utilities waited until mussel infestation had been discovered before installing control systems. The survey found the most common control methods were sodium hypochlorite and mechanical removal and after long-term control programs were initiated mussel maintenance usually became part of routine maintenance.

The US Army Corps of Engineers (USACE) recently completed a study to identify the extent of dreissenid mussel invasion in USACE districts and impacts mussels have on USACE infrastructure (Hay et al. 2019). Mussels were found to be present within 24 of the 36 USACE district boundaries. Infestations were found to be common, but 67% of the districts with infested waters reported minimal or no impacts on the infrastructure or operation and maintenance costs. Districts that did have impacts were not able to provide associated cost figures. Eight of the districts had monitoring programs in place.

Surveys of water management agencies throughout the United States who have mussel infestations suggest that chemical control and physical removal are some of the most common methods for managing mussel fouling (O'Neil 1997; Park and Hushak 1999; Connelly et al. 2007). Several chemical methods have been found to successfully control mussels including chlorine, ammonia, bromine, potassium permanganate, quaternary and polyquaternary ammonium compounds, aromatic hydrocarbons, copper ions, and potassium compounds. Information about the use of chemicals for mussel control can be found in the United States Army Corps of Engineers Zebra Mussel Chemical Control Guide (Glomski 2015). Reclamation and RNT Consulting Inc. have investigated a variety of non-chemical control methods (Pucherelli 2020) that include hydro-optic ultraviolet light treatment.

Methods

The goal of this effort was to compile case studies describing the impact of invasive mussels on hydropower facilities in the United States and Canada to inform managers at plants that are preparing for mussel infestations and for those managers that are considering changes to their existing approaches. Reclamation compiled these case studies in collaboration with RNT Consulting Inc. RNT consulting is familiar with the systems and components vulnerable to dreissenid mussel fouling as a result of their experience conducting facility vulnerability assessments in North America, South America, and Europe.

A list of questions (Appendix 1) was developed with guidance from the facility vulnerability assessment template that RNT developed for Reclamation. Questions were designed to develop a complete understanding of the plants experience with mussels and to identify all mussel related issues even if they are not considered significant. A list of commonly impacted systems and equipment was prepared along with the questions to make sure all impacts were discussed. When mussels do not cause significant day-to-day issues, it is common for those working at the plant to no longer consider mussels to be a problem. Mitigation of mussel fouling often becomes part of the regular O&M schedule and the impacts are not fully appreciated or understood. Interview questions focused on the following topics:

- Design and operation of the hydropower plant that might influence mussel impacts, including:
    - Facility age
    - Number of generator units
    - Maintenance approach

    - Type of raw water intakes
- Mussel infestation timeline, response planning, and monitoring
- Mussel impacts including:
    - Locations impacted
    - Design aspects that have prevented or reduced mussel impacts
    - Unplanned or forced outages due to mussel fouling
    - Increased maintenance
- Control methods utilized or examined
- Expenses associated with mussels

Thirteen hydropower plants, experiencing mussel infestation for different time frames, were selected to be interviewed. A variety of sized, designed, and operated plants were selected in order to represent different scenarios. 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 interview usually lasted one to two hours and any outstanding questions were addressed with follow up emails.

Results

A list of the hydropower plants that were interviewed, and a summary of the impacts and main control methods utilized are included in Table 1. Table 2 provides a summary of the costs associated with preventative control, increased maintenance, unplanned outages, and monitoring. Figure 1 provides information about some of the most common components impacted by invasive mussel fouling across all 13 plants and indicates the severity of problems caused. A detailed narrative of each case study is included in the following sections.

Table 1. Summary of case studies investigating mussel impacts at 13 hydropower plants, including location, number of generators, generating capacity, date mussel issues began, systems most impacted, and main control approach.

Hydropower Plant	Location	Water Body	Operating Agency	Number of Generators	Total Generating Capacity	Year Mussel Issues Began	Impact Level	Most Impacted Locations	Control Approach
Hoover Dam	USA, Arizona/ Nevada	Colorado River, Lake Mead	Bureau of Reclamation	17 and 2 house units	2,000 MW (each house unit has 3 MW)	2010	Moderate	Thrust bearing coolers	Cooling water system redesigned to use tail bay water and HOD UV installation in progress
Davis Dam	USA, Arizona/ Nevada	Colorado River, Lake Mohave	Bureau of Reclamation	5	255 MW	2008	Moderate	Turbine packing box and turbine guide bearing oil cooler	Added 1/8" screens in strainers and regular cleaning. HOD UV installed on one unit
Parker Dam	USA, Arizona, California	Colorado River, Lake Havasu	Bureau of Reclamation	4	120 MW	2008	Moderate	Turbine seal water lines, packing stuffing box, water supply box, and HVAC system	Self-cleaning strainers followed by HOD UV light treatment

Hydropower Plant	Location	Water Body	Operating Agency	Number of Generators	Total Generating Capacity	Year Mussel Issues Began	Impact Level	Most Impacted Locations	Control Approach
Glen Canyon Dam	USA, Arizona	Colorado River, Lake Powell	Bureau of Reclamation	8	286 MW	2013	Moderate	Bailey valves, transformer cooling system, fixed wheel gates and service station air compressors	Added strainers, increased cleaning frequency, heat exchangers treated with a vinegar flush, planning to install HOD UV
Beauharnois Generating Station	Canada, Québec	St. Lawrence River, Lake St. Francis	Hydro Québec	36 (and 2 auxiliary)	1899 MW	1995	Low	Generator and bearing cooling systems	Added a heat treatment, strainers, backwashing, increased cleaning
Jenpeg Generating Station	Canada, Manitoba	Nelson River	Manitoba Hydro	6	144 MW	2020	Low	Generator cooling water wye strainer	Chlorine treatment planned
Lewiston Pump Generating Station	USA, New York	Niagara River	New York Power Authority	12	420 MW	1990	Low	Pump/ generator cooling water system and duplex strainers	Chlorine treatment and optimized cleaning schedules

Hydropower Plant	Location	Water Body	Operating Agency	Number of Generators	Total Generating Capacity	Year Mussel Issues Began	Impact Level	Most Impacted Locations	Control Approach
Sir Adam Beck #1	Canada, Ontario	Niagara River	Ontario Power Generation	8	440 MW	1990	Moderate	Surface air coolers, bearing cooling systems, stilling wells, and duplex strainers	Chlorine
Sir Adam Beck #2	Canada, Ontario	Niagara River	Ontario Power Generation	16	1600 MW	1990	Moderate	Surface air coolers, bearing cooling systems, stilling wells, and duplex strainers	Chlorine
DeCew NF23	Canada, Ontario	Lake Gibson, Welland Canal	Ontario Power Generation	2	144 MW	1990	Moderate	Surface air coolers, bearing cooling systems, stilling wells, and duplex strainers	Chlorine and HOD UV on one unit

Hydropower Plant	Location	Water Body	Operating Agency	Number of Generators	Total Generating Capacity	Year Mussel Issues Began	Impact Level	Most Impacted Locations	Control Approach
Pump Generating Station	Canada, Ontario	Niagara River	Ontario Power Generation	6	174 MW	1998	Moderate	Surface air coolers, bearing cooling systems, stilling wells, and duplex strainers	Chlorine
Wilson Hydropower Plant	USA, Alabama	Tennessee River	Tennessee Valley Authority	21	670 MW	Early 1990's	Significant	Runner seal and piping to the turbine bearing	Increased maintenance, and installation of automated backwash strainers and backup coolers
Gavins Point	USA, South Dakota	Missouri River, Lewis and Clark Lake	US Army Corps of Engineers	3	132 MW	2018	Significant	Generator coolers and irrigation system	Installed self-cleaning strainers followed by HOD UV treatment

Table 2. Costs associated with preventative control, increased maintenance, unplanned outages, and monitoring at hydropower plants that have dreissenid mussel fouling. **Many plants do not track all costs associated with mussels, therefore most of these costs are estimates and are not complete.**

Hydropower Plant	Preventative Control	Increased Maintenance	Mussel Related Outages	Monitoring
Hoover Dam	**$2.1 million:** planned HOD UV installation **$500,000:** convert to tail bay cooling water	**$88,000** for a single thrust bearing cooler replacement **$34,630** for dive team to remove mussels from cooling water inlets and outlets (once)	1-3 per year **$44,000-$80,000** for a single outage	
Totals	$2.6 million	$122,630 (reoccurring)	$44,000- $80,000 (reoccurring)	
Davis Dam		**$26,000** per year: strainer cleaning	2 (total)	
Totals		$26,000 per year		
Parker Dam	**$1 million:** HOD UV installation **$18,000** per year: UV service contract	**8 weeks of labor** per year: heat exchanger cleaning before UV **$4,000** per month: mussel related O&M	1 (total)	
Totals	$1 million and $18,000 per year	$48,000 per year and 8 weeks of labor per year before UV		
Glen Canyon Dam	**$1.9 million:** planned HOD UV and duplex strainer installation **$4,000** per year: flush heat exchangers/ compressors with vinegar solution	**$8,000** per year: mussel specific maintenance **$16,820** per year: remove mussels from head cover packing box strainer **$2,500** per year: fixed wheel gate cleaning **$32,500** per year: generator cooling water maintenance		
Totals	$1.9 million planned and $4,000 per year	$59,820 per year		

Hydropower Plant	Preventative Control	Increased Maintenance	Mussel Related Outages	Monitoring
Beauharnois Generating Station	**$1 million**: Chlorine system installation and first treatment **$135,000** and **1,929** hours: second chlorine treatment **$174,000** and **1,186** hours: third chlorine treatment	**$500** per year: materials **$11,976** per year: cleaning strainers Backwash of generator and bearing cooling systems: 2001: **$12,000** and **182** hours 2016: **$31,200** and **308** hours 2017: **$23,000** and **223** hours 2018: **$20,300** and **178** hours 2019: **$58,200** and **497** hours 2020: **$66,900** and **498** hours		**$60,000** per year
Totals (Canadian)	$1.3 million and 3,115 hours of labor	$211,300 and 1,886 hours of labor and $12,476 per year		$60,000 per year
Jenpeg Generating Station	**$180,000** per year: Chlorine treatment			**$2,500** per year
Totals (Canadian)	$180,000 per year			$2,500 per year
Lewiston Pump Generating Station	**$40,000** and **32** hours per year: Chlorine treatments	**$19,000-$22,000** per cleaning: divers to remove mussels from intakes		**$15,000** per year
Totals	$40,000 and 32 hours per year	$19,000-$22,000 (reoccurring)		$15,000 per year
Sir Adam Beck #1	**$500,000**: Chlorine treatment capital investment **$3,000** per year: chlorine **$8,000**: replacement parts	**$30,000** per year: cleaning stilling wells **$31,250** per year: materials **250** hours and **15** overtime hours per year		**$7,500** per year
Totals (Canadian)	$500,000 and $3,000 per year and $8,000 reoccurring	$61,250 per year, 250 hours and 15 overtime hours per year		$7,500 per year

Hydropower Plant	Preventative Control	Increased Maintenance	Mussel Related Outages	Monitoring
Sir Adam Beck #2	**$1.3 million**: Chlorine treatment capital investment **$8,000** per year: chlorine **$16,000**: replacement parts	**$30,000** per year: cleaning stilling wells **$51,250** per year: materials **400** hours and **72** overtime hours per year		**$7,500** per year
Totals (Canadian)	$1.3 million and $8,000 per year and $16,000 reoccurring	$81,250 per year, 400 hours and 72 overtime hours per year		$7,500 per year
DeCew NF23	**$250,000**: Chlorine treatment capital investment **$2,000** per year: chlorine **$5,000**: replacement parts	**$30,000** per year: cleaning stilling wells **$31,250** per year: materials **200** hours and **25** overtime hours per year		**$7,500** per year
Totals (Canadian)	$250,000 and $2,000 per year and $5,000 reoccurring	$61,250 per year, 200 hours and 25 overtime hours per year		$7,500 per year
Pump Generating Station	**$720,000**: Chlorine treatment capital investment **$3,000** per year: chlorine **$5,000**: replacement parts	**$30,000** per year: cleaning stilling wells **$31,250** per year: materials **250** hours and **25** overtime hours per year		**$7,500** per year
Totals (Canadian)	$720,000 and $3,000 per year and $5,000 reoccurring	$61,250 per year, 250 hours and 25 overtime hours per year		$7,500 per year
Wilson Hydropower Plant	**$72,000**: replacement generator air coolers	**$500,000** per cleaning: generator header cleaning **$4,000-$5,000** per swap: remove and replace generator air coolers	3-12 outages per year	
Totals	$72,000	$505,000 reoccurring		

Hydropower Plant	Preventative Control	Increased Maintenance	Mussel Related Outages	Monitoring
Gavins Point	**$1 million**: HOD UV installation **$31,980** per year: UV service contract **$12,040**: temporary spillway de-icers **$6,600** per year: Becker blowers **$8,000** per year: Rydlyme	**$111,240** per year: Increased labor **$1,000** per unit, per cleaning: Consumable for unit cleaning	**$848,925:** outage costs since mussels were detected in 2014	
Totals	$1.012 million and $46,580 per year	$111,240 per year and $1,000 reoccurring	$848,925	

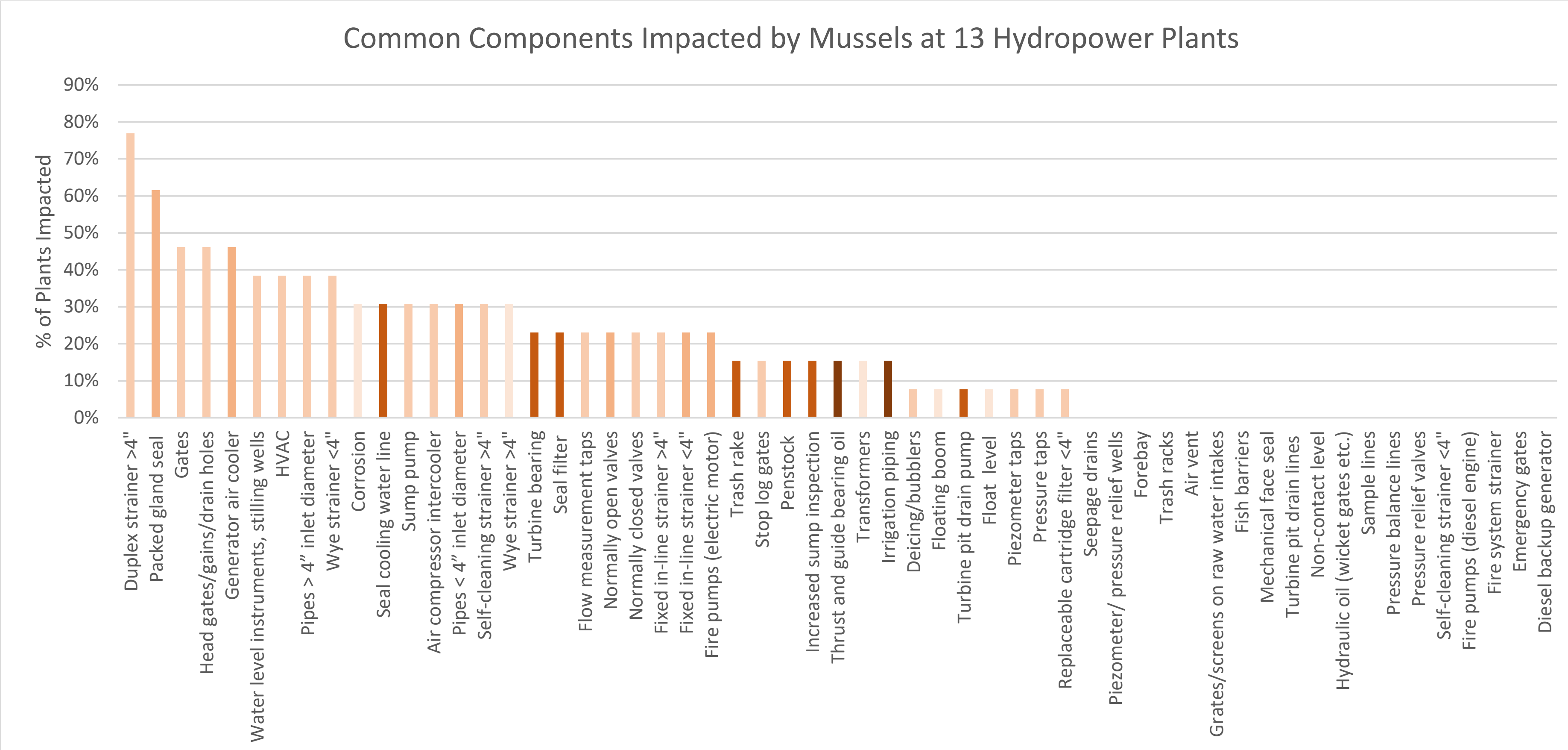

Figure 1. Common components impacted by invasive dreissenid mussel fouling at 13 hydropower plants in the United States and Canada. Darker colored bars indicate components where mussels caused more severe problems and lighter colored bars indicate components where mussels caused less severe problems.

Case Study 1: Hoover Dam

Location: USA, Arizona and Nevada
Water Body: Lower Colorado River, Lake Mead
Operating Agency: Bureau of Reclamation
Contact: Jeff Ommen, Mechanical Engineer P.E.

Summary

Hoover Dam began experiencing invasive mussel issues in 2010. A variety of operations have been impacted but the most significant impact has been mussel plugging of the thrust bearing coolers which has resulted in unplanned outages due to overheating. Mussel shell debris entrained in the penstocks also increases the length of scheduled penstock dewatering due to the increased labor associated with removing mussels. In order to reduce mussel shell debris load entering the generator cooling water system, the high-pressure cooling water system was redesigned to use tail bay water for cooling. The use of tail bay water has resulted in less mussel shells and has reduced the need to manually clean mussel settlement from the intake pipes in the forebay. Hoover Dam is currently in the process of installing hydro-optic disinfection (HOD) ultraviolet (UV) light equipment for mussel control downstream of 1/8-inch duplex strainers for generator cooling water protection on all 17 cooling water systems. The thrust bearings should be protected from mussel settlement and overheating after the HOD UV is installed and operating.

Hydropower Plant Design and Operation

The construction of Hoover Dam was completed in 1936. The hydropower plant includes 17 turbines and 2 house generator units. The powerplant is staffed continuously with approximately 260 employees working at the facility. The total generator capacity is 2,000 MW (at full pool), and each house unit has a 3 MW capacity. The generator units operate under an intermittent peaking duty cycle. Minor maintenance of each generator unit occurs during annual outages where penstocks remain filled. Each unit has a planned outage every 10 years for major maintenance, during this time the penstocks are dewatered. The plant has four, 30-ft-diameter penstocks that can stay watered for 10 years without operational issues. There are multiple penstock takeoffs for service water. Generator cooling water previously came from the penstocks but is now pumped from the tailrace to minimize shell debris. The water enters the plant through 10-12-inch intakes and passes through 1/8-inch duplex strainer screens. Fire protection water comes from a separate penstock takeoff.

Mussel Infestation Timeline

Quagga mussels were first detected at a Lake Mead marina in January 2007. The population had likely been established in the reservoir for many years prior to the first detection. Mussel settlement was first observed at Hoover Dam in a biobox in 2010. Mussel populations and settlement are no longer monitored at Hoover Dam. Southern Nevada Water Authority monitors mussel populations in Lake Mead throughout the year. Because of the warm temperatures, mussels reproduce throughout the year at this site and mussel populations have not significantly declined at any point since infestation. A mussel vulnerability assessment was completed in 2007 prior to mussel arrival at the plant. The response plan was helpful in that it assisted with the procurement process for control equipment. Mussels are considered a moderate problem at the power plant at Hoover Dam and the severity of the issue is viewed differently at each organizational level. Mussel related maintenance is not tracked; therefore, it is difficult to fully realize the extent of the issue.

Mussel Impacts

Hoover Dam began experiencing mussel related maintenance issues three years after mussels were first detected in Lake Mead (at which time the population was already well established). The first mussel impacts at the power plant were in the following locations:

- Oil cooler thrust bearings (most of the plugging occurs in the 3-inch diameter piping in the header boxes and the ¾-inch spin coils).
- Turbine bearing cooling.
- Compressor cooling.
- Turbine packing.
- Wicket gate drains.

Over time the plant has experienced increased mussel-related maintenance and issues, including:

- Increased corrosion, including corrosion on stainless steel shafts and pressure reducing valves.
- Over-heating of compressors.
- Increasing turbine bearing pressure.
- Accumulation of mussel shell debris in the penstock. Most of the mussels are found at the intakes to units and the bottom half of the tunnel is full of mussels. Penstock shutdowns last longer and require significantly more labor. Mussel odor is a problem when cleaning. The entire penstock was recoated, and mussels may have caused the paint to come off.
- Turbine pit drain blockage.
- Generator air coolers were removed because of mussel plugging.
- Transformers use high-pressure water for cooling. They usually start to leak before they get plugged with mussels. Mussel are removed during leakage repairs.
- Occlusion of 3-inch and smaller pipes.
- Mussel settlement in normally open valves. When closing these valves, the actuators are frequently not strong enough due to mussel debris.
- Duplex strainers (with greater than 4-inch inlet diameter) must be emptied and cleaned approximately once per week.
- Fixed in-line duplex strainers (with less than 4-inch inlet diameter) for service water to station transformer require frequent cleaning.

- Longer maintenance outages.

Anticipated problem with drum gate hinges never materialized as water level in Lake Mead never increased to the drum gate level. Floating drum gates could be a problem if full pool were to occur and they were needed for spillway operation.

The plant has experienced major interruptions of operation because of mussels. Mussel settlement in the small diameter pipes associated with the thrust bearings on oil coolers cause 1 to 3 forced or unplanned outages per year. The outages last approximately 2 to 7 days and require 8 to 12 people to work on the problem. Thrust bearings are causing issues at this plant because of the installation location and size. Hoover has observed that mussel settlement and plugging issues still occur in the cooling water systems despite being a peaking plant. Mussels are able to settle in the thrust header and can apparently handle the decline in oxygen that is associated with the cooling water being turned off for 2-3 weeks at a time.

Control Methods

- Preventative control measures
  - Initially planned to install microfiltration units in 2010. The cost to purchase and install would have been $2.5 million but it was discovered that the operation and maintenance cost would be too high, so the plan was abandoned. Microfiltration is planned to be utilized for transformer raw water-cooling protection in fiscal year 2025.
  - Redesigned the high-pressure cooling water system to use tail bay water for cooling to eliminate mussel shell debris load from penstocks into the generator cooling water system. The use of tail bay water has resulted in less mussel shells and has reduced the need to manually clean mussel settlement from the intake pipes in the forebay.
  - Wicket gate bushings were rebuilt in the past 5 years which has reduced leakage and mussel colonization.
  - Currently in the process of installing HOD UV light equipment for mussel control downstream of 1/8-inch duplex strainers for generator cooling water protection. UV units will be installed on all 17 cooling systems.
    - Hoover decided to install UV based on the successful results observed at Parker Dam and Davis Dam (powerplants downstream of Hoover).
    - The design pressure limit of UV systems is 145 psi for larger than 10" systems, the design pressure limit for smaller diameter systems 4"-10" is 220 psi. These piping sizes and psi ranges may be a limitation for high head dams that take cooling water from the penstock.
- Increased maintenance
  - Oil coolers are replaced when overheating becomes a problem. Back-flushing is attempted before replacement.
  - Replace 3-inch cooling water pipes when they become occluded.
  - Water cooled compressors are replaced about every two years.
  - Periodic manual cleaning of penstocks requires huge labor effort and may also result in the need for internal re-coating of the penstocks.

  - The Reclamation Dive Team completed a remote operated vehicle (ROV) inspection of the tail bay cooling inlets and outlets (10" and 14" diameter) and found mussel settlement needed to be removed. The dive team manually cleaned the cooling water inlets and outlets in 2019.
- Design aspects that have served to prevent or reduce mussel issues
  - Generator air coolers have some redundancy and one generator air cooler can be plugged with mussels and still function, but if two adjacent coolers, or more than two at any location, are plugged the generator becomes too hot and must shut down.
  - The thrust bearing cooler is not oversized, but other bearings are significantly oversized, and they do not have similar mussel issues.

Expenses Associated with Mussel Infestation

- Mussel specific maintenance and associated costs are not fully recorded or tracked. Therefore, the estimates provided in this section do not fully capture the expenses associated with mussel specific maintenance and control.
- Hoover Dam has a $1 million budget line item each year for mussel work, it is a capital budget item that may be diverted to O&M.
- Preventative control measures
  - Conversion to tail bay cooling water= $500,000
  - HOD UV treatment installation= $2.1 million
- Increased maintenance
  - Oil cooler thrust bearing replacements due to mussel settlement in small diameter pipes is a reoccurring cost.
    - Each oil cooler thrust bearing replacement costs $30,000
    - Estimated labor for replacement is $58,000
  - Dive team inspection and manual removal of mussels from tail bay cooling water inlets and outlets (one time): $34,630.21
- Mussel related outages
  - 1-3 per year, 3-5 days per outage, with 8-12 people working on the problem
  - Outages result in approximately $20,000 per day of lost production and unrealized revenue.
  - Labor cost range of unplanned outage: $24,000- $60,000 per outage
  - Estimated cost for 1 outage per year: $44,000-$80,000 per year
  - Estimated cost for 3 outages per year: $132,000- $240,000 per year

Case Study 2: Davis Dam

Location: USA, Arizona and Nevada
Water Body: Lower Colorado River, Lake Mohave
Operating Agency: Bureau of Reclamation
Contact: Vince Lammers, Davis Dam Plant Manager

Summary

The power plant at Davis Dam began experiencing invasive mussel issues in 2008. A variety of operations have been impacted but the most significant impact has been mussel plugging in the turbine packing box and the turbine guide bearing oil cooler, resulting in increased maintenance and some instances of overheating. The issue was largely resolved by the addition of 1/8-inch strainers and the implementation of a regular cleaning schedule. Reclamation and contractors have conducted research on several mussel control methods at Davis Dam. An HOD UV light system was installed on a single generator cooling water supply to determine the efficacy of preventing mussel settlement. The research results indicated that HOD UV was an effective method for mussel settlement control. Significantly less maintenance of the strainers is required on the cooling water supply with UV protection due to a reduction in mussel shells and biofilm.

Hydropower Plant Design and Operation

Davis Dam is a 68-year-old hydropower plant with five generator units that have a total generator capacity of 255 MW. The powerplant is staffed with approximately 21 people who are on-site four days per week. Davis Dam is a base-loaded plant that operates continuously. Generator maintenance occurs during one-month long annual outages. Major maintenance occurs every 5-years during a 4-month outage. All of the service water enters from two, 10-inch intakes located behind the trash racks at 80 ft depth in the forebay. Raw service water passes through duplex strainers before entering pumps. Service water is treated with chlorine gas injection downstream of the pumps for use in washdown sinks, toilets, and fire protection systems. Raw water from the top of each scroll case is used for generator cooling.

Mussel Infestation Timeline

Quagga mussels were first detected at Davis Dam in October 2007 when a fixed wheel gate was pulled out of the water and was found to be covered with quagga mussels. The mussel population had been established for several years prior to the first detection because adult mussels that were several years old were found. A mussel vulnerability assessment was completed in 2007 but there was not enough time to prepare a response plan prior to the onset of mussel related issues in 2008. Mussel populations are monitored in bioboxes installed on the generator cooling water and on settlement plates installed in the forebay. Southern Nevada Water Authority monitors mussel populations in Lake Mohave throughout the year. Because of the warm temperatures, mussels reproduce throughout the year at this site and mussel populations have not significantly declined at any point since infestation. Mussels are considered a moderate problem at the power plant at Davis Dam. Mussel related maintenance is not tracked, but maintenance is required in order to control the mussel fouling.

Mussel Impacts

Davis Dam began experiencing mussel related maintenance issues about one year after mussels were first detected in the Lower Colorado River system, upstream at Lake Mead (at which time the population was already widely established). The first operational issues associated with mussels were in the turbine packing boxes and the turbine guide bearing oil coolers (packing gland seals, seal cooling water piping, and filters). The mussel fouling in the turbine packing boxes, and guide bearing oil coolers resulted in approximately 2 unscheduled outages in 2008. The issue has since been resolved and no additional forced outages have occurred. The plant has experienced additional mussel related issues, including:

- Increased maintenance of the 10, small HVAC coolers with 4 inch or less diameter piping and associated strainers.
- Head gate drain holes become plugged with mussels but have not resulted in any serious issues.
- Some bulkhead gates experience heavy mussel fouling, which can significantly increase the weight. A gate at 25-30 ft depth weighed an additional 4,000 pounds due to mussel settlement.
- The gates and screens on raw water intakes occasionally become fouled with mussels and require cleaning by the dive team.
- Increased maintenance associate with mussel settlement in the air compressor intercoolers.
- Some issues with mussel settlement in piping greater than 4-inch diameter.
- Mussel issues observed in normally closed valves. The valves are cleaned during normal outages and require approximately 5 hours to clean. Mussel fouling is addressed during regularly scheduled valve maintenance so there is only a limited increase in time associated with removing the mussels.
- Shell debris in 4-inch diameter or less fixed in-line strainers, replaceable cartridge filters, and wye strainers.
- Have noticed more frequent increases in algae (blue green) since mussel arrival, which has required increasing cleaning of some strainers.

Control Methods

- Preventative control measures
    - Added strainers and implemented regular cleaning schedules to protect turbine packing box and turbine bearing oil cooler.
        - Strainers with 1/8-inch pore size were installed to remove shell debris. Originally strainers with an even smaller pore size were installed resulting in excessive plugging that required frequent cleaning. It is important to choose a reliable vendor when purchasing strainers with smaller pore sizes because the seams of low-quality strainers can fail.
    - Added strainers to protect HVAC heat exchangers.
    - Added strainers to air compressor intercooler heat exchangers.
    - Installed HOD UV treatment on one generator cooling water supply.
        - HOD UV unit was originally installed for research purposes.
        - The downstream strainers on the cooling water supply with HOD UV protection require significantly less cleaning due to a reduction in mussel debris and biofilm.
        - Would recommend HOD UV treatment installed downstream of self-cleaning strainers with a pore size of 1/8-inch or smaller.

- Increased maintenance
    - Increased cleaning.
    - Dive team occasionally manually cleans gates and screens on water intakes.
- Design aspects that have served to prevent or reduce mussel issues
    - Chlorination of service water (0.73 chlorine residual) prevents mussel settlement in pipes downstream of the treatment.
    - Water velocity on generation side means no mussels in penstock scroll case.
    - Generator air coolers are oversized, and cleaning occurs during annual shutdown and dewatering.
    - The trash racks are large (approximately 120-ft tall) and rarely need cleaning because the majority of mussel settlement occurs on the middle 40-ft. The mussel settlement in the middle of the trash racks results in increased velocities above and below. The increased velocities appear to be reducing mussel settlement and there is still enough water entering the plant. Divers inspect the trash racks annually and they remove mussels as necessary.
    - Mussels are found in the generator air cooler water boxes, but the tubes are large (7/8 inch) so mussels pass through without causing issues.
    - Thrust bearing oil cooler tubes are also large and allow mussels to pass through.
    - Transformers do not experience mussel issues because they are air cooled.
    - Annual outages mitigate some issues because mussels are desiccated in the system and the shells are flushed out on restart.

Expenses Associated with Mussel Infestation

- Mussel specific maintenance and associated costs are not recorded or tracked. Therefore, the estimates provided in this section do not fully capture the expenses associated with mussel specific maintenance and control.
- Increased maintenance
    - Despite adding strainers and implementing regular cleaning schedules the strainers protecting the turbine packing box and turbine bearing oil cooler still require approximately 4 hours of labor per week to clean costing approximately $26,000 per year.

Case Study 3: Parker Dam

Location: USA, Arizona and California
Water Body: Lower Colorado River, Lake Havasu
Operating Agency: Bureau of Reclamation
Contact: John Steffen, Parker Dam Plant Manager

Summary

Significant mussel fouling was first observed at Parker Dam in 2008 in the turbine seal water lines, packing stuffing boxes, water supply boxes, and HVAC system. There was an initial need to allocate resources to manage the mussel fouling, but the issue is now under control. HOD UV light treatment was installed on all four, turbine seal cooling water supply lines and the raw water supply for the onsite water treatment facility. The HOD UV treatment has significantly decreased mussel fouling and biofilm issues and the associated labor required to manage the problem. Some piping routes were changed to eliminate low flow zones, dead-end lines, and unnecessary turns and bends where accumulation was occurring. The flow of water through some pipes was increased and high pressure flushing of low flow areas was implemented. Invasive mussels have increased water clarity in Lake Havasu due to filter feeding which has increased weed growth in the reservoir. Significant labor and equipment expenditures are required to remove weeds that accumulate on the trash racks, but the severity of weed issues is variable from year to year.

Hydropower Plant Design and Operation

The construction of Parker Dam occurred between 1934 and 1939. The hydropower plant at Parker Dam has four generator units with a total generator capacity of 120 MW. The powerplant is staffed with 18 people who are on-site four days per week. Parker Dam is a base-loaded plant that operates continuously. Flow is based on downstream water demand. Generator maintenance occurs during one-month long annual outages. Major maintenance occurs every 5-years during a 4-month outage. Service and domestic water, including the fire protection water, enters from a single intake located at the face of the dam. Each generator unit has a separate intake for cooling water from the penstocks. Raw water passes through self-cleaning strainers with 1/8-inch screens.

Mussel Infestation Timeline

Quagga mussels were first detected at Parker Dam in 2007. The population had likely been established in Lake Havasu for many years prior to the first detection at the plant. Mussel populations and settlement were monitored at the power plant when mussels were first detected but are no longer monitored. Reclamation monitors larval populations at Lake Havasu on a quarterly basis. Because of the warm temperatures, mussels reproduce throughout the year at this site and mussel populations have not significantly declined at any point since infestation. Lake Havasu is the reservoir with the largest mussel populations along the lower Colorado River. A mussel vulnerability assessment was completed for the plant and was helpful in developing a response plan especially for a plant that did not have experience dealing with fouling issues. Mussels are considered a moderate problem at the power plant at Parker Dam at this time. Mussel related maintenance is not tracked.

Mussel Impacts

Significant mussel fouling was first observed in 2008 in the turbine seal water lines, packing stuffing boxes, water supply boxes, and HVAC system. Over time, the plant has experienced mussel-related increased maintenance and issues, including:

- Packed gland seal fouling.
- Mussel settlement in low flow areas of the cooling water systems.
- Mussel settlement in heat exchangers resulting in increased cleaning.
- Invasive mussels have increased the clarity of the water due to filter feeding which has increased weed growth in the reservoir. Significant labor and equipment expenditures are required to remove weeds that accumulate on the trash racks. An automated trashrake was installed to help manage the increased weeds. The severity of weed issues changes each year and can be very bad some years, and manageable in other years.
- Some mussel accumulation on water intake head gate tailwater track. Tracks are cleaned before putting gates in to reduce leakage.
- Mussel shells found in the plant sump area are removed as necessary.
- Shell debris in transformer deluge heads is managed by back-flushing main supply header piping.
- The 2-inch drain line on the fixed in-line strainers and automatic strainers can be an issue especially if there is a big slug of mussels.

Control Methods

- Preventative control measures
    - Installed large self-cleaning strainers and HOD UV light equipment to protect the upper and lower seal water lines (2" diameter). Seal water lines have been a major labor issue and a combination of back flush, HOD UV, and filters is managing the issue.
        - A bypass line was installed on the HOD UV system due to limitations on scheduling outages for required maintenance. The bypass line is isolated and drained between uses in order to prevent mussel fouling. The bypass line required an extra isolation valve resulting in a small additional capital cost.
        - HOD UV treatment has prevented long outages that previously occurred due to the major maintenance effort required to remove settled mussels in the heat exchanger water supply lines.
        - HOD UV treatment has reduced mussel fouling and eliminated the need to clean the heat exchangers. Prior to HOD UV treatment the heat exchanger cleaning effort required approximately 8 man-weeks per year.
        - HOD UV has also reduced non-mussel biofilm (bacterial and sponge) accumulation in the heat exchangers, which has further reduced maintenance efforts.
    - 80-micron cleanable filters were installed to protect the stuffing boxes.
    - Some piping routes were changed to eliminate low flow zones, dead-end lines, and unnecessary turns and bends where accumulation was occurring.
    - Increased flow in some pipes where possible.
    - Implemented high pressure flushing to purge mussel accumulation in low flow areas. Flushing, using fire water pumps occurs monthly.
        - This adaptation was completed with minimal extra cost as firewater is tested frequently anyways.

        - Management of mussel debris also eliminated issues occurring on instrumentation lines.
    - Eliminated the need for raw water in the turbine bearing oil coolers. Converted to an air cooled system by installing a closed loop with a radiator and fan used to cool the oil.
    - The HVAC system was redesigned to use filtered water.
    - Some low flow oil coolers were converted from raw water to air cooled.
- Increased maintenance
    - Prior to HOD UV installation, eight weeks of labor was required annually to remove mussel settlement in the heat exchangers. Heat exchanger cleaning is no longer required with HOD UV treatment.
    - Removal of settlement and shell debris.
    - Some increased cleaning of strainers and filtration systems.
    - Backflushing helps manage slugs of mussel shell debris entering the raw water system.
- Design aspects that have served to prevent or reduce mussel issues
    - The flow rate of water passing through the generator and thrust bearings is fast enough that mussels are not able to settle in these systems.
    - The forebay trash racks have wide spacing and complete occlusion has not occurred. There are some locations where mussel settlement is abundant and reduces the spacing enough to increase the velocity of water. The increased velocity usually prevents additional mussels from settling and prevents complete occlusion. Mussel settlement occurs on unit trash racks during a unit outage but when the unit starts up the high flow flushes away all mussels.

Expenses Associated with Mussel Infestation

- Mussel specific maintenance and associated costs are not fully recorded or tracked at Parker Dam. Therefore, the estimates provided in this section do not fully capture the expenses associated with mussel specific maintenance and control.
- Preventative control measures
    - Replacement of strainers and service water cooling lines with 14" welded stainless steel and installation of HOD UV with contractor: $1,000,000.
        - Service contact for all UV units: $18,000 per year.
- Increased maintenance
    - Prior to UV installation, cleaning of mussels and other biofilm in the heat exchangers required approximately 8 weeks of labor per year.
    - Estimate $4,000 per month for all parts and labor for all O&M mussel related costs.
- Mussel related outages
    - There has only been one unplanned outage since mussels were detected and the outage was not significant.

Case Study 4: Glen Canyon Dam

Location: USA, Arizona and Utah
Water Body: Colorado River, Lake Powell
Operating Agency: Bureau of Reclamation
Contact: Clifton (Shane) Mower, Environmental Protection Specialist

Summary

Quagga mussel issues first began at the Glen Canyon power plant in 2013. Mussels are considered a moderate problem at the power plant, but the issues are not as severe as experienced at other hydropower plants along the Colorado River. Mussel settlement on the fixed wheel gates significantly increases the effort and time for cleaning. Some preventative maintenance has been increased from annually to quarterly and some quarterly maintenance has been increased to monthly in order to stay ahead of mussel fouling. Annual outages require increased duration and frequency for mussel removal. Mussel issues have been successfully mitigated with the addition of extra strainers, increased frequency of maintenance, and treatment of heat exchangers with a vinegar solution flush. Installation of 1/8-inch duplex strainers followed by HOD UV on each unit is planned in the next 2 years.

Hydropower Plant Design and Operation

The construction of Glen Canyon Dam was completed in 1966. The hydropower plant at Glen Canyon Dam has eight generator units, four have a generator capacity of 150 MW and the other four have a generator capacity of 136 MW. The powerplant is staffed continuously and approximately 75 people work at the plant. The plant is a hybrid between a base load and an intermittent peaking plant as generation is controlled by grid demand. Generators are running most of the time, but there are periods where some are watered up but not running. Generator maintenance occurs during two to three weeklong annual outages. A pair of generators are serviced each year and during this time the penstock, generator, and bearing cooling water lines are dewatered. There is a single intake for the service water from the penstock and raw water is taken off the scroll case. Fire water comes from the common service water header. Each penstock has a single trash rack and the raw water used for bearing cooling, fire water, and transformer cooling pass through 1/8-inch self-cleaning Hayward strainers installed before the common header and just after the scroll case.

Mussel Infestation Timeline

Quagga mussel issues first began at the Glen Canyon power plant in 2013. Adult mussels were observed in Lake Powell in 2012, and in 2013 adult mussels were observed on a fixed wheel gate after it was removed for regular maintenance. The population had likely been established in Glen Canyon for several years prior to the first detection at the plant. Mussel populations are monitored quarterly by the Park Service and mussel populations have remained steady. A mussel vulnerability assessment was completed for the plant in 2010. The response plan provided valuable information to staff about where to monitor for mussels and resulted in a quick reaction time after mussels were detected. The assessment accurately predicted the fouling that has since occurred. Mussels are considered a moderate problem at Glen Canyon, and the issues are not as severe as those experienced at other hydropower plants along the Colorado River. Mussel related maintenance is not fully tracked, but some work orders do specify if the work is mussel related.

Mussel Impacts

Quagga fouling was first observed on the pressure reducing Bailey valves, transformer cooling system, fixed wheel gates and service station air compressors. Over time the plant has experienced additional mussel related increased maintenance and issues, including:

- Fixed wheel gates are still heavily impacted, each gate is cleaned once every eight years, and cleaning requires more effort and time due to the removal of significant amounts of mussels. The whole gate is usually covered by 2-3 inches of settled mussels.
- Increased duration and frequency of outages. Some preventative maintenance has been increased from annual to quarterly and some quarterly maintenance has been increased to monthly.
- Prior to mussel arrival generator cooling system maintenance was completed annually during a 10-hour period. Mussel fouling has increased the duration of cleaning to 40 hours during quarterly maintenance.
- Mussel removal from the unit head cover packing box strainer now occurs monthly, these were previously only cleaned annually.
- Mussel settlement is observed in the turbine bearings, packed gland seals, and seal filters.
- Increased cleaning of the fixed in-line strainers on the generator cooling and stuffing box and duplex strainers.
- Mussel accumulation is a problem in piping with dead ends or areas of low flow.
- A 2019 study found rapid progression of mussel settlement on the trash racks since a previous survey in 2017. Heavy fouling was observed near the penstock intake trash racks, but little fouling was observed near the penstock intake elevation. Complete occlusion is not likely but extensive fouling has the potential to increase velocities and increase head loss. The fouling is also a source of mussel debris which can be drawn into the intakes.

Control Methods

- Preventative control measures
    - Plan to replace Hayward strainers on each unit with 1/8-inch duplex strainers followed by HOD UV in the next 2 years.
    - Extra strainers were installed on small diameter pipes including the turbine bearing lines.
    - Generator cooling water systems are now on a quarterly maintenance cycle instead of annual.

    - The four heat exchanger compressors are treated with a vinegar solution for two hours every quarter.
    - Some flow meter piping was changed so that maintenance can be done without shut down.
    - The water boxes on the bottom of the generator air coolers in the air houses are drained for the duration of the annual outage to allow boxes to dry and mussels to die.
    - Heat exchangers on all of the HVAC units are cleaned with a power brush and rod and a vinegar solution is circulated through the AC units that cannot be easily cleaned.
    - Meters have been moved to a new location to prevent mussel fouling.
    - Increased focus on conducting opportunistic maintenance when units are down.
- Increased maintenance
    - Increased cleaning of locations with known issues including the turbine gland packing, generator cooling, and stuffing box strainers.
    - The head cover packing box strainers are cleaned monthly.
    - Some pipes have been replaced.
- Design aspects that have served to prevent or reduce mussel issues
    - Automated self-cleaning strainers have functioned to remove most of the mussel shell debris from the piping and has prevented what could have been a major increase in operation and maintenance cost.
    - The standard dewatering associated with annual maintenance has helped stay ahead of some fouling issues.
    - The ability to pull water from different depths in the reservoir throughout the year has helped reduce the number of mussels entering the raw water systems. Colder service water may help limit the growth of mussels.
    - Generator cooling water is taken from the tail race draft tube, which has resulted in less mussel shell debris.
    - The intake for the water supplied to the city of Page, AZ is at a deep depth which limits mussel fouling.
    - Station service air compressors have a chlorinated water back up which can be used to kill mussels if they were to become an issue.
    - Many of the smallest diameter pipes in the plant transport treated potable water instead of raw water.
    - The annual reservoir drawdown helps control mussel populations to a certain degree, killing many mussels settled near the surface.
    - The large size of the trash racks prevents complete occlusion by mussel settlement.

Expenses Associated with Mussel Infestation

- Mussel specific maintenance and associated costs are not a line item and therefore are not fully tracked at Glen Canyon Dam, but some work orders do specify if work was mussel related. Therefore, the estimates provided in this section do not fully capture the expenses associated with mussel specific maintenance and control.
- Preventative control measures

  - Plan to install 1/8-inch duplex strainers and HOD UV treatment: Budget is $1,900,000.
  - Flushing heat exchangers/ compressors with vinegar solution requires 8 hours per quarter: $4,000 per year.
- Increased maintenance
  - Eight additional days of labor per year are required to deal with mussel specific maintenance: $8,000 per year.
  - Removal of mussels from the unit head cover packing box strainer on eight units: $16,820 per year.
  - Fixed wheel gate cleaning requires more time (20 extra hours) = $2,500 per year.
  - Increased generator cooling water maintenance (air compressor intercooler) requires an additional 260 hours: $32,500 per year.
- Mussel related outages
  - Occasional mussel specific unplanned outages do occur. Most outages are brief and occur upon unit start-up after annual cleaning and are related to mussel shell debris accumulation.

Case Study 5: Beauharnois Generating Station

Location: Canada, Québec
Water Body: St. Lawrence River (Lake St. Francis)
Operating Agency: Hydro Québec
Contact: Ginette Vaillancourt, Plant Engineer

Summary

The first adult zebra mussels were observed at the Beauharnois Generating Station around 1995. Mussels were originally a major concern for the plant, and a work group was organized to identify possible control methods that could be implemented. Chlorine treatment was utilized after the initial findings and was considered a short-term solution because of environmental concerns. A heat treatment was considered the most reliable and cost-effective long-term solution. The heat treatment was installed and tested but has never been used. Mussel settlement and shell debris is an issue at the plant but is no longer a major concern. Mussel issues in the generator cooling system and bearing cooling system are managed by filtration using strainers and backwashing. This increased maintenance approach reduces but does not eliminate the problem. Backwash on the generator cooling system may be sufficient at Beauharnois because the heat exchangers are over-designed and fully operational even with 30% fouling. Mussel settlement and obstruction of the generator coolers may result in premature aging of the winding due to operation at higher temperatures. When coolers are partially obstructed the stator winding temperatures stabilize within, but close to the design limits. Therefore, settlement prevention, instead of reduction would allow optimization of the operating temperature of the stator to prevent premature aging of the winding.

Hydropower Plant Design and Operation

Beauharnois Generating Station is 88 years old and houses 36 generator units, and two auxiliary units with a total generator capacity of 1899 MW. Beauharnois is a base-loaded plant with a 77% average operating factor. The powerplant is staffed continuously and approximately 200 people work at the plant. Routine maintenance occurs during 1-week long annual outages and more in-depth maintenance occurs during longer outages (>1 month) that are scheduled every 6 years. The plant has multiple intakes for service water from the scroll case and the raw water passes through motorized Hayward self-cleaning strainers and then is distributed through two headers to feed the fire protection system, bearings, generators cooling systems, and air conditioning systems. A portion of the water is filtered through a sand filter which feeds the turbine shaft sealing and air conditioning systems.

Mussel Infestation Timeline

Zebra mussels were first observed in 1990 in the St. Lawrence River, near Montreal. Mussel monitoring began in 1991, and bioboxes were installed at the plant to monitor mussel settlement and density. Mussel populations have remained stable since they were first discovered. The first adult mussels were observed at the plant around 1995. In 1996 low density zebra mussel settlement was observed in the power plant piping network. A mussel vulnerability assessment was not completed, but a work group was organized to identify possible control methods that could be implemented at the plant. One of the original solutions was to install an independent pumping station, but the idea was abandoned around 1996 because it was found to be too expensive and did not fully resolve the issue. From 1994 to 1996 several physical, chemical, coatings and thermal control methods were analyzed. Chlorine treatment was the first treatment to be implemented and was considered a short-term solution. In 1996 a heat treatment was considered the most reliable and cost-effective long-term solution. The heat treatment was installed but has never been used. Mussels were originally a major concern for the plant, but significant issues did not occur, and they are no longer a major concern. Mussel population monitoring is continuing due to the potential cyclical nature of the problem.

Mussel Impacts

Zebra mussel fouling was first observed on the generator and bearing cooling systems and on spillway gate rollers. Over time the plant has experienced additional mussel related increased maintenance and issues, including:

- Increased backwash and maintenance of the generator cooling system due to mussel settlement.
- Strainers on the bearing cooling system experience increased obstruction. Strainer clogging issues are primarily related to the presence of an aquatic plant (bulrush), but approximately 30% of the issues are related to mussel debris.
- Mussel clogging is an issue in nozzles on the transformer fire protection and irrigation systems.

- Gate rollers require increased periodic cleaning.
- The presence of zebra mussels is potentially increasing the localized pitting corrosion inside the headers that distribute raw water to other systems.

Control Methods

- Preventative control measures
  - Chlorine (12%) treatment:
    - The first treatment was performed in 1994 and after the first treatment chlorination was only performed when necessary and based on the results of pipe inspection with a fiberscope. Additional treatments were done in 2001 and 2005.
    - The treatment was fast and effective but was expensive and not environmentally friendly, and therefore could not be considered a long-term solution.
    - Strainers were installed on the bearing cooling system to collect mussels after the chlorine treatment and are still in use.
  - Heat treatment
    - Installed in 2007 as a permanent solution
    - The heat treatment was tested but has never been used due to the complexity and duration of the treatment.
    - The treatment was recommended for application every two years, but the plant is still trying to establish an appropriate treatment schedule.
- Increased maintenance
  - Increased backwashing (flow of water is reversed through the heat exchangers) and maintenance conducted to remove mussel shell debris from the generator cooling system when overheating or flow restriction occurs.
  - Increased strainer cleaning to remove mussel shell debris and bulrush on the bearing cooling system.
  - Increased cleaning of the gate rollers.
  - Increased cleaning to remove mussels from fire protection system nozzles during transformer water tests.
- Design aspects that have served to prevent or reduce mussel issues
  - Over-designed generator water coolers.
  - Some bearings are not water cooled.
  - Some generators are air cooled.
  - Some of the raw water is filtered through a multilayer sand filter.

Expenses Associated with Mussel Infestation

- The plant did not track mussel specific costs until 2016.
- All dollar values listed are Canadian.
- Preventative control measures
  - Chlorine treatments:

        - First treatment in 1994 including: piping modification, temporary equipment rental and installation and monitoring: $1,000,000.
        - 2001 treatment: 1,929 labor hours and $135,000 for materials (costs may have been higher).
        - 2005 treatment: 1,186 labor hours and $174,000 for materials (costs may have been higher).
    - Heat treatment:
        - 1,535 labor hours and $10,500. This estimate does not include the initial investment to purchase the boiler, heat exchanger, pumps, and tubing.
- Increased maintenance
    - Materials: approximately $500 per year.
    - Maintenance costs have increased during the last two years.
    - Generator cooling systems and bearing cooling systems backwash:
        - 2001 was the first year that backwash was necessary: $12,000 and 182 hours
        - 2016: $31,200 and 308 labor hours
        - 2017: $23,000 and 223 labor hours
        - 2018: $20,300 and 178 labor hours
        - 2019: $58,200 and 497 labor hours
        - 2020: $66,900 and 498 labor hours
        - The labor hours listed do not include the labor of plant operators when they have to go to the plant to increase the flow on a cooling water system when temperature or flow alarms occur.
    - Strainer clogging: average per year $39,920 (30% is about $11,976)
        - 30% or less of the clogging issues are related to mussels. Bulrush and silt clogging are the majority of the problem.
- Monitoring
    - Mussel settlement and density is monitored in bioboxes: $60,000 per year

Case Study 6: Jenpeg Generating Station

Location: Canada, Manitoba
Water Body: Nelson River
Operating Agency: Manitoba Hydro
Contacts: Colin Jones, Mechanical Engineer; Ainslie Chaze, Environmental Specialist

Summary

Zebra mussels were first detected at Jenpeg Generating Station in 2020 and have not yet caused any issues at the plant. The plant has several design features that will potentially prevent significant mussel fouling. A mussel vulnerability assessment was completed several years before the mussels arrived at the plant which helped identify the highest-risk systems and prepare for the installation of a chlorine treatment. Chlorination injection ports are currently being installed and a contractor will treat once per year in the fall with a portable system.

Hydropower Plant Design and Operation

Jenpeg Generating Station is 43 years old and houses 6 generator units, with a total generator capacity of 144 MW. Jenpeg is a base-loaded plant that uses bulb-type turbine generators and a spillway to regulate about 85% of the outflow from Lake Winnipeg. The plant was built in cooperation with the Soviets and has some uniquely designed flanges and equipment which can be challenging to find replacements. The powerplant is staffed continuously and has a staff of 25-30 people. Routine maintenance occurs on paired units during a 3, 6, 9, and 12-year maintenance cycle. The plant has multiple intakes for the service water (water passage/low head) and the water is filtered through a self-cleaning 0.75-inch mesh basket strainer. Fire water comes from two separate intakes. The raw water carries heavy silt loads and much of the cooling water used in the plant is demineralized.

Mussel Infestation Timeline

Zebra mussels were first observed in Lake Winnipeg in 2013 and upstream of Jenpeg in 2019. Mussels were first detected in the powerplant in 2020 and so far, the mussels are not causing significant issues. Bioboxes and sampling plates were installed in 1990 to monitor for mussels and veligers, monitoring in the forebay began in 2018. A mussel vulnerability assessment was completed by a contractor in 2015, and an additional internal assessment was completed to look more closely at the cooling water, fire suppression, and domestic water systems because they were thought to be at highest risk. These assessments were helpful in identifying the high-risk systems that needed to be protected and monitored and also assisted with the planning of a chlorination system.

Mussel Impacts

Zebra mussel fouling was first observed on the generator cooling water wye strainer, just upstream of the plate style heat exchangers during normal maintenance. Mussels have not caused any issues at this point.

- Locations where mussel impacts are expected:
    - Gates
    - Water level instruments
    - Corrosion of shaft seal
    - Floating booms
    - Water intake drain holes and entire gate surface
    - Water takeoff grates
    - Sump pumps and intake screens may require more cleaning
    - Increased monitoring of the sump float level
    - Air compressor intercooler
    - All instruments and tubing in contact with raw water
    - Shell debris in strainers

Control Methods

- Preventative control measures
    - Installing injection points for chlorination treatment in the compressor cooling, fire suppression, and auxiliary demineralized domestic systems.
        - Annual, end of season treatment is planned in the Fall.
        - A contractor will provide the portable chlorination system and materials needed for chlorination and dechlorination. Metabisulfite is used for dechlorination.
        - Manitoba requires discharged chlorine to be neutralized.
    - Jenpeg is considering installing additional strainers and ultraviolet light treatment in the future but are concerned about the effectiveness of the treatment because the silt loads increase the turbidity.
- Design aspects that may serve to prevent or reduce mussel issues
    - The plant has had issues with silt load in the raw water system leading to the installation of redundant heat exchangers and strainers with extra capacity which should also help prevent mussel issues.
    - Many of the Soviet design components include robust equipment that are expected to handle an increase in mussel fouling.
    - The modern plate heat exchanger design may prevent significant issues, as they are easier to clean relative to other designs.
    - The plant has limited reliance on raw water because of the demineralized cooling-water loop.
        - Generator air coolers use demineralized water.

Expenses Associated with Mussel Infestation

- Mussel specific maintenance and other expenses are not currently tracked.
- All dollar values listed are Canadian.
- Preventative control measures
    - Chlorine treatment: $180,000 per year (does not include plant retrofits)
- Increased Maintenance
    - Mussels were detected at Jenpeg in 2020 and the plant is expecting little to no increase in maintenance associated with the mussel infestation.
    - Additional outages to deal with mussel issues are not expected, but planned outages are expected to be longer.
    - The cost of additional supplies needed to manage mussel settlement and debris is expected to be moderate.
- Monitoring
    - Mussel veliger populations are monitored in the forebay, and settlement and density are monitored in bioboxes and on settlement plates: $2,500 per year at Jenpeg ($30,000 per year for all locations in the system).

Case Study 7: Lewiston Pump Generating Plant

Location: USA, New York
Water Body: Niagara River
Operating Agency: New York Power Authority
Contact: Kevin King, Mechanical Maintenance Supervisor

Summary

Lewiston Pump Generating Plant has had zebra mussels since 1990 and has implemented and optimized chlorine treatment and cleaning schedules so that the mussels do not cause any significant increase in maintenance. Zebra mussel fouling was first observed in the pump/generator cooling water system. Without regular chlorine treatment and cleaning mussel fouling on gates, intake screen wells, traveling screens and duplex strainers resulted in a large cleaning effort requiring divers and pressure washing. The chlorine treatment was optimized 10 years ago and is now effectively controlling the majority of mussel fouling in the service water. The chlorine is applied upstream of the service water intakes and is now applied twice per year for 10 days.

Hydropower Plant Design and Operation

Lewiston Pump Generating Plant (LPGP) is 55 years old and houses 12 generator units with a maximum generator capacity of 420 MW. All 12 generators are not always running at the same time. LPGP is a peaking plant that generates power during the day and pumps during the evening. Approximately 20 staff work at the plant which is staffed continuously. Major maintenance occurs every 5 years. The raw service water used for generator unit cooling water, transformers, fire protection water, and ancillary equipment enters the plant through two intakes with travelling screens and a trash rack. The water does not pass through a self-cleaning strainer.

Mussel Infestation Timeline

Zebra mussels were introduced to Lake St. Clair in 1986 and were first detected at LPGP around 1990. Veligers and mussel settlement are monitored continuously in the pump/generator cooling water. Mussel populations have not significantly declined or increased. A mussel response plan was prepared after the first mussels were detected at the plant and it was useful for implementing control measures. Mussel fouling is no longer considered a significant issue at the plant.

Mussel Impacts

Zebra mussel fouling was first observed in the pump/generator cooling water system. Over time the plant has experienced additional mussel related increased maintenance and issues, including:

- Prior to 2010 regular mussel removal was not done and a large buildup of mussels was discovered.
- In the late 2000's LPGP had to do an end of year treatment in cold water to remove mussel settlement after not treating for a few years. Several dumpster-loads of mussel shells were removed from the manual duplex strainers and surrounding pipes, and almost shut down the plant. Mussel treatment in cold water is difficult, it takes very long time to achieve mortality.
- The strainers (1/16-inch pore size) downstream of the duplex strainers, for the seal water and bearing cooling water get plugged 3-4 days after the start of chlorine treatments.
- Mussel fouling is found on water level instrument sensors (float type).
- Mussel fouling is found on the sump pump traveling screen.
- The HVAC system for both plant equipment and office cooling requires periodic cleaning to remove mussel shells, especially after chlorine treatments.
- Duplex strainers require additional but infrequent cleaning.

Control Methods

- Preventative control measures
  - Chlorine treatment (12.5%)
    - A contractor administers two chlorine treatments per year in June and October. The contractor administers treatment, maintains all of the equipment, and supplies the chlorine.
    - Chlorination is administered via a drip application on the upstream side of the service water intake and traveling screens. This point of chlorination would not be available to users with intakes directly in the river or reservoir, due to regulatory concerns.
    - Each treatment lasts for 10 days.
    - Prior to 2012, chlorine treatments only occurred once per year.
    - Targeting 0.65-2 ppm total residual chlorine.
    - The treatment efficacy is monitored in online bioboxes at the end of the system.
    - Minor increase in strainer cleaning 3 days after the start of chlorine treatments.
    - The treatment has been effective and mussel fouling has not been observed in the generator/stator cooler manifolds.
- Increased maintenance
  - Regular cleaning schedules were not implemented until 2010. Prior to 2010 mussel shells were removed by pressure washers when necessary from the gates, pumpwells, and traveling screens.
  - Divers removed mussel settlement from intake screen wells (every three years), diver cleaning was required more frequently before the current treatment schedule was implemented.
  - Water level instruments are flushed once per year.

Expenses Associated with Mussel Infestation

- Mussel specific expenses are tracked.
- Preventative control measures
  - Two chlorine treatments per year are administered by a contractor: $40,000 per year.
    - LPGP labor to assist with chlorine treatments: 32 hours per year.
- Increased maintenance
  - The mussel infestation has resulted in little to no increase in maintenance costs with chlorine treatment.
  - Diver removal of mussels from the intake screen/wells: $19,000- $22,000 per cleaning.
- Monitoring
  - Veliger and settlement monitoring in the pump/generator cooling water: $15,000 per year.

Case Studies 8, 9, 10, 11: Sir Adam Beck #1, Sir Adam Beck #2, DeCew NF23, and Pump Generating Station

Location: Canada, Ontario
Water Body: Niagara River, DeCew NF23: Lake Gibson/ Welland Canal
Operating Agency: Ontario Power Generation
Contact: Ray DeJonge, Work Center Manager

Summary

Zebra mussels were first detected at all four powerplants around 1990 and the first mussel fouling was observed in the surface air coolers. A 10-day chlorine treatment is administered once per year at the end of August or early September at each plant. The chlorine treatment has controlled the mussel fouling issues in the cooling system and very little additional maintenance is required. Auto-backwash strainers were installed to capture and remove mussel shell debris. Mussel fouling does occur at other locations at each plant and requires increased maintenance. Mussel settlement in the stilling wells requires annual cleaning, flushing, and removal of mussel shells with a vacuum truck, and duplex strainers need to be cleaned weekly. The mussel impacts at the plants are considered moderate and somewhat predictable and are now largely under control. A moderate increase in labor and materials is required to manage the mussel infestation.

Hydropower Plant Design and Operation

Sir Adam Beck 1 (SAB1): A 100-year-old plant with 8 generator units and a total generator capacity of 440 MW. The plant is base-loaded, and generator units have a 50 percent duty cycle. The plant is staffed continuously and approximately 25 people work at the plant. Major maintenance occurs during annual outages on a 2, 4, and 8-year schedule. Service water, including the fire protection water enters through a single intake from the penstock and passes through auto backwash and duplex strainers.

Sir Adam Beck 2 (SAB2): A 60-year-old plant with 16 generator units and a total generator capacity of 1600 MW. The plant is base-loaded, and generator units have a 75 percent duty cycle. The plant is staffed continuously and approximately 35 people work at the plant. Major maintenance occurs during annual outages on a 2, 4, and 8-year schedule. Service water, including the fire protection water enters through multiple intakes from the penstocks and passes through auto backwash and duplex strainers. In the winter, service water is sourced from the tailrace.

DeCew NF23 (Decew2): A 75-year-old plant with 2 generator units and a total generator capacity of 144 MW. The plant is base-loaded, and generator units have a 98 percent duty cycle. The plant is staffed continuously and approximately 25 people work at the plant. Major maintenance occurs during annual outages on a 2, 4, and 8-year schedule. Service water enters through multiple intakes from the penstocks and passes through auto backwash and duplex strainers. City water (from fire hydrants) is used for fire protection water at the plant.

Pump Generating Station (Pump GS): A 60-year-old plant with 6 generator units and a total generator capacity of 174 MW. The plant design configuration is a combination of pumping and generating units, and generator units have a 10 percent duty cycle. The plant is staffed continuously and approximately 25 people work at the plant. Major maintenance occurs during annual outages on a 2, 4, and 8-year schedule. Service water enters through multiple intakes from the penstocks and passes through duplex strainers. In the winter, service water is taken from the tailrace. Fire protection water is also pumped from the tailrace.

Mussel Infestation Timeline

Zebra mussels were first observed in Lake St. Clair (about 250 miles upstream from the Niagara plants) in 1988. Mussels were first observed at all four powerplants around 1990. SAB1 and SAB2 immediately had fouling issues but DeCew2 and Pump GS did not appear to have any issues until around 1998. A mussel vulnerability assessment was not completed at any of the sites, and a response plan was not in place prior to mussel arrival, therefore the response was reactive and required several years of refinement. Mussel settlement is monitored in bioboxes and on settlement plates in the headworks, and mussel veliger populations are monitored near the water intakes. Monitoring efforts occur weekly to monthly. The fire water systems (for plants using raw water) is also monitored once per year for live veligers and to confirm low oxygen levels that would prevent their survival. Zebra mussels were the first species to invade and overtime quagga mussels have become more prevalent. Mussel populations have remained the same during the infestation. The mussel impacts at the plants are considered moderate and somewhat predictable and are now largely under control. A moderate increase in labor and materials is required to manage the mussel infestation.

Mussel Impacts

Zebra mussel fouling was first observed in the surface air coolers at all four plants. Chlorine treatment has controlled the issue and very little additional maintenance is required in the treated systems. Mussel fouling of the stilling wells requires annual cleaning, flushing, and removal of mussel shells with a vacuum truck. Cleaning of the piping on the stilling wells for measuring water levels (piezometer taps) has recently been required. Mussel fouling is also observed in the wye strainers (with 4-inch or less inlet diameter) and accumulated shell debris in the duplex strainers and self-cleaning strainers require additional cleaning. Very little zebra mussel fouling has been observed in the penstocks at all sites, but mussel settlement has been observed around the access points where the water velocity slows. Mussel fouling and increased maintenance has also been observed at the following site-specific locations:

- SAB1:
  - Duplex strainers
  - Normally closed valves on the penstock drains, scroll cases, and penstocks
- SAB2:
  - Gates
  - Turbine packing gland seals
  - Some of the older air conditioning units that still use raw cooling water experience clogging in the small diameter piping. These units will be replaced with newer units that do not use raw water for cooling.
  - Normally closed valves on the penstock drains, scroll cases, and penstocks
  - Fire pumps
- DeCew2:
  - Occasional need for divers to clean the gates
  - Installed a trashrake to manage the increase in weeds accumulating on the trash racks.
  - Headgates/gate tracks/and drain holes
  - Bulkhead gate
  - Transformers were water cooled and the piping became occluded with mussels. The water-cooled system has been replaced with an air-cooled system.
- Pump GS:
  - Gates
  - Need to clean the gains more than other sites to allow gates to seal properly for outages.
  - Mussels found in the sumps have not resulted in maintenance issues, but odor resulting from mussel decay is problematic. Pump GS has had the most odor issues and chlorine is periodically added to the sumps.
  - Generator surface air coolers still have some issues, but prior to optimization of the chlorination treatment the manifold coolers would become occluded with mussel shells.

- Normally closed valves in the penstock drains, scroll cases, and penstocks get plugged with mussel shells and must be manually cleaned every time the scroll case is drained.
- Fire pumps receiving water from the tailrace need to be monitored and sometimes need to be cleaned by divers.

Control Methods

- Preventative control measures
  - Chlorine treatment (all 4 plants)
    - One, 10-day treatment per year at the end of August or early September.
    - Treating the cooling water system.
  - Auto-backwash strainers installed to capture and remove mussel shell debris (all 4 plants).
  - SAB2: Implemented a high-pressure water flow through the coolers once per day that flushes accumulated mussel shells and microbial biofilm out of the manifolds. The plant has issues with microbial induced corrosion which the flushing mitigates.
  - DeCew2: Installed strainers followed by HOD UV on one generator cooling water unit as a trial.
    - UV treatment was effective after first year trial.
  - Tested Zequanox at DeCew2 and SAB1. The trial was successful at DeCew2, but there was limited success at SAB1. The treatment was found to have quality control issues and was expensive.
- Increased maintenance
  - Duplex strainers are cleaned weekly, requiring 2-3 hours of labor per week at each plant. The strainers are usually cleaned on a Friday to reduce clogging issues and the need for overtime on the weekends for cleaning.
  - Annual cleaning, flushing, and removal of mussels from the stilling wells.
  - Pump GS: Cleaning and scraping of gains for stoplogs for unit isolation.
- Design aspects that have served to prevent or reduce mussel issues
  - Redundancy of equipment
  - Equipment robustness
    - Trash racks have wide spacing
    - Coolers at Pump GS are overdesigned
  - Limited reliance on raw water
    - DeCew2:
      - Domestic, treated, water used to cool air compressors
      - Transformers are now air cooled
      - Fire pumps use city water
    - SAB1:
      - Domestic, treated, water is used to cool the heat exchanger air compressor intercooler
    - SAB2:
      - Diesel backup generator is air cooled

Expenses Associated with Mussel Infestation

- Mussel specific maintenance and costs are tracked through work orders. Operation and maintenance costs for mussel control are tracked annually as well as capital costs.
- All dollar values listed are Canadian.
- Preventative control measures
  - SAB1:
    - Chlorine treatment capital investment: $500,000
    - Chlorine: $3,000 per year
    - Replacement parts and other materials for chlorine treatment: $8,000
  - SAB2:
    - Chlorine treatment capital investment: $1,300,000
    - Chlorine: $8,000 per year
    - Replacement parts and other materials for chlorine treatment: $16,000
  - DeCew2:
    - Chlorine treatment capital investment: $250,000
    - Chlorine: $2,000 per year
    - Replacement parts and other materials for chlorine treatment: $5,000
  - Pump GS:
    - Chlorine treatment capital investment: $720,000
    - Chlorine: $3,000 per year
    - Replacement parts and other materials for chlorine treatment: $5,000
- Increased maintenance
  - Additional supplies and materials: $125,000 per year (total for all 4 plants)
  - Annual cleaning of the stilling wells with a vacuum truck: $30,000 per year, per plant
  - SAB1:
    - 250 hours per year
    - 15 overtime hours per year
  - SAB2:
    - 400 hours per year
    - 72 overtime hours per year
  - DeCew2:
    - 200 hours per year
    - 25 overtime hours per year
  - Pump GS:
    - 250 hours per year
    - 25 overtime hours per year
- Monitoring: $30,000 per year for all 4 plants

Case Study 12: Wilson Hydropower Plant

Location: USA, Alabama
Water Body: Tennessee River

Operating Agency: Tennessee Valley Authority (TVA)
Contact: Tabitha Lolley, Plant Manager

Summary

Zebra and quagga mussel fouling is considered a significant issue at Wilson Hydropower Plant. Mussel fouling results in unplanned/forced outages and requires a significant increase in maintenance. Chemical treatments are not permitted because there are protected native mussel species living in the river downstream of the plant. Mussel fouling is managed by removing and replacing pipes, swapping generator coolers with backups, backwashing, hydro-blasting, and vacuuming mussel shells from pipes. Automated backwash strainers were installed to capture and remove shell debris and monitoring of temperature and flow have been optimized to reduce the likelihood of overheating.

Hydropower Plant Design and Operation

Wilson Hydropower Plant is 97 years old and houses 21 generator units with a total generator capacity of 670 MW. Wilson is an automated, base-loaded plant. Approximately 30 employees work at the plant. Major maintenance on every unit occurs every 3-5 years based on operating hours. The raw service water used for units 1-8 comes from a single intake approximately 14 feet below the surface in the forebay. Units 9-21 receive cooling water from the scroll case from each penstock, which comes from approximately 45 feet below the surface. The cooling water is gravity fed; the plant does not have cooling water pumps. Raw water is pumped for the fire protection deluge system.

Mussel Infestation Timeline

Invasive mussels were first detected at Wilson Hydropower Plant in the early 1990's. Both zebra and quagga mussel settlement were detected in bioboxes. A facility vulnerability assessment and response plan were not in place prior to the detection of mussels at the plant. When mussels were first detected, the plan was to apply a quaternary ammonium compound (SUEZ Spectrus CT1300) treatment for control but it was found that chemical injection was not permitted at the site due to the presence of several protected native mussel populations in the Tennessee River, downstream of the plant. Mussel fouling is considered a significant issue at the plant between May and November, resulting in a significantly increased maintenance.

Mussel Impacts

Mussel fouling is most significant on units 1-8 as cooling water comes from an intake at the face of the dam that is at 14 feet depth. An extensive outage is required to clean the headers on units 1-8 and includes cutting into the pipes and hydro-blasting to remove mussels. Mussel fouling has resulted in up to 12 forced outages per year, implementation of backwash flushing, and optimization of temperature and flow monitoring has reduced the unplanned outages to about 3 per year (approximately 8 outages related to mussel fouling per year across all of TVA's facilities). The runner seal and piping to the turbine bearing are locations that have major problems. The runner seal piping is ¾-inch-diameter and a single mussel can plug the line. Mussel fouling is also experienced in the following locations:

- Penstocks
- Ring header
- Heat exchangers
- Automatic strainers
- Basket strainers
- Turbine bearings
- Turbine packing gland
- Turbine seal cooling water lines
- Turbine seal filters
- Turbine pit sump pumps (five, 55-gallon drums full of mussels were removed from under the head cover on recent maintenance outage)
- Thrust and guide bearing oil heat exchangers
- Gates
- Flow measurement taps
- Normally open and closed valves

Control Methods

- Preventative control measures
  - Installed automated backwash strainers to remove mussel shells.
  - Purchased four replacement generator coolers so that coolers can be swapped out when overheating occurs.
  - Utilize backwash to remove mussels from pipes by changing the flow and direction of water.
  - Tees have been installed in locations where shells accumulate in the pipes. The shells can be easily vacuumed from the tee. All removed shells must be collected and discarded because they cannot be discharged into the river.
  - Planning to install UV and strainers.
  - Planning to apply a bio-release coating on some structures.
  - Increased sump inspections to weekly.
  - Flow measurement taps are being replaced by flow meters because mussels are disrupting the differential pressure.
  - Removing manual strainers.
  - Improved flow and temperature condition monitoring to identify issues sooner.
- Increased maintenance
  - Increased the number of maintenance outages (up to 10 per month).
  - Pipes are hydro-blasted and rodded out mechanically and ultrasonic pipe wall measurements are taken to determine integrity and to detect flow restrictions.

    - Plans are to replace generator air cooler piping during future large maintenance outages.
    - Manually clean trash racks and screens from a barge.
    - Increased cleaning of the turbine guide bearing.
- Design aspects that have served to prevent or reduce mussel issues
    - Transformers are air cooled.

Expenses Associated with Mussel Infestation

- Not all mussel specific maintenance and associated costs are recorded or tracked. Therefore, the estimates provided in this section do not fully capture the expenses associated with mussel specific maintenance and control.
- Preventative control measures
    - Purchased 4 replacement generator air coolers: $72,000
- Increased maintenance
    - Cleaning the headers of units 1-8 requires an extensive outage and cutting into pipes and hydro-blasting: $500,000 per cleaning
    - Removal and replacement of generator air coolers with backups: $4,000-$5,000 per swap. Outages are required and additional staff and overtime is often required.
- Mussel related outages
    - Mussel fouling has resulted in up to 12 forced outages per year, implementation of backwash flushing, and optimization of temperature and flow monitoring has reduced the unplanned outages to about 3 per year.
        - Approximately 8 outages related to mussel fouling per year across all of TVA's facilities.

Case Study 13: Gavins Point Hydropower Plant

Location: USA, South Dakota
Water Body: Missouri River, Lewis and Clark Lake
Operating Agency: US Army Corps of Engineers
Contacts: Michael Schnetzer, Senior Mechanic; Lacey Gould, Electronics Mechanic

Summary

Zebra mussel fouling causes significant maintenance and operational issues at Gavins Point. The mussel infestation has most significantly increased maintenance of the generator coolers and irrigation system. The plant has experienced outages and interruption of operation because of overheating units due to mussel settlement reducing flows in the coolers. The HOD UV treatment installed at Gavins Point has been overall effective but does experience some issues related to the turbidity of the water and the installation location. Additional treatments and control methods are being pursued.

Hydropower Plant Design and Operation

Gavins Point Hydropower Plant is 66 years old and houses 3 generator units with a total generator capacity of 132 MW. Gavins point is a low head, base-loaded plant with three separate intakes. Water passes through a 4 basket, self-cleaning Hellan brand strainer with an automated self-cleaning system. The fire protection system utilizes carbon dioxide instead of raw water. Heat exchangers are shell tube and fin-type.

Mussel Infestation Timeline

Invasive zebra mussels were first detected in the reservoir in 2014 and populations were firmly established and detected at Gavins Point by 2016. Mussels were first found on the spillway stop logs and mussel specific issues were first experienced at the power plant around 2018 to 2019. Mussels cause significant maintenance and operational issues at Gavins Point.

Mussel Impacts

The mussel infestation has most significantly increased maintenance of the generator coolers and irrigation system. The plant has experienced outages and interruption of operation because of overheating units due to mussel settlement reducing flows in the coolers. Mussel settlement and clogging is most significant in the air coolers, thrust bearing coolers and packed gland strainers. In 2018 the coolers had to be cleaned every two weeks for up to three days (including overtime). The plant has also experienced flooding caused by clogged drain lines. The plant also experiences Bryozoan fouling which causes similar issues in the heat exchangers. Several other locations and systems within the plant have experienced mussel fouling, including:

- The stator air housing coolers and thrust bearing oil coolers experience mussel issues between May and October and it is not uncommon to have 1-2 units down per month for cleaning. Each unit typically is taken out of service 3 times per summer for cleaning. Each shut down results in 4 days of lost power generation.
- The bubble curtain de-icing system has to be operated year-round to prevent plugging.
- Fouling is most significant on the back of the trash racks.
- Headgates covered with mussel fouling results in increased maintenance, increased crane load and corrosion.
- The turbine pit sumps need more frequent cleaning and if they are not cleaned, water storage capacity is lost resulting in the sump pumps running more often.
- Turbine seal packing
- Normally open and closed valves become fouled and have to be manually cleaned or replaced.
- Mussels attach to the inside of the strainer and filter housing (1/8-inch filter size) and mussel shells plug the 2-inch backwash drains.
- Mussels are increasing the corrosion on the generator and turbine shafts. Equipment that has not had corrosion for 60 years has now started to corrode with the presence of mussels.

- Mussels clog the built-in strainer and HVAC heat exchangers, requiring the booster pumps to be shut down to remove the shells. This typically occurs twice per summer per pump and heat exchanger.
- Intake bulkheads are completely submerged in water and there is a concern that the weight of settled mussels will overload the crane. Mussel fouling increased the complexity of inspecting the intake gates and roller chains because mussel must be removed before inspecting.
- Mussel settlement in the station and unwatering sumps increase the difficulty and time required to clean.
- Compromised reliability of Winter Kennedy pressure taps discharge measurements for penstocks.
- The irrigation intake, lines, and sprinkler heads are completely blocked with mussels.
- Reduced flow in the heat exchanger results in inefficient heat exchange in the closed loop.
- Headbolt deterioration is a concern because water leaking through the packing introduces veligers into the turbine pit.
- Prior to mussel establishment all 3 generators could be online while one of the intakes was shut down for maintenance. Mussel fouling does not allow for this to occur as cooling water flow is too low without all intakes in operation.
- Packing gland water strainers need to be cleaned weekly throughout the year. The water is recirculated in the winter and maintains a temperature between 70-85 degrees F, allowing the Bryozoa and likely the mussels to flourish.
- Mussels have been observed setting and growing on copper pipes.

Control Methods

- Preventative control measures
    - HOD UV installed with upstream self-cleaning strainers
        - The HOD UV treatment has had some issues because of the turbidity of the water (low UVT) and debris clogging the strainers during storm events. The installation location and piping configuration along with strainer backwash drain design also contributed to some of the issues.
        - After addressing some of the issues the treatment does appear to be effective.
    - A de-scaler (Rydlyme) is poured down the drains to dissolve mussels.
    - Applied a mussel resistant coating to the intake grates.
    - Planning to install more access points for cleaning.
    - Planning to install duplex strainers and filtration on the generator cooling water pumps and thrust bearing.
    - Considering applying coatings.
    - Considering applying a copper treatment.
- Increased maintenance
    - Mechanical pigging of coolers.
    - Replacement of fouled pipes and other equipment in the coolers.
    - Increased cleaning of strainers and filtration systems.

- Can flush coolers that are starting to overheat for a few days with the emergency cooling water pump before a shutdown is required.
- Prior to the mussel infestation, planned maintenance occurred every 5 years. Since mussels arrived each unit needs to be serviced 4 times per year.
- Heat exchanger maintenance increased from once every three years to at least twice per year.
- Drain lines were cleaned and re-lined by a contractor.
- Increased maintenance of the spillway and intake deicing systems. The system is now run year-round to keep lines clear of mussel settlement and this requires more labor and equipment.

Expenses Associated with Mussel Infestation

- Mussel specific maintenance is tracked by work orders.
- Preventative control measures
  - HOD UV light treatment and strainer installation on the two raw water intakes: $1,000,000.
    - HOD UV service contract: $31,980 per year
  - Temporary de-icers for spillway: $12,040
  - Becker blowers: $6,600 per year
  - Rydlyme: $8,000 per year
- Increased Maintenance
  - Increased labor as a result of mussels: 2,182.5 hours (approximately $111,240 per year)
  - Overtime: 82 hours
  - Cost of consumables needed for unit cleaning: $1,000 per unit per cleaning
- Mussel related outages
  - 542 hours and 16 min: $664,256
  - 2 forced outages
    - 150 hours: $184,669
  - Outage cost calculation $35 per MW/H
    - Gavin's point is producing 35 MW, is a small site with little head. A larger USACE site would be around $1,897,000 for 100 MW unit with 542h of downtime.
  - Numerous more mussel cleaning tied to other planned outages.

Conclusions

The thirteen case studies presented in this report provide examples of the range of impacts and control strategies that hydropower facilities encounter and utilize when dealing with dreissenid mussel infestations. The goal of the survey was to interview hydropower plants that ranged in size, design, and number of years dealing with mussel infestation. The survey includes hydropower plants with 2 (144 MW) to 36 (1899 MW) generator units with a range of raw water system designs and usage in the plants. The hydropower plants interviewed have experienced mussel fouling from 1 to 31 years.

The impact of mussels at hydropower plants is site dependent. Two of the plants consider mussel impacts to be significant, 8 consider the impacts to be moderate, and 3 plants experience little to no impact. For sites that have had mussels longer than twenty years it was difficult to capture information about initial mussel impacts, because many of the staff working at the site during the initial invasion had since retired and detailed records were not available. This study confirms that mussel impacts are primarily dependent on the design configurations of hydropower plants and how they utilize raw water. The size or number of generators at a plant does not usually correlate to the severity of impacts or expenditures. For example, the two sites that expressed having significant mussel impacts were one of the smallest (2 generators) and one of largest (36 generators) plants interviewed. The mussel population size, dynamics and number of population cycles also play a role in their impacts to hydropower plants. All of the Reclamation plants are in locations where water temperatures support year-round mussel reproduction, whereas other sites in Canada have colder winter temperatures that limit fouling to warm times of the year.

Mussel fouling in hydropower plants results in increased maintenance to remove mussels from locations where they accumulate, reduce flow, and result in overheating. Five of the plants included in this study are currently managing mussel fouling by relying on increased cleaning, physical removal or implementing design and operational changes. Some of the more common maintenance approaches for mussel removal include:

- Removing and replacing pipes and equipment once they become fouled.
- Hydro-blasting or pigging.
- Employing dive teams to remove mussels from submerged structures, like intakes and screens.
- Increasing cleaning of common problem areas like strainers.
- Using acid and de-scaler solutions to dissolve mussel shells.
- Implementation of pro-active cleaning strategies that are refined overtime and with experience.

Many sites also implement design and operation changes including:

- Increasing the speed of flow in pipes so that mussels cannot settle.
- Implementing backflushing and high-pressure flushing to remove accumulated mussels.
- Changing piping routes to eliminate low-flow zones, dead-ends, and unnecessary bends where mussels can accumulate.
- Adding strainers with or without auto-backwash.
- Changing the location or depth from where raw cooling water is sourced.

Several plants indicated the following design features had served to reduce the impacts of mussels:

- System or component redundancy.
- Certain systems or components being “overbuilt” or larger than what is required.
- Reduced reliance on raw cooling water.
- Location and depth of intakes.
- Regular cycling of generators to reduce unplanned outages.

Eight plants have implemented treatments to prevent mussel fouling. The most common preventative control treatments utilized by the plants in this study were chlorine and HOD UV. The reported capital investment to install chlorine treatment ranged between $100,000 and $1.3 million. The reported capital investment to install HOD UV ranged between $1 million and $2.1 million. While these treatments are effective at mitigating mussel fouling, they will not always be appropriate for every hydropower plant. Chlorination requires discharge permitting and may not be appropriate for sites that have sensitive species in downstream locations. Some jurisdictions prohibit the use of chlorine or have discharge limits necessitating de-chlorination using sodium metabisulphite or other means. Chlorine permitting can be very onerous for companies and creates a risk for legal noncompliance. HOD UV is environmentally friendly, and thus may benefit from less restrictive permitting requirements or no permitting required in some cases. While HOD UV has been shown to be effective, it is a newer technology, and in some cases, still working out some technological issues. Although chlorine and HOD UV were most commonly utilized in this survey, there are several other treatment options that are available and should be explored when trying to select the most effective treatment for a hydropower plant.

Expenses associated with mussel fouling are not recorded at the majority of plants interviewed. Therefore, it is difficult to provide exact costs associated with an infestation. Tracking the labor hours and equipment required to resolve issues associated with mussels is difficult because the corrective actions commonly become associated with regular maintenance. For example, more frequent cleaning of strainers due to mussel shells is often just reported as strainer cleaning.

Five of the thirteen sites have experienced or currently are experiencing unplanned outages as a result of mussel fouling in the generator cooling systems. Most of the sites that experienced unplanned outages were in locations with warmer temperatures where mussels have more population cycles each year quickly building up population density. The occurrence of an unplanned outage can be costly when considering the potential overtime hours required and the lost power revenue. For example, lost power generation revenue could range from $9,934- $61,456 per unit per day at Reclamation hydropower plants along the Colorado River (data collected from the U.S. Energy Information and Administration and Reclamation Power Resource Office).

Hydropower plants that implement early detection monitoring by collecting veliger samples upstream of the plant may have approximately five years to prepare for mussel fouling at the plant. Along with monitoring, a facility vulnerability assessment and response plan can help prepare and mitigate against significant operational impacts at the plant. Seven of the 13 plants interviewed in this study had prepared for mussel infestation by conducting a mussel facility vulnerability assessment or prepared a response plan. All of plants that had prepared indicated the assessment or plan was useful for detecting mussels sooner and implementing control methods before fouling became unmanageable.

The case studies in this report provide insight into the types of impacts mussels can have at hydropower plants and some of the associated economic consequences. Mussel vulnerability assessments and the information provided in this report can provide insight and guidance to managers at plants that are preparing for a mussel infestation or are considering changes to their mitigation strategy.

References

Connelly, N.A., C.R. O'Neill Jr., B.A. Knuth, T.L. Brown. 2007. Economic Impacts of Zebra Mussels on Drinking Water Treatment and Electric Power Generation Facilities. Environmental Management 40 (1) pp. 105-112.

Glomski, L.M. 2015. Zebra Mussel Chemical Control Guide. US Army Corps of Engineers. Engineer Research and Development Center. https://apps.dtic.mil/dtic/tr/fulltext/u2/a621371.pdf

Hay, K.J., I.E. MacAllister, R.C. Wilson, A.M. Brake. 2019. Incidence of Zebra Mussel on U.S. Army Corps of Engineers Structures. Engineer Research and Development Center. https://hdl.handle.net/11681/35273

O'Neill, C.R. 1997. Economic Impact of Zebra Mussels- Results of the 1995 National Zebra Mussel Information Clearinghouse Study. Great Lakes Research Review, 3 (1).

Park J., L. Hushak. 1999. Zebra Mussel Control Costs in Surface Water Using Facilities. Ohio Sea Grant College Program, Ohio State University. OHSU-TS-028.

Phillips, S., T. Darland, M. Sytsma. 2005. Potential Economic Impacts of Zebra Mussels on the Hydropower Facilities in the Columbia River Basin. Prepared for the Bonneville Power Administration. http://www.aquaticnuisance.org/wordpress/wp-content/uploads/2009/01/Phillips-Darland-and-Sytsma.pdf

Pimentel, D., R. Zuniga, D, Morrison. 2005. Update on the Environmental and Economic Costs Associated with Alien-Invasive Species in the United States. Ecological Economics 52, pp. 273-288.

Prescott, T.H., R. Claudi, K.L. Prescott. 2014. Impact of Dreissenid Mussels on the Infrastructure of Dams and Hydro-Electric Power Plants. In: Nalepa, T.F., and D.W. Schloesser, eds. *Quagga and Zebra Mussels: Biology, Impacts, and Control.* CRC Press, Boca Raton FL, USA. pp. 243-257.

Pucherelli, S.F. 2020. Compendium of Reclamation Mussel Control Research for Hydropower Facilities. Reclamation Science and Technology Program. ST-2019-7136-01.

Appendix A

Invasive Mussel Interview Questions

Facility Name/ Location:
Water Body:
Contact Name/ Job Title:
Objective: The Bureau of Reclamation, the 2nd largest generator of hydroelectric power is the Western US, is seeking information about the specific systems and equipment in your facility where you have observed issues associated with mussels, how mussels impact regular operation and maintenance, and the types of control methods that have been implemented. This information will be used to prepare a report to serve as a reference for facility managers throughout the US and Canada that are preparing for a potential mussel infestation and to direct future Reclamation control research.

Hydropower Plant Information

Design and Operation

What is the facility age?
How much does the reservoir water level fluctuate?
Number of generator units?
Total generator capacity or total outlet works flow capacity?
What is the duty cycle of generator units (operation schedules)?
What is the design configuration (select)?

- Base-loaded plant (continuous operation)
- Intermittent operation/peaking plant (frequent down time/ penstocks filled)
- Peaking plants with spinning reserves
- Combined pump/ generating units

What is the major maintenance approach (select)?

- Annual unit outages (more than a week), timing and dewatering procedure
- Longer term planning based on equipment experience and performance
- Other

Water Intakes

Type of raw water intake (select)?

- Separate single intake for all service water (non-penstock), (e.g. face of the dam/tailrace)
- Multiple intakes for service water (non-penstock)
- Single Intake for service water from the penstock
- Multiple intakes for service water from penstocks

Does the raw water/ service water system have primary strainers? If so what type?
Type of fire protection intake (select)?

- Separate intake
- Part of service water

Staffing
Number of employees working at the facility?
Staffed continuously? or mostly unmanned with regular visits by technicians?

Mussel Infestation Timeline

Detection
Date adult mussels first observed in water body?
How far away is the powerplant from the location where mussels were first observed in the water body?
Date mussels first observed at powerplant?
Date first mussel related issues observed?
Which operations were impacted first?
Have the issues changed with time?
Planning and Monitoring
Was there a vulnerability assessment done prior to mussel arrival?

Was there a response plan in place prior-to or after mussels arrived?

- Did it help?
- What was the reaction time?

Were /are mussel populations monitored at your facility or water body?

- What types of monitoring were/are conducted?
- What was/is the frequency of monitoring?
- What were/are the costs associated with monitoring?

Mussel Impacts and Costs

Are/ were mussels considered a problem at your power plant? Or have their impacts been mitigated to the point where they are no longer seen as a concern?
How would you qualify the degree of issues caused by mussels?

- Significant
- Moderate
- Low

Are there design aspects of your facility that have served to prevent or reduce mussel issues?

- Redundancy of equipment
- Robustness of equipment
- Limited reliance on raw water
- Frequent routine planned outages
- Other?

Do you track mussel specific maintenance and cost?

Have you experienced unplanned outages or any major interruption of operation because of mussels?

- How frequently do mussel specific outages or interruptions occur?
- Length of outage or interruption
- Average cost of outage or interruption
- What was the frequency of unplanned outages/interruptions before mussels?

Changes to your operations/maintenance practices or schedules:

- Maintenance labor increase: significant, moderate, little or none
- Planned maintenance: more outages, same outages but longer, little or no change
- Costs for additional materials and supplies: significant, moderate, little or none

What specific location(s) or system(s) require (or used to require) increased maintenance because of mussels?

- How many extra man-hours per month or year are required as a result of the increased maintenance?
- Increased cost associated with purchase of materials?

For sites with long term infestations (> 10 years)

- Have mussel populations declined?
- Have mussel related man-hours and O&M costs also declined?

Provide estimates for the following…

- Average man-hours spent on mussel maintenance per month
- Average overtime hours spent on mussel maintenance per month
- Average annual O&M mussel related costs for the facility, including periodic/intermittent replacement costs?

Response

Have you installed any treatment or equipment specifically to deal with mussels**?**

- Chemicals
- Strainers followed by UV
- Coatings
- Filtration
- Self-cleaning intake screens/racks
- Installation of redundancy
- Other?

If yes, what location and for what reason, and what was the cost?

Has it been effective?

Has it decreased annual O&M costs?

Would you recommend it to other facilities with mussels?

What types of maintenance are required to deal with mussels?

- Mechanical cleaning of intake structures such as trash racks
- Mechanical removal of settlement and shell debris
    - Raking, scraping, hydro jetting, pipeline pigging, etc.
- Replacement of fouled pipes and other equipment
- Increased cleaning of strainers and filtration systems

Do you use chemicals to control mussels?

- Which chemicals do you use?
    - bromine, chlorine, chlorine dioxide, hydrogen peroxide, potassium permanganate, ozone etc.
- Do you use molluscicides?
- Treatments at end of season or multiple treatments throughout the year?

Have these changes made the problem more easily managed or do new issues continuously arise? Have you had to implement new control measures overtime?

Detail Item/Component Impacts

On a scale of 1 to 10 (1 = none, 10 = severe, use N/A if not applicable or not known), please rate the increase in maintenance hours and total increase in costs due to mussels for the following locations:

Item No.	*Item*	*Labor (1-10)*	*Cost ($)*	*Comments*
1	**General for Dams, Reservoirs, and Materials of Construction**			
1.1	Seepage drains			
1.2	Gates			
1.3	Piezometer wells/pressure relief wells.			
1.4	Water level instruments, stilling wells			
1.5	Deicing/bubbler equipment			
1.6	Corrosion or change of materials			
1.7	Other			
2	**Water Intake Structures**			
2.1	Forebay (specify lining material)			
2.2	Floating boom			
2.3	Trash racks (specify bar spacing, and fouling with mussels?)			
2.4	Trash rake, (Issues with weeds or floating debris)			
2.5	Head gates/gains/drain holes			
2.6	Stop log gates			
2.7	Air Vent			
2.8	Penstock			
2.9	Grates/screens on raw water intakes			

2.10	Fish Barriers			
3	**Turbines**			
3.1	Turbine bearing			
3.2	Mechanical face seal			
3.3	Packed gland seal			
3.4	Seal cooling water line			
3.5	Seal filter			
3.6	Turbine pit drain pump			
3.7	Turbine pit drain lines			
3.8	Other			
4	**Wells and Sumps**			
4.1	Sump pump			
4.2	Float level			
4.3	Non-contact level			
4.4	Increased sump inspection			
5	**Heat Exchangers**			
5.1	Generator air cooler			
5.2	Thrust and guide bearing oil			
5.3	Hydraulic oil (wicket gates etc.)			
5.4	HVAC			
5.5	Air compressor intercooler			

5.6	Transformers			
5.7	Other			
6	**Piping**			Including supply and drain lines
6.1	Greater than 4” inlet diameter			
6.2	4” inlet diameter or less			
6.3	Irrigation piping			
7	**Instrument Tubing and Instruments**			
7.1	Flow measurement taps			
7.2	Piezometer taps			
7.3	Pressure taps			
7.4	Sample lines			
7.5	Pressure balance lines			
7.6	Other - specify			
8	**Valves**			**Identify type if known (i.e. gate, butterfly etc.)**
9.1	Normally open (NO) valves.			
8.2	Normally closed (NC) valves			
8.3	Pressure relief valves			
9	**Strainers and Filters**			**Note mesh size if possible**
	Greater than 4” inlet diameter			
9.1	Fixed In-line strainer			
9.2	Duplex strainer			

9.3	Self-cleaning strainer			
9.4	Wye (Y) strainer			
	4" inlet diameter or less			
9.5	Fixed In-line strainer			
9.6	Replaceable cartridge filter			
9.7	Self-cleaning strainer			
9.8	Wye (Y) strainer			
9.9	Other type - specify			
10	Safety Related Equipment			
10.1	Fire pumps (electric motor)			
10.2	Fire pumps (diesel engine)			
10.3	Fire system strainer			
10.4	Emergency gates			
10.5	Diesel backup generator			

Data Requests

Can you provide water quality data?

- Calcium
- pH
- Temperature

Can you provide mussel population data?
Can you provide documentation of mussel specific maintenance and cost?
Do you know of any other facility's we should contact?

- Please send any additional data or information to Sherri Pucherelli at spucherelli@usbr.gov
- Please let us know if any of the information you shared today should be protected

THANK YOU FOR YOUR TIME AND INFORMATION!!