Dreissenid Mussels and Alberta's Irrigation Infrastructure:

Strategic Pest Management Plan and Cost Estimate

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Paterson Earth & Water Consulting Ltd.
Lethbridge, Alberta

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Prepared for
Eastern Irrigation District

Dreissenid Mussels and Alberta's Irrigation Infrastructure: Strategic Pest Management Plan and Cost Estimate

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Letter of Transmittal

Alberta, the irrigation capital of Canada, has about 704,000 ha of irrigated land, that contributes about $3.6 billion to the provincial gross domestic product and generates about $1.26 billion in annual revenue to the Governments of Alberta and Canada. About 82% of Alberta's irrigated area is in the 13 Irrigation districts, and is served by more than 50 water storage reservoirs, and 8,000 km of water supply canals and underground pipelines.

Alberta's irrigation districts and the Government of Alberta are working to prevent the introduction of invasive mussels to Alberta's lakes and reservoirs through a comprehensive education, monitoring and watercraft inspection program. The discovery zebra mussels in Lake Winnipeg (2013), and possibly the Tiber Reservoir in Montana (2016) underscored the potential threat of dreissenid mussels being introduced to Alberta's irrigation reservoirs, irrigation conveyance systems, and on-farm irrigation systems.

The irrigation districts recognized that the extensive irrigation network, particularly the underground pipeline network, could experience significant reductions in water conveyance capacity if invasive mussels are introduced to irrigation water supply reservoirs. There are currently no registered options for eradication of invasive mussels in Canada, although chlorine is being used extensively for dreissenid mussel control in the Great Lakes Basin under an exemption permit. Potassium chloride (potash) has been shown to eradicate these mussels, and work is underway in Alberta for its registration for invasive mussel control. The Eastern Irrigation District, in partnership with Alberta Agriculture and Forestry, and Alberta Innovates is undertaking research to develop potassium chloride injection procedures for Alberta's irrigation pipelines.

In February 2017, a request for proposals was issued for a comprehensive strategic pest management plan and cost estimate for treatment and control of invasive mussels, in the event they are found in the Alberta's irrigation water supply reservoirs. Paterson Earth & Water Consulting Ltd. was selected to lead this study.

This report provides recommendations for preventing the introduction of dreissenid mussels in irrigation water supply reservoirs, and options for the control and eradication of mussels if they should infest irrigation water supply canals, pipelines, and on-farm irrigation systems. Cost estimates are also presented for the use of potassium chloride to eradicate dreissenid mussels in underground pipelines.

Sincerely,

B. Paterson

Brent Paterson, P. Ag.

Executive Summary

Introduction

Alberta is home to about 704,000 ha of irrigated land, that accounts for almost 70% of Canada's total irrigated land base. About 82% of Alberta's irrigated area is in the 13 irrigation districts (Figure 1). There are more than 50 water storage reservoirs, and 8,000 km of conveyance works that supply water for irrigation, municipalities, industries, and recreation uses throughout southern Alberta.

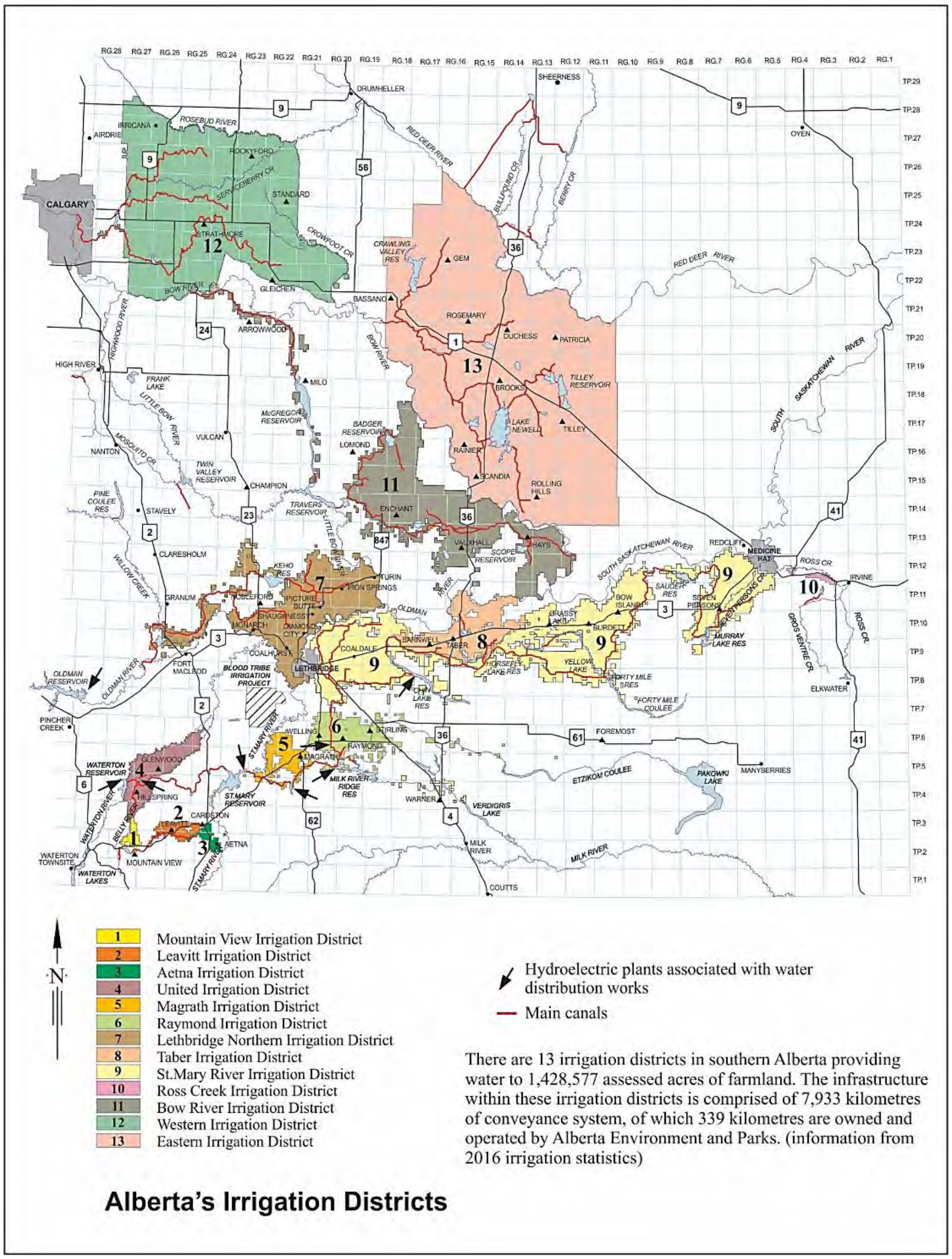

Figure 1 Irrigation districts and major irrigation works in southern Alberta

About 53% of the water conveyance system has been converted from surface canals to underground pipelines to minimize water losses and increase water use efficiency. More canals will be converted to pipelines in the future. The value of the irrigation districts' infrastructure is about $3.6 billion, plus an additional $1 billion for on-farm irrigation infrastructure, that includes an estimated 4,800 km of producer-owned irrigation water supply lines, and 8,500 pivot irrigation systems.

Alberta's irrigation districts and the Government of Alberta (GoA) are working to prevent the introduction of invasive dreissenid (zebra and quagga) mussels to Alberta water bodies through education, monitoring, and pre-emptive inspection programs. It is estimated that zebra and quagga mussels have cost industries, businesses and communities in North America about $5 billion between 1993 and 1999 because of clogged water-intake pipes, with $3.1 billion of that cost related to the power industry. Dreissenid mussels have spread from the Great Lakes region along the Mississippi River and lower Colorado River basins, and were been discovered in Arizona, California, Colorado, Kentucky, Missouri, Nevada, and Utah. Discovery of these mussels on pleasure boats in Washington and Oregon increase the likelihood they will continue to spread to new water bodies.

In 2013, zebra mussels were found in Lake Winnipeg (Manitoba). There was also concern that mussels had been discovered in the Tiber Reservoir (Montana) in November 2016. However, further investigations carried out in August 2017 found no evidence of mussels in the Tiber Reservoir. In 2013, mussel-infested boats were discovered at inspection stations at several central Alberta lakes (Sylvan, Pigeon, Gull, and Wabamun lakes), and also one lake in southern Alberta (Chestermere), which supplies water to the Western Irrigation District (WID). The discovery of dreissenid mussels in water bodies that are close to southern Alberta's borders, combined with the high volume of boat and watercraft traffic into Alberta from mussel-infested areas in Canada and the United States, makes it likely that dreissenid mussels will be introduced into Alberta irrigation water supply reservoirs in the future.

The extensive irrigation water supply network in southern Alberta will be vulnerable if invasive mussels are introduced to the irrigation water supply reservoirs in the province. Twenty-two reservoirs that supply irrigation water were identified as high risk to invasive mussels due to the water chemistry, as well as the high amount of boating activity. The detrimental effects of mussels are of particular concern for buried water supply pipelines and on-farm irrigation systems. Invasive mussel establishment in Alberta would also negatively impact recreational opportunities and the aquatic environment. As seen in other jurisdictions, the effects of invasive mussels are far reaching environmentally, socially, and economically. An assessment in 2013 by Alberta Environment and Parks (AEP) indicated the total annual cost of invasive mussels to Alberta would be about $75.5 M.

Currently, there are no registered control options for invasive mussels in Canada. Potassium chloride (potash) has been shown to be effective in eradicating dreissenid mussels, and is considered the primary approach for dealing with a potential dreissenid mussel infestation in Alberta's irrigation distribution system. Work is underway by the GoA to register potash as a pesticide for invasive mussel control with the federal Pest Management Regulatory Agency (PMRA). Additionally, the Eastern Irrigation District (EID), in partnership with Alberta Agriculture and Forestry (AAF), and Alberta Innovates is undertaking research to develop potassium chloride injection methods for Alberta's irrigation water supply pipeline, and on-farm irrigation infrastructure.

Study Methodology

This study was carried out to obtain a comprehensive strategic management plan for the control and management of invasive dreissenid mussels in Alberta's irrigation distribution systems. The study assessed relevant North American data for the control and management of dreissenid mussels, the GoA dreissenid mussel prevention strategies being undertaken, existing water quality and water temperature data for irrigation water supply reservoirs and irrigation distribution systems, and current research data developed by AAF for successful injection of potassium chloride into irrigation water supply pipelines.

The study focussed on five key objectives:

1. Assess the potential for dreissenid mussels to develop and grow in Alberta's irrigation water supply reservoirs and irrigation distribution systems.
2. Assess additional prevention techniques to minimize the potential for dreissenid mussels to establish in Alberta's irrigation water supply reservoirs.
3. Prepare a strategic pest management plan for the irrigation districts for a coordinated invasive mussel control program.
4. Develop a range of dreissenid mussel management and treatment approaches for injecting potassium chloride into irrigation district water supply pipelines, and irrigation producer-owned water supply pipelines and on-farm irrigation systems.
5. Prepare estimates of the annual operational costs associated with potassium chloride treatment approaches in the 13 irrigation districts.

Conclusions

Alberta is fortunate that dreissenid mussels do not appear to be currently present in any of the province's water bodies. The extensive irrigation water supply network in southern Alberta will be especially vulnerable if invasive mussels are introduced to irrigation water supply reservoirs in the province. An enhanced program to prevent the introduction of dreissenid mussels into these reservoirs should be a high priority for the GoA and irrigation districts.

This report identifies the need for Alberta's irrigation districts and GoA to prevent the spread of dreissenid mussels into irrigation water supply reservoirs, and potential management and control options if a mussel infestation occurs. An enhanced prevention strategy includes controlling boat launch sites on reservoirs to certify that all incoming boats and other watercraft are free of mussels, combined with a comprehensive public education program. Targeted monitoring of irrigation water supply reservoirs will help irrigation districts better understand the growth and development potential of the dreissenid mussels, and this will support the development and assessment of more effective mussel management and control options.

Southern Alberta's relatively long and cold winters are considered a key element in the control of dreissenid mussels in water supply reservoirs, irrigation canals, and pipelines. Where winter desiccation and freezing are not practical for selected pipelines, injection of potassium chloride solution (potash) into mussel-infected pipelines is considered to be the most effective, practical, and environmentally benign mussel control option available to the irrigation districts. While there are many other chemical and non-chemical treatment options that are being used to control dreissenid mussels, most are being used in relatively small, stand-alone operations.

The following provides a more detailed description of the report's key conclusions and supporting rationale.

1. **Dreissenid mussels (zebra and quagga) entered the eastern United States from Europe in the 1980s, and have since spread to the Great Lakes and waterways, rivers, and lakes in many parts of North America.**
    a. Dreissenid mussels can reproduce rapidly, and the accumulation of adult mussels results in challenges due to fouling of water structures and pipelines.
    b. Ongoing management and treatment costs to control dreissenid mussels can be very high for industries and municipalities.
    c. In 2013, the total annual cost of invasive mussel control for Alberta was calculated at about $75.5 M.
    d. This total cost does not include costs associated with irrigation district or rural water supply pipelines.

2. **It is likely that dreissenid mussels will appear in irrigation water supply reservoirs under the current prevention program being implemented in Alberta.**
    a. Recreational boats are the primary means by which dreissenid mussels move from one body of water to another. Adult mussels attach to the hull of boats, larval stages can be transported in water filled internal ballast tanks or live wells, and both life stages can survive overland transport to new water bodies.
    b. In 2013, zebra mussels were found in Lake Winnipeg (Manitoba). There was concern that mussels had been discovered in the Tiber Reservoir (Montana) in November 2016. However, further investigations carried out in 2017 found no evidence of mussels.
    c. In 2013, mussel-infested boats were discovered at inspection stations at several central Alberta lakes (Sylvan, Pigeon, Gull, and Wabamun lakes), and Chestermere Lake, which supplies water to the WID in southern Alberta.
    d. The discovery of dreissenid mussels in water bodies that are relatively close to southern Alberta's borders, combined with the high volume of boat and

watercraft traffic into Alberta from mussel-infested areas in Canada and the United States, makes it likely that dreissenid mussels will be introduced into Alberta irrigation water supply reservoirs in the future.

3. **Alberta's irrigation water supply reservoirs and irrigation district water supply infrastructure will support the growth and development of dreissenid mussels.**
    a. Key factors such as calcium, pH, dissolved oxygen, and temperature in irrigation water supply reservoirs and water supply infrastructure meet the requirements for dreissenid growth and development.
    b. Mussel development will likely be limited to the shallower portions in many of the irrigation water supply reservoirs, where summer water temperatures are warmer.
    c. Growth rates for the dreissenid mussels are expected to be 1 to 1.5 mm/mo for most of the reservoirs.
    d. The length of the reproductive season is likely to be relatively short, as reproductive temperature timelines are generally short for most irrigation water supply reservoirs in southern Alberta. Increasing temperatures related to climate change may increase the length of the reproductive season.
    e. From the time mussels first appear in an upstream reservoir to when there is an adequate number of veligers present to settle in downstream irrigation systems will likely take three to five years.
    f. Only one irrigation water supply reservoir in Alberta may be naturally resistant to mussel establishment. High levels of naturally occurring potassium in Cavan Lake Reservoir will likely prevent growth and development of dreissenid mussels in the Ross Creek Irrigation District (RCID).

4. **A mussel infestation in an upstream reservoir will likely affect several downstream reservoirs, and the rivers that accept return water related to the infested reservoir(s).**
    a. Active treatment of most water supply reservoirs to eradicate these mussels is not feasible.
    b. Since mussel development will mainly take place in the shallower zones of most irrigation water supply reservoirs, drawdown of these reservoirs for normal winter operations will kill any exposed mussels due to desiccation and freezing.
    c. Once a reservoir becomes infected, water supply canals and underground pipelines located downstream of the infested reservoirs will become infested.
    d. Control and eradication of the dreissenid mussels in the irrigation water supply infrastructure will likely become the focus of the irrigation districts.

5. **Natural desiccation and freezing during the winter provides the most cost-effective means of controlling dreissenid mussels in Alberta's irrigation water supply canals and pipelines.**

a. Southern Alberta winters, which require that all irrigation water delivery and on-farm irrigation systems be drained, can effectively kill exposed mussels.
b. Mussels in surface canals are particularly vulnerable during the winter months, and 100% mortality is expected each winter.
c. All exposed mussels in underground pipelines will be killed through desiccation during the winter months, because of prolonged exposure and relatively low humidity.
d. Mussels present in pools of water that remain in pipelines after drainage in the fall may survive the winter if the water does not freeze, and dissolved oxygen levels exceed 3 mg/L.
e. Complete drainage of underground pipelines, and/or exposure of pipelines to cold winter air, is required to ensure complete mortality of mussels during the winter season.

6. **Currently, there are no registered control options for invasive mussels in open bodies of water or irrigation pipelines in Canada.**
   a. To date, most successful treatment options to control or eradicate dreissenid mussels in North America have been carried out in relatively small, stand-alone facilities, such as power stations, industrial plants, and municipal water treatment facilities.
   b. Chlorine is used extensively for dreissenid mussel control in the Great Lakes Basin, through an exemption to registration by the Ontario Ministry of Environment. The use of chlorine as well as discharge is controlled by an individual facility's permit for use.
   c. Potassium chloride (potash) has been successfully used to control mussels in water bodies in Canada and the United States, and is currently considered to be the primary approach for controlling dreissenid mussels in Alberta's irrigation water delivery systems.
   d. Alberta Environment and Parks is currently working to register potassium chloride with the PMRA for use in Alberta water systems.
   e. Research is being carried out to develop practical, cost-effective potassium chloride injection methods for Alberta's irrigation water supply pipelines.

7. **Irrigation districts have three options to consider for management and/or control of dreissenid mussels that are present in underground water delivery pipelines.**
   a. Winter desiccation.
      i. Nearly all mussels that accumulate in the underground pipelines during the summer will be exposed after the pipelines are drained in the fall. These exposed mussels are expected to die during the prolonged winter period through desiccation.
      ii. The small pools of water remaining in the pipeline after drainage, where mussels might survive, generally represent a small fraction of the total pipeline capacity.

iii. Mussels present at these locations during the winter will be isolated, because the remainder of the drained pipeline will be too dry to sustain them.
iv. These colonies of mussels living in these pools of water are likely to have a minimal impact on the flow and capacity of the affected pipelines.
v. This option would have minimal costs to the irrigation district, and should pose no impacts on the ability to delivery water to all users.
vi. This option does not address the possible accumulation of mussels in producer-owned water supply pipelines that are not properly drained in the fall.

b. Kill all mussels by injecting sufficient volume of potassium chloride to fill the pipeline.
    i. Potassium chloride solution is injected into the irrigation district pipeline until the desired potassium concentration of 100 mg/L is reached in the pipeline, and producer-owned water supply pipelines, and irrigation pivot systems. The treated water is held in the irrigation district and producer-owned water supply pipelines for five to six days. After the treatment is completed, fresh water is injected into the pipeline, and the treated water is applied to the irrigated fields through the pivots.
    ii. This option is relatively costly, and requires a significant amount of time and manpower to complete.
    iii. This option aims to have all treated water applied to the land, and potash-treated water does not return to an irrigation canal or other surface water body.
    iv. An initial flush of water through the treated pipeline segments in the spring should remove all detached mussel shells from the pipeline.
    v. This option may be logistically difficult to achieve during the spring and fall time periods, that are the most conducive to irrigation producers.

c. Introduce a relatively small volume of potassium chloride into the pipelines to kill mussels that may survive in remaining pools of water.
    i. Since the surviving mussels are concentrated in the small pools of water on the pipeline floor, injecting a relatively small volume of potassium chloride solution, enough to cover the remaining pools of water after drainage, should achieve 100% mortality of any remaining mussels. The volume of treated water would have to be sufficient to flow into all pipeline segments. The potash solution could be pumped into the pipeline inlet, without it needing to be completely sealed. The treated water could be discharged onto the land through producer-owned pivot systems, or left in the pipeline during the winter months, and discharged from the pipeline when the water is turned on in the spring.

ii. This option will require much less volume of potassium chloride solution than the above option, will be easier to introduce into the pipeline, and require less time and manpower to implement.
iii. This option would not address the potential accumulation of mussels in producer-owned water supply pipelines.

8. **Complete treatment of all irrigation district and producer-owned water supply pipelines with potassium chloride (potash) is estimated to cost about $1.1 million.**
   a. This estimate is based on the costs associated with the use of potash to control mussels in Lake Winnipeg.
   b. The majority of the cost is associated with manpower and equipment. The actual cost of the potash represents about 11% of the total cost estimate.
   c. Actual costs to treat the 900+ pipeline segments within the 13 irrigation districts, if required, may be greater because of the number of mobile treatment systems that may be required. In addition, this equipment will have to be moved many times over relatively long distances.
   d. Treatment periods in the spring and fall of each year are likely the most agreeable to irrigation producers, given their need for irrigation to meet crop demands during the summer. Treatment in early May and late September/early October would provide about 30 days of active pipeline treatment activities.

9. **It will be logistically difficult to treat all 900+ pipeline segments during the 30-day spring and fall periods.**
   a. At least nine days will be required to initiate, implement, and complete the potassium treatment of each pipeline segment.
      i. Cool water temperatures at these times will require the potassium-treated water to remain in the pipeline segment and pivots for five to six days to ensure 100% mortality of the dreissenid mussels.
      ii. Additional time will be required to set up and charge the pipelines to achieve the target potassium concentration.
      iii. An additional two days are required, after the treatment is complete, to determine if all mussels in the treated water have been killed.
   b. It is estimated that at least 60 mobile treatment systems, operating simultaneously, would be required to treat all pipeline segments in the combined 30-day window during the spring and fall.
   c. The number of mobile treatment systems could be reduced to about 10 if continuous treatment of the 900+ pipeline segments took place from May 1 to October 30 each year.

Recommendations

1. **The GoA and irrigation districts should consider implementing additional prevention measures to minimize the threat of mussel infestation at high-risk water storage reservoirs.**
    a. Remaining mussel free should be a very high priority for the GoA and the irrigation districts to avoid the difficulties and high costs of control and treatment programs once dreissenid mussels become established.
    b. The current boat monitoring program at key entry points is beneficial, but may not be totally effective, as boats can continue to enter the province at many locations that may not be fully monitored.
    c. An enhanced GoA/irrigation district prevention strategy is recommended, which includes:
        i. Restricting and controlling the number of boat launch sites on reservoirs, and staffing each boat launch site to ensure all incoming boats and other watercraft are free of mussels; and
        ii. A comprehensive public education program that precedes and complements actions such as limiting boat access to reservoirs. Public education regarding the effects associated with dreissenid mussel infestation should also be an ongoing activity for the irrigation districts. This will reinforce the understanding of current and future recreation users of the economic and environmental effects of a dreissenid mussel infestation, and increase understanding and acceptance for the irrigation districts' actions.
    d. Cost of prevention measures will be less than those related to management and control of a dreissenid mussel infestation, and will prevent potentially harmful environmental effects to reservoirs, rivers, and irrigation district water supply systems.

2. **An ongoing monitoring program should be implemented to detect the presence of dreissenid mussels in irrigation water supply reservoirs.**
    a. Existing data indicates it will take three to five years for mussels introduced into a reservoir to become a significant problem in downstream irrigation water supply systems.
    b. At minimum, annual monitoring of veliger and adult mussels in GoA and irrigation district reservoirs should be continued. The following are recommendations for annual monitoring of veligers and adult mussels in GoA and irrigation district reservoirs.
        i. Collection of a plankton sample in August/September provides a good opportunity to determine if veligers are present.
        ii. Visual inspection of exposed infrastructure in the fall of the year, after the reservoirs have been drawn down, would provide a good opportunity to determine if adult mussels are present.

        iii. These, combined with additional monitoring to obtain information related to mussel growth potential for a particular reservoir, will help determine the timing and expected severity of a mussel infestation in downstream water delivery canals and pipelines, and on-farm irrigation systems.
    c. It is important to know, as soon as possible, when dreissenid mussels are present in a reservoir.
    d. This, combined with available information related to mussel growth potential for a particular reservoir, will help determine the timing and expected severity of a mussel infestation in downstream water delivery canals and pipelines, and on-farm irrigation systems.

3. **Monitoring water in the irrigation districts' water supply reservoirs should continue, to assess the growth and development potential of dreissenid mussels.**
    a. There are many factors that determine the ability of dreissenid mussels to develop and grow in southern Alberta reservoirs, and the GoA and irrigation districts have collected a significant amount of information for many of these factors.
    b. The AAF irrigation water quality monitoring program (2006 to 2007 and 2011 to 2016) provides good information on growth factors such as calcium, pH, and temperature. However, chlorophyll a data were somewhat limited.
    c. Additional information related to these key factors, while not critical, would be useful to more accurately assess mussel growth and development potential within each of the reservoirs.
    d. This information may allow the GoA and irrigation districts to more effectively target and develop prevention and control measures.
        i. Water profile temperature data for reservoirs will help determine the depths where most mussel development will take place. These data may help determine the feasibility to kill, through desiccation and freezing, a significant percentage of the mussels through normal reservoir drawdown for winter operations.
        ii. The data may also show that periodically drawing the reservoir down slightly more than normal may kill a much higher percentage of the mussel population.
    e. The use of portable water quality meters (e.g. Hydrolab DS5X) may provide a more cost-effective alternative than laboratory analyses to carry out "spot-check" measurement of these parameters.

4. **Irrigation districts should exploit Alberta's cold winter temperatures to control dreissenid mussels that settle in irrigation water delivery infrastructure.**
    It is recommended the irrigation districts and irrigation producers take the following actions to assess the desiccation and freezing potential of the underground pipeline systems, and implement appropriate actions to correct any deficiencies.
    a. Assess the dewatering potential of all underground pipelines.

i. Identify all depressions or other locations within the pipeline where water may remain after the pipeline is drained each fall.
ii. Complete drainage of a pipeline will result in desiccation and death of any dreissenid mussels in the pipeline.
iii. Mussels located in small pools of water may survive the winter if oxygen levels in the water are adequate (>3 mg/L), and the water does not freeze completely. During several years, this population may grow, not from the reproduction of the mussels present, but from upstream recruitment.
iv. Depending on the intensity of upstream infestation, three years of recruitment may result in partial obstruction of the pipe as well as a continuing source of shell debris as adult mussels die.

b. Assess the natural freezing potential of all underground pipelines.
   i. Install temperature sensors during the winter season to measure the temperature in representative pipelines sections, to determine if complete freezing of any ponded water will occur.
   ii. Assess the oxygen level of retained water in the pipelines.
   iii. These measurements should be carried out for a number of years, as oxygen levels and freezing potential may change.
c. Implement a pumping program to remove excess water from pipelines.
   i. Discussions with irrigation district representatives indicated that significant volumes of water may remain in some small sections of pipelines.
   ii. Pumping is already being carried out to remove excess water in some sections. This program should be expanded to include all sections where mussels are present.
d. Assess and develop the potential to introduce freezing winter air into pipelines.
   i. For those pipelines located below the winter frost line, some type of suction fan installed at the downstream end of the pipeline should be tested to draw sufficient cold winter air into the pipeline to freeze any pools of water where mussels are present.
   ii. Air vents strategically located along the pipelines may also increase the potential to draw the cold air into the entire pipeline.
e. Assess and retrofit pipelines to allow for the disposal of dead mussel shells.
   i. Removing mussels that have been killed through winter desiccation and freezing may require changes to the downstream end of irrigation district pipeline segments.
      - Discussions with irrigation district representatives indicate that some type of valve assembly is located at the end of the pipelines to allow drainage at the end of the irrigation season.
      - This valve opening may be relatively small, and mounted part way up the side of the pipeline.

- This may not allow all water to be drained from the pipeline, and not permit flushing of mussel shells from the pipeline.

ii. It is recommended that the downstream end of all pipelines be retrofitted to allow it to be opened completely during drainage, to allow flushing of all mussel carcasses from the system.

iii. Provided that only one year of mussel recruitment is present in the pipeline, the mussel volume should be manageable, given the size of the population and the size of the individual mussels.

5. **Irrigation producers should work with the irrigation districts to assess the drainage and freezing potential of all underground pipelines that supply water to their on-farm sprinkler irrigation systems.**
   a. Pump out any remaining water in underground water supply pipelines that do not freeze in winter, and where mussels may congregate.
   b. Ensure that pump intake screens for sprinkler irrigation systems are suitable to exclude dreissenid mussels that may plug sprinkler nozzles. Additional cleaning and maintenance of the screens may be required, depending on the extent of the mussel infestation.

6. **New pipelines being installed within the irrigation districts should be designed and constructed to optimize winter control of dreissenid mussels.**
   a. Ensure that pipelines are installed on-grade to minimize the number of depressions in the pipelines, that may create after-drainage pools of water where mussels can collect and survive during the winter.
   b. Use eccentric, rather than concentric reducers wherever possible to minimize the number of sites where mussels can survive after drainage of the pipeline.
   c. Consider installing air vents at strategic locations on pipelines located below the frost line to optimize the transfer of cold winter air into the entire length of the pipeline.
   d. At the downstream end of pipeline segments, incorporate a system that:
      i. Allows the pipeline to be completely drained, and effectively flushed to remove any mussel shells from the pipeline; and
      ii. Accommodates installation of a suction fan to draw cold winter air into the pipeline to ensure freezing of any ponded water.

7. **Design and implement a comprehensive research study to assess the potential to manage and/or control dreissenid mussels in irrigation district and producer-owned irrigation water delivery pipelines through winter desiccation and freezing.**
   a. Select representative pipelines in the 13 irrigation districts and identify the locations and volumes of water that remain after dewatering in the fall of the year.
   b. Assess if remaining water in the pipelines will freeze during the winter periods.

c. Determine if dissolved oxygen in water that remains in the pipelines is sufficient for mussels to survive the winter period.
d. Assess whether these mussels pose a threat to the pipeline integrity, flow characteristics, and capacity to effectively serve all water users.
e. Design and test practical and economically feasible methods to transfer sufficient cold winter air into the pipelines to freeze all remaining water.
f. Design and test systems that can effectively allow dead mussels shells to be removed from pipeline segments.
g. Develop and test pipeline design and construction technologies that will minimize the amount of water that remains in the drained pipelines during the winter, to increase the proportion of mussels killed through desiccation.

8. **Develop a potash injection strategy for those underground pipeline segments where winter desiccation and freezing may not be viable.**
    a. Identify pipeline segments that may require potash injection to kill mussels that are present.
        i. Maximize the number of pipeline segments where mussel control can be accomplished by winter desiccation and freezing; and
        ii. Minimize the number of pipeline segments that will require potash injection treatment.
    b. Determine if this work can be most effectively provided by private contractors or by irrigation district staff.
        i. If the decision is to use irrigation district staff, determine what mobile equipment will be required to transport, mix, and inject the potash solution into mussel-infested pipeline segments.
        ii. Develop and implement a training program for irrigation district staff for the injection of potash into the pipelines.
    c. For pipelines where potash may be required, there may be a need to install:
        i. Potash injection valves near pipeline inlets; and
        ii. Some type of gate structure at the pipeline inlet to isolate and retain the potash solution in the pipeline segment.
    d. Develop a coordinated pipeline treatment program with irrigation producers served by the pipeline segment, to ensure potash injection activities are effectively coordinated.

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Conversions and Abbreviations

Imperial Units	Abbreviation	Metric Conversion	Abbreviation
acre	ac	0.405 hectares	ha
acre-foot	ac-ft	1.234 cubic decametres	dam^3
acre-foot	ac-ft	1,234 cubic metres	m^3
cubic feet/second	ft^3/s	0.0283 cubic metres/second	m^3/s
foot	ft	0.305 metres	m
inch	in	25.4 millimetres	mm
inch	in	2.54 centimetres	cm
mile	mi	1.609 kilometres	km
square mile	mi^2	2.59 square kilometres	km^2
Metric Units	**Abbreviation**	**Empirical Conversion**	**Abbreviation**
hectare	ha	2.471 acres	ac
cubic metre/second	m^3/s	35.31 cubic feet/second	cfs or ft^3/s
cubic decametre	dam^3	0.811 ac-ft	ac-ft
millimetre	mm	0.03937 inches	in
centimetre	cm	0.3937 inches	in
metre	m	3.28 feet	ft
kilometre	km	0.621 miles	mi
square kilometre	km^2	0.386 square mile	sq mi

Acronyms

Irrigation Districts	
AID – Aetna Irrigation District	RID – Raymond Irrigation District
BRID – Bow River Irrigation District	RCID – Ross Creek Irrigation District
EID – Eastern Irrigation District	SMRID – St. Mary River Irrigation District
LID – Leavitt Irrigation District	TID – Taber Irrigation District
LNID – Lethbridge Northern Irrigation District	UID – United Irrigation District
MVID – Mountain View Irrigation District	WID – Western Irrigation District
MID – Magrath Irrigation District	

Other	
AAF – Alberta Agriculture and Forestry	kPa – kilopascal
DNR – Department of Natural Resources	MIC – Microbially-induced corrosion
Dreissenid mussels – zebra and quagga mussels	mg/L – milligams per litre
USEPA – United States Environmental Protection Agency	mW – megawatt(s)
AEP – Alberta Environment and Parks	NTU – nephelometric turbidity units
GoA – Government of Alberta	PMRA – Pest Management Regulatory Agency
GoC – Government of Canada	µg/L – micrograms per litre
K^+ – Potassium	TSS – total suspended solids

1 Introduction

St. Mary Dam and Reservoir

Alberta is the irrigation capital of Canada. About 704,000 ha of land is currently irrigated within the province (AAF, 2017), and this represents almost 70% of Canada's total irrigation area. About 82% of Alberta's irrigated area is in the 13 irrigation districts (Figure 1.1). Fifty seven water storage reservoirs supply water for irrigation, municipalities, industries and recreation uses in southern Alberta through about 8,000 km of conveyance works. Forty two of the reservoirs are owned and operated by the irrigation districts, and the remaining 15 reservoirs are owned and operated by the Government of Alberta (GoA). About 53% of the water conveyance system has been converted to underground pipelines to minimize water losses and increase water use efficiency. More canals will be converted to pipelines in the future. The value of the irrigation districts storage and conveyance infrastructure is about $3.6 billion (AAF, 2017), plus an additional $1 billion of on-farm irrigation infrastructure (AARD, 2014), which includes an estimated 4,800 km of irrigation producers-owned water supply lines, and 8,500 on-farm pivot irrigation systems.

Armoured irrigation canal

Underground irrigation pipeline installation

1.1 Background

Alberta's irrigation districts and the GoA are working to prevent the introduction of invasive dreissenid (zebra and quagga) mussels to Alberta water bodies through education, monitoring, and watercraft inspection programs. It is estimated that zebra and quagga mussels have cost industries, businesses, and communities in North America about $5 billion between 1993 and 1999 because of clogging water intake pipes, with $3.1 billion of that cost related to the power industry alone (Roefer et al., 2009). Quagga mussels are of particular concern in the Great Lakes region, where they have replaced zebra mussels as the dominant dreissenid mussel, and their populations continue to expand rapidly. Quagga mussels have spread along the Mississippi River and lower Colorado River basins, and have been discovered in Arizona, California, Colorado, Kentucky, Missouri, Nevada, and Utah. Discovery of these mussels on pleasure boats in Washington and Oregon increase the likelihood they will continue to spread into new water bodies.

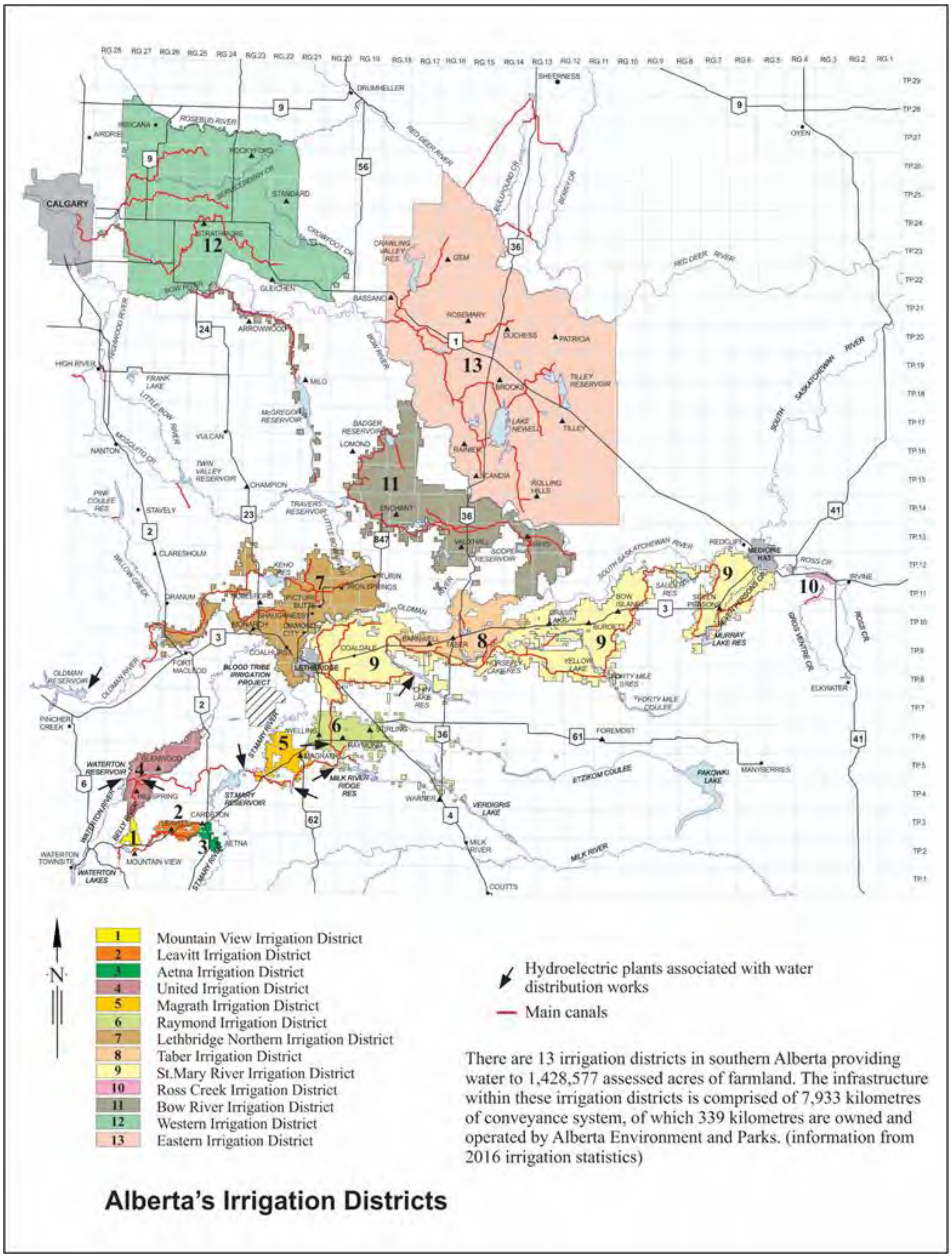


Figure 1.1 Irrigation districts and major irrigation works in southern Alberta

In 2013, zebra mussels were found in Lake Winnipeg (Manitoba). There was concern that mussels had also been discovered in the Tiber Reservoir (Montana) in November 2016. However, further investigations carried out in 2017 found no evidence of this. In 2013, mussel-infested boats were discovered at inspection stations at several central Alberta lakes (Sylvan, Pigeon, Gull, and Wabamun lakes), and also one lake in southern Alberta (Chestermere), which supplies water to the Western Irrigation District (WID) (Kennedy, 2013). The discovery of dreissenid mussels in water bodies that are relatively close to southern Alberta's borders, combined with the high volume of boat and watercraft traffic into Alberta from mussel-infected areas in Canada and the United States, increases concerns that dreissenid mussels may be discovered in Alberta irrigation reservoirs in the future.

Dreissenid mussels are filter feeders that reproduce rapidly. Their lifecycle includes juvenile free-living veligers (larvae) with a flexible see-through shell, and sessile adults with a robust carbonate shell. The accumulation of adult mussels results in challenges for water infrastructure due to fouling. Mussel offspring are capable of reaching sexual maturity within four to five months under favourable temperature and food supply conditions (Delmott and Edds, 2014), and result in downstream biofouling of structures and pipelines if they become established in water storage reservoirs.

The extensive irrigation water supply network in southern Alberta will be vulnerable if invasive mussels are introduced to the irrigated areas of the province. The detrimental effects of mussels are a particular concern for buried water supply pipelines and on-farm sprinkler irrigation systems. Invasive mussel establishment in Alberta would also affect recreational opportunities and the aquatic environment. As has been seen in other jurisdictions, the effects of invasive mussels are far reaching environmentally, socially, and economically.


Pivot irrigation system

Alberta Environment and Parks (AEP) completed *"An Estimate of Annual Economic Costs of Invasive Dreissenid Mussels to Alberta"* in November 2013 (AEP, 2015). The total annual cost of invasive mussels to Alberta was calculated at about $75.5 M (Table 1.1). These costs did not include irrigation district pipelines or rural water supply pipelines.

Table 1.1 Estimated annual costs of an Alberta invasive mussel infestation

Category	Annual Cost ($)
Power Generation	5,938,487
Drinking Water Systems	20,839,921
Boat Maintenance	390,600
Recreational Fishing	21,830,892
Water Management Structures	8,841,373
Water Diversion Intakes	3,910,000
Property Value	13,789,500
Non-Use	Not quantified
Total	**75,540,773**

Source: Neupane, 2013

Twenty-one reservoirs in Alberta, that supply irrigation water, were originally identified as high risk to invasive mussels due to the water chemistry, as well as the high volume of boating activity (AAF, 2017c). This was increased to 22 high-risk reservoirs (Table 1.2) with the addition of the Sherburne Reservoir in the St. Mary River Irrigation District (SMRID) (Personal communication, Barry Olson, AAF, Lethbridge, Alberta). The mussel infestation of a reservoir by invasive mussels will have an effect on the irrigation districts that are served by the reservoir as well as an effect on other irrigation districts that are downstream of the infested reservoir.

Table 1.2 Irrigation reservoirs that are considered high risk for invasive mussel infestation.*

Reservoir or Lake	Operated by	Irrigation District(s) Served	Irrigation District(s) Downstream
Oldman River Basin (12 reservoirs)			
Payne Lake	AEP	MVID/LID/AID	8
Waterton	AEP	SMRID/MID/RID/UID/TID	6
St. Mary	AEP	SMRID/MID/RID/TID	5
Jensen	AEP	MID/RID/TID/SMRID	5
Milk River Ridge	AEP	RID/TID/SMRID	4
Chin Lake	SMRID	SMRID/TID	2
Stafford	SMRID	SMRID/TID	2
Forty Mile	SMRID	SMRID	2
Sauder/Rattlesnake	SMRID	SMRID	2
Sherburne**	SMRID	SMRID	2
Oldman River	AEP	LNID	1
Keho	AEP	LNID	1
Park Lake	LNID	LNID	1
Bow River Basin (9 reservoirs)			
Chestermere	WID	WID	3
McGregor	AEP	BRID	1
Travers	AEP	BRID	1
Little Bow	AEP	BRID	1
Badger	BRID	BRID	1
H Reservoir	BRID	BRID	1
Crawling Valley	EID	EID	1
Lake Newell	EID	EID	1
Rolling Hills	EID	EID	1

* This list is not considered a comprehensive list of irrigation reservoirs that could be infected.
Source: AAF, 2017c
** Sherburne Reservoir was added to this list as a high-risk reservoir.

Currently, there are no registered control options for invasive mussels in Canada, although chlorine is used extensively for dreissenid mussel control in the Great Lakes Basin. Chlorine as sodium hypochlorite or chlorine gas was granted an exemption to registration by the Ontario Ministry of Environment when mussels first arrived in the Great Lakes Basin. The use of chlorine as well as chlorine-treated discharge water is controlled by individual facilities permit for use. Work is underway within the GoA to register potassium chloride (potash) as a pesticide for invasive mussel control with the federal Pest Management Regulatory Agency (PMRA). Additionally, the Eastern Irrigation District (EID), in partnership with AAF, is undertaking research to develop potassium chloride injection methods for Alberta's irrigation water supply pipeline, and on-farm irrigation infrastructure. Currently, potassium chloride is considered the primary approach for dealing with a potential dreissenid mussels, if they become established in Alberta.

In 2017, the EID requested proposals to "obtain a comprehensive strategic pest management plan and cost estimate for on-going potassium chloride (potash) treatment control of invasive mussels in the event mussels are found in the irrigated areas of Alberta". The focus of the project is to be within irrigation district and farmer-owned irrigation pipelines, canals, and irrigation pivot systems.

1.2 Project Objectives

The target audience for this project is the irrigation industry and the GoA, and includes the following four objectives, as outlined in the original request for proposals.

1. Develop a range of treatment approaches for injecting potassium chloride into irrigation infrastructure for invasive mussel control in Alberta's 13 irrigation districts, including irrigation district and farmer-owned infrastructure.
2. Prepare a strategic pest management plan for all irrigation districts, incorporating integrated pest management strategies specific to the variety of irrigation infrastructure, as well as requirements for a coordinated invasive mussel control response among affected irrigation districts.
3. The strategic pest management plan must address stages of treatment from early infestation (e.g. - eradication in pipelines and canals) to wide-spread infestations. The plan will also consider treatment if an infestation becomes permanent and maintenance of pipelines and canals are required in perpetuity.
4. Prepare estimates of the annual operational costs associated with potassium chloride treatment approaches in the 13 irrigation districts.

Paterson Earth & Water Consulting Ltd. was awarded the contract to complete the strategic planning report for the irrigation districts. This work was carried out in partnership with RNT Consulting Inc. (Picton, Ontario), and ASI Group Ltd. (Sarnia, Ontario).

In addition to the above four project objectives, the potential for the growth of invasive mussels in Alberta was assessed, plus an assessment of additional prevention techniques. Objectives 2 and 3 were combined and the study focussed on the following five key objectives.

1. Assess the potential for dreissenid mussels to develop and grow in Alberta's irrigation water supply reservoirs and irrigation distribution systems.

2. Assess additional prevention techniques to minimize the potential for dreissenid mussels to establish in Alberta's irrigation water supply reservoirs.
3. Prepare a strategic pest management plan for the irrigation districts for a coordinated invasive mussel control program.
4. Develop a range of dreissenid mussel management and treatment approaches for injecting potassium chloride into irrigation district water supply pipelines and irrigation producer owned water supply pipelines and on-farm irrigation systems.
5. Prepare estimates of the annual operational costs associated with potassium chloride treatment approaches in the 13 irrigation districts.

2 Dreissenid Mussels

Quagga and zebra mussels are members of the dreissenid family of bi-valves. These non-native, invasive mussels are an environmental and economic nuisance throughout North America and Europe. Dreissenid mussels are bi-valve mollusks. Typically, they have:

- Two equal sized shells, also referred to as valves
- Unequal adductor muscles, which is the main muscular system in bivalve mollusks. Bivalve mollusks generally have either one or two adductor muscles. The muscles are strong enough to enable the animal to close its valves tightly when necessary, such as when the bivalve is exposed to the air by low water levels, when attacked by a predator, or exposed to a noxious chemical. Most bivalve species have two adductor muscles, that are located on the anterior and posterior sides of the body.
- They are filter feeders, using an inhalant siphon to bring in food, sieving small particles from the water, and exhaling the sieved water and waste through the exhalant siphon.

There are four main species of freshwater bivalves.

Native Bivalves

- The Sphaeriidae or Fingernail Clams (named for their shape).
- The Unionidae, or Pearly Mussels (named for the mother-of-pearl layer on the interior of their shell).

Introduced/Exotic Bivalves

- The Corbiculidae, or Asiatic Clam (named for their Asiatic origin).
- The Dreissenidae, Zebra and Quagga Mussels (named for the zebra-stripe pattern on their shells) and Conrad's false mussel are the only fresh water mussels in North America that possess a byssus - a bundle of strong filaments secreted by the animal to attach themselves to surfaces (Figure 2.1).

Figure 2.1 Zebra mussel with a byssus

2.1 External Biology

The shell of the zebra mussel is distinct, taking its name from its zebra-like stripes on the exterior of its shell. Its scientific name (*D. polymorpha*) refers to the many variances (or morphs) that occur in the shell's colour pattern, that can include albino, black and brown. The quaggas (*D. bugensis*) have an equally variable pattern to their shell, but the bottoms of their shells are more rounded than those of zebra mussels. Usually the way to tell zebra and quagga mussels apart is to place a closed shell on its ventral side; the quagga mussel will topple over due to its rounded bottom surface, while the zebra mussel will remain upright (Figure 2.2).

Figure 2.2 Zebra mussel (left), quagga mussel (right)

Most adult dreissenid shells average 1 to 2.5 cm in size, but may reach 4 cm on occasion. Their shells are designed to survive on hard surfaces, and their strong byssal attachment makes it difficult for predators to pry the mussels from surfaces. The cross-section of these mussels is tent shaped, again making it difficult for predators to access.

2.2 Interior Biology

The shells hinge open and closed through a ligament, which is internal and anterior. The pointed end of the shell has an apical septum, or myophore plate, which attaches the small anterior adductor muscle that helps close the two valves. The broad, round posterior end of the shell houses the large posterior adductor muscle scar, that serve to close the valves. The ligament serves to open the valves when the adductors relax.

A thin tissue, called the mantle, envelops the internal body of the mussel. The mantle (also known by the Latin word pallium meaning mantle, robe or cloak) is a significant part of the anatomy of molluscs: it is the dorsal body wall that covers the visceral mass and usually protrudes in the form of flaps well beyond the visceral mass itself. In dreissenid mussels the epidermis of the mantle secretes calcium carbonate to create a shell.

The mantle has two openings; one for the inhalant siphon and one for the exhalent siphon. Siphons are tube-like structures in which water flows in and out. The water flow is used for feeding, respiration, and elimination of waste. The siphons are part of the mantle. The inhalant siphon is the larger opening and is ringed with 80 to 100 tentacles, which assist in selecting food particles. The exhalent siphon is cone-shaped, has no tentacles and is dorsal to the inhalant siphon. The only opening of the shell is the pedal gape, which allows for the extrusion of the large byssus. Dreissenids have a large muscular foot, which is used to pull the animal over the substrate (typically rock, sand, or gravel) when not attached. It does this by repeatedly advancing the foot, expanding the end so it serves as an anchor, and then pulling the rest of the animal forward. It also serves as a fleshy anchor when the animal is stationary.

The byssal glands are housed adjacent to the foot, and are responsible for secreting byssal threads, which allow mussels to adhere to objects. The threads are formed one at a time, branching from a central stem. To detach itself from an object, enzymes are secreted at the base of the byssal mass and the entire mass of byssal threads are released, after which the mussel secretes new threads. Mussels 2.5 cm in length may have up to 600 threads holding it in place.

On each side of the body of dreissenid mussels are gills, which are divided into a series of water tubes by septa or filaments. These filaments make up sheets or lamellae (thin plate-like structures with space in between). Through the small openings in the lamellae, water is able to circulate.

Dreissenid mussels' gills are covered in small cilia, that create currents that aids in pulling water through the inhalant siphon, into the mantle cavity and over the gills. As digestible particles pass over the gills, they are removed by the cilia, and directed towards the mouth for digestion. Inedible particles are wrapped in mucous and rejected as pseudofeces.

The mouth is comprised of a pair of flaps called labial palps and is located at the anterior end of the body. The labial palps assist in guiding and selecting digestible food into the mouth, through a short esophagus and into a large, thin-walled stomach. Undigested food is passed by cilia from the stomach to eventually be expelled at an anal papilla located within the exhalant siphon.

2.3 Reproduction and Life Cycle

Zebra and quagga mussels have separate sexes. Eggs and sperm begin maturing when the water temperature reaches about 12°C, but their numbers do not begin to peak until water temperatures near 15 to 17°C. After eggs and sperm are released by the adults, fertilization occurs externally in the water. Some females can produce up to one million eggs in two years.

In the Great Lakes, the peak reproductive season is in June/July, but the larvae that are born in the spring can reach sexual maturity (at a length of 8 to 10 mm) by mid-summer, and contribute to the production of new larvae (veligers) by the fall. Spawning may last three to five months, though it can last longer in warmer climates, or warmer conditions caused by climate change. The development from fertilized egg to ready-to-settle larvae requires three to five weeks depending on the ambient temperature of the water.

The larval life cycle has three stages (Figure 2.3). After fertilization, the embryo develops into free-swimming larvae (veliger) in 6 to 20 hours. Several days after fertilization, the veliger secretes its first larval shell. The next stage is D-shaped or straight hinge shape, followed by a clam shape. Up to this point all larval stages are capable of limited “swimming”, using an apparatus called the velum. This ability makes it possible for them to maintain their position in the water column, but it is not possible for them to swim against any current. Eventually the larvae lose their velum, acquire a foot and the name pediveliger. Unless carried by current, they fall to the bottom seeking a place to attach. The pediveliger uses its foot for crawling. When it finds suitable surfaces, it will secrete several byssal threads and undergoes metamorphosis to become a plantigrade (a stage between pediveliger and an adult shape).

The plantigrade continues to grow, acquiring the adult triangular shape. It is now called a juvenile, and with time, further growth and sexual maturity, an adult. Mussels can grow incredibly fast, as much as 0.5 to 1mm/d under ideal conditions related to water temperature and food. Typically, adults grow 1.5 to 2 cm/yr with average daily growth rates in summer at about 0.1 to 0.15 mm/d. Mussels can reach sexual maturity in as little as eight weeks. In the Great Lakes the maximum lifespan of the adult mussels appears to be two to three years.

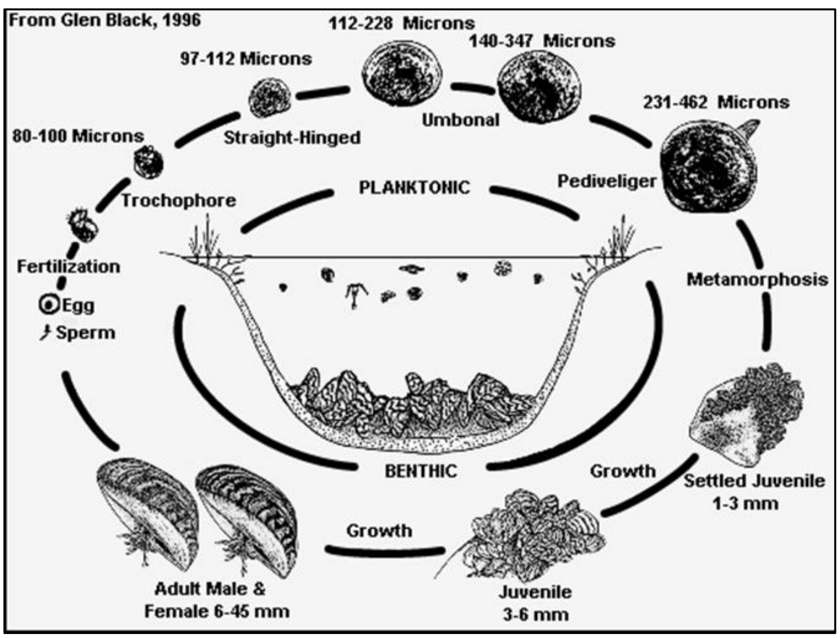


Figure 2.3 Dreissenid life cycle

2.4 Ecological Effects

2.4.1 Filter Feeding

The feeding behavior of dreissenid mussels directly affects ecosystems. Zebra and quagga mussels are efficient filter feeders that process up to approximately one litre of water per mussel per day (Mackie and Claudi, 2010). Microscopic phytoplankton (algae) in the water column are removed and either eaten by the mussels or wrapped in mucus and ejected as psuedofeces. Phytoplankton forms the base of the food chain. Large populations of dreissenid mussels can significantly decrease or eliminate the presence of these microscopic organisms thereby disrupting the food chain, and reducing fish populations. This can negatively affect the recreational fishing industry.

Mussel filter feeding also indirectly affects the aquatic environment by removing particulates from the water, thereby increasing water clarity. While clear water is attractive from an aesthetic standpoint, significant increases in water clarity can profoundly change the aquatic ecosystem. Increased clarity allows light to penetrate deeper into the water column, that encourages the growth of rooted aquatic vegetation on the lake bottom. Increase in aquatic plants, along with bottom-dwelling forms of algae, can drive a shift from fish dwelling in the top layers of the lake (pelagic fish) to those that thrive by feeding on the bottom (Strayer et al., 2004).

2.4.2 Bioaccumulation of Pollutants and Toxic Metals

Zebra mussels also have the potential to accumulate environmental contaminants. Because of the large volumes of water they filter, and their high body-fat content, zebra mussels bio-accumulate contaminants at greater levels than native mussels. Recent studies have shown that zebra mussels may mobilize toxic materials from the sediments into the food chain in two ways.

1. When the mussels consume algae that has absorbed toxic materials, they either ingest the toxic materials, that accumulate and concentrate in the mussel's fatty tissue or shells and are then passed onto fish and ducks that prey on mussels, or they release the toxins as waste (or pseudofeces), returning toxic waste into the water column.
2. Amphipods that graze on the pseudofeces containing the toxins are then eaten by fish, thereby introducing toxins to the food chain via a new mechanism. If sport fish mobilize heavy metals from the bottom substrates, it can lead to poor spawning success or shortened life span, resulting in fewer adults.

Consumption of zebra mussels by migrating or overwintering waterfowl has been noted. Changes in waterfowl abundance and migratory flight patterns can occur if zebra mussel abundance is sufficient to attract the attention of passing birds. Diving ducks (like canvasbacks, redheads, scaups, and mergansers) are most attracted to zebra mussels as food. Because zebra mussels can bioaccumulate pollutants, predation on zebra mussels by waterfowl can threaten the health of these birds or their offspring.

In certain circumstances, dreissenid mussels can have some positive effects on aquatic ecosystems. Many native fish, birds, and other animals eat young and adult mussels. Some species of waterfowl (e.g. lesser scaup, *Aythya affinis*) and fish (e.g. freshwater drum, *Aplodinotus grunniens)* eat mussels. Yellow perch also feed heavily on dreissenid mussels, as do catfish, and many species of sunfish. However, predatory consumption is typically negligible given mussel reproduction rates, and is insufficient to keep the population in check. In addition, the increase in macrophytes (large aquatic plants), due to improved water clarity, can result in more nursery habitat for young fish and can increase some species such as smallmouth bass.

3 Mussel Control

To date, most successful treatment options to control or eradicate dreissenid mussels have been carried out in relatively small, stand-alone facilities, such as power stations, industries, and municipal water treatment facilities. Eradication of mussels in reservoirs by chemical treatment has only succeeded in relatively small, isolated bodies of water. The best-known case study used potassium chloride (potash) to eradicate mussels in the Millbrook Quarry in the state of Virginia. This quarry contained about 680 dam^3 of water and was treated with 650 tonnes of 20% potassium chloride solution during a three-week period. It took 31 days for the potassium-treated water to achieve complete mortality of the mussel population. The potash solution did not pose a threat to humans or the environment, and the eradication process cost about $420,000, which is about $0.60/$m^3$ of treated water. Only one injection site was required to treat the entire quarry.

Most successful treatment options to control dreissenid mussels have been carried out in small, stand-alone facilities, such as power stations, industries and municipal water treatment facilities.

3.1 Treatment of Stand-alone Facilities

The principal mussel-control treatment choice for most facilities in Europe and North America is chemical control, as it has often proven to be convenient and cost-effective. The major advantage offered by chemical treatments is that they can be engineered to protect almost the entire facility, from intake to discharge, and can be applied continuously or on a periodic basis.

The difficulty in pursuing chemical treatment options is limiting the discharge of toxic materials to the environment, and meeting local environmental regulations.

The difficulty in pursuing chemical treatment options is limiting the discharge of toxic materials to the environment, and meeting local environmental regulations. As facilities continue to find themselves in increasingly stringent regulatory environments, the use of chemicals may have to be limited. The exception to this is the relatively new biopesticide Zequanox, from Marrone Bio Innovations. The advantage of this product is that it appears to affect only dreissenid mussels, and requires no detoxification. In Canada, this product has a label that allows use only in once-through cooling systems of hydropower generating stations, but less stringent labeling is currently under negotiation. When fully approved, it could be used in any facility.

3.1.1 End-of-Season Treatment

End-of-season treatment is performed after the mussel breeding season is complete. Sufficient oxidizing or non-oxidizing chemical is applied for a long enough period to kill all adults established in the system. The end-of-season treatment pre-supposes that the system in question can tolerate one season's worth of macrofouling, and that the accumulated biomass and shells can be removed from the system after the treatment. Adult mussels will release from the internal walls of systems during and after the treatment. The system components must be able to tolerate the predicted mass of shell material that is released, and maintenance staff must be on hand to remove the debris.

3.1.2 Periodic Treatment

Periodic treatment is a variation on the end-of-season treatment. Adults are again targeted, but the chemical is applied more often, basically eliminating the fouling while the densities and physical size of the adult mussels remain fairly low. The chemical concentration needed, and the duration of application will be similar to that used for the end-of-season treatment. The biomass that must be removed following the application is proportionally smaller, but the system in question must be capable of tolerating a degree of fouling. If implemented frequently, periodic treatment will prevent the presence of large individual mussels in the system and minimize shell debris.

3.1.3 Preventative Control using Chemicals

The following chemical treatments are designed to be used proactively to prevent the settlement of mussels in raw water systems.

Intermittent Treatment - Chemical treatment of pipelines at frequent intervals (every 12 to 24 hours) is designed to prevent infestations before they begin. It is generally accepted that the freshly settled post-veligers are more susceptible than adults, and this means the concentration of chemical used, and the duration of application to control this life stage will be significantly less than if adults are targeted. Most intermittent treatments will not eliminate adults already present in the system or translocators that gain access.
Effective treatments include:

- Chlorine, as sodium hypochlorite, used for 30 minutes every 12 hours, at 2 mg/L is used to prevent freshly settled post-veligers from developing. This strategy was used at several Ontario Hydro plants for a number of years with good results.
- The addition of 5 to 8 mg/L of ozone for five minutes every 12 hours can prevent the development of dreissenid mussel populations.
- Chlorine dioxide applied for 15 minutes every six hours at a concentration of 0.25 mg/L and ambient temperature of 12.8°C, has been shown to achieve 95% reduction in the new settlement of mussels.
- An intermittent strategy, using the molluscicide Mexel, was developed in Europe. An addition of 6 mg/L of the Mexel chemical for three hours prevents infestation. More recently, the manufacturer suggests that a once-per-day, 30-minute addition of Mexel at a level of 4 to 5 mg/L will control freshly settled mussels and avoid infestation of the system.

Semi-continuous Treatment - The semi-continuous treatment was developed after observing the response of zebra mussels to a chemical irritant. Upon exposure to a noxious substance (oxidizing chemical), mussels will stop filtering and quickly close their shell. It will then take 15 to 30 minutes before they will reopen the shell and attempt to resume filtering. This means that the treatment schedule can be adjusted to 15 minutes on and 15 to 45 minutes off. This is particularly advantageous to facilities that have multiple systems to be treated. The chemical addition system will work continuously, but the chemical can be directed sequentially to the different systems to be treated. This strategy has resulted in complete control of all stages of zebra mussels in the piping, while using significantly less chemical than if applied continuously. In addition, there are minimum discharge levels due to large volume of water available for dilution.

This semi-continuous strategy has been further refined under the trademark Pulse-chlorination®. Using electrodes attached to shells of mussels within a specially constructed monitor, Pulse-chlorination® determines the precise timing for semi-continuous chlorine treatment by observing if the mussels in the monitor have their shell open or closed. The system only applies chlorine when the mussels have opened their shells and discontinues the addition when the shells are closed. This technique significantly reduces the amount of chlorine required (up to 50%) for a treatment compared to a continuous application.

Continuous Treatment - The continuous treatment strategy is designed to eliminate any mussel settlement in the system. The incoming larvae (veligers) do not necessarily suffer 100% mortality, but the presence of a noxious substance is enough to discourage settlement. Any adults present will either succumb to the toxin (if the low level chemical addition is carried out for the entire reproductive season) or detach themselves and attempt to leave the system being treated. The concentrations of chemical needed can be quite low, but the application must be continuous. Typically, continuous treatment is chosen for systems that cannot tolerate even the smallest degree of fouling. Fire protection and other safety related systems for example, often utilize this type of treatment. To date, this type of treatment has been attempted primarily with oxidizing chemicals such as chlorine or with continuous feed of copper ions. Potentially, other chemical strategies, such as depression or elevation of the pH or continuous addition of flocculants, could be used as a continuous treatment.

3.2 Chemical Treatment Options

If fouling organism mortality was the only consideration when designing a treatment, a number of chemicals could be successfully used to control fouling. Due to economic and environmental concerns, only a relatively small number of chemicals are ever likely to be used in practice. When approached by a vendor of either new or existing chemical treatment for macrofouling control, it is best to direct them to the local regulatory agency for an assessment of their product. In many cases, the manufacturer will not be willing or able to provide the money, data, or empirical studies required by regulators to gain approval for use. This reality sometimes keeps promising new products from reaching the market.

Oxidizing Chemicals - Oxidizing chemicals have been utilized as disinfecting agents in water supply systems for more than one hundred years. In most cases, their effect on the environment is understood and well documented. Treatment with oxidizing chemicals (primarily chlorine) has been the most frequently used as a proactive chemical treatment to date. Oxidizing chemicals have also been used in periodic and end-of-season treatments by a number of different industries.

- **Chlorine -** One of the most effective and popular methods of macrofouling control is chlorination, where chlorine is added as diatomic chlorine gas, liquid sodium hypochlorite, or solid calcium hypochlorite. Chlorine has been used for more than one hundred years in the treatment of potable water. It is a well-known and studied chemical with well-documented use and by-products. One of the major concerns in using chlorination in surface water supplies is that it will combine with various organic compounds to form trihalomethanes, which are considered carcinogens. Many regulatory agencies permit the use of chlorine in flow through systems but have stringent limitations on the level of total residual chlorine in the discharge water. To meet these requirements, most facilities must de-chlorinate the treated stream, or else use a storage lagoon or a large volume of diluting water. Before deciding on a chemical treatment strategy, it is wise to contact the local regulatory agency to check on their policy for chemical treatment in general and the use of chlorine. Chlorine-based mitigation can be used for all strategies discussed above. Chlorine treatment strategies and concentrations have been successfully used to control zebra mussels and quagga mussels.

- **Chlorine Dioxide -** Chlorine dioxide has been implemented as a disinfectant in the water treatment industry for more than fifty years. It is effective on aerobic and anaerobic bacteria. Unlike chlorine-based treatments, chlorine dioxide does not form trihalomethane by-products and is equally effective at all pH levels. Chlorine dioxide does not react with ammonia and therefore does not form chloramines. The by-products generated in the breakdown of chlorine dioxide in aqueous solution consist primarily of sodium chlorite, chlorate, and chloride. All regulatory bodies consider these products to be acceptable at low levels. However, the United States Environmental Protection Agency did find that bromate and aldehyde by-products can be formed by the addition of chlorine dioxide to water. The by-products include benzaldehyde, methyl glyoxal, and glyoxal that may be of some interest depending on specific facility concerns.

  Chlorine dioxide can be manufactured on-site from various precursors such as sodium chlorite and hydrochloric acid, sodium chlorite and chlorine gas, sodium chlorite and sodium hypochlorite, and hydrochloric acid or sodium chlorate and hydrogen peroxide and sulphuric acid. The manufacture of chlorine dioxide requires specialized equipment, and there have been past concerns regarding worker safety. In Germany, chlorine dioxide generators are permitted for drinking water applications only if they meet the technical requirements for automatic and airtight generation on-site.

  Recently, manufacturers have started producing 3,000 mg/L solutions of chlorine dioxide off-site and delivering these solutions to the client. Although an aqueous solution of 3,000 mg/L chlorine dioxide is not classified as a hazardous substance, at room temperature it will sublimate into a gaseous phase, which is extremely poisonous. If the injection equipment is not airtight and carefully controlled, this can lead to health and safety concerns. For this reason, on-site generation with state of the art equipment is recommended.

- **Chloramines -** Chloramines are formed when free available chlorine reacts with nitrogen containing compounds, such as ammonium and amino acids. Chloramines are formed naturally when chlorine or sodium hypochlorite is added to lake water. The more ammonium that is present, the higher the level of chloramines formed. Chloramines can be generated in bulk by co-injection of ammonium as either ammonium gas or ammonium hydroxide and sodium hypochlorite. Although chloramines have generally been found to be a less powerful oxidant than hypochlorous acid, they have been used as disinfectants in various applications. Monochloramine has been used as a disinfectant in drinking water, and it was also found effective in controlling veligers of the Asiatic clam. At two French power plants, monochloramine is produced on-site by mixing sodium hypochlorite and ammonium chloride, and it is used to control zebra mussels as well as bryozoans (*Plumatella sp).* Currently, it appears that the use of chloramines rather than chlorine may be advantageous for some facilities. This is particularly true if the formation of trihalomethanes is a concern.
- **Ozone** - Ozone is a well-known bactericidal agent in the sewage treatment and water treatment industry. The first experiments with ozone in drinking water treatment were conducted in France in the late 19^{th} century. It was first used commercially as a drinking water disinfectant at Nice in 1906. Since that time, ozone has gained increasing popularity worldwide, particularly for its viral and bacterial inactivation properties. Viruses and bacteria are eliminated within 30 seconds by a dissolved ozone residual of less than 0.5 mg/L. Ozone improves taste, odour, and colour of drinking water, and can also be used to prevent various other forms of biofouling. Concentrations of 0.25 to 0.5 mg/L have been reported to eliminate the blue mussel (*Mytilus*) from seawater systems in some European studies. In terms of contact time at comparable residual levels, ozone outperforms other oxidizing chemicals. The most significant negative aspect to an ozone-based mitigation strategy is the high initial capital cost of the equipment, and the difficulties involved in maintaining it. Additionally, one of the main characteristics of ozone that make it attractive for use in once-through flow systems also turns out to be a major drawback. The relatively unstable ozone molecule dissipates quickly in water, depending on factors such as temperature, pH, and organic matter concentration.

  In practical applications ozone has performed remarkably well in controlling dreissenid infestations. In Canada, ozone treatment is currently being used in an electricity generating station on Lake Ontario to prevent biofouling of once-through service water systems. The ozone generating equipment was installed in the spring of 2000 and put into immediate use. Ozone is injected at the start of the system at 0.3 to 0.5 mg/L continuously throughout the mussel breeding season. At this location, ozone has provided excellent control of all biofouling, including the prevention of zebra mussel settlement. It has also eliminated any adults that had previously settled in the system prior to the installation of the ozone generator. This elimination took place within the first six months of the initiation of the treatment system. Caged fish fingerlings placed in the discharge stream of the generating station did not suffer any mortality, upholding ozone’s reputation as an ecologically friendly treatment option. The Lake Ontario data mirrors the experience in Belgium at a power plant on the river Meuse. At this installation, ozone was injected at the level of 0.3 to 0.5 mg/L. This treatment achieved complete control of Asian clams and zebra mussels, as well as bacteria and algae in the secondary cooling system. The discharge into the river had less than 10 µg/L of residual ozone. Significant mortality of adults was observed after 20 days of exposure, with complete mortality achieved in 48 days.

A fish hatchery in New England currently utilizes an ozone treatment system. The facility is relatively small, using approximately 3,800 m^3 per day of raw water. The mussel-control regime involves continuous application of ozone at a concentration of 0.3 mg/L. The system is designed to treat a 760-m long pipeline, inactivating the zebra mussel veligers to limit infestation in the hatchery raceways. The ozone injection at the intake is followed by removal of ozone at the hatchery using ultraviolet light.

- **Hydrogen Peroxide -** Hydrogen peroxide has the reputation of being a benign oxidizing agent, dissociating into hydrogen and oxygen and leaving no detrimental environmental by-products. While this may not be completely true, it is frequently used as an algaecide or biocide in small, contained systems such as spent fuel bays in nuclear generating stations.

  Several trials on adult zebra mussels and veligers have shown that relatively high doses of hydrogen peroxide are required to induce mortality. A concentration of 12 mg/L was required for adults and 6 mg/L was needed for veligers. Ninety percent mortality of adult zebra mussels in 21 days of exposure to hydrogen peroxide was achieved at a concentration of 5.4 mg/L. The duration of the treatment decreased with increasing hydrogen peroxide concentration. Total mortality was achieved after 7.8, 4.8, and 3.0 days at concentrations of 10, 20, and 40 mg/L, respectively. In the same study, Asiatic clams were observed to be less sensitive to hydrogen peroxide than zebra mussels. Total mortality for the clams was observed after 13.5, 9.5, and 9 days at concentrations of 10, 20, and 40 mg/L, respectively. As hydrogen peroxide is quite expensive when compared to sodium hypochlorite, it would not seem economically practical to treat large volume, flow-through systems using this chemical.

- **Magnacide™ H -** The active agent for this herbicide is acrolein, and is used effectively in Alberta for control of submerged and floating weeds in irrigation canals. This product is classified as a "Restricted Use Pesticide" by the United States Environmental Protection Agency because of its inhalation hazard to humans, and toxicity to aquatics.

  There is limited information on the use of Magnacide™ H for the control of dreissenid mussels in irrigation distribution systems. A study carried out for Hoechst Holland NV (Vissingen, Netherlands) assessed the potential of acrolein (the main active ingredient in Magnacide™ H) to control the growth of small (1.0 to 2.5 mm) common mussels (*Mytilus edulis*) in a seawater cooling system (Rustenbil and van Galen, 1981). The study showed that the percentage of mussels that closed their valves increased as the concentration of acrolein increased. About 84% and 100% of mussels detached from the test chamber after being exposed to an acrolein concentration of 0.6 mg/L for 24 and 29 h., respectively.

An acrolein concentration of 0.6 mg/L, when applied for 8 h per day reduced mussel settlement by 42%. Increasing the acrolein concentration to 1.0% reduced mussel settlement by 70%.

Because of environmental limitations related to the discharge of the acrolein-treated water, it was recommended that Hoescht Holland NV implement a program to control the settlement of mussels using a 0.6 mg/L solution of acrolein, that was added to the cooling water over one 24 h period every three days, during seven months of the year, or for as long as the water temperature exceeded 8ºC. Additional testing would be required to assess the potential of using Magnacide™ H to control the settlement of mussels in Alberta's irrigation district water supply pipelines.

- **Potassium Permanganate** - Potassium permanganate is another oxidizing chemical commonly used in municipal facilities for water purification. It is widely utilized to protect against oxidation of iron and manganese, and for control of taste and odour problems. Effective control of adults has been achieved at a concentration of 2 mg/L and veliger settlement was prevented using a concentration of 1 mg/L. These results suggest that potassium permanganate may prevent the settlement of mussels, but that it is not acutely toxic to either veligers or adults. Utilizing potassium permanganate as a mitigation strategy seems most applicable in potable water treatment facilities, especially considering that many already utilize this chemical for sanitation purposes or to eliminate trihalomethanes already in solution.

3.3 Non-oxidizing Chemical Options

Many non-oxidizing chemicals have been developed for bacterial disinfection, algae control, and as molluscicides. Some of these chemicals have regulatory registration for use in once-through cooling systems. With few exceptions, these products require detoxification upon discharge to the environment. Most of these products are used for end-of-season or periodic treatments.

- **Proprietary Molluscicides -** The term molluscicide is somewhat of a misnomer as generally these formulations are toxic to a wide variety of species and not just molluscs. Many of these proprietary formulations are based either on quaternary amines (Betz-Clamtrol) or on isothiazolones (Buckman-Bulb 6002) or on other organic compounds (Bayer-Baylucide). The use of these products in closed systems is unrestricted. In once-through applications, most of the products must be detoxified with the addition of a bentonite clay slurry.

  The major form of use for these chemicals is as an end-of-season or, in some cases, periodic treatment. These chemicals are not detected by mussels as noxious compounds, allowing them to continue filtering normally without closing up until death. Thus, mortality can be achieved quite quickly. Depending on the concentration used and the ambient temperature of the water, significant mortality can occur in 4 to 24 hours.

There are two considerations when using non-oxidizing chemical treatments. First, when a facility uses bentonite clay for detoxification of periodic or seasonal treatments; the amount of material that will accumulate in the discharge during the period of some years needs to be considered. The active product will adhere to the clay particles and be carried to the bottom. The fate of some of these complex products in sediment is not well documented, but some products are believed to be quite persistent. Second, most of these products require relatively warm ambient water temperatures to work swiftly. In temperate zones, this may mean a treatment well in advance of the end of spawning, leaving a sizable population of macrofoulers in the system to grow during the winter.

One category of non-oxidizing chemicals is proprietary compounds that act as filming agents and are based on fatty amines. The Mexel® line of products belongs in this category. These products consist of filming aliphatic amines that are thought to inhibit corrosion, prevent slime, scaling, and various forms of macrofouling. The active ingredient in Mexel® is an alkyltrimethylenediamine. Mexel ® was found to inhibit the formation of byssal threads of dreissenid mussels at concentrations of 2, 6, and 10 mg/L. Unlike other proprietary products, Mexel® can be used as an intermittent treatment. When added at the water intake point, typically once a day for 30 minutes at a level of 4 to 5 mg/L, Mexel® has been reported to keep all treated systems free of dreissenid mussels. Unlike other proprietary products, Mexel® does not require detoxification on discharge. High concentrations of total suspended solids (TSS) or organic matter content in the water will require larger concentrations of chemical to maintain an effective residual treatment level.

- **Zequanox -** During the last decade, a significant amount of work was undertaken by a team led by Dr. Dan Molloy from the New York State Museum studying the use of a common soil bacterium as a specific control agent for dreissenid mussels. The team found that the bacterial species *Pseudomonas fluorescens*, strain CL145A (Marrone Bio Innovations, 2011), can cause mortality in adult mussels. When dreissenid mussels ingest artificially high densities of the bacteria (living or dead), a toxin within the bacterial cell destroys the mussels' digestive system. To date, no other aquatic species tested has demonstrated any susceptibility to this bacterium.

Zequanox, a common soil bacterium, has the ability to cause mortality in adult mussels. Zequanox is currently going through the regulatory approval process in Canada.

Zequanox has been commercialized and registered for use in enclosed and confined flowing water systems within dams and associated hydroelectric power plants (GoC, 2013). Marrone Bio Innovations is the company behind this effort. Currently, this product is very expensive. A preliminary cost analysis carried out by AAF in 2015 calculated that the cost of a single treatment of Zequanox would be about \$44/m^3 of treated water, which is about 50 times more expensive than treating with potash. With economies of scale these costs may be reduced, and potentially offer an alternative to chemical control for relatively small stand-alone facilities. However, supply, storage and cost-effectiveness are likely to be challenges for treatment of large-scale pipeline applications in the irrigation districts.

- **Ammonium Nitrate -** At concentrations of 400 to 500 mg/L, ammonium nitrate has been reported to cause 100% mortality of adults in five to six days when ambient water temperature was 16.1 to 19.4°C. Ammonia concentrations exceeding 3 mg/L have been reported to cause 100% mortality in veligers. This treatment is not feasible for once-through systems that return water to rivers or lakes, but could be used within a closed loop system, and in agricultural circumstances where on-farm chemical fertilization is already being used. The use of ammonium nitrate could, along with the use of potassium chloride, be a potential mussel control option for Alberta's irrigation pipelines, provided the treated water is applied to the agricultural land, and not allowed to enter downstream canals, reservoirs, or rivers.

- **Copper Ions -** Dissolution of copper and aluminum anodes by electrolysis has been used to protect ship cooling systems from macrofouling for at least 40 years. Based on the marine experience, a series of experiments was conducted to determine if the same technology could be used against dreissenid mussels. A continuous treatment of 20 µg/L of copper ions appears to limit veliger settlement in systems protected in this manner. This technology was commercialized under the trademark of MacroTech Copper Ion generator.

  Wisconsin Energy Corporation utilizes this copper ion technology to control dreissenid mussel infestations in its Oak Creek Power Plant service water system in West Lake, Michigan. The copper ion generator does not eliminate all macrofouling in the service water system, but the level of infestation is acceptable to the plant personnel. The copper ion generator equipment has significant short-comings for use in industrial settings, such as uneven release of copper ions, no built-in feedback loop, and no alarm system for low levels of copper. The discharge of copper ions into the aquatic ecosystem may not be permitted in all jurisdictions.

  Copper sulphate and the copper rich algaecide, Cutrine-Ultra® and EarthTec, have been reported to eliminate adult mussels while being used for algal control in various systems at levels of 30 to 50 µg/L applied for many days (Table 3.1).

Table 3.1 Mortality of adult zebra mussels when exposed to various levels of EarthTec under flow-through conditions.

Treatment (EarthTec) (mg/L)	Treatment (Element) (µg/L)	Mortality After Number of Days (%)				
		6	11	13	19	25
3	150	100				
2	100	100				
1	50	50	100			
0.6	30	15	55	70	80	100

- **Potassium Salts** - Potassium compounds are toxic to most bivalves, including dreissenid mussels and corbiculids. ASI Group Ltd. has been using potassium chloride as an end-of-season treatment for many different systems. They have found that 100 mg/L for a period of five days, on average, at ambient temperatures of 15°C resulted in 100% mortality of dreissenid adult mussels in the system treated (Figure 3.1). The length of treatment increased with decreasing temperatures. It is important to note that the exposure period does not include the time required to charge the system to target concentrations nor does this include the 48-hour latency period required to determine final mortality results.

Potassium chloride (potash), at concentrations of 100 mg/L for an average of 5 days, resulted in 100% mortality of dreissend mussels. Additional time is required to charge the system to target concentrations, plus an assessment period to ensure mortality is achieved.

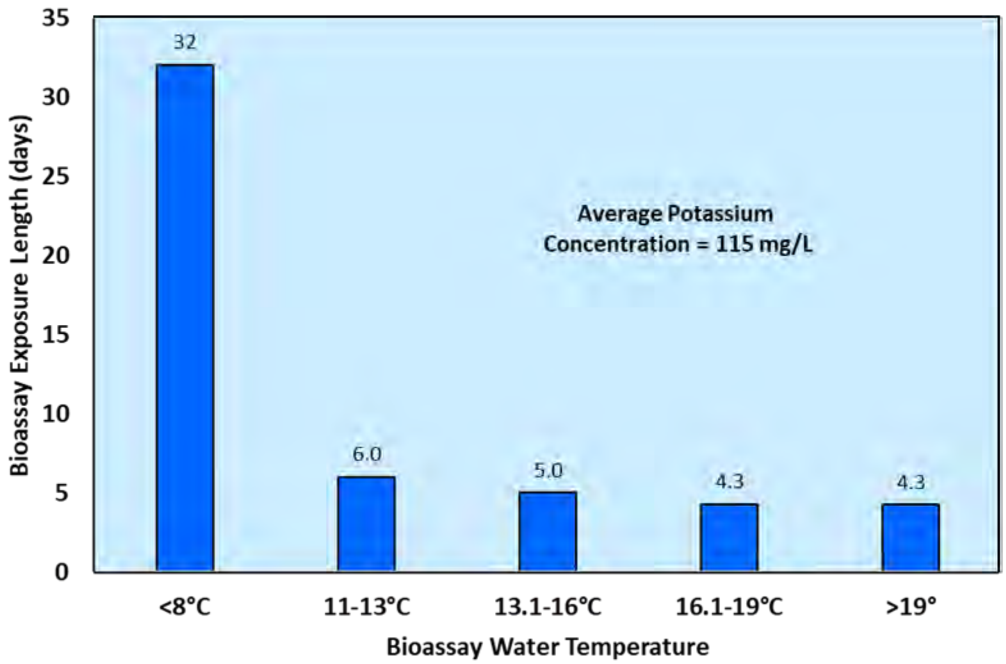


Figure 3.1 Time required to eradicate dreissenid mussels with potassium chloride
Source: personal communication, Dan Butts, ASI Group Ltd., 2017

In 2006, ASI Group Ltd. treated an isolated quarry in Virginia with potassium chloride to eradicate an infestation of zebra mussels (Personal communication, Dan Butts, ASI Group Ltd., 2017). A total of 131,000 kg of 20% potassium chloride solution was used with apparent success. In 2014, ASI Group Ltd. also worked with the Manitoba Government to conduct a successful eradication of zebra mussel in several small harbours on Lake Winnipeg (Personal communication, Dan Butts, ASI Group Ltd., 2017).

Although potassium compounds are nontoxic to higher organisms such as fish, the toxicity to native bivalves may require special procedures before approval for use of potassium salts in once-through systems. In closed loop systems, the use of potassium salts appears to be an attractive option.

Sodium Metabisulfite - Dreissenid mussels are relatively intolerant of low dissolved oxygen concentrations (< 25% of full air saturation levels), that at 20°C is approximately 2.3 mg/L at sea level or 1.8 mg/L at an elevation of 2,133 m. Systems with less than 3 mg/L at 20°C would have little chance of mussels surviving. Dissolved oxygen concentrations exceeding 50% saturation seem to be required for sustained, healthy populations. Depressing the dissolved oxygen level in a system infested by dreissenid mussels could be a form of end-of-season treatment. Several dual intake water treatment plants in Wisconsin have received permission to add either chlorine or sodium bisulphite to the intake they wish to take out of service. The chemical is added just before the intake is capped and kept static for 4 to 10 weeks. At the end of the lay-up period, all zebra mussels will be dead either from the effects of chlorine or from anoxia caused by sodium bisulphite removing all available oxygen.

The use of sodium metabisulfite as a dechlorinating and oxygen stripping agent prompted speculation if this chemical could be used effectively as a treatment for zebra mussels. Sodium metabisulfite by itself is not very toxic to zebra mussels. A minimum concentration of about 177 mg/L of sodium metabisulfite would be required to kill all adult mussels in closed systems. Below this level, toxic effects are absent. Anoxia caused by the addition of sodium metabisulfite will contribute to mussel mortality on prolonged exposure as sodium metabisulfite is an effective oxygen stripper. Depending on facility-specific conditions, anoxic conditions combined with higher water temperatures will increase dreissenid mortality more than the effects of either alone.

Sodium metabisulfite is not considered to be a practically feasible chemical to kill zebra mussels in pipelines or conduits because enormous amounts of the compound are required for treatment where water is renewed continuously. However, it may be practical for use in closed systems, such as fire protection systems, that hold water for long periods of time. The potential for unacceptable growth of sulphate-reducing bacteria should be evaluated before using this method as the bacteria can cause serious corrosion problems in the system.

- **pH Adjustment -** Dreissenid mussels have a range of pH values within which they flourish. Outside those pH range of values, the mussels do not survive for prolonged periods of time. Given the relatively narrow range of pH tolerance, water systems with a pH near the limit for successful survival of dreissenid veligers may be protected if the pH is either depressed below 7.0 or raised above 9.5 at the raw water intake. This could create a hostile environment that would preclude dreissenid settlement. Recent research suggests that, at pH 6.9 or 9.6, new settlement by veligers is essentially prevented, while a pH of 3 or 12 will cause adult mussel mortality in approximately 140 hours.

  The lowering of pH can be particularly useful for drinking water facilities that adjust the pH of the incoming water before processing. If the point of pH adjustment could be moved to the intake of a facility, it would protect all structures and systems. Increasing the pH to 9.6 will not only prevent mussel settlement but it may also inhibit bio-film formation in the system treated. However, if the raw water has a high calcium saturation index, precipitation of calcium carbonate may occur when pH is increased. In such water bodies, high pH treatment is not considered a viable option.

Injection of carbon dioxide, which forms carbonic acid when mixed with water, has been used to reduce the pH of water in municipal water plants. However, carbonic acid is relatively weak, and is not likely capable of reducing the pH of water to less than 5.5. This would not be sufficient to kill dreissenid mussels that remain in pools of water in irrigation district pipelines after dewatering in the fall of the year. Continuous carbon dioxide injection into the pipelines during the operating season would be required to prevent mussels from settling, but would be very expensive.

- **Chemical Cleaning -** Chemical cleaning is an option to be used if small diameter piping or perhaps heat exchangers become plugged by mussels and mechanical cleaning is difficult or impossible at that location. Several products exist on the market, mostly proprietary inorganic acid mixtures (e.g. phosphoric acid mixtures), that will rapidly dissolve mussel shells. The chemicals will often remove accumulated corrosion products as well. The suitability of the pipe material of construction needs to be checked to ensure the pipe will not be degraded beyond acceptable limits. The vendor generally assists in delivering the product in a suitable container. The chemical product is circulated through the piping in a closed loop manner for three to four hours and then removed for recycling by the vendor. The system is then flushed and, if found satisfactory, is returned to service. This is an expedient remedy for small, neglected systems but is not appropriate for large volume systems.

3.4 Non-Chemical Mussel Control

Just as there are proactive and reactive techniques using chemicals, there are proactive and reactive non-chemical strategies for macrofouling control.

3.4.1 Non-Chemical Proactive Techniques

Infiltration Galleries and Sand Filters - Infiltration galleries and sand filters can remove all mollusk stages of growth, and protect all downstream systems and components. An infiltration gallery can be described as a "built-in-place" rapid or slow sand filter. Those designed as rapid sand filters have flow rates of 7 to 15 L/min per 0.1 m^2 of filter area. Others are slow filters, at a rate of 0.15 to 0.3 L/min per 0.1 m^2. Given these projected flow rates, obtaining large amounts of filtered water would require construction of an infiltration area of substantial dimensions. Such an undertaking undoubtedly requires regulatory approval as it takes place in or near a water body and generally involves shoreline alteration. Additional engineering factors must be incorporated into the design process, including raw water quality, proximity to sources of high turbidity, hydraulic considerations, and cleaning method and frequency.

Although infiltration galleries and sand filters offer full system protection, they are not appropriate for existing facilities using large volumes of water. The retrofit required is likely to be very expensive, difficult to implement, and may result in an unacceptable pressure drop to the system. For new intakes, an infiltration gallery could be a viable option. Currently, infiltration galleries are being considered for many water withdrawal applications.

Mechanical Filtration - Mechanical filtration can remove all stages of all mussels if an appropriate screen size and configuration is used. Most conventional industrial strainers have strainer screen openings that will prevent some translocation of mussels and most shell debris from fouling the raw water systems. None, however, will protect against the introduction of larval stage organisms. In most instances, it is not possible to retrofit existing strainers with finer screens and hope for successful mitigation. The performance of such a modified strainer or filter tends to deteriorate, excessive clogging of the screen may result in stretching and tearing of the material, the backwash system may prove to be inadequate, and the pressure drop caused by the strainer may be unacceptable.

Different types of filters, designed primarily for the removal of small particles, have been tested for dreissenid veliger control by a several different organizations. Wedge wire slot filters have difficulty in excluding larval stages of mussels. This is likely because wedge wire type screen filters are designed to remove inorganic matter such as quartz or metal shavings, but they are not designed to stop organic matter from passing through the screen. Organic particles, due to their flexible nature, tend to “sneak through” the wedges of the screen. Excellent results were obtained by Ontario Hydro using a continuous backwash, pleated screen filter and by the New York Power Authority using a modified clean-in-place bag filter to eliminate dreissenid veligers from incoming water.

Hydro-cyclone or centrifugal separators were initially thought to be a mitigation option for facilities that already employ this technology for silt removal. Studies have shown that centrifugal separators removed at most 50% of veligers present.

Many filters are very good at removing all or most particles from the water stream, but most filters are not able to process large volumes of water efficiently. Filters that use stainless steel, square weave mesh and periodic backwash seem to have the best balance between particle removal efficiency and volume of water filtered. Several manufacturers produce such filters and the evaluation process of individual units can be confusing.

Filter Mesh - Some manufacturers do not distinguish between nominal and absolute size of the pores in the mesh they offer. It is important to understand the difference. There are various test methods used to establish the absolute size of pores in woven wire cloths. One such method is the Bubble Point Test. The absolute mesh size rating done using this test corresponds to the diameter of the largest, hard spherical particle that can pass through the filter medium under steady flow conditions. Nominal value, on the other hand, is an arbitrary term generally corresponding to removal of 98% of all incident particles larger than the nominal value given. Various methods are used to determine the nominal rating and the reproducibility using these methods is poor.

Therefore, it is advisable to determine the quality and the absolute mesh size rating the filter manufacturer is offering.

Smythe et al. (1993) reports on the performance of the Kinney Strainer (equipped with a 40, 95, or 142-µm mesh) and the Bromm Filter (nominal mesh size 60 µm and 100 µm). Although the Kinney Strainer (40 nominal µm mesh) and the Bromm Filter (60- µm nominal mesh) reduced the densities of ready-to-settle veligers (>250 µm) in the filtrate by up to 97%, they did not totally exclude all individuals from the system. Examination of the mesh used in each case revealed that the nominal micron ratings were not reliable indicators of the largest opening found in the mesh.

Even great quality wire weave mesh will allow some organic particles greater than the absolute micron size to pass through. This is not surprising given the test protocol uses hard spherical particles to test the mesh openings. Soft or flexible particles of size greater than the absolute mesh pore rating will be able to pass through. During filter trials, it was noted that a 120-micron absolute mesh allowed some veligers of up to 200 µm through. A 57 µm absolute screen passed some veligers of up to 100 µm in size. Although the veligers could pass through the mesh, it was not possible to determine if they were viable and capable of attachment.

To have as much open area as possible in the mesh, the wires used to create the mesh tend to be very thin. This means that unless the mesh is properly supported, the individual pores may be distorted by pressure and the cloth may be torn by the backwash system. Strong support of the screen to prevent distortion and tearing is essential. Three to four layers of "sandwich" is recommended. The various layers should be sintered together for best support and performance.

Filter Construction - Sturdy materials of construction are essential. Plastic parts generally do not stand up to the rigors of industrial application. Excellent sealing between filter components is required to prevent water interchange between filtered and non-filtered water in different chambers.

- **Filter Backwash System** - The more water a filter uses for its backwash, the less there is available for application use. Under normal conditions, 1 to 3% of the total filtered flow is required for backwash. This percentage increases as the TSS load increases. The filter should be capable of backwash cycles that are based on time elapsed and differential pressure across the screen. The greater the differential pressure across the screen, the more likely it is that soft organic material will be forced through. A differential of no more than 20 to 34 kPa is generally recommended.

  In addition to removing all larval stages of mussels, filters remove substantial portions of particulate matter, such as sediment. How much they remove is a question of mesh size and size distribution of the particulate matter in the water column. At one installation, it was estimated that a self-cleaning filter installed on a system carrying 4,000 L/min of water removed more than 10,000 kg of silt each year. Sediment removal results in improved performance and decreased in maintenance for most industrial systems.

Filtration systems are not appropriate for water streams with continuously high sediment load. Under such conditions, the backwash system may not be able to remove the sediment cake that builds up on the screen. Very efficient backwash systems are capable of coping with higher sediment loads. BallastSafe® reported that a filter using a 40-µm screen continued to perform even when incoming water had 250 mg/L of TSS. The filter flushed continuously, with the backwash consuming between 8 to 12% of the total flow water. Since the amount of TSS a filter can cope with is somewhat related to the particle size distribution in the incoming water, a small-scale, site specific trial with the filter being considered is recommended.

- **Filter Field Installation -** Operating experiences suggest that, in critical applications, a backup system (i.e. a parallel arrangement of multiple units) is a must if filtration is to be considered as a viable control measure option. For example, two filters, each capable of filtering 100% of the flow, would represent a guarantee that only filtered water reached downstream systems. If some ingress of unfiltered water can be tolerated, a system by-pass may be installed to guarantee uninterrupted supply of water in case of filter upset.

  To monitor the performance of the filter, at least one manufacturer suggests installing a small fixed filter screen downstream of the self-cleaning filter. The fixed screen should be the same or a slightly larger pore size than that used in the self-cleaning filter. If this fixed screen becomes plugged, it is an alert that the self-cleaning filter is passing particles larger than the rating would suggest.

  In the United States, the State of Vermont has successfully used a series of Amiad® automatic backwashing filters for zebra mussel control at the Edgar Weed Fish Culture Station facility since 1996. At this installation, due to the line pressure required by the filtration unit, the filter had to be located downstream from the pump. This requirement means that the intake piping must be mechanically cleaned periodically using a “pigging” unit, and that the pump itself must be allowed to dry out biannually to allow for mussel desiccation and elimination.

  In the fall of 1999, a full-scale filter experiment was set up at the Nanticoke Thermal Generating Station by Ontario Power Generation. The self-cleaning filter, equipped with a 40-µm absolute woven mesh, was installed downstream of a self-cleaning wedge wire strainer with an approximately 3-mm gap. The designed filter capacity was 0.76 m^3/s, but the system rarely required more than 0.38 m^3/s. Typically, backwashing cycles were triggered about once every hour. During a backwash cycle, the water flow would decrease to about 0.28 m^3/s, which represents a drop of about 15 to A 20%. The design specifications required that a minimum 207 kPa differential across the cleaning nozzles be available for the system to work effectively. This had to be increased to about 310 to345 kPa for the filter to cope with the incoming sediment load. The system generally ran well when TSS was 15 mg/L or less. The filter could handle a TSS loading of 60 to 80 mg/L, but it had to backwash almost continuously. It was concluded that the system would be unable to cope when the TSS exceeded 80 mg/L.

In terms of efficacy, defined as the difference between veligers entering the system and those passing through the filter (dead or alive), the filter achieved between 95.9% and 100% veliger removal. In all instances where veligers did pass through the filter screen, they were dead. The downstream bio-box sampler was free of any adult settlement at the end of the experiment, while the bio-box placed just ahead of the filter had hundreds of large mussels settled on walls and sampling plates.

Recent advances in filtration technology have allowed several manufacturers to design filters capable of removing all particles greater than 25 µm from relatively large streams of water. These filters are designed to minimize pressure drop in the system and have corrected many of the problems encountered in the above described installation. Several of these filters are currently being tested as part of ballast water treatment systems.

Filter construction for mussel exclusion should recognize that the shape of mussels is somewhat like a flat disc. In addition, at the age where they are ready-to-settle their shell still has some limited flexibility allowing them to be flattened beyond their normal thickness without harm. Therefore, wedge wire filters are not effective at excluding mussels. The recommended filter basket material is woven wire square mesh designs. Figure 3.2 depicts a suitable commercial mesh for mussel exclusion.

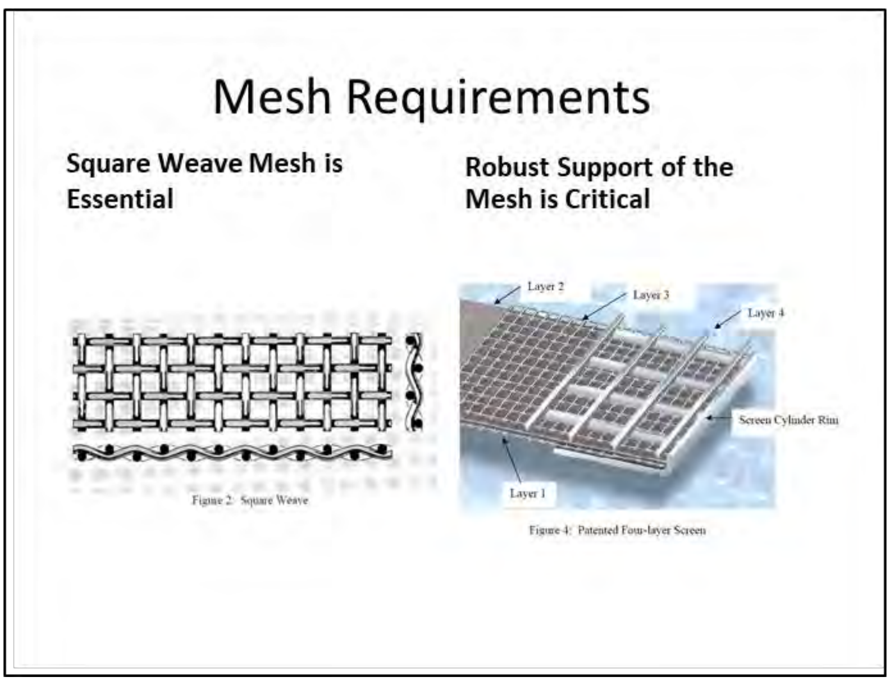


Figure 3.2 Recommended filter screen construction for mussel exclusion

3.4.2 Ultraviolet Light

The use of ultraviolet (UV) radiation is appropriate for larval stages of mussels, which have transparent shells. The term ultraviolet is applied to electromagnetic radiation emitted from the region of the spectrum between visible light and x-ray wavelengths. The UV light ranges between 190 to 400 nm and has been subdivided into UVA, UVB, and UVC. Based on work by numerous authors in the early 1990s, UVB and UVC wavelengths were found to be most effective for dreissenid veliger control. The basis for the control is thought to be the effect of the UV light on the essential functions of the veliger, inactivating the organism and preventing attachment. The most effective wavelength and the radiation dose (Dose = intensity x residence time) that the veliger must receive to experience either immediate or latent mortality have been the subject of numerous experiments.

A full-sized pilot UV system was installed at a power plant on Lake Huron in 1999. Twenty medium pressure lamps were arranged in four frames each containing five lamps. The treated flow was 0.76 m^3/s. The system was sized to deliver a radiation dose of 0.07 to 0.1 Watt-seconds per square centimeter (W-s/cm^2) to all particles passing through. This UV system was the only means of protection for the power plant cooling system. During the operation of the UV system, lamps had to be serviced, the system experienced numerous upsets, and occasionally, it was even taken out of service accidentally. Despite these challenges, there was an 85% reduction in settlement in the system when compared to the control.

The effectiveness of a UV system is dependent on the characteristics of the raw water being treated. Factors such as water transmittance, presence and size of suspended solids, iron, hardness, and temperature all affect the efficacy of the UV system. Treatment systems must be designed for the worst-case scenarios. This means designing for peak flows, end of lamp life intensity, minimum transmittance, and maximum suspended solids at the installation location. The aim of the system is to achieve 100% immediate or latent mortality in all ready-to-settle veligers that pass through. If an adequate dose is not delivered at this point, downstream settlement will occur as UV based systems have no residual toxicity that could affect areas outside the influence of the lamps.

In 2012 Atlantium Technologies sponsored an evaluation of Atlantium medium pressure UV system as preventative treatment for the settlement of quagga mussel veligers. This study was carried out on the lower Colorado River. Four separate experiments, each one with UV dosage levels between 80 and 200 mW/cm^2/s, were carried out. Each level provided settlement inhibition in excess of 95%.

In 2013, Davis Dam installed a full sized medium pressure UV system from Atlantium Technologies to protect all cooling water (total flow of 0.224 m^3/s) on a key power generating unit. Davis Dam management agreed to allow the UV system to be adjusted to deliver various levels of UV irradiation. This in turn allowed for second evaluation of downstream quagga veliger settlement after exposure to various UV treatments using an actual industrial installation. It was found that for complete elimination of all settlement, UV doses from 100 to 120 mW/cm^2/s are recommended.

3.4.3 Anti-Fouling and Foul Release Coatings

Most of the developmental work in anti-fouling paints/coatings has been directed towards prevention of barnacle growth on ships. In fresh water, anti-fouling coatings' primary use has been for the prevention of mussel attachment to structures exposed to raw lake water. Coatings do not offer any protection to the rest of a facility and therefore must be combined with other mitigation strategies. For new facilities, appropriate selection of materials of construction may minimize the need for coatings. The following is a general substrate preference by mussels when using settling plates: copper < galvanized iron < aluminum < acrylic < PVS < teflon < vinyl < pressure treated wood < black steel < pine < polypropylene < asbestos < stainless steel. For pipes, the preference for mussel attachment is as follows: copper < brass < galvanized iron < aluminum < acrylic < black steel < polyethylene < PVC < ABS. Pipes oriented horizontally had significantly greater settlement than vertical pipes, and rough surfaces were more heavily colonized than smooth. The strength of attachment of zebra mussels also varies with substrates. Within the substrate, the strength of attachment increases with surface roughness. Strongest attachment is to limestone and mild steel of all roughness. Attachment strength is intermediate on marine concrete, polyvinyl chloride, stainless steel, and coal tar epoxy coated mild steel. Smooth polytetrafluoroethylene, polymethylmethacrylate, and aluminum have the weakest attachment. However, most facilities must deal with existing structures, and coatings present one of the best methods for minimizing the fouling on external surfaces.

The trend is toward the use of environmentally benign foul release coatings that form a physical barrier to attachment. The most promising coatings now are nontoxic silicone-based paints that prevent or greatly decrease the strength of attachment. Silicone-based coatings applied to the pump well wall at a nuclear power plant were found to be effective at minimizing mussel settlement for almost 10 years. The silicone based coatings usually require several different layers to be applied to a perfectly clean, white metal surface or very clean, almost dry (10% or less moisture level) concrete. This tends to make them very costly ($80 to $\$100/m^2$). In addition, the foul release coatings tend to perform better in areas of high or moderate flow, rather than in quiescent areas.

The best performing coatings were those developed by Fuji Film Company, and Intersleek (manufactured by International Paints).

Vendors with known successful anti-fouling coatings include:

- CPM Coatings/Chugoku Paint (Boolean-Si);
- Kansai Paint (Bio Si);
- International Paints (Intersleek);
- GE Coatings (Exile); and
- Fuji Film Smart Surfaces.

The United States Bureau of Reclamation (USBR) has a coatings research program that has evaluated many of the same coatings and has published the summary report from a six-year study (USBR, 2014). When considering which coating to choose to protect external structures of a facility, consider the cost of coatings and the problems associated with the application (e.g. – sandblasting of surfaces, exposure of personnel to toxic fumes, problems of keeping large areas dewatered, etc.) with that of mechanical cleaning and the disposal of mussel debris on a regular basis. If, after this evaluation, application of a coating is still the appropriate strategy, carefully examine the data provided by the vendor. Make sure that the coating has been successfully used in an industrial environment for at least three years and has shown a capability to prevent settlement of mussels. Furthermore, make sure that no toxic substances are likely to either leach from this coating or be released into the environment when the "top-coat" of the coating is "reactivated" (i.e. abraded to expose fresh coating). Check with the local regulatory agency as to any possible constraints on the use of any product.

3.4.4 Speed of Flow

When the speed of flow in a raw water system continuously exceeds 1.5 m/s, there is minimal, if any, veliger settlement observed. However, very few systems are designed for such fast flow ,and it would involve a major expense to redesign existing systems. In fact, intake structures are frequently designed to maintain the slowest possible flow to prevent entrainment of fish. If the speed of flow periodically drops less than 1.5 m/s, mussel attachment will occur, and the attached mussels will not be removed when flow increases again.

3.5 Non-Chemical Reactive Techniques

Thermal Shock - Hot water has proven very effective in killing mussels. Thermal backwash appears feasible for some facilities and systems as an end-of-season or periodic treatment. The temperature and duration of the treatment can be combined in different ways. A temperature of 32°C for 48 hours has caused 100% mortality in dreissenid mussels, as has 40°C for one hour. Between these temperatures is a grey area where the exact temperature and time to death is dependent on several factors, including the acclimation temperature of the mussels (Table 3.2). The lower the acclimation temperature, the more susceptible the mussels are. A second factor is the rate of temperature increase. If the rate of increase is very gradual, the mussels may acclimate during the process and survive for a longer period than anticipated. The last factor is the possible genetic variation in local populations. It is possible that zebra mussels from a geographic area may

Table 3.2 Resistance time (minutes) for 100% mussel mortality in relation to temperature.

Temperature	Acclimation Temperature			
	5°C	10°C	20°C	25°C
34°C	419	396	687	-
35°C	243	231	271	525
36°C	209	107	202	261
37°C	116	52	126	153
38°C	-	-	66	78

Source: Personal communication, Renata Claudi, RNT Consulting Inc.

be more temperature tolerant than mussels from another geographic area.

There are problems associated with using thermal shock for mussel control. Regulations governing discharge of heated water must be considered. Facilities that do not already possess the capability to recirculate hot water are likely to be unable to retrofit to do so, and will only be able to apply thermal shock in small systems using an external heat source such as a steam generator. In addition, manual cleaning of components may be required after a thermal treatment to clear away accumulated dead mussels and shells. Nevertheless, several facilities have used this method of treatment and achieved good results. Commonwealth Edison heat treated one of its plants by raising the water temperature from 31.6 to 37.2°C in 10 hours. They maintained this temperature for six hours, resulting in 100% mussel mortality. Plants in Italy, France, and Spain have also used thermal treatments for mussel control. Most regulatory authorities regard heat treatment as a more environmentally safe and benign method than chemical treatment.

Desiccation - Desiccation involves draining systems and subjecting the mussels to drying. Unless the process is speeded up using hot-air circulating in the pipes, a prolonged dewatering may be required. Adult dreissenid mussels can survive considerably more than 10 days in a cool (<15°C), moist environment. At 25°C, zebra mussels can survive for less than 150 hours regardless of relative humidity. At 35°C, death occurs in less than 40 hours particularly at high relative humidity. It appears that the inability of mussels to cool tissues through evaporation at high relative humidity accelerates mortality rates rather than the actual loss of water from the tissues (Figure 3.3).

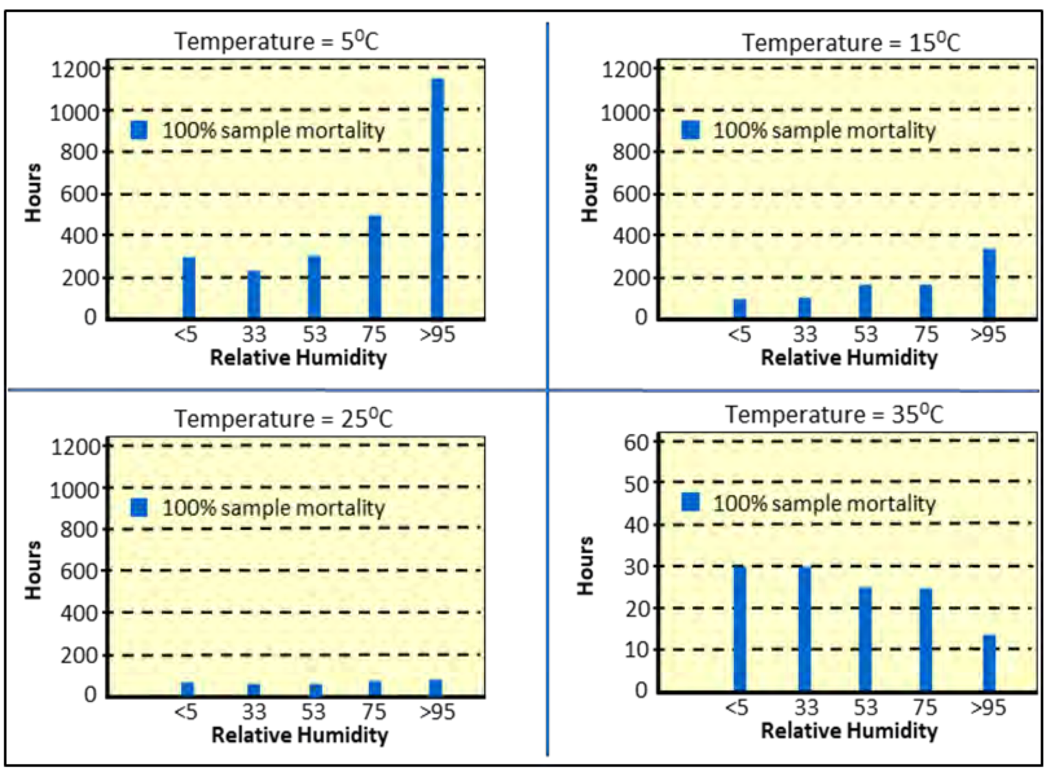


Figure 3.3 Effect of temperature and relative humidity on adult zebra mussels
Derived from Clarke and McMahon (1993)

Freezing - When mussels are exposed to freezing temperatures after dewatering, mortality may occur more quickly than when they are exposed to high temperatures. Figure 3.4 (Clarke and McMahon, 1993) illustrates the time to death of individual and clustered mussels exposed to several different sub-zero temperatures. Clustered mussels survived freezing approximately twice as long as separated mussels, and the time to death decreased exponentially with decreased exposure at temperatures less than -30^{o}C. This indicates that dewatering structures during low ambient temperatures is a viable and expedient way to control mussels.

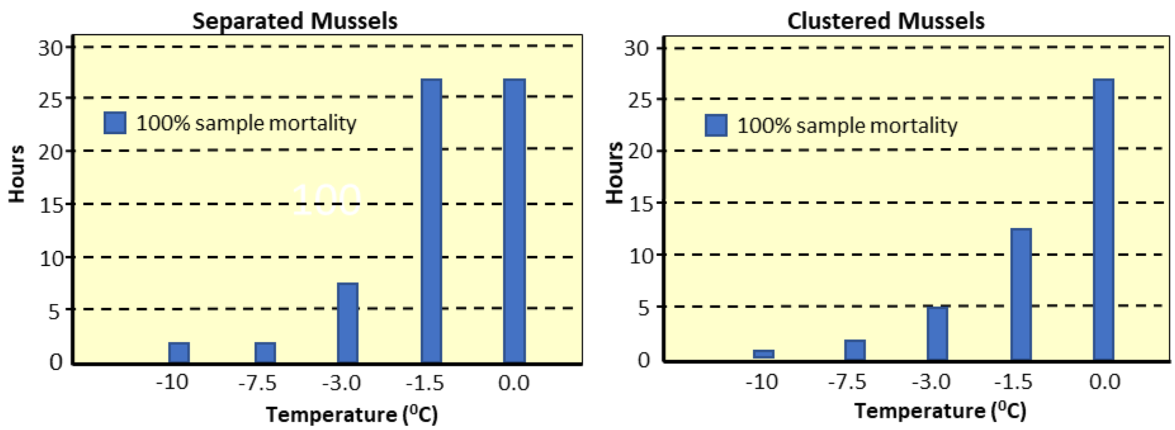


Figure 3.4 Freeze survival of separated and clustered mussels
Source: Clarke and McMahon (1993)

Oxygen Deprivation - Oxygen deprivation could be accomplished by adding an oxygen scavenging chemical into a closed system or by keeping a system such as a pipeline static for sufficient time. Mortality due to lack of oxygen occurs faster at higher temperatures (Table 3.3).

Table 3.3 Approximate number of days to 100% mortality for zebra mussels at different oxygen and temperature levels.

O_2 Partial Pressure (Torr)*	O_2 Saturation (%)	Temperature (°C)		
		5°C	15°C	25°C
7.9	5	x**	70	12
11.9	7.5		x	15
15.9	10		x	19
23.8	15	x	x	x

* Torr = a unit of pressure (1 torr = 133.32 pascals).
**x = mortality was observed but 100% mortality was not reached in the experimental time frame.

For facilities that have two intakes but only need to use one, oxygen deprivation could be an efficient method of control. One intake is capped until the other one is fouled and then the two are switched. The treatment would work best at high ambient water temperatures. A word of caution is given here; lack of oxygen frequently results in a dramatic increase of sulphate reducing bacteria, that in turn are responsible for some microbially-induced corrosion. Limiting the amount of oxygen in a system may exacerbate corrosion problems.

Mechanical Cleaning - Accumulated zebra mussel populations can be removed from all external structures and some large diameter piping by a variety of manual methods. This provides a short-term solution that must be repeated at regular intervals. New tools for mechanical cleaning are being introduced at such frequent intervals that it is impossible to mention them all. To date, all mussels removed by all types of mechanical cleaning have been disposed of in regular landfill sites or composted at site. Several tests done on these mussels did not uncover any high concentrations of toxic materials that would have forced disposal at a hazardous waste site.

- **Mechanical Cleaning of Large Diameter Pipes -** Mechanical "pigs" or scrubbers have been used effectively to knock and scrape mussels and other debris from large-bore pipelines. Pigs are available in a wide variety of designs and they are manufactured to clean pipes up to 1.8 m in diameter.

  The pipeline is unavailable during cleaning, and the disposal of mussels dislodged can cause a problem. Drinking water plant intakes are particularly suitable for this method. However, several have expressed concern that their structures may not be able to withstand the pressure generated by the mechanical pig on the pipeline.

- **Underwater Cleaning Using Divers -** Due to operational requirements, Ontario Hydro has concentrated on developing an efficient and economic strategy for underwater cleaning. Several different diver-operated tools and techniques were tested during the summer and fall of 1990 on a variety of infested surfaces. A continuous flow, 15-cm hydraulic pump reduced to 7.6 cm, with a flow velocity of 45 L/s and equipped with two scraper assemblies (two diver operation), was found to be the best available option for the cleaning of vertical walls. Power wash was used on the pump bells with some success, but a more efficient technique is needed. New diver-operated tools are being introduced. This, as well as the development of remotely-operated tools, could make mechanical cleaning a more viable option for pipelines and external structures.

- **High and Low-Pressure Water Cleaning -** Hydro-blasting, or hydro-lasing, has been used to remove corrosion products, unwanted coatings, and biofouling. The area to be cleaned is generally dewatered and then cleaned with a jet of water. It is advisable to proceed with cleaning as soon as the structure is dewatered. If the mussels are allowed to die in place, the cleaning crew can face very unpleasant working conditions.

  At Detroit Edison, a jet at 20,684 kPa was adequate to remove a thick build-up of mussels on the concrete wall of the pump well. A variety of nozzle and hose configurations are possible as is a combination of pressure and volume. The choice will depend on the personal preference of the user, since the integrity of the surface being cleaned must be preserved, and it is desirable to remove as much of the byssal thread and byssal pad as possible.

In 2008, the USBR initiated a demonstration project on the use of water jetting for removal of mussels from an underwater intake pipeline. A water jetting nozzle delivering a water stream at 68,950 kPa was inserted into a 25-cm diameter pipe which was more than 30 m long. The pipe was heavily fouled by adult quagga mussels. The water jet could remove the majority of the fouling and restore the pipe to fully operational conditions.

- **Barriers or Biobullets -** Curtains or barriers to contain chemical treatment in a local area or using biobullets to localize delivery with chemical treatment (e.g. potassium chloride) have been considered to control a mussel population.

- **Reservoir Drawdown -** There have been some successful reductions in population size by drawing down the level of a lake or reservoir. If such a drawdown was to occur, it would be important to remove any buoys, floating docks, and watercraft from the lake to make sure that there was no seed population of mussels remaining on such structures until the drawdown was completed. Analyzing dissolved oxygen levels throughout the year at different depths and modelling oxygen behaviour during a major drawdown event are important factors to evaluate the potential success of this method.

- **Boat Inspections -** Recreational boaters have been identified as the primary cause of overland dispersal of zebra mussels, so addressing this route of dispersal is essential. Boater education, boat inspections, and acquisition and use of boat washing equipment have been shown to be essential actions in many jurisdictions to prevent the spread of dreissenid mussels.

4 Distribution of Dreissenid Mussels in North America

Dreissenid mussels (zebra and quagga) arrived in the eastern United States and Canada from Europe in the 1980s, and quickly spread to many waterways, rivers, and lakes on the eastern portion of the continent. Since 2007, quagga mussels have been present in the lower Colorado River. Adult zebra mussels were found at San Justo Reservoir in California in 2008. In addition to Arizona, California and Nevada, dreissenid mussels are present in Texas, Kansas, Nebraska, and Oklahoma and have been detected in New Mexico, Utah, and Manitoba. There was concern that mussels had been discovered in the Tiber Reservoir (Montana) in November 2016. However, further investigations carried out in August 2017 found no evidence of mussels. Figure 4.1 shows the current extent of dreissenid mussels in the United States and Canada. The United States Geological Survey website (USGS, 2017) shows the annual progression of zebra and quagga mussels across the United States and Canada (https://nas.er.usgs.gov/queries/SpeciesAnimatedMap.aspx?speciesID=5).

4.1 Habitat

Dreissenid mussels are epifaunal, meaning they live upon or on top of all types of solid substrates, including rocks, floating logs, break-walls, pipelines, cooling water systems, wet

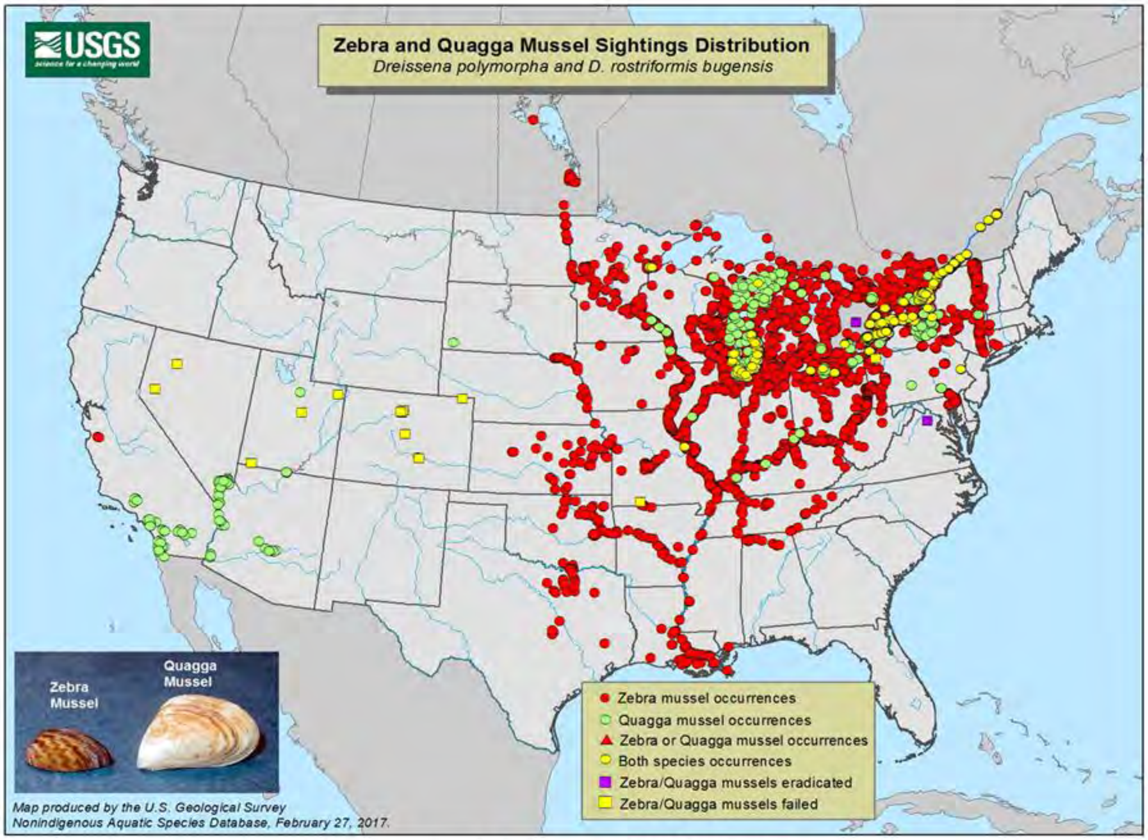


Figure 4.1 Zebra and quagga mussel sightings distribution map

wells, intake structures, hulls of boats and large living invertebrates such as crayfish. Dreissenid mussels are found at varying depths. Quagga mussels have been found as deep as 120 m in Lake Ontario. They tend to be most numerous in the zone below ice formation and above the thermocline (1 to 10 m). Densities of up to 100,000/m^2 have been recorded in many infested areas.

Young dreissenid mussels will settle in internal piping where the water flow is slow (less than 1.5 m/s), allowing for easy attachment. When they first settle they increase the coefficient of friction within most pipes, often causing a decrease in head pressure. Further settlement and growth will result in a decreased supply of water to vital areas, obstruction of valves, and loss of heat exchange efficiency. If mussels are allowed to infest a system and are then eliminated, many byssal threads are left behind; up to 500 per mussel. These byssal threads can continue to disturb the flow of water through pipelines. Byssal threads can also affect iron and steel pipelines by increasing corrosion rates under areas of attachment. Bacteria thrive underneath the mussel colonies and anaerobic respiration produces acidic compounds, which can accelerate corrosion and pitting of pipelines.

Dreissenid mussels will attach to any non-toxic hard surface. They also attach to each other, that creates large clump-like colonies. These clumps can break off and cause downstream plugging of small components. Though dreissenid mussels have a distinct set of environmental preferences, they can survive in many subpar conditions, often successfully facing starvation, desiccation, extreme variances in temperature and variable oxygen levels. They can survive in static lakes and reservoirs and in the fast currents of pipelines, in nutrient poor and nutrient rich lakes. Though a freshwater species, they can survive for some time in brackish areas, and can tolerate a certain degree of pollution. If intolerable conditions are present, mussels can close their shells for up to two weeks before reopening.

If intolerable conditions are present, mussels can close their shells for up to two weeks before reopening.

In most areas, dreissenid mussels extend their range at a rate of approximately 250 km/yr. This may be accomplished by veligers being carried by currents, or by adults becoming attached to floating vegetation or wood. The primary means of reaching unconnected bodies of water is with human assistance, on the hulls of ships or boats, in ballast water, or bait buckets of sport fishermen.

4.2 Alteration of Freshwater Ecosystem

If mussels were placed in water polluted with activated sewage sludge, water clarity would be restored within 96 hours. Nearly all suspended organic material would be processed and deposited on the bottom as pseudofeces. Because dreissenid mussels prefer relatively shallow near-shore areas as habitat, it's likely that they assimilate pollutants such as PCB, pesticides, herbicides, chromium, lead and mercury.

Dreissenid mussels have a great ability to clarify water, and this is a benefit and a concern for their ecosystem. The benefits are outlined in the example shown in the text box. Dreissenid mussels' ability to filter water may not always work in favour of the ecosystem and the life it supports. Dreissenid mussels remove suspended particles from the water column and deposit them into sediment. This action makes nutrients available to the benthic species on the freshwater floor leaving less food material for the planktonic species. The increased clarity of water also means that the euphotic zone (water that the sunlight can reach) will increase, and this may stimulate the growth of rooted aquatic weeds in areas that were previously too shady. These changes in habitat may have severe effects on many freshwater species, and on commercial and sport fisheries.

5 Vulnerability Assessment of Dreissenid Mussel Infestation for Alberta's Irrigation Districts

5.1 Growth and Survivability Factors

The success of an infestation of dreissenid mussels depends on the quality of water and the health of the receiving ecosystem. The quality of water in a storage reservoir depends in part on the chemistry of the water supply. Every reservoir has its own watershed, and the chemistry of the soil and bedrock in the watershed will largely, but not entirely, dictate the chemistry of the water flowing through it. The chemistry may change with time, depending on factors such as type and amount of bedrock, climate, weathering processes, and anthropologic inputs from agriculture, industry and municipal developments. The success of an infestation also depends on the physiological and ecological requirements, and tolerances of the species. Table 5.1 summarizes the criteria to determine infestation levels of dreissenid mussels, and the criteria was derived from the values reported by various authors in North America and Europe. Calcium and pH are considered the two key factors as predictors of dreissenid mussel development and survival in water systems (Claudi and Prescott, 2011).

Table 5.1 Survival and development criteria for dreissenid mussels.

Parameter	Adults: No Long-term Survival	Veligers: Uncertainty of Survival	Moderate Infestation Level	High Infestation Level
Calcium (mg/L)	**<8 - <10**	**<15**	**16 - 24**	**≥24**
Alkalinity (mg CaCO3/L)	< 30	30 - 55	45 - 100	>90
Total hardness (mg CaCO3/L)	<30	30 - 55	45-100	≥90
pH	**<7.0 or >9.5**	**7.1 - 7.5 or 9.0 - 9.5**	**7.5 - 8.0 or 8.8 - 9.0**	**8.2 - 8.8**
Mean summer temperature (°C)	<17	17 - 20 or >29	20 - 22 or 25 - 28	22 - 24
Dissolved oxygen mg/L (% saturation)	<3 (25)	5 - 7 (25-50)	7 - 8 (50-75)	≥8 (>75)
Conductivity (µS/cm)	<30	<30 - 60	60 - 110	≥100
Salinity (mg/L)	>10	8 - 10	5 - 10	<5
Secchi depth (m)	<0.1 >8	0.1 - 0.2 or >2.5	0.2 - 0.4	0.4 - 2.5
Chlorophyll a (µg/L)	<2.5 or >25	2.0 - 2.5 or 20-25	8 - 20	2.5 - 8
Total phosphorous (µg/L)	<5 or >50	5 - 10 or 30 - 50	15 - 25	25 - 35

Source: Claudi and Prescott, 2011.

- **Calcium -** Dreissenid mussels need calcium to build their shells, and is considered the most essential environmental constituent when assessing the likelihood of long-term mussel survival. The larval forms of dreissenid mussels (veligers) require higher levels of calcium to develop than is required by adult mussels for survival. Adult mussels, if introduced into a body of water with low calcium, may survive for some time, but the population may fail to reproduce and therefore will be eliminated with time.

Calcium and pH are considered the two key factors for dreissenid mussel development and survival in water. Calcium and pH values in the irrigation district water supply systems will support the growth and development of dreissenid mussels.

- **pH -** Water with a pH greater than 7.5 is generally required for veliger development. A pH of 7.5 is usually given as the lower limit for long-term veliger survival. Higher values, up to a pH of 9.0, are suitable for mussel development and survival.
- **Temperature -** Temperature is also an important variable that determines the length of the reproductive season and the rate of growth of adults (Figure 5.1). The release of eggs and sperm, and subsequent fertilization in the dreissenid mussel population occurs when the ambient water temperature reaches 12 to 15°C. Reproduction ceases when the water temperature is less than 12°C, but veligers usually continue to be present in the water column for about three weeks after reproduction stops. After three weeks in the plankton, veligers generally lose their ability to swim, develop a foot and leave the water column to settle and attach to substrate.

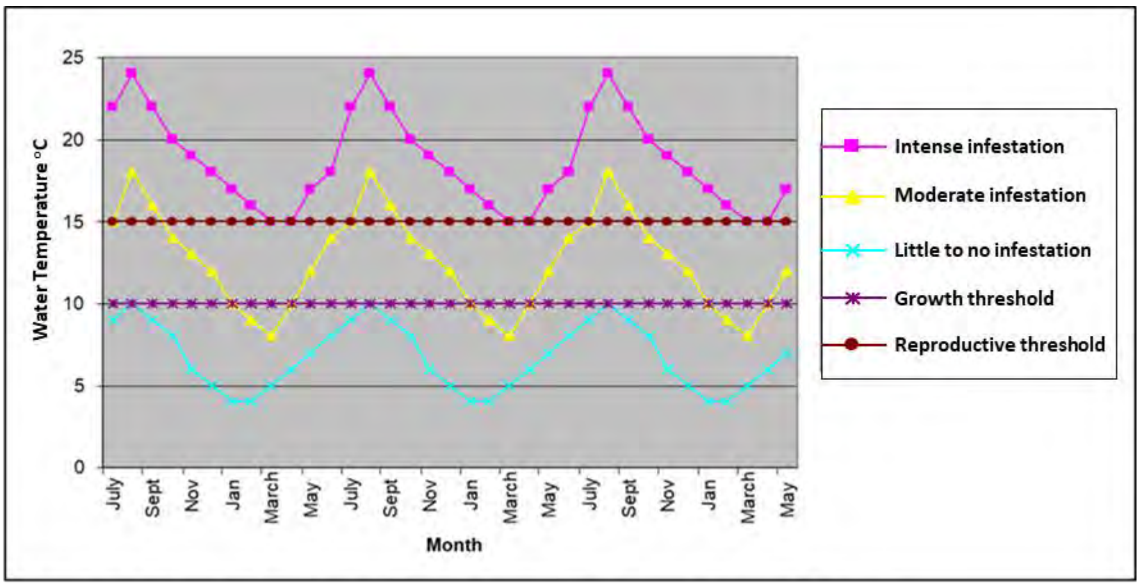


Figure 5.1 Effects of water temperature on dreissenid mussel development

- **Substrate -** To settle, survive and grow into adults each mussel larva must land on firm substrate. The settlement stage is when larvae experience major mortality.
- **Dissolved Oxygen -** During this settlement stage, if the dissolved oxygen levels near the bottom are from 3 to 4 mg/L, the pediveligers are unlikely to survive and develop into adults.
- **Chlorophyll a -** Chlorophyll a is used as an indicator of the presence of green algae that is considered the primary food source for dreissenid mussels. Levels of chlorophyll a from 2.5 to 8 µg/L are considered optimum. Concentrations of chlorophyll a lower than these values may represent inadequate food supply to support adult dreissenid population. Concentrations greater than 25 µg/L may signify an algal bloom and high turbidity that in turn may interfere with veliger survival in the water column.

- **Turbidity -** While further research is required to determine the upper turbidity limit for dreissenid mussels, there is some documented evidence that high turbidity/TSS can negatively affect metabolic function of dreissenid mussels (Madon et.al., 1998), and that high turbidity/TSS can have a negative effect on pumping rates of individual mussels (Garton et.al., 2014). Madon et.al. (1998) reported that suspended inorganic sediment more than 1 mg/L greatly reduced the ability of adult zebra mussels to feed. Alexander et al. (1994) concluded that periodic turbidity between 10 and 20 nephelometric turbidity units (NTU) affects the metabolic rate of zebra mussels, particularly at high ambient temperatures (25°C). The Missouri River, with turbidity swings from 10 to 1,000 NTU (average levels between 25 to 54 NTUs) has remained essentially free of dreissenid mussel infestation to date. The effect of turbidity on adult mussels varies considerably with particle size, organic vs. inorganic composition of the TSS and temperature. The effect of turbidity on survival of dreissenid veligers is unknown, but likely to be even more profound than the effect on adults.

5.2 General Vulnerability Assessment of Irrigation Districts

A water quality monitoring program was implemented within Alberta's 13 irrigation districts by AAF from 2006 to 2007 and from 2011 to 2016 (Little et al., 2010; Charest et al., 2015; AAF, 2017a). Approximately 90 sites, including source water supply sites, secondary source sites (representing water supply sites for on-farm irrigation), and return flow sites, were sampled from June to September each year (Figure 5.2). The database for this monitoring program included parameters related to mussel growth and development.

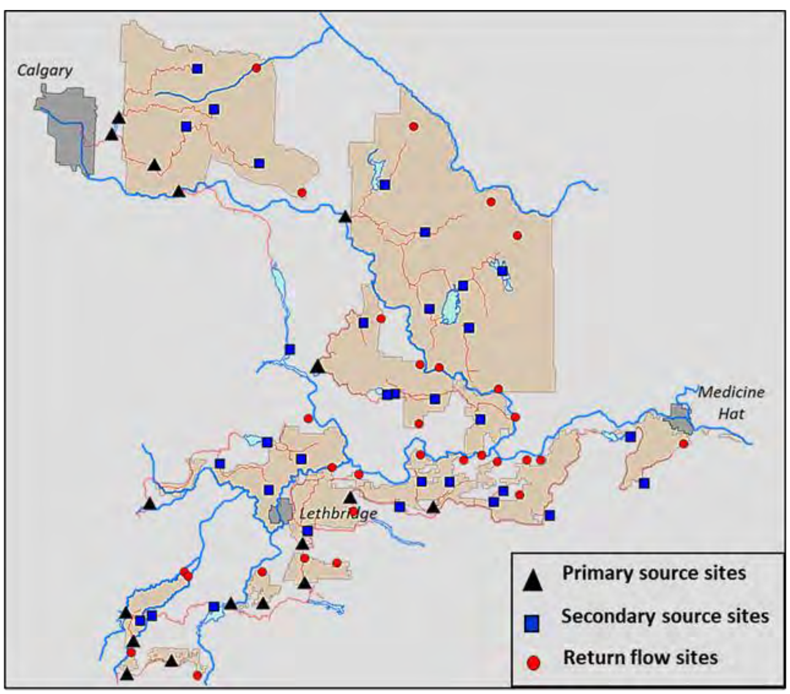


Figure 5.2 Sampling locations for water quality monitoring program
Source: Water Quality Section, Alberta Agriculture and Forestry

With few exceptions, the irrigation water supply reservoirs and irrigation district water supply systems contain adequate calcium (>20mg/L) to support the development of dreissenid mussels. The pH (7.6 to 9.3) is also in a range conducive to mussel infestation, and there is sufficient dissolved oxygen to support adult mussels (>4 mg/L). The limited chlorophyll a data is variable, but appears to be adequate to sustain mussel development.

Median turbidity (NTU) levels for rivers in the South Saskatchewan River basin are generally quite low, and are not expected to be an impediment for dreissenid mussel growth and development. For example, the median open water turbidity (NTU) for the Bow River at Cochrane is about 4.0, and at Cluny is about 8.0 (AEP, 2014).

Alberta Environment and Parks periodically monitored the water quality at several depths for many irrigation water supply reservoirs from 1983 to 2016. Ambient water temperature profiles indicate that mussel reproduction will take place mainly in the shallower parts of the irrigation water supply reservoirs. Figures 5.3, 5.4, and 5.5 show the water temperature profiles for the Waterton, St. Mary, and Oldman reservoirs in 2015, which are key upstream GoA-owned irrigation water supply reservoirs. Generally, water temperature in the summer months are conducive for mussel reproduction and development. However, the length of the reproductive season is likely to be relatively short as water temperatures are cool in the spring and fall seasons.

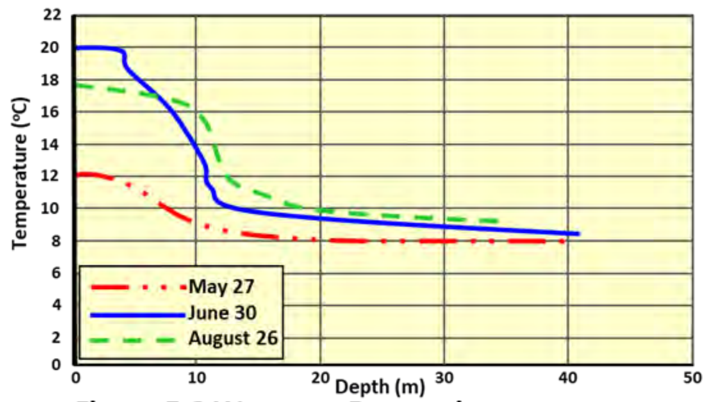


Figure 5.3 Waterton Reservoir: water temperature profiles (2015)

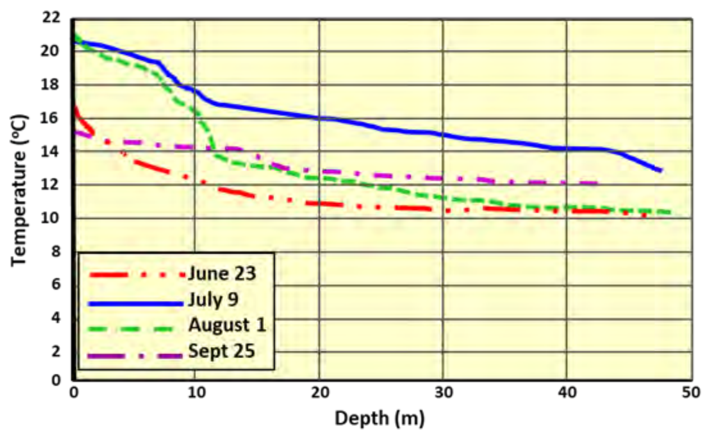


Figure 5.4 St. Mary Reservoir: water temperature profiles (2015)

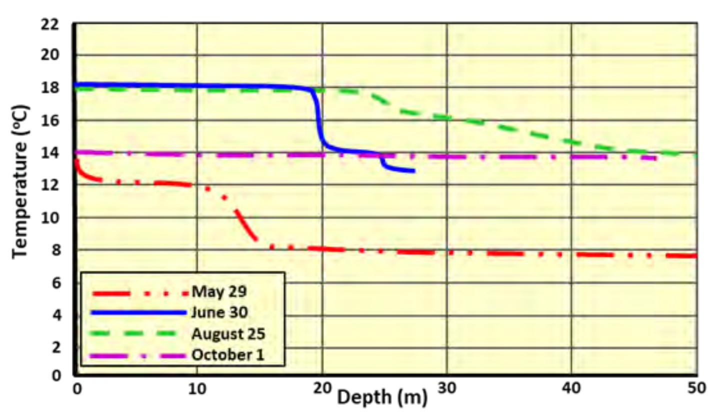


Figure 5.5 Oldman Reservoir: water temperature profiles (2015)

The growth of individual mussels is based on the quality and quantity of the food supply, and the ambient water temperature. The quantity and quality of the food supply is somewhat uncertain in most reservoirs, and the ambient water temperature rarely exceeds 25°C. The combination of uncertain food supply and relatively low ambient temperature suggest that the rate of growth would be relatively slow. A two-year study on the Great Lakes indicated a growth rate of 1 to 1.5 mm/mo (Personal communication, Renata Claudi, RNT Consulting Inc.). It is expected that growth rates in Alberta would follow a similar pattern.

Research studies have shown that sufficient levels of potassium in the water can prevent or eradicate mussels. Imlay (1973) found that >10 mg/L of potassium in the water will prevent the long-term viability of most fresh water mussels. Lewis et al. (1997) found that chronic exposure of adult and larval zebra mussels in water with potassium concentrations of 20 mg/L caused 100% mortality in 52 days, and prevented settlement. Within Alberta's irrigation districts, potassium concentration in the distribution systems for 12 of the 13 irrigation districts averages about 2.6 mg/L, which is much lower than the levels required to prevent establishment or eradication of the mussels.

Potassium concentration in the water originating from Cavan Lake averages about 21 mg/L, which should be sufficient to prevent establishment of dreissenid mussels in the RCID irrigation distribution system.

The Ross Creek Irrigation District (RCID) is the exception. Potassium concentration in the water originating from Cavan Lake was consistently greater than 20 mg/L from 2012 to 2015, and the average potassium concentration is about 21 mg/L. These levels of potassium should be sufficient to prevent the establishment of dreissenid mussels in the irrigation distribution system.

An ongoing water quality monitoring program by AEP also found elevated potassium concentrations in three other reservoirs, including Bullshead Creek, Forty Mile Coulee, and Twin Valley. However, potassium was measured only sporadically, and the high potassium levels were not consistently found. As a result, it cannot be determined if potassium in these reservoirs would potentially affect dreissenid mussel development. If an adult mussel or veliger is found in a reservoir, the first priority is to limit further spread to other water bodies by:

- Implementing a quarantine on all boats leaving the infested reservoir; or
- Performing a thorough decontamination, and completely draining all possible areas in the boats.

Excellent examples of such procedures are available, including the procedure used by Arizona (Arizona Game and Fish Department, 2011).

From the time mussels first appear in an upstream reservoir to when there is an adequate number of veligers present to settle in downstream irrigation district systems will likely take three to five years.

From the time mussels first appear in an upstream reservoir to when there is an adequate number of veligers present to settle in downstream irrigation district systems will likely take three to five years. This time lag is because the population of adults in the reservoir needs to increase for several spawning seasons, and this will increase the number of veligers from a few per litre to several hundred per litre. Of that number, only those that are ready to settle will attach when they reach the irrigation system. Those not sufficiently mature will be discharged with the irrigation water.

The few mussels settling in an irrigation pipeline, and growing to perhaps 4 mm within one season, are unlikely to cause problems to irrigation producers as most if not all will be killed by desiccation during dewatering each October, and freezing during the winter. This will generally confine the potential fouling of a canal or pipeline to one reproductive season. Only where water remains in the pipe (e.g. located below the frost line), could adults survive from one irrigation season to the next. Screening devices used by irrigation producers to control algae from entering the sprinkler irrigation systems are likely sufficient to prevent adult dreissenid mussels from effecting sprinkler nozzles. If mussel infestation levels in a pipeline are high, more frequent cleaning of the screening devices may be required.

Control of dreissenid mussels in the reservoirs may be difficult. The use of chemical treatments to kill the mussels in most of the irrigation water supply district reservoirs would be very expensive, and unlikely to receive regulatory approval because of potential effects to the environment. Decreasing the water level in the reservoirs to winter operating levels each fall may expose many of the adult mussels that settle in the relatively warm shallow areas. These mussels would be killed by desiccation and freezing during the winter months. Identifying the link between reservoir depth and mussel development would be useful to determine what effect lowering reservoir levels during the winter months would have in killing mussels. In small reservoirs, the addition of potash could be considered, particularly if the water retention time in the reservoir is long. Even low levels of potassium (30 to 50 mg/L) will eliminate adult dreissenid mussels, given adequate contact time.

5.3 Vulnerability Assessment of Individual Irrigation Districts

5.3.1 Western Irrigation District

The WID supplies irrigation water to about 39,000 ha of land through a water supply network of 1,000 km of canals and pipelines. About 24% of the water distribution system is in pipeline. The average volume of water delivered to the district from the Bow River, via Chestermere Reservoir, is about 153,000 dam^3 (AAF, 2017). About 98% of the irrigated land is served by either high-pressure or low-pressure pivot irrigation systems (AAF, 2017). The district also supplies municipal water to about 12,000 people in four communities.

Water quality monitoring was carried out by AAF at numerous sites throughout the WID from 2006 to 2007 and from 2011 to 2016. All sites monitored have calcium and pH values in the range that will support mussel development (Figures A-1.1 and A-1.2). Maximum summer water temperatures suggest a relatively short breeding season for the mussels (Figure A-1.3).

Chlorophyll a data are somewhat limited, with a continuous record only for 2011 and 2012. The available data are variable, and suggests there is a lack of food for the mussels at numerous sites (Figure A-1.4), and this would likely limit population levels. Water with chlorophyll a levels less than 2 to 2.5 µg/L provides little potential for dreissenid mussel larvae development, and is not considered sufficient to support long-term survival of adult mussels. It is recommended that additional chlorophyll a monitoring be carried out to better assess dreissenid mussel growth and development.

5.3.2 Bow River Irrigation District

Water for the Bow River Irrigation District (BRID) is diverted from the Bow River to Lake McGregor, Travers Reservoir, and Little Bow Reservoir. These water storage reservoirs supply water to about 106,000 ha of irrigated land through about 1,000 km of canals and underground pipelines. The water supply infrastructure consists of about 450 km of surface canals and 550 km of underground pipelines.

The average volume of water delivered to the district from the Bow River is about 370,000 dam^3 (AAF, 2017). About 93% of the irrigated land is served by either high-pressure or low-pressure pivot irrigation systems (AAF, 2017). Water is also supplied to several communities and for domestic, industrial, recreation, and wildlife use.

Water quality monitoring was carried out by AAF at numerous sites throughout the BRID from 2006 to 2007 and from 2011 to 2016. Nearly all sites monitored have calcium and pH values that will support significant mussel population (Figures A-2.1 and A-2.2). Maximum summer water temperatures suggest a relatively short breeding season for the mussels (Figure A-2.3); however, yearly profiles from associated reservoirs are not available.

Chlorophyll a data are somewhat limited, with a continuous record only for 2011 and 2012. The available data are variable, and suggests there is adequate food for the mussels at several sites (Figure A-2.4). At site BR-S2 there was very high level of chlorophyll a found in 2011 (>80 µg/L). Levels between 20 and 25 µg/L are considered too high for successful larval development. It is recommended that additional chlorophyll a monitoring be carried out to better assess dreissenid mussel growth and development.

5.3.3 Eastern Irrigation District

The EID, which is bounded by the Bow River in the south and the Red Deer River in the north, encompasses about 600,000 ha of land. Water for the EID is diverted from the Bow River via the Bassano Dam. It delivers water to approximately 1,100 irrigation producers that irrigate about 122,000 ha of land (AAF, 2017). The water is delivered through a distribution system comprised of about 720 km of surface canals and 1,200 km of underground pipelines. The EID also conveys water for municipal, industrial, wildlife habitat, and recreational purposes.

The average volume of water delivered to the district from the Bow River is about 635,000 dam^3 (AAF, 2017). About 83% of the irrigated land is served by either high-pressure or low-pressure pivot irrigation systems (AAF, 2017).

Water quality monitoring was carried out by AAF at numerous sites throughout the EID from 2006 to 2007 and from 2011 to 2016. All sites monitored have calcium and pH values that will support a significant mussel population (Figures A-3.1 and A-3.2). Maximum summer water temperatures suggest a relatively short breeding season for the mussels (Figure A-3.3). However, yearly profiles from associated reservoirs are not available.

Chlorophyll a data are somewhat limited, with a continuous record only for 2011 and 2012. The available data are quite variable, and suggests there is adequate food for the mussels at a several sites (Figure A-3.4). At site E-S6 there was very high level of chlorophyll a found in 2011 (>50 µg/L). Levels from 20 to 25 µg/L are considered too high for successful larval development. It is recommended that additional chlorophyll a monitoring be carried out to better assess dreissenid mussel growth and development.

5.3.4 St. Mary River Irrigation District

The SMRID delivers water to approximately 160,000 ha of land (AAF, 2017). The water is delivered through a distribution system comprised of about 840 km of surface canals and 960 km of underground pipelines. The SMRID also conveys water for municipal, industrial, wildlife habitat, and recreational purposes.

Water for the SMRID is supplied from the Waterton and St. Mary reservoirs via the SMRID main canal. The average volume of water delivered to the district is about 470,000 dam^3 (AAF, 2017). About 90% of the irrigated land is served by either high-pressure or low-pressure pivot irrigation systems (AAF, 2017).

Water quality monitoring was carried out by AAF at numerous sites throughout the SMRID from 2006 to 2007 and from 2011 to 2016. All sites monitored have calcium and pH values in the range that will support mussel development (Figures A-4.1 and A-4.2). At several sites, pH appears to exceed 9.5, which could preclude mussel veliger development. Maximum summer water temperatures suggest a relatively short breeding season for the mussels (Figure A-4.3); however, yearly profiles from associated reservoirs are not available.

Chlorophyll a data are somewhat limited, with a continuous record only for 2011 and 2012. The available data are quite variable, and suggests there is adequate food for the mussel development and growth (Figure A-4.4). At several sites, there were very high levels of chlorophyll a recorded. Levels from 20 to 25 µg/L are considered too high for successful larval development. It is recommended that additional chlorophyll a monitoring be carried out to better assess dreissenid mussel growth and development.

5.3.5 Taber Irrigation District

The Taber Irrigation District (TID) delivers water to approximately 34,000 ha of land (AAF, 2017). The water is delivered through a distribution system comprised of about 140 km of surface canals and 205 km of underground pipelines. The TID also conveys water for municipal, industrial, wildlife habitat, and recreational purposes.

Water for the TID is supplied from the Waterton and St. Mary reservoirs, via the SMRID main canal. The average volume of water delivered to the district is about 113,000 dam^3 (AAF, 2017). About 87% of the irrigated land is served by either high-pressure or low-pressure pivot irrigation systems (AAF, 2017).

Water quality monitoring was carried out by AAF at numerous sites throughout the TID from 2006 to 2007 and from 2011 to 2016. All sites monitored have calcium and pH values in the range that will support mussel development (Figures A-5.1 and A-5.2). Maximum summer water temperatures suggest a relatively short breeding season for the mussels (Figure A-5.3); however yearly temperature profiles from associated reservoirs are not available.

Chlorophyll a data are somewhat limited, with a continuous record only for 2011 and 2012. The available data are quite variable, and suggests there is adequate food for the mussel development and growth (Figure A-5.4). It is recommended that additional chlorophyll a monitoring be carried out to better assess dreissenid mussel growth and development.

5.3.6 Raymond Irrigation District

The Raymond Irrigation District (RID) delivers water to approximately 300 irrigation producers that irrigate about 19,000 ha of land (AAF, 2017). The water is delivered through a distribution system comprised of about 100 km of surface canals and 145 km of underground pipelines. The RID also conveys water for municipal, industrial, wildlife habitat, and recreational purposes.

Water for the RID is supplied from the Waterton and St. Mary reservoirs via the SMRID main canal. The average volume of water delivered to the district is about 42,000 dam^3 (AAF, 2017). About 70% of the irrigated land is served by either high-pressure or low-pressure pivot irrigation systems (AAF, 2017).

Water quality monitoring was carried out by AAF in the RID from 2006 to 2007 and from 2011 to 2016. All sites monitored have calcium and pH values in the range that will support significant mussel populations (Figures A-6.1 and A-6.2). Maximum summer water temperatures suggest a relatively short breeding season for the mussels (Figure A-6.3); however, yearly profiles from associated reservoirs are not available.

Chlorophyll a data are somewhat limited, with a continuous record only for 2011 and 2012. The available data are variable, and suggests there is adequate food for mussel development and growth (Figure A-6.4). It is recommended that additional chlorophyll a monitoring be carried out to better assess dreissenid mussel growth and development.

5.3.7 Magrath Irrigation District

The Magrath Irrigation District (MID) delivers water to producers that irrigate about 7,400 ha of land (AAF, 2017). The water is delivered through a distribution system comprised of about 40 km of surface canals and 60 km of underground pipelines. The MID also conveys water for municipal, industrial, wildlife habitat, and recreational purposes.

Water for the MID is supplied from the Waterton and St. Mary reservoirs, via the AEP canal. The average volume of water delivered to the district is about 18,000 dam^3 (AAF, 2017). About 60% of the irrigated land is served by either high-pressure or low-pressure pivot irrigation systems (AAF, 2017).

Water quality monitoring was carried out by AAF at several sites at the MID from 2006 to 2007 and from 2011 to 2016. All sites monitored have calcium and pH values in the range that will support mussel development (Figures A-7.1 and A-7.2). Maximum summer water temperatures suggest a relatively short breeding season for the mussels (Figure A-7.3); however, yearly profiles from associated reservoirs are not available.

Chlorophyll a data are somewhat limited, with a continuous record only for 2011 and 2012. The available data are quite variable, and shows a diverse range of chlorophyll a values. Some values can support mussel growth and development infestation, while others may be too low (Figure A-7.4). Water with chlorophyll a levels less than 2 to 2.5 µg/L has little potential for dreissenid mussel larvae development and is not considered able to support long-term survival of adult mussels. It is recommended that additional chlorophyll a monitoring be carried out to better assess dreissenid mussel growth and development.

5.3.8 Lethbridge Northern Irrigation District

The Lethbridge Northern Irrigation District (LNID) delivers water to producers that irrigate about 74,000 ha of land (AAF, 2017). The water is delivered through a distribution system comprised of about 155 km of surface canals and 252 km of underground pipelines. The LNID also conveys water for municipal, industrial, wildlife habitat, and recreational purposes.

Water for the LNID is diverted from the Oldman River, downstream of the Oldman Reservoir. The average volume of water delivered to the district is about 207,000 dam^3 (AAF, 2017). About 85% of the irrigated land is served by either high-pressure or low-pressure pivot irrigation systems (AAF, 2017).

Water quality monitoring was carried out by AAF at numerous sites at the LNID from 2006 to 2007 and from 2011 to 2016. All sites monitored have calcium and pH values in the range that will support mussel development (Figures A-8.1 and A-8.2). Maximum summer water temperatures suggest a relatively short breeding season for the mussels (Figure A-8.3).

Chlorophyll a data are somewhat limited, with a continuous record only for 2011 and 2012. The available data are variable, and suggests there is adequate food for the mussel development and growth (Figure A-8.4). It is recommended that additional chlorophyll a monitoring be carried out to better assess dreissenid mussel growth and development.

5.3.9 United Irrigation District

The United Irrigation District (UID) delivers water to producers that irrigate about 14,000 ha of land (AAF, 2017). The water is delivered through a distribution system comprised of about 110 km of surface canals and 120 km of underground pipelines. The UID also conveys water for municipal, industrial, wildlife habitat, and recreational purposes.

Water for the UID is diverted from the Belly River and the Waterton Reservoir. The average volume of water delivered to the district is about 25,000 dam^3 (AAF, 2017). About 56% of the irrigated land is served by either high-pressure or low-pressure pivot irrigation systems (AAF, 2017).

Water quality monitoring was carried out by AAF at three sites in the UID from 2006 to 2007 and from 2011 to 2016. All sites monitored have calcium and pH values in the range that will support mussel development (Figures A-9.1 and A-9.2). Maximum summer water temperatures suggest a relatively short breeding season for the mussels (Figure A-9.3); however, yearly profiles from associated reservoirs are not available.

Chlorophyll a data are somewhat limited, with a continuous record only for 2011 and 2012. The available data are variable, and shows that some chlorophyll a values are adequate to support mussel growth and development, while other values are too low (Figure A-9.4). Water with chlorophyll a levels less than 2 to 2.5 µg/L has little potential for dreissenid mussel larvae development, and is not considered able to support long-term survival of adult mussels. It is recommended that additional chlorophyll a monitoring be carried out to better assess dreissenid mussel growth and development.

5.3.10 Mountain View Irrigation District

The Mountain View Irrigation District (MVID) delivers water to about 1,520 ha of irrigated land (AAF, 2017). The water is delivered through a distribution system comprised of about 23 km of surface canals and 19 km of underground pipelines. The MVID also conveys water for municipal, industrial, wildlife habitat, and recreational purposes.

The water source for the MVID is Payne Lake. The average volume of water delivered to the district is about 3,775 dam^3 (AAF, 2017). About 7% of the irrigated land is served by either high-pressure or low-pressure pivot irrigation systems (AAF, 2017).

Water quality monitoring was carried out by AAF at two sites in the MVID from 2006 to 2007 and from 2011 to 2016. All sites monitored have calcium and pH values in the range that will support mussel development (Figures A-10.1 and A-10.2). Maximum summer water temperatures suggest a relatively short breeding season for the mussels (Figure A-10.3); however, yearly profiles for the associated reservoir are not available.

Chlorophyll a data are somewhat limited, with a continuous record only for 2011 and 2012. The available data are variable, and shows that some chlorophyll a values are adequate to support mussel growth and development, while other values may be too low (Figure A-10.4). Water with chlorophyll a levels less than 2 to 2.5 µg/L has little potential for dreissenid mussel larvae development and is not considered able to support long-term survival of adult mussels.

It is recommended that additional chlorophyll a monitoring be carried out to better assess dreissenid mussel growth and development.

5.3.11 Aetna Irrigation District

The Aetna Irrigation District (AID) delivers water to about 1,900 ha of irrigated land (AAF, 2017). The water is delivered through a distribution system comprised of about 15 km of surface canals and 23 km of underground pipelines.

The water source for the MVID is Payne Lake. The average volume of water delivered to the district is about 4,640 dam^3 (AAF, 2017). About 21% of the irrigated land is served by either high-pressure or low-pressure pivot irrigation systems (AAF, 2017).

Water quality monitoring was carried out by AAF at two sites in the AID from 2006 to 2007 and from 2011 to 2016. All sites monitored have calcium and pH values in the range that will support significant mussel populations (Figures A-11.1 and A-11.2). Maximum summer water temperatures suggest a relatively short breeding season for the mussels (Figure A-11.3); however, yearly profiles from associated reservoir are not available.

Chlorophyll a data are somewhat limited, with a continuous record only for 2011 and 2012. The available data are variable, and shows that some chlorophyll a values are adequate to support mussel growth and development, while other values are too low (Figure A-11.4). Water with chlorophyll a levels below 2 to 2.5µg/L has little potential for dreissenid mussel larvae development and is not considered able to support long-term survival of adult mussels. It is recommended that additional chlorophyll a monitoring be carried out to better assess dreissenid mussel growth and development.

5.3.12 Leavitt Irrigation District

The Leavitt Irrigation District (LID) delivers water to about 2,050 ha of irrigated land (AAF, 2017). The water is delivered through a distribution system comprised of about 25 km of surface canals and 30 km of underground pipelines.

The water source for the LID is Payne Lake. The average volume of water delivered to the district is about 7,500 dam^3 (AAF, 2017). About 24% of the irrigated land is served by either high-pressure or low-pressure pivot irrigation systems (AAF, 2017).

There are no environmental water quality data available for the LID. However, it is likely that water quality values will be similar to those found in the AID.

5.3.13 Ross Creek Irrigation District

The RCID delivers water to about 450 ha of irrigated land (AAF, 2017). The water is delivered through a distribution system comprised of about 3 km of surface canals and 12 km of underground pipelines.

The water source for the RCID is Cavan Lake. The average volume of water delivered to the district is about 1,250 dam^3 (AAF, 2017). About 75% of the irrigated land is served by either high-pressure or low-pressure pivot irrigation systems (AAF, 2017).

Water quality monitoring was carried out by AAF at one site in the RCID from 2006 to 2007 and from 2011 to 2016. The site has calcium and pH values in the range that will support mussel development (Figures A-12.1 and A-12.2). Maximum summer water temperatures suggest a relatively short breeding season for the mussels (Figure A-12.3); however, yearly profiles from associated reservoir are not available. Chlorophyll a data are not available for the RCID.

Potassium concentration in the water originating from Cavan Lake was consistently greater than 20 mg/L from 2012 to 2015. These levels of potassium should be sufficient to prevent the establishment of dreissenid mussels in the irrigation distribution system.

6 Analysis of Strategic Mussel Control Options for Alberta's Irrigation Districts

To date, much of the experience regarding the control of dreissenid mussels in freshwater systems has been related to treatment of small enclosed reservoirs (e.g. Millbrook Quarry in Virginia), or individual facilities such as power stations, and municipal water supply systems. There has been little experience with treatment and control of mussels for large, complex water systems that supply Alberta's 13 irrigation districts.

6.1 Irrigation District Complexity

More than 50 water storage reservoirs, with a total storage capacity of about 2.9 million dam^3, supply water to the 13 irrigation districts. On average, about 2 million dam^3 of water is diverted annually to the irrigation districts, with about 67% (1.4 million dam^3) of that volume diverted to irrigation producers (AAF, 2017). Fifteen of these reservoirs, most that are located at upstream locations relative to the irrigation districts, are owned by the GoA. They have a combined storage of about 1.8 million dam^3.

The water storage reservoirs distribute water through a complex system of about 3,800 km of surface water supply canals, and 4,200 km of underground pipelines. Many of these distribution systems have return channels that discharge unused water back into a river system, that may limit the dreissenid mussel control options irrigation districts can use. A mussel infestation in an upstream reservoir will, with time, affect all downstream reservoirs, and rivers that receive return water related to the infected reservoir(s). Active treatment of the upstream water supply reservoirs to eradicate the mussels does not appear to be a feasible option. The high costs, logistical difficulties, and environmental challenges would be significant. Once the mussels infest any of the large reservoirs

A mussel infestation in an upstream reservoir will, over time, affect all downstream reservoirs, and rivers that receive return water related to the infected reservoir(s)

that supply water to the irrigation districts, management options, rather than control options, will become the reality for most of the infested reservoirs. For irrigation districts, once a reservoir becomes infected, controlling the mussels in water supply canals and underground pipelines downstream of the infected reservoirs will become the primary focus.

6.2 Prevention Options

Alberta is currently free of dreissenid mussels, and this is an enviable position compared with many other jurisdictions in North America. Remaining mussel free should be a very high priority for the GoA and the irrigation districts to avoid the difficulties and high costs of control and treatment programs once dreissenid mussels become established. The GoA and the irrigation districts have recognized the serious threat that a mussel infestation would impose on the irrigation industry in the province, and are taking steps to prevent their establishment in southern Alberta reservoirs and lakes. The current boat monitoring program at key entry points is good, but may not be totally effective as boats enter the province at locations that may not be monitored. Public education programs, including signage at reservoirs, help educate the public on the dangers of a mussel infestation. However, the GoA and irrigation districts may want to consider additional measures that will further minimize the threat of mussel infestation at high-risk water storage reservoirs.

Remaining mussel free should be a very high priority for the GoA and the irrigation districts to avoid the difficulties and high costs of control and treatment programs once dreissenid mussels become established.

6.2.1 Limit Boat Access

Many reservoirs that supply water to the irrigation districts have a few “official” access locations and many “unofficial” access locations where pleasure boats may be launched. Reducing boat access to only official access locations, that can be monitored and controlled, would significantly reduce the potential for mussel infestation. The SMRID is currently initiating a program to reduce access to several of their key reservoirs to “official” access locations only. All boats accessing the reservoirs at these locations are checked before being allowed to launch. The Government of Canada (GoC) has taken the additional precaution of not allowing any motorized boats in Waterton Lakes National Park (GoC, 2017). It is recognized that these measures will require funding for manpower and infrastructure, but the costs will be less than trying to manage and control an infestation of mussels in the reservoirs and irrigation distribution systems.


Upper Waterton Lake

6.2.2 Monitor and Inspect

Since all watercraft have the potential to carry dreissenid mussels, monitoring and inspection of all watercraft entering reservoirs and lakes should be carried out on an ongoing basis.

Alternatively, the irrigation districts could implement a policy that requires that all watercraft entering a reservoir must be certified as being mussel-free. This includes kayaks, canoes, paddle boards, personal watercraft (e.g. Sea-Doo). In addition, anglers using live bait should also be inspected and requested to safely dispose of any live bait water from other water sources, as mussels can be present in live-bait water that may originate from mussel-infected sources.

Dreissenid mussel veliger monitoring

Monitoring of key reservoirs to detect if mussel veligers are present provides an important early warning system for the irrigation districts, and will allow the irrigation districts time to develop a control and eradication strategy before an adult mussel infestation takes place. The Water Quality Section of AAF is working with the irrigation districts and AEP to monitor 22 high-risk reservoirs for the presence of invasive mussel veligers. It may be reasonable to reduce the intensity of the existing program to an annual monitoring schedule, but it could be expanded to include a larger number of irrigation district reservoirs.

6.2.3 Public Education

A good public education program should precede and coincide with any actions, such as limiting boat access to reservoirs. Public education regarding the dangers associated with dreissenid mussel infestation should also be an ongoing activity for the Irrigation districts. This will ensure that current and future recreation users of the irrigation district reservoirs are fully aware of the economic and environmental effects of a dreissenid mussel infestation, and have a better understanding of the rationale for the irrigation districts' actions.

Signage at Chin Reservoir boat launch site

Signage at Chin Reservoir boat launch site

The current signage programs initiated by the GoA and irrigation districts at key boat launch sites is an excellent example of an ongoing, proactive public education program. The signage program could be further enhanced through more "hands-on" activities such as public forums and field days held at key reservoirs and lakes where recreational boat traffic is high. Speaking directly to the boaters and other recreational water users will provide a valuable opportunity to interact and communicate with water users.

Ongoing development and distribution of dreissenid mussel factsheets and brochures to irrigation reservoir water users, similar to the current programs of the GoA and irrigation districts, will further emphasize the importance of preventing a mussel infestation, and notify potential reservoir users of pending mussel prevention actions being taken by the irrigation districts. Examples of factsheets are shown in Appendix Tables B-1 and B-2.

6.3 Mussel Mortality Through Winter Desiccation and Freezing

Water remaining in canal after fall drainage

The southern Alberta winters are relatively cold, with average low January temperatures ranging from -10 to -16°C and high temperatures ranging from -4 to 1°C. The cold winter temperatures require that all irrigation water delivery and on-farm irrigation systems be drained to prevent damage to infrastructure from freezing. Irrigation canals and pipelines are drained in early October each year, and remain unused until early May the following year.

Drainage of the surface canals in the fall will expose nearly all mussels that have accumulated during the summer. Winter desiccation and freezing will result in 100% mortality of the exposed mussels. After canal drainage, some mussels may survive in small pools of water immediately upstream of control structures, or in minor depressions in the canal bed. During the winter months, these pools of water will freeze solid for several weeks, which will kill all remaining mussels. The combination of drainage and freezing will ensure that 100% of the mussels in the surface canal system will be killed each winter.

Nearly all mussels that accumulate in the underground pipelines during the summer will be exposed after the pipelines are drained in the fall. These exposed mussels should be killed during the prolonged winter period through desiccation. Based on experience in eastern North America, the dead mussel shells are expected to detach from the inside of the pipe, or removed with the first flush of water in the spring (Personal communication, Renata Claudi, RNT Consulting Inc.; Personal communication, Dan Butts, ASI Group Inc.; Ludwig, 2011). However, direct experience is not available in western Canada to confirm exactly how the dead mussels will react in Alberta's irrigation pipelines.

Pipe size reduction junction

In the drained pipelines, some mussels may survive in pools of water that accumulate in minor depressions, caused by uneven settlement of the pipeline, or at pipe size reduction junctions. These pools of water may not freeze during the winter months (Personal communication, Richard Phillips, BRID, Vauxhall, Alberta; Ron Hust, MPE Engineering Ltd., Lethbridge, Alberta), because the minimum soil cover of 1.0 m (AAF, 2010) for pipelines installed in the irrigation districts may place the pipelines below the frost line. Mussels in these unfrozen pools of water may survive the winter if dissolved oxygen levels in the water exceed 3 mg/L.

These unfrozen pools of water likely represent a small fraction of the total pipeline capacity, particularly for the larger irrigation district pipelines. Mussels in these pools of water will be isolated during the winter, because the remainder of the drained pipeline will be too dry to allow them to move outside their water habitat. The total mussel population in these pools will be limited by dissolved oxygen levels, temperature, and food supplies.

During several years, this population may grow, not from the reproduction of the mussels present, but from upstream recruitment. Expected life span of the mussels in these pools of water, if they survive, is about three years, which means that about 33% of the mussels will die off each year, after the initial build-up. Mortality may be higher because of the relatively poor habitat conditions in these pools of water.

The colonies of mussels living in these pools of water are likely to have minimal impact on the flow and capacity of the affected pipelines. If these conclusions are confirmed through monitoring and observation, it might be practical for irrigation districts not to pursue any active mussel control measures. While this option would have minimal costs to the irrigation district, modifications to the pipeline would be required to remove the mussel shells killed through winter desiccation. It is also recognized that this option does not address the possible accumulation of mussels in producer-owned water supply pipelines that are not properly drained in the fall.

6.4 Potash Treatment to Eradicate Dreissenid Mussels

Mortality of dreissenid mussels in pipelines can be achieved with the use of potassium chloride, which is commonly available as potash fertilizer. ASI Group Ltd. found that 100 mg/L of potassium for an average of five days, at ambient temperatures of 15°C, resulted in 100% mortality of dreissenid adult mussels (Figure 3.1). However, potash is not currently registered for use in Canada to kill mussels in water systems. AEP is attempting to have potash registered as a mussel treatment option for Alberta's water systems.

Potash is not currently registered for use in Canada for control of mussels in water systems. Alberta Environment and Parks is attempting to have potash registered as a mussel treatment option for Alberta's water systems.

6.4.1 Project Experience

In 2006, ASI Group Ltd. treated a relatively small quarry in the state of Virginia with potassium chloride to eradicate an infestation of zebra mussels. The total volume of water in the quarry was

Millbrook Quarry, Haymarket, Virginia

about 682,000 m^3, and was somewhat unique in that no water entered or left during the treatment process. A total of 650,000 kg of 20% potassium chloride solution was pumped into the quarry at a single location, to achieve an average potassium concentration of 103 mg/L. It required a total of 31 days to achieve complete mortality of the zebra mussel population in the reservoir. The total cost for this treatment option was about $420,000, which equates to about $0.62/m^3 of water treated.

In 2014, ASI Group Ltd., using private contractors, successfully applied 923,000 kg of 20% potassium chloride solution to four small harbours on Lake Winnipeg to eradicate zebra mussels. Approval for this project was granted by the GoC as a special research project. The cumulative volume of water in the four harbours was slightly more than 1 million m^3. The goal was to achieve an average potassium concentration of at least 100 mg/L in each of the harbours. Treatment was more challenging than for the Milllbrook Quarry because of the increased number of water bodies to treat, and the open water of Lake Winnipeg linking each of the harbours. The treatment work was carried out in early spring, and lake water temperature was quite cold. After the potash was introduced into the harbours, a total of 28 days was required to achieve complete mortality of the mussel population. The total cost of this project was $850,000 (2014), which equates to about $0.83/m^3 of water treated.

Town of Gimli on Lake Winnipeg

6.4.2 Treatment of Water Storage Reservoirs in Alberta

The 57 water storage reservoirs that supply water to the irrigation districts in southern Alberta vary in size from about 120 dam^3 to about 490,000 dam^3 (AAF, 2017). Total storage capacity of these reservoirs is about 2.9 million dam^3 (AAF, 2017). It may be feasible to effectively treat a few of the smaller reservoirs with potash to eradicate a dreissenid mussel infestation, given the positive experiences with treating the Millbrook Quarry in Virginia, and the harbours on Lake Winnipeg. However, Health Canada does not currently approve the commercial use of potash to treat mussel infestations in flow-through water systems, including reservoirs and irrigation district water supply infrastructure. The use of potash to treat larger reservoirs, even if regulatory approvals were provided, is unlikely given the large volumes of stored water to be treated. To treat Chin Reservoir (SMRID), for example, which has a storage capacity of about 207 million m^3, would require >41 million kg of potash.

6.4.3 Research to Treat Underground Pipelines in Southern Alberta Using Potash

Based on the success with using potash to eliminate zebra mussels, AAF has been working with irrigation districts on research to develop potash injection methods to eliminate dreissenid mussels from irrigation district water supply pipelines, and producer-owned irrigation water supply pipelines (AAF, 2016). Granular potash fertilizer, which consists of about 95% potassium chloride, was purchased from a local distributor and dissolved into potable water at a rate to achieve a concentration of about 120,000 mg/L potassium (Figure 6.1).

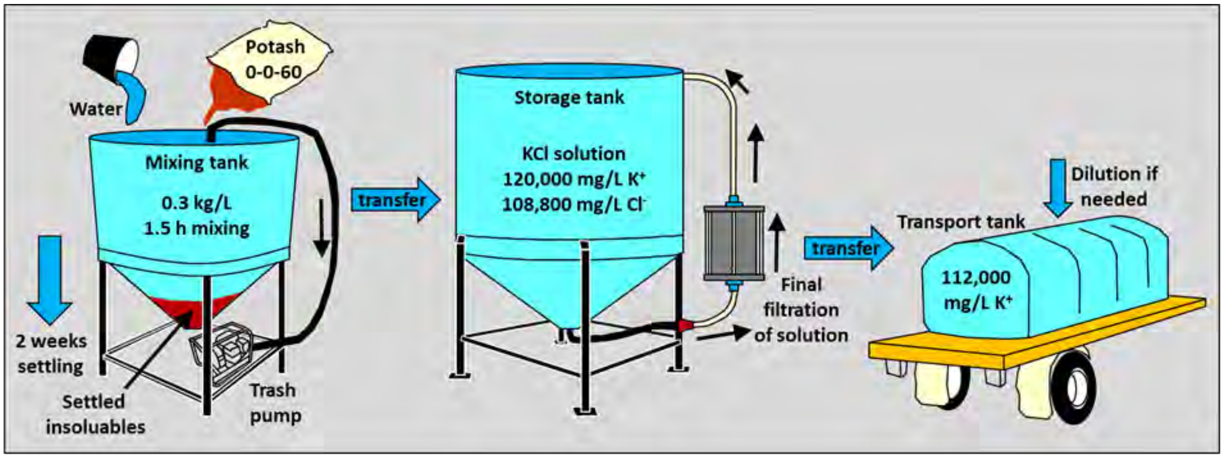


Figure 6.1 Preparation of KCl solution for injection into an irrigation district pipeline and pivot
Source: AAF (2016)

The potassium chloride solution was injected into the irrigation district pipelines near the inlet to the pipelines. The pipeline supplies water to low-pressure, drop-tube pivot systems, which were turned on during this procedure to ensure the potassium chloride solution filled the entire pivot systems (Figure 6.2). Once the desired potassium concentration of 100 mg/L was reached in the pipeline and pivot systems, the injection process was terminated, and the treated water held in the irrigation district and producer-owned water supply pipeline for one to two days. Treated water injected into the pivot drained through the sprinkler nozzles once the injection process was completed. Once the treatment was completed, the treated water was applied to the irrigated fields through the pivots, ensuring that none of the treated water was returned to the irrigation canal. A total of five pipeline irrigation trials were carried out in three irrigation districts (EID, TID, SMRID) from 2016 to 2017 (Personal Communication, Barry Olson, AAF, Lethbridge, Alberta).

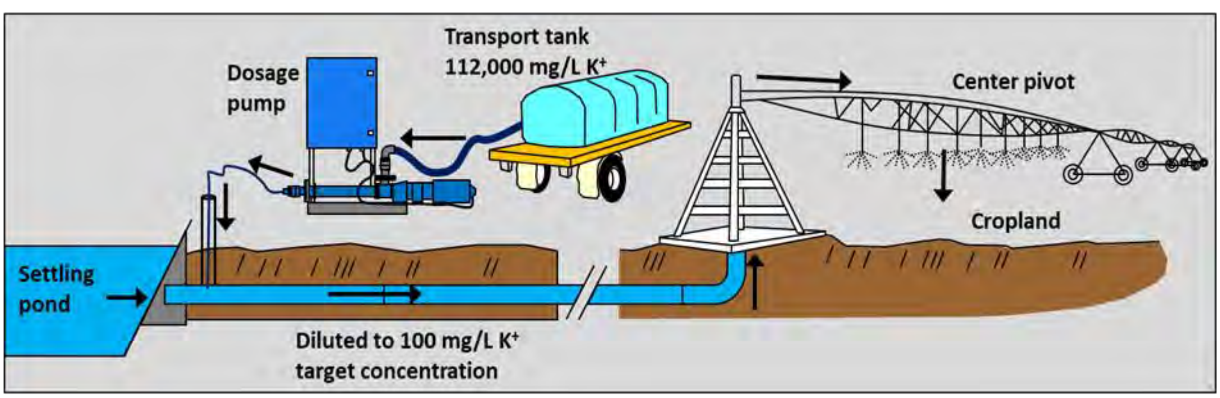


Figure 6.2 Injection of KCl solution into an irrigation district pipeline and pivot
Source: AAF (2016)

The number of days required to hold the treated water in the pipelines and pivots to achieve 100% mortality of the dreissenid mussels will depend on the temperature of the water during the treatment period. During the operating period for the 13 irrigation districts, water temperatures in the canals and pipelines range from about 13°C in the spring and fall, to as high as 24°C during the summer months. Depending on when the treatment process occurs, the treated water would need to remain in the pipelines and pivot for five to six days to achieve 100% mortality of the mussels (Figure 3.1). It is also important to carry out monitoring and analysis during the treatment process to determine when 100% mortality is achieved, which may take an additional two days.

6.4.4 Comprehensive Potash Treatment for Irrigation District and Producer-owned Water Supply Pipelines

The use of potash to treat mussel-infested irrigation district water supply pipelines, and irrigation producer-owned water supply pipelines, is considered the most technically feasible, and environmentally friendly option at this time. Potash is widely used as a fertilizer for crop production in Alberta, has been commercially used to kill dreissenid mussels in waters in Canada and the United States, and is undergoing the registration process by AEP as a mussel treatment option for Alberta's water systems.

Based on commercial experience with treatment to control mussels in pipelines in the Great Lakes region, it is expected that the mussels, once they are killed, will decay and detach from the inside of the irrigation water supply pipelines during the winter months (Personal Communication, Renata Claudi, RNT Consulting Inc.; Ludwig, 2011). For those mussels that remain attached, an initial flush of the pipeline during spring start-up is expected to remove them. The ability to open the downstream end of the pipeline will increase the success of removing the dead mussel shells from the pipeline during the spring flush.

There are currently about 4,200 km of irrigation district water supply pipelines within the 13 irrigation districts (AAF, 2017), which consists of more than 900 individual pipeline segments. Some pipeline segments serve many individual irrigation producers, while others serve only a few irrigation producers. The following pipeline information, for each irrigation district, was generated from work carried out by AAF to identify and characterize existing pipelines downstream of irrigation water supply reservoirs in Alberta (AAF, 2017b).

- Length, diameter, and volume of each pipeline segment.
- Potash requirement (kg) to attain a potassium concentration of 100 mg/L for each pipeline segment.
- Cost of the potash.

This information for each irrigation district is summarized in Table 6.1.

The total volume of all irrigation district pipeline segments in the 13 irrigation districts is estimated to be about 1.1 million m^3 (Table 6.1). In addition to the irrigation district water supply pipelines, there are an estimated 4,800 km of irrigation producer-owned pipelines that supply water to about 8,500 pivot irrigation systems within the 13 irrigation districts. Based on these data, and pivot irrigation area data for each irrigation district (AAF, 2017), the total volumes of producer-owned water supply lines and pivots were calculated for each irrigation district (Table 6.1). The total volume for these water supply pipelines and the pivot systems for the 13 irrigation districts is estimated to be 268,000 m^3 (Table 6.1). More detailed information regarding producer-owned pipeline volumes, potash requirements, and treatment costs are shown Appendix Table C-1.

The total combined water volume (irrigation district pipelines, plus producer-owned water supply pipelines and pivot systems) is estimated to be about 1.4 million m^3 (Table 6.1). It is estimated that about 268,000 kg of potash will be required to achieve the desired concentration of potassium in the treated irrigation district pipelines, producer-owned pipelines and pivot systems (Table 6.1). This will require about 1,140 m^3 of potassium chloride solution to achieve a concentration of 120,000 mg/L of potassium in the pipeline segments.

The total combined water volume (irrigation district pipelines, plus producer-owned water supply pipelines and pivot systems) is estimated to be about 1.4 million m^3.

Table 6.1 Projected costs for potash treatment of irrigation district pipelines and producer-owned water supply pipelines and pivots.

ID	Pivot Irrigated Area (ha)	Irrigation District Pipelines*		Producer-owned Water Supply Pipelines and Pivots		Total Volume (m^3)	Total Potash* (kg)	Total Cost of Potash# ($)	Total Treatment Cost^ ($)
		Volume (m^3)	Potash** (kg)	Volume (m^3)	Potash** (kg)				
BRID	90,663	131,208	26,032	52,371	10,390	183,579	36,422	16,390	152,371
EID	93,646	363,746	72,167	54,094	10,732	417,840	82,899	37,305	346,807
LNID	62,237	158,846	31,515	35,951	7,133	194,797	38,648	17,391	161,682
RID	12,659	22,585	4,481	7,312	1,451	29,897	5,932	2,669	24,815
SMRID	137,683	257,510	51,090	79,532	15,779	337,042	66,869	30,091	279,745
TID	28,098	57,847	11,477	16,231	3,220	74,078	14,697	6,614	61,485
UID	7,757	20,502	4,068	4,481	889	24,983	4,957	2,230	20,736
WID	25,565	65,454	12,986	14,767	2,930	80,221	15,916	7,162	66,584
RCID	272	1,841	365	157	31	1,998	396	178	1,658
MVID	102	2,070	411	59	12	2,129	422	190	1,767
LID	474	4,487	890	274	54	4,761	941	423	3,952
AID	273	2,862	568	158	31	3,020	599	270	2,506
MID	4,318	9,419	1,869	2,494	495	11,913	2,364	1,064	9,888
Total	**463,747**	**1,098,377**	**217,919**	**267,881**	**53,147**	**1,366,258**	**271,062**	**121,977**	**1,133,996**

* Source: AAF, 2017

** Calculated assuming a target concentration of 100 mg/L potassium and 50.4% potassium in potash. Potash required to treat a pipeline segment is 0.1984 kg potash/m^3 (AAF, 2017b).

Cost of potash was $0.45/kg, based on quote from Coaldale Crop Production Services on April 27, 2017 (AAF, 2017b).

^ Assumed a total treatment cost of $0.83/$m^3$ (Personal Communication, Dan Butts, ASI Group Ltd).

Cost estimates to complete a one-time treatment of all irrigation district pipelines were based on the costs related to the Lake Winnipeg potash treatment project in 2014. This project utilized independent contractors to complete the treatment, which included the: acquisition and transport of the potash to the Lake Winnipeg site; mixing the potash to a suitable slurry, and application of the slurry mixture to the four designated harbours. The total cost for this work equated to about \$0.83 per m^3 of treated water.

Based on these data, the cost to complete a one-time treatment of all irrigation district pipelines, and the associated producer-owned water supply pipelines and pivot systems within the 13 irrigation districts is estimated to be about \$1.1 million (Table 6.1). The actual costs to treat the 900+ pipeline segments within the 13 irrigation districts, if required, may be higher because numerous mobile injection systems (manpower, mixing containers, pumps, injection equipment, and fittings) may be required to complete this volume of work within specific time requirements. In addition, the mobile injection equipment may need to be moved many times over relatively long distances, and potentially challenging road networks.

6.4.5 Abbreviated Potash Treatment of Irrigation District Pipelines

Drainage of the underground pipelines in the fall should result in nearly all mussels that remain in the pipeline being killed during the winter through desiccation. However, some mussels may remain in pools of water that accumulate in minor depressions, caused by uneven settlement of the pipeline, or at pipe reduction junctions. These mussels may survive the winter if the water does not freeze, and there is sufficient oxygen.

Since these mussels are concentrated in the small pools of water on the pipeline floor, injecting a relatively small volume of the appropriate potassium chloride solution, enough to cover the remaining pools of water, should achieve 100% mortality of any remaining mussels. This option targets the potassium chloride solution only where it is required. The volume of potassium chloride solution needs to be sufficient to ensure the treated water flows into all main and lateral pipeline segments. It may be possible to pump the potash solution directly into the pipeline inlet, rather than injecting it through a special valve assembly, and without the need to completely seal the inlet. Where there is no danger of freezing, the potash solution could be left in the pipeline during the winter months, and drained when irrigation water is available in the spring.

Compared with the complete potash treatment option, this option may require up to 95% less potassium chloride solution to be mixed, transported, and placed into each pipeline segment, which should result in significant cost savings. The potassium chloride solution may also be easier to introduce into the pipeline, and require less time and manpower to implement. The treated water may also be left in the pipeline during the winter, eliminating the need for staff to return to the pipeline immediately after the treatment is completed. This would increase the ability of staff to treat more pipeline segments during the same period of time.

This option would not address the potential accumulation of mussels in producer-owned water supply pipelines, and there would be no incentive for irrigation producers to allow the treated water to be applied to the land through their irrigation pivots. In addition, regulatory approvals may need to be in place to allow the treated water to be discharged through the irrigation district pipeline after the treatment is completed.

6.4.6 Timing of Potash Treatments

Determining the most appropriate time to treat mussel infested pipelines will be an ongoing challenge for irrigation districts and irrigation producers. Treatment periods in the spring and fall of each year are likely the most agreeable to irrigation producers, given their need to supply water to meet crop demands during the summer.

- **Early May -** The period immediately after water is turned into the irrigation canals and pipelines, and before there is a significant and widespread demand for water by the irrigation producers should be acceptable for most irrigation districts. This period may be a challenge during dry, warm springs when irrigation producers wish to apply irrigation water early to help with crop germination and development.
- **Late September to Early October -** After most crops have been harvested and/or demand for irrigation water is reduced is probably the most ideal time to treat the pipelines and canals. Any mussels that have developed during the summer can be killed before irrigation water operations are initiated the following year.

Combined, these two periods would allow for up to 30 days of active pipeline treatment activities to take place. Because water temperature during these periods are likely to be relatively cool, in the range of 13 to 16°C, treated water will need to remain in the pipelines and pivots for five to six days to ensure 100% mortality of the dreissenid mussels (Figure 3.1). Additional time will be required to set up and charge the pipelines to achieve the target potassium concentrations, and another two days are required, after the treatment is complete, to determine if all mussels in the treated water have been killed. Realistically, it should be assumed that at least nine days will be required to initiate and complete treatment of a pipeline segment.

Realistically, it should be assumed that at least nine (9) days will be required to initiate and complete the potash treatment of each pipeline segment.

Based on these data, one mobile treatment unit may be able to treat up to 15 pipeline segments within the 30 days, assuming the pipeline segments were located relatively close to each other. Successfully treating 900+ pipeline segments would require at least 60 mobile treatment units operating simultaneously. Continuous treatment of this number of pipeline segments from May 1 to October 30 each year would require the simultaneous operation of about 10 mobile treatment units.

For some locations, it may be possible to treat several pipeline segments at once, by applying the potash directly to the surface water supply canal that serves multiple pipeline segments. This is possible if there are check/drop structures and gates that allow water to be held in the canal during the treatment process. During the treatment process, water would not be allowed to flow to downstream water users, that may be an inconvenience. The following procedures would be required to implement this treatment process.

1. The downstream check/drop structure is closed. Care must be taken to ensure that treated water cannot escape downstream.

2. Water is released into the canal through the upstream drop/check structure at a rate equal to the volume of water being removed from the canal segment by the on-farm irrigation systems. This will need to be adjusted repeatedly during the injection process, because as individual pivots and pipelines reach the target potassium concentrations, they would be shut down to minimize the amount of potassium chloride used. This will require a significant amount of coordination and producer co-operation.
3. The liquid potash mixture is concurrently discharged into the canal segment to attain the desired potassium concentration.
4. The treated water, as it flows into the pipeline segments and irrigation systems, is continuously monitored and analyzed until the desired potassium concentration of 100 mg/L is achieved in the pipeline segments and all irrigation systems.
5. Release of water into the canal segment is discontinued.
6. The treated water is allowed to remain in the canal, and pipeline segments for the time required to kill the dreissenid mussels.
7. Once the mussels have been killed, the irrigation producers re-start their systems to discharge the treated water onto the land, and fresh water is released into the canal segment.
8. The water quality in the canal, pipelines and pivots are again monitored and analyzed until all treated water has been applied to the land through the irrigation systems.
9. Only then can the downstream check/drop structure be opened to allow water to again flow downstream.

Regardless of which procedure is used to treat a large-scale mussel infestation, a successful potash treatment program will require:

- A well-coordinated treatment strategy between irrigation districts and irrigation producers;
- Readily available supply of suitable potash;
- Robust mobile equipment to mix, transport and inject the liquid potash into the pipeline segments at all locations;
- The simultaneous operation of numerous mobile treatment systems;
- At least four trained staff for each mobile treatment system;
- In-place infrastructure, including an injection port near the pipeline inlet to allow injection of potash into the pipeline, and some type of cover to seal the pipeline inlet to allow the treated water to be held in the pipeline; and
- A road network that allows timely transport of the mobile treatment equipment.

7 Strategic Dreissenid Mussel Control Plan for the Irrigation Districts

Based on the assessment of options available to the irrigation districts for prevention, management, control, and eradication of dreissenid mussels, the following strategic plan is proposed.

7.1 Prevention

Preventing the introduction of mussels into the reservoir system should be a high priority for the irrigation districts, as the economic costs to irrigation districts and producers for prevention will be less than the potential economic costs to control mussels once they are introduced. Boating is the primary means by which dreissenid mussels move from one body of water to another. The mussels can transfer from the boat's hull, motor or ballast tank to the new water body. Before a boat becomes a successful carrier, mussels must:

- Attach to the hull or internal surfaces such as ballast tanks or live wells if present;
- Survive air exposure during draining of water, and overland transport; and
- Establish a viable population in the new body of water to which they are introduced (Collas et
-
- al., 2016).

Johnson and Carleton (1996) also identified recreational boating as a primary means of mussel dispersion. Survival of adult dreissenid mussels during transport increases with lower air temperature, increased humidity and increased size of the mussels. This was confirmed by Collas et al. (2016). DeVentura et al. (2016) identified boats present seasonally or year-round in infected water bodies as having the highest rate of fouling compared to boats immersed in infected water bodies for a short period of time. Dispersal via recreational boats was also reported in Ireland (Minchin et al., 2003) and in Switzerland (De Ventura et al., 2016).

Given the above findings, a key irrigation district prevention strategy would be to restrict and control the number of boat launch sites on their reservoirs, and staff each boat launch site to ensure all incoming boats and other watercraft are free of mussels. Restricting boat access to specific locations that are monitored and controlled, would significantly reduce the potential for a mussel infestation. Requiring boat owners to obtain a "mussel-free" certification before allowing entry to a reservoir is probably the easiest mechanism for the irrigation districts. It is recognized these measures will require additional funding for manpower and infrastructure, but these costs will be less than the costs to manage and control a dreissenid mussel infestation.

It is recommended that the irrigation districts and the GoA jointly develop a boat access and control strategy for all reservoirs as soon as possible to safeguard reservoirs from a mussel infestation.

To be effective, boat launch restriction measures must also be implemented at the GoA reservoirs, particularly Payne, Oldman, St. Mary, Waterton, Milk River Ridge, Jensen, Little Bow, McGregor and Travers reservoirs. It is recommended that the irrigation districts and GoA jointly develop a boat access and control strategy for all irrigation water supply reservoirs as soon as possible to safeguard reservoirs from mussel infestation.

7.2 Public Education

Development and implementation of a comprehensive public education program should precede and run concurrently with the controlled boat access program. This will ensure that current and future recreation users of the irrigation district reservoirs are fully aware of the significant economic and environmental effects of a dreissenid mussel infestation, and allow the public to better understand and appreciate the rationale for the irrigation districts' actions. The current signage programs initiated by the GoA and irrigation districts at key boat launch sites is an excellent example of an ongoing, proactive public education program. This could be further enhanced with public forums and field days to speak directly to boaters and other recreational water users, and development and distribution of dreissenid mussel factsheets and brochures (Figure B-1.1) to irrigation reservoir water users to further emphasize the importance of preventing a mussel infestation, and notify potential reservoir water users of pending mussel prevention actions being taken by the irrigation districts.
An example of a successful mussel prevention program was developed by the State of Minnesota, where zebra mussels were first observed in 1989. Minnesota has almost 12,000 water bodies (lakes, rivers, and wetlands), and it was recognized that a mussel infestation in these lakes and waterways could have very serious consequences. An aggressive campaign was therefore implemented to prevent and minimize the spread of mussels in the state, through education, monitoring, inspection, and legislative programs. Minnesota is home to about 867,000 boats, and a key focus of the prevention program was to minimize the transport of zebra mussels by recreational boats, through public education, inspections, and regulation. Figure B-1.2 is an example of a factsheet prepared and distributed by the State of Minnesota. The prevention program has been considered successful, as shown in Figure 7.1 (MDNR, 2002). Compared with other states such as Michigan and Wisconsin, the spread of zebra mussels has been significantly less. In 2014, less than 100 water bodies had recorded the presence of zebra mussels (MDNR, 2015).

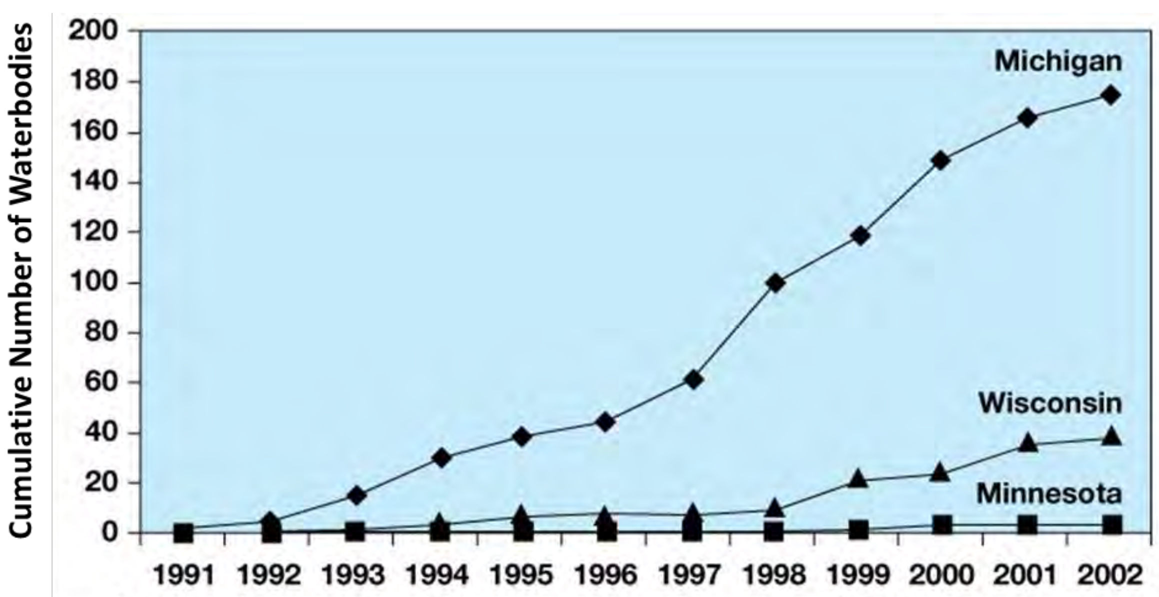


Figure 7.1 Spread of zebra mussels in Minnesota, Wisconsin, and Michigan
Source: Minnesota Department of Natural Resources, Exotic Species Program, 2002 Annual Report

7.3 Preparing for a Dreissenid Mussel Infestation

7.3.1 Assessing the Risks

Mussel Development - There are many factors that will determine the ability of dreissenid mussels to develop and grow in southern Alberta reservoirs (Table 5.1), and the GoA and irrigation districts have collected a significant amount of useful information for many of these factors. Additional information for key factors, while not critical, would be valuable to more accurately assess growth and development potential within each of the reservoirs. This information may allow the GoA and irrigation districts to more effectively target and develop prevention and control measures. The use of portable water quality meters (e.g. Hydrolab DS5X) may provide a more cost-effective alternative than laboratory analyses to carry out "spot-check" measurement of these parameters.

Collecting additional water profile temperature data for reservoirs will help determine the depths where most of the mussel development is expected to take place. If the temperature profile indicates that development will be restricted to the shallow regions of the reservoir, it may prove feasible to kill, by desiccation and freezing, a significant percentage of the mussels during normal reservoir drawdown for winter operations. The data may also show that drawing the reservoir down to slightly lower levels than normal may kill a much higher percentage of the mussel population.

Monitoring for Mussels - The existing data indicates that it will take three to five years for mussels introduced to a reservoir to become a significant problem in downstream irrigation water supply systems. While it is recommended that some form of veliger and adult mussel monitoring program in the reservoirs continue, an annual monitoring program may be adequate. The following are plausible options for annual monitoring of veligers and adult mussels in GoA and irrigation district reservoirs.

- Collection of a plankton sample in August/September would provide a reasonable opportunity to determine if veligers are present.
- Visual inspection of exposed infrastructure in the fall, after the reservoirs have been drawn down, would provide an good opportunity to determine if adult mussels are present.

This, combined with additional monitoring to obtain information related to mussel growth and development potential for a particular reservoir, will help determine the timing and expected severity of a mussel infestation in downstream water delivery canals, pipelines, and on-farm irrigation systems.

7.3.2 Adapting Existing Irrigation Water Delivery Systems

Draining the water from the irrigation delivery and on-farm irrigation systems during the cold winter months is the most cost-effective dreissenid mussel control option available to the irrigation districts.

Draining the water from the irrigation delivery and on-farm irrigation systems during the winter months appears to be the most cost-effective dreissenid mussel management and control option available to the irrigation districts. For all surface canals, drains, and on-farm sprinkler irrigation systems, desiccation and prolonged freezing winter temperatures will kill any mussels that are present.

Draining the water from the irrigation district and producer-owned water supply pipelines should result in 100% mortality of any exposed mussels through desiccation. Additional information is required to determine if mussels, which are present in pools of water that remain after the pipelines are drained, are able to survive the winter. Pipelines installed below the winter frost line may not freeze sufficiently to kill mussels trapped in the small pools of water, if dissolved oxygen levels in the water is adequate.

It is recommended the irrigation districts and irrigation producers take the following actions to assess the potential winter survivability of mussels in the underground pipeline systems.

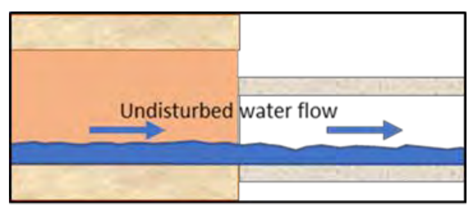
- Assess the dewatering potential of all underground pipelines.
    - Identify depressions or other locations within the pipeline where water may remain after the pipeline is drained each fall. If possible, estimate the total volume of the remaining water, and compare this to the total canal capacity. Pipelines with significant pools of water that remain after fall drainage, and do not freeze during the winter, may require additional treatment to kill the mussels.
    - Mussels located in small pools of water may survive the winter if oxygen levels in the water are adequate (>3 mg/L), and the water does not freeze completely.
- Assess the natural freezing potential of the underground pipelines.
    - Installing temperature sensors in representative pipelines during the winter season would be useful to determine if, and how often, complete freezing of any ponded water will occur.
    - Assess the dissolved oxygen levels of remaining pools of water in the pipelines throughout the winter.
    - These measurements should be carried out for a number of years, as dissolved oxygen levels and freezing potential may change.
- Implement a pumping program to remove excess water from pipelines.
    - Discussions with irrigation district representatives indicated that significant volumes of water may remain in some small sections of pipelines.
    - Pumping is already being carried out to remove excess water in some sections. This program should be expanded to include all sections where significant volumes of water that remain after fall drainage may harbour the dreissenid mussels.
- Assess and develop the potential to introduce freezing winter air into pipelines.
    - For those pipelines located below the winter frost line, some type of suction fan installed at the downstream end of the pipeline could be tested to draw sufficient cold winter air into the pipeline to freeze any pools of water where mussels are present.
    - Air vents strategically located along the pipelines may also increase the potential to draw the cold air into the entire pipeline.

- Assess and retrofit existing pipelines to allow for the disposal of dead mussel shells.
    - Removing mussels that have been killed through winter desiccation and freezing may require changes to the downstream end of irrigation district pipeline segments. Existing drainage valve assemblies located at the end of the pipelines, may not allow all water to be drained from the pipeline, and my not be large enough to permit flushing of dead mussel shells from the pipeline.
    - Provided that only one year of mussel recruitment is present in the pipeline, the mussel shell volume should be relatively small.
- Irrigation producers should work with the irrigation districts to assess the drainage and freezing potential of their underground water supply pipelines.
    - Pump out any remaining water in underground water supply pipelines that do not freeze in winter, and where mussels may congregate.
    - Ensure that pump intake screens for sprinkler irrigation systems are suitable to exclude dreissenid mussels that may plug sprinkler nozzles. Additional cleaning and maintenance of the screens may be required, depending on the extent of the mussel infestation.

7.3.3 Design of New Pipelines

It is recommended that new pipelines installed within the irrigation districts are designed and constructed to optimize winter desiccation of dreissenid mussels. Desiccation of remaining mussels will be the easiest control method, if remaining water in the pipelines can be eliminated, or minimized. The following recommendations are suggested.

- Ensure that pipelines are installed on-grade to minimize the number of depressions in the pipelines that may create after-drainage pools of water where mussels can collect and survive during the winter.
- Use eccentric, rather than concentric reducers wherever possible to minimize the number of sites where mussels can survive after drainage of the pipeline.
- Consider installing air vents at strategic locations on pipelines located below the frost line to optimize the transfer of cold winter air into the entire length of the pipeline.



Eccentric pipeline reducer

- At the downstream end of pipeline segments, incorporate a system that:
    - Allows the pipeline to be completely drained, and effectively flushed to remove any mussel shells from the pipeline; and
    - Accommodates installation of a suction fan to draw cold winter air into the pipeline to ensure freezing of any ponded water.

7.4 Killing Dreissenid Mussels in Pipelines with Potash

For those pipeline segments where winter desiccation and freezing may not be viable, and if regulatory approvals are in place, the use of potash is considered the most effective, and environmentally benign option to control dreissenid mussels. Ongoing research being carried out by AAF indicates that a potassium chloride solution, injected into the irrigation district pipeline near the pipeline inlet, can effectively deliver and maintain a potassium concentration in the pipeline that will achieve 100% mortality of mussels that are present. Discharge of the treated water, after the mussels are dead, may depend on the level of potash treatment applied, and regulatory approvals for the use of potash.

- A complete potash treatment, which completely fills the irrigation district and producer-owned water supply pipelines with the potash solution, will likely result in the treated water, once the mussels are dead, being discharged onto the land through on-farm sprinkler irrigation systems. This process would not allow any of the treated water to flow into open water bodies (canals, reservoirs, rivers).
- An abbreviated potash treatment, which introduces only a sufficient volume of treated water to submerge the remaining pools of water in the pipeline after fall drainage, could also be discharged through the producer-owned sprinkler irrigation systems. If regulatory approvals were in place, the treated water could instead be flushed through the end of the treated pipeline. This could happen immediately after the treatment is completed, or the next spring, when the pipeline would be flushed to dispose of any dead mussel shells.

If the number of mussel-infested pipeline segments are relatively small, the potash treatments can take place near the beginning and/or end of an irrigation season. This will reduce the inconvenience to irrigation districts and irrigation producers, and reduce potential economic effects on irrigation producers. Higher numbers of mussel-infested pipeline segments may require that treatment work also take place during the irrigation season, which could be economically challenging for irrigation producers.

The following are recommended actions related to the potash treatment options.

- Mobile equipment will be required to transport, mix, and inject the potash solution into mussel-infested pipeline segments.
    - This work could be provided to the irrigation districts by private contractors that have the appropriate equipment and trained staff, or
    - Irrigation districts could purchase the necessary equipment, either individually or co-operatively, and utilize district staff to carry out the treatments on an as-needed basis. Irrigation district staff will need training for this work, but given their ongoing experience working with pumps and water delivery systems, this training should not pose a significant challenge.
    - Depending on the severity of a dreissenid mussel infestation, staff may be required to work on the pipeline potassium treatment program for several weeks each year. This may affect completion of their regular responsibilities during the busy spring and fall seasons.

    - The potash treatment storage and pumping equipment will need to be large enough to allow for the effective treatment of all sizes of pipeline segments. This equipment also needs to be sufficiently mobile and robust to access all potential sites where treatment is required.
        - For example, complete treatment of a 1.2-m diameter pipeline, about 5 km long, will require injection of about 4,700 L of potassium chloride solution, at a concentration of 120,000 mg/L potassium, into the pipeline to achieve the desired 100 mg/L potassium concentration in the pipeline.
        - The volume of potassium chloride solution will increase depending on the number of sprinkler irrigation systems served by the pipeline segment.
- Pipeline segments undergoing the complete potash treatment require that an appropriate injection valve be installed near the pipeline inlet, and some type of gate structure at the pipeline opening to allow the treated water to be held in the treated pipeline segment(s). Abbreviated potash treatment may require less structural improvements.
- Utilizing producer-owned sprinkler systems to discharge the treated water on the land, after the treatment process is completed, may be an important environmental requirement by the GoA. It will be useful to coordinate each pipeline treatment with irrigation producers served by the pipeline segment, to ensure the treated water can be discharged onto the land after the treatment process is complete.
- An early awareness and education program is strongly recommended to inform irrigation producers about the need, and the shared responsibilities required to achieve a successful treatment program for mussel eradication.

8 Conclusions

Alberta is fortunate that dreissenid mussels do not appear to be currently present in any of the province's water bodies. The extensive irrigation water supply network in southern Alberta will be especially vulnerable if invasive mussels are introduced to irrigation water supply reservoirs in the province. An enhanced program to prevent the introduction of dreissenid mussels into these reservoirs should be a high priority for the GoA and irrigation districts.

This report identifies the need for Alberta's irrigation districts and GoA to prevent the spread of dreissenid mussels into irrigation water supply reservoirs, and potential management and control options if a mussel infestation occurs. An enhanced prevention strategy includes controlling boat launch sites on reservoirs to certify that all incoming boats and other watercraft are free of mussels, combined with a comprehensive public education program. Targeted monitoring of irrigation water supply reservoirs will help irrigation districts better understand the growth and development potential of the dreissenid mussels, and this will support the development and assessment of more effective mussel management and control options.

Southern Alberta's relatively long and cold winters are considered a key element in the control of dreissenid mussels in water supply reservoirs, irrigation canals, and pipelines. Where winter desiccation and freezing are not practical for selected pipelines, injection of potassium chloride solution (potash) into mussel-infected pipelines is considered to be the most effective, practical, and environmentally benign mussel control option available to the irrigation districts. While there are many other chemical and non-chemical treatment options that are being used to control dreissenid mussels, most are being used in relatively small, stand-alone operations.

The following provides a more detailed description of the report's key conclusions and supporting rationale.

1. **Dreissenid mussels (zebra and quagga) entered the eastern United States from Europe in the 1980s, and have since spread to the Great Lakes and waterways, rivers, and lakes in many parts of North America.**
    a. Dreissenid mussels can reproduce rapidly, and the accumulation of adult mussels results in challenges due to fouling of water structures and pipelines.
    b. Ongoing management and treatment costs to control dreissenid mussels can be very high for industries and municipalities.
    c. In 2013, the total annual cost of invasive mussel control for Alberta was calculated at about $75.5 M.
    d. This total cost does not include costs associated with irrigation district or rural water supply pipelines.

2. **It is likely that dreissenid mussels will appear in irrigation water supply reservoirs under the current prevention program being implemented in Alberta.**
    a. Recreational boats are the primary means by which dreissenid mussels move from one body of water to another. Adult mussels attach to the hull of boats, larval stages can be transported in water filled internal ballast tanks or live wells, and both life stages can survive overland transport to new water bodies.
    b. In 2013, zebra mussels were found in Lake Winnipeg (Manitoba). There was concern that mussels had been discovered in the Tiber Reservoir (Montana) in November 2016. However, further investigations carried out in 2017 found no evidence of mussels.
    c. In 2013, mussel-infested boats were discovered at inspection stations at several central Alberta lakes (Sylvan, Pigeon, Gull, and Wabamun lakes), and Chestermere Lake, which supplies water to the WID in southern Alberta.
    d. The discovery of dreissenid mussels in water bodies that are relatively close to southern Alberta's borders, combined with the high volume of boat and watercraft traffic into Alberta from mussel-infested areas in Canada and the United States, makes it likely that dreissenid mussels will be introduced into Alberta irrigation water supply reservoirs in the future.

3. **Alberta's irrigation water supply reservoirs and irrigation district water supply infrastructure will support the growth and development of dreissenid mussels.**
    a. Key factors such as calcium, pH, dissolved oxygen, and temperature in irrigation water supply reservoirs and water supply infrastructure meet the requirements for dreissenid growth and development.
    b. Mussel development will likely be limited to the shallower portions in many of the irrigation water supply reservoirs, where summer water temperatures are warmer.
    c. Growth rates for the dreissenid mussels are expected to be 1 to 1.5 mm/mo for most of the reservoirs.
    d. The length of the reproductive season is likely to be relatively short, as reproductive temperature timelines are generally short for most irrigation water supply reservoirs in southern Alberta. Increasing temperatures related to climate change may increase the length of the reproductive season.
    e. From the time mussels first appear in an upstream reservoir to when there is an adequate number of veligers present to settle in downstream irrigation systems will likely take three to five years.
    f. Only one irrigation water supply reservoir in Alberta may be naturally resistant to mussel establishment. High levels of naturally occurring potassium in Cavan Lake Reservoir will likely prevent growth and development of dreissenid mussels in the Ross Creek Irrigation District (RCID).

4. **A mussel infestation in an upstream reservoir will likely affect several downstream reservoirs, and the rivers that accept return water related to the infested reservoir(s).**
    a. Active treatment of most water supply reservoirs to eradicate these mussels is not feasible.
    b. Since mussel development will mainly take place in the shallower zones of most irrigation water supply reservoirs, drawdown of these reservoirs for normal winter operations will kill any exposed mussels due to desiccation and freezing.
    c. Once a reservoir becomes infected, water supply canals and underground pipelines located downstream of the infested reservoirs will become infested.
    d. Control and eradication of the dreissenid mussels in the irrigation water supply infrastructure will likely become the focus of the irrigation districts.

5. **Natural desiccation and freezing during the winter provides the most cost-effective means of controlling dreissenid mussels in Alberta's irrigation water supply canals and pipelines.**
    a. Southern Alberta winters, which require that all irrigation water delivery and on-farm irrigation systems be drained, can effectively kill exposed mussels.
    b. Mussels in surface canals are particularly vulnerable during the winter months, and 100% mortality is expected each winter.

c. All exposed mussels in underground pipelines will be killed through desiccation during the winter months, because of prolonged exposure and relatively low humidity.
d. Mussels present in pools of water that remain in pipelines after drainage in the fall may survive the winter if the water does not freeze, and dissolved oxygen levels exceed 3 mg/L.
e. Complete drainage of underground pipelines, and/or exposure of pipelines to cold winter air, is required to ensure complete mortality of mussels during the winter season.

6. **Currently, there are no registered control options for invasive mussels in open bodies of water or irrigation pipelines in Canada.**
    a. To date, most successful treatment options to control or eradicate dreissenid mussels in North America have been carried out in relatively small, stand-alone facilities, such as power stations, industrial plants, and municipal water treatment facilities.
    b. Chlorine is used extensively for dreissenid mussel control in the Great Lakes Basin, through an exemption to registration by the Ontario Ministry of Environment. The use of chlorine as well as discharge is controlled by an individual facility's permit for use.
    c. Potassium chloride (potash) has been successfully used to control mussels in water bodies in Canada and the United States, and is currently considered to be the primary approach for controlling dreissenid mussels in Alberta's irrigation water delivery systems.
    d. Alberta Environment and Parks is currently working to register potassium chloride with the PMRA for use in Alberta water systems.
    e. Research is being carried out to develop practical, cost-effective potassium chloride injection methods for Alberta's irrigation water supply pipelines.

7. **Irrigation districts have three options to consider for management and/or control of dreissenid mussels that are present in underground water delivery pipelines.**
    a. Winter desiccation.
        i. Nearly all mussels that accumulate in the underground pipelines during the summer will be exposed after the pipelines are drained in the fall. These exposed mussels are expected to die during the prolonged winter period through desiccation.
        ii. The small pools of water remaining in the pipeline after drainage, where mussels might survive, generally represent a small fraction of the total pipeline capacity.
        iii. Mussels present at these locations during the winter will be isolated, because the remainder of the drained pipeline will be too dry to sustain them.

iv. These colonies of mussels living in these pools of water are likely to have a minimal impact on the flow and capacity of the affected pipelines.
v. This option would have minimal costs to the irrigation district, and should pose no impacts on the ability to delivery water to all users.
vi. This option does not address the possible accumulation of mussels in producer-owned water supply pipelines that are not properly drained in the fall.

b. Kill all mussels by injecting a sufficient volume of potassium chloride to fill the pipeline.
   i. Potassium chloride solution is injected into the irrigation district pipeline until the desired potassium concentration of 100 mg/L is reached in the pipeline, and producer-owned water supply pipelines, and irrigation pivot systems. The treated water is held in the irrigation district and producer-owned water supply pipelines for five to six days. After the treatment is completed, fresh water is injected into the pipeline, and the treated water is applied to the irrigated fields through the pivots.
   ii. This option is relatively costly, and requires a significant amount of time and manpower to complete.
   iii. This option aims to have all treated water applied to the land, and potash-treated water does not return to an irrigation canal or other surface water body.
   iv. An initial flush of water through the treated pipeline segments in the spring should remove all detached mussel shells from the pipeline.
   v. This option may be logistically difficult to achieve during the spring and fall time periods, that are the most conducive to irrigation producers.

c. Introduce a relatively small volume of potassium chloride into the pipelines to kill mussels that may survive in remaining pools of water.
   i. Since the surviving mussels are concentrated in the small pools of water on the pipeline floor, injecting a relatively small volume of potassium chloride solution, enough to cover the remaining pools of water after drainage, should achieve 100% mortality of any remaining mussels. The volume of treated water would have to be sufficient to flow into all pipeline segments. The potash solution could be pumped into the pipeline inlet, without it needing to be completely sealed. The treated water could be discharged onto the land through producer-owned pivot systems, or left in the pipeline during the winter months, and discharged from the pipeline when the water is turned on in the spring.
   ii. This option will require much less volume of potassium chloride solution than the above option, will be easier to introduce into the pipeline, and require less time and manpower to implement.

    iii. This option would not address the potential accumulation of mussels in producer-owned water supply pipelines.

8. **Complete treatment of all irrigation district and producer-owned water supply pipelines with potassium chloride (potash) is estimated to cost about $1.1 million.**
    a. This estimate is based on the costs associated with the use of potash to control mussels in Lake Winnipeg.
    b. The majority of the cost is associated with manpower and equipment. The actual cost of the potash represents about 11% of the total cost estimate.
    c. Actual costs to treat the 900+ pipeline segments within the 13 irrigation districts, if required, may be greater because of the number of mobile treatment systems that may be required. In addition, this equipment will have to be moved many times over relatively long distances.
    d. Treatment periods in the spring and fall of each year are likely the most agreeable to irrigation producers, given their need for irrigation to meet crop demands during the summer. Treatment in early May and late September/early October would provide about 30 days of active pipeline treatment activities.

9. **It will be logistically difficult to treat all 900+ pipeline segments during the 30-day spring and fall periods.**
    a. At least nine days will be required to initiate, implement, and complete the potassium treatment of each pipeline segment.
        i. Cool water temperatures at these times will require the potassium-treated water to remain in the pipeline segment and pivots for five to six days to ensure 100% mortality of the dreissenid mussels.
        ii. Additional time will be required to set up and charge the pipelines to achieve the target potassium concentration.
        iii. An additional two days are required, after the treatment is complete, to determine if all mussels in the treated water have been killed.
    b. It is estimated that at least 60 mobile treatment systems, operating simultaneously, would be required to treat all pipeline segments in the combined 30-day window during the spring and fall.
    c. The number of mobile treatment systems could be reduced to about 10 if continuous treatment of the 900+ pipeline segments took place from May 1 to October 30 each year.

9 Recommendations

1. **The GoA and irrigation districts should consider implementing additional prevention measures to minimize the threat of mussel infestation at high-risk water storage reservoirs.**

a. Remaining mussel free should be a very high priority for the GoA and the irrigation districts to avoid the difficulties and high costs of control and treatment programs once dreissenid mussels become established.
b. The current boat monitoring program at key entry points is beneficial, but may not be totally effective, as boats can continue to enter the province at many locations that may not be fully monitored.
c. An enhanced GoA/irrigation district prevention strategy is recommended, which includes:
    i. Restricting and controlling the number of boat launch sites on reservoirs, and staffing each boat launch site to ensure all incoming boats and other watercraft are free of mussels; and
    ii. A comprehensive public education program that precedes and complements actions such as limiting boat access to reservoirs. Public education regarding the effects associated with dreissenid mussel infestation should also be an ongoing activity for the irrigation districts. This will reinforce the understanding of current and future recreation users of the economic and environmental effects of a dreissenid mussel infestation, and increase understanding and acceptance for the irrigation districts' actions.
d. Cost of prevention measures will be less than those related to management and control of a dreissenid mussel infestation, and will prevent potentially harmful environmental effects to reservoirs, rivers, and irrigation district water supply systems.

2. An ongoing monitoring program should be implemented to detect the presence of dreissenid mussels in irrigation water supply reservoirs.
a. Existing data indicates it will take three to five years for mussels introduced into a reservoir to become a significant problem in downstream irrigation water supply systems.
b. At minimum, annual monitoring of veliger and adult mussels in GoA and irrigation district reservoirs should be continued. The following are recommendations for annual monitoring of veligers and adult mussels in GoA and irrigation district reservoirs.
    i. Collection of a plankton sample in August/September provides a good opportunity to determine if veligers are present.
    ii. Visual inspection of exposed infrastructure in the fall of the year, after the reservoirs have been drawn down, would provide a good opportunity to determine if adult mussels are present.
    iii. These, combined with additional monitoring to obtain information related to mussel growth potential for a particular reservoir, will help determine the timing and expected severity of a mussel infestation in downstream water delivery canals and pipelines, and on-farm irrigation systems.

c. It is important to know, as soon as possible, when dreissenid mussels are present in a reservoir. This, combined with available information related to mussel growth potential for a particular reservoir, will help determine the timing and expected severity of a mussel infestation in downstream water delivery canals and pipelines, and on-farm irrigation systems.

3. **Monitoring water in the irrigation districts' water supply reservoirs should continue, to assess the growth and development potential of dreissenid mussels.**
   a. There are many factors that determine the ability of dreissenid mussels to develop and grow in southern Alberta reservoirs, and the GoA and irrigation districts have collected a significant amount of information for many of these factors.
   b. The AAF irrigation water quality monitoring program (2006 to 2007 and 2011 to 2016) provides good information on growth factors such as calcium, pH, and temperature. However, chlorophyll a data were somewhat limited.
   c. Additional information related to these key factors, while not critical, would be useful to more accurately assess mussel growth and development potential within each of the reservoirs.
   d. This information may allow the GoA and irrigation districts to more effectively target and develop prevention and control measures.
      i. Water profile temperature data for reservoirs will help determine the depths where most mussel development will take place. These data may help determine the feasibility to kill, through desiccation and freezing, a significant percentage of the mussels through normal reservoir drawdown for winter operations.
      ii. The data may also show that periodically drawing the reservoir down slightly more than normal may kill a much higher percentage of the mussel population.
   e. The use of portable water quality meters (e.g. Hydrolab DS5X) may provide a more cost-effective alternative than laboratory analyses to carry out "spot-check" measurement of these parameters.

4. **Irrigation districts should exploit Alberta's cold winter temperatures to control dreissenid mussels that settle in irrigation water delivery infrastructure.**
   It is recommended the irrigation districts and irrigation producers take the following actions to assess the desiccation and freezing potential of the underground pipeline systems, and implement appropriate actions to correct any deficiencies.
   a. Assess the dewatering potential of all underground pipelines.
      i. Identify all depressions or other locations within the pipeline where water may remain after the pipeline is drained each fall.
      ii. Complete drainage of a pipeline will result in desiccation and death of any dreissenid mussels in the pipeline.
      iii. Mussels located in small pools of water may survive the winter if oxygen levels in the water are adequate (>3 mg/L), and the water does not

freeze completely. During several years, this population may grow, not from the reproduction of the mussels present, but from upstream recruitment.

   iv. Depending on the intensity of upstream infestation, three years of recruitment may result in partial obstruction of the pipe as well as a continuing source of shell debris as adult mussels die.

b. Assess the natural freezing potential of all underground pipelines.
   i. Install temperature sensors during the winter season to measure the temperature in representative pipelines sections, to determine if complete freezing of any ponded water will occur.
   ii. Assess the oxygen level of retained water in the pipelines.
   iii. These measurements should be carried out for a number of years, as oxygen levels and freezing potential may change.
c. Implement a pumping program to remove excess water from pipelines.
   i. Discussions with irrigation district representatives indicated that significant volumes of water may remain in some small sections of pipelines.
   ii. Pumping is already being carried out to remove excess water in some sections. This program should be expanded to include all sections where mussels are present.
d. Assess and develop the potential to introduce freezing winter air into pipelines.
   i. For those pipelines located below the winter frost line, some type of suction fan installed at the downstream end of the pipeline should be tested to draw sufficient cold winter air into the pipeline to freeze any pools of water where mussels are present.
   ii. Air vents strategically located along the pipelines may also increase the potential to draw the cold air into the entire pipeline.
e. Assess and retrofit pipelines to allow for the disposal of dead mussel shells.
   i. Removing mussels that have been killed through winter desiccation and freezing may require changes to the downstream end of irrigation district pipeline segments.
      - Discussions with irrigation district representatives indicate that some type of valve assembly is located at the end of the pipelines to allow drainage at the end of the irrigation season.
      - This valve opening may be relatively small, and mounted part way up the side of the pipeline.
      - This may not allow all water to be drained from the pipeline, and not permit flushing of mussel shells from the pipeline.
   ii. It is recommended that the downstream end of all pipelines be retrofitted to allow it to be opened completely during drainage, to allow flushing of all mussel carcasses from the system.

    iii. Provided that only one year of mussel recruitment is present in the pipeline, the mussel volume should be manageable, given the size of the population and the size of the individual mussels.

5. **Irrigation producers should work with the irrigation districts to assess the drainage and freezing potential of all underground pipelines that supply water to their on-farm sprinkler irrigation systems.**
    a. Pump out any remaining water in underground water supply pipelines that do not freeze in winter, and where mussels may congregate.
    b. Ensure that pump intake screens for sprinkler irrigation systems are suitable to exclude dreissenid mussels that may plug sprinkler nozzles. Additional cleaning and maintenance of the screens may be required, depending on the extent of the mussel infestation.

6. **New pipelines being installed within the irrigation districts should be designed and constructed to optimize winter control of dreissenid mussels.**
    a. Ensure that pipelines are installed on-grade to minimize the number of depressions in the pipelines, that may create after-drainage pools of water where mussels can collect and survive during the winter.
    b. Use eccentric, rather than concentric reducers wherever possible to minimize the number of sites where mussels can survive after drainage of the pipeline.
    c. Consider installing air vents at strategic locations on pipelines located below the frost line to optimize the transfer of cold winter air into the entire length of the pipeline.
    d. At the downstream end of pipeline segments, incorporate a system that:
        i. Allows the pipeline to be completely drained, and effectively flushed to remove any mussel shells from the pipeline; and
        ii. Accommodates installation of a suction fan to draw cold winter air into the pipeline to ensure freezing of any ponded water.

7. **Design and implement a comprehensive research study to assess the potential to manage and/or control dreissenid mussels in irrigation district and producer-owned irrigation water delivery pipelines through winter desiccation and freezing.**
    a. Select representative pipelines in the 13 irrigation districts and identify the locations and volumes of water that remain after dewatering in the fall of the year.
    b. Assess if remaining water in the pipelines will freeze during the winter periods.
    c. Determine if dissolved oxygen in water that remains in the pipelines is sufficient for mussels to survive the winter period.
    d. Assess whether these mussels pose a threat to the pipeline integrity, flow characteristics, and capacity to effectively serve all water users.
    e. Design and test practical and economically feasible methods to transfer sufficient cold winter air into the pipelines to freeze all remaining water.

f. Design and test systems that can effectively allow dead mussels shells to be removed from pipeline segments.

g. Develop and test pipeline design and construction technologies that will minimize the amount of water that remains in the drained pipelines during the winter, to increase the proportion of mussels killed through desiccation.

8. **Develop a potash injection strategy for those underground pipeline segments where winter desiccation and freezing may not be viable.**
   a. Identify pipeline segments that may require potash injection to kill mussels that are present.
      i. Maximize the number of pipeline segments where mussel control can be accomplished by winter desiccation and freezing; and
      ii. Minimize the number of pipeline segments that will require potash injection treatment.
   b. Determine if this work can be most effectively provided by private contractors or by irrigation district staff.
      i. If the decision is to use irrigation district staff, determine what mobile equipment will be required to transport, mix and inject the potash solution into mussel-infested pipeline segments.
      ii. Develop and implement a training program for irrigation district staff for the injection of potash into the pipelines.
   c. For pipelines where potash may be required, there may be a need to install:
      i. Potash injection valves near pipeline inlets; and
      ii. Some type of gate structure at the pipeline inlet to isolate and retain the potash solution in the pipeline segment.
   d. Develop a coordinated pipeline treatment program with irrigation producers served by the pipeline segment, to ensure potash injection activities are effectively coordinated.

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Appendix A Vulnerability of Individual Irrigation Districts

All data based on water quality sampling program carried out by AAF from 2006 to 2007 and from 2011 to 2016.

Appendix A-1 Western Irrigation District (2006 to 2007 and 2011 to 2016)

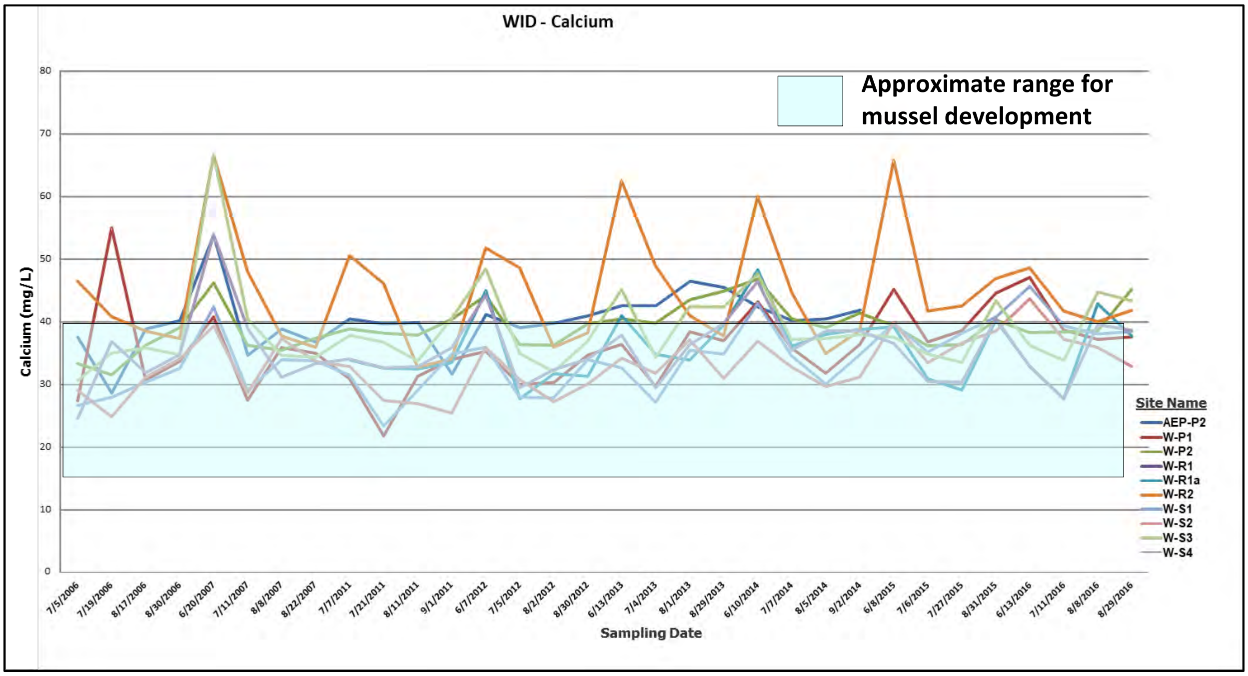

Figure A-1.1 WID - Calcium concentration in irrigation water

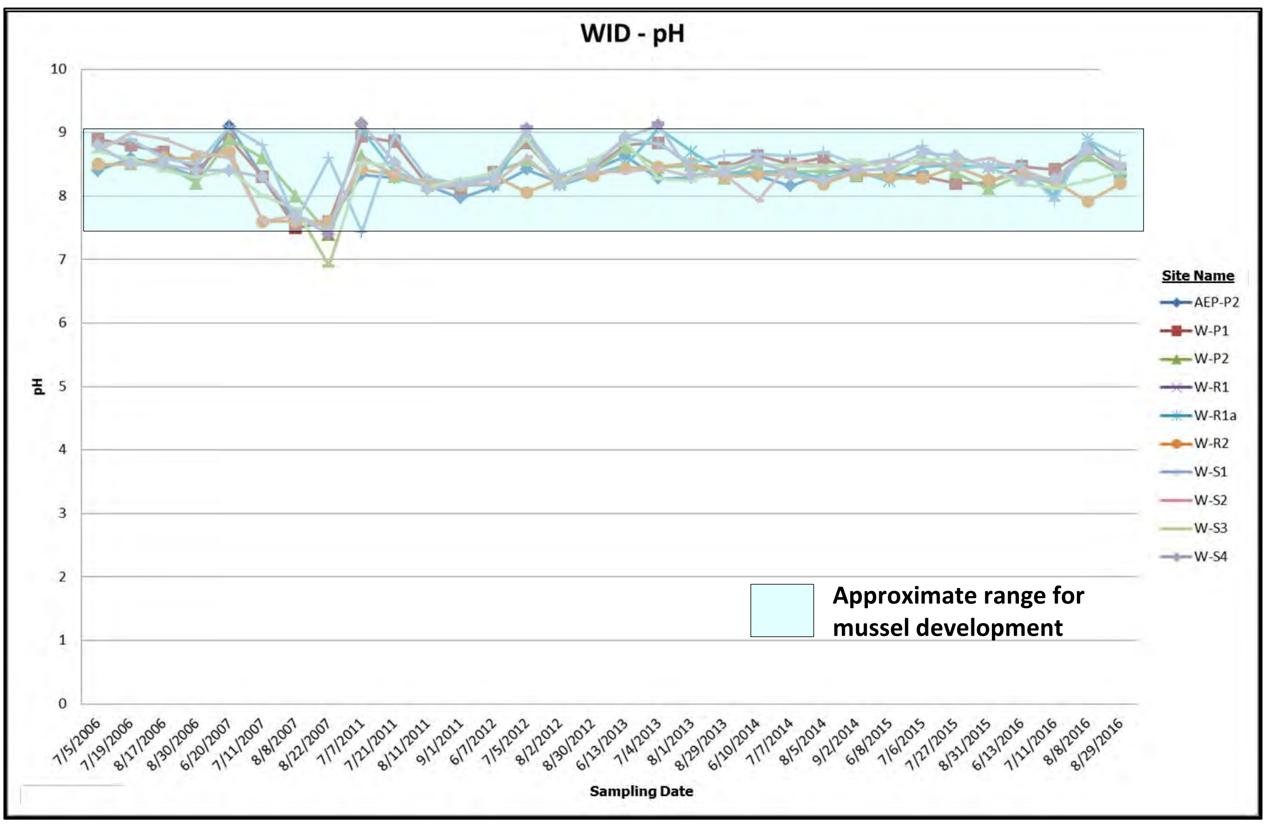

Figure A-1.2 WID – pH of irrigation water

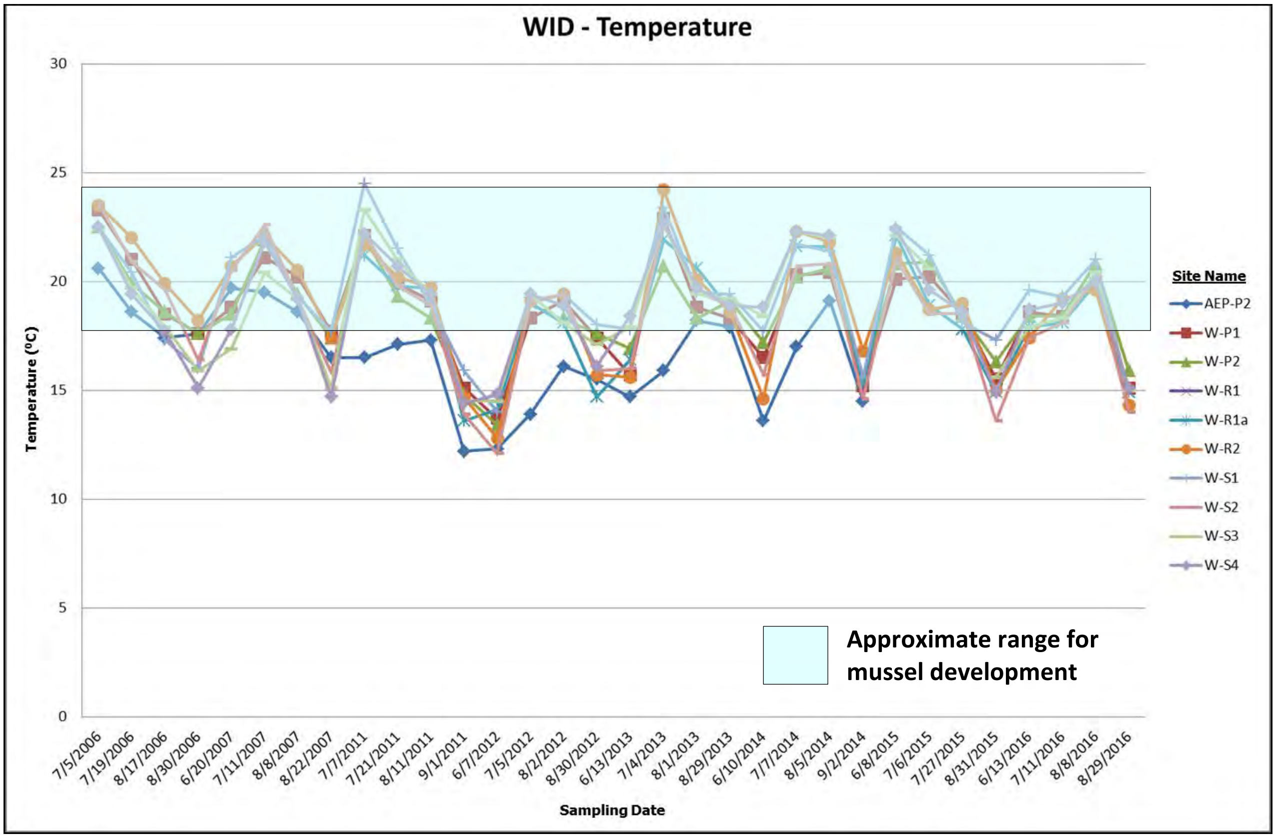

Figure A-1.3 WID – Temperature of irrigation water

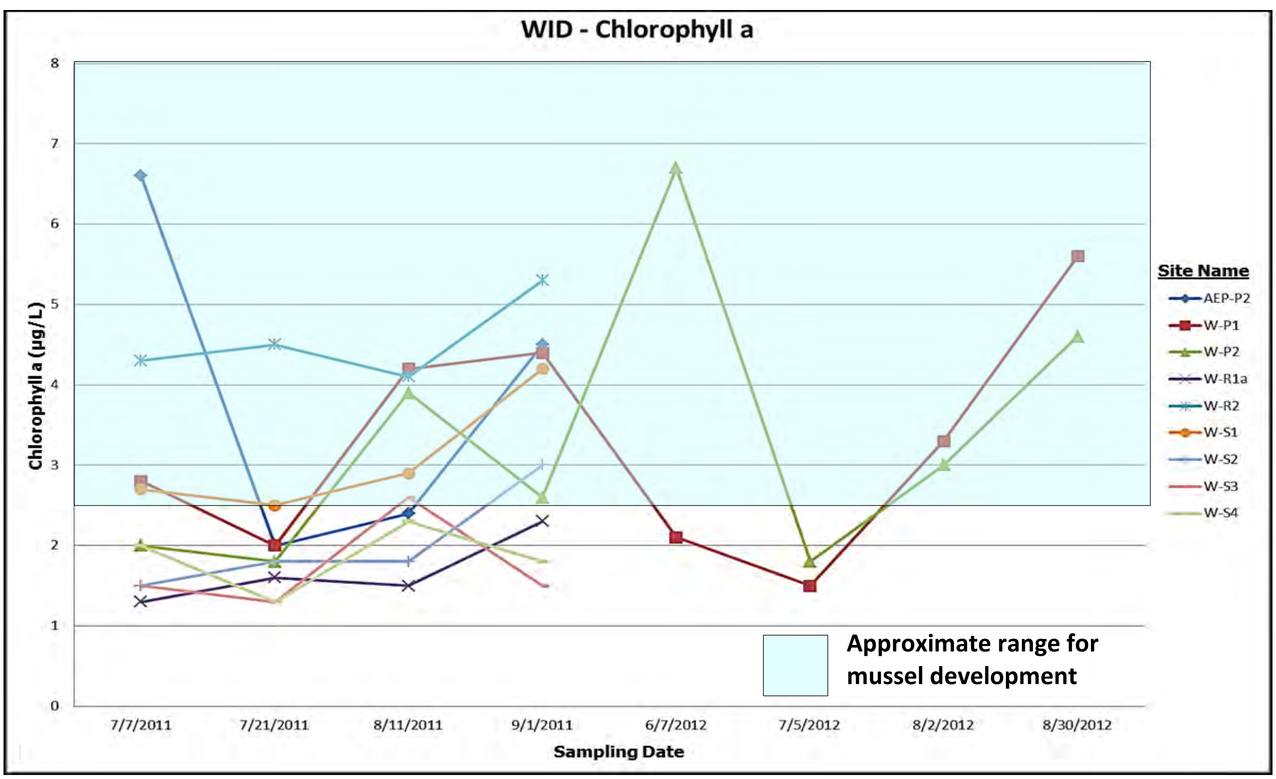

Figure A-1.4 WID – Chlorophyll a in irrigation water

Appendix A-2 Bow River Irrigation District (2006 to 2007 and 2011 to 2016)

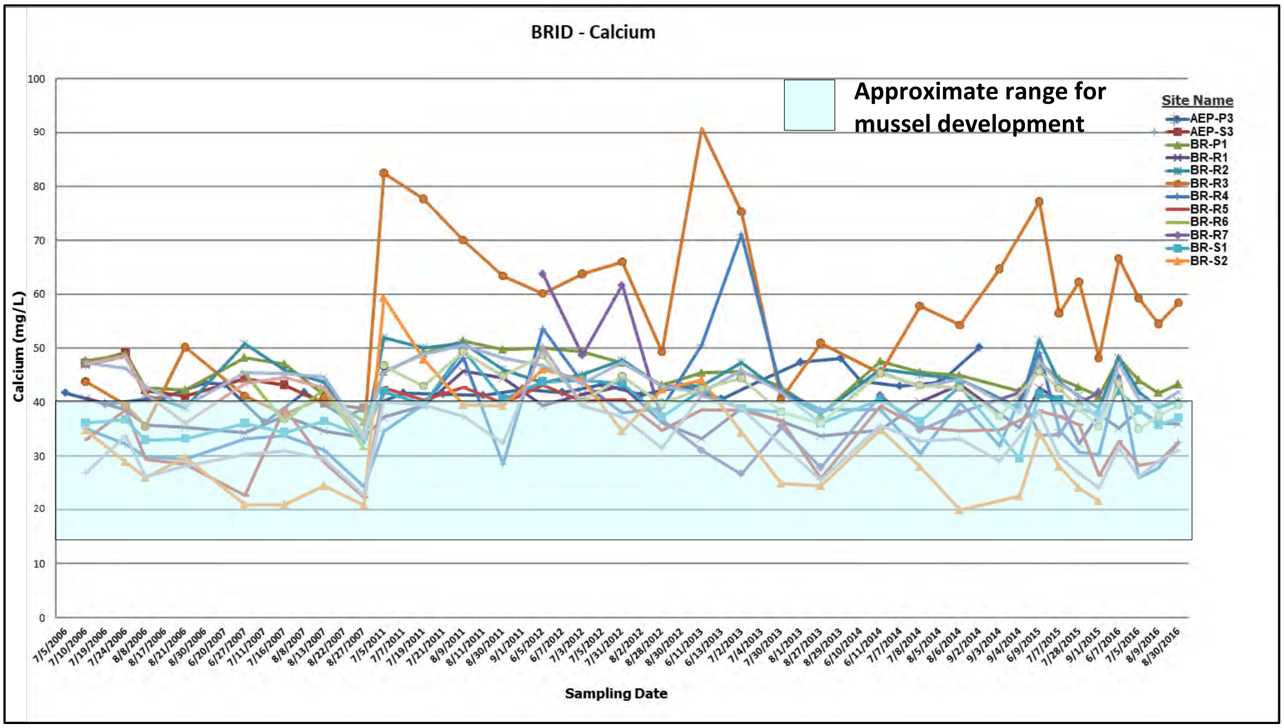

Figure A-2.1 BRID – Calcium in irrigation water

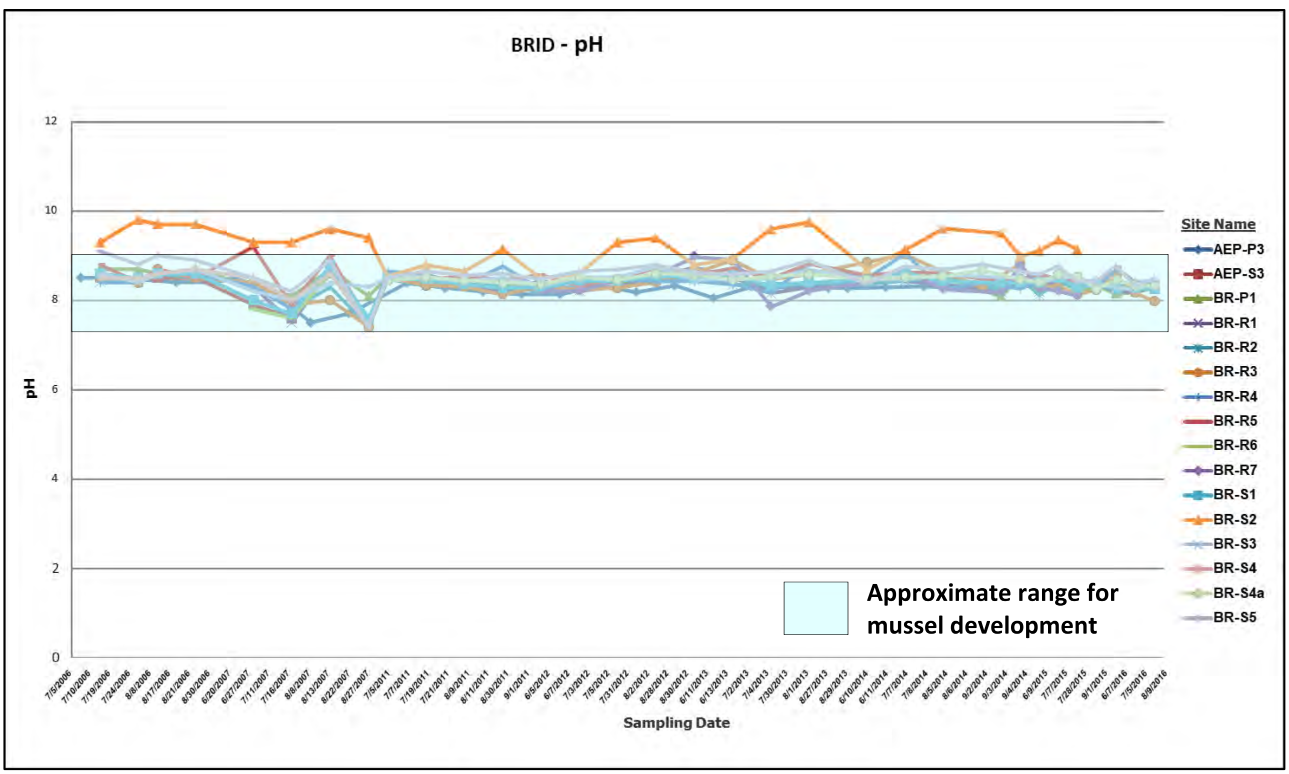

Figure A-2.2 BRID – pH of irrigation water

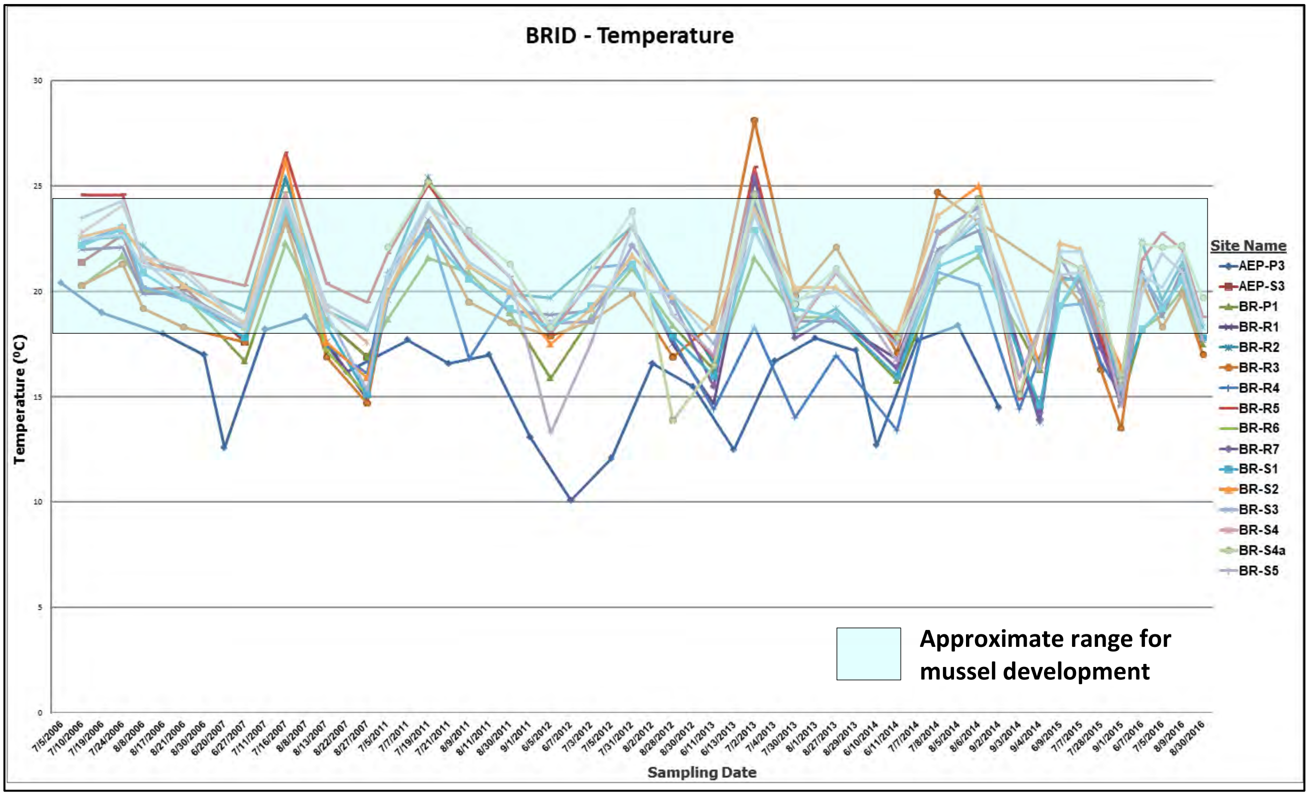

Figure A-2.3 BRID – Temperature of irrigation water

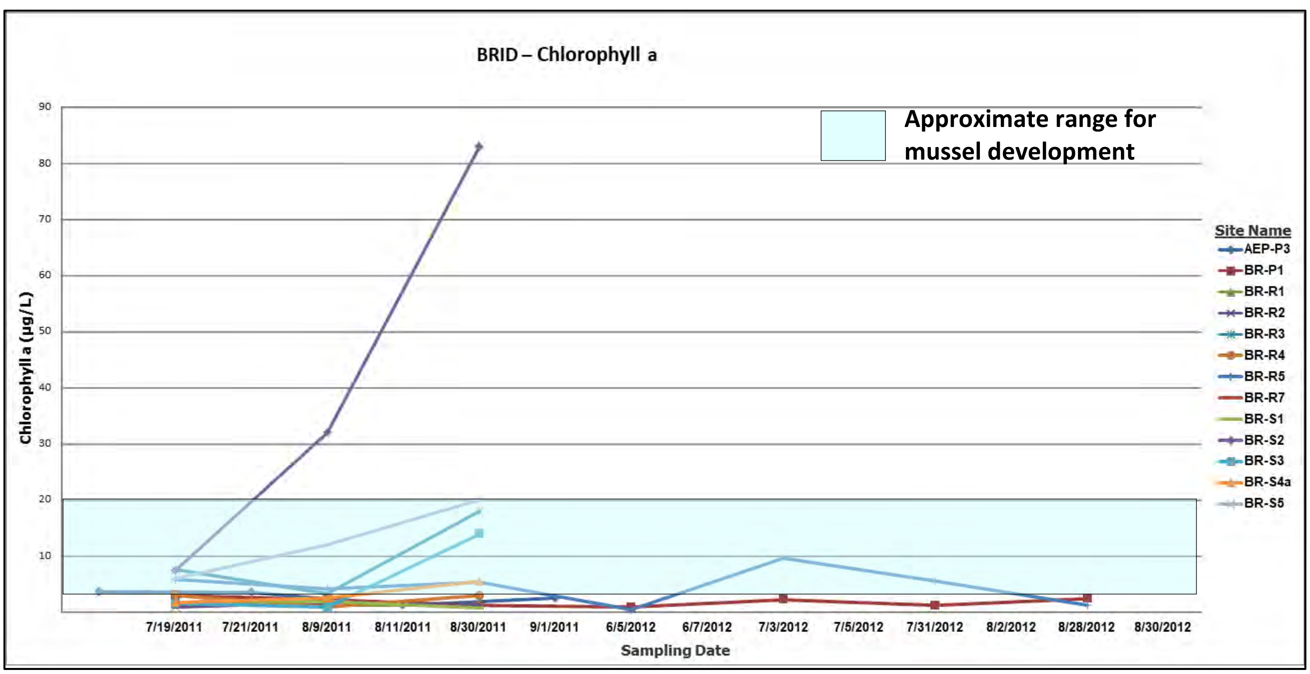

Figure A-2.4 BRID – Chlorophyll a in irrigation water

Appendix A-3 Eastern Irrigation District (2006 to 2007 and 2011 to 2016)

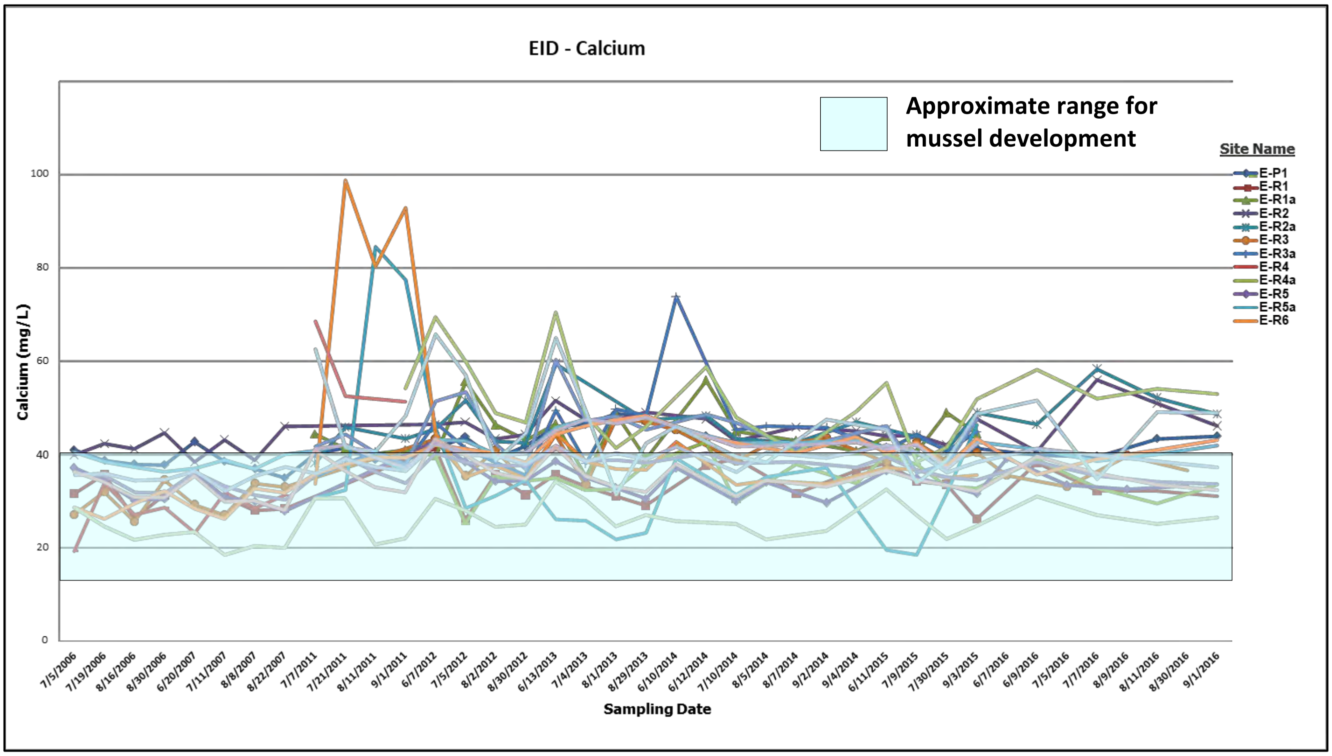

Figure A-3.1 EID – Calcium in irrigation water

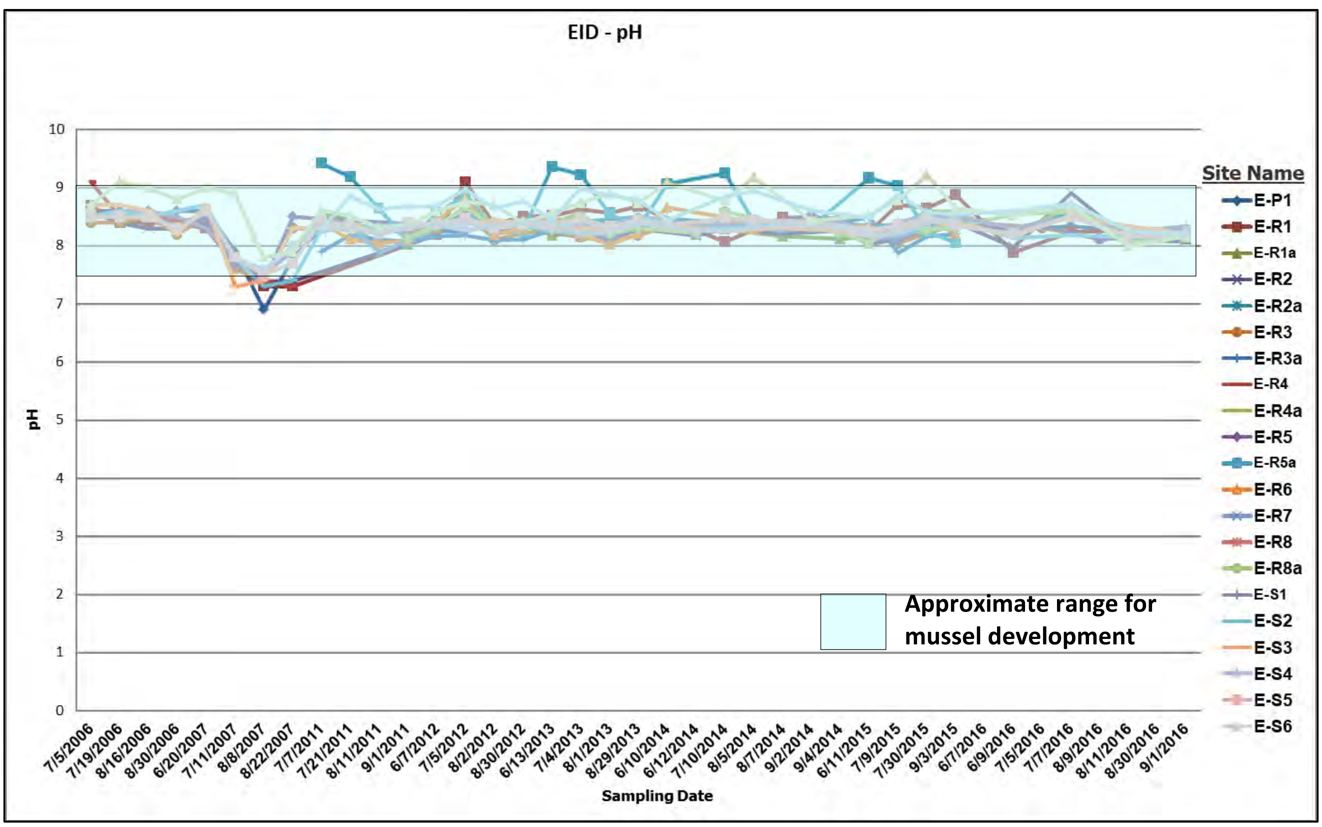

Figure A-3.2 EID – pH of irrigation water

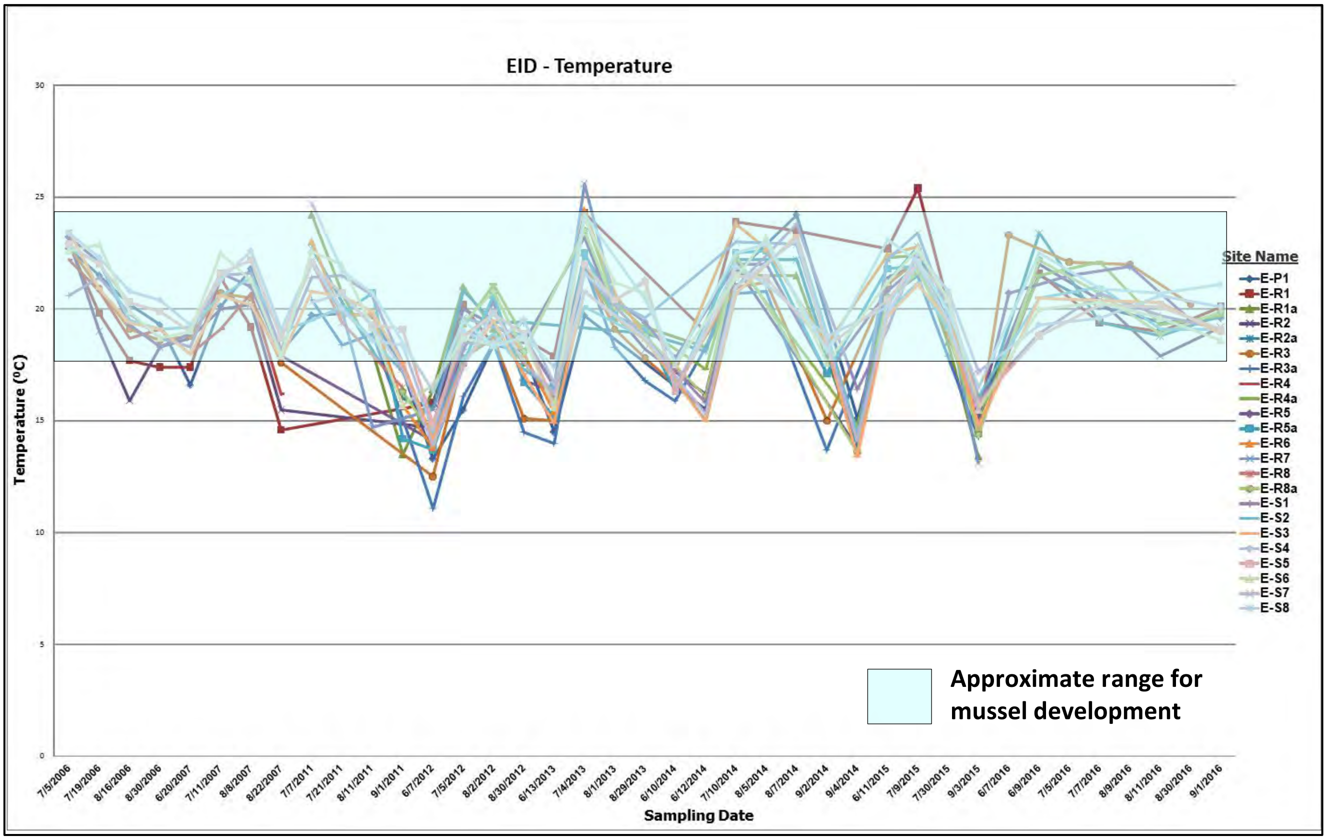

Figure A-3.3 EID – Temperature of irrigation water

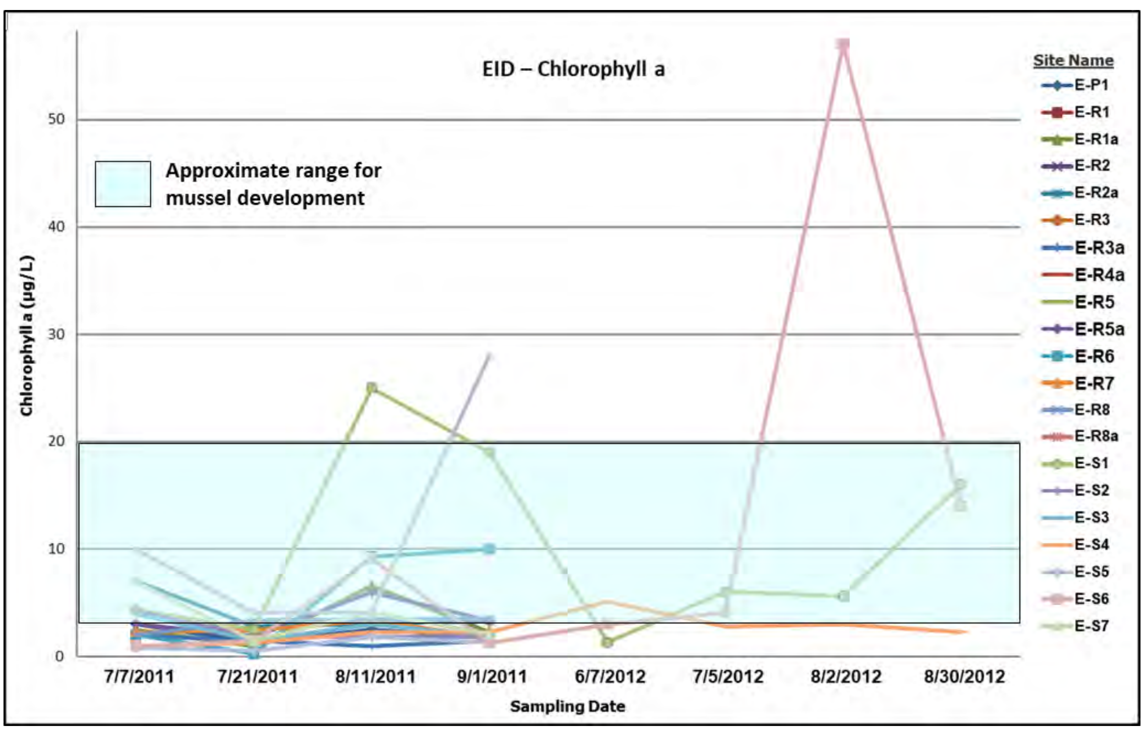

Figure A-3.4 EID – Chlorophyll a in irrigation water

Appendix A-4 St. Mary River Irrigation District (2006 to 2007 and 2011 to 2016)

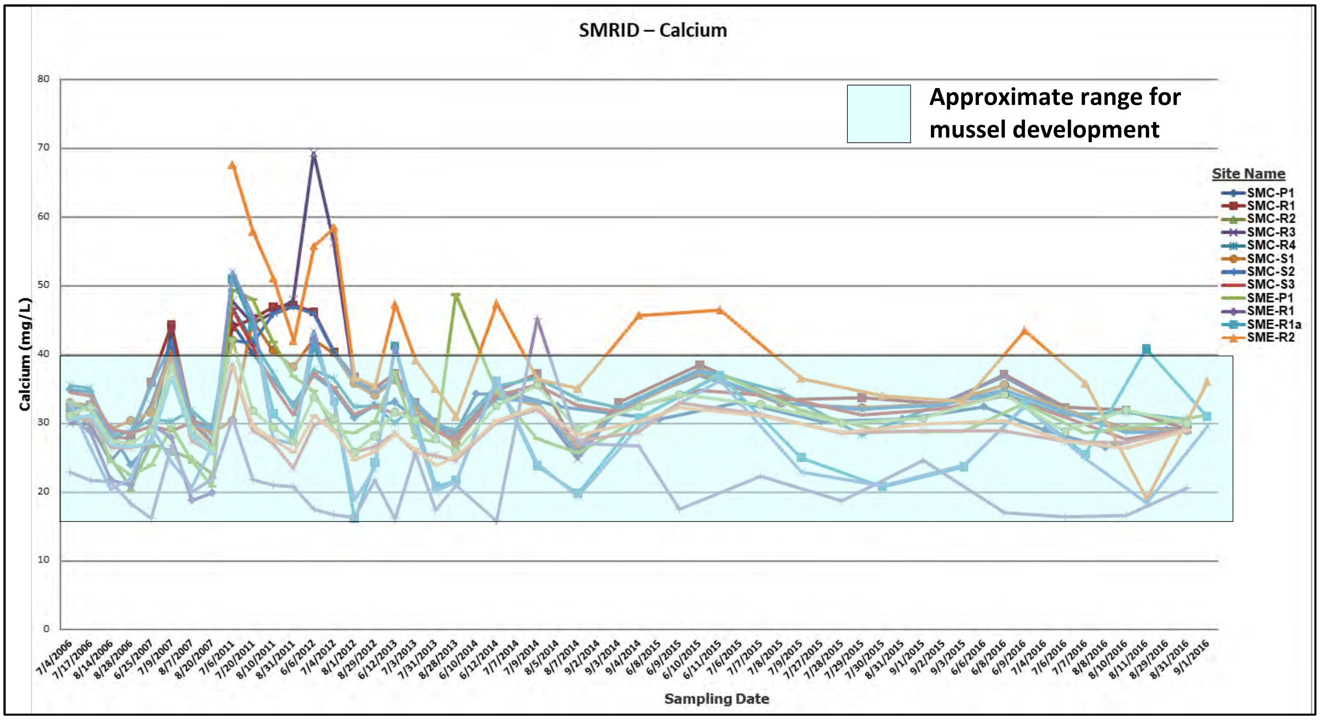

Figure A-4.1 SMRID – Calcium in irrigation water

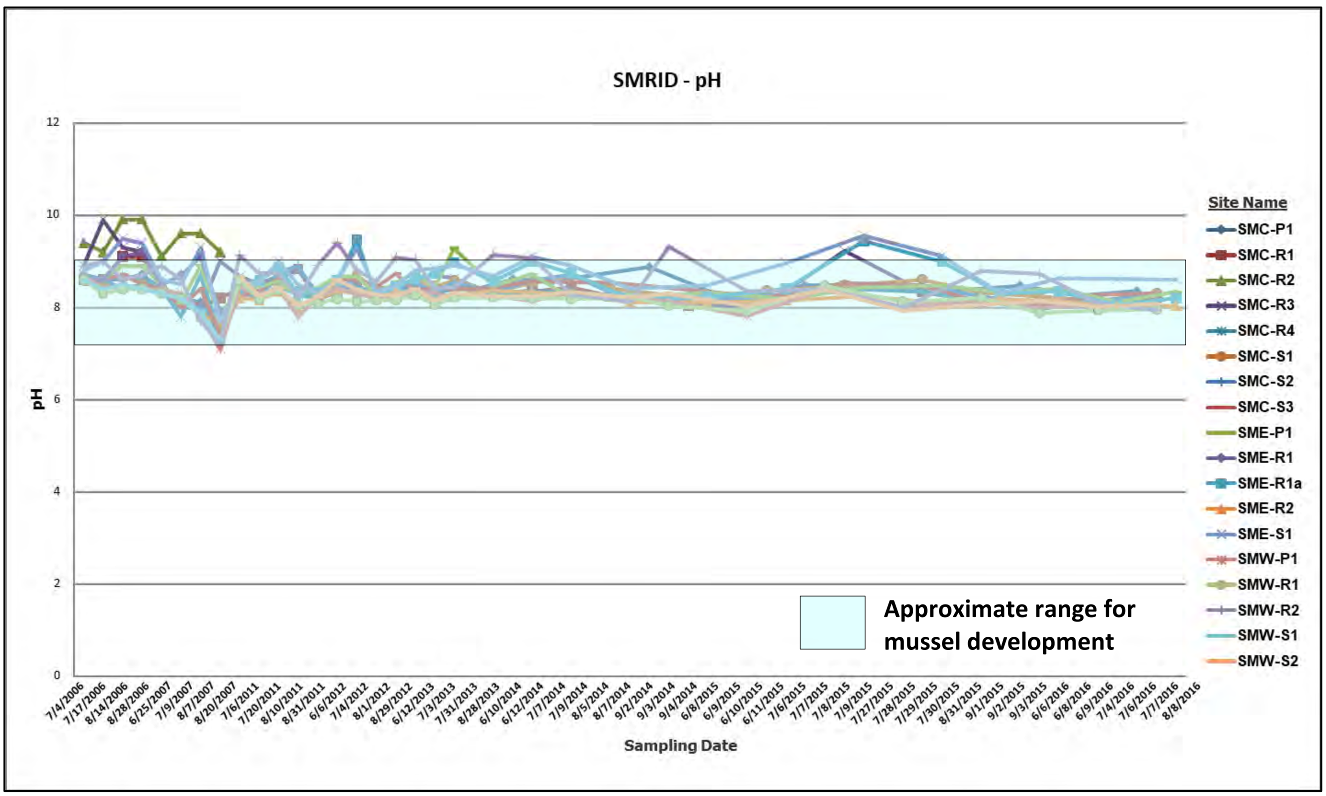

Figure A-4.2 SMRID – pH of irrigation water

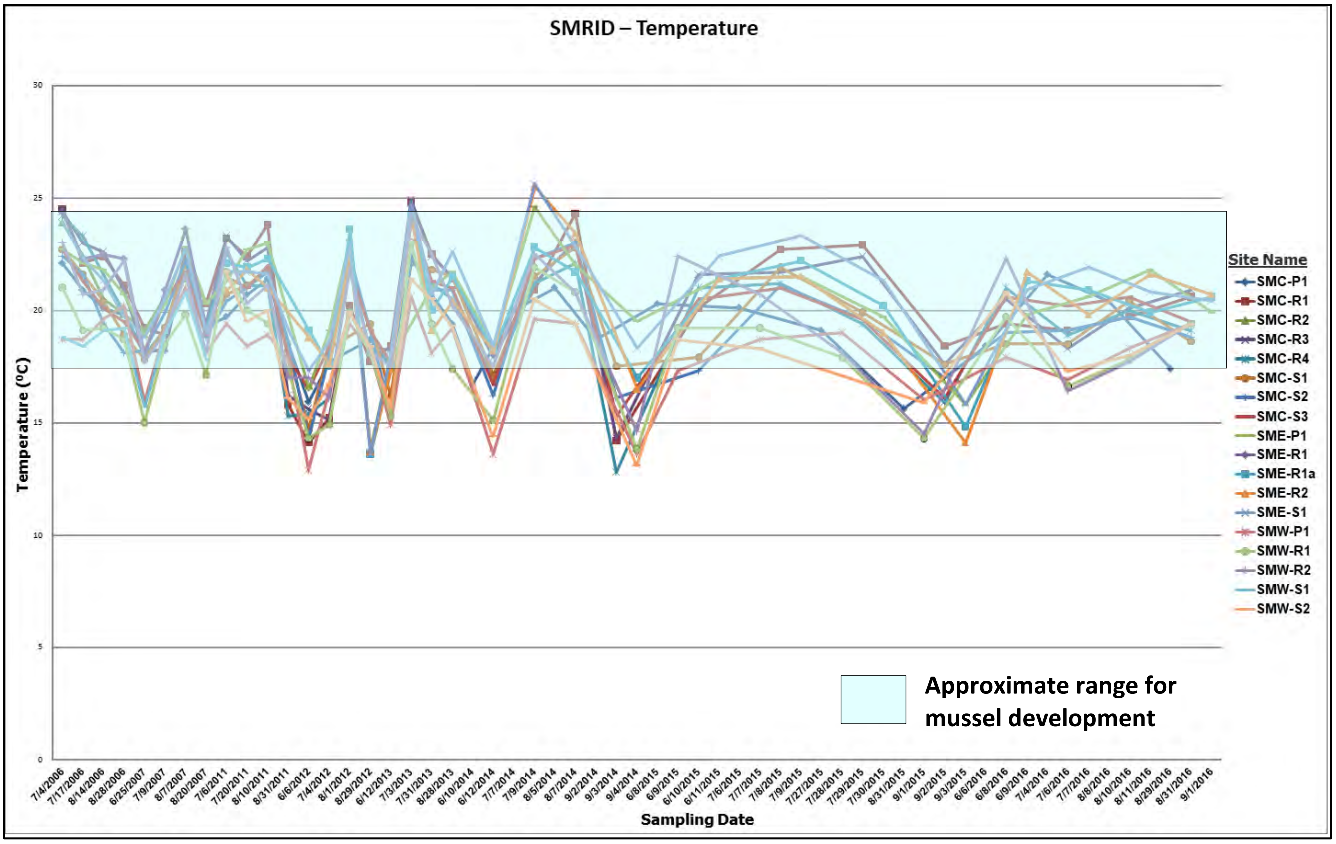

Figure A-4.3 SMRID – Temperature of irrigation water

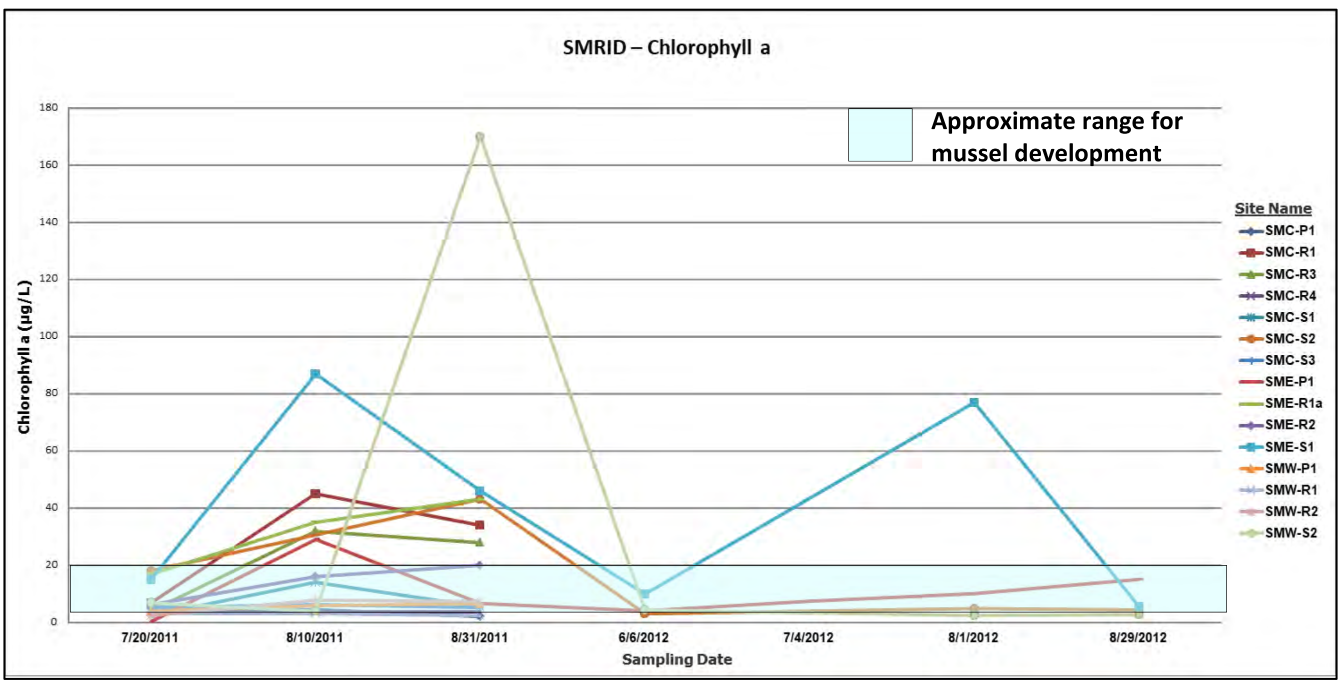

Figure A-4.4 SMRID – Chlorophyll a in irrigation water

Appendix A-5 Taber Irrigation District (2006 to 2007 and 2011 to 2016)

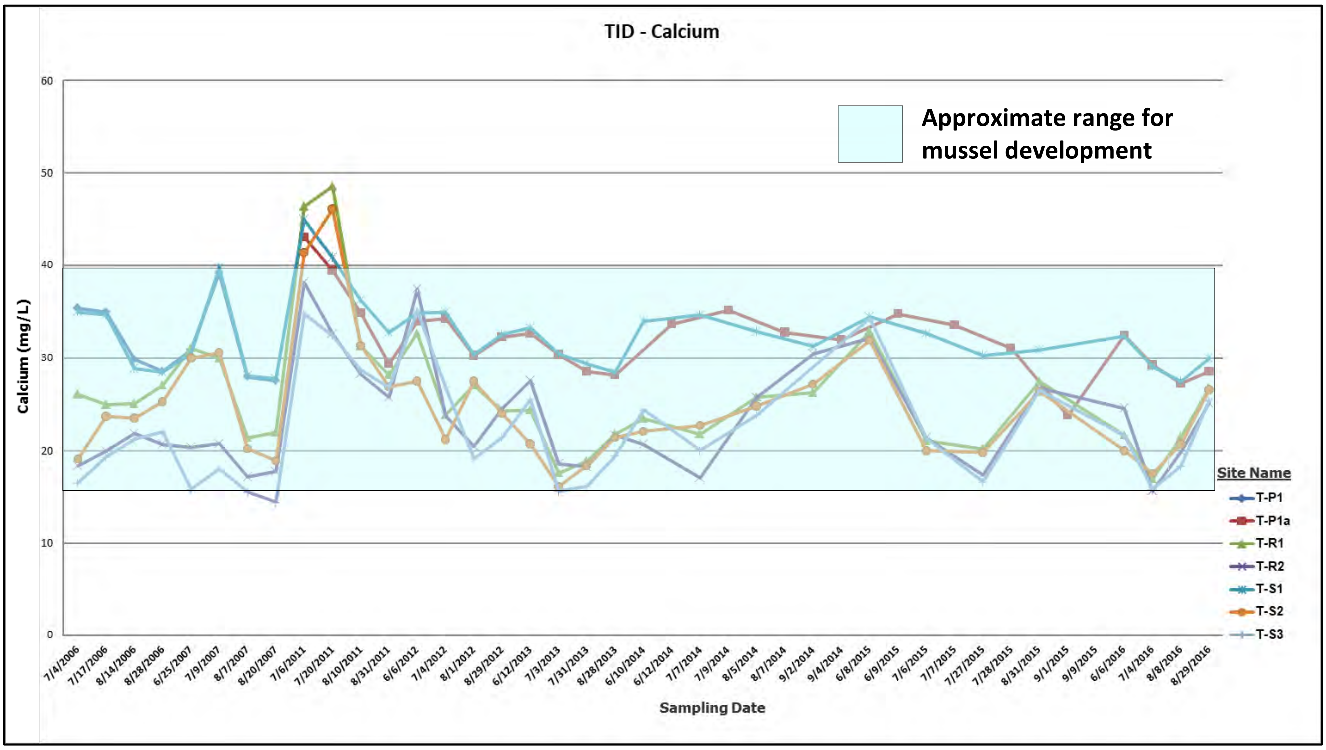

Figure A-5.1 TID – Calcium in irrigation water

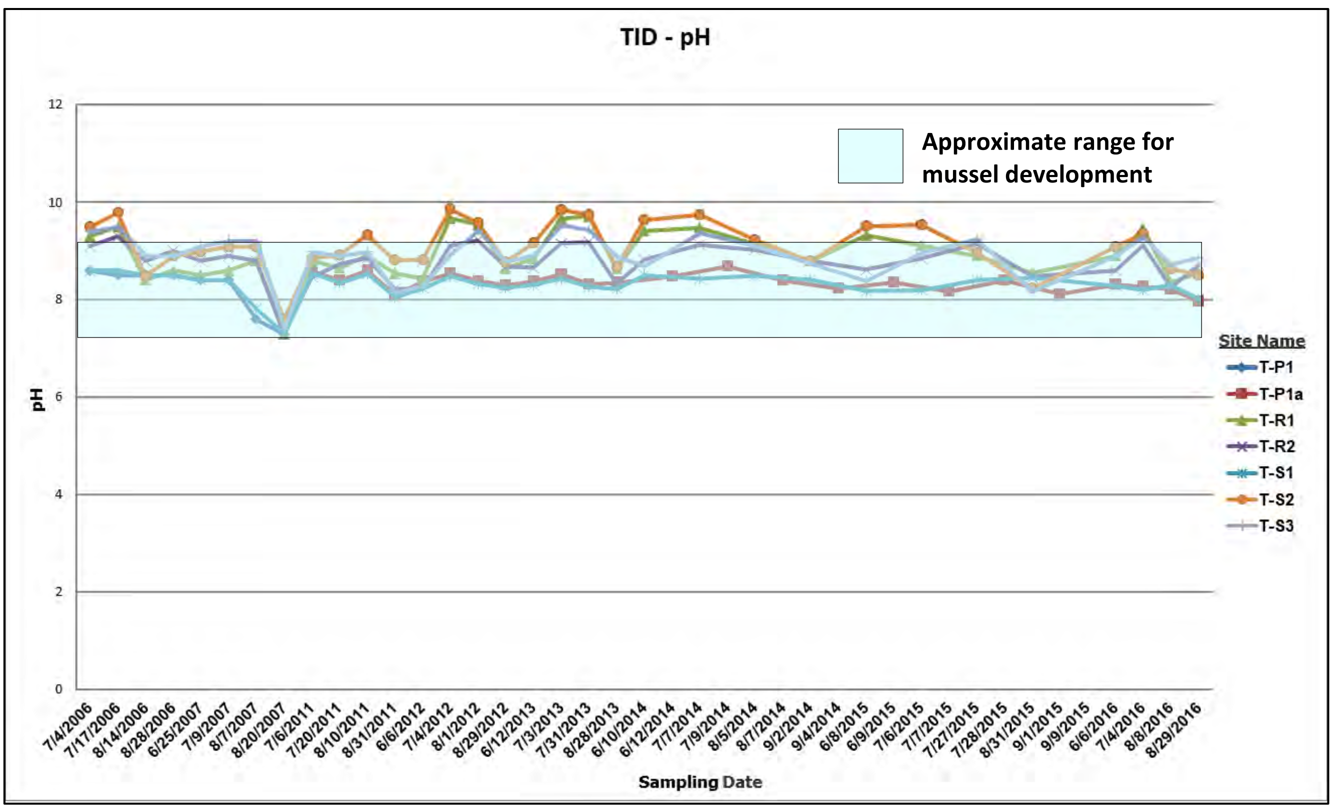

Figure A-5.2 TID – pH of irrigation water

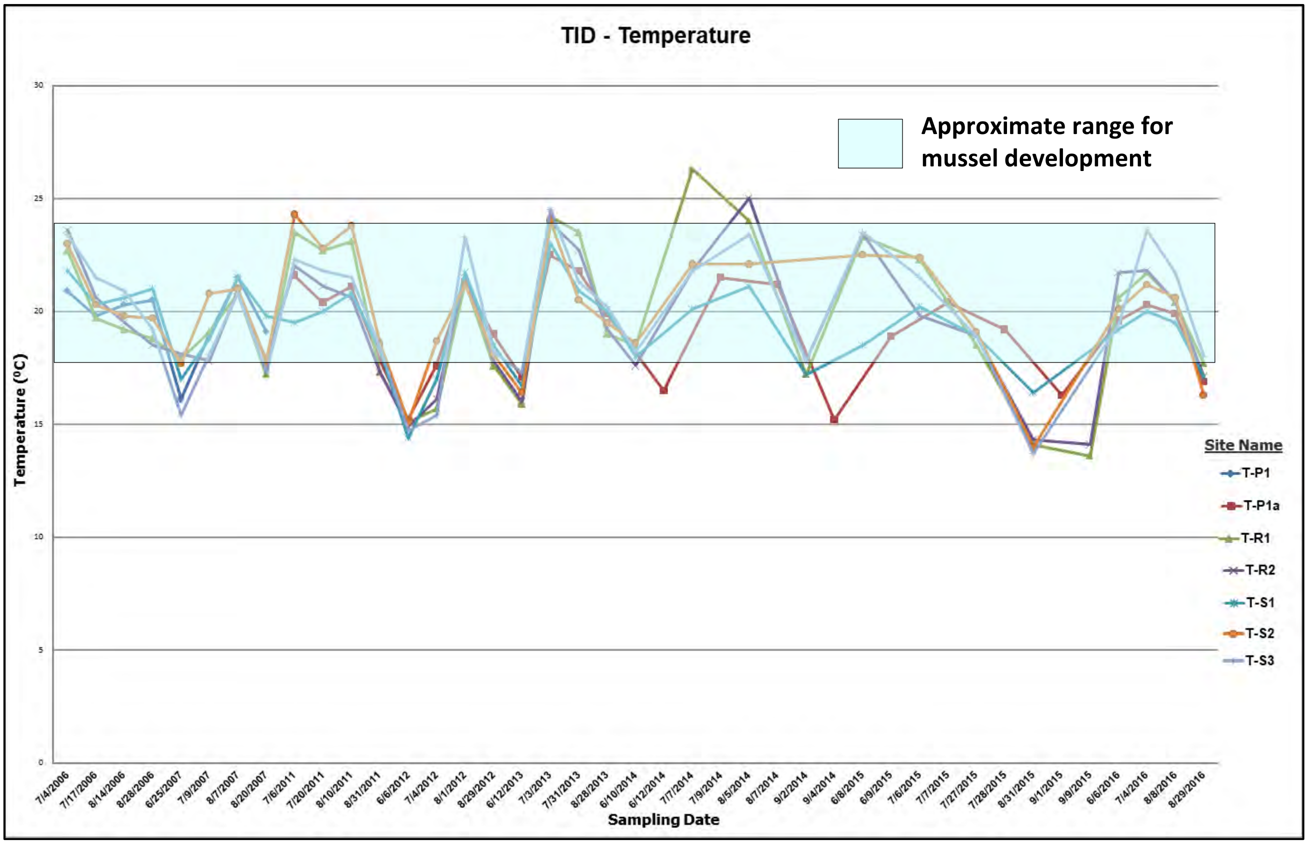

Figure A-5.3 TID – Temperature of irrigation water

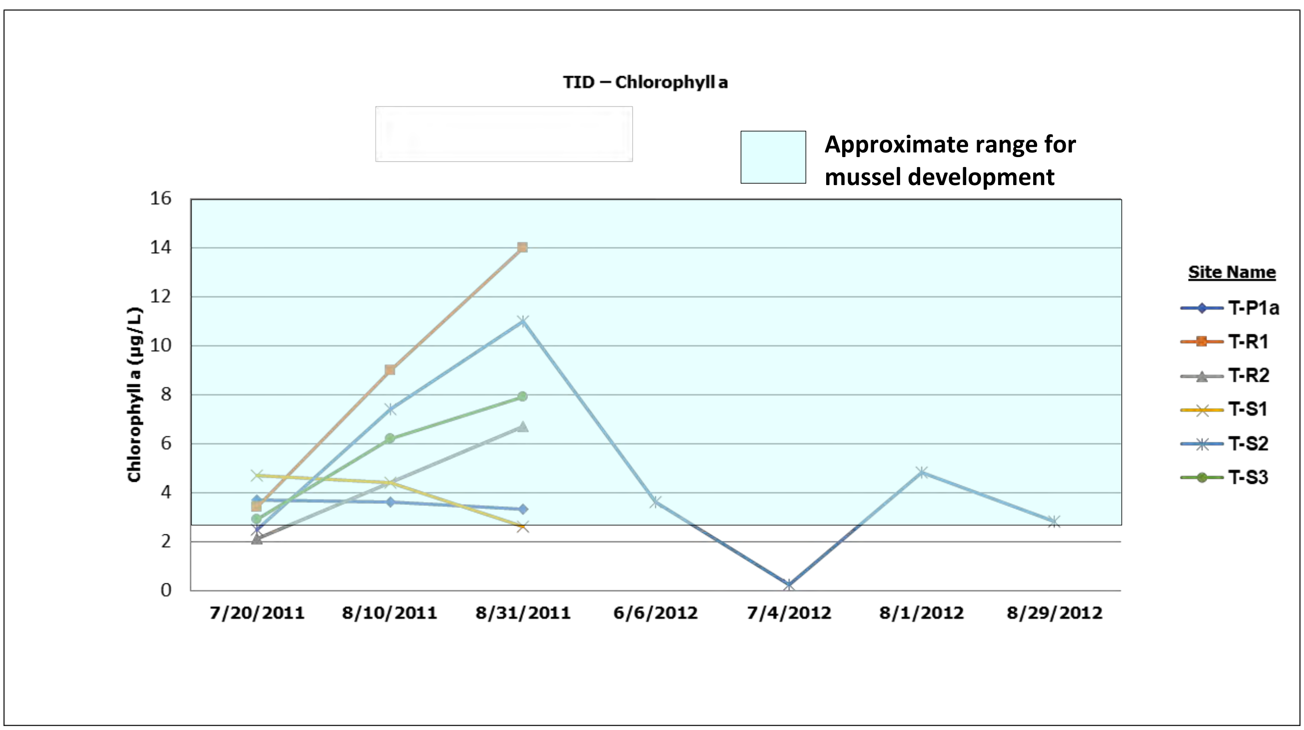

Figure A-5.4 TID – Chlorophyll a in irrigation water

Appendix A-6 Raymond Irrigation District (2006 to 2007 and 2011 to 2016)

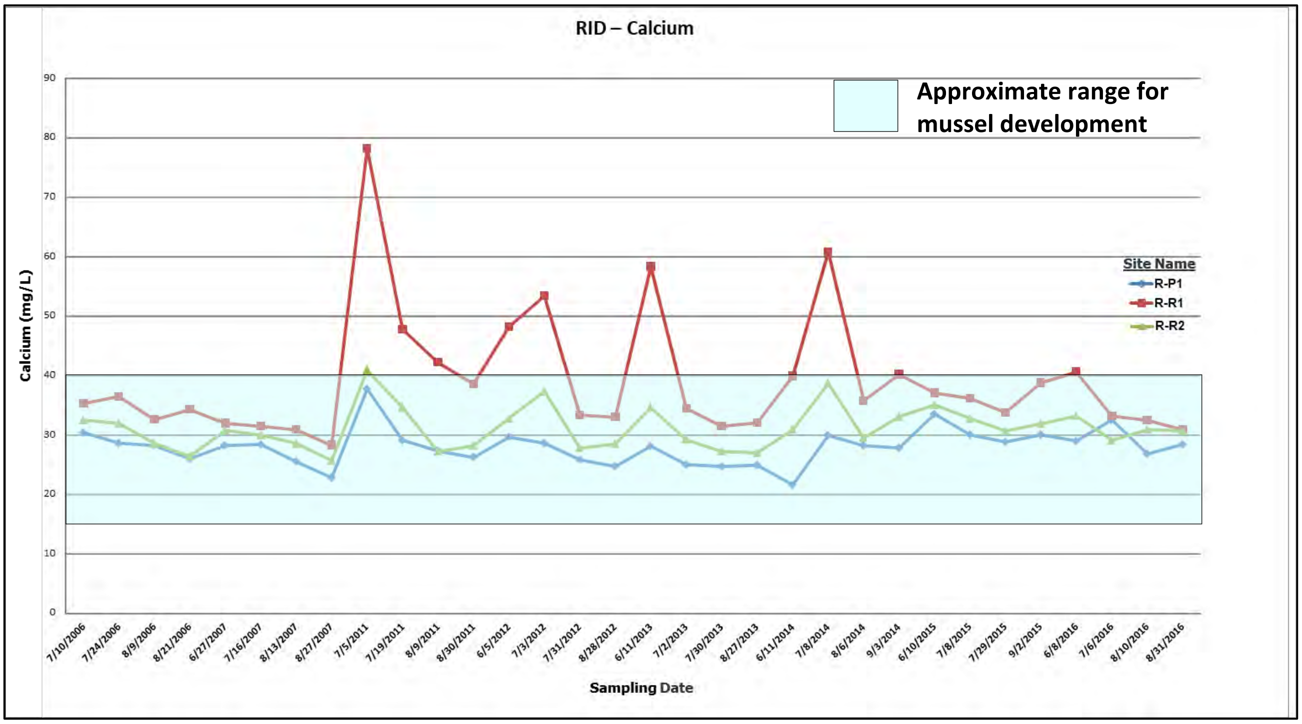

Figure A-6.1 RID – Calcium in irrigation water

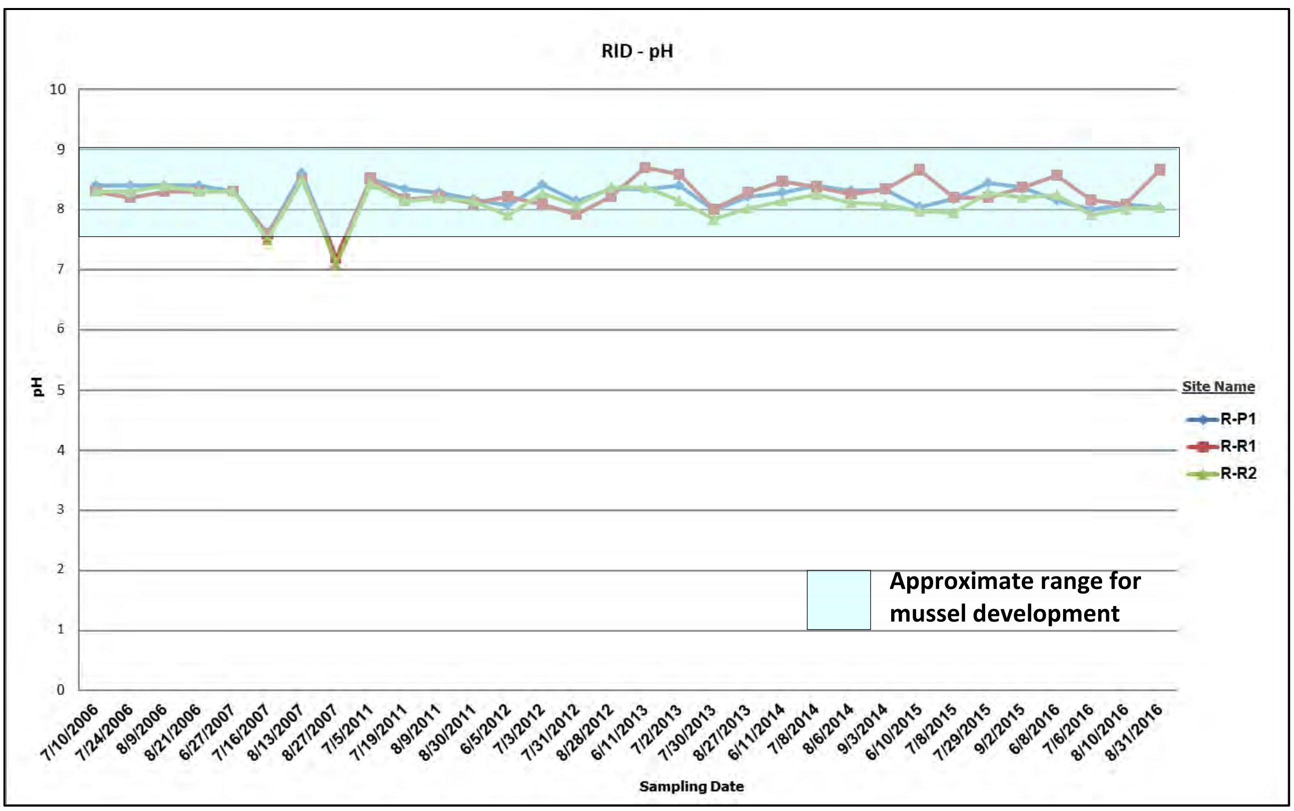

Figure A-6.2 RID – pH of irrigation water

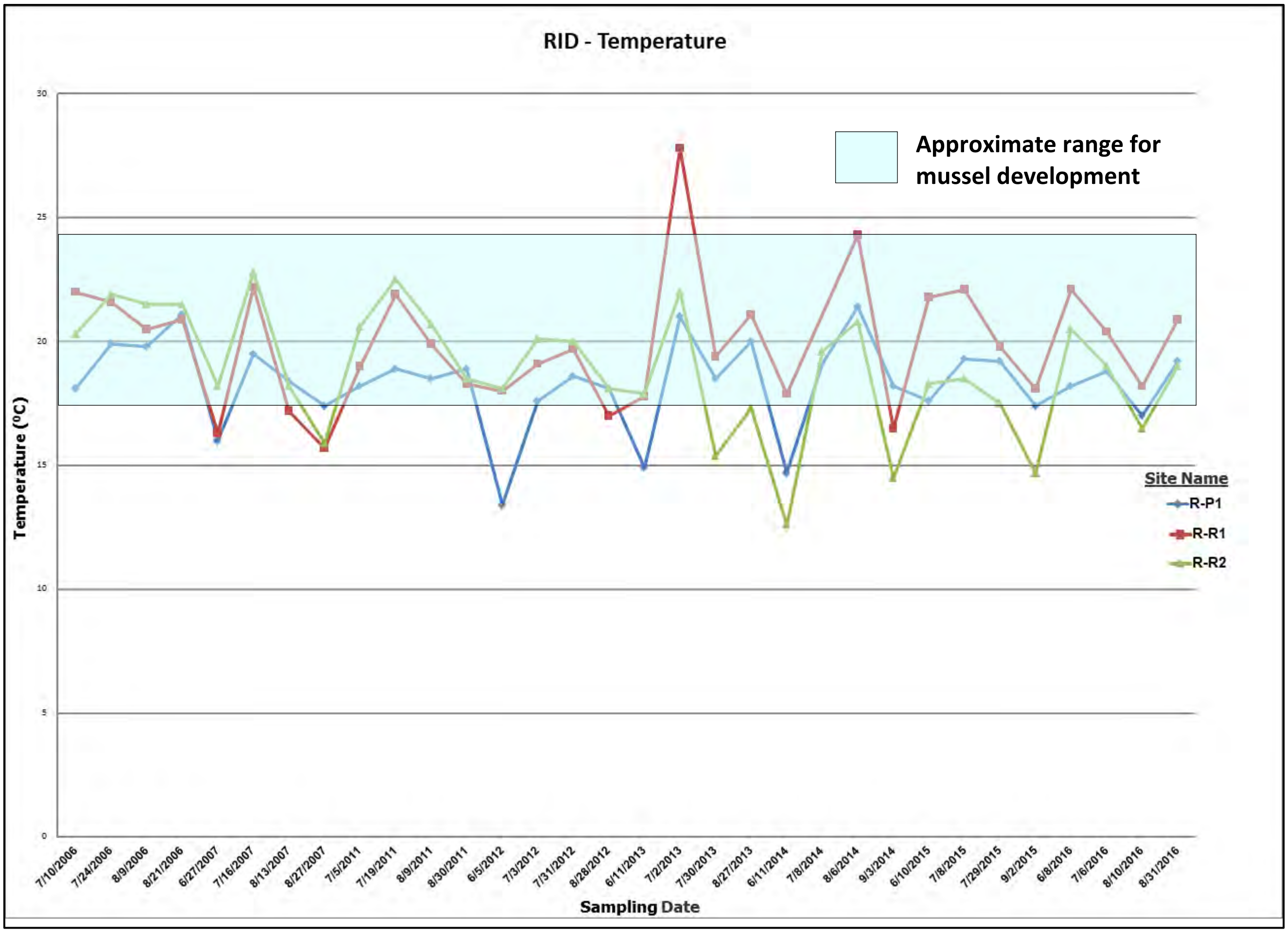

Figure A-6.3 RID – Temperature of irrigation water

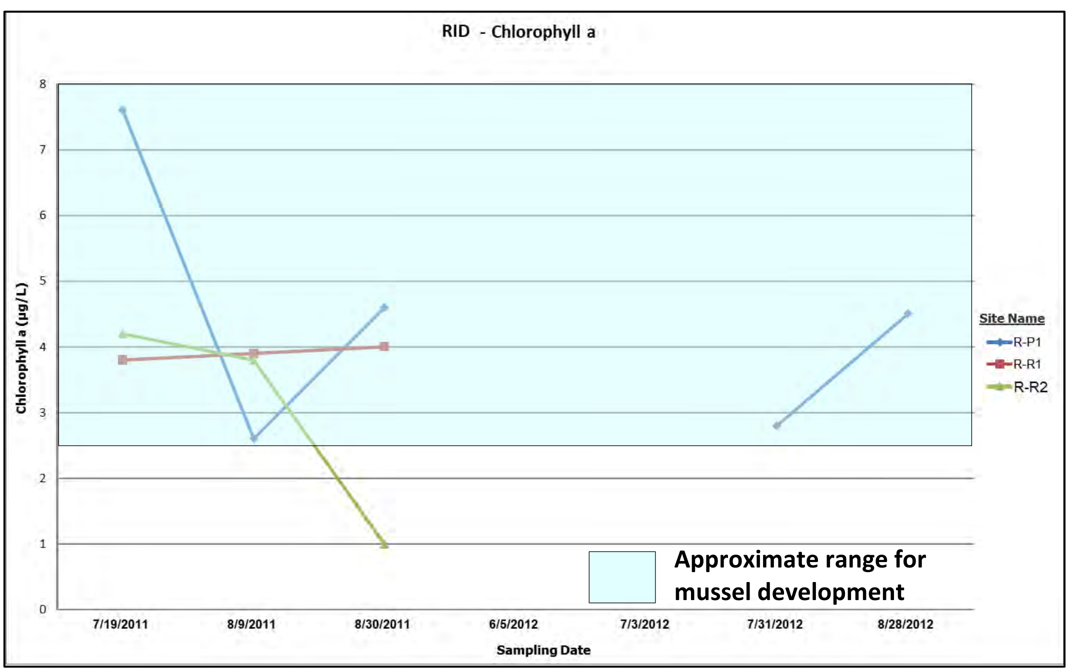

Figure A-6.4 RID – Chlorophyll a in irrigation water

Appendix A-7 Magrath Irrigation District (2006 to 2007 and 2011 to 2016)

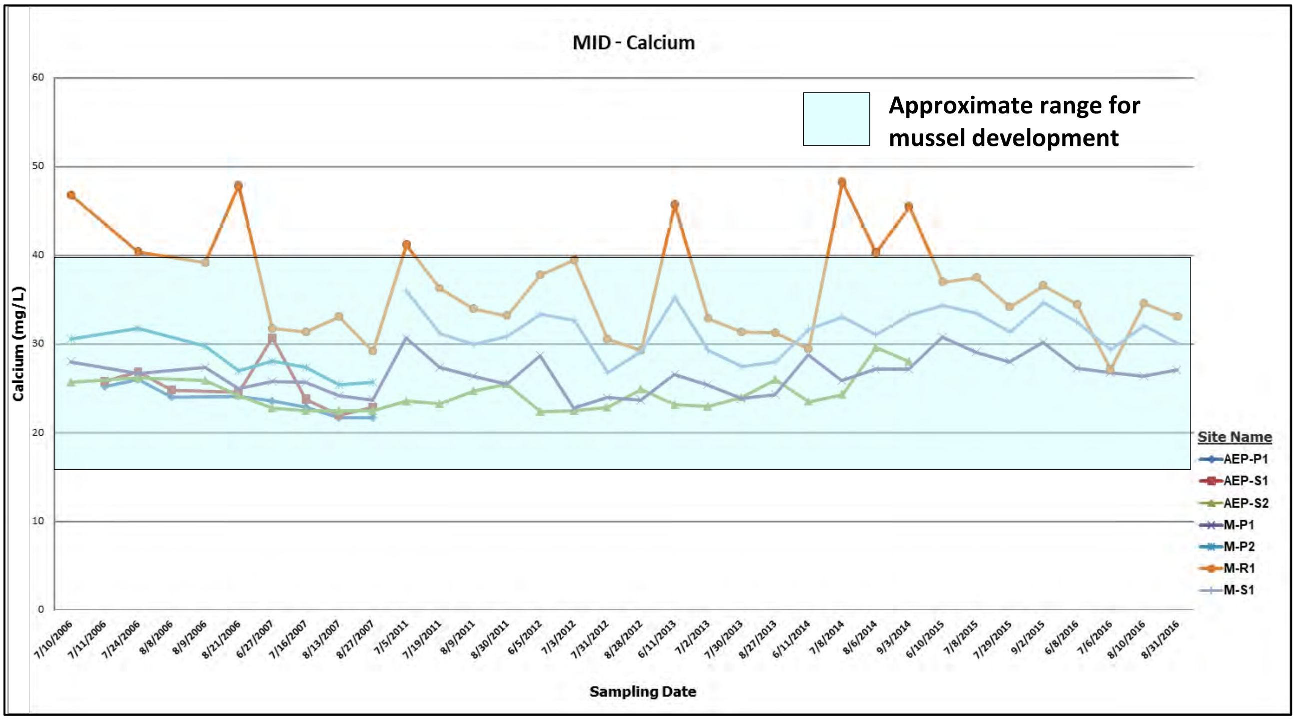

Figure A-7.1 MID – Calcium in irrigation water

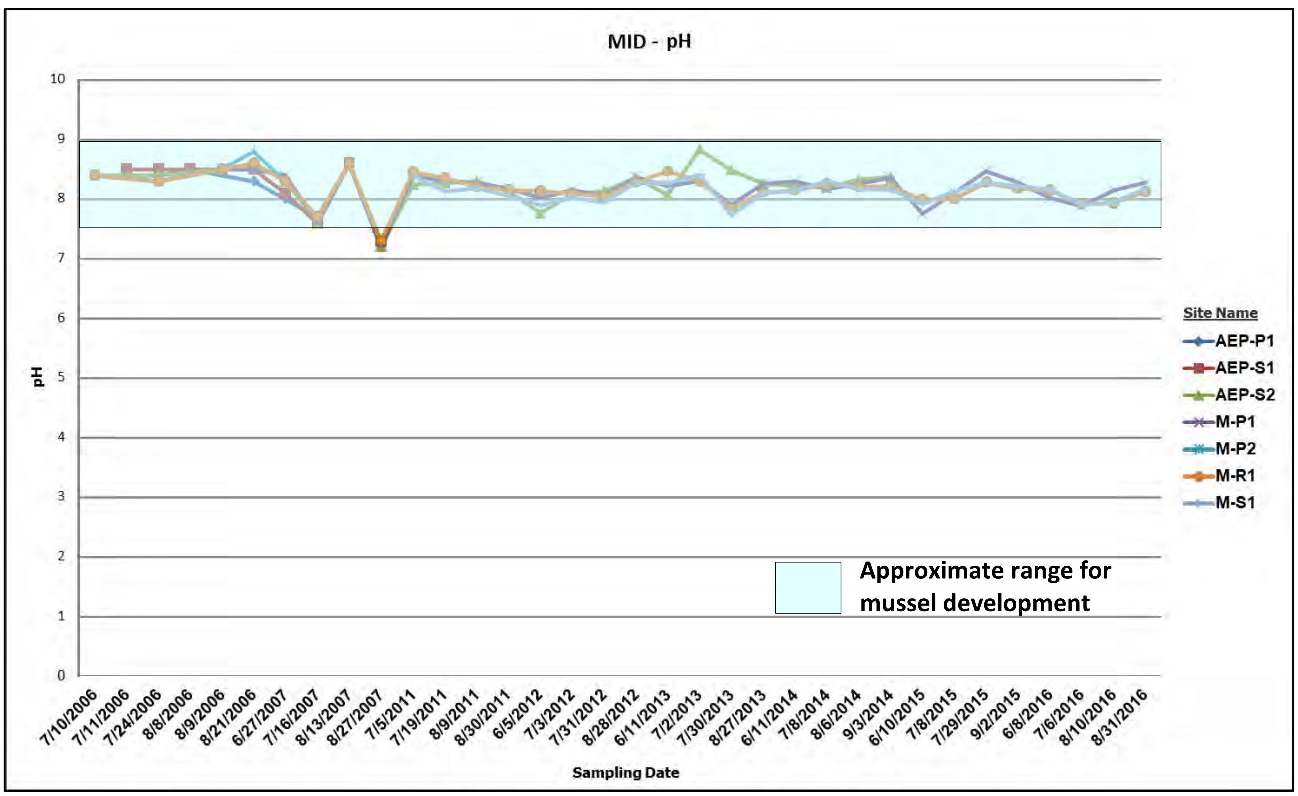

Figure A-7.2 MID – pH of irrigation water

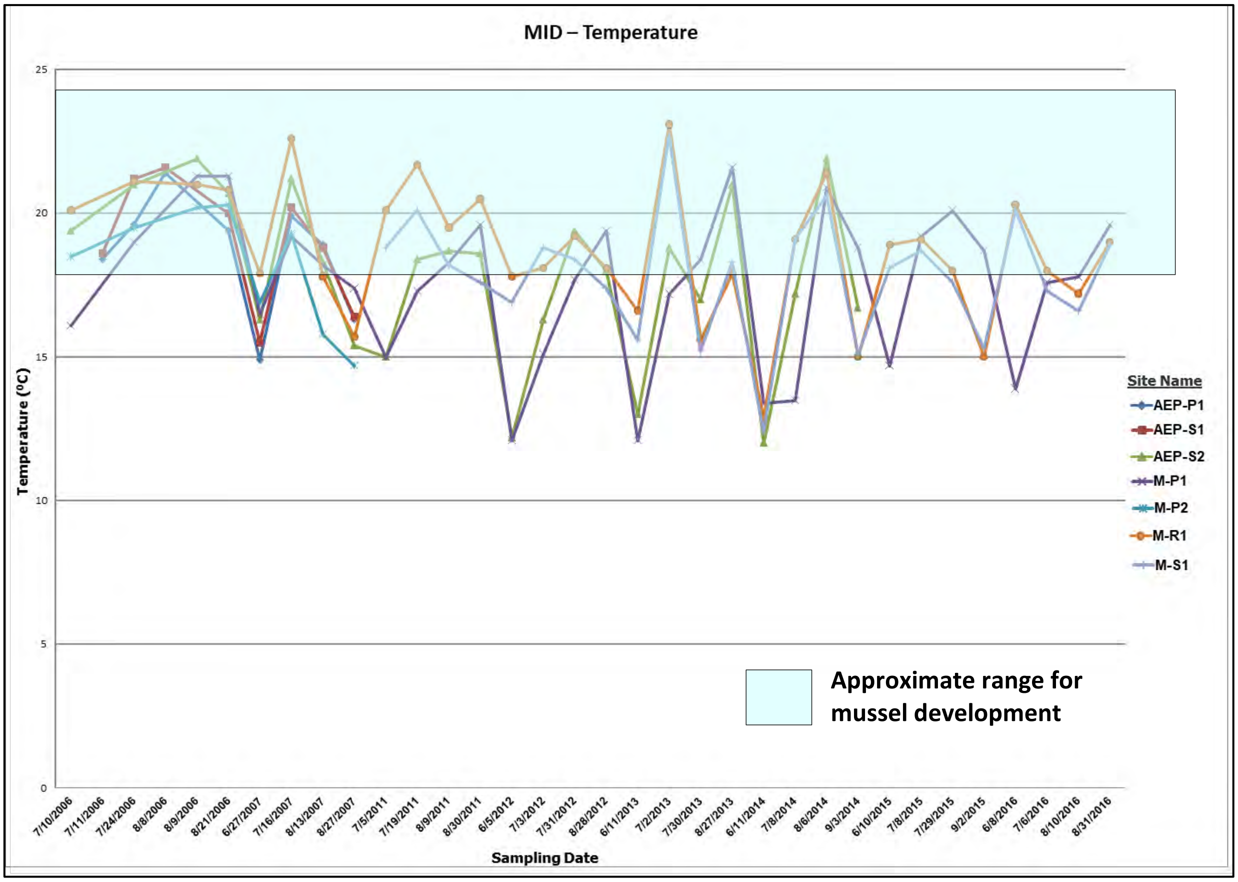

Figure A-7.3 MID – Temperature of irrigation water

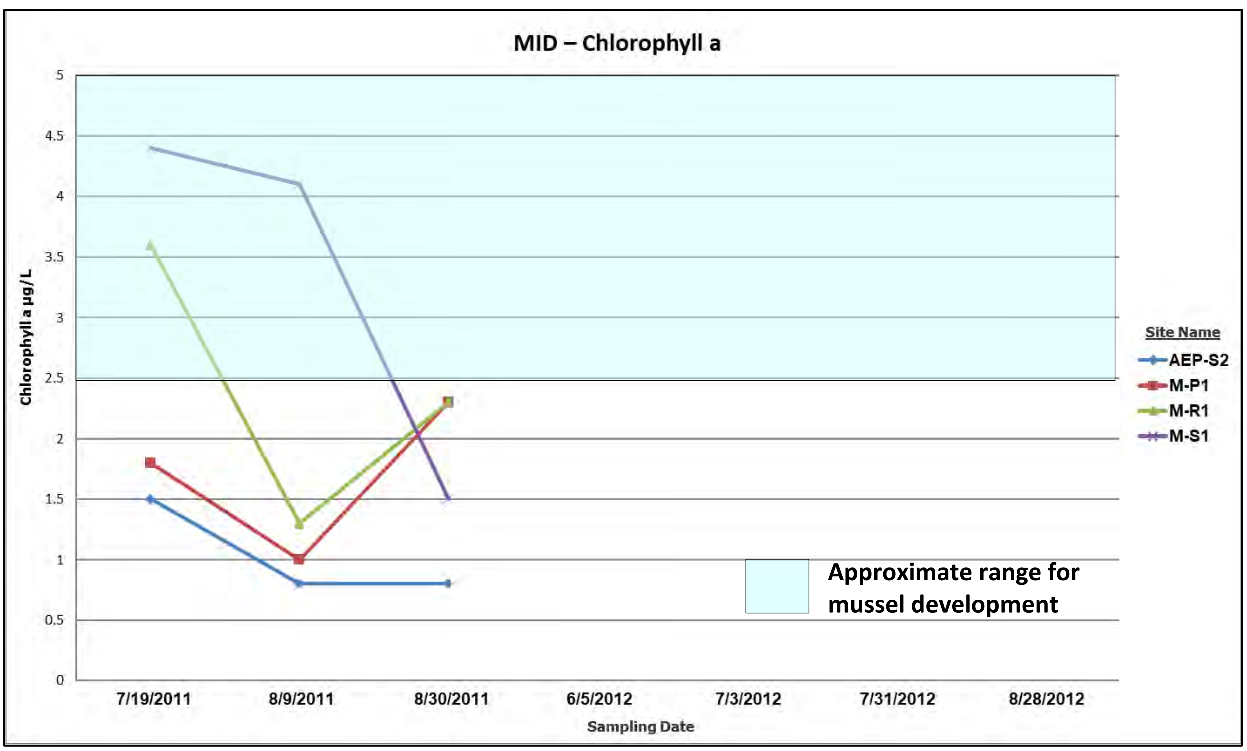

Figure A-7.4 MID – Chlorophyll a in irrigation water

Appendix A-8 Lethbridge Northern Irrigation District (2006 to 2007 and 2011 to 2016)

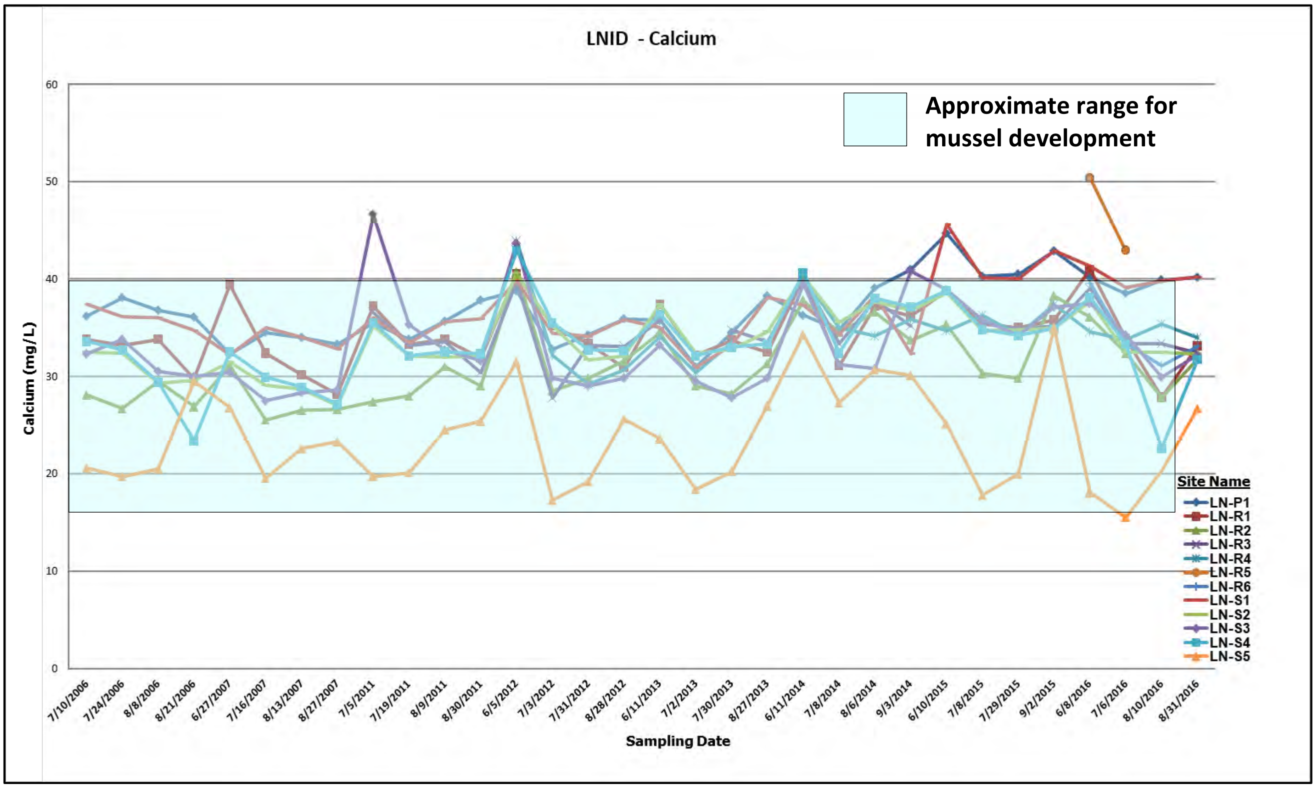

Figure A-8.1 LNID – Calcium in irrigation water

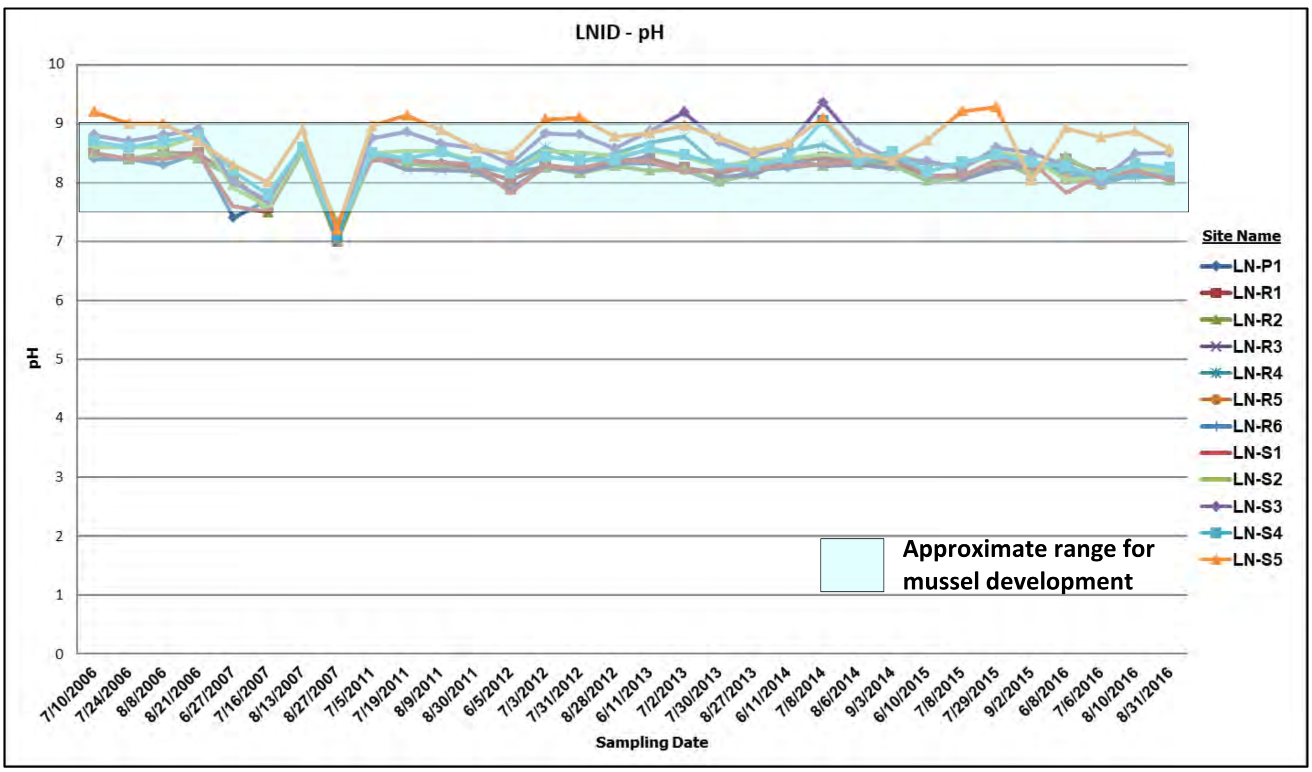

Figure A-8.2 LNID – pH of irrigation water

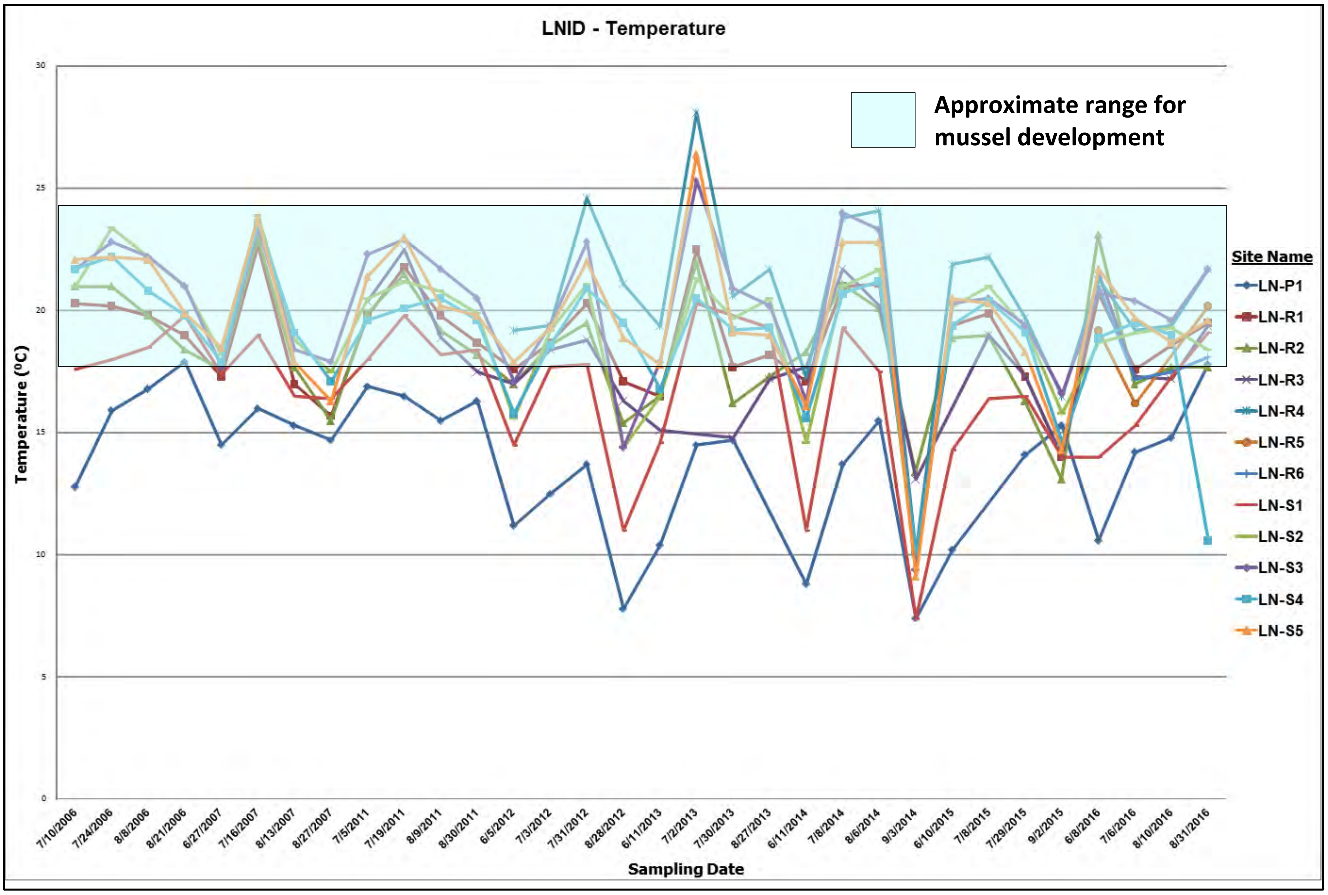

Figure A-8.3 LNID – Temperature of irrigation water

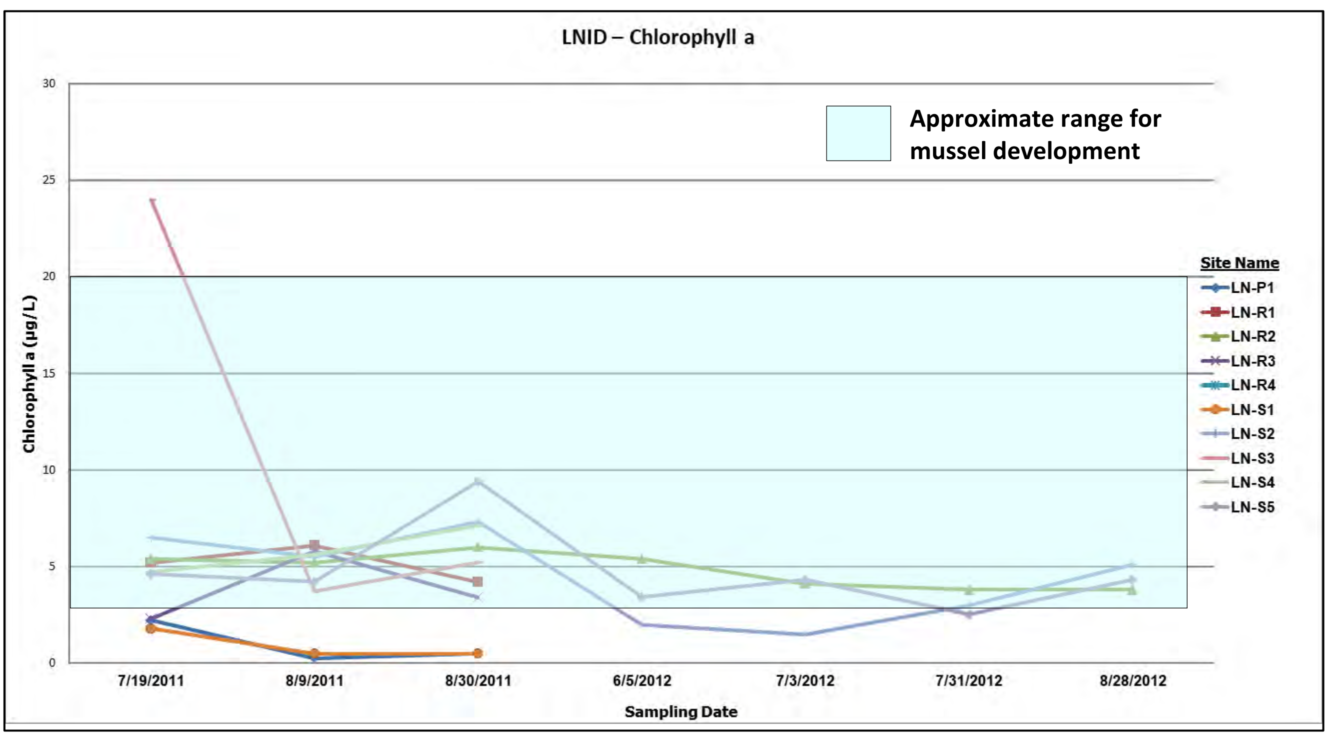

Figure A-8.4 LNID – Chlorophyll a in irrigation water

Appendix A-9 United Irrigation District (2006 to 2007 and 2011 to 2016)

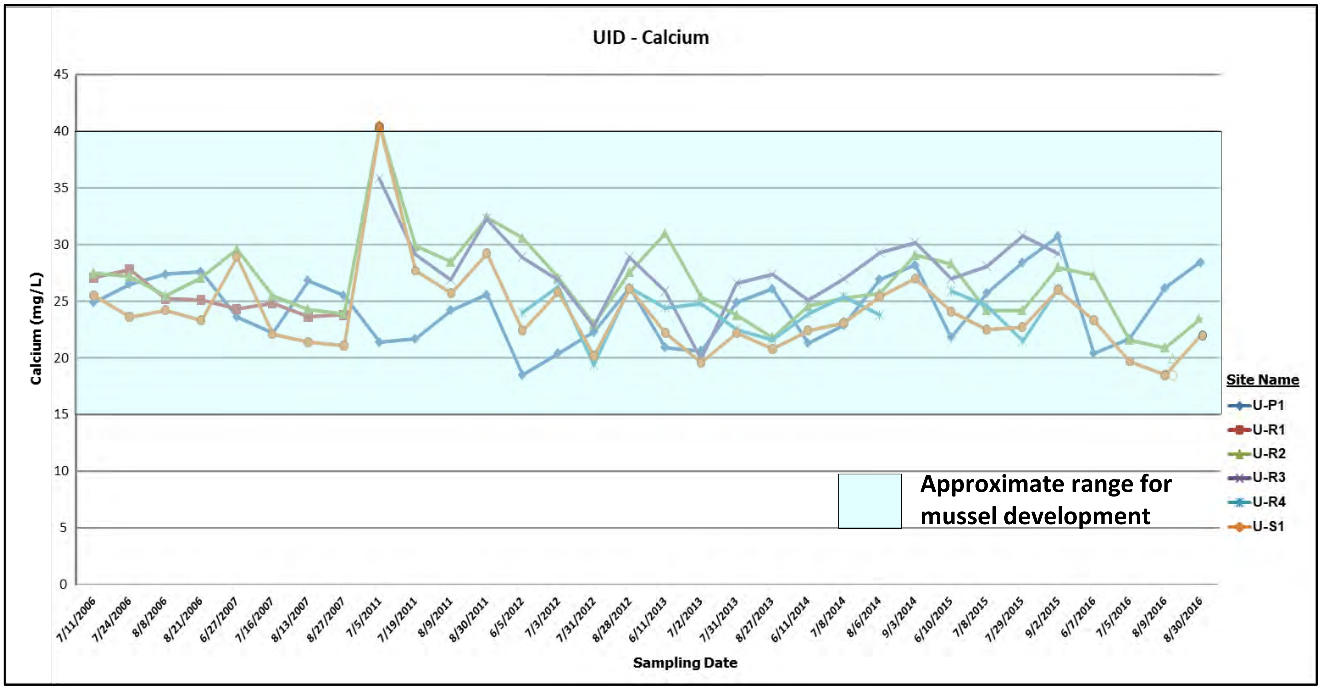

Figure A-9.1 UID – Calcium in irrigation water

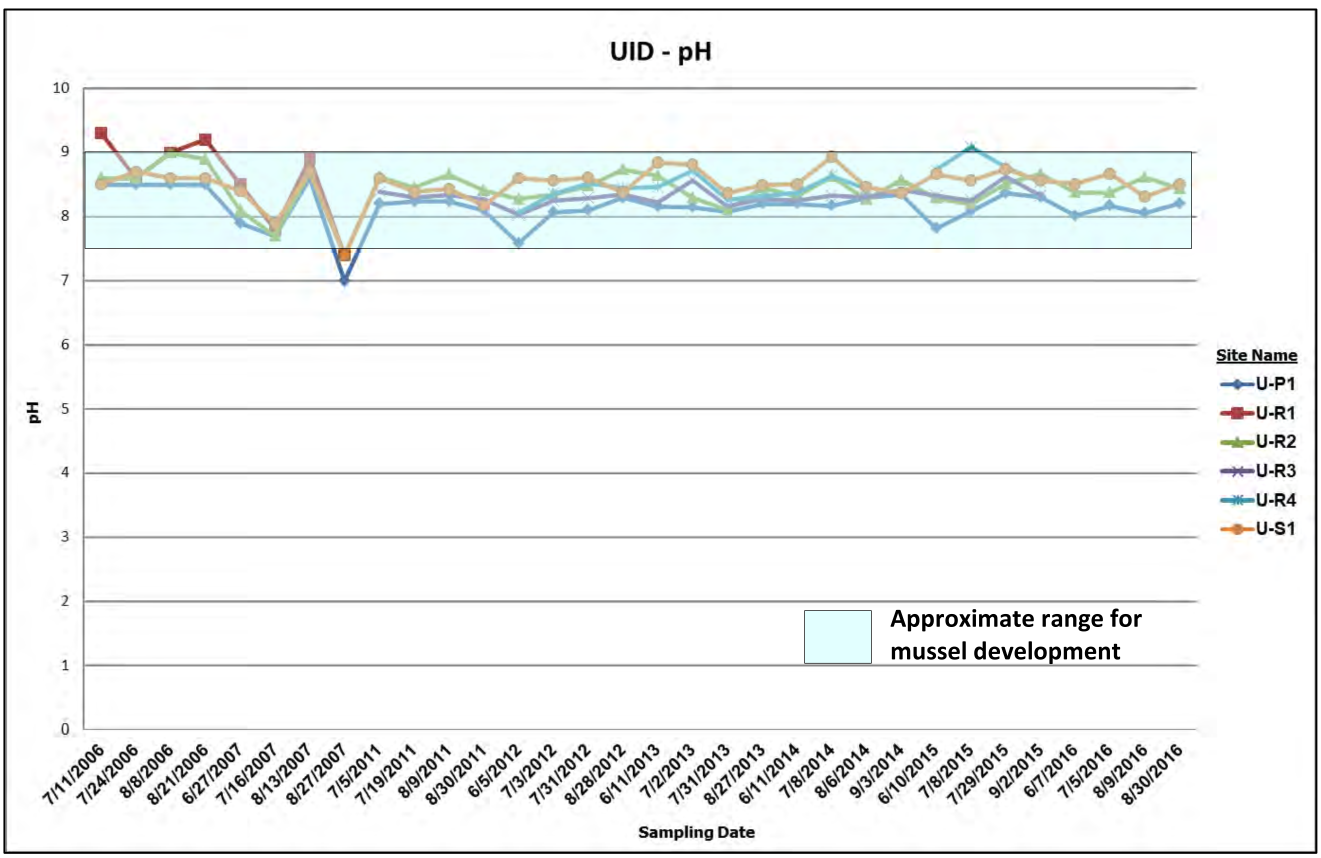

Figure A-9.2 UID – pH of irrigation water

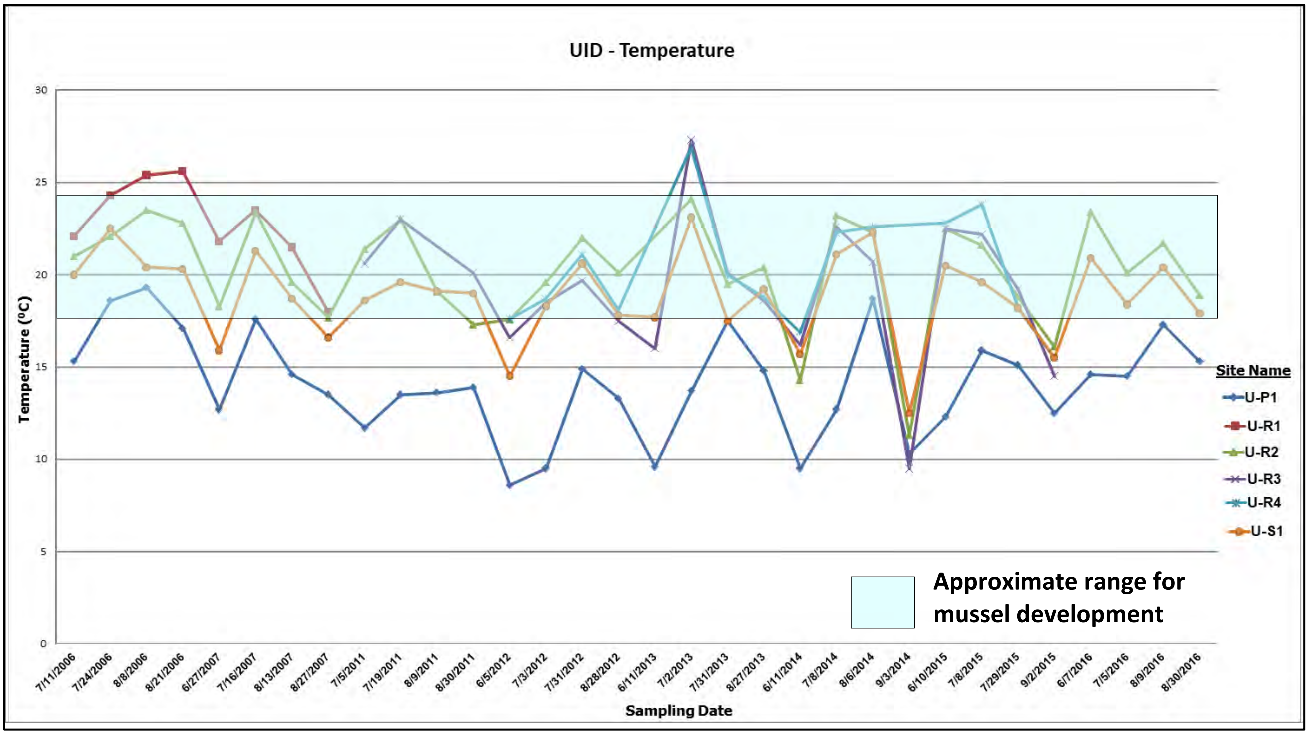

Figure A-9.3 UID – Temperature of irrigation water

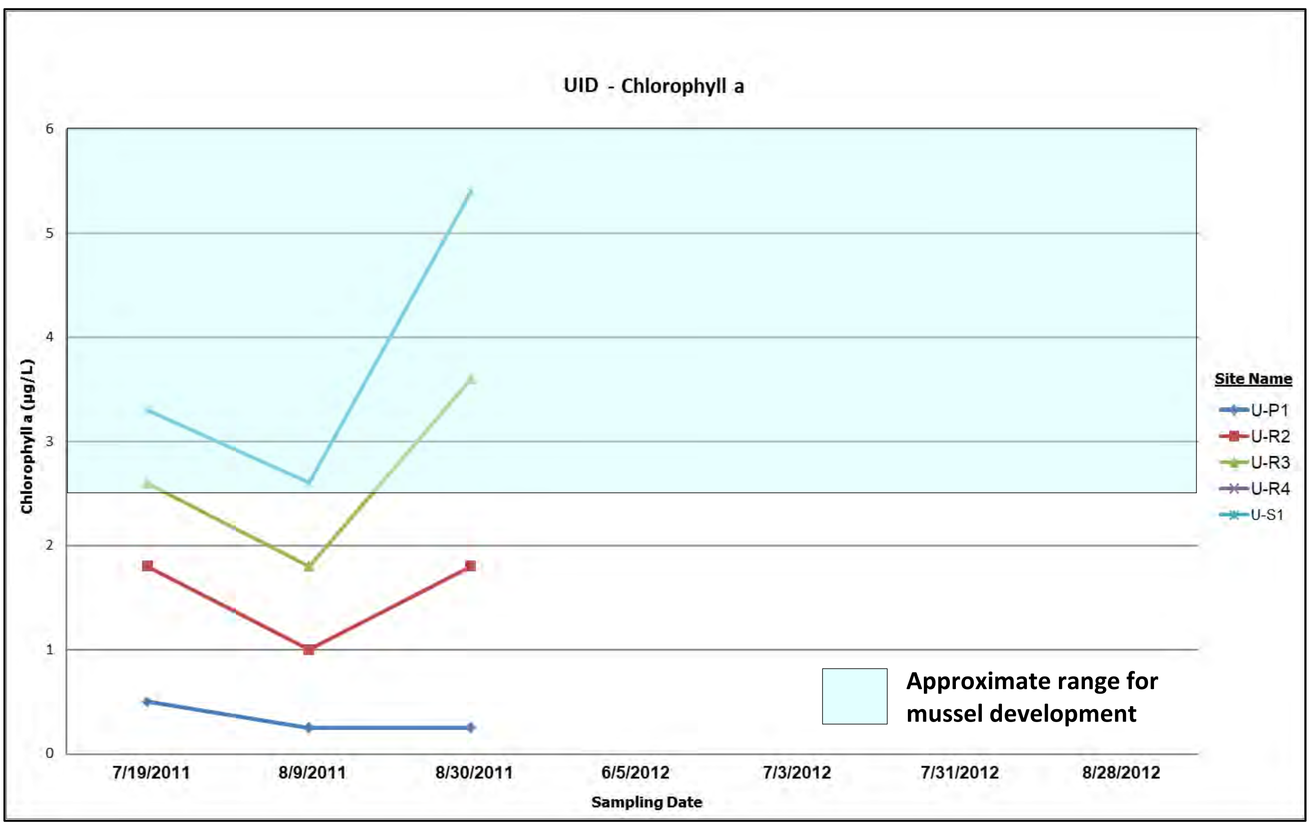

Figure A-9.4 UID – Chlorophyll a in irrigation water

Appendix A-10 Mountain View Irrigation District (2006 to 2007 and 2011 to 2016)

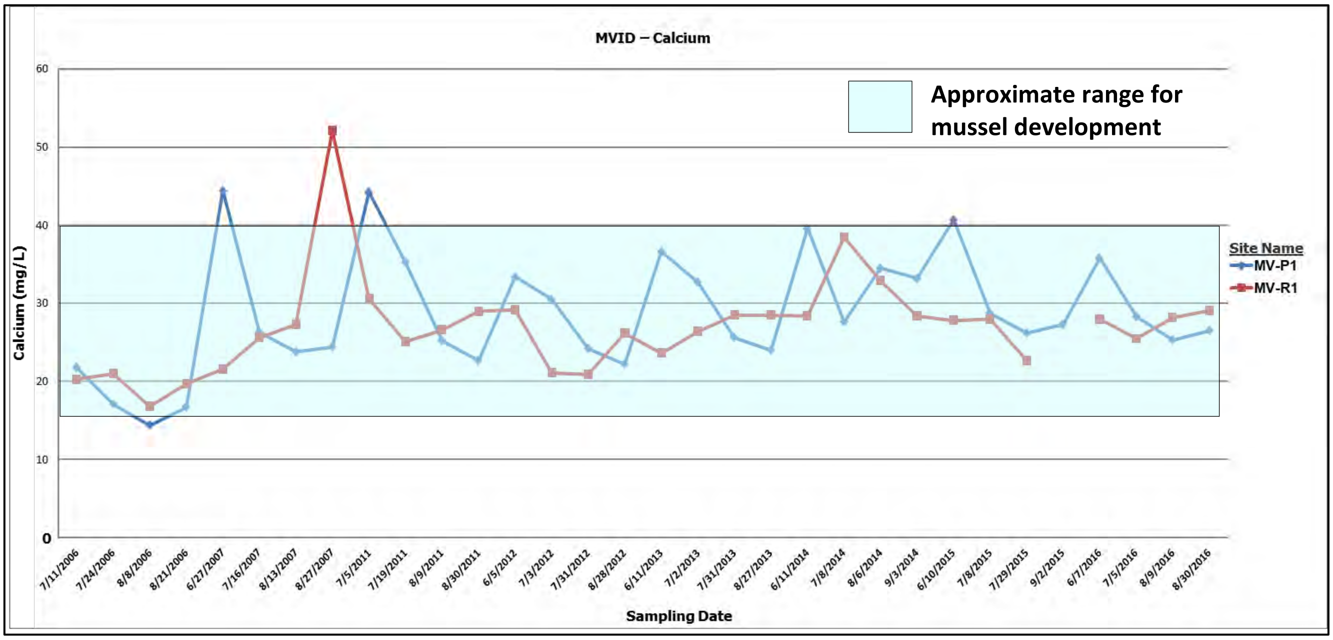

Figure A-10.1 MVID – Calcium in irrigation water

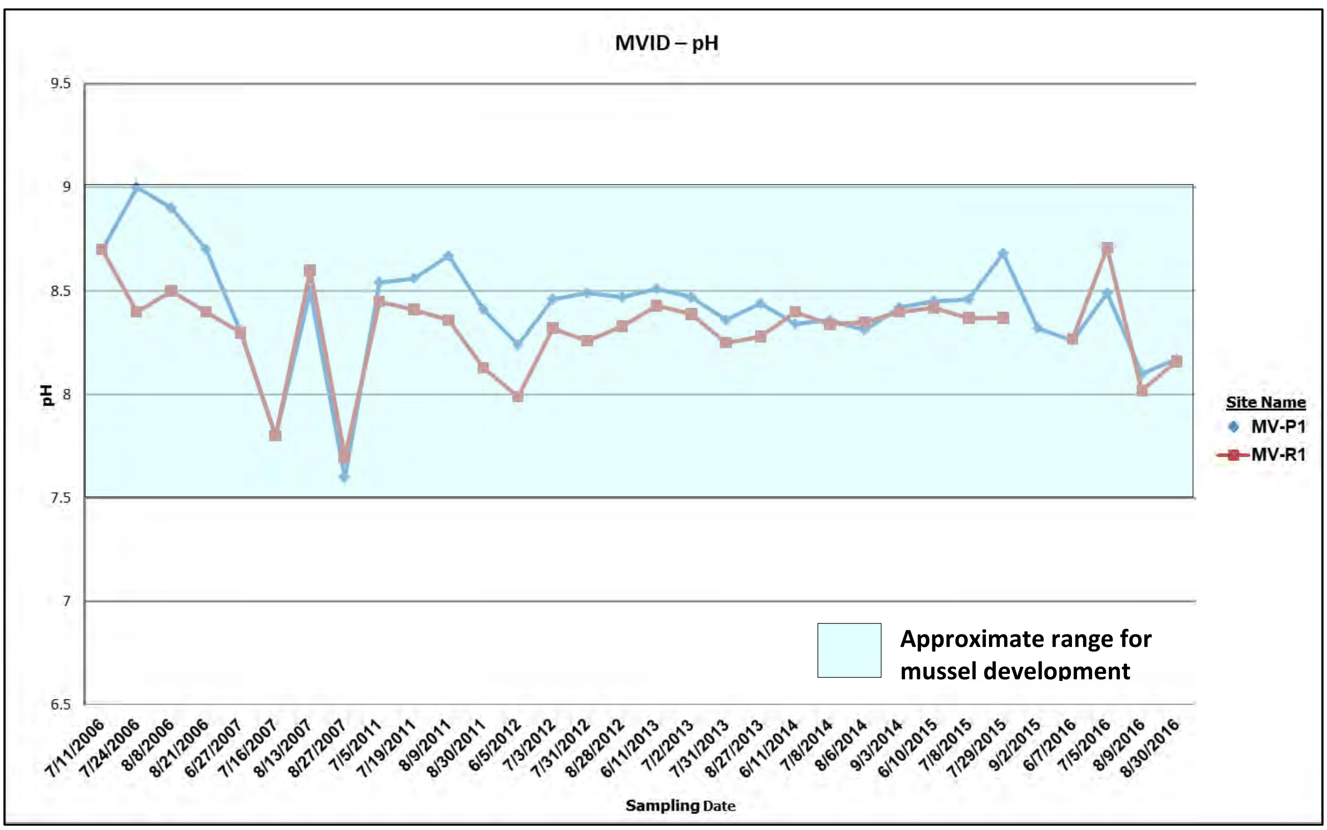

Figure A-10.2 MVID – pH of irrigation water

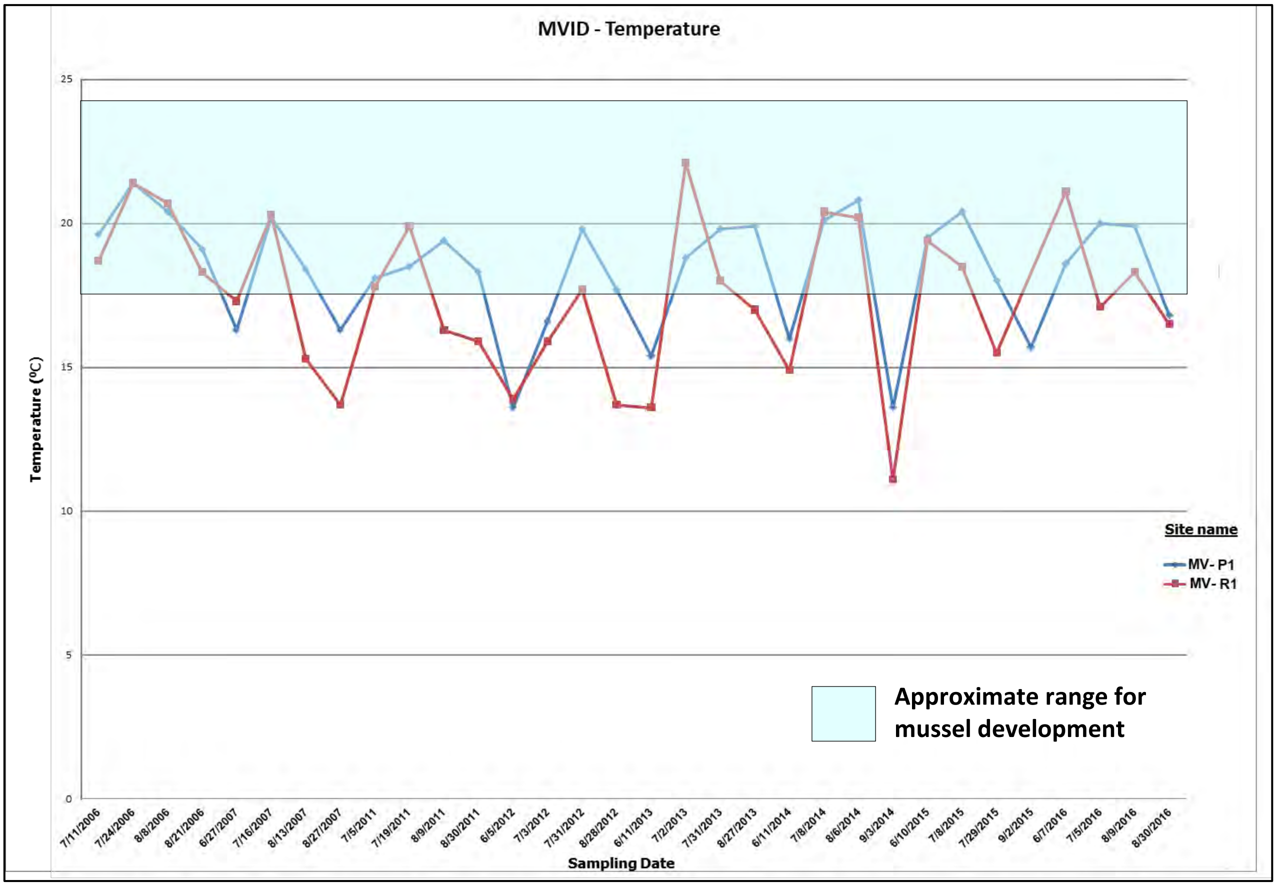

Figure A-10.3 MVID – Temperature of irrigation water

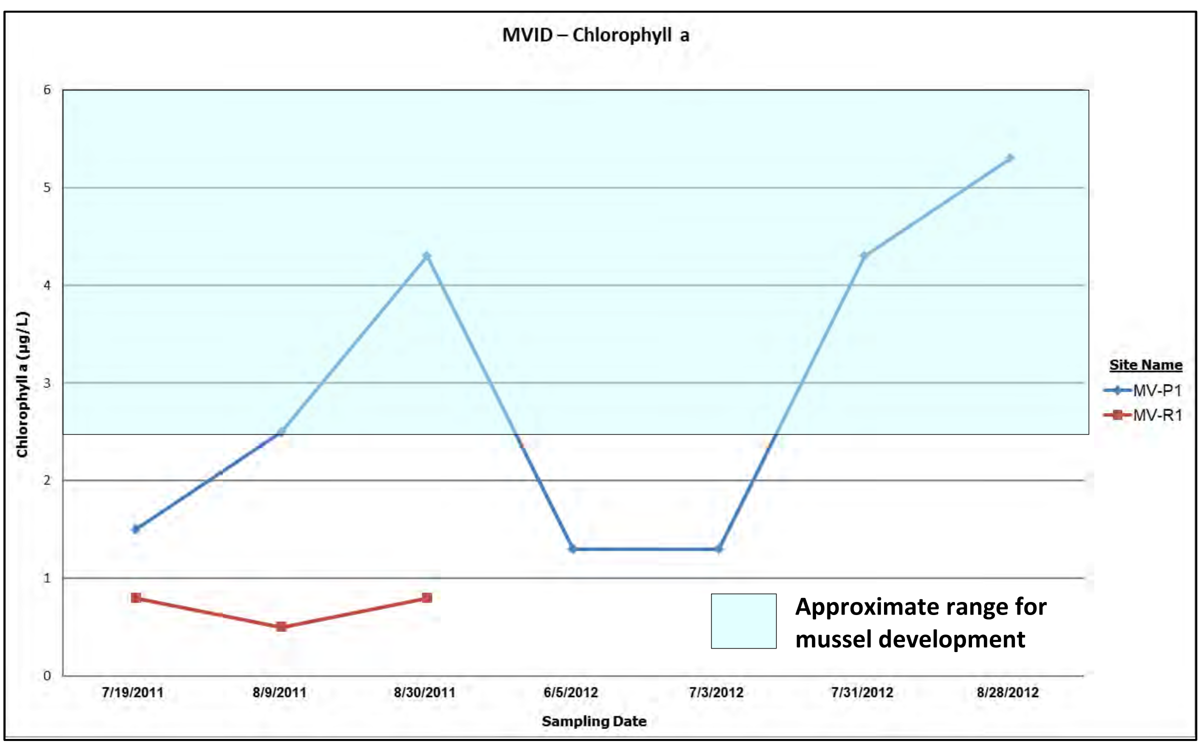

Figure A-10.4 MVID – Chlorophyll a in irrigation water

Appendix A-11 Aetna Irrigation District (2006 to 2007 and 2011 to 2016)

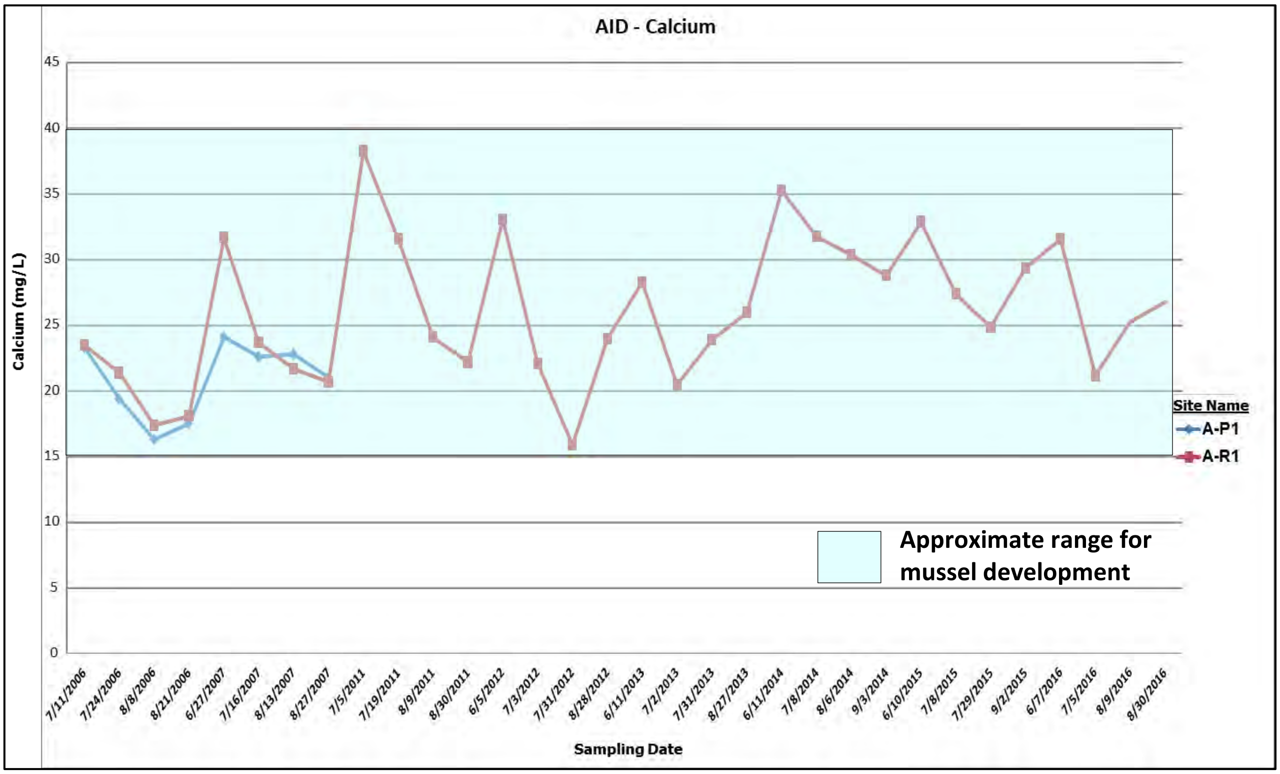

Figure A-11.1 AID – Calcium in irrigation water

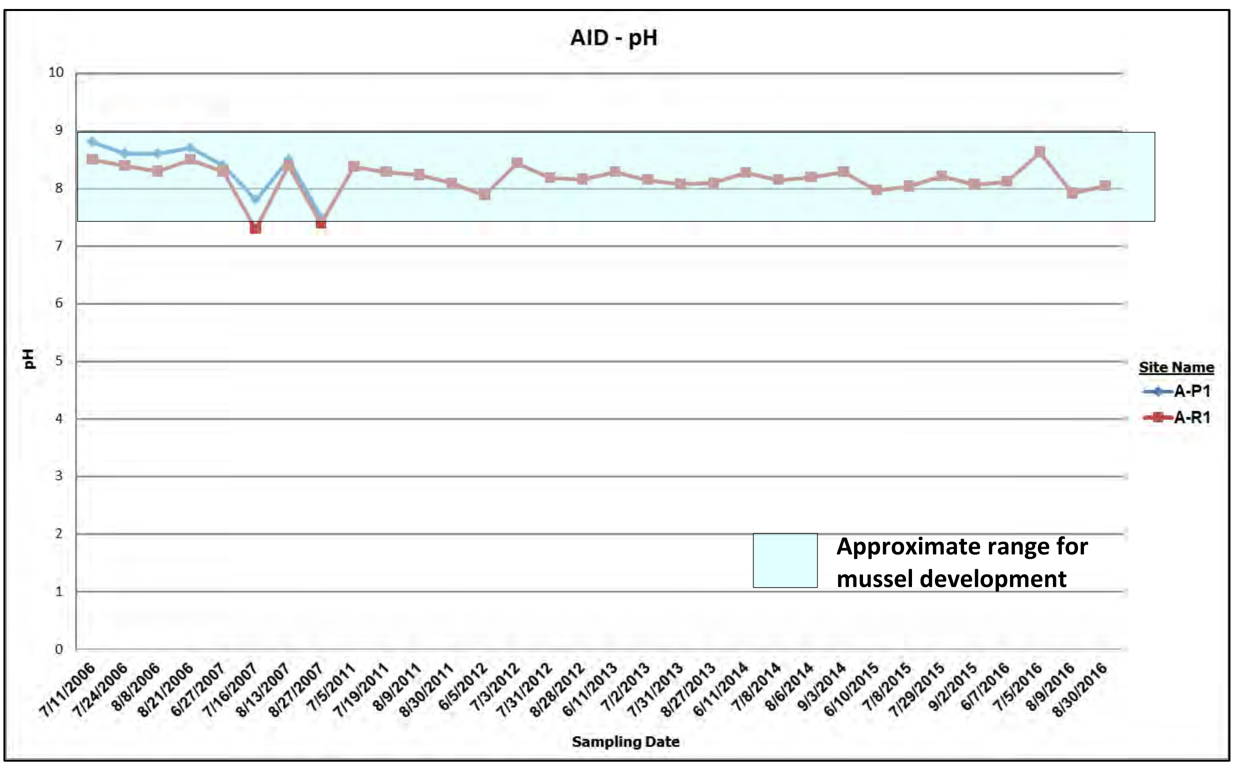

Figure A-11.2 AID – pH of irrigation water

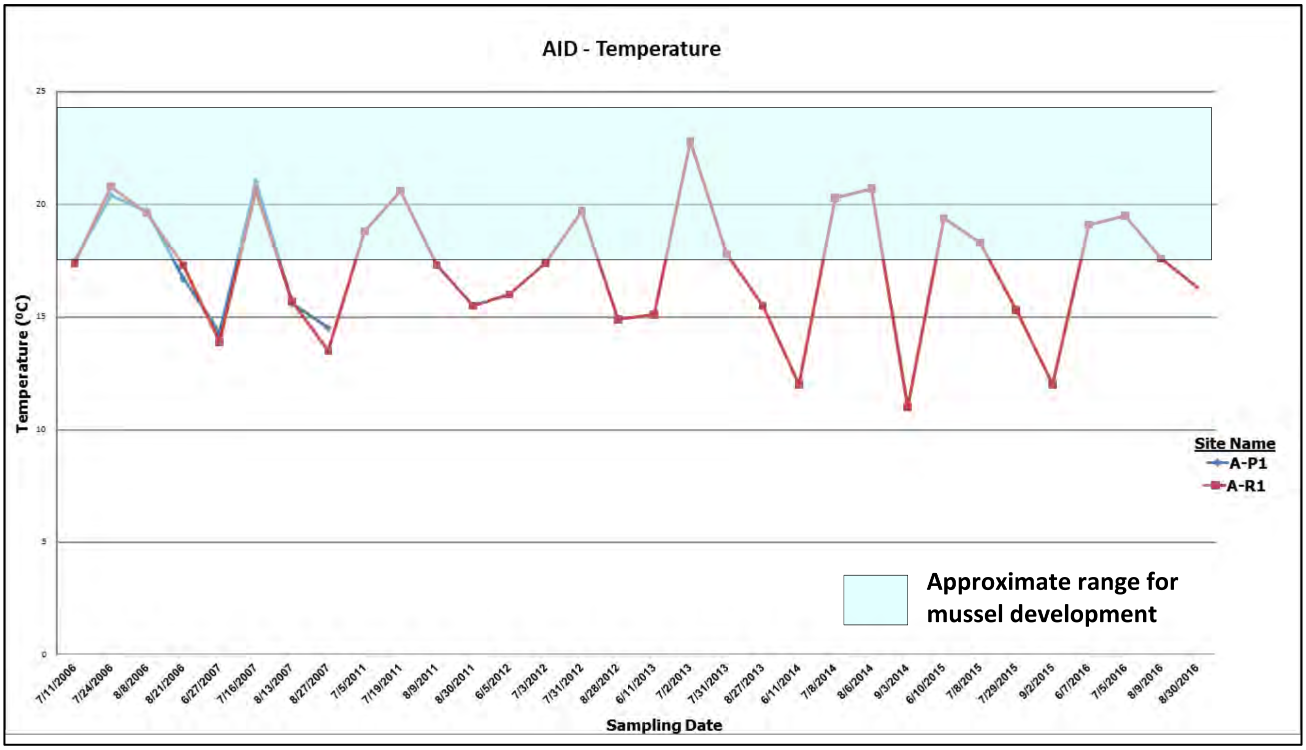

Figure A-11.3 AID – Temperature of irrigation water

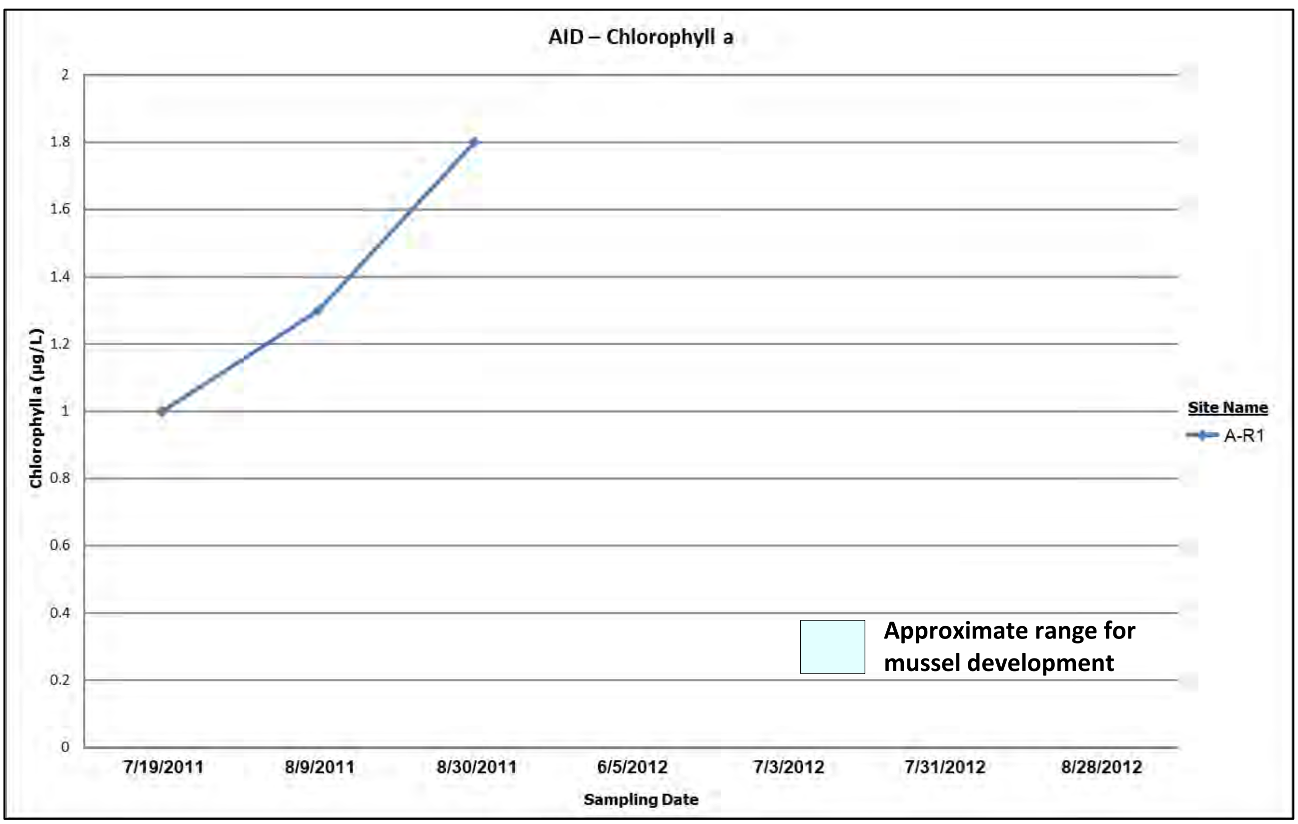

Figure A-11.4 AID – Chlorophyll a in irrigation water

Appendix A-12 Ross Creek Irrigation District (2006 to 2007 and 2011 to 2016)

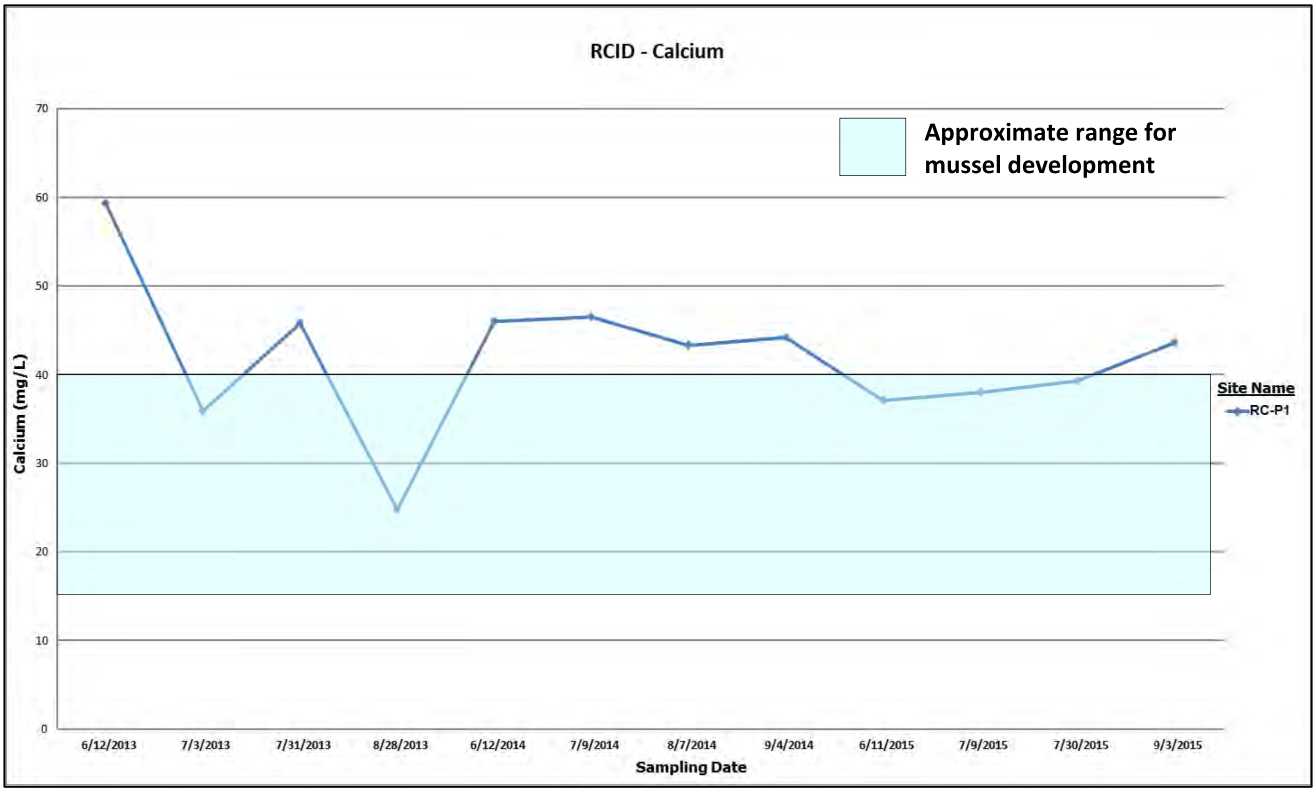

Figure A-12.1 RCID – Calcium concentration in irrigation water

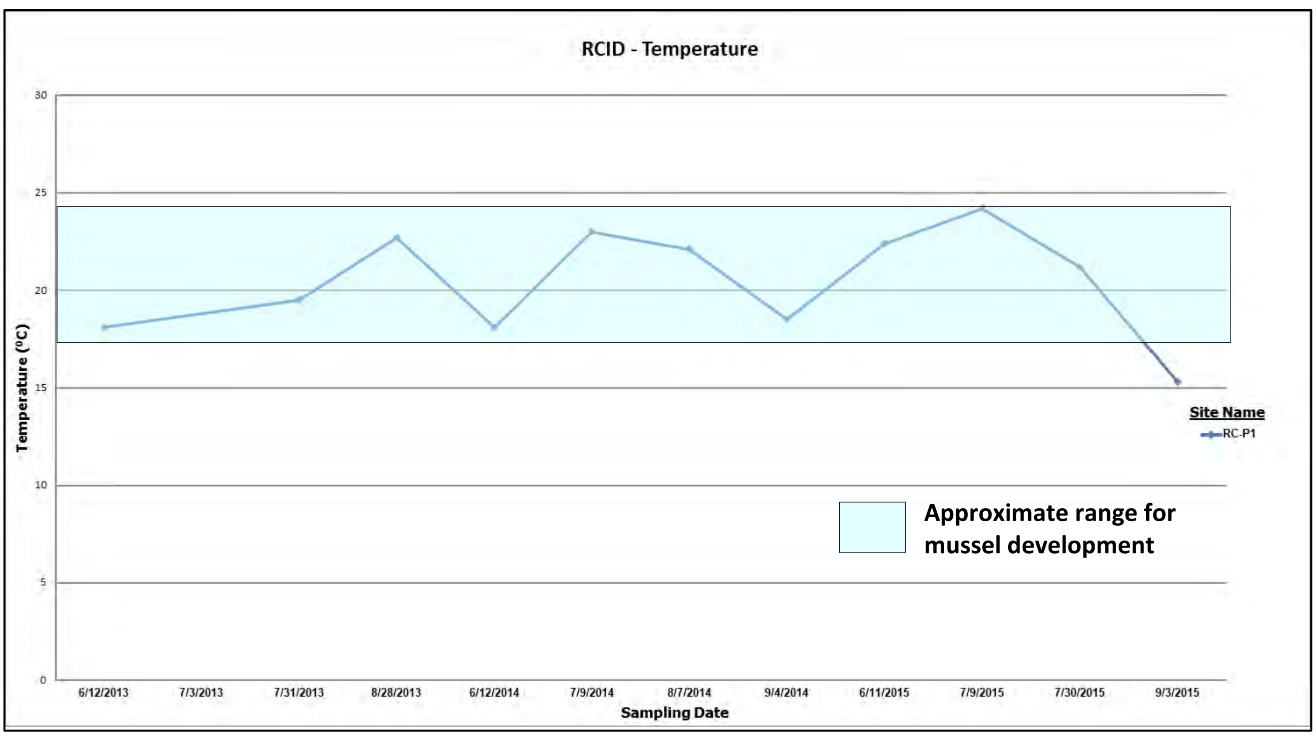

Figure A-12.2 RCID – Temperature of irrigation water

Appendix B Examples of Education Factsheets on Invasive Mussels

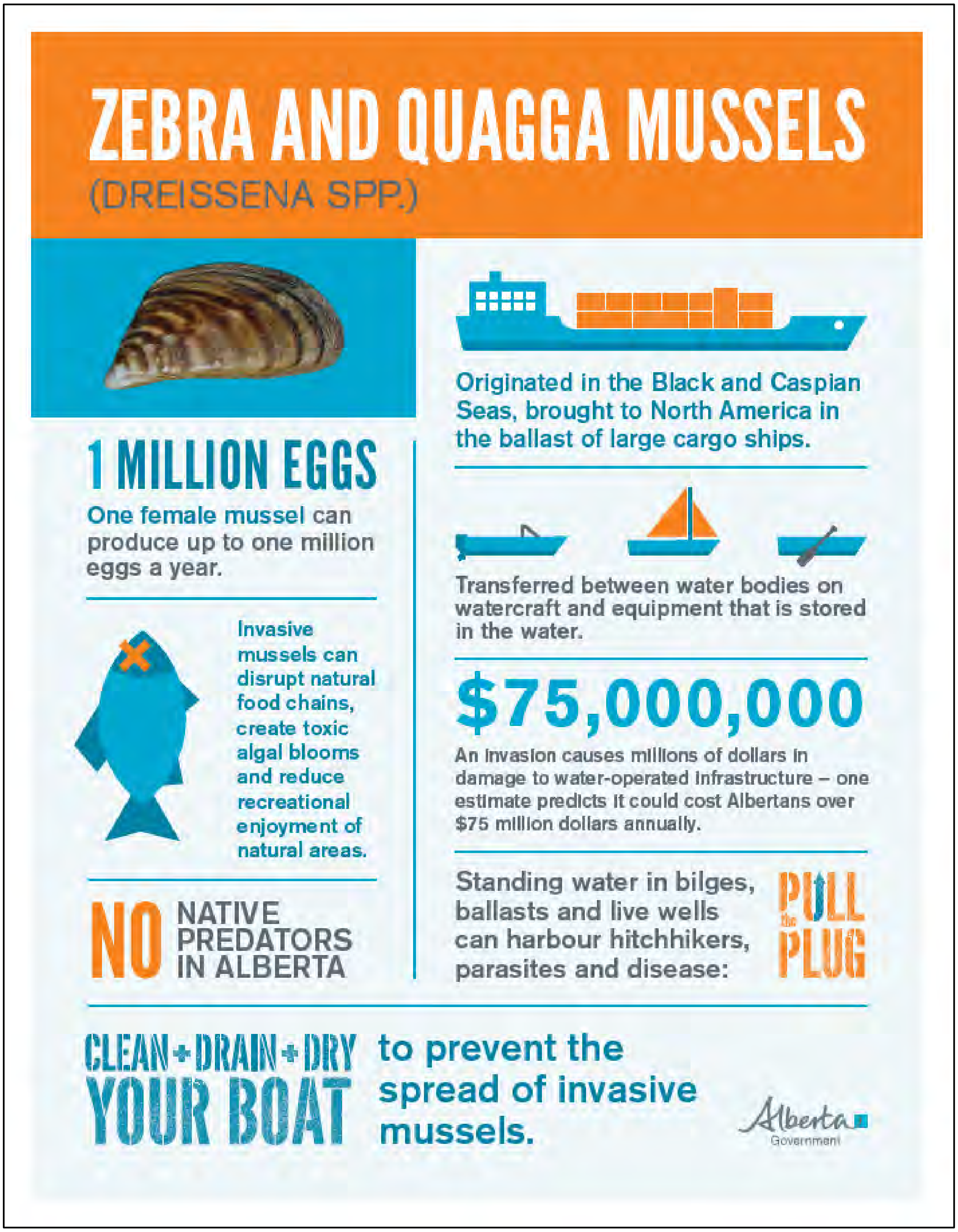

Figure B-1 Government of Alberta factsheet about zebra and quagga mussels

MNDNR

Aquatic Invasive Species

Zebra mussel

(*Dreissena polymorpha*)

What are zebra mussels?

Zebra mussels are small freshwater mussels that are not native to Minnesota. Adults range from ¼ to 1 ½ inches long and have yellow and brown striped shells. Unlike native mussels, they can attach themselves to hard surfaces in the water.

Zebra mussel (*Dreissena polymorpha*)

Where did zebra mussels come from?

Zebra mussels are native to Eastern Europe and Western Russia. They have spread throughout much of Europe and Asia over the past 200 years. They were likely brought to North America in the ballast water of ships and were discovered in Lake Erie in 1988.

What problems can they cause?

Zebra mussels can:

- clog irrigation intakes and other pipes,
- attach to boat motors and boat hulls, reducing performance and efficiency,
- attach to rocks, swim rafts and ladders where swimmers can cut their feet on the mussel shells,
- attach to and smother native mussels, and
- eat tiny food particles that they filter out of the water, which can reduce available food for larval fish and other animals, and cause more aquatic vegetation to grow as a result of increased water clarity.

Zebra mussels in Minnesota

Zebra mussels were discovered in the Duluth harbor in 1989. As of 2014, the DNR had documented zebra mussels in fewer than 100 water bodies in Minnesota. The DNR has listed a total of 213 water bodies as "infested" with zebra mussels, a regulatory classification which includes some water bodies that are connected to water bodies where zebra mussels have been found.

How do they spread?

Zebra mussels can attach to boats or aquatic vegetation and be carried to a different lake or upstream in a river. The microscopic larvae (called "veligers") may be carried in bait buckets, live wells, or other water.

Zebra mussels attached to a native mussel

What should you do to prevent their spread?

Before you leave any water access, clean weeds and debris from your boat, remove drain plugs and keep them out while traveling, and dispose of unused bait in the trash. For additional recommendations see mndnr.gov/AIS.

Regulatory classification

Zebra mussels and quagga mussels (a related species) are both classified as *prohibited invasive species* in Minnesota. It is illegal to import, possess, buy, sell, transport, or introduce them into state waters.

Aquatic Invasive Species
Best Management Practices

Zebra mussel

(*Dreissena polymorpha*)

What can be done to control zebra mussels?

In the U.S. and Canada, facility managers use pesticides to control zebra mussels in closed systems, such as water-cooling systems of power plants, in order to maintain functioning infrastructure. Many of the pesticides used in closed systems are not allowed for use in open water. In open systems such as natural lakes, attempts to control zebra mussels are uncommon and considered experimental at this time.

To date, we have documentation of less than ten attempts to control zebra mussels by treatment with pesticides in North America outside Minnesota.

Attempts to control zebra mussels in Minnesota

In Minnesota, we have documentation of five lakes where people attempted to eradicate zebra mussels using pesticide treatments. In addition, one Minnesota lake was drawn down in an attempt to reduce zebra mussels.

Pesticides and zebra mussels

The pesticides that have been used for zebra mussel control in Minnesota are: Zequanox®; copper products such as copper sulfate; and potassium chloride (also known as potash; use in open water requires review and approval from the U.S. Environmental Protection Agency).

What might be achieved by controlling zebra mussels?

Because pesticides have rarely been used to control zebra mussels in open water, pilot projects in Minnesota will help answer this question. In situations where zebra mussels are found in an isolated area or in a small water body, it may be possible to kill all the target zebra mussels using pesticides. Even if the mussels are killed, their shells will persist and can remain attached to surfaces even after the animals are dead.

What control of zebra mussels will the DNR permit?

Most lakes that are currently infested with zebra mussels are not good candidates for these pilot projects and permits. Pilot projects would be more likely to be permitted in situations where:

- the water body has been surveyed, and the survey finds zebra mussel populations are limited in size and localized, not scattered throughout the water body (the DNR may require third-party verification of zebra mussel distribution); and
- there are sufficient resources or partners (e.g., watershed districts, local units of government, lake groups) available to fulfill monitoring requirements.

We will assess all proposed projects on a case-by-case basis.

Permits and technical assistance

If you would like more information on management of zebra mussels or other aquatic invasive species, contact your local invasive species specialist:

Park Rapids	218-699-7293
Fergus Falls	218-739-7576 ext. 254
Grand Rapids	218-999-7805
Brainerd	218-203-4354
Saint Cloud	320-223-7847
Saint Paul	651-259-5828
Hutchinson	320-234-2550 ext. 238
Waterville	507-362-8786

Minnesota Department of Natural Resources
500 Lafayette Road, Box 25
St. Paul, Minnesota 55155
1-888-646-6367 or 651-259-5121
www.mndnr.gov/AIS

Prepared by the Invasive Species Program, Minnesota Department of Natural Resources
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Figure B-2 Minnesota factsheet about the dangers posed by zebra mussels

Appendix C Potash Requirements and Costs to Treat Pipelines

Table C-1 Volumes, potash requirements and estimated costs for one-time treatment of producer-owned water supply lines and pivot systems.

ID	Pivot Area (ha)*	Water Supply Lines**		Pivots**		Total Volume (m^3)	Potash Required (kg)	Treatment Cost ($)
		Length*** (km)	Volume*** (m^3)	Number	Volume (m^3)			
BRID	90,663	938	30,656	1,662	21,715	52,371	10,390	43,468
EID	93,646	969	31,665	1,715	22,429	54,094	10,732	44,898
LNID	62,237	644	21,045	1,141	14,907	35,951	7,133	29,839
RID	12,659	131	4,280	232	3,032	7,312	1,451	6,069
SMRID	137,683	1,425	46,555	2,524	32,977	79,532	15,779	66,012
TID	28,098	291	9,501	515	6,730	16,231	3,220	13,472
UID	7,757	80	2,623	142	1,858	4,481	889	3,719
WID	25,565	265	8,644	469	6,123	14,767	2,930	12,257
RCID	272	3	92	5	65	157	31	130
MVID	102	1	35	2	25	59	12	49
LID	474	5	160	9	114	274	54	227
AID	273	3	92	5	65	158	31	131
MID	4,318	45	1,460	79	1,034	2,494	495	2,070
Total	**463,747**	**4,800**	**156,808**	**8,500**	**111,074**	**267,881**	**53,147**	**222,341**

* Source: AAF, 2017, p. 7.

** Total number of pivots for the 13 irrigation districts assumed to be 8,500. Pivot numbers per district are based on percentage of irrigated area by pivot systems.

*** All water supply lines and pivot lines are assumed to have a diameter of 0.203 m. Each pivot is assumed to be 400 m in length.