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Method Development to Apply Potash to Irrigation Pipelines for the Control of Invasive Mussels

Barry Olson[2], Ivan Friesen[1], Brad Calder[2], and Lloyd Healy[2]

[1]Eastern Irrigation District, Brooks, Alberta
[2]Alberta Agriculture and Forestry, Lethbridge, Alberta

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Executive Summary

Introduction

Alberta is currently free of invasive aquatic mussels, which includes zebra (*Dreissena polymorpha*) and quagga (*Dreissena bugensis*) mussels. However, this threat is approaching Alberta's waters, with invasive mussels now in Manitoba and possibly in Montana. A major concern is the threat invasive mussels possess to the extensive irrigation infrastructure in southern Alberta. The irrigation districts and the irrigation industry as a whole understands the risk of invasive mussels if they should become established in the irrigation infrastructure. Even though the irrigation industry has been activity participating and supporting preventative measures, the industry also need to prepare for the possibility of an infestation and need tools and options to respond. The question is, what can we do if mussels should arrive?

Currently, there are no registered products to control mussels in Canada. However, it has been shown that potash, or potassium chloride (KCl), is lethal to mussels when potassium (K^+) concentration in water is high enough. After considering other options to control mussels, particularly in irrigation pipelines, it was decided to carry out a 2-yr research project in partnership with Alberta Agriculture and Forestry (AAF) to investigate the feasibility of using potash as a treatment option for irrigation pipelines.

This project included four objectives, and these objectives remained unchanged throughout the project:

1. Develop and test potash preparation methods and pipeline injection equipment.
2. Determine how to ensure a steady concentration of 100 mg L^{-1} of K^+ as a lethal dose in pipelines.
3. Document and assess the irrigation of potash-treated water on soil and crop health.
4. Confirm economic costs and considerations for treating Alberta's irrigation systems with potash.

Methods

Preparation of Potash for Injection. A stock solution of potassium chloride (KCl) was prepared by dissolving solid, granular potash (special standard grade product from Agrium® Inc.) into potable water at a rate of about 0.3 kg L^{-1}. Following mixing, removal of solids, and filtration, the resulting clear stock solution had a final concentration of about 120,000 mg L^{-1} potassium (K^+) and 108,800 mg L^{-1} chloride (Cl^-)

Pipeline Injection Study. Five irrigation pipelines within three irrigation districts were used to test the injection of dissolved KCl into pipelines to achieve a target concentration of 100 mg L^{-1} K^+. Three pipelines (Pipelines A, B, C) in the EID, one pipeline (Pipeline D) in the Taber Irrigation District (TID), and one pipeline (Pipeline E) in the St. Mary River Irrigation District (SMRID) were used in the study. The pipelines ranged in size from 207 to 3194 m^3. The number of irrigation systems supplied by the pipelines ranged from 1 to 18 systems.

The KCl stock solution was injected using an injection wand inserted through vertical air-vent pipes at the pipeline inlets. When the pivots were turned on to start flow through the pipeline, a dosing pump was used to inject the KCl stock solution. When the last pivot was turned off, the injection was stopped and the pipeline inlet closed. The KCl-treated water was held in the pipelines for about 24 to 48 h. After the hold period, the pivots were turned on and the pipeline inlet open and the KCl-treated water was purged from the pipelines and applied to the fields.

Water samples were collected at the pivots to determine the final concentration of K^+ in the water. Surface soil samples (0–2.5 cm and 0–15 cm layers) were collected in ten locations before and after the KCl-treated water was applied to the fields. Samples were analyzed for extractable K^+, extractable Cl^-, and electrical conductivity (EC). Alfalfa sampled were collected at Site 3, Pipeline B in two transects: one transect where KCl-treated water was not applied and the other transect where KCl-treated water was applied. The plant samples were analyzed for chemical content.

Small-plot Study. The site for this 2-yr study was a circular field, about 100 m in diameter, with a single-span irrigation pivot system at the Alberta Irrigation Technology Centre near Lethbridge. The field was divided into 12, pie-shaped plots, and the plots were grouped into four quadrants (replicates), with three plots per quadrant. The three plots within each replicate were randomly assigned one of three treatments: 0, 100, or 500 mg L^{-1} K^+ (0T, 100T, 500T, respectively) concentration in irrigation water. Treatments were applied using a fertigation unit connected to the center pivot. Water samples were collected from the pivot for each plot and the samples were analyzed in the lab to determine the actual concentrations.

The site was seeded to barley (*Hordeum vulgare* L. var. Amisk) in 2016 and 2017. Crop samples were collected at the silage or green-feed stage on July 26, 2017 for yield and tissue analysis. Samples were not collected in 2016 because the treatments were applied late in the growing season.

The treatments were applied two times late in the 2016 growing season and once after the crop was harvested. In 2017, the 500T only received untreated irrigation water. Based on the initial pipeline trial in 2016 (i.e., Pipeline A), it was reasoned that such a high application rate of KCl is unrealistic. The 100T treatment was applied three times in 2017 before the crop was harvested at the green-feed stage.

Rain gauges were placed at the subplots to record the amount of water applied during treatment applications.

Soil samples were collected in late September 2016 (0 to 15, 15 to 30, and 30 to 60 cm) and 2017 (0 to 15, 15 to 30, 30 to 60, 60 to 90, 90 to 120, and 120 to 150 cm). In addition, a single sample from the 0- to 2.5-cm soil layer was collected. Samples were analyzed for extractable K^+, extractable Cl^-, and EC.

Economic Assessment. This component of the project was carried out through a contract with Paterson Earth & Water Consulting. Details on how this work was carried out are in the contractor’s final report. Briefly, a literature review was carried out using relevant data and information from Canada and the United States to develop a comprehensive strategic management plan for the control and management of invasive mussels in Alberta's irrigation infrastructure. The assessment also included a cost estimate for wide-spread control in southern Alberta. The development of the management plan was also facilitated by direct discussion with staff of several irrigation districts. The study addressed five key objectives:

1. Assess the potential for invasive 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 invasive 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 invasive 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.

Key Findings

Objective 1. Earlier lab-bench trails were successfully scaled up to prepare large batches of dissolved KCl using commercial granulated potash. Mixing 0.3 kg potash per 1 L of water generated a concentrated stock solution of about 120,000 mg L^{-1} K^+, and most impurities were removed or filtered. Additional improvements on large-scale preparation and improved efficiencies would likely be needed for commercial production for wide-spread use if required.

Objective 2. The application of the K^+ stock solution to three of the five irrigation district pipelines was successful in that the target concentration of 100 mg L^{-1} K^+ in the pipeline was achieved or nearly achieved. For the other two pipelines, the final concentration was 13 to 24% less than the target in one pipeline and 22 to 30% greater than target in the other pipeline. The discrepancies for these two pipelines was likely due to using inaccurate estimates of flow in the pipelines. Having accurate flow values is critical when treating pipelines, particularly for larger pipelines serving several irrigation systems, which will cause the flow to change as systems are turned on and off. Also, to treat pipelines with potash will require extensive coordination among the applicator, irrigation districts, and water users.

Objective 3. A single application of potash-treated water onto cropland will not adversely affect soil or crop quality. Single applications from district pipelines resulted in a significant increase in soil K^+ and Cl^- in only a few fields and no effect on soil EC. The treated water was only applied to a small portion of each field (<7.5 ha) and the application rate averaged 12 kg ha^{-1} K^+, which is less than what most crops grown in Alberta will remove. Repeated applications did cause an increase in soil K^+, Cl^-, and EC. By managing the distribution of repeated potash-treated water applications on fields and through crop removal, K^+ accumulation should not be a concern. A single application of potash-treated water from one district pipeline had no effect on tissue quality of an alfalfa crop. Similarly, repeated applications of potash-treated water had no effect on the yield and tissue quality of barley at the silage stage.

Objective 4. The final report prepared by the contractor (Paterson Earth & Water Consulting) included nine key conclusions and eight recommendations.

Conclusions:

- 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.
- It is likely that dreissenid mussels will appear in irrigation water supply reservoirs under the current prevention program being implemented in Alberta.
- Alberta's irrigation water supply reservoirs and irrigation district water supply infrastructure will support the growth and development of dreissenid mussels.
- 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).
- Currently, there are no registered control options for invasive mussels in open bodies of water or irrigation pipelines in Canada.
- Irrigation districts have three options to consider for management and/or control of dreissenid mussels that are present in underground water delivery pipelines.
- Complete treatment of all irrigation district and producer-owned water supply pipelines with potassium chloride (potash) is estimated to cost about $1.1 million.
- It will be logistically difficult to treat all 900+ pipeline segments during the 30-day spring and fall periods.

Recommendations:

- The Government of Alberta and irrigation districts should consider implementing additional prevention measures to minimize the threat of mussel infestation at high-risk water storage reservoirs.
- An ongoing monitoring program should be implemented to detect the presence of dreissenid mussels in irrigation water supply reservoirs.
- Monitoring water in the irrigation districts' water supply reservoirs should continue, to assess the growth and development potential of dreissenid mussels.
- Irrigation districts should exploit Alberta's cold winter temperatures to control dreissenid mussels that settle in irrigation water delivery infrastructure.
- 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.
- New pipelines being installed within the irrigation districts should be designed and constructed to optimize winter control of dreissenid mussels.
- 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. Develop a potash injection strategy for those underground pipeline segments where winter desiccation and freezing may not be viable.

Table of Contents

List of Tables

List of Figures

1 Project Description

1.1 Introduction

Alberta is currently free of invasive aquatic mussels, which includes zebra (*Dreissena polymorpha*) and quagga (*Dreissena bugensis*) mussels. However, this threat is approaching Alberta's waters, with invasive mussels now in Manitoba and possibly in Montana. A major concern is the threat invasive mussels possess to the extensive irrigation infrastructure in southern Alberta. The irrigation districts and the irrigation industry as a whole understands the risk of invasive mussels if they should become established in the irrigation infrastructure. Even though the irrigation industry has been activity participating and supporting preventative measures, the industry also need to prepare for the possibility of an infestation and need tools and options to respond. The question is, what can we do if mussels should arrive?

Currently, there are no registered products to control mussels in Canada. However, it has been shown that potash, or potassium chloride (KCl), is lethal to mussels when potassium (K^+) concentration in water is high enough. After considering other options to control mussels, particularly in irrigation pipelines, it was decided to carry out a 2-yr research project in partnership with Alberta Agriculture and Forestry (AAF) to investigate the feasibility of using potash as a treatment option for irrigation pipelines.

1.2 Research Description

This research project included three main components. The first component was a laboratory and shop investigation to develop a method to prepare potash for use in the treatment of irrigation district pipelines. The second component include two field studies: one to test the injection of dissolved KCl into five irrigation district pipelines and the other to investigate the effects of repeated applications of KCl on soil and crop quality in a small-plot study. The third component was contract work to carry out a literature review and consult with irrigation districts on the feasibility and economics of wide-spread treatment for invasive mussels within the irrigation infrastructure in southern Alberta.

1.3 Objectives

This project included four objectives, and these objectives remained unchanged throughout the project:

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2. Determine how to ensure a steady concentration of 100 mg L^{-1} of K^+ as a lethal dose in pipelines.
3. Document and assess the irrigation of potash-treated water on soil and crop health.
4. Confirm economic costs and considerations for treating Alberta's irrigation systems with potash.

1.4 Work Scope Overview

This project was an applied research project and was carried out in partnership with other irrigation districts and AAF. Alberta Agriculture and Forestry successfully obtained a Growing Forward 2 grant, which was used to partly support the overall project. The project was 2 yr long from April 2016 to March 2018, and involved extensive collaboration among irrigation district staff, AAF staff, and landowners and irrigators, as well as retaining and working with a contractor. The main scope of the project was to provide, based on empirical field studies and current literature, a preliminary assessment of options for the irrigation industry in southern Alberta to consider for the possible control of invasive mussels.

2 Approach and Results

2.1 Literature Review

2.1.1 Irrigation in Alberta

Irrigation in Alberta is essential for high agricultural production and crop diversity. The irrigation conveyance network supplies water to thousands of rural homes and more than 30 communities for household potable water, municipal pools, parks, and industrial use including food processing plants and factories. The conveyance network also supplies water for several other uses including livestock production, wildlife habitat, and recreational activities such as fishing, boating, and camping on irrigation reservoirs. Irrigation infrastructure in Alberta includes 13 irrigation districts, 57 reservoirs, about 8000 km of conveyance works, with a total value of about $3.6 billion. About 690,000 ha of land are irrigated in the province (Paterson Earth & Water Consulting 2015), and approximately 98% of Alberta's irrigation occurs in the South Saskatchewan River Basin.

In recent years, the irrigation industry has been concerned with the threat of the introduction of aquatic invasive mussels into Alberta. Invasive mussels are present throughout much of North America, with invasive mussels now as close as Manitoba and possibly in Montana. The introduction of invasive mussels to the irrigation infrastructure will likely compromise the function and conveyance capabilities of the irrigation network in the province. The Government of Alberta understands the value of the irrigation industry, and is working with the irrigation industry to ensure the long-term supply to water users, while maintaining the economic benefits provided to local communities.

2.1.2 Invasive Mussels

Invasive mussels consist of the zebra (*Dreissena polymorpha*) and the quagga (*Dreissena bugensis*) mussels, and they originated from the Black and Caspian seas region in southeastern Europe, respectively. Invasive mussels are small, freshwater mussels that are filter feeders ingesting small planktonic algae and zooplankton. Zebra mussels have a triangular striped carbonate shell with dark rings, maturing to 3 cm in size. The Quagga mussels have a rounded stripped carbonate shell with shaded concentric rings, maturing to 2 to 5 cm in size, with an average life span of 3 to 5 yr. Quagga mussels can inhabit greater depths than zebra mussels and are tolerant of colder temperatures (Spidle et al. 1995; Mills et al. 1996). Generally, quagga mussel population densities are far greater than zebra mussels (Karatayev et al. 2015).

Invasive mussels are dioecious and rapidly reproduce with up to one million eggs per mussel per season (Benson et al. 2014a,b). The mussels release sexual gametes at two seasonal reproductive events, with an optimal temperature range for spawning of 18 to 28°C. The gametes combine forming an egg, which hatches to release a veliger offspring. Veligers mature into a microscopic trochophore, straight-hinged, umbonal, and pediveliger stages (80–100 µm). Mature veligers will settle out of the water column forming a juvenile stage while developing carbonate secretions forming a shell maturing during 1 to 2 yr into a viable adult stage. Invasive mussels use byssal threads to attach to most hard surfaces, often completely covering solid objects and surfaces.

Invasive mussels were first found in the United States in the Great Lakes in 1989. They were introduced through the release of ballast water from ships. They became established in Nevada in 2007 and in California in 2008. Invasive mussels were observed in the Red River water basin in the United States in 2009 and in Lake Winnipeg in October 2013.

Invasive mussel distribution and dispersal is related to human population density (Quinn et al. 2014). Human-mediated dispersal is considered to be the greatest transmission vector, specifically recreational boating activities including overland transport of boat trailers and water-based equipment are important vectors contributing to the spread of invasive mussels in North America. Natural dispersal downstream is also considered substantial transmission vector in major river systems and can occur rapidly over large distances.

In 2012, the Department of Fisheries and Oceans conducted a risk assessment for zebra mussels in Canada (Therriault et al. 2013). Zebra mussels were found to pose a high risk in most regions of western Canada. The probability of survival (habitat suitability) was determined primarily based on calcium concentrations, which indicated that most watersheds in the prairies were highly suitable for survival and establishment of zebra mussels. Zebra mussel establishment has been shown to have significant, irreversible ecological effects to freshwater ecosystems.

Since 2013, the Government of Alberta committed to increased protection measures against aquatic invasive species. Invasive mussels are typically introduced to new water bodies on trailered watercraft, and can have significant negative effects on the lake ecosystem, and any water infrastructure such as raw-water treatment or conveyance works, e.g., irrigation systems. Effects of invasive mussel introductions are far reaching environmentally, socially, and economically. Alberta Environment and Parks estimate that the total annual cost incurred by the province if invasive mussels were introduced at $76 million, with $8.8 million associated with water management structures and $3.9 million associated with water diversion intakes (Neupane 2013).

2.1.3 Control of Invasive Mussels

Preventing the infestation of invasive mussels in a region through education, regulations, and monitoring is considered less costly than trying to manage the presences of mussels. However, if invasive mussels become established, control options include the use mechanical, biological, and chemical methods. Of these, chemical control is likely the most practical option for the large-scale, irrigation conveyance system in Alberta.

Potential chemical treatments include oxidizing chemicals (chlorine, chloride dioxide, chloramines, ozone, bromine, hydrogen peroxide, potassium permanganate, ferrate) and non-oxidizing chemicals (molluscicides, biobullets, ammonium nitrate, copper ions, potassium salts, sodium metabisulfite, flocculation, salinity, and pH adjustment) (Mackie and Claudi 2010). Currently, there are no registered chemical products for the control of mussels in Canada.

The successful application of a chemical treatment requires a treatment strategy including several aspects such as correct timing, frequency, concentration, and application method. The available options for chemical treatment methods were evaluated for practicality, effectiveness, product availability, cost, environmental risk, and health and safety. Based on this evaluation, it was determined that potassium chloride (KCl) in the form of commercial potash may be the best option under Alberta conditions. Potassium (K^+) can be highly toxic to mussels, has low implications to crops and water quality, economical availability, and it has been used successfully in other jurisdictions.

Evidence suggests K^+ kills zebra mussels by interfering with gill respiration and it is a presumed anesthetic as it can prevent the defense response of shell valve closure (Mackie and Claudi 2010; Sykes and Wilson 2015). The K^+ interacts with the gill epithelium cells resulting in depolarization of the membranes, and this results in the impairment of cell volume regulation, cellular vacuolation, and ultimately, disruption of the tissue and death (Fisher et al. 1991). Previous studies into the use of K^+ to control invasive mussels have used 100 mg L^{-1} of K^+ for 48 h, at an ambient temperature >15°C resulted in mortality of adult zebra mussels and juvenile veligers (Sprecher and Getsinger 2000).

The effects of chemical control options on invasive mussels has been shown to vary dependent upon water temperature, pH, and water hardness (Sprecher and Getsinger 2000). However, for the purpose of the current research project, a concentration of 100 mg L^{-1} K^+ and an exposure duration of 48 hours were selected.

2.1.4 Potash

Potash, also known as Muriate of Potash, consists mainly (>95%) of KCl, which is a metal halide salt. Potash mining is a valuable industry in Canada, and potash is mainly used as a commercial, agricultural-grade, fertilizer in solid or aqueous forms. Solid Muriate of Potash is primarily marketed as 0-0-60 fertilizer, containing no nitrogen or phosphorus and 60% by weight K^+ expressed as potassium oxide (K_2O), which is equivalent to about 95% KCl — the actual chemical form of K^+ in potash. The colour of potash can ranged from white to pink/red, with the reddish colours caused by iron oxides.

Potassium chloride is odourless and has a white or colourless crystal appearance. It was a molar mass of 74.5513 g mol^{-1}, a melting point of 770^{o}C, and density of 1.984 g cm^{3}. Potassium chloride is readily soluble in water. The solubility of KCl in 100 mL of water is 28 g at 0^{o}C, 31.2 g at 10^{o}C, 34.2 g at 20^{o}C, and 37.2 g at 30^{o}C. The density of a saturated aqueous solution of KCl at 15^{o}C is 1.172 kg L^{-1}.

2.2 Materials and Methods

2.2.1 Preparation of Potash for Injection

Lessons learned from the laboratory investigations carried out prior to the start of the project were applied to develop a method for large-scale dissolution of granular potash (special standard grade product from Agrium® Inc.). A stock solution of potassium chloride (KCl) was prepared by dissolving solid, granular potash into potable water at a rate of about 0.3 kg L^{-1}.

The stock solution was prepared in batches by mixing in a mixing tank (1100 L) using a trash pump for 1.5 h until all the potash was dissolved. As the potash dissolved, residual flocculants and residue floated to the solution surface, and these residues were removed by skimming the solution surface by hand throughout the mixing step and during the settling period. After mixing, the solution was allowed to settle for 2 wk to allow other, insoluble residual particulates to settle to the bottom and sides of the tank. Following the settling period, the solution was pumped from the mixing tank to a storage tank (6826 L), leaving behind the settled residues. The resulting stock solution was reasonable clear and colourless. However, a circulating filtration system was developed for the storage tank to further clarify the stock solution. The concentration of the final stock solution was about 120,000 mg L^{-1} K^{+} and 108,800 mg L^{-1} chloride (Cl^{-}).

2.2.2 Pipeline Injection Study

A total of five irrigation pipelines within three irrigation districts were used to test the injection of soluble KCl into pipelines to achieve a target concentration of 100 mg L^{-1} K^{+}. Three pipelines (Pipelines A, B, C) in the EID, one pipeline (Pipeline D) in the Taber Irrigation District (TID), and one pipeline (Pipeline E) in the St. Mary River Irrigation District (SMRID) were used in the study (Table 1; Figure 1).

Table 1. Specifics about the five pipelines used in the field trials in 2016 and 2017.

Pipeline^{z}	District	Total length (km)	Total volume (m^{3})	Number of irrigation systems on pipeline	Number of irrigation systems used	Number of producers participated	Date of trial
A	EID	2.9	207	1	1	1	July 4–7, 2016
B	EID	5.7	951	7	3	3	June 7–9, 2017
C	EID	4.3	779	5	2	1	June 20–21, 2017
D	TID	9.5	3194	18	9	7	September 12–13, 2017
E	SMRID	7.3	1112	7	6	3	September 19–20, 2017

^{z} Actual names of the pipelines were not used for reporting purposes.

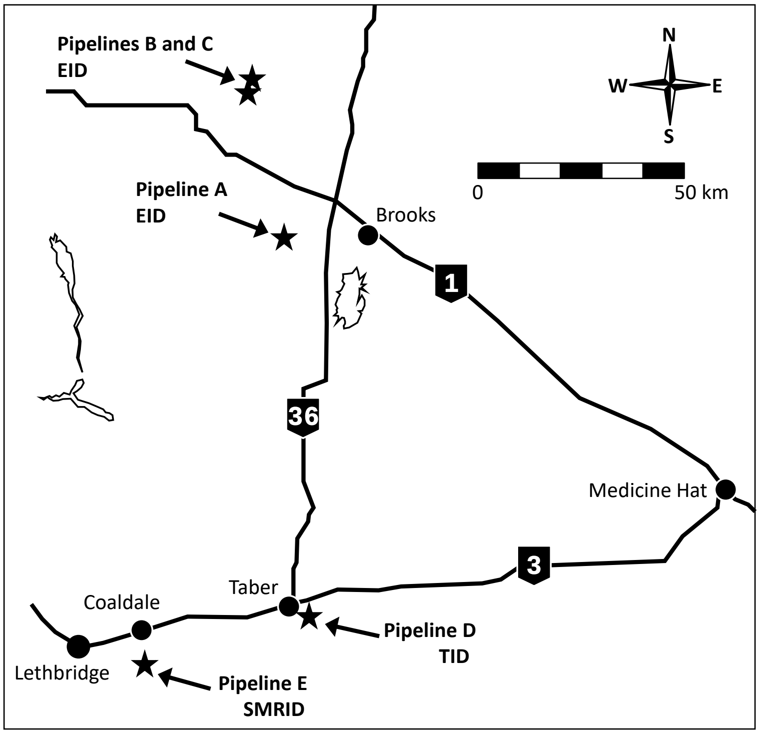

Figure 1. Pipeline sites used for the potash injection trails in 2016 and 2017.

2.2.3 Small-plot Study

All five pipelines were supplied with water from settling ponds. The KCl stock solution was injected using an injection wand inserted through vertical air-vent pipes at the pipeline inlets. When the pivots were turned on to start flow through the pipeline, a dosing pump was used to inject the KCl stock solution. Individual pivots were turned off when the KCl-treated water reached the pivots. When the last pivot was turned off, the injection was stopped and the pipeline inlet closed. The KCl-treated water was held in the pipelines for about 24 to 48 h. After the hold period, the pivots were turned on and the pipeline inlet open and the KCl-treated water was purged from the pipelines and applied to the fields. The area within each field that received the KCl-treated water was recorded. Rain gauges were placed in the field to determine how much KCl-treated water was applied. The pivots were operated until untreated water reached the pivots.

Water samples were collected at the pivots, and in-field measurements were carried out using electrical conductivity (EC) to determine when the KCl-treated water had reach each pivot during the injection phase and when untreated water had reach each pivot during the purging phase. Water samples were also analyzed in the laboratory following each pipeline trial to confirm K^+ concentrations.

Surface soil samples (0–2.5 cm and 0–15 cm layers) were collected in ten locations before and after the KCl-treated water was applied to the fields. Samples were air-dried, ground (<2 mm), and analyzed for extractable K^+, extractable Cl^-, and EC.

There was only one opportunity to collect crop samples. Alfalfa samples were collected at Site 3, Pipeline B (Figure 1) on June 29, 2017, 8 d after the KCl-treated water was applied to the field. Two transects of 10 sampling points were located in the field: one transect where KCl-treated water was not applied (i.e., control), and the other transect where KCl-treated water was applied (i.e., treatment). At each sampling point, a 0.25-m^2 area was harvested by hand removing all plant material above ground. The samples were placed into perforated paper bags and dried at 35^oC. The plant samples were analyzed for the content of total K, nitrogen (N), phosphorus (P), sulphur (S), calcium (Ca), magnesium (Mg), zinc (Zn), boron (B), copper (Cu), iron (Fe), and manganese (Mn).

2.2.3 Small-plot Study

Site. The site for this 2-yr study was a circular field, about 100 m in diameter, with a single-span center pivot irrigation system at the Alberta Irrigation Technology Centre near Lethbridge. The field was divided into 12, pie-shaped plots, and the plots were grouped into four quadrants, with three plots per quadrant. The quadrants were designated as Replicates A, B, C, and D. The three plots within each replicate were randomly assigned one of three treatments: 0, 100, or 500 mg L^{-1} K^+ (0T, 100T, 500T, respectively) concentration in irrigation water. A sub-plot (3 by 3 m) was located near the outer edge and in the center of each main plot. Soil and crop samples were collected from these subplots.

Crop. The site was seeded to barley (*Hordeum vulgare* L. var. Amisk) in 2016 and 2017. Routine agronomic practices were used in terms of seeding, fertilizing, weed control, irrigation scheduling, and harvesting. Crop samples were collected at the silage or green-feed stage (about 65% moisture) on July 26, 2017. At each subplot, a 0.25-m^2 area was harvested by hand, and all of the above ground material was placed in a bag. These samples were used to determine dry-matter yield. A second, smaller sample was collected for plant tissue analysis. All samples were placed in a drying room at 35^oC for 2 d. The 0.25-m^2 samples were weighed after drying. The plant tissue samples were analyzed for the content of total K, N, P, S, Ca, Mg, Zn, B, Cu, Fe, and Mn. Crop samples were not collected in 2016 because of the late application of the treatments.

Treatment Applications. Treatments were applied using a fertigation unit (Milton Roy A Series Metering Pump model MRAIIX0002) connected to the center pivot. The fertigation unit was turned on to inject the appropriate rate of stock solution for the 100T and 500T plots. The 0T plots received regular irrigation water, during which the fertigation unit was turned off.

The treatments were applied two times late in the 2016 growing season and once after the crop was harvested. In 2017, the 500T only received untreated irrigation water. Based on the initial pipeline trial in 2016 (i.e., Pipeline A), it was reasoned that such a high application rate of KCl is unrealistic. Plus, applying only untreated irrigation water provided an opportunity to assess the effects on the elevated EC, K^+, and Cl^- levels observed in 2016. The 100T were applied three times in 2017 before the crop was harvested at the green-feed stage.

The concentration of K^+ in the prepared potash stock solution ranged from 103,022 to 107,500 mg L^{-1}. The fertigator injection rate was adjusted so that either 100 mg L^{-1} or 500 mg L^{-1} K^+ was in the water applied by the pivot. Water samples were collected from the pivot for each plot and the samples were analyzed in the lab to determine the actual concentrations.

Rain gauges were placed at the subplots to record the amount of water applied during treatment applications.

Soil Samples. Soil samples were collected from the subplots in late September 2016 and 2017. In 2016, five core samples were collected in increments of 0 to 15, 15 to 30, and 30 to 60 cm using a Dutch hand auger. Composite samples were prepared for each soil layer. In addition, a single sample from the 0- to 2.5-cm soil layer was collected using a hand scoop. In 2017, two core samples were collected in increments of 0 to 15, 15 to 30, 30 to 60, 60 to 90, 90 to 120, and 120 to 150 cm using a truck-mounted, hydraulic-powered core tube. Composite samples were prepared for each soil layer. In addition, a single sample from the 0- to 2.5-cm soil layer was collected using a hand scoop. The soil samples were air dried, ground (2-mm sieve), and analyzed for extractable K^+, extractable Cl^-, and EC.

2.2.4 Economic Assessment

This component of the project was carried out through a contract with Paterson Earth & Water Consulting. Details on how this work was carried out are in Paterson Earth & Water Consulting (2018). Briefly, a literature review was carried out using relevant data and information from Canada and the United States to develop a comprehensive strategic management plan for the control and management of invasive mussels in Alberta’s irrigation infrastructure. The assessment also included a cost estimate for wide-spread control. The development of the management was also facilitated by direct discussion with staff of several irrigation districts. The study addressed five key objectives:

1. Assess the potential for invasive 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 invasive 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 invasive 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.

2.3 Results and Discussion

2.3.1 Pipeline Injection Study

Potassium Chloride Injection and Purging. The injection of the KCl stock solution was carried out successfully at all five pipeline trials. The efforts required for pipeline treatment were much greater for the larger pipelines with multiple irrigation systems in terms of coordination of irrigators and the irrigation districts.

For the four pipeline trials carried out in 2017, not all of the irrigation systems were used in the trials. About half the systems serviced by Pipelines B, C, and D were used, and nearly all of the systems serviced by Pipeline E were used (Table 1). There were a number of reasons why irrigators did not participate either in whole or in part. These reasons included not being interested in the project, concerns about possible effects on their crop, interference with crop management practices (e.g., pollination by bees), and unexpected last-minute changes that prevented an irrigator from operating their pivot system(s). Other factors such as limited window-of-opportunities relative to main agronomic activities, including seeding, pesticide application, and harvesting, had to be considered.

The time required to inject the KCl stock solution into the pipelines varied from 1.1 to 6.1 h (Table 2). The length of time was a function of the total pipeline volume (Table 1) and the number of irrigation systems in operation at a given time. Even though Pipeline E was larger than Pipelines B and C, the time required to treat the former pipeline was about 30 to 40% less time. This was because only two to three pivot systems were operated during the Pipeline B and C trials; whereas, up to five pivots were operated at the same time during the Pipeline E trial. As a result, the flow was higher through Pipeline E. The injection of Pipeline D took about 2.3 to 3.8 times longer to inject with KCl solution than the other four pipelines (Table 2). This is mainly because Pipeline D was three to four times larger than the other three pipelines. Even though Pipeline D had a larger number of irrigation systems used in the trial, not all of the irrigation systems were operated at the same time.

Table 2. Time required to treat the pipelines and the final mean potassium (K^+) concentration in the treated water achieved measured at the pivots.

Pivot	Number of pivot systems	Treatment time (h)	Final K^+ concentration (mg L^{-1})
A	1	1.1	106
B	3	2.7	102–105
C	2	2.3	89
D	9	6.1	122–130
E	6	1.6	76–87

The target concentration of 100 mg L^{-1} K^+ was generally achieved in Pipelines A, B, and C (Table 2). In contrast, the final concentrations were consistently greater than the target for Pipeline D, and were constantly less than the target for Pipeline E.

A key factor in treating pipelines is to have an accurate value of water flow in the pipeline at the point of injection. The flow changes as pivots are turned on and off, and changes in flow requires adjusting the injection rate of stock solution. During the trials, different methods were used to estimate the flow. For Pipelines B and C, a MACE flow meter was used at the inlet. The MACE meter is accurate to within 0.2% of full scale at constant temperature in a static stream, and 1% of full scale over a stream 5 to 55°C. However, there was some uncertainty with the accuracy of the flow measurements due to the installation of the meter on the flexible ABS plastic injection wand, and this resulted in slight shifting and vibrations. For Pipelines D and E, the flow was estimated by calculation using the flow values of the pivots during when a particular set of pivots were in operation. Each time a pivot was turned on or off, the flow was re-calculated and the injection pump re-adjusted accordingly. It is believed that the reason why the target concentration was not achieved for Pipelines D and E is because the flow values provided for the pivots were not accurate. Some of the values used may have been the rated flow value for the pivots as appose to an actual measurement with a flow meter. However, flow meters are generally only accurate to within 2% (personal communications, Lloyd Healy, AAF, Lethbridge). Even a couple of percentage points, either consistently too high or too low, would result in a cumulative effect among several pivots supplied by the same pipeline, easily resulting in being 10 to 30% above or below the target concentration.

Purging of the KCl-treated water held in the pipelines was successful for all five pipelines. The amount of irrigated water applied to fields during purging ranged from 3 to 24 mm, depending on the pivot. The concentration of K^+ at the center pivots after the hold periods, but before purging, ranged from 76 to 123 mg L^{-1}. Based on the concentration of K^+ and the amount of water applied, the application rate of K^+ on the fields ranged from 3 to 29 kg ha^{-1}, with a mean of 12 kg ha^{-1} among the fields for the five pipeline trials. In all cases, only a small proportion of each field (0.7 to 7.4 ha) received KCl-treated water.

The amount of K^+ applied to the fields was generally less than what would be expected to be removed by crops typically grown in southern Alberta. In comparison, the annual removal of K^+ by harvested crops can range from 16 to 26 kg ha^{-1} for cereal grains, from 11 to 17 kg ha^{-1} for oilseed crops, from 30 to 48 kg ha^{-1} for pulse crops, and from 114 to 270 kg ha^{-1} for forage crops (Canadian Fertilizer Institute 2001). Harvested sugar beet and potato can remove 133 and 201 kg ha^{-1}, respectively (Canadian Fertilizer Institute 2001).

Considering the relative low application rates of K^+ and the small application areas for a single treatment, the accumulation of K^+ in soil from repeated treatments can be avoided by managing the distribution of applications throughout the field and with annual crop removal. For example, if the area that receives KCl-treated water is one-eighth the area of the field, then eight treatments could be applied before applying more than once on the same area. And it is likely that eight treatments would occur over two or more years. Also, operating pivots at 100% during purging is recommended in order apply the lowest application rate of K^+.

Soil Samples. Generally, a single application of KCl-treated water on the fields had no significant effect on extractable K^+ in surface soil layers (Table 3). However, K^+ concentration was significantly increased by 12 to 26% at three fields. For one of these fields (Site 2, Pipeline D), the significant increase occurred in the 0- to 2.5-cm layer but not in the 0- to 15-cm layer. For the other two fields (Site 4, Pipeline D; Site 6, Pipeline E), the significant increase occurred in the 0- to 15-cm layer, but not in the 0- to 2.5-cm layer, and this would not be expected. An increase in the 0- to 2.5-cm layer but not in the 0- to 15-cm layer can be expected, but not the opposite. The amount of K^+ applied to the fields was generally less than what would be expected to be removed by crops typically grown in southern Alberta. Plus, the amount of K^+ applied was small compared to the exiting K^+ content in the soil.

Of the 18 fields sampled, nine had significantly higher Cl^- concentration in the 0- to 2.5-cm soil layer after the application of potash-treated water. This was also true for the 0- to 15-cm soil layer at five of the fields. Unlike K^+, the amount of Cl^- added was relatively large compared to the existing Cl^- content in soil, and this resulted in the ability to detect significant increases.

For most of the fields, the application of potash-treated water did not affect soil EC. Significant effects on EC did occur in six fields; however, the effect was not consistent, with EC increasing in three fields and decreasing in three fields. Therefore, the apparent significant effect on EC may be due to field variability.

Plant Tissue Samples. There was no significant effect ($P \leq 0.05$) caused by the application of KCl-treated water on the alfalfa crop at Site 3, Pipeline B (data not shown). The concern with the application of K^+ to a crop used for livestock feed is the possibility of causing grass tetany (or hypomagnesemia), which is the result of low Mg content in blood. High levels of K^+ in feed can reduce the absorption of Mg by cattle, and alfalfa can accumulate high levels of K^+ (Marx 2004). The mean K:(Mg+Ca) ratio in the control and treatment alfalfa samples was 1.6 ± 0.2 and 1.8 ± 0.3, respectively. A feed ration should have a K:(Mg+Ca) ratio less than 2.2 (Marx 2004). Therefore, a one-time application of KCl-treated water did not affect the nutrient quality of the alfalfa crop under the conditions of this trial.

2.3.2 Small-plot Study

Potassium and Water Applications. The target concentration of K^+ for 100T was generally achieved during the six applications, with an overall mean (n = 24; four reps x six application dates) of 105 mg L^{-1} (Table 4). The mean K^+ concentration was 485 mg L^{-1} for the 500T plots in 2016.

The amount of irrigation water applied during the application of the treatments ranged from 12 to 18 mm for individual plots, with a mean of 15 mm per application for the 2 yr. Based on the concentration of K^+ and the amount of irrigation water applied, the mean total load of K^+ applied to the 100T plots was 92 kg ha^{-1}; whereas, the mean total load applied was twice this amount for the 500T plots, even though K^+ was only applied in 2016 for the latter treatment (Table 4).

Table 3. Mean (n = 10) concentrations of soil electrical conductivity, extractable potassium, and extractable chloride in the fields prior to (pre) and after (post) potash-treated water application.

Pipeline	Site	Soil layer (cm)	Electrical conductivity[z] Pre	Electrical conductivity[z] Post[x]	Extractable potassium[y] Pre	Extractable potassium[y] Post[x]	Extractable chloride[z] Pre	Extractable chloride[z] Post[x]
			-------- (dS m^{-1}) --------		-------- (mg kg^{-1}) --------		-------- (mg kg^{-1}) --------	
A	4	0–2.5	6.80	6.86	800	780	16	29*
	4	0–15	7.13	7.12	586	592	15	16
B	2	0–2.5	1.12	0.73*	911	894	27	14*
	2	0–15	0.83	0.73	639	615	20	16
	3	0–2.5	0.72	0.90*	798	670	9	21*
	3	0–15	0.68	0.91*	331	377	8	14*
	4	0–2.5	1.06	0.80*	576	644	16	19
	4	0–15	1.51	1.28	537	595	28	25
C	2	0–2.5	0.72	0.91*	478	499	9	46*
	2	0–15	1.51	1.51	377	397	26	25
	3	0–2.5	0.86	0.81	886	863	13	27*
	3	0–15	1.01	0.93	506	536	17	18
D[w]	2	0–2.5	1.34	1.06	396	497*	19	36*
	2	0–15	1.97	2.10	333	348	27	35
	3	0–2.5	1.01	0.91*	371	350	47	37*
	3	0–15	0.96	1.01	289	294	34	41*
	4	0–2.5	0.76	0.90*	432	475	6	15*
	4	0–15	0.64	0.80*	319	396*	5	10*
	6	0–2.5	1.27	1.00	1021	942	43	33
	6	0–15	1.36	1.21	971	984	36	42
	8	0–2.5	0.89	0.96	456	474	12	25*
	8	0–15	0.70	0.75	377	359	6	18*
	9	0–2.5	1.61	1.46	750	683	138	113
	9	0–15	1.04	1.04	324	301	62	61
	10	0–2.5	0.66	0.72	349	336	8	16*
	10	0–15	0.57	0.60	269	242	5	7
E[u]	2	0–2.5	1.53	1.34	762	794	46	52
	2	0–15	ns[v]	ns	ns	ns	ns	ns
	3	0–2.5	1.24	1.34	490	474	31	30
	3	0–15	ns	ns	ns	ns	ns	ns
	4	0–2.5	0.92	0.78	649	632	15	22
	4	0–15	0.56	0.46	358	327	7	12
	6	0–2.5	1.14	1.11	403	440	78	80
	6	0–15	0.58	0.59	198	222*	16	23*
	7	0–2.5	1.62	1.71	973	1015	54	73
	7	0–15	4.36	4.38	588	583	47	50

[z] Determined using the saturated paste extraction method.

[y] Determined using the modified Kelowna extraction method.

[x] Post-mean concentrations followed by an asterisk (*) are significantly different ($P \leq 0.05$) from the pre-mean concentrations based on the paired t-test.

[w] Sites 11 and 12 were not soil sampled.

[v] ns = not sampled.

[u] Site 5 was not soil sampled.

Table 4. Potassium (K^+) concentration in the irrigation water and K^+ load applied for the 100T and 500T treatments.

	Mean (n = 4) concentration of K^+						Mean load of K^+						
	Aug 5, 2016	Aug 16, 2016	Sep 16, 2016	Jul 11, 2017	Jul 17, 2017	Jul 20, 2017	Aug 5, 2016	Aug 16, 2016	Sep 16, 2016	Jul 11, 2017[z]	Jul 17, 2017[z]	Jul 20, 2017[z]	Total load
	---------------------- (mg L^{-1}) ----------------------						-------------------------- (kg ha^{-1}) --------------------------						
100T[z]	85	125	102	115	104	101	12	18	15	17	15	15	92
500T[y]	450	507	497				66	73	69				208

[z] 100T = 100 mg L^{-1} K^+ target treatment applied in both years.

[y] 500T = 500 mg L^{-1} K^+ target treatment applied in 2016 only.

Soil Samples. The application of KCl-treated water in 2016 had minimal effect on the concentration of extractable K^+ in soil. In the 0- to 2.5-cm layer, K^+ concentration increased with K^+ concentration in the irrigation water; however, the differences among the treatment means were not statistically significant (Table 5). In contrast, Cl^- concentration was significantly increased in the top 2.5-cm layer with the 500T plots containing seven times more Cl^- compared to the 0T plots. Significant effects for Cl^- was also observed in the 0- to 15-cm and 15- to 30-cm layers, suggesting leaching of Cl^-. The application of KCl-treated water also caused a significant increase in EC in the 0- to 2.5-cm and 0- to 15-cm soil layers in 2016.

Table 5. Mean[z] extractable potassium (K^+), extractable chloride (Cl^-), and electrical conductivity (EC) in soil at the small-plot site in September 2016.

Parameter	Soil layer (cm)	0 mg L^{-1} K^+ treatment	100 mg L^{-1} K^+ treatment	500 mg L^{-1} K^+ treatment
K^+ (mg kg^{-1})	0–2.5	487[y]	633	799
	0–15	292	282	310
	15–30	168	181	160
	30–60	142	127	130
	0–60	182	180	178
Cl^- (mg kg^{-1})	0–2.5	18.8a	56.8ab	135b
	0–15	16.3a	29.5a	70.3b
	15–30	6.9a	15.3a	32.2b
	30–60	3.0	4.6	6.0
	0–60	7.2a	13.9a	29.3b
EC (dS m^{-1})	0–2.5	0.70a	1.02ab	1.68b
	0–15	0.81a	0.84a	1.10b
	15–30	0.86	0.79	0.97
	30–60	1.49	1.52	1.82
	0–60	1.10	1.09	1.33

[z] n = 4.

[y] Means within the same row with the same letter or no letters are not significantly different ($P \leq 0.05$). The Tukey test was used as the post-hoc test.

As pointed out for the pipeline study, the amount of K$^+$ applied to soil was relatively small compared to the exiting K$^+$ content in the soil. Whereas, the amount of Cl$^-$ added was relatively large compared to the existing Cl$^-$ content in soil, and this resulted in the ability to detect significant increases of Cl$^-$.

In 2017, the concentration of K$^+$ was still highest in the 0- to 2.5-cm soil layer for 500T, followed by 100T, and then by 0T; however, the means were not significantly different (Table 6). The higher level in 500T is not surprising, as the 2-yr of 100T applications (45 kg ha^{-1} in 2016 and 47 kg ha^{-1} in 2017) was less than the amount applied to the 500T plots (208 kg ha^{-1}) in 2016 (Table 4). The 100T value in 2017 were similar to the 2016 value. Even though K$^+$ was applied in 2017 to 100T, crop removal during 2017 may have resulted in the similar concentrations between the two years.

Table 6. Mean[z] extractable potassium (K$^+$), extractable chloride (Cl$^-$), and electrical conductivity (EC) in soil at the small-plot site in September 2017.

Parameter	Soil layer (cm)	0 mg L^{-1} K$^+$ treatment	100 mg L^{-1} K$^+$ treatment	500 mg L^{-1} K$^+$ treatment
K$^+$ (mg kg^{-1})	0–2.5[y]	505	617	728
	0–15	275	278	383
	15–30	159	138	148
	30–60	149	138	152
	60–90[x]	166	157	135
	90–120[x]	179	144	110
	120–150[x]	189	127	123
	0–150[x,w]	178	153	180
Cl$^-$ (mg kg^{-1})	0–2.5	4.1a	12.2a	37.4b
	0–15	8.7a	44.9ab	71.4b
	15–30	14.4	40.4	51.9
	30–60	3.7	6.9	13.4
	60–90[x]	2.4	3.3	2.5
	90–120[x]	3.9	4.5	3.2
	120–150[x]	2.5	5.4	4.3
	0–150[x,w]	5.7	15.1	16.4
EC (dS m^{-1})	0–2.5	0.78a	0.94ab	1.17b
	0–15	0.65a	0.87ab	1.10b
	15–30	1.21	0.89	0.92
	30–60	1.99	2.15	1.80
	60–90[x]	3.81	4.51	3.33
	90–120[x]	2.72	4.75	2.95
	120–150[x]	2.28	4.19	2.83
	0–150[x,w]	2.24	3.08	2.26

[z] n = 4, expect n = 3 for the control treatment for the 60–90, 90–120, and 120–150 cm soil layers.

[y] Means within the same row with the same letter or no letters are not significantly different (*P* ≤0.05). The Tukey test was used as the post-hoc test.

[x] The three bottom soil layers (60–90, 90–120, and 120–150 cm) were not sampled for the control treatment in Replicate C, and therefore, did not contribute to the total soil depth (0–150 cm) mean values.

[w] Replicate C results were not used for the statistical test for treatment effect.

The K^+ concentration was nearly identical in the 0- to 15-cm layer between the 0T and 100T treatments in 2017 (Table 6). Whereas, in comparison, the concentration was about 39% higher in this soil layer for the 500T plots, reflecting residual carryover from the 2016 applications. Below the 15-cm depth, the concentration of K^+ was similar among the treatments, suggesting that the applied K^+ remained in the 0- to 15-cm layer and did not leach into the soil profile. In fact, much of the added K^+ likely remained in the top few centimetres of soil.

The concentration of Cl^- in the 0- to 2.5-cm layer was significantly higher for 500T compared to the other two treatments in 2017 (Table 6). The mean concentration of Cl^- for 500T was more than nine times higher than 0T and more than three times higher than 100T in this surface soil layer. Significant differences were also observed in the 0- to 15-cm soil layer with 500T eight times and 1.5 times higher than 0T and 100T, respectively. The Cl^- in 500T represents residual carryover from the applications in 2016. However, the Cl^- concentration in the 0- to 2.5-cm layer decreased from 135 mg kg^{-1} in 2016 (Table 5) to 37 mg kg^{-1} in 2017. Therefore, the application of regular irrigation water to 500T in 2017 likely caused leaching of the Cl^-. The concentration in the 0- to 15-cm and 15- to 30-cm layers were higher than in the 0- to 2.5-cm layer, also suggesting leaching of Cl^- further into the soil. Though not significantly different from the other two treatments, the 500T plots also had the highest Cl^- concentration in the 30- to 60-cm soil layer. Below the 60-cm depth, the concentration of Cl- was low and similar among the three treatments, signifying that very little, if any Cl^- leached deeper than 60 cm under the conditions of this study.

As in 2017, EC in the 0- to 2.5-cm and 0- to 15-cm soil layers was significantly higher for the 500T plots compared to the 0T plots (Table 6). The 500T treatment was also higher than the 100T treatment in 2017, however, the differences were not significant. Electrical conductivity mean values for the 0T and 100T plots were similar between the two years in the 0- to 2.5-cm layer. In contrast, EC decreased from 1.68 dS cm^{-1} in 2016 to 1.17 dS m^{-1} in 2017, and this may have been cause by leaching with the application of irrigation water in 2017. However, there was no evidence of leaching based on EC results below the 15-cm depth.

Crop Yield and Nutrient Content. Even though the dry-matter yield in 2017 was higher (about 18%) for 100T and 500T compared to 0T, the three treatments were not significantly different (Table 7).

Nutrient content of plant issue was not significantly different among the treatments for nearly all parameters, expect for Cu, which was significantly less for 100T and 500T compared to 0T (Table 7). Of particular interest is the application of K^+ did not caused an increase in the uptake of this cation, as the tissue concentration was very similar among the treatments.

The mean dry-matter yield among all treatments was 13.2 Mg ha^{-1}, and the mean K^+ concentration was 12.4 g kg^{-1}. Based on these two values, the crop removal of K^+ was 166 kg ha^{-1}. This amount removed by the crop in 2017 was nearly double the total amount of K^+ added to 100T in 2016 and 2017, and 80% of the amount added to 500T in 2016. These results show that repeated applications of KCl-treated irrigation water will likely not cause an accumulation of K^+ in soil, particularly if crops with high K^+ requirements are grown, such as forages. In addition, as the pipelines trials demonstrated, only a small portion of an irrigated field will receive KCl-treated water from a single application. A combination of distributing successive applications throughout a field and crop removal is expected to prevent K$^+$ accumulation in soil.

Table 7. Barley dry-matter yield and plant tissue nutrient content in 2017.

		Treatment mean ± standard deviation[z]		
Parameter	Unit	0 mg L^{-1} K$^+$ treatment	100 mg L^{-1} K$^+$ treatment	500 mg L^{-1} K$^+$ treatment
Dry-matter yield[y]	Mg ha^{-1}	11.8 ± 0.3[x]	14.1 ± 3.6	13.8 ± 3.3
Total nitrogen	g kg^{-1}	19.8 ± 1.7	19.7 ± 1.8	21.8 ± 2.0
Total phosphorus	g kg^{-1}	2.0 ± 0.5	1.9 ± 0.3	2.2 ± 0.4
Total potassium	g kg^{-1}	11.9 ± 3.4	12.8 ± 3.4	12.4 ± 4.5
Total sulphur	g kg^{-1}	2.4 ± 0.6	1.9 ± 0.2	1.9 ± 0.3
Total calcium	g kg^{-1}	4.33 ± 0.75	4.24 ± 1.27	3.92 ± 1.09
Total magnesium	g kg^{-1}	2.18 ± 0.38	2.11 ± 0.34	2.12 ± 0.16
Total zinc	mg kg^{-1}	10.71 ± 1.76	10.52 ± 1.53	11.05 ± 2.09
Total boron	mg kg^{-1}	5.4 ± 1.4	5.1 ± 0.8	5.4 ± 1.1
Total copper	mg kg^{-1}	3.28 ± 0.20a	3.01 ± 0.20b	2.75 ± 0.13c
Total iron	mg kg^{-1}	54.82 ± 14.34	48.57 ± 6.94	44.51 ± 8.86
Total manganese	mg kg^{-1}	22.52 ± 6.35	19.50 ± 3.08	20.71 ± 5.36

[z] n = 4.

[y] Whole, above-ground barley plants were harvested at the silage/green-feed stage.

[x] Means within the same row with the same letter or no letters are not significantly different ($P \leq 0.05$). The Tukey test was used as the post-hoc test.

The K:(Mg+Ca) ratio in the barley tissue was 2.0 for 100T and 500T. In comparison, 0T had a ratio value of 1.8. To prevent the onset of grass tetany in cattle, it is recommended that diets have a K:(Mg+Ca) ratio of less than 2.2 (Marx 2004). Therefore, the application of KCl-treated water did not negatively affect the quality of barley as livestock feed.

2.3.3 Economic Assessment

The final report included nine key conclusions and eight recommendations, which are listed below. Further details and supporting information for the conclusions and recommendations are in Paterson Earth & Water Consulting (2018).

Conclusions

- 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.
- It is likely that dreissenid mussels will appear in irrigation water supply reservoirs under the current prevention program being implemented in Alberta.
- Alberta’s irrigation water supply reservoirs and irrigation district water supply infrastructure will support the growth and development of dreissenid mussels.

- 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).
- Currently, there are no registered control options for invasive mussels in open bodies of water or irrigation pipelines in Canada.
- Irrigation districts have three options to consider for management and/or control of dreissenid mussels that are present in underground water delivery pipelines.
- Complete treatment of all irrigation district and producer-owned water supply pipelines with potassium chloride (potash) is estimated to cost about $1.1 million.
- It will be logistically difficult to treat all 900+ pipeline segments during the 30-day spring and fall periods.

Recommendations

- The Government of Alberta and irrigation districts should consider implementing additional prevention measures to minimize the threat of mussel infestation at high-risk water storage reservoirs.
- An ongoing monitoring program should be implemented to detect the presence of dreissenid mussels in irrigation water supply reservoirs.
- Monitoring water in the irrigation districts' water supply reservoirs should continue, to assess the growth and development potential of dreissenid mussels.
- Irrigation districts should exploit Alberta's cold winter temperatures to control dreissenid mussels that settle in irrigation water delivery infrastructure.
- 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.
- New pipelines being installed within the irrigation districts should be designed and constructed to optimize winter control of dreissenid mussels.
- 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.
- Develop a potash injection strategy for those underground pipeline segments where winter desiccation and freezing may not be viable.

3 Relevance and Impact

Currently, Alberta is free of aquatic invasive mussels. The primary focus for the Government of Alberta and stakeholders, including the irrigation districts, is to prevent mussels from becoming established in the province through various programs and regulations. Therefore, as long as Alberta remains mussel free, particularly regarding the irrigation infrastructure, the requirements of control options, including the use of potash, will not be needed. However, being prepared and having options to manage a mussel outbreak is an important priority for the irrigation districts. This project, including the field studies and the contracted study provided valuable insight on the technical challenges that may be involved for the control of mussels in the irrigation infrastructure. The strategic pest management plan that was prepared by Paterson Earth & Water Consulting (2018) highlights the large-scale efforts, resources, and cost that would be required to treat all 900 plus irrigation district pipelines in southern Alberta. It was concluded that it would be logistically difficult to treat all 900 plus pipelines during the irrigation season. It was also pointed out that because of the relatively short reproductive season for mussels in southern Alberta, if invasive mussels did infest water bodies in southern Alberta, it would take 3 to 5 yr before the population became well established and spread downstream. As well, the irrigation infrastructure in Alberta is grouped into three main systems: the Bow River, Oldman River, and the Waterton River/St. Mary River systems. Therefore, a mussel infestation in one main system may not result in mussel establishment in the other systems. The location of an initial infestation will also determine the potential spread, with infestations closer to the headwaters likely resulting in more of the infrastructure being affected. There may be a commercial opportunity for preparation of potash and treatment for invasive mussels on this large scale. However, potential companies will not make investments as long as Alberta remains mussel free. In the event of a mussel outbreak within the irrigation infrastructure, the provincial rapid response plan will assess the situation and hopefully contain or minimize any spread. If long-term control is then required, there would likely a reasonable amount of time (i.e., 2 to 3 yr) to have the required resources put in place.

4 Overall Conclusions

This was the first project in Alberta to investigate the use of potash as a possible control product for invasive mussels if they should become established in the province's irrigation infrastructure. The ability of potash (i.e., K^+) to kill mussels had already demonstrated by others, and the focus of this project was on the logistics of using potash primarily to treat irrigation pipelines. The project had four main objectives, which were all met.

4.1 Objective 1

The lab-bench trails were successfully scaled up to prepare large batches of dissolved KCl using commercial granulated potash. Mixing 0.3 kg potash per 1 L of water generated a concentrated stock solution of about 120,000 mg L^{-1} K^+, and most impurities were removed or filtered. Additional improvements on large-scale preparation and improved efficiencies would likely be needed for commercial production for wide-spread use if required.

4.2 Objective 2

The application of the K^+ stock solution to three of the five irrigation district pipelines was successful in that the target concentration of 100 mg L^{-1} K^+ in the pipelines was achieved or nearly achieved. For the other two pipelines, the final concentration was 13 to 24% less than the target in one pipeline and 22 to 30% greater than target in the other pipeline. The discrepancies for these two pipelines was likely due to inaccurate estimates of flow in the pipelines. Therefore, having accurate flow values is critical when treating pipelines, particularly for larger pipelines serving several irrigation systems, which will cause the flow to change as systems are turned on and off. Also, to treat pipelines with potash will require extensive coordination among the applicator, irrigation districts, and water users.

4.3 Objective 3

A single application of potash-treated water from a district pipeline onto cropland will not adversely affect soil or crop quality. A single application resulted in a significant increase in soil K^+ and Cl^- in only a few fields, and no effect on soil EC. The treated water was only applied to a small portion of each field (<7.5 ha) and the application rate averaged 12 kg ha^{-1} K^+, which is less than what most crops grown in Alberta will remove. Repeated applications did cause an increase in soil K^+, Cl^-, and EC. By managing the distribution of repeated potash-treated water applications on a field and through crop removal, K^+ accumulation should not be a concern. A single application of potash-treated water from one district pipeline had no effect on tissue quality of an alfalfa crop. Similarly, repeated applications of potash-treated water had no effect on the yield and tissue quality of barley at the silage stage.

4.4 Objective 4

The conclusions and recommendation from the contracted study has been summarized in Section 2.3.3, and full details are in Paterson Earth & Water Consulting (2018).

5 Next Steps

The conclusions and recommendations from the Paterson Earth & Water Consulting (2018) report will be discussed by the irrigation districts through the Alberta Irrigation Projects Association. Discussion points will include potential further measure to prevent mussel infestation of irrigation reservoirs, continued monitoring, and the potential of examining the possibility of using cold winter air to control invasive mussels. Monitoring of high-risk irrigation reservoirs will continue through partnership efforts among the irrigation districts, the Alberta Irrigation Projects Association, AAF, and Alberta Environment and Parks. Further measures to prevent infestation and the potential of using cold winter air would require new/additional resources to proceed.

6 Communications Plan

The final report of the contract work (Objective 4) has been circulated to the other irrigation districts, Alberta Irrigation Projects Association, AAF, and Alberta Environment and Parks. Preliminary findings of this study was presented at the Canada Water Resources Association in June 2017. The results of the field study was recently presented at the annual Alberta Irrigation Technology Conference in March 2018. The final results of the field studies (pipeline and small-plot studies) will be circulated to the irrigation districts and the Alberta Irrigation Projects Association. A poster about the pipeline study will be presented at the International Commission on Irrigation and Drainage in Saskatoon, Saskatchewan in August 2018.

All final reports from this project are available online at the following AAF website.
https://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/irr15127

7 Scientific Achievements

Event/activity	**Type**	**Location**	**Date**
19th International Conf. on Aquatic Invasive Species	Presentation	Winnipeg	Apr 11–14, 2016
Alberta Innovates - EES Workshop	Presentation	Edmonton	Jun 30–31, 2016
PNWER Summit - Aquatic invasive species session	Presentation	Calgary	Jul 19, 2016
North American Lakes Management Society	Presentation	Banff	Nov 03, 2016
Potash Project workshop	Workshop	Lethbridge	Nov 08, 2016
CANCID/CWRA webinar	Webinar		Nov 26, 2016
Webinar to Alberta Environment and Parks	Webinar		Jan 18, 2017
Presentation to BRID Board	Presentation	Lethbridge	Jan 25, 2017
Presentation to the Alberta Institute of Agrologists Br.	Presentation	Lethbridge	Jan 26, 2017
Alberta Soil Science Workshop	Presentation	Lethbridge	Feb 15–17, 2017
Invasive Mussel Collaborative/Great Lakes Commission	Webinar		Mar 06, 2017
Presentation to LNID Annual General Meeting	Presentation	Picture Butte	Apr 11, 2017
Alberta Innovates	Presentation	Edmonton	May 24, 2017
Canadian Water Resources Assoc. National Conference	Presentation (2)	Lethbridge	Jun 05, 2017
Farming Smarter Conference	Presentation	Medicine Hat	Oct 26, 2017
Lethbridge College agriculture students irrigation class	Presentation	Lethbridge	Oct 27, 2017
Alberta Irrigation Projects Associ. Water Conference	Presentation	Lethbridge	Nov 22, 2017
Presentation to Manitoba Hydro, Environment	Presentation	Winnipeg	Dec 15, 2017
Irrigation Technical Conference	Presentation	Taber	Mar 01, 2018
SEAWA Community Education Forum	Presentation	Medicine Hat	Apr 06, 2018
Dreissenid mussels and Alberta's irrigation infrastructure — A report on strategic pest management plan and cost estimate	Final report		Jan 31, 2018
Media interviews/articles:			
Grains West Magazine	Interviews/articles		Jan 2017
Top Crop Manager			Jan 2017
Bow Island Commentator			Mar 2017
Call of the Land (2)			2017, 2018
Farming Smarter			Mar 2018

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