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1. PROJECT INFORMATION:

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AI Project Advisor:	Brett Purdy, Vicki Lightbown

2. APPLICANT INFORMATION:

Applicant (Organization):	**Monica B. Emelko**
Address:	Department of Civil and Environmental Engineering University of Waterloo 200 University Avenue West Waterloo, ON N2L 3G1
Applicant Representative Name:	Thiam Phouthonephackdy
Title:	Professor
Phone Number:	519-888-4567 x.32208
Email:	mbemelko@uwaterloo.ca

3. PROJECT PARTNERS

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- Alberta Agriculture and Forestry (AAF),
- Alberta Environment and Parks (AEP),
- BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development (BCFLNRORD),
- City of Calgary, Water Services (Calgary),
- Regional Municipality of Wood Buffalo (RMWB), and
- Veolia Water Technologies Canada.

A. EXECUTIVE SUMMARY

Wildfire impacts to drinking water treatability across different forest regions have some broad similarities. An understanding of key similarities and differences in wildfire impacts to source water quality and treatability in Alberta and best available technologies (BATs) for in-plant drinking water treatment in response to severe wildfire is crucial to sustaining water supplies and enhancing the sustainability of municipal water systems for Albertans. Thus, this project addressed five key knowledge gaps. Gap 1 focused on the impacts of severe wildfire on drinking water treatability in the Boreal Plain ecozone of Alberta, which had not been previously reported. Related, Gap 2 focused on the immediate and initial-term impacts of severe wildfire on drinking water in Alberta, which also had not been previously reported. Gap 3 focused on describing the resilience of the presumed best available technology (BAT) for treating highly deteriorated and rapidly changing source water quality to produce safe drinking water in the initial period (<3 years) after severe wildfire in both the Montane Cordillera and Boreal Plains ecozones, which represent the extremes in eco-hydrological character between which most of Alberta's forested drinking water supplies can be generally characterized. This capacity had not been evaluated anywhere globally. Closely related, Gap 4 focused on identifying real-time operational control tools for rapid optimization of drinking water treatment performance during operational challenge periods such as post-fire drinking water treatment. Gap 5 focused on describing the immediate drinking water treatment cost implications of severe wildfire-associated source water quality changes.

The most important strategic outcomes of this work were the evaluation of an immediate and longer-term (i.e., at least three years post-fire) shift in DOC aromaticity (i.e., elevated and more variable UV_{254}) in the RMWB's source water as a result of wildfire in a system as big and already challenged (i.e., frequently high turbidity and high DOC source water quality) as the Athabasca river and an associated, sustained need for increased coagulant dosing, and the (unexpected) direct documentation of nutrient-enriched fine sediment promotion of post-fire blooms of potentially toxin-forming cyanobacteria. The resilience of the presumed best available technology (ballasted sand flocculation; BSF) for treating highly deteriorated and rapidly changing source water quality to produce safe drinking water in the initial period (<3 years) after severe wildfire in both the Montane Cordillera and Boreal Plains ecozones (i.e., the extremes in eco-hydrological character in Alberta) was characterized. Zeta potential analysis was shown to be a useful tool for rapid optimization of drinking water treatment performance during operational challenge periods such as post-fire drinking water treatment. The investigation further demonstrated that the 2016 Horse River wildfire resulted in continued impacts on water and at least $9.9 million in additional water treatment costs in Fort McMurray. The work further showed that BSF technology can largely treat severely deteriorated water representative of post-fire runoff that washes ash directly in to surface water source supplies. This new knowledge is critical to informing drinking water treatment infrastructure planning, source water protection (SWP) and drinking water safety plans as well as emergency response plans and associated benefit/cost and trade-off analyses. It will be invaluable to most drinking water utilities across Alberta that are reliant on surface water from fire-prone, forested landscapes.

This project has contributed to building Alberta's innovation capacity. Over the next five to ten years, it will contribute to advancing Alberta technology experts to the international forefront of integration between the water and forestry technology sectors, advancing the bio-economy and clean technologies in Alberta and avoiding costs associated with potentially catastrophic, natural disturbance-associated disruptions to the provision of safe drinking water through the development of active SWP policies and integrated green and grey technologies that support the multi-barrier approach to the provision of safe drinking water, prioritize healthy forests, and enable treatment technology resilience for responsiveness in extreme conditions of extreme challenge.

Table of Contents

B. INTRODUCTION

Drinking Water Supply and Treatment in Alberta

The majority of Alberta's drinking water supply (~72% on a volume basis)—and the drinking water for approximately 2 out of 3 Albertans—originates in the wildfire-prone, forested regions of the Rocky Mountain eastern slopes (Robinne et al. 2019). Landscape disturbances (e.g., wildfire, insects, logging, petrochemical extraction) in these critical water producing regions impact water quality and quantity. While, Alberta's economy and society depend on natural resources, the province's long-term ability to maintain sustainable ecosystem services such as secure water supplies, is uncertain. Severe wildfire is generally understood to be potentially catastrophic for the provision of safe drinking water because it can cause increasingly variable or deteriorated source quality, thereby challenging in-plant treatment technologies beyond design and operational response capacity, to the point of severe and costly service disruptions, or even outages (Bladon et al. 2014; Emelko et al. 2011). Thus, it is commonly believed that severe wildfire threatens drinking water "treatability" because of insufficient treatment technology resilience. Here, "resilience" pertains to the ability to consistently meet treatment process performance target(s) (by removing, reducing, or inactivating chemical, physical, or microbiological components of the untreated water matrix) with minimal deviation, despite changes or fluctuations in source water quality. Drinking water "treatability" refers to key attributes of untreated source water quality that drive the need for and performance of different water treatment technologies and operational strategies. Thus, drinking water treatability assessments involve interpreting source water quality and variability with respect to the ability to meet specific treatment targets with certain combinations of treatment process infrastructure and operational capacity. Drinking water treatability impacts are not typically considered in water supply risk assessment and management policies.

As a result of global concerns that conventional in-plant drinking water treatment technologies (i.e., "grey infrastructure") cannot adequately treat deteriorated and/or increasingly variable source water after severe wildfire, many regions (e.g., Colorado, Arizona, Australia) reliant upon water originating in forested areas have been rapidly implementing fuel management by forest harvesting. In other words, they have been investing in "green infrastructure" because of the belief that it can mitigate the potentially catastrophic impacts of wildfire on drinking water treatability. Alberta municipal drinking water system managers have observed those activities, but their cautiousness as an industry and awareness of recent work from Alberta that has shown that the deleterious water quality and treatability impacts of landscape disturbances can be greater and significantly longer lasting in parts of Alberta than elsewhere (Emelko et al. 2011, 2016) has left them uncertain about the wisdom of investing in forest harvesting-based "green infrastructure" because of its unknown potential to negatively impact drinking treatability. Despite these significant uncertainties, municipal drinking water system managers must develop adaptive strategies for responding to climatic variability and associated challenges to drinking water treatability when completing mandated drinking water safety plans (DWSPs) and source water protection (SWP) plans.

Significant and notable recent experiences in Alberta have underscored the pressing need to systematically evaluate the resilience of existing in-plant drinking water treatment technologies (i.e., grey infrastructure) in responding to potential changes in source water quality and treatability during and after severe wildfire. For example, recent experiences associated with the catastrophic 2016 wildfire—the costliest insured disaster in Canadian history with an estimated almost $9 billion in insured costs—in Fort McMurray have suggested that specialized in-plant treatment technologies such as ballasted sand flocculation (BSF) processes that can be integrated with existing conventional treatment infrastructure may be capable of treating severely deteriorated and/or rapidly changing source water after wildfire, especially when coupled with appropriate, state-of-the-art operational control infrastructure (i.e., zeta potential analysis) for optimizing real-time treatment performance. This technology platform (BSF with online zeta potential for operational control) was instrumental to delivering the uninterrupted production of high quality drinking water during the June 2013 flood that devastated much of Calgary—its worst flood in 80 years—but during which safe drinking water was continuously provided. Of course, these technology platforms are costly and their resilience and capacity as adaptive strategies for responding to climate change and associated challenges to drinking water treatability remains unproven. As a result, municipal drinking water system managers and regulators were left uncertain of how to best invest in or advocate investment in grey and/or green infrastructure to enhance the sustainability of municipal water systems in Alberta and to develop complementary watershed management and SWP policies for the ultimate goal of ensuring safe, secure drinking water. New knowledge was required to meet these pressing needs.

Knowledge and Technology Gaps

To meet the long term goal of sustaining water supplies and enhancing the sustainability of municipal water systems, new knowledge was required to enable the development of optimal adaptation and risk mitigation strategies. This process started by first recognizing that wildfire remains the most catastrophic agent of landscape disturbance in the forested source water regions of Alberta. Here, the mean annual area burned by wildfire is ~150,000 ha; over the last decade, 700,000 people and over 250 communities have been impacted by wildfires (CCFM, 2005). While the Southern Rockies Watershed Project (SRWP) has provided significant new knowledge regarding initial (<3 years) and medium-term (~3-12 years) effects of wildfire on water in the steep-sloped, Montane Cordillera ecozone of southwestern Alberta (Bladon et al. 2008; Silins et al. 2009; Emelko et al. 2011; Stone et al. 2011; Allin et al. 2012; Bladon et al. 2014; Wagner et al. 2014; Silins et al. 2014; Stone et al. 2014; Wagner et al. 2014; Emelko et al. 2016; Martens et al. 2019; Williams et al. 2019), the effects on drinking water treatability were only studied in the medium term (i.e., the immediate and initial effects on drinking water treatability were not characterized). The Boreal Plains ecozone is the largest forest ecological region in Alberta; in contrast to the Montane Cordillera, this region with much less topographic relief is largely comprised of upland mixed-wood, and peatland dominated forests. No knowledge or experience regarding immediate, initial, nor medium-term impacts of wildfire on drinking water treatability in the Boreal Plains ecozone had ever been reported prior to the present investigation. Accordingly, whether impacts on water quality and treatability in the Boreal Plains could be expected to be similar to those observed in the Montane Cordillera was unknown. Furthermore, no knowledge or experience regarding immediate and initial-term impacts of severe wildfire on drinking water treatability anywhere in Alberta had ever been reported—to date, relatively little such information is available globally. Not surprisingly, even less is known about either the direct or indirect costs of drinking water treatment resulting from wildfire.

Municipal water system experiences with the 2013 flood in Calgary and the 2016 Horse River wildfire in Fort McMurray and elsewhere globally (Writer et al. 2014; Hohner et al. 2016) have underscored the pressing need to systematically evaluate the resilience of existing, specialized in-plant drinking water treatment technologies (i.e., “grey infrastructure”) in responding to potential changes in source water quality and treatability after severe wildfire. BSF is an innovative, emerging technology that is neither used widely across North America nor globally for drinking water treatment. Veolia’s Actiflo® version of BSF has been retrofitted into several drinking water treatment plants (DWTPs) in Alberta to respond to rapid fluctuations in source water quality, such as those often experienced during the spring freshet. Actiflo® BSF is the technology that enabled—and has continued to enable—the provision of safe drinking water after the severe 2016 Horse River wildfire in the RMWB, despite significant post-fire fluctuations in source water quality. BSF is a high-rate, physico-chemical clarification process in which water is flocculated with metal-salt coagulant, microsand and polymer. Microsand enhances the formation of robust flocs (aggregates) and acts as ballast, significantly increasing their settling velocity. This technology is designed to react quickly to changing raw water quality and provide consistently high quality treated water. Thus, it may represent a best available technology (BAT) for the treatment of worst-case scenario, highly deteriorated, and rapidly changing source water quality in the initial period after severe wildfire—this capacity and resilience needs to be systematically evaluated in a post-wildfire context. Notably, appropriate chemical dosing is critical to ensuring optimal BSF treatment performance. Thus, BSF technology resilience can be maximized when real time feedback regarding chemical dosing is provided. While such real time support technologies have not been formally integrated with the BSF process, anecdotal evidence including municipal drinking water system experiences in Calgary and the RMWB has suggested that online zeta potential analysis may offer this capacity (Kundert et al. 2014), thereby further enhancing BSF technology resilience.

While wildfire impacts to drinking water treatability across different forest regions will have some broad similarities, an understanding of (1) key similarities and differences in wildfire impacts to source water quality and treatability in Alberta and (2) best available technologies (BATs) for in-plant drinking water treatment in response to severe wildfire is crucial sustaining water supplies and enhancing the sustainability of municipal water systems for all Albertans. In summary, to enhance the sustainability of municipal water systems and enable future water supplies and watershed management in Alberta, five key knowledge gaps were identified. They are:

Gap 1. The impacts of severe wildfire on drinking water treatability in the Boreal Plains ecozone of Alberta are not known.

Gap 2. The immediate and initial-term impacts of severe wildfire on drinking water in Alberta are not known. While the SRWP provided significant new knowledge regarding initial (<3 years) and medium-term (~3-12 years) effects of wildfire on water in the steep-sloped, Montane Cordillera ecozone of southwestern Alberta, the effects on drinking water treatability were only studied in the medium term.

Gap 3. The resilience of the presumed best available technology (BAT) for treating highly deteriorated and rapidly changing source water quality to produce safe drinking water in the initial period (<3 years) after severe wildfire in Alberta is not known. This capacity has not been evaluated anywhere globally.

Gap 4. Real-time operational control tools for rapid optimization of drinking water treatment performance during extreme challenge periods have not been directly identified or rigorously demonstrated.

Gap 5. The immediate drinking water treatment cost implications of severe wildfire-associated source water quality changes have never been quantified in Alberta or globally. The costs to drinking water utility infrastructure only have been described generally as incorporated into the costs of normal business activities, with user fees or water rates as their primary source of funding for these activities.

These knowledge gaps were addressed by the research described herein.

C. PROJECT DESCRIPTION

Knowledge and Technology Description

To enhance the sustainability of municipal water systems and sustain water supplies in Alberta over the long term, municipal water suppliers urgently needed new knowledge to respond to increasing wildfire threats to the uninterrupted provision of adequate amounts of safe, secure drinking water in Alberta. Simply stated, two key knowledge sets were required to respond to these threats. First, wildfire impacts on drinking water treatability in Alberta's two major forested ecozones (i.e., the Boreal Plains and Montane Cordillera) needed to be characterized. Second, the capacity and resiliency of available drinking water treatment infrastructure in response to those threats had to be described and associated opportunities for enhanced performance had to be identified.

This project built on other Alberta Innovates (AI) projects, which addressed knowledge gaps related to wildfire and forest harvesting impacts on water quality and treatability in the eastern slopes of the Rocky Mountains in the Montane Cordillera ecozone of Alberta and supported the establishment of the Southern Rockies Watershed Project (SRWP) watershed research observatory (WRO) where land disturbance effects on water in Alberta's critical eastern slopes have been studied for >17 years. The SRWP generated one of the most comprehensive and long term data sets available globally on wildfire impacts on water, including ecosystems and drinking water treatability in the Montane Cordillera (Bladon et al. 2008; Silins et al. 2009; Emelko et al. 2011; Stone et al. 2011; Allin et al. 2012; Bladon et al. 2014; Wagner et al. 2014; Silins et al. 2014; Stone et al. 2014; Wagner et al. 2014; Emelko et al. 2016; Martens et al. 2019; Williams et al. 2019). In contrast, the present project provides insight regarding wildfire impacts on drinking water treatability in the Boreal Plains ecozone. In the Montane Cordillera ecozone, the Rocky Mountain region of southwest Alberta is characterized by high elevation (approximately 1100 to 3100 MASL), steep topographic relief, high annual precipitation (approximately 700-1700 mm/yr), and deep mountain snowpacks. Hydrology of the region is characterized by strongly snowmelt dominated runoff regimes, with substantial groundwater contributions to annual flow. In contrast, the Boreal Plains ecozone region of north-central Alberta is sub-humid and the regional climate alternates between 3-4 years of dry (potential evapotranspiration [PET] > precipitation) and mesic (PET=precipitation) conditions, punctuated approximately every 20 years or so with wet conditions (PET<precipitation) (Devito et al. 2005a; Mwale et al. 2011). The region has subtle relief, deep quaternary deposits, and surficial geology of roughly equal portions of fine-textured glacio-lacustrine deposits, hummocky clay-rich till moraines and coarse-textured glacio-fluvial deposits. Climate cycles interact with surficial geology and antecedent moisture conditions to produce extreme inter-annual and spatial variability in catchment runoff responses (Devito et al. 2005b; Sass et al. 2008). Importantly, these two ecozones represent extremes or "book ends" in eco-hydrological character between which most of Alberta's forested drinking water supplies can be generally characterized—they also encompass essentially the entire forested area of Alberta.

Immediate and short-term impacts of wildfire on drinking water treatability in the Boreal Plains ecozone were investigated after the occurrence of the severe 2016 Horse River wildfire in the Regional Municipality of Wood Buffalo (RMWB). This wildfire literally occurred "on top of" the city of Fort McMurray, impacting at least 56 km of the Athabasca River directly upstream of the DWTP. Thus, it was hypothesized that, despite the large scale of the Athabasca River, wildfire impacts on source water quality and treatability might still be discernible within that supply because of limited dilution prior to water entering the RMWB's raw water storage reservoir and DWTP. Rapid mobilization and coordination of watershed and DWTP sampling for drinking water treatability analyses by Alberta Environment and Parks (AEP) and RMWB partners who provided critical hydrometric and meteorological data as well as critical in-kind support in the form of sample collection, sample shipping, basic drinking water treatability analyses, all relevant treatment process performance data, historical water quality and treatment process performance data, and treatment and associated infrastructure management cost data. This research could not be meaningfully completed without this support, which is truly invaluable.

While numerous approaches could be proposed to address the need to respond to increasing wildfire threats to the provision of safe, secure drinking water in Alberta, this project focused on responding to global water industry consensus has thus voiced an urgent need for new approaches that better integrate landscape management-based SWP and in-plant treatment capabilities. Specifically, a mixed grey/green technology approach for mitigation of threats from climate change-exacerbated landscape disturbances such as wildfires was recommended by 30 leading scientists and practitioners from Canada, the U.S., and abroad who were convened by the Canadian Water Network (CWN) and the Water Research Foundation (WRF) for an international project entitled "Wildfire Impacts on Water Supplies and the Potential for Mitigation" (Emelko and Sham, 2014). The group noted that the optimal balance between these two approaches would depend on the region, however. Thus, in Alberta that meant characterizing wildfire threats to drinking water treatability in the Boreal Plains ecozone and evaluating both existing treatment technology platforms and identifying opportunities for retrofitting those platforms to achieve enhanced performance in response to key threats to drinking water treatability that are posed by severe wildfires. Specifically, those commonly recognized threats are from (1) increased turbidity/suspended solids and dissolved natural organic matter (NOM), which can challenge chemical coagulant dosing when they rapidly fluctuate in concentration and/or character (e.g., NOM aromaticity) and (2) nutrient-rich fine sediments that can serve as sources of bioavailable phosphorus and promote algal proliferation that can clog treatment processes and/or produce human toxins of public health concern that are difficult to treat using technologies that are available in conventional drinking water treatment plants, including those in most of Alberta (Emelko et al. 2011). To inform more optimal investment of limited financial resources for resilient in-plant drinking water treatment and given the city of Calgary's experiences with BSF during the 2013 flood (Kundert et al. 2014), BSF technology supported by online zeta potential and turbidity analyses for enhanced chemical coagulant dosing control were identified and investigated as a potential innovative solution for achieving the treatment resilience that would be necessary to treat severely deteriorated and/or increasingly variable (i.e., periodically severely deteriorated) drinking water source quality after severe wildfire.

Research Objectives

Four research objectives were developed to address the five key knowledge gaps (i.e., Gaps 1 to 5) that were identified above. These were:

1. The immediate and initial-term impacts of severe wildfire on drinking water treatability in Alberta will be evaluated. Specifically, the immediate and initial-term impacts of the 2016 Horse River wildfire on drinking water treatability in Fort McMurray will be described and quantified. It will also be compared to the medium-term impacts of wildfire observed after the 2003 Lost Creek wildfire in southwestern Alberta (to address Gaps 1 and 2),
2. The resilience of BSF treatment processes (i.e., the presumed BAT) for treating worst-case scenario, highly deteriorated, and rapidly changing source water quality after wildfire will be evaluated using water matrices representative of those that may be experienced in the initial period (<3 years) after severe wildfire in the two major forested ecozones of Alberta (i.e., the Boreal Plains and the Montane Cordillera ecozones) (to address Gap 3),

3. Existing real-time water quality analysis tools that may serve as operational controls for rapid optimization of BSF treatment process performance during extreme challenge periods (i.e., when process influent water quality rapidly fluctuates) will be evaluated (to address Gap 4), and
4. The immediate and initial-term direct (e.g., incremental chemical coagulant costs and sludge treatment and disposal, etc.) and indirect (e.g., the need to dredge the raw water reservoirs and remove surrounding vegetation, purchase additional support infrastructure for operational support, etc.) drinking water treatment costs of the 2016 Horse River wildfire on drinking water treatability in Fort McMurray will be described and quantified (to address Gap 5).

Deliverables

Key deliverables for milestone completion include:

1) Objective 1: a completed evaluation of key aspects of post-fire water quality (i.e., turbidity, total/dissolved organic carbon, and total phosphorus) and treatability (i.e., coagulant dosing, zeta potential, disinfection by-product [DBP] formation and/or formation potential) for the three years after the 2016 wildfire (i.e., 201-2018, inclusive) in Fort McMurray and characterization of sediment-associated phosphorus in the RMWB's raw water storage reservoir and comparison to results from the SRWP WRO in the Montane Cordillera ecozone,
2) Objective 2: a thorough evaluation of pilot-scale BSF performance (evaluated relative to performance targets detailed in Table 1) in treating severely deteriorated source water (i.e., representing immediate post-fire ash runoff into source water) in Calgary (i.e., representing the Montane Cordillera ecozone) and Fort McMurray (i.e., representing the Boreal Plains ecozone),
3) Objective 3: a completed evaluation of the utility of zeta potential analysis for operational control in coagulant dosing in conjunction with pilot-scale BSF performance testing for Objective 2, and
4) Objective 4: completion of an engineering accounting analysis of the immediate and initial-term direct (e.g., incremental chemical coagulant costs and sludge treatment and disposal, etc.) and indirect (e.g., the need to dredge the raw water reservoirs and remove surrounding vegetation, purchase additional support infrastructure for operational support, etc.) drinking water treatment costs of the 2016 Horse River wildfire on drinking water treatability in Fort McMurray.

Table 1. Key performance indicators for identifying best available technology (BAT) for treating severely deteriorated and/or rapidly changing source water after wildfire

Metric	**Ideal target**	**Minimum requirement**	**Achievements to date**
Turbidity (in BSF effluent)	< 5 NTU; preferably <3 NTU; more preferably <1 NTU	turbidity reduction	N/A
Dissolved organic carbon (DOC) (in BSF effluent)	< 8 mg/L; preferably < 5 mg/L; more preferably < 3 mg/L	DOC reduction	N/A

D. METHODOLOGY

The scope of this project broadly included evaluating 1) immediate and initial-term impacts of the Horse River wildfire on drinking water quality and treatability and 2) evaluating BSF as a BAT for treatment of highly deteriorated and/or increasingly variable source water quality (as might be experienced after severe wildfire) in Alberta. Thus, this project involved delivering new knowledge regarding the impacts of wildfire on water in the Boreal Plains ecozone (i.e., RMWB) and comparing and contrasting it with knowledge already delivered by the SRWP regarding wildfire effects on water in the Montane Cordillera ecozone to evaluate drinking water treatment strategies for responding to the most extreme shifts in source water quality that *might* be experienced—even though they might not be the most probable—after severe wildfire in Alberta. Importantly, these two ecozones represent extremes or "book ends" in eco-hydrological character between which most of Alberta's forested drinking water supplies can be generally characterized—they also encompass essentially the entire forested area of Alberta. The project Milestones and associated Tasks that were identified to complete those Milestones are detailed below.

Milestone 1. Evaluation of the impacts of Horse River wildfire on drinking water source quality and treatability.

Task 1.1 Evaluate river water quality **and** ***Task 1.2 Evaluate river water treatability.*** This task involved in a two-pronged approach. First, the project team worked with AEP on an AEP-led initiative to evaluate data from AEP's multi-faceted water quality monitoring program to demonstrate that brief (hours to days) wildfire signatures can be detected in large river systems, such as the Athabasca river system serving the RMWB. Precipitation and river flow data from regional monitoring networks (governments of Canada and Alberta) were used to evaluate pre- and post-fire river flow and water quality responses to precipitation. A multiple-method approach for sampling river water chemistry of an unburned control site (Athabasca River at Grand Rapids) and three sites influenced by burned landscapes (Athabasca River upstream of Fort McMurray [left bank]; Clearwater River near the mouth; Hangingstone River at Fort McMurray) was implemented for the first year after the fire. These river locations drain a gradient of watershed size (Hangingstone < Clearwater < Athabasca) and reflected a contrasting gradient of relative burned area and area burned at a high severity in their watersheds (Athabasca < Clearwater < Hangingstone). Pre-fire water quality data from long-term provincial and oil sands monitoring programs were used to supplement the post-fire sampling program at the three impacted sites. Monthly surface water sampling has been ongoing in the Athabasca River upstream of Fort McMurray for many decades, while the Clearwater and Hangingstone rivers have been monitored monthly for several years. Water collection and analytical methods from historical programs were consistent with those used during the post-fire grab sample program. Because this effort was led by AEP, only a brief overview of wildfire impacts on water quality will be presented herein.

Second, given that the initiative led by AEP that focused on characterizing the effects of the Horse River wildfire on source water quality in the Athabasca River, the complementary analysis described herein focused on characterizing implications to drinking water treatability. This detailed assessment was especially important because of the RMWB's necessary reliance on raw (i.e., untreated) water storage reservoirs, which not only serve to store untreated source water, but also provide pre-treatment in the form on continuous solids separation through the use of a recirculating pump. Turbidity and dissolved organic carbon concentrations and aromaticity (UV_{254}) were characterized to inform key treatment needs (both infrastructure and operational). Fluorescence emission-excitation matrices (FEEM) were not extensively evaluated because methods for their evaluation are not adequately quantitative at present. Instead, carbon characterization using liquid chromatography with organic carbon detection (LC-OCD) was conducted (Huber et al. 2011). These additional analyses inform additional treatability risks (membrane fouling and distribution system regrowth potential) that are not informed by the analyses that were originally proposed (those analyses inform coagulant demand and DBP formation potential). Coagulant demand was evaluated at full-scale and regulated DBP formation potential (DBP-FP) of trihalomethanes (TMHs) and haloacetic acids (HAAs) was also periodically evaluated. N-Nitrosodimethylamine (NDMA) formation was not evaluated extensively because it was never detected in initial sampling—this was expected as NDMA precursors are generally of anthropogenic origin and their main source in water have been recognized to be wastewater discharges (i.e., chloramination is the most common process that results in formation of NDMA during water and wastewater treatment; however, ozonation of wastewater or highly contaminated surface water can also generate significant levels of NDMA; Sgroi et al. 2018). Further analysis would be an efficient use of resources. Additionally, both reservoir and river water quality were evaluated. The risks from fine sediment and associated contaminants were characterized. Although not originally proposed, given AEP's detailed analysis of river water quality impacts from the Horse River wildfire, an additional analysis of historic plant intake water quality was conducted. Thus, this collective analysis provided extensive insight into source water quality, reservoir loading, and drinking water treatability in Fort McMurray as a result of the wildfire. Collectively, the approach used to evaluate drinking water treatability addresses a broad range of treatability challenges and is the most extensive used to evaluate drinking water treatability implications of wildfire to date.

Task 1.3 Determine levels of sediment-associated contaminants of concern. Metals, polycyclic aromatic hydrocarbons (PAHs), and polychlorinated, aromatic hydrocarbons (e.g. dioxins and furans) are sediment-associated contaminants of human health concern that can be released into water supplies as a result of wildfire. Sediment was collected from the RMWB's raw water reservoirs and the potential presence of these contaminants was evaluated to inform risk management strategies such as the need for reservoir dredging to prevent the release of these materials into the water column.

Task 1.4 Determine physical and geochemical properties of reservoir sediment and ***Task 1.5 Evaluate sorption behavior of reservoir sediment.*** Sediment is the primary vector of P transport in aquatic systems. Because of increased erosion, wildfire can accelerate P delivery to receiving waters. The transport and bioavailability of P in aquatic environments is influenced by several physico-chemical factors. Sediment from the Athabasca River and the RMWB's raw water reservoirs was collected and particle size distribution, major elements, and nutrients were evaluated. This analysis was especially important because P is the limiting nutrient in most freshwater systems. Increased levels of P in sediment or the water column can promote algal productivity, which can challenge water treatment processes or lead to service disruptions, particularly when the algae produce harmful toxins. Thus, particulate P forms (non-apatite inorganic phosphorus [NAIP], apatite phosphorus [AP], organic phosphorus [OP]) were measured to assess the relative bioavailability of P in the sediment. Batch sorption experiments were conducted to inform the bioavailable P release potential of post-fire fine sediment (i.e., potentially enriched in bioavailable P) in the reservoirs and the associated potential increased probability of algal proliferation.

ADDITIONAL TASK: Although not originally proposed, the occurrence of significant algal blooms in the RMWB's raw water storage reservoirs and inside the WTP after the wildfire prompted

Milestone 2. Evaluation of BSF process in treating severely deteriorated and/or rapidly changing drinking water quality.

Task 2.1 Develop deteriorated water matrices. Post-fire ash was collected and used to develop source water quality matrices with general water quality and/or dissolved organic carbon (DOC) concentrations, DOC hydrophobicity/aromaticity, and turbidity levels consistent with or somewhat more deteriorated than those that have been reported after severe wildfire. These matrices represent the immediate “wash in” (i.e., runoff) of post-fire ash into a drinking water source supply; thus, they represent the worst-case scenario of minimal/no dilution or transformation (e.g., DOC degradation) of water quality.

Task 2.2 Evaluate BSF treatment process: Montane Cordillera and ***Task 2.3 Boreal Plains contexts.*** A pilot-scale BSF treatment evaluation of Elbow and Athabasca River water (Tasks 2.2 and 2.3, respectively) mixed with fresh burned materials (using the protocol developed in Task 2.1) was conducted. An Actiflo® mini unit (1.0-2.1 m^3/h) was operated at maximum flowrate of 2.1-2.8 m^3/h, corresponding to a rise rate of 60-80 m/h. The unit includes chemical skids, PLC control, data acquisition and online instruments (flow, pH, temperature, and turbidity). Turbidity, DOC concentration and character and regulated DBP-FPs through the process were evaluated to assess process capacity and resilience.

Milestone 3. Evaluation of real-time operational controls for BSF performance optimization

Task 3.1 Evaluate online zeta potential as a BSF process control technology. The sensitivity and responsiveness of online zeta potential analysis for providing real time feedback and control for chemical coagulant dosing during BSF was evaluated during the Task 2.2 and 2.3 evaluations. Though not originally proposed, the role of zeta potential analysis in either an online of bench-top mode was also evaluated at full-scale for informing coagulant dosing to control the passage of aromatic DOC (i.e., UV_{254}).

Milestone 4. Quantification of direct and indirect drinking water treatment costs of Horse River wildfire

Task 4.1 Collect historic WTP operational data. RMWB source and treated water quality, as well as DWTP operational data were collected over the project period and the seven years prior to it. This period was set based on the establishment of a new historian for the collection of online data in Fort McMurray in 2010. All available DOC, UV_{254}, turbidity, and other source and treated/finished water quality data were collected and evaluated. This analysis included plant flows and chemical dosing requirements. Key changes in pre- and post-fire treatment performance were identified, described, and quantified.

Task 4.2 Collect direct and indirect cost data. Key Fort McMurray drinking water treatment plant (DWTP) operational costs were identified and quantified. Key direct costs included coagulant, polymer, sand (for BSF), acid/caustic, permanganate, and sludge treatment and disposal costs. Key indirect costs will include non-routine laboratory analyses, reservoir dredging, reservoir vegetation removal, and purchase and maintenance of operational control or other support tools.

Task 4.3 Quantify incremental costs of wildfire to drinking water treatment. The historic WTP operational data (Task 4.1) and the direct and indirect WTP operational costs data (Task 4.2) were integrated to identify and quantify the incremental costs of wildfire to drinking water treatment to date.

E. PROJECT RESULTS

Milestone 1. Evaluation of the impacts of Horse River wildfire on drinking water source quality and treatability.

Task 1.1 Evaluate river water quality and ***Task 1.2 Evaluate river water treatability***. As part of a complementary initiative, a multi-faceted water quality monitoring program to demonstrate that brief (hours to days) wildfire signatures can be detected in large river systems, such as the Athabasca river system serving the RMWB (led by Drs. Colin Cooke and Craig Emmerton, AEP). In brief, automated, high-frequency monitoring of flow and water quality during the first year after the wildfire showed distinct, precipitation-associated signatures of ash-transport in rivers draining extensive (800–100,000 km^2) and partially-burned (<1–22%) watersheds, which were not evident in nearby unburned regions. Post-fire river water quality sampling showed episodic increases in suspended sediment concentrations that were exceptional relative to long-term records and occurred more frequently as watershed sizes decreased.

Prediction intervals calculated using historic (i.e., pre-fire) C-Q relationships from the Athabasca River (upstream of Fort McMurray) were exceeded on two occasions during the study period after the wildfire (Figure 1). These exceedances occurred on June 09 and July 31, 2016, when the two largest recorded rainfalls in the Fort McMurray region occurred during that summer. Subsequent sampling during following years showed no similar notable concentrations. More exceedances of the upper historic prediction interval (five) occurred in the Clearwater River at Draper during precipitation events in 2016, though they did not occur in subsequent years, even during precipitation events. The Hangingstone River basin experienced 17 exceedances relative to the historic concentration-discharge relationship, including one during runoff in April 2017. These exceedances occurred during both large and smaller precipitation events (Figure 1). Several exceedances also occurred during non-event periods across multiple years after the fire. Compared to suspended sediment concentrations, only four exceedances (all from the Clearwater River) of the upper historic prediction interval for total calcium concentration were observed across all rivers. Collectively, suspended sediment concentration exceedances of historic 95% prediction intervals in impacted rivers became more frequent as watershed size decreased, and the proportion of burned area and area burned at high intensities across watersheds increased. In contrast to these episodic water quantity and quality differences described above, aggregated flow regressions between upstream (unburned) and downstream (burned) Athabasca River stations showed similar slopes and variabilities before and after the fire (data not shown; Ancova: $t=-1.339$; $p=0.181$) with no post-fire outliers relative to historic data. Collectively, the water quality and discharge data discussed herein indicated that water quality changes in rivers draining burned watersheds were observed periodically when a threshold condition (i.e., an intensity and duration of rainfall) was reached, in which elevated suspended sediment concentrations were likely attributable to precipitation event-associated erosion. These multiple lines of evidence indicate that low-relief landscapes can mobilize wildfire-related material to rivers similarly, though less-intensively, than headwater regions. Critically, these results comprise the first global evidence that wildfire impacts on river water quality can be evident at very large scales and have implications for communities that depend on these water resources; as well, it was speculated that uneven mixing of heavily-impacted tributaries with large rivers likely explain differences in the magnitude and duration of wildfire signals observed in high-order rivers relative to headwater streams (Emmerton et al. *in review*).

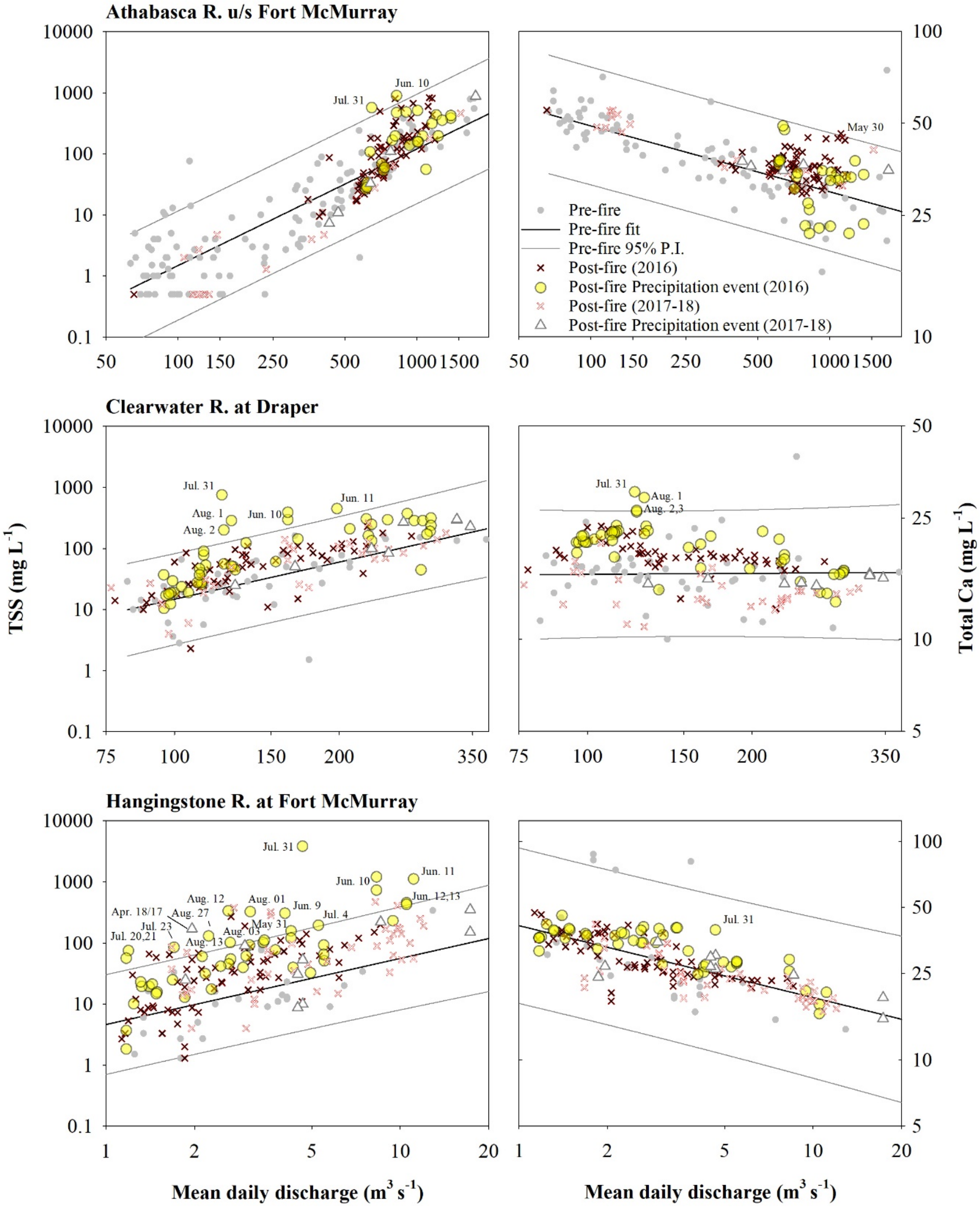


Figure 1. Log-transformed concentration-discharge relationships of total suspended solids (TSS) and total calcium (Ca) of historic and post-fire data from three rivers draining burned watersheds in the lower Athabasca River region following the 2016 Fort McMurray wildfire. 95% prediction intervals and linear fit lines on historic data are also shown. (Source: Emmerton et al. *in review*)

The Athabasca River begins at the Columbia Glacier in Jasper National Park and travels about 1500 km northeast across Alberta and drains into Lake Athabasca in the north-east; after joining the Slave and McKenzie Rivers, it eventually flows to the Arctic Ocean. The Athabasca river basin is approximately 159,000 km^2, which is about 24% of Alberta's landmass. The 2016 Horse River wildfire burned approximately 5,900 km^2 or 4% of that river basin. An approximately 50 km stretch of that fire affected the basin upstream of the RMWB's WTP serving the City of Fort McMurray. A combination of the (1) June 11, 2016 Horse River fire boundary polygon, (2) wet areas mapping LiDAR products and stream network information (provided by AAF and Dr. Jae Ogilvie from the University of New Brunswick), and (3) peatland distribution data (provided by Dr. Dan Thompson; Northern Forestry Centre) were analyzed at 1-m resolution to identify 254 wildfire-impacted watersheds affecting the Athabasca River above Fort McMurray that would contribute post-fire runoff (sediment, organic carbon, etc.) to the Athabasca River (Figure 2). The vast majority of these are smaller ephemeral drainages along the river; eleven larger watersheds drain the region further back, away from the river. The majority of the burned watershed area further back away from river is dominated by peatlands (with some connected and unconnected uplands or upland islands). This larger burned area is likely poorly connected to stream networks because peatlands are typically not nearly as hydrologically connected to streams relative to upland areas dominated by mineral soils. Thus, these regions were not likely to produce surface runoff/erosion of sediments/organic carbon that might be expected of upland landscapes under similar climatic/physiographic settings. In contrast, the lower, downstream sections of five larger watersheds (denoted 28, 21, 71, 73, 93 in Figure 2) were the areas most likely to affect water quality and drinking water treatability at the Fort McMurray WTP. Notably, these five tributaries discharge into the Athabasca River between 2.4 and 16.3 km upstream of the RMWB's WTP intake.

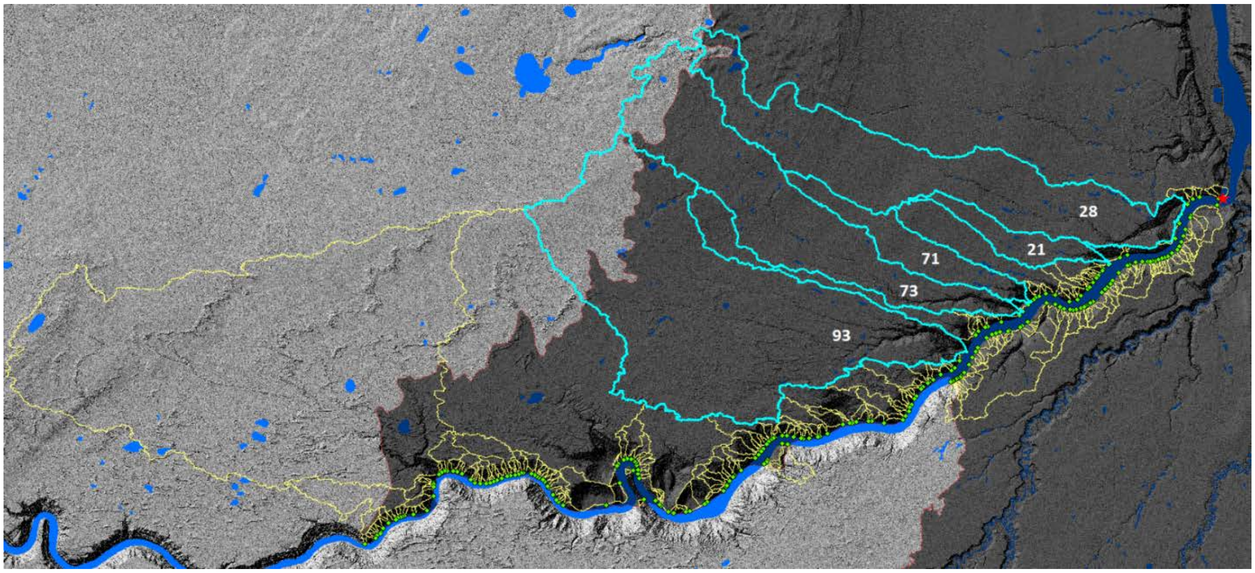


Figure 2. Wildfire impacted watersheds affecting the Athabasca River above Fort McMurray. Lower, downstream sections of five larger watersheds (28, 21, 71, 73, 93) were the areas most likely to affect water quality and drinking water treatability at the RMWB's Fort McMurray WTP.

As expected in the analysis described above, aerial watershed assessment confirmed relatively poor mixing in the Athabasca River—contaminant plumes appeared relatively unmixed (within 10-25m from shore) for up to 1 km downstream of tributary inflows (Figure 3).

Figure 3. Sediment and associated contaminant plume from the Little Fisheries Creek, 2.4 km upstream of the RMWB's water treatment plant intake in Fort McMurray. This plume was visible for at least 1 km downstream of its confluence with the Athabasca River.

Wildfire impacts on source water quality given potentially uneven mixing of heavily-impacted tributaries with the large Athabasca River just upstream of the Fort McMurray WTP were thus further explored. Between June 2016 and August 2017, 25 20-L and 225 1-L water samples were collected by AEP and key aspects of water quality were analyzed. While more than this number of samples was initially anticipated, this level of sample collection by helicopter was expensive (more than $100K per month). Thus, after the first six months of sample collection, subsequent sampling in 2017 was limited to GOA's routine sampling program (which included collection of smaller sample volumes and some helicopter time); the cost over six months was approximately $103,140 (as opposed to $104,483 per month). Given the complex hydrology of the Athabasca River system, further sample collection and analysis focused directly on implications to the RMWB and drinking water treatment at the Fort McMurray WTP. The sample collection locations are shown in Figure 4. Implications to the RMWB and drinking water treatment at the Fort McMurray WTP involved sample collection on the Athabasca River just upstream of the WTP and near the plant intake (approximately 0.25 km upstream of the WTP), the WTP's raw storage reservoirs, and treated water during the period from Summer 2016 to 2019. Source water quality and drinking water treatability was evaluated at these locations during "baseline" and "post-storm" conditions. Because a field program focused on local hydrology was well outside of the scope of the investigations, these conditions were identified based on simple visual inspection: the presence of a plume from Little Fisheries Creek to the Athabasca signaled "post-storm" conditions.

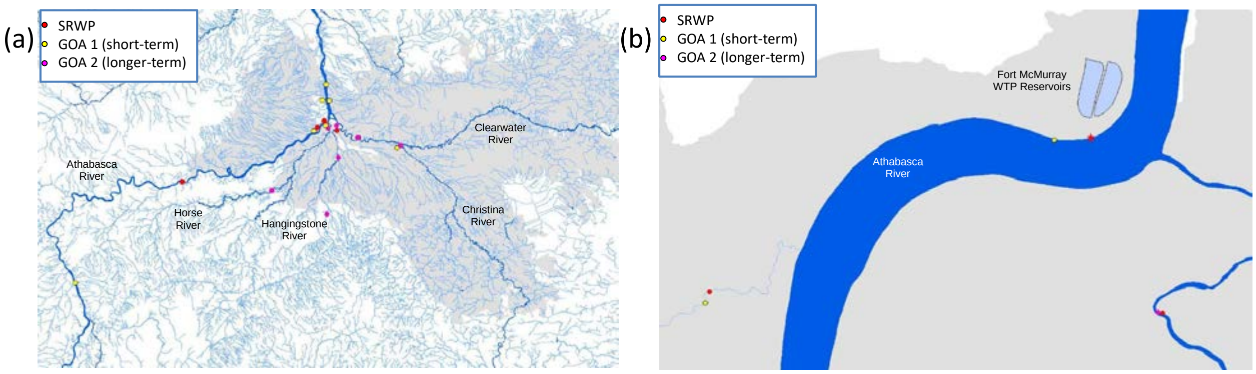


Figure 4. Government of Alberta (GOA; specifically AEP) and Southern Rockies Watershed Project (SRWP) sampling locations in the Athabasca River Watershed (2016-2017) after the Horse River wildfire.

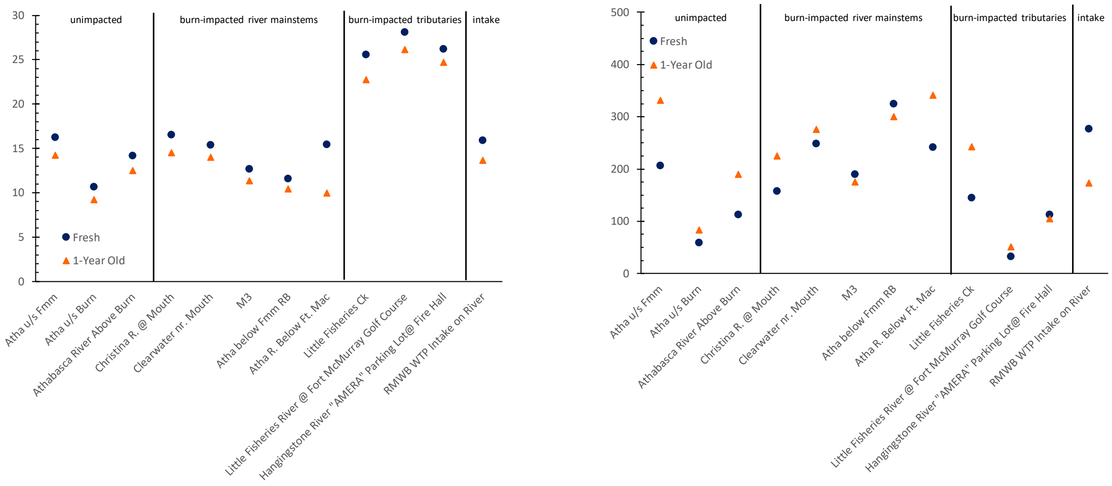
Samples collected during AEP's monitoring program in the Athabasca River basin were held (refrigerated) by AEP for periods ranging from months to a year. Thus, prior to their analysis, the stability of dissolved organic carbon and associated compounds in this matrix was evaluated. Accordingly, key source water quality and treatability indicators (DOC concentration, turbidity, UV_{254}, specific UV absorbance (SUVA), total trihalomethane formation potential (THM-FP), and total haloacetic acid formation potential (HAA-FP) were evaluated for samples collected immediately after the wildfire in June 2016 by the SRWP team and analyzed within two weeks of sample collection. The samples were then refrigerated for one year and re-analyzed to investigate the extent of DOC degradation.

Although its formation was not expected because the primary source of its precursors in surface water are municipal wastewater discharges, *N*-nitrosodimethylamine (NDMA) (also called dimethylnitrosamine [DMN]) was evaluated in a limited number of samples. It is highly hepatotoxic and a known carcinogen in laboratory animals (IARC classification Group 2A: probably carcinogenic to humans). As expected, NDMA was below detection limits in all samples analyzed; thus, it is not discussed further herein.

Water quality and DBP-FPs in samples from the SRWP sampling locations in the Athabasca River Watershed analyzed immediately- and one-year after the Horse River wildfire are presented in Figure 5. Turbidity fluctuated in the samples without any consistent pattern (Figure 5b). This might be expected because of the various factors that might be attributable to these fluctuations (e.g., particle size distribution present in the sample, DOC concentration and character, shifts in water quality resulting from biological activity, etc.) In contrast, consistent with the generally understood presence of two fractions—rapidly and slowly degrading—DOC in natural waters, the DOC data in Figure 5a indicate that DOC concentrations in all of the samples degraded by approximately 1 to 2 mg/L relatively quickly (i.e., within two weeks) and with remarkable consistency. Thereafter, no further degradation was observed over the one-year sample holding period. This same, notably consistent trend was observed in UV_{254} (Figure 5c); thus, little change was observed in SUVA (Figure 5d). While, DOC and UV_{254} both decreased slightly over time, THM-FPs notably increased (Figure 5e), while mixed shifts were observed for HAA-FPs (Figure 5f). While the THM-FP observation might seem surprising at first because increases in DOC aromaticity as indicated by UV_{254} are generally associated with increased THM-FP, it is also critical to note that not all aromatic forms of carbon are highly reactive.

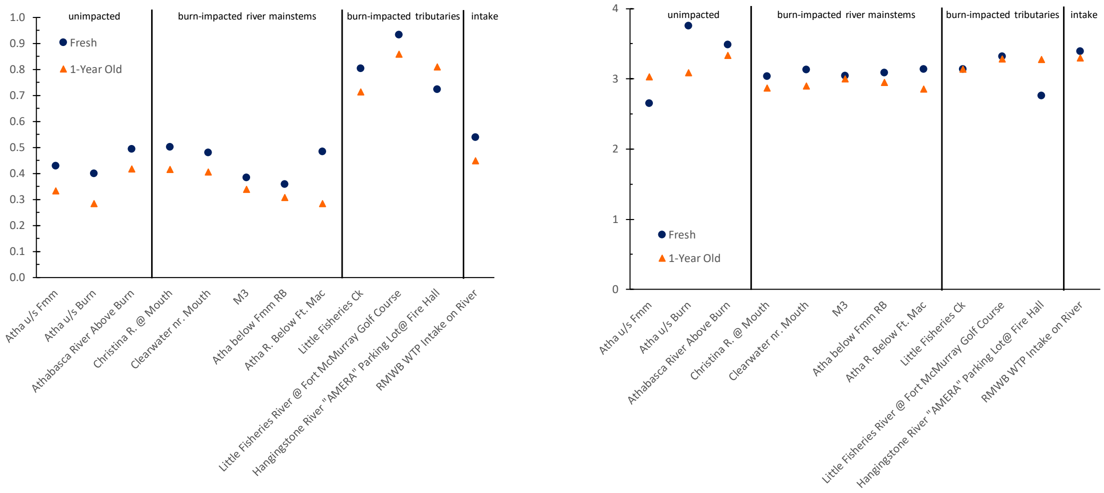
(a) DOC (mg/L)

(b) Turbidity (NTU)



(c) UV (cm^{-1})

(d) SUVA (L/mg-m)



(e) THM-FP (mg/L)

(f) HAA-FP (mg/L)

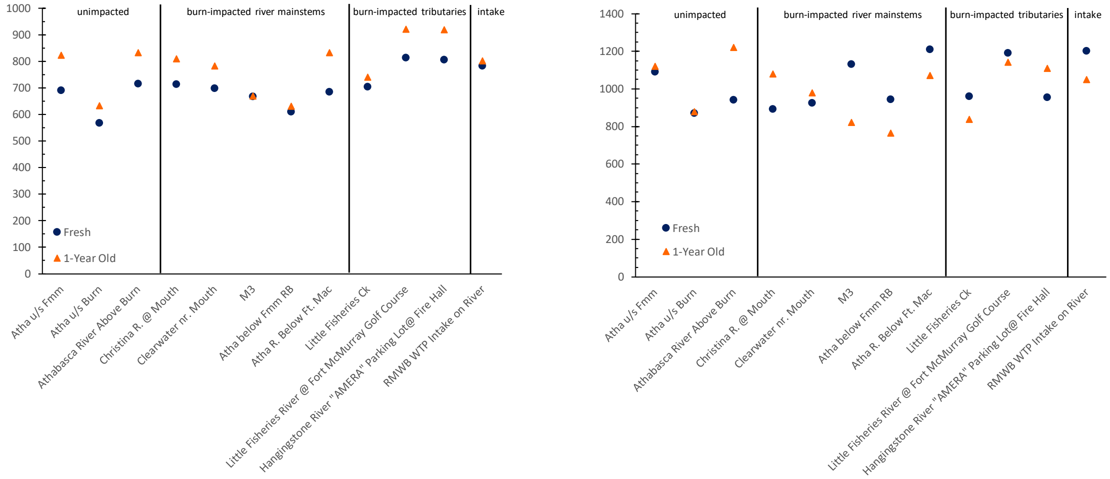


Figure 5. Water quality and DBP-FPs in samples from SRWP sampling locations in the Athabasca River Watershed (2016-2017) analyzed immediately- and one-year after the Horse River wildfire.

Dissolved organic matter (DOM) generally originates from either (1) external (allochthonous) sources such as watershed inflows comprised of a myriad of terrestrial inputs or (2) internally produced aquatic (autochthonous) sources that include phytoplankton, periphyton, macrophyte and bacterial production, and DOM released from bottom sediments (especially in reservoirs). In addition, processes such as microbial biodegradation and photolysis also lead to the transformation and loss of DOM. Accordingly, DOM production, transformation, and loss can alter both the overall concentration and character of DOM, including the fraction that reacts to form DBPs. In the case of the data presented in Figure 5, the moderate shifts in bulk DOC concentration and aromaticity indicated that terrestrial-derived material in the samples was degraded and replaced by aquatic-derived DOM produced within the samples. The changes in the propensity of the DOM pool to form THMs and HAAs illustrate that the DBP precursor pool was not exclusively coupled to bulk DOC concentration and indicate that microbial (potentially algal) production is also an important source of DBP precursors. This result is consistent with the general understanding that reservoirs can attenuate DOM amount and reactivity (as related to DBP precursors) via degradative processes; however, these benefits can be decreased or even negated by the production of algal-derived DOM (Kraus et al. 2011).

A simple comparison of the very limited source water quality and treatability data from locations not impacted by the wildfire and the Athabasca River at the Fort McMurray WTP intake does not suggest any impact of wildfire on water quality and treatability (Figure 5). While water quality is relatively degraded (i.e., higher DOC and UV_{254}) in the tributary inflows, the observed differences could be attributed to inputs (especially of DOM) from the peatlands and riparian areas in those watersheds. Notably, these data only provide a snapshot of one point in time and should not be over-interpreted. Regardless, the data presented in Figure 5 clearly indicated that the samples from AEP's monitoring program that were held (refrigerated) for periods ranging from months to a year were very likely stable and could still be meaningfully analyzed and interpreted.

NOM-associated water quality and DBP-FPs at several of AEP's sampling locations in the Athabasca River Watershed during the period from 2016 to 2017 after the Horse River wildfire are presented in Figure 6. These data demonstrate the range and variability in DOC concentrations, UV_{254}, SUVA, THM-FPs, and HAA-FPs across the basin (Figure 6)—what is most notable about these data is that all of these parameters follow the same trend across the sample locations. Thus, while bulk DOC concentrations may vary at the different sampling locations, the nature and reactivity of the DOM appears generally consistent across the basin.

The samples were further analyzed by LC-OCD—these results are summarized in Figure 7. As would be expected, humic substances comprised the majority of the DOC (72-78% on average) and followed the same spatial trend as the other NOM-associated water quality and DBP parameters presented in Figure 6. Building blocks were the next most abundant fraction (12-14% on average), followed by low molecular weight (LMW) neutrals (5-7% on average) and biopolymers (2-5% on average). LMW acids were the least abundant of the organic carbon fractions (2-3% on average). Consistent with the other metrics of NOM-associated water quality, all of these fractions of DOC also generally followed the same spatial trends.

Overall, the observations summarized in Figures 6 and 7 are consistent with the broader AEP initiative in which differences in water quality across the basin were not evident until higher frequency monitoring of flow and water quality during the first post-fire year was concurrently evaluated and indicated distinct, precipitation-associated signatures of ash-transport in rivers draining wildfire-impacted watersheds (Figure 1).

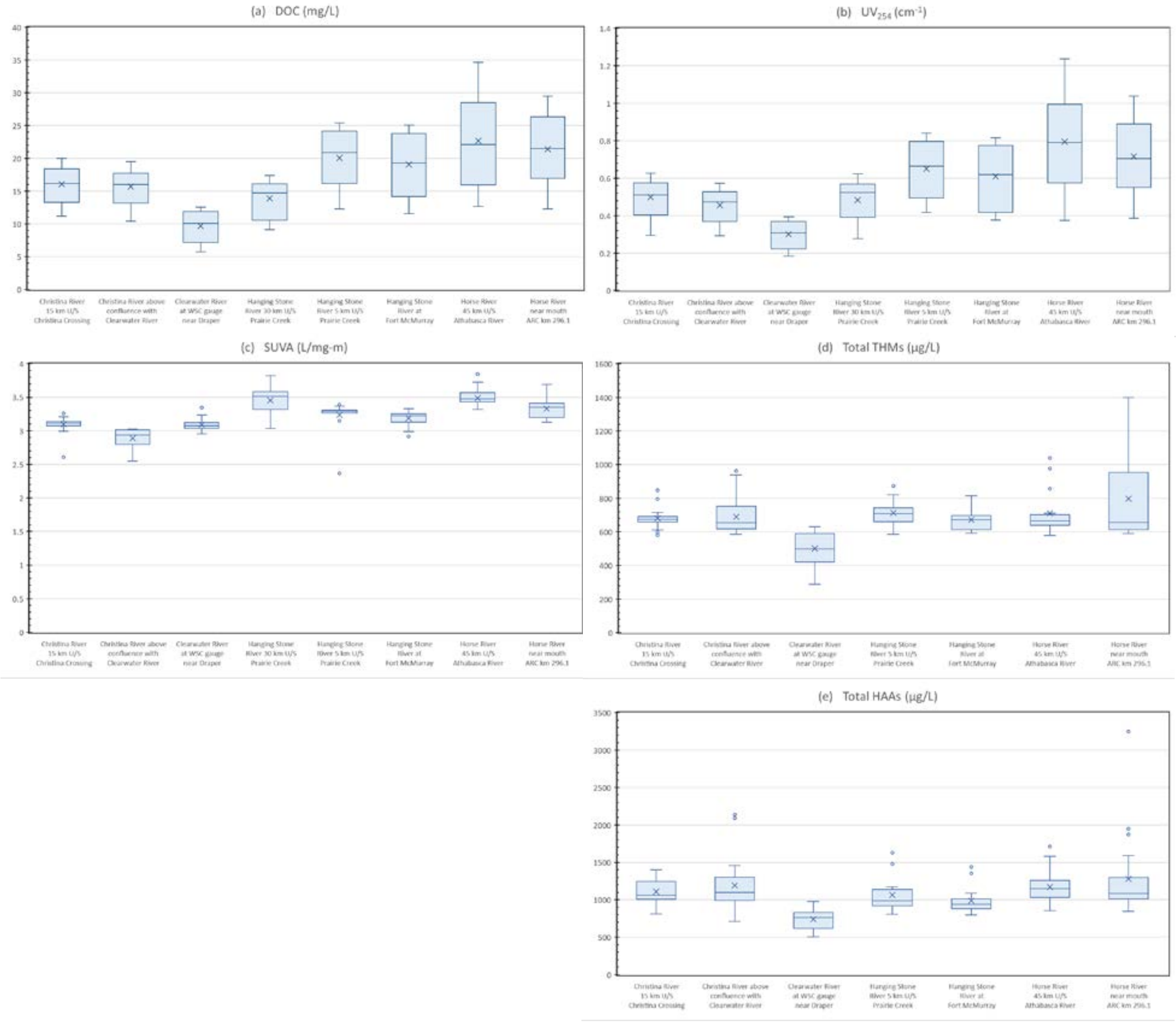
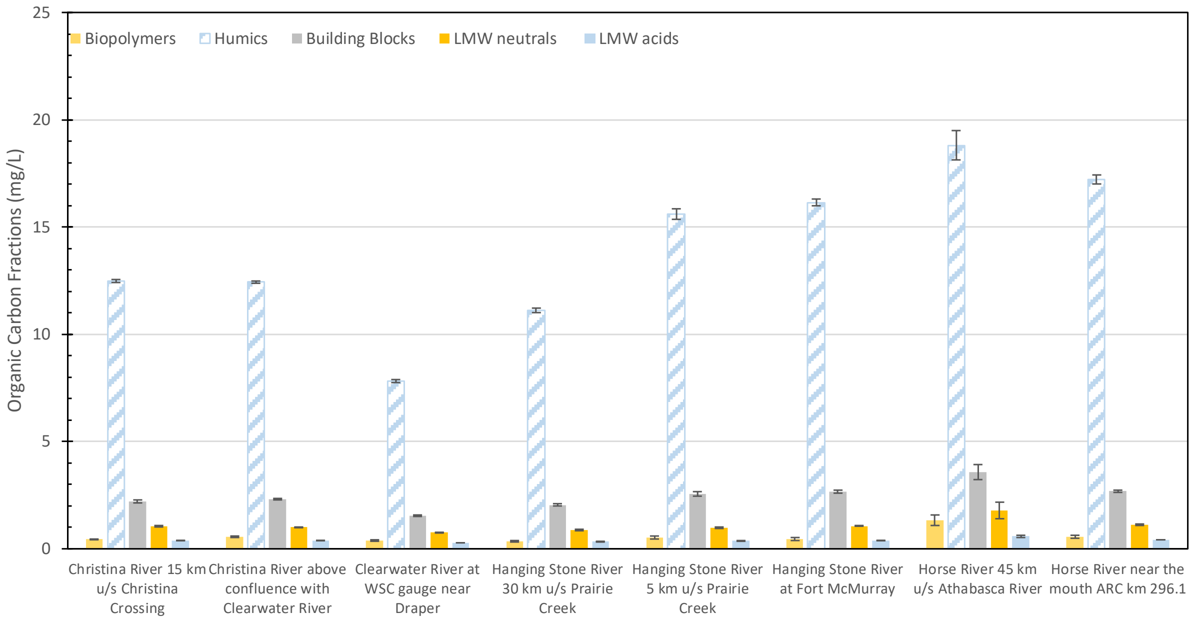


Figure 6. NOM-associated water quality and DBP-FPs at GOA sampling locations in the Athabasca River Watershed (2016-2017) after the Horse River wildfire.

(a) Organic Carbon Fractions



(b) Organic Carbon Fractions (humics removed)

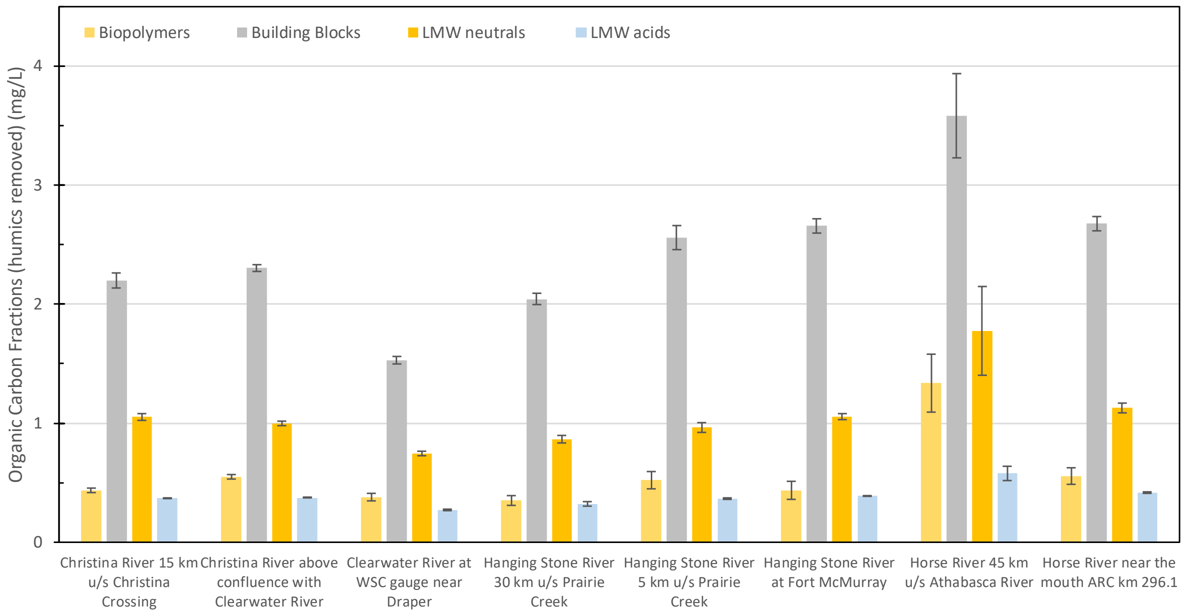


Figure 7. Organic carbon fractions (mean ± standard deviation) separated by size using LC-OCD at GOA sampling locations in the Athabasca River Watershed (2016-2017) after the Horse River wildfire. All five fractions (from least to most hydrophobic: biopolymers, humics, building blocks, low molecular weight (LMW) neutrals, and LMW acids are presented in (a); humics are removed for clarity in (b).

Organic carbon fractions in a limited subset of the samples from the Athabasca upstream of the wildfire, Little Fisheries Creek at the golf course, and upstream of the RMWB's intake on the Athabasca River is presented in Figure 8. These data are generally consistent with the data from Figures 6 and 7, but also demonstrate significantly elevated biopolymers and LMW neutrals in the Athabasca River just upstream of the RMWB's WTP intake—these values are presumably elevated because of inputs from Little Fisheries Creek. Notably, they suggest the potential for increased biofouling of membranes and increased regrowth in the distribution system, respectively. These observations, while not incontrovertible, provide the first global evidence of these implications for water treatability and supply as a result of wildfire.

River basins collect, store and release water and depending upon the nature of the landscape (vegetation, slope, geology, landuse and disturbance type)—several hydro-climatic catchment responses can occur. While some catchments with a high degree of hydrologic connectivity (e.g., Montane Cordillera) rapidly translate precipitation into runoff and associated contaminant transport to streams, other catchments with poor hydrologic connectivity tend to store water and sediment-associated contaminants; their transport and delivery to receiving streams can be delayed for decades. Catchments located in the Western Boreal Forest of the Boreal Plain ecozone typically have poor hydrologic connectivity with receiving streams (DeVito et al., 2012). In addition, the long term residence of surface water (ponds), variations in surficial geology and groundwater-surface water connectivity can mask the initial impact of disturbances such as fire on the hydro-chemistry of lake ecosystems (Olefeldt et al. 2013). At the large landscape scale, measurable impacts of the Horse River wildfire in Fort McMurray on water quality and treatability of the Athabasca River will likely be delayed due to the poor hydrological connectivity of watersheds impacted by fire as well as dilution effects of sediment-associated contaminant inputs in the river. However, as demonstrated by the plume in the Athabasca River from Little Fisheries Creek (Figure 3), streams/rivers in close proximity to the Fort McMurray WTP at least occasionally discharge sediment and associated contaminant plumes to the Athabasca River (within 10-25m from shore), which appear to remain relatively unmixed for more than 1 km downstream of the tributary inflows (Figure 3). Thus, it was hypothesized that sediment and associated contaminant delivery from these sources could disproportionally affect reservoir water quality and treatability, at least on some occasions. Accordingly, water samples were collected from the Athabasca River just upstream of the WTP and near the plant intake (approximately 0.25 km upstream of the WTP), the WTP's raw storage reservoirs, and treated water during the period from Summer 2016 to 2019 and source water quality and drinking water treatability was evaluated at these locations during "baseline" and "post-storm" conditions, as described earlier.

Water quality and DBP-FPs in the Little Fisheries Creek (tributary Athabasca River immediately upstream of the Fort McMurray WTP), Athabasca River at the WTP intake, and in the WTP's raw water storage reservoir during baseline and post-storm periods over three years after the Horse River wildfire are presented in Figure 9. These data indicate that despite the complicated hydrology of the Athabasca River basin, observed increases in coagulant demand at the Fort McMurray WTP after the wildfire (detailed later) were likely driven by shifts in bulk DOC concentrations and aromaticity (UV_{254}) (Figures 9a and 9c, respectively) that resulted from tributary (e.g., Little Fisheries Creek) inflows to the Athabasca River and poor lateral mixing (that resulted in visible plumes), immediately upstream of the WTP intake. Specifically, these figures demonstrate while these parameters were similar in the Athabasca River near the WTP intake and the raw water reservoir during baseline conditions, they were relatively elevated in the Athabasca River near the WTP intake during post-storm conditions, when plumes from Little Fisheries Creek to the Athabasca River were visible. As would be expected, the same trend was observed in THM-FP (Figure 9e). Interestingly, this trend was generally consistent, but not quite as evident for HAA-FP (Figure 9f); likely due to recognized differences in precursor materials. These trends were also reflected in the various DOC fractions measured by LC-OCD (Figure 10).

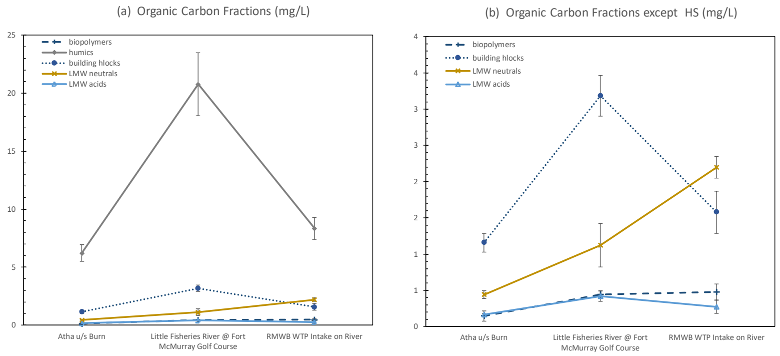


Figure 8. Organic carbon fractions (mean ± standard deviation) separated by size using LC-OCD at sampling locations in the Athabasca River Watershed (2016-2017) after the Horse River wildfire. All five fractions (from least to most hydrophobic: biopolymers, humics, building blocks, low molecular weight (LMW) neutrals, and LMW acids are presented on the right; humics are removed for clarity on the left. Trendlines are included only to assist with data visualization.

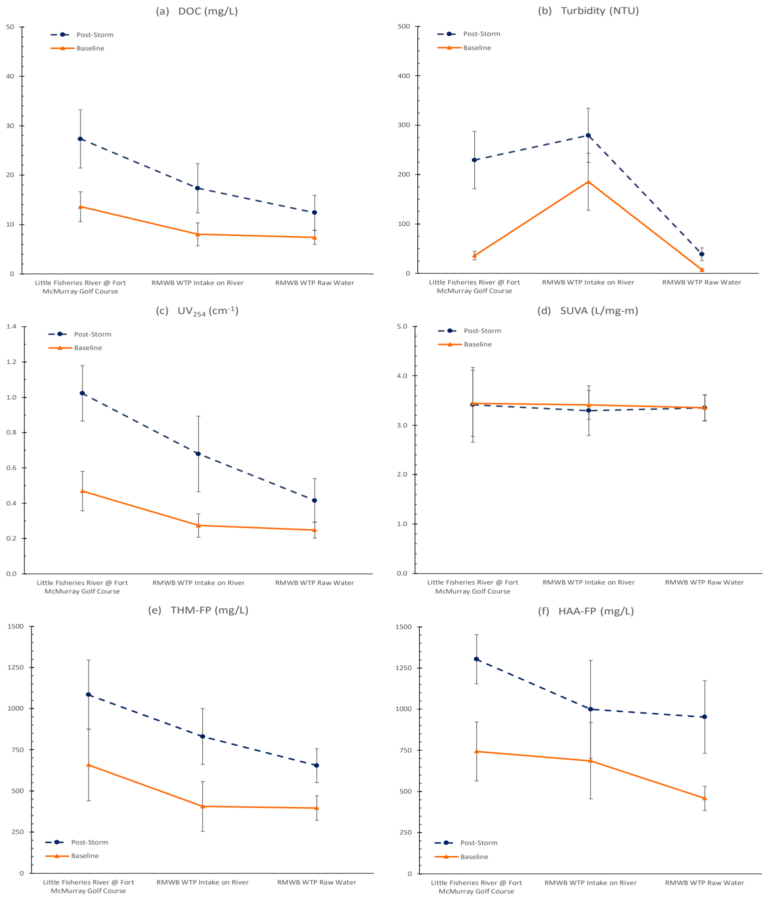
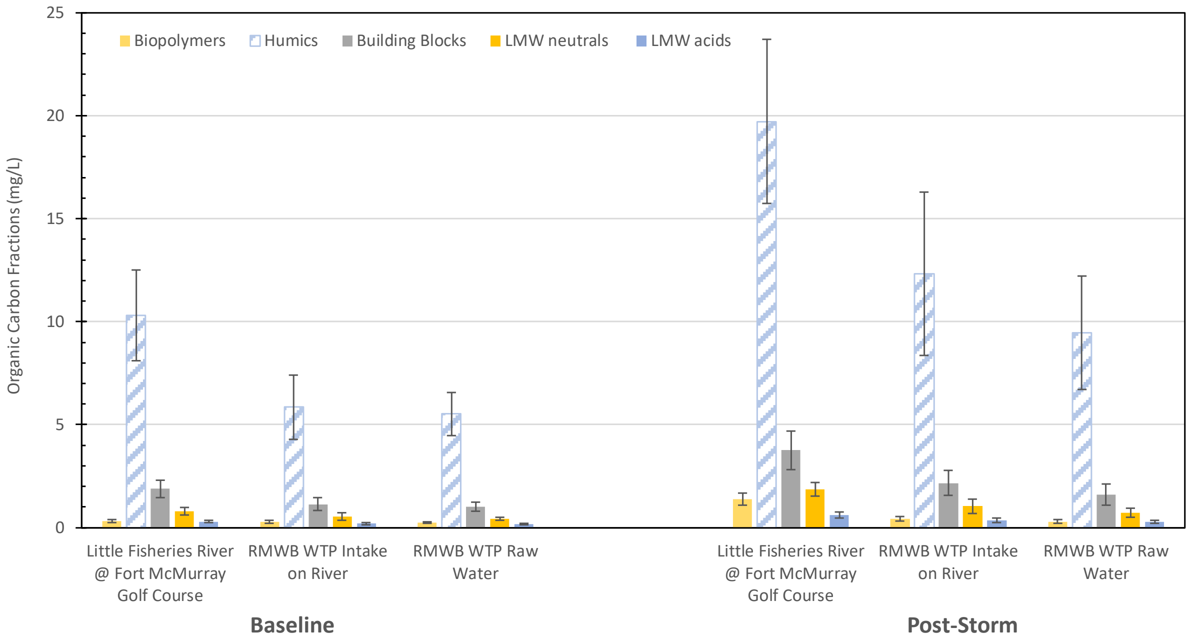


Figure 9. Water quality and DBP-FPs (mean ± standard deviation) in the Little Fisheries Creek (tributary Athabasca River immediately upstream of the Fort McMurray WTP), Athabasca River at the WTP intake, and in the WTP's raw water storage reservoir (2016-2019) during baseline and post-storm periods. Trendlines are included only to assist with data visualization.

(a) Organic Carbon Fractions



(b) Organic Carbon Fractions (humics removed)

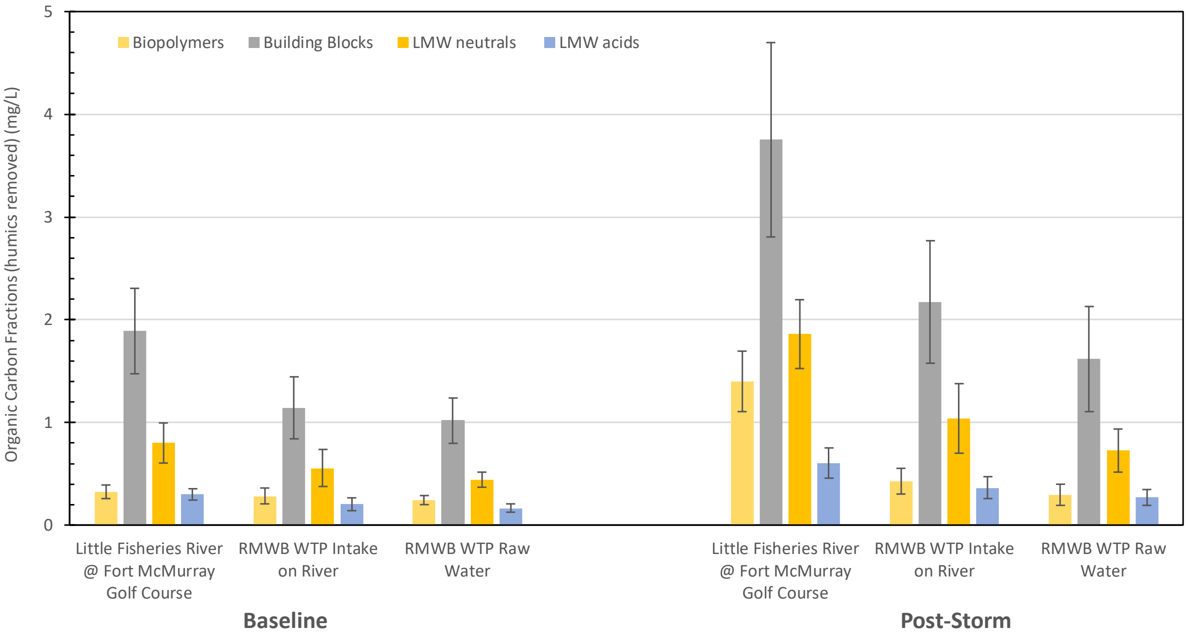


Figure 10. Organic carbon fractions (mean + standard deviation) separated by size using LC-OCD in Little Fisheries Creek (tributary Athabasca River immediately upstream of the Fort McMurray WTP), Athabasca River at the WTP intake, and in the WTP's raw water storage reservoir (2016-2019) during baseline and post-storm periods. All five fractions (from least to most hydrophobic: biopolymers, humics, building blocks, low molecular weight (LMW) neutrals, and LMW acids are presented in (a); humics are removed for clarity in (b).

Given the limited inferences that could be drawn from the basin-scale and field sampling programs because of limitations in frequency of data collection, significant effort was put in to synthesizing and evaluating all available laboratory and online full-scale performance data from the RMWB's Fort McMurray WTP. Weekly total organic carbon (TOC) concentrations in the raw water reservoir and treated water from January 2012 to January 2019 were available. Weekly TOC concentrations in the Athabasca river water at the plant intake were only available from May 2016 onward. Several high frequency, online data were also collected. Average daily turbidity, UV_{254}, total dissolved solids (TDS), color, and alkalinity data from January 2010 to January 2019 were evaluated. All of these data are presented in Figure 11.

Daily raw and treated water TDS and alkalinity (Figures 11d and 11f, respectively) demonstrate the stability of the Athabasca River source water, as well as the treated water. As expected, there were no differences in these parameters before and after the wildfire. TDS and alkalinity were cyclically higher in colder months and lower in ones because ice cover in rivers decreases dissolved oxygen concentrations due to continued respiration coupled with very low rates of primary productivity. Accordingly, these conditions increase under ice concentrations of CO_2 and HCO_3^{-1}, thereby increasing alkalinity and TDS.

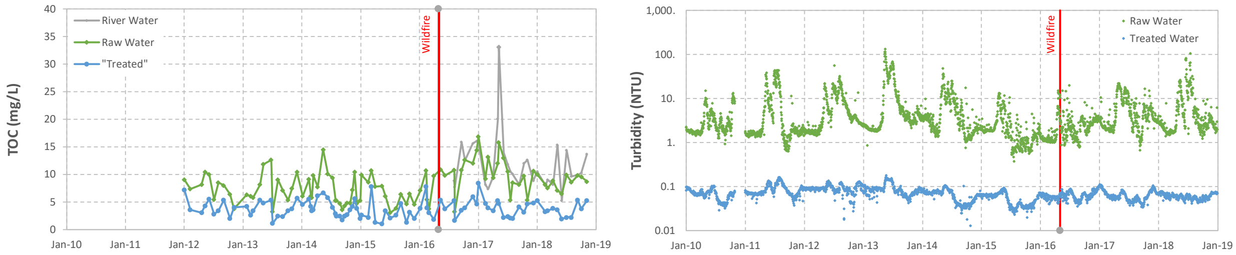
While substantial variability in raw water turbidity (spanning three orders of magnitude) was observed both before and after the wildfire (Figure 11b), clear shifts in turbidity as a result of wildfire were not observed. It is possible that continued high frequency sampling may yet reveal subtle shifts in this parameter. Notably, excellent treated water turbidity was maintained throughout the pre- and post-fire study period. In contrast, notable wildfire impacts on NOM-associated aspects of water quality and treatability were observed because of the availability of high frequency laboratory and online data. As shown in Figure 11a, TOC concentrations appear slightly more variable, with an increased baseline after the wildfire. The relatively low number of data precludes adequate statistical analysis, however.

DOC aromaticity of raw and treated drinking water in Fort McMurray before and after the wildfire in May, 2016 is indicated by UV_{254} in Figure 11c. Notably, color data essentially mirrored the UV_{254} data, as would often be expected because color is largely driver by DOM. The color data reflect the incremental nature of the analysis (i.e., interval as opposed to continuous data). The raw water data feature prolonged peaks, generally between the months of May and December, which appear to have become more frequent after the wildfire. The treated water data feature a similar pattern with less pronounced peaks. Non-parametric bootstrapping with 1000 iterations was used to evaluate uncertainty in several key statistics: the mean, the 10th percentile, and the fraction of data over 0.250 and 0.200 cm^{-1} (for raw water) or 0.080 cm^{-1} (for treated water). For each of these statistics, a 95% equal-tailed confidence interval is provided (interval range is in parentheses). For a group of 941 data (the smallest of four datasets), a single iteration of bootstrapping consists of drawing 941 values from the original data with replacement after each draw.

In the raw water, the mean UV_{254} was 0.213 cm^{-1} (0.209, 0.217) before the wildfire and increased to 0.269 cm^{-1} (0.264, 0.274) afterward. The 10th percentile was 0.115 cm^{-1} (0.109, 0.121) before the wildfire and increased to 0.184 cm^{-1} (0.178, 0.190) afterward. Thus, both of the mean and 10th percentile UV_{254} were elevated after the wildfire. Collectively, these results suggest a general increase in UV_{254} after the wildfire. This increase appeared to correspond to an increase in the number of peaks rather than their height. To evaluate this, the fraction of data over 0.250 cm^{-1} was determined: 22.0% (20.3, 20.8) before the fire and 49.6% (46.5, 52.8) afterward. The fraction of data over 0.200 cm^{-1} was also determined: 43.0% (40.9, 45.1) before the fire and 79.3% (76.6, 81.8) afterward. Thus, it can be concluded that wildfire resulted in significantly increased baseline (10th percentile) and mean values as well as variability (fraction of UV_{254} above 0.250 and 0.200 cm^{-1}; i.e., "above average") of UV_{254} in the Fort McMurray WTP's raw water. This observation is unprecedented in the reported literature and provides clear, incontrovertible evidence that explains the continued, increased chemical coagulant costs at the WTP since the wildfire.

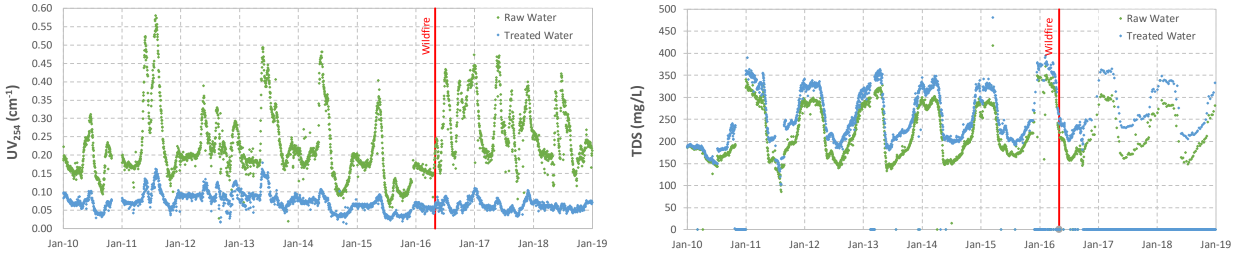
(a) TOC

(b) Turbidity



(c) UV_{254}

(d) TDS



(e) Color

(f) Alkalinity

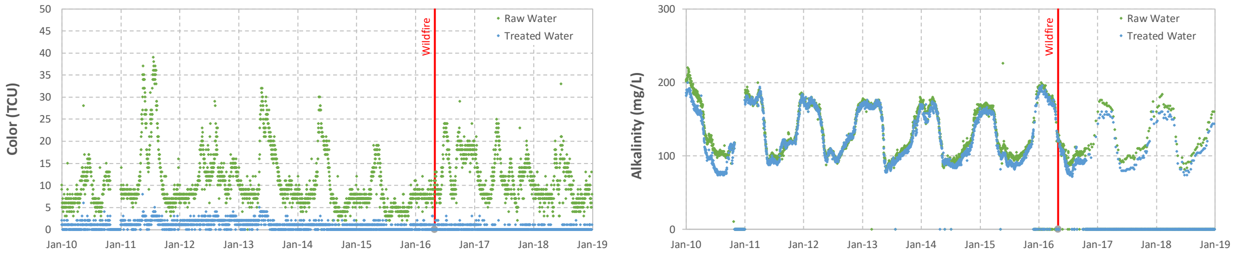


Figure 11. (a) Weekly total organic carbon (TOC) concentration (mg/L) in the raw water reservoir/plant intake and treated water at the RMWB's Fort McMurray WTP from January 2012 to January 2019. Weekly TOC concentrations in the Athabasca river water at the plant intake were only available from May 2016 onward. Daily average (b) turbidity (NTU), (c) UV_{254} (cm^{-1}), (d) total dissolved solids (mg/L), (e) color (TCU), and (f) alkalinity (mg/L) from January 2010 to January 2019.

Notably, in the treated water, the mean UV_{254} was 0.074 cm^{-1} (0.073, 0.075) before the wildfire and decreased to 0.063 cm^{-1} (0.062, 0.064) afterward. The 10th percentile UV_{254} was 0.039 cm^{-1} (0.038, 0.041) before the wildfire and increased slightly to 0.047 cm^{-1} (0.046, 0.048) afterward. There was no clear threshold to distinguish between baseline and peak data for the treated water. Notably, the 90th percentile was 0.104 cm^{-1} (0.101, 0.108) before the wildfire and decreased to 0.082 cm^{-1} (0.078, 0.084) after. In absence of further information, the observed significant improvement in treated water quality appears to directly contradict the significantly more degraded and more variable source water quality that would undoubtedly challenge coagulant dosing and associated treatment performance relative to pre-fire conditions. As might be expected, the observed treatment performance corresponded to improved operational capacity—this issue is further detailed below in the discussion of Milestone 3.

Daily average polyaluminum chloride (PACl) chemical coagulant doses required for ballasted sand flocculation (BSF) and conventional pretreatment processes prior to chemically-assisted filtration at the RMWB's Fort McMurray WTP from January 2015 to January 2019 are presented in Figure 12. Notably, mean PACl concentrations were approximately 65-70 mg/L prior to the wildfire. Required coagulant doses increased immediately as a result of the wildfire and reached 145-150 mg/L. The required PACl coagulant concentrations continued to increase and reach over 167 mg/L in June 2017. At that point, a new coagulant (different supplier of PACl) was identified and implemented as of Fall 2017; coagulant dosing then stabilized, and excellent treated water quality was maintained (Figures 11a-c). Notably, coagulant dosing requirements significantly decreased for a period of approximately three months in August 2018 after raw water storage reservoir dredging (discussed in detail below) and then returned to post-fire baseline levels. Notably, significant shifts in key parameters such as DOC concentration and UV_{254} were not experienced at this time. Thus, it is hypothesized that the removal of phosphorus-rich fine sediment from the reservoir led to a decrease in microbial and especially cyanobacterial populations in the raw water storage reservoirs leading to the decrease in chemical coagulant dose requirements (as algal organic matter is known to be negatively charged and increases coagulant demand). Re-establishment of these populations until a pseudo-steady state condition was reached would have then contributed to the observed increases and return to post-fire coagulant dose requirements in November 2018 (Figure 12).

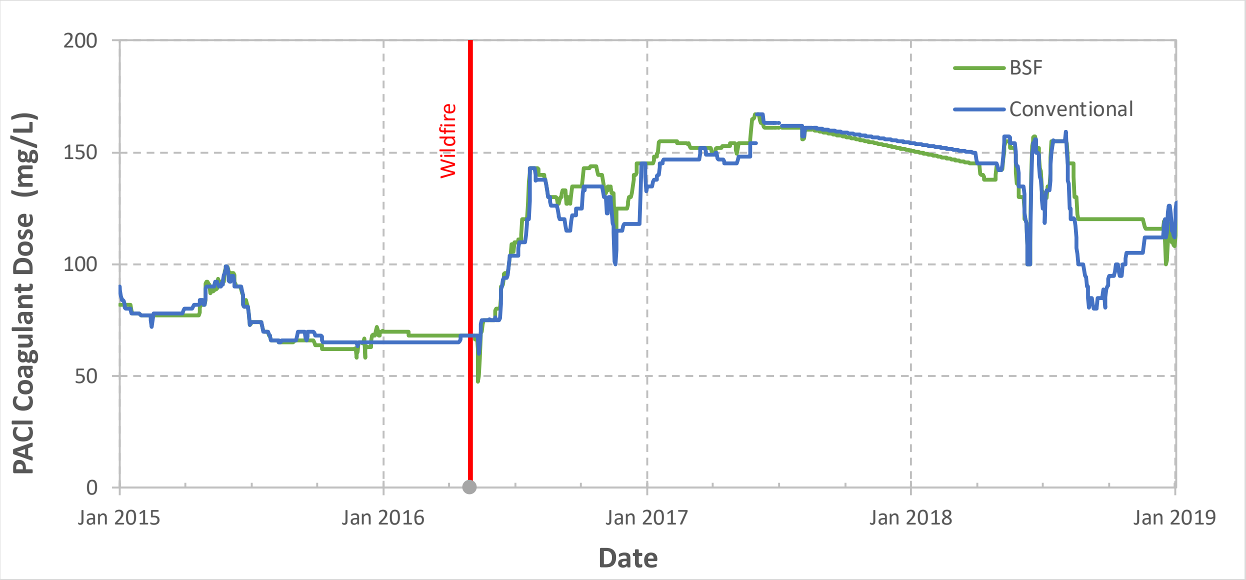


Figure 12. Daily average polyaluminum chloride (PACl) chemical coagulant dose (mg/L) required for ballasted sand flocculation (BSF) and conventional pretreatment processes prior to chemically-assisted filtration at the RMWB's Fort McMurray Water Treatment Plant from January 2015 to January 2019.

Task 1.3 Determine levels of sediment-associated contaminants of concern. Metals, polycyclic aromatic hydrocarbons (PAHs), and polychlorinated, aromatic hydrocarbons (e.g. dioxins and furans) are sediment-associated contaminants of human health concern that can be released into water supplies as a result of wildfire. In forested regions, landscape disturbance by wildfire can accelerate the delivery of nutrients and many contaminants of concern to receiving waters, the majority of which are associated primarily with fine sediment (Silins et al. 2009; Silins et al. 2014). The downstream propagation of fine sediment and associated contaminants of concern can have an impact on downstream water quality (Emelko et al. 2016) and the subsequent deposition of these materials in reservoirs can pose water treatment challenges for the provision of safe drinking water (Emelko et al. 2011).

Sediment was collected from the RMWB's raw water reservoirs and the potential presence of these contaminants (metals, PAHs, dioxins, furans, particulate phosphorus forms) was evaluated to inform risk management strategies such as the need for reservoir dredging to prevent the release of these materials into the water column. Bottom sediment was collected with a Ponar sampler at five locations in the east and west portions of the reservoir [east reservoir north (ERN), east reservoir middle (ERM), west reservoir North (WRN), west reservoir middle (WRM), west reservoir south (WRS)]. An additional (grab) sample of recently deposited surficial fine sediment was collected on the west bank of the Athabasca River above the WTP intake and immediately below Little Fisheries Creek.

The metal content (As, Cd, Cr, Cu, Fe, Hg, Pb, Mn, Ni, Zn) of Fort McMurray reservoir and Athabasca river bank sediment are presented in Table 1 and compared to sediment quality guidelines (SQGs) that include the consensus based Threshold Effect Concentration (TEC) and Probable Effect concentration (PEC) reported by MacDonald et al. (2000). Metals levels were higher in the river bank sediment than the reservoir sediment. For example, concentrations of metals in river sediment such as As, Cu, Hg, Pb, Mn and Ni were higher than reservoir sediment by a factor of 12.6, 1.9, 3.1, 1.9, 4.5 and 2.4, respectively. Concentrations of As, Cr and Hg in reservoir sediment exceeded the SQG TEC level while As and Pb levels in the river sediment exceeded the SQG PEL. From a drinking water perspective these levels are not of concern because metals preferentially bind to fine sediment and are easily removed during the drinking water treatment process.

Table 1. Distribution of metals in reservoir and river bank sediment.

Site	Al %	As ppm	Cd ppm	Cr ppm	Cu ppm	Fe %	Hg ppb	Pb ppm	Mn ppm	Ni ppm	Zn ppm
ERN	9.31	7.5	0.5	60.4	34.7	4.4	70	20.3	625	37.3	117
ERM	8.46	7.2	0.4	59.6	31.9	4.18	60	18.9	650	36.8	116
WRN	8.45	7.8	0.5	60.9	34.7	4.24	50	20.1	565	38	119
WRM	8.75	7.1	0.5	56.7	31.1	4.26	100	20	601	37.4	123
WRS	8.04	7.8	0.4	80.4	29.7	4.07	80	18.7	570	36.5	117
RS	1.74	94.2	1.8	35	62.2	8.23	220	37.9	2680	89.2	90
TEL		7.24	0.7	52.3	18.7		170	35			123
PEL		41.6	4.2	160	108		486	91.3			

Many northern river basins in Canada drain vast areas that integrate widespread atmospheric contaminant deposition and point-source inputs (MacDonald et al. 2000). Studies conducted to date on the quality of sediment in these rivers report elevated levels of persistent organic contaminants such as dioxins/furans (Culp et al., 2000) and polycyclic aromatic hydrocarbons (Yunker et al. 1993, 1996, 2002; Stone et al. 2013). Because of their carcinogenic and mutagenic properties, the US EPA has classified 16 PAH congeners as priority pollutants (Gremm & Frimmel 1994). Although these compounds can originate from geological deposits (petrogenic origin) they are mainly derived from processes such as combustion (pyrogenic origin) or microbial degradation (diagenic origin) (Yunker et al., 1993). PAHs are hydrophobic and preferentially bind to organic coatings of small particles in aquatic sediments and soils (Yang et al. 2011) and the fate of these compounds are related to transport and depositional processes along the river continuum. Accordingly, PAHs are present in many ecosystems and can enter the environment along multiple pathways that include releases to air, water, soil and sediment and the environmental impacts of PAH exposure to fish and humans are well documented (MacDonald et al. 2000).

The distribution of PAHs in reservoir and Athabasca river sediment are presented in Table 2. The data show that PAHs are present in reservoir and Athabasca River sediment, but at concentrations well below the consensus based threshold effect condition (TEC) defined by MacDonald et al. (2000). The total PAH concentration (ΣPAH) ranged from 1.6 to 4.7 ng/g in reservoir sediment and 231 ng/g in deposited fine river bank sediment. Thus, PAH concentrations in bottom sediment of the Fort McMurray drinking water reservoir are extremely low. Accordingly, at the concentrations reported herein, sediment associated PAHs pose no risk to drinking water source quality because fine solids are removed in the raw water storage reservoirs at the Fort McMurray WTP and during the water treatment process with coagulation and flocculation.

Table 2. Distribution of 16 USEPA priority PAHs in reservoir and Athabasca River sediment (ng/g).

Compound	TEC	ERN	ERM	WRN	WRM	WRS	RS
Napthalene	176	0.77	0.95	0.83	0.83	0.8	1.25
Acenaphthylene							1.16
Acenaphthene							2.45
Fluorene	77.4						1.62
Phenanthrene	204	0.85	1.86	1.04	0.94	0.52	8.79
Anthracene	57.2		0.58				3.7
Fluoranthene	423		0.58				13.8
Pyrene	195		0.74				28.8
Benzo(a)anthracene	108						7.4
Chrysene	166						58.5
Benzo(b)fluoranthene							42.8
Benzo(k)fluoranthene							2.84
Benzo(a)pyrene	150						15.8
Indeno(123-cd)pyrene							7.04
Dibenzo(ah)anthracene	33						20.4
Benzo(ghi)pyrene							14.4

The Northern Rivers Basins Study (NRBS) was conducted to better understand of how anthropogenic developments have impacted the ecology of the Peace, Athabasca and Slave rivers, Canada (Wrona et al., 1996). The NRBS used a weight of evidence cumulative effects assessment (CEA) approach to determine the exposure and effects of multiple disturbance pressures on these northern rivers. Dioxins and furans are persistent organic pollutants that induce toxicity in both wildlife and humans. These compounds are formed during combustion of organic compounds in the presence of chloride and primary sources include wildfire, waste incinerators, pulp mills and industrial processes (White and Birnbaum, 2009).

Concentrations of polychlorinated dibenzo-para-dioxins (dioxins) and polychlorinated dibenzofurans (furans) and the related Toxic Equivalency Factor (TEQ) for both reservoir and river bank sediment are presented in Table 3. To obtain TEQs the mass of each chemical in a mixture is multiplied by its toxic equivalency factor (TEF) and is then summed with all other chemicals to determine the total toxicity-weighted mass. TEQs are then used for risk characterization and management purposes, such as prioritizing areas of cleanup. In general, the concentrations of dioxins and furans in the reservoir sediment were low and the related TEQ values were < 1. Pulp and paper mills and wildfire are reportedly the two primary sources of dioxins and furans in the Athabasca River and the levels of these compounds decrease with distance downstream due to mixing. It is unknown whether the Fort McMurray wildfire produced dioxins and furans and how much and how long the effects of wildfire on the transport of these compounds from the terrestrial to the riverine environments will be. However, given that dioxins and furans preferentially partition in the particulate phase and that the raw water reservoirs in Fort McMurray and the water treatment process effectively removes particles, the potential health risk due to ingestions of dioxins and furans in drinking water is exceedingly low.

Table 3. Distribution of dioxins and furans (pg /g sediment) in reservoir and river bank sediment. Samples were collected in east reservoir north (ERN), east reservoir middle (ERM), west reservoir north (WRN), west reservoir middle (WRM), and west reservoir south (WRS) locations.

Dioxins & Furans	**ERN**	**ERM**	**WRN**	**WRN**	**WRM**	**WRS**	**River Bank**
2,3,7,8-Tetra CDD	0.111	0.101	0.112	0.119	0.111	0.103	0.116
1,2,3,7,8-Penta CDD	0.108	0.11	0.116	0.118	0.113	0.119	0.109
1,2,3,4,7,8-Hexa CDD	0.106	0.107	0.103	0.101	0.11	0.105	0.107
1,2,3,6,7,8-Hexa CDD	0.113	0.114	0.124	0.108	0.118	0.112	0.114
1,2,3,7,8,9-Hexa CDD	0.132	0.101	0.120	0.0955	0.104	0.0989	0.101
1,2,3,4,6,7,8-Hepta CDD	1.87	1.69	2.18	1.72	1.24	0.713	0.612
Octa CDD	12.3	14.8	14.6	10.1	6.80	3.49	3.75
2,3,7,8-Tetra CDF	0.127	0.114	0.140	0.107	0.109	0.108	0.359
1,2,3,7,8-Penta CDF	0.112	0.101	0.107	0.107	0.112	0.106	0.116
2,3,4,7,8-Penta CDF	0.115	0.104	0.11	0.11	0.115	0.109	0.119
1,2,3,4,7,8-Hexa CDF	0.105	0.0992	0.101	0.109	0.102	0.107	0.099
1,2,3,6,7,8-Hexa CDF	0.104	0.0982	0.0998	0.107	0.101	0.106	0.098
2,3,4,6,7,8-Hexa CDF	0.111	0.105	0.107	0.115	0.108	0.114	0.105
1,2,3,7,8,9-Hexa CDF	0.12	0.114	0.115	0.124	0.117	0.123	0.113
1,2,3,4,6,7,8-Hepta CDF	0.365	0.252	0.419	0.369	0.211	0.122	0.0954
1,2,3,4,7,8,9-Hepta CDF	0.137	0.124	0.129	0.123	0.13	0.133	0.123
Octa CDF	0.610	0.469	0.607	0.557	0.366	0.223	0.110
TEQ	0.38	0.36	0.39	0.39	0.37	0.36	0.38

Sediment associated contaminants do not pose significant risk to drinking water source quality in Fort McMurray. Nonetheless, visual inspection of the dual-stage, in-line reservoir at the RMWB's water treatment plant in Fort McMurray clearly indicates the critical importance of this process for reducing suspended sediment concentrations entering the treatment plant (Figure 13). A centrifugal pump is relied upon to return a significant fraction of coarser, suspended solids to the river. Fine sediment does remain in the reservoir, however.

Figure 13. Aerial view of dual-stage, in-line reservoir at the RMWB's Fort McMurray WTP indicating reduction of suspended solids within the reservoir. Higher levels of suspended solids are seen in the east basin (left) closer to the river and substantial settling of suspended sediment is evident in the west basin (right).

Task 1.4 Determine physical and geochemical properties of reservoir sediment. The median diameter (D_{50}) of the reservoir sediment is ~35 µm and this material consists predominantly of silt and clay sized fractions. The fine grain nature of the sediment in the reservoir is due to the treatment process (centrifugation) of pre-screening larger sediment fractions from the Athabasca River to the Fort McMurray reservoir inflow. The major element composition was remarkably consistent within the reservoir sediment, but differed from the river bank (Table 4). Compared to the reservoir sediment, SiO_2 of the river bank sediment was lower by a factor of 0.3, but MnO and organic matter content were elevated by a factor of 5.1 and 4.8, respectively. Increased levels of MnO and organic matter in sediment following wildfire are commonly reported in the literature. Increased MnO content is related to increased binding potential of P to sediment and is a key geochemical control of P sorption dynamics in aquatic systems. Increased levels of these nutrients have been show to contribute to increased levels of microbial activity in some systems (e.g., Lake Erie); thus, these data suggested potential shifts in microbial species.

Table 4. Major element composition of reservoir and river bank sediment

Site	SiO_2	Al_2O_3	Fe_2O_3(T)	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	Cr_2O_3	LOI
	%	%	%	%	%	%	%	%	%	%	%	%
ERN	53.38	15.74	5.67	0.07	2.19	4.38	0.41	2.41	0.62	0.23	0.02	13.43
ERM	54.33	15.16	5.54	0.074	2.26	4.55	0.49	2.42	0.64	0.22	0.02	12.95
WRN	55.21	15.32	5.67	0.065	2.3	4.37	0.43	2.52	0.67	0.21	0.02	12.19
WRM	55.57	14.8	5.46	0.067	2.3	4.59	0.5	2.48	0.67	0.19	0.03	11.87
WRS	57.08	14.67	5.41	0.063	2.24	4.22	0.52	2.39	0.67	0.19	0.02	11.39
RS	18.49	3.38	11.11	0.34	0.77	5.01	0.05	0.4	0.27	0.25	< 0.01	58.43

Phosphorus (P) is the limiting nutrient in freshwater systems (Schindler 1977) and increased levels of P in bottom sediments or the water column can promote algal productivity and challenge water treatment processes (He et al. 2016). Sediment is the primary vector for phosphorus transport and increasing concentrations of particulate phosphorus are associated with fine sediment fractions. A sequential extraction procedure was used to determine the distribution of particulate phosphorus forms (NAIP, AP, OP) as a proxy to assess the potential bioavailability of particulate P to the reservoir water column (Stone and English 1993). Nonapatite P (NAIP) is the most bioavailable particulate P form and is considered a potentially mobile P pool (internal source) that is available for primary production in the reservoir.

The distributions of particulate P forms in the Fort McMurray reservoir and Athabasca River sediment are presented in Table 5. The data show that total particulate P (TPP) in reservoir and Athabasca River sediment was 761 to 892 µg/g and 1091 µg/g, respectively. The most bioavailable particulate P form (NAIP) comprised 34 to 42% of TPP in the reservoir sediment. In contrast ~67% of the TPP in the Athabasca River sediment was NAIP. While high levels of bioavailable P do not necessarily mean that toxin-forming algal blooms or unpleasant taste and odour events will occur in a water supply, elevated levels of bioavailable P significantly increase the probability of those events occurring, especially when other nutrients like biodegradable organic carbon and ammonium-N are available. These nutrients are also known to be elevated in aquatic systems impacted by severe wildfire. Emelko et al. (2016) characterized the effects of wildfire on the form and propagation of particulate P in the Oldman River basin and found comparable levels of TPP and NAIP in the Castle and Crowsnest River (as part of our previous Alberta Innovates project) and reported that particulate P export in burned tributaries had not recovered to unburned levels seven years after the wildfire. As part of that project, Stone et al. (2014) used fingerprinting to show that ~80% of the sediment deposited in the reservoir originated from ~14% of the landscape that was burned. Implications of the two previously reported studies suggest that the effects of wildfire on water quality in the Fort McMurray wildfire may be prolonged (i.e., decades), but the impact on sediment quality may be muted because 1) flow in the Athabasca River will cause a dilution effect on fire-related sediment and associated P in the river, 2) poor terrestrial-riverine coupling in the fire impacted regions of the Athabasca watershed will lower the transfer of pyrogenic materials to the river, and 3) differences in hydroclimatic regimes between the snow melt-dominated high sloping Oldman River basin and the drier Athabasca river basin results in lower runoff rates in the Athabasca River basin.

Table 5. Distribution of particulate P forms (NAIP, AP, OP, TPP) in reservoir and river bank sediment.

Site	NAIP µg/g	AP µg/g	OP µg/g	TPP µg/g	NAIP/TPP %
ERN	286	366	121	773	37
ERM	379	401	112	892	42
WRN	339	384	95	818	41
WRM	261	416	94	772	34
WRS	261	408	92	761	34
RS	727	264	100	1091	67

Task 1.5 Evaluate sorption behavior of reservoir sediment. The quality of water in reservoirs is a function of several interrelated factors including reservoir morphology, watershed characteristics, hydro-climatology and land use. Nutrient enrichment in reservoirs can promote the growth of algae, including cyanobacteria (Orihel et al. 2017) which lead to water treatment challenges (Wagner and Erickson 2017; He et al. 2016; Emelko et al. 2011). Internal phosphorus loads can increase in lakes and reservoirs when external sediment associated phosphorus loads are reduced. This occurs because phosphorus bound to redox-sensitive iron compounds or fixed labile organic forms in lake sediments are released to the lake water. A key aspect of internal loading is related to the partitioning of phosphorus between deposited bottom sediment and dissolved phosphorus in the water column. Sediments buffer dissolved phosphorus concentrations in aquatic systems via sorption/desorption reactions across the sediment water interface (Reddy et al. 1999). The internal phosphorus pool stored in reservoir bottom sediments may potentially be available for re-release as soluble reactive phosphorus (SRP), which is the main dissolved bioavailable form of phosphorus and a key factor in promoting the growth of algal blooms.

The equilibrium phosphate concentration (EPC_0) is a measure of the potential of sediments to adsorb or release SRP depending on the ambient aqueous SRP concentration in the water column (Froelich, 1988) and it can be used to estimate phosphorus flux transfers from sediment in aquatic systems (Stone and Mudroch 1989). A series of batch tests were used to assess the phosphorus sorption behavior of sediment in the Fort McMurray WTP's raw water reservoirs and to evaluate its potential to promote the proliferation of cyanobacteria and other algae in the reservoirs. Measurements of the Equilibrium Phosphorus Concentration (EPC_0) were conducted to determine the extent to which reservoir sediments represent either a source or sink of soluble reactive phosphorus (SRP) to/from the overlying water column. The data show that P sorption behavior of the sediment was relatively consistent in both the west and eastern reservoir cells (Figure 14). The EPC_0 of reservoir sediment ranged from 50 to 75 µg/L; given that SRP concentrations in reservoir source water (Athabasca River) were typically low (< 10 µg/L), the data suggest that even under oxic conditions, it is estimated that bottom sediment will release approximately 3 to 4 µg P/g sediment to the water column. The release of phosphorus from the sediment to the water column will be increased if zones of anoxia are present in the reservoir (He et al., 2016). Accordingly, Fort McMurray reservoir sediment constitutes an important internal source of phosphorus to the water column and may promote the proliferation of cyanobacteria and other algae.

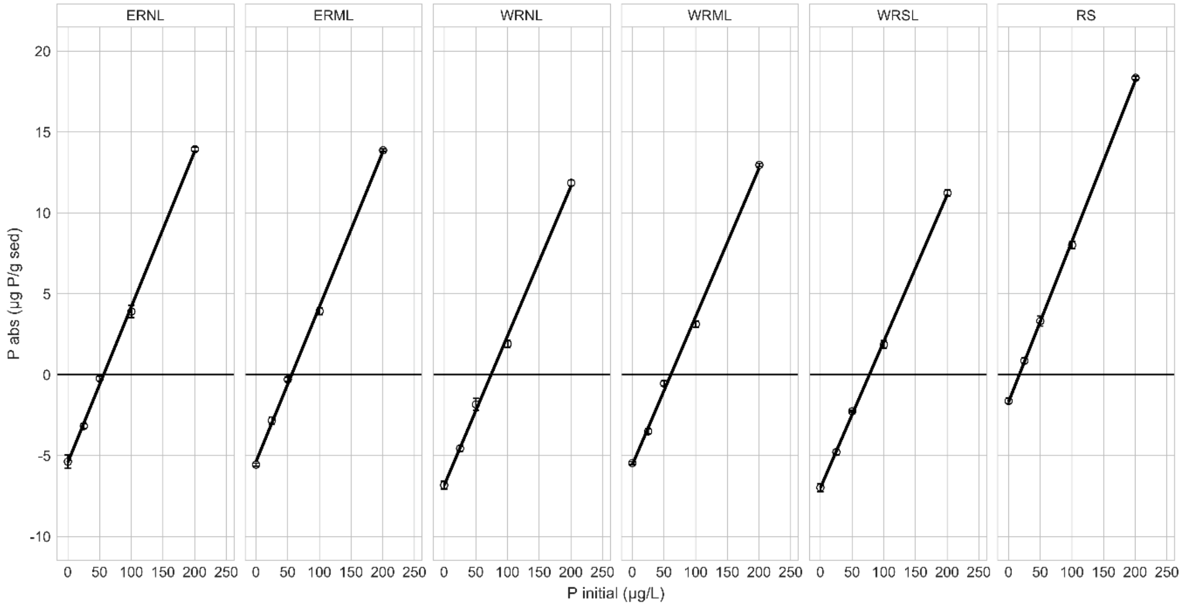


Figure 14. Phosphorus sorption characteristics of reservoir and riverbank sediment (RS). Sample collection locations in the reservoir included: east reservoir north location [ERNL], east reservoir mid-reservoir location [ERML], west reservoir north location [WRNL], west reservoir mid-reservoir location [WRML], and west reservoir south location [WRSL].

Cyanobacteria bloomed in the RMWB's Fort McMurray WTP raw water storage reservoirs in 2017, 2018, and 2019. The occurrence of these blooms in each year post-fire and in a reservoir containing post-fire, nutrient-enriched fine sediment at a utility that had not experienced significant blooms of algae historically makes an extremely compelling case for causality. Samples were collected from the WTP clarifiers during the August 2018 bloom (Figure 15) and characterized. They were sequenced for the variable region of the 16S rRNA gene that can identify major bacterial groups that are present in the water column. The community of bacteria was primarily comprised of Proteobacteria and cyanobacteria comprised 1.21-2.26 of the proportion of bacteria. It is likely that the amount of cyanobacteria in these samples decreased during transport due to the large amount of zooplankton observed in them (samples were not filtered prior to transport). Of the cyanobacteria observed in the water samples (Tables 6-8), primarily *Microcystis, Aphanizomenon, Dolichospermum* (also known as *Anabaena*), all have the *potential* to produce microcystin, anatoxin and cylindrospermopsin. *Cyanobium* has the *potential* to produce microcystin. Thus, while the species of cyanobacteria that were identified using microbial community analysis by amplicon sequencing are known toxin formers, further confirmation that the strains carry the specific genes for toxin production is underway. It should be underscored that even if the genes are present, they must be expressed for toxins to be present in the water supply. In order to determine whether or these organisms observed are potentially toxic, sequencing of the genomes is required—this is underway (as our laboratories do not currently have the capacity to conduct this analysis). Nonetheless, caution is necessary and water bodies that have these organisms should be presumed toxic until analysis determines otherwise. Accordingly, this work underscores that wildfire represents a significant, long-term threat to drinking water supplies in physiographic settings in which wildfire is a significant disturbance regime and surficial geology is rich in fine sediment.

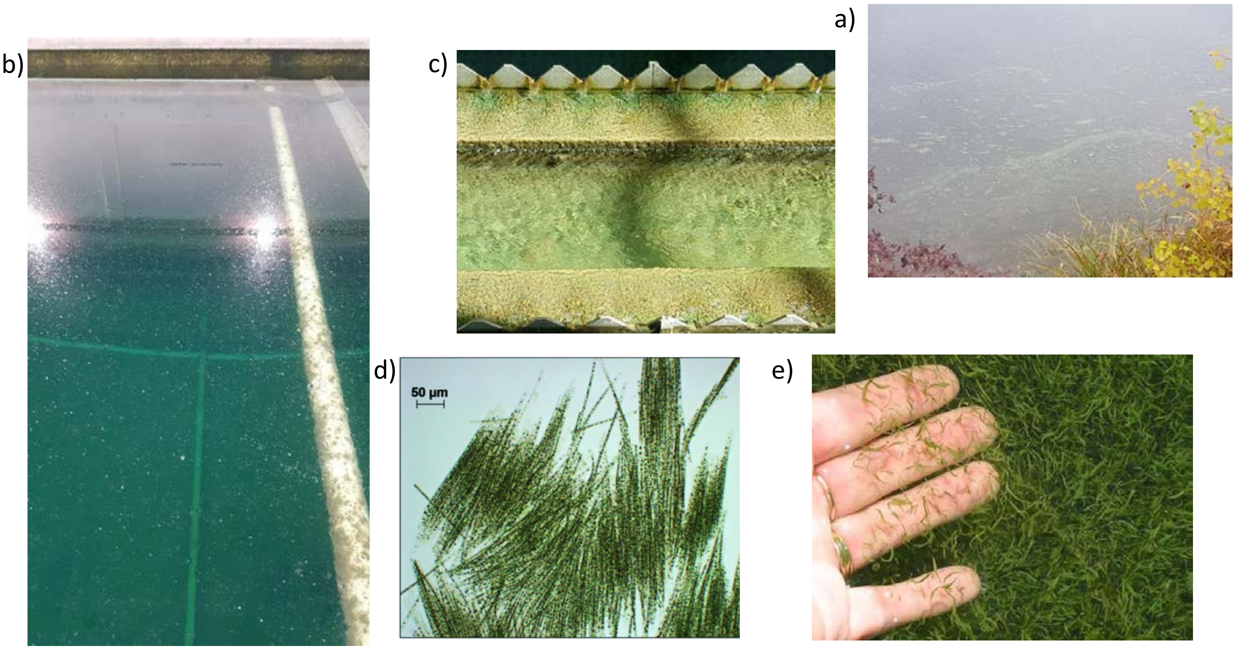


Figure 15. August 2018 bloom of cyanobacteria (a) in the Fort McMurray WTP's raw water storage reservoir, (b) WTP clarified, and (c) clarifier weirs. The predominant species that were identified were of the *Aphanizomenon* genus (d) and were extremely abundant (e).

Table 6. Number of sequence reads for V4 region of 16S rRNA gene (mitochondria and chloroplasts removed)

Sample IDs	**Input**	**Filtered**
FM-1	16234	15275
FM-PW	24119	23268

Table 7. Bacterial Phylum-level proportions after filtering mitochondria and chloroplast sequences (in %)

Phylum	**FM-1**	**FM-PW**
Proteobacteria	52.68	62.57
Bacteroidetes	35.86	17.31
Actinobacteria	5.73	13.95
Cyanobacteria	1.21	2.26
Planctomycetes	0.43	1.13
Other	4.10	2.76

Table 8. Unique cyanobacterial amplified sequence variants with closest matches to DNA database at 70% and above cutoff.

ID	FM-1	FM-PW	Family	Genus/Species matches in database
FMCyan1	2	0	Nostocaceae	*Aphanizomenon* MDT14a*
FMCyan2	2	0	Nostocaceae	*Aphanizomenon* NIES81*
FMCyan3	0	14	Nostocaceae	*Aphanizomenon* NIES81*
FMCyan4	0	5	Nostocaceae	*Aphanizomenon* NIES81*
FMCyan5	0	60	Nostocaceae	*Aphanizomenon* NIES81*
FMCyan6	0	36	Nostocaceae	*Aphanizomenon* NIES81*
FMCyan10	0	21	Nostocaceae	*Calothrix* PCC-6303
FMCyan13	71	0	Cyanobiaceae	*Cyanobium* PCC-6307*
FMCyan14	3	0	Cyanobiaceae	*Cyanobium* PCC-6307*
FMCyan15	36	29	Cyanobiaceae	*Cyanobium* PCC-6307*
FMCyan16	0	18	Cyanobiaceae	*Cyanobium* PCC-6307*
FMCyan17	0	13	Cyanobiaceae	*Cyanobium* PCC-6307*
FMCyan18	0	30	Thermosynechococcaceae	*Cyanothece* PCC 7425
FMCyan19	31	0	Nostocaceae	*Dolichospermum* NIES41
FMCyan20	0	26	Nostocaceae	*Dolichospermum* NIES41
FMCyan21	0	5	Microcystaceae	*Microcystis* PCC-7914*
FMCyan22	2	0	Microcystaceae	*Microcystis* PCC-7914*
FMCyan25	0	65	Pseudanabaenaceae	*Pseudanabaena* PCC-7429
FMCyan26	0	4	Pseudanabaenaceae	*Pseudanabaena* PCC-7429
FMCyan27	0	5	Microcystaceae	*Snowella* 0TU37S04

While there was no appreciable production of microcystin (which is regulated) as a result of these blooms, evaluation of the potential production of anatoxin and cylindrospermopsin was not possible. While it has been widely speculated that wildfires can increase the probability of cyanobacterial bloom occurrence, this investigation represents the first documentation of this impact at a drinking water utility globally. Moreover, this investigation is also the first globally to provide direct evidence of wildfire as a causal agent of cyanobacteria blooms that have the potential to produce toxins.

The blooms necessitated costly dredging of sediment from the raw water storage reservoirs (east reservoir in 2017, west reservoir in 2018). It is very likely that these algae blooms were triggered by desorption of bioavailable phosphorus from post-fire, phosphorus-enriched fine sediment deposited in the reservoirs—levels of the particulate phosphorus forms (NAIP, AP and OP) in the reservoir were elevated and consistent with levels previously reported for wildfire-impacted sediment after the Lost Creek wildfire in southern Alberta and where algae also proliferated after wildfire (reported in an earlier Alberta Innovates project). Notably, as mentioned in the discussion above, coagulant dosing requirements significantly decreased for a period of approximately three months after raw water storage reservoir dredging and then returned to post-fire baseline levels (Figure 12). Algae and cyanobacteria are present in water supplies year round; regardless of bloom occurrence, algal organic matter is known to be negatively charged and increases coagulant demand. Thus, it is possible that algal and cyanobacterial populations re-established themselves in the reservoir once it accumulated adequate amounts of nutrient enriched fine sediment.

Milestone 2. Evaluation of BSF process in treating severely deteriorated and/or rapidly changing drinking water quality.

Task 2.1 Develop deteriorated water matrices. Post-wildfire pyrogenic material (ash) was collected thus at two separate locations in British Columbia, in critical close partnership with the BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development, which provided access to the wildfire sites and the necessary guidance to complete sampling in restricted fire zones. Before entering each field site, a safe work plan was completed and a site safety assessment was conducted. The first sampling event was conducted north of Kamloops, BC, near the town of Little Fort, from July 30-August 02, 2017 (indicated as Sample Area 1 in Figures 16-18). The sampling sites were situated near Thuya Lake and Dunn Lake. In total, 51 19-L pails of ash were collected from three recent wildfire burn sites. After the samples were collected, they were transported to the city of Calgary's Glenmore Water Treatment Plant, where they were stored. Notably, the first field visit assisted in developing the best methods for collecting post-fire material (Figure 19; using with soft bristle broom and shovel), which were applied to the second round of sample collection. The second sampling event was conducted north-west of Kamloops, BC on September 15-16, 2017 and is denoted as Sample Area 2 on Figure 16 and 17. In total, 61 19-L pails of ash were collected there. After collection, these samples also were transported to the city of Calgary's Glenmore Water Treatment Plant, where they were stored (Figure 20).

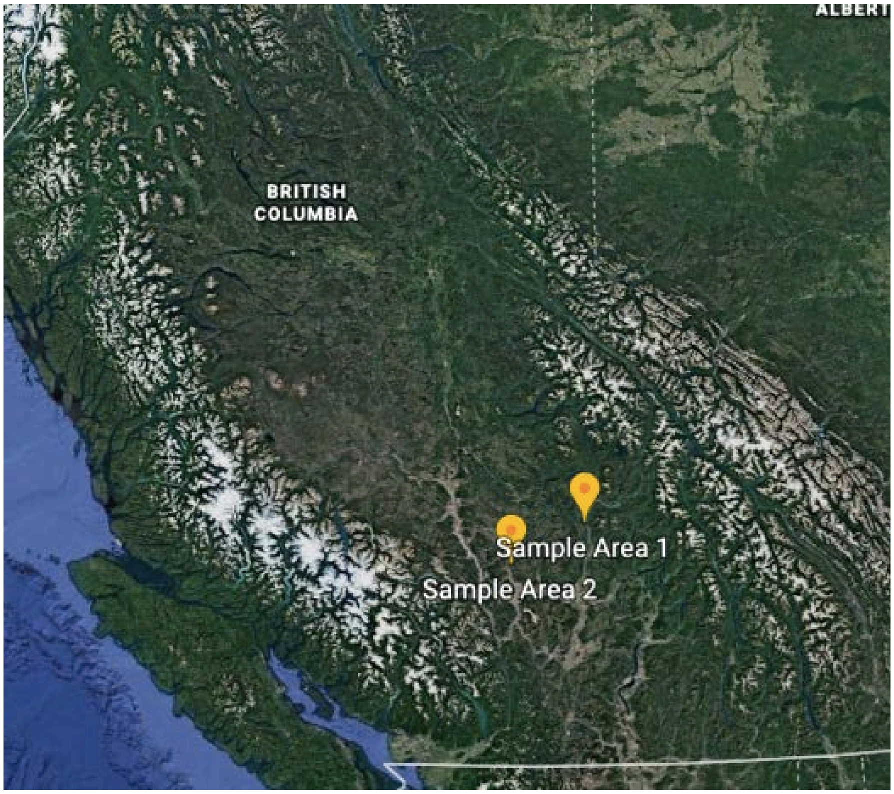


Figure 16. Locations of ash collection in British Columbia. Sample Area 1 is near the town of Little Fort, BC and Sample Area 2 is northwest of Kamloops, BC.

Figure 17. Detailed view of ash collection sites in British Columbia. Sample Area 1 is near the town of Little Fort, BC and Sample Area 2 is northwest of Kamloops, BC.

Figure 18. Sample Area 1 (Thuya Site) near the town of Little Fort, BC.

Figure 19. Ash collection with soft bristle broom and shovel at Sample Area 1 (Thuya Site).

Figure 20. Ash storage in the city of Calgary. Overall, 112 19-L pails of ash were collected.

The collected ash was used to create a suite of post-wildfire water matrices that represent a "worst-case scenario" of source water impacted by wildfire. Specifically, these matrices represent the immediate "wash in" (i.e., runoff) of post-fire ash into a drinking water source supply; thus, they represent the worst-case scenario of minimal/no dilution or transformation (e.g., DOC degradation) of water quality. The consistency of water quality resulting from batch to batch variability was first evaluated. Many factors (temperature/burn severity, vegetation, minerology, soil composition, etc.) may impact ash composition and thus water quality. After the collection of the first round of post-wildfire material in BC, tests were conducted at the Glenmore Water Treatment Plant to create a series of severely deteriorated ("black-water") matrices by adding the ash to Elbow River water from the Glenmore reservoir (Figure 21). Various levels of mixing were investigated as well. With support from the city of Calgary's Water Quality Lab, over 60 potential matrices were screened for key water quality and treatability characteristics, (including turbidity, DOC concentration, UV_{254} ,etc.). Notably, DOC concentration and UV_{254} remained relatively proportional to mass of ash added (form a given source), regardless of extent of mixing (Figure 22). Maintenance of this type of proportionality in turbidity would not be expected because it is an aggregate measure that is impacted by particle size distribution (which would likely be impacted by extent of mixing).

Task 2.2 Evaluate BSF treatment process: Montane Cordillera contact (Calgary) and **Task 2.3 Evaluate BSF treatment process: Boreal Plains contact (Fort McMurray).** An initial jar test was then conducted to investigate turbidity, DOC, and UV_{254} removal. Jar testing of BSF with a rise rate of 40 m/hr and sand dose of 10 mg/L was investigated using various (over 30) polymer (cationic, anionic, and non-ionic), coagulant (alum, PACl, ferric sulphate, 3737 [proprietary blend], and PAC (wood, coal, coconut); comparisons were based on metal equivalents) types and doses—a representative result is presented in Figure 23. As might be expected, relatively little performance difference was observed between the various coagulant and polymer combinations because the high alkalinity of the water matrices (in part induced by ash addition) resulted in stable pH; thus, precluding enhanced coagulation without pH adjustment. In general, and as expected, the jar testing demonstrated that BSF could effectively remove turbidity, but was less effective at reducing DOC—this result is visually depicted in Figure 24 and representative data from one of four trials are presented in Figure 25. Accordingly, enhanced coagulation (with pH reduced to 5.83 to enable co-precipitation of NOM) was evaluated (Figure 26); in this case, DOC removal increased to 23%, which was a good result, but still not to target (i.e., while a DOC concentration of <5 mg/L was targeted, it was still approximately 9.25 mg/L).

Figure 21. Generation of simulated severely deteriorated ("black-water") water matrices representative of "worst-case scenario" conditions after severe wildfire.

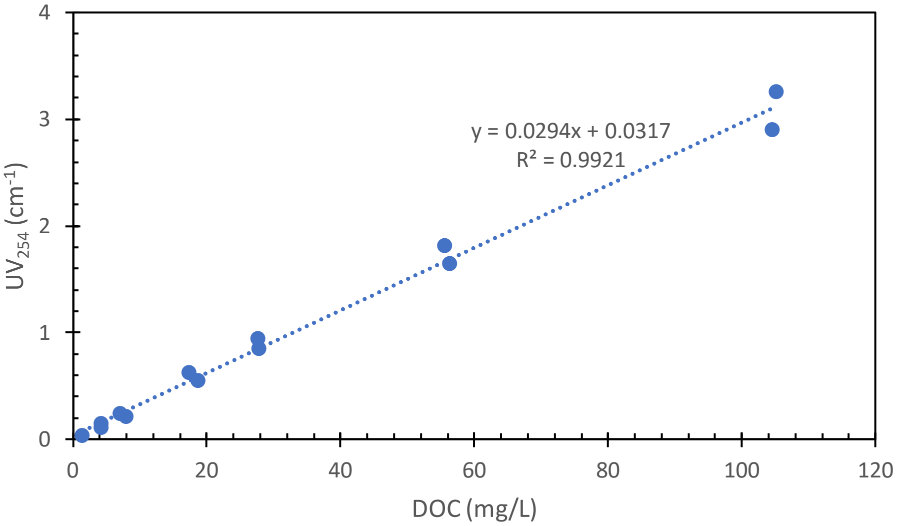


Figure 22. Relationship between DOC concentration and UV_{254} when generating simulated severely deteriorated ("black-water") water matrices representative of "worst-case scenario" conditions after severe wildfire.

Figure 23. Jar testing of BSF with a rise rate of 40 m/hr and sand dose of 10 mg/L. A polymer dose 0.5 mg/L was used throughout the tests.

Figure 24. Calgary (Elbow River) raw water, simulated severely deteriorated ("black-water") water without coagulant addition, and "black water" after four different combinations of coagulant and polymer addition during jar testing, respectively from left to right. Settled solids were removed from the jars. Residual yellow color in the water inadequate removal of natural organic matter/DOC.

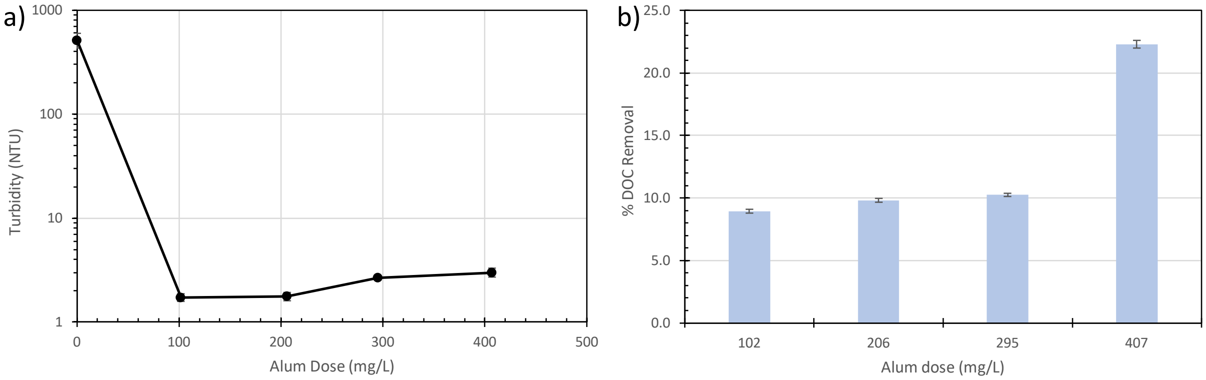


Figure 25. Removal of (a) turbidity and (b) DOC by BSF of Calgary (Elbow River) simulated severely deteriorated ("black-water") water after four different alum doses during jar testing (mean ± standard deviation). Turbidity (a) was removed from well from the suspension. Residual yellow color in the water indicated inadequate removal of NOM/DOC. The original "black-water" matrices had a turbidity of 513 NTU and DOC concentration of ~13 mg/L. This result is typical of what was observed with BSF alone over 30 (jar testing bench-scale) trials.

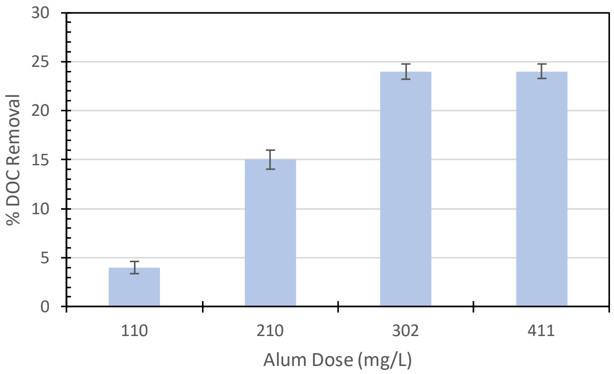
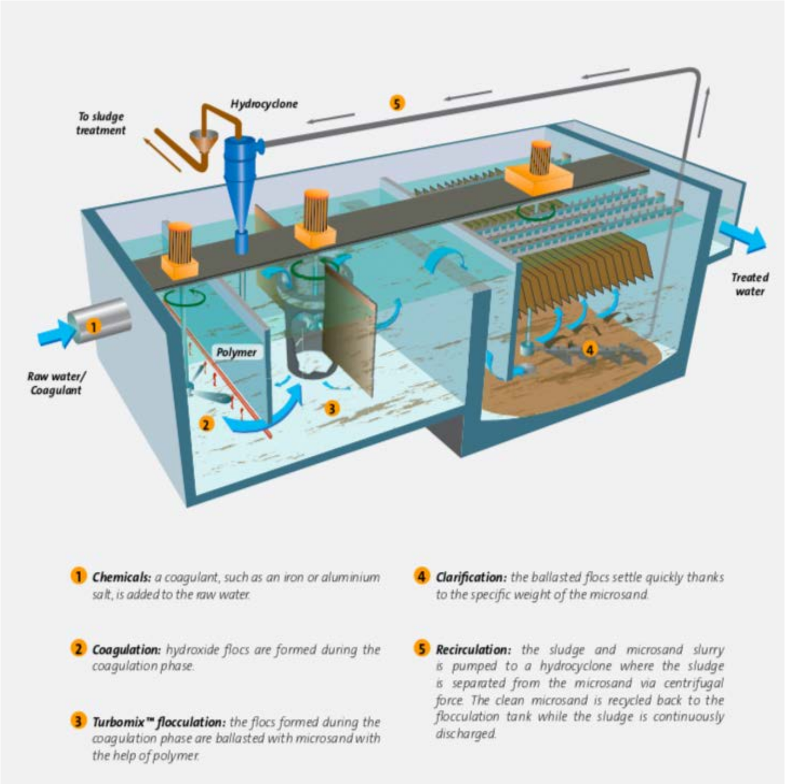


Figure 26. Removal of DOC by BSF with enhanced coagulation (i.e., pH maintained at 5.83) of Calgary (Elbow River) simulated severely deteriorated ("black-water") water after four different alum doses during jar testing (mean ± standard deviation). Turbidity (a) was removed from well from the suspension. Residual yellow color in the water indicated inadequate removal of NOM/DOC. In this trial, the original "black-water" matrices had a turbidity of 513 NTU and DOC concentration of ~13 mg/L. This result is representative of what was observed in 8 BSF with enhanced coagulation trials. While DOC removal increased to approximately 23% at an alum dose of 302 mg/L, this dose was high and the DOC concentration was still not to target (i.e., while a DOC concentration of <5 mg/L was targeted, it was still approximately 9.25 mg/L).



1 **Chemicals:** *a coagulant, such as an iron or aluminium salt, is added to the raw water.*

2 **Coagulation:** *hydroxide flocs are formed during the coagulation phase.*

3 **Turbomix™ flocculation:** *the flocs formed during the coagulation phase are ballasted with microsand with the help of polymer.*

4 **Clarification:** *the ballasted flocs settle quickly thanks to the specific weight of the microsand.*

5 **Recirculation:** *the sludge and microsand slurry is pumped to a hydrocyclone where the sludge is separated from the microsand via centrifugal force. The clean microsand is recycled back to the flocculation tank while the sludge is continuously discharged.*

Figure 27. Schematic of BSF process utilized at pilot-scale (*Source*: Veolia Canada).

A schematic of the BSF process is presented in Figure 27. While most drinking WTPs that rely on surface water supplies use several conventional chemically-assisted filtration, BSF invovles the addition of ballasting agent (microsand) and polymer to the conventional treatment process to increase the weight of the flocs formed and increase the rate at which they settle. While some have noted that the microsand acts as a 'seed' for floc formation, others have noted that microsand is incorporated into the floc matrix after it has formed. Most notably, the BSF process is resilient and is not easily upset by shifts in raw water quality. Given the substantial shifts and increased variability in water quality that can be experience after wildfire (as discussed above), BSF may be an effective treatment technology to respond to fluctuating conditions. It has been reported to remove 90-99% of turbidity in drinking water. BSF also has a relatively small footprint when compared to conventional treatment systems and takes up less than 10% of the volume needed by a conventional basin; thus, it to be designed into mobile treatment plants which may be transported relatively easily. While there are many benefits to BSF, this technology relies heavily on mechanical equipment and may require high coagulant doses that can lead to downstream process issues, such as reduced filter run times.

Although only one trial (with sub-experiments focused on chemical dosing) was planned for each location, three trials (each with sub-experiments focused on chemical dosing) were conducted at pilot-scale at each of the Calgary and Fort McMurray locations. They were enabled by the successful ash collection campaign that enabled several ~3,000L batches of severely deteriorated water to be prepared at evaluated at pilot scale (Figure 28). The three trials included BSF, BSF + enhanced coagulation (through pH adjustment), and BSF + PAC; however, the initial focus was on BSF in absence of other processes.

Figure 28. Raw water storage tank (5,000L capacity) used to prepare severely deteriorated "black-water" matrices using during pilot-scale BSF investigations (left) and raw water storage tank during pilot-scale BSF investigation (right).

Pilot-scale DOC removal by BSF in Calgary, BSF in Fort McMurray, BSF + PAC in Calgary, and BSF + PAC in Fort McMurray are presented in Figure 29. An overview of the pilot-scale experiments that were conducted is provided in Appendix A. The synthetic source water matrix included DOC concentrations of 10 to 14 mg/L in all cases at pilot-scale. It was slightly lower during jar testing of BSF + PAC in Fort McMurray (case d), thereby explaining the one anomalous result in which jar testing outperformed pilot testing. Overall, these data demonstrate BSF operated with high doses of coagulant with concurrent application of PAC can likely treat even the most severely deteriorated source water quality representative of a worst-case scenario of direct runoff of ash into a source water reservoir. It should be underscored that in most cases, the extreme deterioration in source water quality (i.e., very high turbidity, and DOC concentration and aromaticity) would likely be episodic. This is a critical consideration because it emphasizes the importance of evaluating trade-offs. Specifically, is it worth investing in expensive (e.g., millions to tens of millions for small communities of several thousand; multiple tens of millions or hundreds for larger communities like Fort McMurray or Calgary; depending on the infrastructure already available) infrastructure for an extreme scenario that may or may not occur after severe wildfire? And if the extreme event does occur, it may only last for a period of days.

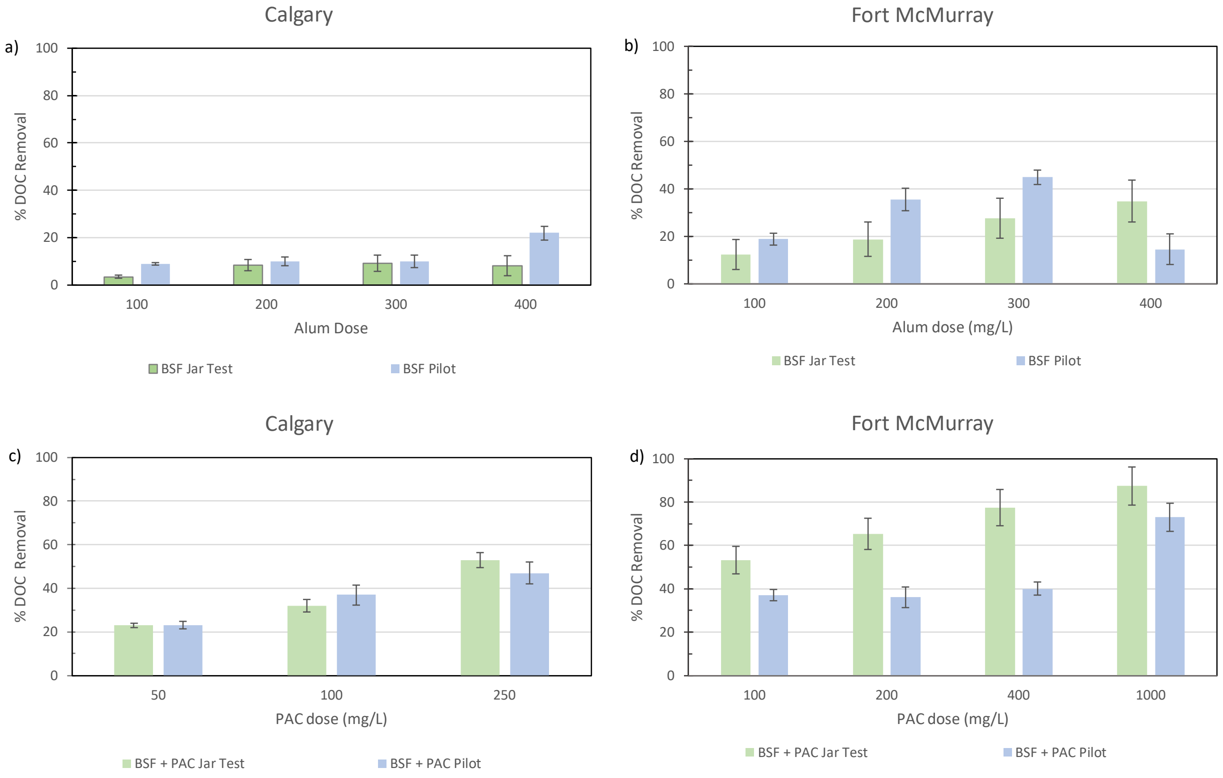


Figure 29. Pilot-scale DOC removal (%; mean ± standard deviation) by (a) BSF in Calgary, (b) BSF in Fort McMurray, (c) BSF + PAC in Calgary, and (d) BSF + PAC in Fort McMurray. The synthetic source water matrix included DOC concentrations of 10 to 14 mg/L in all cases at pilot-scale. It was slightly lower during jar testing of BSF + PAC in Fort McMurray (case d)—this explains the inconsistent result in which jar testing outperformed pilot testing. A minimum of three replicate analyses were conducted at each dosing scenario.

Milestone 3. Evaluation of real-time operational controls for BSF performance optimization.

Conventional drinking water treatment systems utilize chemical pretreatment and filtration to remove particles, including microbial contaminants. Most particles in suspended in water carry a negative charge because of the presence adsorbed NOM, which carries a negative charge, on their surfaces. Chemical pretreatment during drinking water treatment also enhances the removal of organic molecules found at elevated levels in some source waters. Organics removal is an important step, prior to chemical disinfection, to minimize the formation of DBPs. Coagulation and flocculation processes condition suspended particles and aggregate them into larger floc particles for subsequent removal during sedimentation or filtration. Positively charged cations and/or polymer chains are typically added to water to destabilize and bind particles together.

Zeta potential provides an indication of the extent of repulsive interaction between particles. Zeta potentials near the zero point of charge indicate that particles suspended in water are unstable, i.e. that the conditions for aggregation are maximized. Zeta potential provides a measurable quantity that can be used to identify maximum particle aggregation conditions in a given matrix. Zeta potential is often plotted as a function of chemical coagulant dose and used to evaluate the efficacy of various coagulants such as metal salts (e.g., alum, ferric sulfate, etc.) and cationic polymers. Zeta potential can also be used to adjust coagulant doses levels periodically to minimize cost of chemicals for water purification. While zeta potentials near the zero point of charge are desirable for enhancing coagulation, clarification, and chemically-assisted filtration performance during drinking water treatment, it is critical to note that no one value of zeta potential will necessarily be associated with optimum treatment performance. This is because zeta potential analyzers measure the average electrophoretic mobility of particles in suspension; thus, various particle size and charge distributions can lead to any given value of zeta potential. Accordingly, optimal zeta potential values must be established for each treatment configuration (i.e., combination of raw water matrix, chemicals, and treatment process configuration being utilized).

In the present investigation, Milestone 3 was addressed concurrently with Milestone 2. The availability of a long dataset of high frequency UV_{254} data especially facilitated an evaluation of the utility of zeta potential analysis for rapid screening of optimal coagulant doses. As discussed above for Figure 11c, the mean treated water UV_{254} was 0.074 cm^{-1} (0.073, 0.075) during the period from January 2010 until the May 2016 wildfire and then decreased to 0.063 cm^{-1} (0.062, 0.064) afterward. The 10th percentile UV_{254} was 0.039 cm^{-1} (0.038, 0.041) before the wildfire and increased slightly to 0.047 cm^{-1} (0.046, 0.048) afterward. There was no clear threshold to distinguish between baseline and peak data for the treated water. Notably, the 90th percentile was 0.104 cm^{-1} (0.101, 0.108) before the wildfire and decreased to 0.082 cm^{-1} (0.078, 0.084) after the wildfire. Critically, the main operational change that occurred after the wildfire was the purchase and periodic use (as needed) of zeta potential analysis for gauging coagulant dosing requirements. The present analysis clearly demonstrates that treated water quality as measured by UV_{254} (which typically drives coagulant demand) improved with the use of zeta potential analysis because while the baseline (i.e., 10th percentile) values shifted upward in a manner consistent with changes in raw water quality, the mean and upper values (and associated variability) of UV_{254} significantly decreased after the wildfire, presumably due to better operational control in the WTP.

Milestone 4. Quantification of direct and indirect drinking water treatment costs of Horse River wildfire.

Historic Fort McMurray WTP operational data were presented in Figure 11. These data coupled with operator discussion were utilized to approximate key operational costs of the 2016 Horse River wildfire on drinking water supply and treatment in the RMWB. A more in depth analysis was originally proposed and planned; however, the continued occurrence of cyanobacterial blooms in the WTP's raw water storage reservoirs precluded the operator overtime required to extract the requisite data from the WTP's online supervisory control and data acquisition (SCADA) system and the laboratory logs (which would have to be accessed manually in some cases).

At present, it has been estimated that in the three years since the 2016 Horse River wildfire, the RMWB spent an additional $9.9 million (at least) on direct costs related to drinking water treatment and distribution as a result of the wildfire. Of these, at least $0.5 million per year are ongoing operational costs. These costs include approximately $2 million for distribution system flushing, 2 x $3 million for dredging each of the two raw water storage reservoirs (Figure 30), approximately $1.5 million in extra coagulant costs ($0.5 million annually), and $0.1 million for the purchase of a zeta potential analyzer.

This analysis will be expanded as part of our continued collaborative work in the RMWB, and as part of our new Alberta Innovates project (at no additional cost to the project, consistent with the present project).

Figure 30. Dredging of the RMWB's raw water storage reservoir (west cell) at the Fort McMurray WTP in August 2018 (left). Water extraction by centrifugation to reduce sediment mass by approximately 40% (center). Collection of dewatered bottom sediment for landfill disposal (right). The process of reservoir dredging continued for approximately four months.

F. KEY LEARNINGS

This project has delivered several critical new insights in understanding wildfire risks to drinking water supply and treatment in Alberta and advances in technology approaches to managing those risks. Notably, this evaluation includes several "first of its kind" insights and strategies that are already informing policy and practice for drinking water utilities in Alberta and globally. Key project learnings and the importance of those learnings is discussed below. Broader impacts to the industry and beyond are also highlighted.

1. **The 2016 Horse River wildfire had an appreciable impact on water quality in the Athabasca River watershed, although only <4% of the watershed was burned and thus, substantial dilution of any wildfire impacts on water quality might have been expected.** This is a globally unprecedented observation that is supported by the data collected by both this project and AEP in their regional water quality monitoring program. Most of our understanding of wildfire impacts on river water quality has come from studying small, steep watersheds. In contrast, very little is known about wildfire impacts on river water quality in the Boreal Plains of western Canada. Despite draining sizeable, partially-burned watersheds, brief pulses of suspended solids that were exceptional relative to historic records were observed in the study rivers following the wildfire. This observation is a global first—it demonstrates that wildfire has the potential to alter water quality even at large basin scales where buffering of these impacts would be expected. This investigation demonstrates that all drinking water systems in wildfire-prone areas of Alberta are vulnerable to wildfire-associated impacts on source water quality and should reflect these threats in their provincially-mandated drinking water safety plans, as well as their source water protection plans.

2. **The 2016 Horse River wildfire had a significant and long-lasting impact on the *treatability* of the Athabasca River water used as the source of drinking water in Fort McMurray.** While the impacts of the wildfire were periodically measurable across the watershed (as discussed above) and somewhat buffered by dilution effects, streams/rivers (e.g., Little Fisheries Creek) in close proximity to the Fort McMurray WTP at least occasionally discharged sediment and associated contaminant plumes to the Athabasca River (within 10-25m from shore), which appeared to remain relatively unmixed for more than 1 km downstream of these tributary inflows. While quantification of poor lateral mixing in the Athabasca River was beyond the scope of the present investigation, this investigation provides compelling evidence that the delivery of sediment and associated contaminants (including bioavailable phosphorus) from these sources disproportionally affected reservoir water quality and treatability in Fort McMurray. These specific impacts are detailed below. Consistent with previously-reported headwaters investigations, increased variability and maxima in coagulant demand and disinfection by-product (i.e., THM and HAA) formation potentials were reported over the first three post-fire years at the Fort McMurray WTP. Such extreme, long-lasting shifts in drinking water treatability as a clear result of wildfire have not been reported globally to date. Moreover, this investigation further demonstrated that the wildfire also significantly increased the potential for both membrane fouling and distribution system regrowth systems—these implications of wildfire on these aspects of drinking water treatability and supply have not been evaluated anywhere globally to date. The observation of clear wildfire impacts on drinking water treatability at such a large river basin scale in a system with poor hydrologic connectivity to the landscape was unexpected and thus has profound implications for drinking water security and climate change adaptation globally—it suggests that wildfire represents a significant, long-term threat to drinking water supplies in physiographic settings in which wildfire is a significant disturbance regime and surficial geology is rich in fine sediment.

3. **The 2016 Horse River wildfire altered the character and quality of sediment entering the RMWB's raw water reservoirs.** All of the lines of inquiry (sediment particle size distribution and major element composition, metals, dioxins and furans, particulate P forms, and P sorption/desorption assessments) strongly indicated this impact. Thus, they also suggested an elevated probability of cyanobacteria and/or algae blooms, and/or taste and odour events occurring in the reservoirs. The close proximity of sediment and associated contaminant sources (e.g., Little Fisheries Creek) to the reservoir as well as the apparent lack of complete mixing of those materials within the Athabasca River suggested that further sampling and analysis of reservoir sediment was warranted to evaluate post-fire water quality legacy effects. The ability to conduct those analyses was precluded by the occurrence of cyanobacterial blooms in 2017, 2018, and 2019 however. The blooms necessitated costly dredging of sediment from the raw water storage reservoirs (east reservoir in 2017, west reservoir in 2018). It is very likely that these algae blooms were triggered by desorption of bioavailable phosphorus from post-fire, phosphorus-enriched fine sediment deposited in the reservoirs—levels of the particulate phosphorus forms (NAIP, AP and OP) in the reservoir were elevated and consistent with levels previously reported for wildfire-impacted sediment after the Lost Creek wildfire in southern Alberta and where algae also proliferated after wildfire (reported in an earlier Alberta Innovates project). This work broadly underscores the critical importance of reservoir monitoring—not just for source water storage, but for source water *quality* and *treatability* implications. Landscape disturbances such as wildfires and floods increase runoff and frequently result in significant inputs of phosphorus-enriched fine sediment to reservoirs and lakes, which can promote the proliferation of cyanobacteria and other algae. Notably, drinking water reservoirs are not typically managed for water quality and even when solids are managed, fine sediment (which typically is only a small fraction of total sediment by mass) is not managed. Thus, best management practices (BMPs) for evaluating and mitigating these risks are urgently needed because cyanobacteria blooms have the potential to lead to drinking water service disruptions and outages (i.e., plant shutdowns, such as the famous 2014 shutdown of a WTP in Toledo, Ohio), especially if cyanotoxins are produced. Drinking water utilities in Alberta are generally not equipped to treat cyanotoxins (unlike utilities in agriculturally-dominated headwaters regions); thus, these risks are especially relevant to Alberta (because of the presence of sediment-rich surficial geology in many parts of the province) and other such jurisdictions.

4. **Wildfire-associated inputs of phosphorus-enriched fine sediment to the raw water storage reservoirs likely triggered blooms of cyanobacteria in Fort McMurray in each of the first three years after the 2016 Horse River wildfire (2017 to 2019)—the presence of cyanobacteria species often capable of forming microcystin, anatoxin and cylindrospermopsin (hepatoxins, neurotoxins, and nephrotoxins) was confirmed; however, further confirmation that the strains present carried the specific genes needed for toxin production is still pending.** While there was no appreciable production of microcystin (which is regulated) as a result of these blooms, evaluation of the production of anatoxin and cylindrospermopsin was not possible. While it has been widely speculated that wildfires can increase the probability of cyanobacterial bloom occurrence, this investigation represents the first documentation of this impact at a drinking water utility globally. The occurrence of these blooms in each of the first three years since the wildfire at a utility that has not experienced significant blooms of algae historically makes an extremely compelling case for causality. This investigation is also the first globally to provide direct evidence of wildfire as a causal agent of cyanobacteria blooms that have the potential to produce toxins. Specifically, while the species of cyanobacteria that were identified using microbial community analysis by amplicon sequencing are known toxin formers, further confirmation that the strains carry the specific genes for toxin production is underway. Nonetheless, this work underscores that wildfire represents a significant,

long-term threat to drinking water supplies in physiographic settings in which wildfire is a significant disturbance regime and surficial geology is rich in fine sediment. Accordingly, policies focused on ensuring drinking water security (e.g., drinking water safety plans, source water protection [SWP] plans) and resilience for climate change adaptation must necessarily consider implementation of strategies for mitigating wildfire threats to drinking water treatability that include both SWP/landscape management and in-plant treatment.

5. **Coagulant dosing requirements significantly decreased for a period of approximately three months after raw water storage reservoir dredging and then returned to post-fire baseline levels, thereby suggesting re-establishment of microbial and likely cyanobacterial populations in the reservoirs.** While far from incontrovertible, given that no other measured aspects of raw water quality substantially fluctuated during this time, this observation suggests that the fine sediment deposited in the reservoir after dredging accumulated and served as an internal source of bioavailable phosphorus that enabled microbial and algal proliferation in the reservoir until a pseudo-steady state condition was reached after a period of time (approximately three months). Algae and cyanobacteria are present in water supplies year round. Regardless of bloom occurrence, algal organic matter is known to be negatively charged and increases coagulant demand. This observation further underscores the importance of developing BMPs for managing fine sediment and associated phosphorus and/or other approaches for managing/mitigating the proliferation of cyanobacteria in drinking water reservoirs. It also further underscores that reservoirs should be managed not just for source water storage, but for mitigation of source water *quality* and *treatability* impacts from landscape disturbances—the alternative is investment in expensive infrastructure (e.g., advanced oxidation processes or powdered activated carbon) for treating algal toxins.
6. **PAH concentrations in bottom sediment of the Fort McMurray drinking water reservoir were extremely low.** Accordingly, at the concentrations reported herein, sediment associated PAHs pose no risk to drinking water source quality because fine solids are removed during the water treatment process with coagulation and flocculation. While these contaminants were not found in post-fire sediments in Fort McMurray reservoir, they may be present elsewhere in the RMWB.
7. **Polychlorinated dibenzo-para-dioxins (dioxins) and polychlorinated dibenzofurans (furans) were present at low concentrations in reservoir sediment.** The two primary sources of dioxins and furans in the Athabasca River are pulp and paper mills and wildfire, however, the exact source of these organic, sediment-associated contaminants in the Fort McMurray reservoir is unknown. Notably, these compounds were not present at levels of public or aquatic health concern.
8. **Worst-case scenario, severely deteriorated source water matrices representing direct runoff of post-fire ash and burned surficial material can be generated with reasonable consistency for performance testing of drinking water treatment technologies.** This means that treatment technology resilience can be evaluated at pilot-scale, as was done herein.
9. **Ballasted sand flocculation (BSF) can effectively treat "worst-case scenario" post-fire fluctuations in source water turbidity—**increases in the concentration and aromaticity of particulate and dissolved organic carbon (POC and DOC, respectively) can challenge BSF processes when alkalinity is high and precludes enhanced coagulation for DOC removal. In these cases, BSF coupled with powdered activated carbon (PAC) would likely be required. This work comprises the first global demonstration that severely deteriorated source water representative of post-fire quality can be treated with available in-plant technologies when their performance is optimized. Accordingly, this new knowledge represents a potential target for consideration in the development of drinking water safety and source

water protection plans, especially when evaluating potential trade-offs. Notably, there is significant experience with this technology in Alberta; thus, the capacity to optimize its performance represents a potential technology leadership that can be utilized within Alberta and exported globally.

10. **Zeta potential analysis is useful in optimizing coagulant dosing when responding to rapidly fluctuating water quality.** Here, it supported significant improvements in treated water quality (UV_{254}) at relatively challenged conditions (i.e., elevated source water DOC concentrations and UV_{254} after wildfire). Thus, this *relatively* inexpensive tool offers the potential to support and increase the operational resilience of Alberta's WTPs. It therefore also has the potential to serve as a climate change adaptation tool.
11. **In the three years during and after the 2016 Horse River wildfire, the RMWB spent an additional \$9.9 million (at least) on direct costs related to drinking water treatment as a result of the wildfire. Of these, at least \$0.5 million per year are ongoing operational costs.** These costs include approximately \$2 million for distribution system flushing, 2 x \$3 million for dredging each of the two raw water storage reservoirs, approximately \$1.5 million in extra coagulant costs (\$0.5 million annually), and \$0.1 million for the purchase of a zeta potential analyzer. This engineering accounting analysis can inform decision-making with respect to investment in SWP- and in-plant treatment-focused climate change adaptation approaches.

G. OUTCOMES AND IMPACTS

PROJECT OUTCOMES AND IMPACTS

This project commenced with the recognition that while wildfire impacts to drinking water treatability across different forest regions will have some broad similarities, an understanding of (1) key similarities and differences in wildfire impacts to source water quality and treatability in Alberta and (2) best available technologies (BATs) for in-plant drinking water treatment in response to severe wildfire is crucial to sustaining water supplies and enhancing the sustainability of municipal water systems for Albertans. Thus, the project was designed to address five key knowledge gaps.

Gap 1 focused on the impacts of severe wildfire on drinking water treatability in the Boreal Plain ecozone of Alberta, which had not been previously reported. Related, Gap 2 focused on the immediate and initial-term impacts of severe wildfire on drinking water in Alberta, which also had not been previously reported. While the SRWP provided significant new knowledge regarding initial (<3 years) and medium-term (~3-12 years) effects of wildfire on water in the steep-sloped, Montane Cordillera ecozone of southwestern Alberta, the effects on drinking water treatability were only studied in the medium term. **The most important strategic outcomes of this work were:**

> **(1)** the evaluation of an immediate and longer-term (i.e., at least three years post-fire) shift in DOC aromaticity (i.e., elevated and more variable UV_{254}) in the RMWB's source water as a result of wildfire in a system as big and already challenged (i.e., frequently high turbidity and high DOC source water quality) as the Athabasca river and an associated, sustained need for increased (2.5x) coagulant dosing, and
>
> **(2)** the (unexpected) direct documentation of nutrient-enriched post-fire sediment promotion of post-fire blooms of potentially toxin-forming cyanobacteria (i.e., species known for toxin formation were identified, but presence of the toxin genes within the specific strains was not confirmed) in the RMWB's raw water reservoir in every year after the wildfire.

Gap 3 focused on describing the resilience of the presumed best available technology (BAT) for treating highly deteriorated and rapidly changing source water quality to produce safe drinking water in the initial period (<3 years) after severe wildfire in both the Montane Cordillera and Boreal Plains ecozones, which represent the extremes in eco-hydrological character between which most of Alberta's forested drinking water supplies can be generally characterized. This capacity had not been evaluated anywhere globally. Closely related, Gap 4 focused on identifying real-time operational control tools for rapid optimization of drinking water treatment performance during operational challenge periods such as post-fire drinking water treatment. **The most important strategic outcomes of this work were:**

> **(4)** the proof-of-concept demonstration that BSF can adequately reduce source water turbidity and somewhat reduce DOC from severely deteriorated water representative of post-fire runoff that washes ash directly in to surface water source supplies. This work was the first globally to demonstrate that severely deteriorated source water supplies can be treated with the appropriate combination of treatment infrastructure and operational response capacity (e.g., skilled operators, adequate support technology and telemetry). The greatest treatment challenge was relatively more aromatic post-fire DOC, which can be challenging to treat depending on several water quality factors (e.g., dilution, alkalinity, etc.); however, if needed, this DOC can be treated with approaches such as powdered activated carbon (PAC), which would be expensive to install and operate, but likely effective (further clarifying this is a key objective of the current project), and

(5) the demonstration of the utility of zeta potential analysis in adjusting coagulant dosing in response to elevated and more variable post-fire source water DOC aromaticity to achieve better treated water quality (than without use of zeta potential analysis).

Gap 5 focused on describing the immediate drinking water treatment cost implications of severe wildfire-associated source water quality changes, which have not been extensively quantified in Alberta or globally. **The key outcome of this work was (6)** the identification of key treatment costs that have not been quantified as well as direct quantification of the >$9.9 million that can be attributed to increases in coagulation costs and post-fire reservoir dredging, as well as other treatment-associated costs as a result of the wildfire in the RMWB over the first three post-fire years.

This new knowledge is critical to informing drinking water treatment infrastructure planning, source water protection (SWP) and drinking water safety plans as well as emergency response plans and associated benefit/cost and trade-off analyses. It will be invaluable to most drinking water utilities across Alberta that are reliant on surface water from fire-prone, forested landscapes.

PROJECT OUTPUTS

There have been outputs delivered over the course of the SRWP (of which this project is a component). As many research elements and outputs have spanned multiple projects, they are collectively summarized below. The outputs denoted with an asterisk (*) are most directly linked with the current project.

Refereed Publications in Preparation or Review

Collins AL, Blackwell M, Boeckx P, Chivers CA, Emelko MB, Evrard O, Foster I, Gellis A, Gholami H, Granger S, Harris P, Horowitz AJ, Laceby JP, Martinez-Carreras N, Minella J, Mol L, Nosrati K, Pulley S, Silins U, da Silva YJ, Stone M, Tiecher T, Upadhayay HR, Zhang Y. Sediment source fingerprinting: benchmarking recent outputs, remaining challenges and emerging themes. J. Soil Sed. (*In-Review*, January 28, 2020)

*Emmerton CA, Cooke C, Hustins S, Silins U, Emelko MB, Lewis T, Kruk MK, Taube N, Zhu D, Jackson B, Stone M, Kerr JG, Orwin JF. Severe western Canadian wildfire affects water quality even at large basin scales. Water Res. (*In-Review*, WR54047, January 23, 2020)

*Skwaruk J, Emelko MB, Silins U, Stone M. Treatment of simulated, severely deteriorated post-fire runoff: Diverse settings, similar challenges. *In preparation* for submission to Environmental Science & Technology, March 2020.

*Skwaruk J, Kundert KL, Emelko MB, Stone M, Silins U. Pilot-scale conventional clarification and ballasted sand flocculation of simulated, severely deteriorated post-fire runoff in a high quality source watershed. *In preparation* for submission to Environmental Science & Technology, April 2020.

*Skwaruk J, Emelko MB, Silins U, Stone M. Pilot-scale conventional clarification and ballasted sand flocculation of simulated, severely deteriorated post-fire runoff in an already challenged source watershed. *In preparation* for submission to Environmental Science & Technology, May 2020.

*Skwaruk J, Bahramian S, Emelko MB, Schmidt PJ, Silins U, Stone M, Müller KM. Characterizing water quality drivers of long-term, increased coagulant dosing requirements after severe wildfire. *In preparation* for submission to Environmental Science & Technology, June 2020.

*Emelko MB, Müller KM, Silins U, Stone M, Skwaruk J, Schmidt PJ, Emmerton CA, Cooke C. Immediate and long-term drinking water supply and treatment implications of severe wildfire in Fort McMurray, Canada. *In preparation* for submission Nature Climate Change, April 2020.

*Emelko MB, Stone U, Müller KM, Silins U. Understanding long-term threats to drinking water supply and treatment after severe wildfire: Shifts in sediment-phosphorus dynamics can lead to recurring, potentially toxin-forming cyanobacterial blooms. *In preparation* for submission to Global Change Biology, June 2020.

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*Rhoades CC, Nunes JP, Silins U, Doerr SH. 2019. The influence of wildfire on water quality and watershed processes: New insights and remaining challenges. Int. J. Wildand Fire 28(10):721-725.

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Martens AM, Silins U, Proctor HC, Williams CHS, Wagner MJ, Emelko MB, Stone M. 2019. Long-term impact of severe wildfire and post-wildfire salvage logging on macroinvertebrate assemblage structure in Alberta's Rocky Mountains. Int. J. Wildland Fire 28(10):738-749.

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*Nunes JP, Doerr SH, Sheridan G, Neris J, Santín C, Emelko MB, Silins U, Robichaud PR, Elliot WJ, Keizer J, 2018. Assessing Water Contamination Risk from Vegetation Fires: Challenges, Opportunities and a Framework for Progress. Hydrological Processes 32:687–694. *(Invited commentary)*

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Robinne FN, Miller C, Parisien MA, Emelko MB, Bladon KD, Silins U, Flannigan M. 2016. A global index for mapping the exposure of water resources to wildfire. Forests 7:22-38.

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Jin C, Mesquita M, Emelko MB, Wong A. 2016. Automated enumeration and size distribution analysis of Microcystis aeruginosa via fluorescence imaging. Jour. Computational Vision and Imaging Systems. 2:1.

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Jin C, Glawdel T, Ren CL, Emelko MB. 2016. Non-linear, Non-monotonic Effect of Nano-scale Roughness on Particle Deposition in Absence of an Energy Barrier: Experiments and Modeling. (Nature Publishing Group) Scientific Reports. 5, 17747:1-14.

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Stone M, Silins U, Emelko MB, Collins AL, Williams CHS. 2019. Source, transport and fate of cohesive sediment in aquatic systems: Implications for water quality and ecosystem health. Abst. IUGG19-3301, IUGG, 27th General Assembly, July 8-18, 2019. Montreal, QC.

*Emelko MB, 2019. AEESP Lecture: More Important than Ever: Drinking Water Treatability and Resilience Assessment for Climate Change Adaptation. AWWA's Annual Conference Exposition (ACE), Denver, CO, USA, June 10, 2019. *Plenary Keynote*.

*Emelko MB, 2019. Modeling Critical Infrastructure Interdependencies. CWWA's Window on Ottawa, Ottawa, ON, Canada, June 3, 2019. *Panel Discussion*.

*Emelko MB, Silins U, Stone M. 2019. Ensuring safe, secure drinking water when extreme events are the new normal: Strategies learned from research and practice, AB. Water Wastewater Operators Assoc. Ann. Conf., March 11-15, 2019, Banff, AB.

*Silins U, Emelko MB, Stone M, Williams CHS, Wagner MJ, Martens AM, Hawthorn K, Spencer SA, Adamowicz W, Anderson A, Collins AL, Dyck M, Krishnappan BG, Mueller K, Quideau S. 2019. Watershed resistance and resilience to extreme events: Insights from wildfire and flooding in Alberta. 56th Annual Alberta Soil Science Workshop, February 19-21, 2019, Calgary AB. (Invited Plenary).

Silins U, Herlein K, Williams CHS, Cherlet E, Stone M, Collins AL, Emelko MB, Wagner MJ, Hawthorn K. 2018. Impact of contemporary forest harvesting strategies on sediment production in Alberta's Rocky Mountains: New insights on an old story? Am. Geophys. Union Fall Meeting, Abst. H13J-1884, December 10-14, 2018, Washington DC, USA.

Stone M, Krishnappan BG, Collins AL, Silins U, Emelko MB. 2018. A modelling framework for flow and cohesive sediment transport in wildfire impacted watersheds: Implications for reservoir management. Am. Geophys. Union Fall Meeting, Abst. H23L-2105, December 10-14, 2018, Washington DC, USA.

*Doerr S, Nunes JP, Sheridan GJ, Neris J, Santin C, Emelko MB, Silins U, Robichaud P, Elliott W, Keize J. 2018. Fire impacts on water quality: current challenges and opportunities for progress. VIII International Conference on Forest Fire Research, Abst. FIM-31, November 9-16, 2018, Coimbra, Portugal.

Silins U, Wagner MJ, Martens AM, Hawthorn K, Williams CHS, Karpyshin S, Herlein K, Emelko MB, Stone M, Dyck M, Quideau S, Bladon KD, Anderson A, Adamowicz W, Collins AL. 2018. Fires, flooding, and forestry: Aquatic ecosystem resilience in Alberta's Rocky Mountain streams. 110th Canadian Institute of Forestry Annual Conference and AGM, September 18-20, 2018, Grande Prairie, AB. (Invited)

Stone M, Krishnappan BG, Emelko MB, Collins AL, Silins U. Camm E. 2018. Modelling the effect of water level conditions and return flow periods on resuspension of bottom sediment in the Glenmore Reservoir:

Implications for reservoir management. 2018 Joint meeting of the Can. Geophysical Union, Can. Soil Sci. Soc., Comp. Infrastr. Geodynamics, Seismology Soc. of Am., Can. Soc. Ag. For. Met., Niagara Falls, ON, June 11-13, 2018.

Adamowicz, WL. What makes markets for ecosystem services work? Plenary presentation to the Alberta Land Institute annual conference. May 31, 2018. Edmonton, AB.

Silins U, Emelko MB, Bladon KD, Stone M, Williams CHS, Herlein KD, Martens AM, Spencer SA. 2018. Alternate trajectories for post-fire watershed recovery: Crystal balling nitrogen production a decade after wildfire and beyond. Fire Continuum Conf. Forests to flames to faucets. Missoula, MT, USA, May 21-24, 2018.

*Emelko MB, Stone M, Silins U, Skwaruk J, Shams S, Cooke CA, Emmerton CA, Kendel T. 2018. The 2016 Fort McMurray wildfire: Drinking water treatability challenges in an already-challenged watershed. Fire Continuum Conf. Forests to flames to faucets. Missoula, MT, USA, May 21-24, 2018.

*Nunes JP, Doerr SH, Sheridan G, Neris J, Santín C, Emelko MB, Silins U. 2018. Assessing water contamination risk following vegetation fire: challenges, opportunities and a framework for progress. Fire Continuum Conf. Forests to flames to faucets. Missoula, MT, USA, May 21-24, 2018.

*Emmerton CA, Cooke CA, Kruk M, Hustins S, Jackson B, Kerr J, Taube N, Zhu D, Silins U, Emelko MB. 2018. Assessing the impacts of the Fort McMurray wildfire on the water quality of the lower Athabasca River and its tributaries. Fire Continuum Conf. Forests to flames to faucets. Missoula, MT., USA, May 21-24, 2018.

*Emelko MB, Stone M, Silins U. 2018. Wildfire Threats to Water Security: Source-to-Tap Case Studies from Western Canada. College of Science Seminar Series, Swansea University, Swansea, UK, May 8, 2018. (*Invited*)

*Nunes JP, Doerr SH, Sheridan G, Neris J, Santín C, Emelko MB, Silins U, Robichaud PR, Elliot WJ, Keizer J. 2018. A coherent framework to assess water contamination risk following vegetation fires. European GeoSciences Union General Assembly, Geophysical Research Abstracts Vol. 20, EGU2018-11163, Vienna, Austria, April 8-13, 2018.

Silins U, Emelko, Stone M, Anderson A, Adamowicz V, Dupont D, Flannigan M, Cooke C, Williams CHS, Herlein KD, Martens AM, Hawthorn K, Wagner MJ, Krishnappan BG, Collins AK, Bladon KD. 2018. Mine the data – mind the resource: Déjà Vu or grand challenge for Alberta water management? Can. Water Res. Association, Alberta Branch Annual Conference, Red Deer, AB, March 25-27, 2018. (*Plenary keynote*).

*Emelko MB, Stone M, Silins U. 2018. Wildfire, Water Quality, Drinking Water: Experiences in Canada. Payments for Ecosystem Services: Forests for Water, European Union COST Action, Lisbon, Portugal, February 14, 2018. (*Invited*)

*Stone M, Silins U, Emelko MB. 2018. Connecting burnt hillslopes, streams and reservoirs: impacts of fires on water quality. Payments for Ecosystem Services: Forests for Water, European Union COST Action, Lisbon, Portugal, February 14, 2018. (*Invited*)

Emelko MB, Stone M, Silins U, Martens AM, Williams CHS, Collins AL. 2018. Sediment-phosphorus Legacy Effects of Wildfire in Large River Systems: A Canadian Case Study. Payments for Ecosystem Services: Forests for Water, European Union COST Action, Lisbon, Portugal, February 14, 2018. (*Invited*)

Yang A, Stone M, Mueller K, Emelko MB, Silins U. 2018. Evaluating Reservoir Sediment Contributions to Algal and Cyanobacterial Proliferation. 53rd Central Can. Symp. on Water Quality Res., Toronto, ON, February 22, 2018.

*Doerr SH, Nunes JP, Sheridan G, Neris J, Santin C, Emelko MB, Silins U, Robichaud PR, Elliot WJ, Keizer J. 2018. When the smoke clears the waters muddy – vegetation fire impacts on water resources and how science can help. TERRAenVISION Environmental Issues Today: Scientific Solutions for Societal Issues Conference, Barcelona, Spain, January 29 – February 2, 2018. (*Plenary keynote*).

Devito K, Hokanson K, Chasmer L, Kettridge N, Lukenback M, Mendoza CA, Moore P, Peters D, Silins U. 2017. Threshold responses in runoff from sub-humid heterogeneous low relief regions. Abst. H43K-1787, Am. Geophysical Union Fall Meeting, New Orleans, LA, December 11-15, 2017.

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Silins U, Emelko MB, Bladon KD, Williams CHS, Martens AM, Wagner MJ, Stone M, Spencer SA. 2017. Ecohydrological drivers of watershed resilience: Crystal balling nitrogen production a decade after wildfire and beyond. Abst. H11-01. Can. Geophysical Union and Can. Soc. Agric. Forest Met. Joint Meeting, Vancouver, BC, May 28-31, 2017. (*Invited*)

Emelko MB, Ruecker N, Mayberry P, Schmidt PJ. Assessing Parasite Concentrations in Source Water for Decision Making and Risk Assessment. 17th Canadian *National Conference on Drinking Water,* Ottawa, ON, *October 16-18, 2016.*

*Emelko MB, Silins U, Ruecker NJ, Stone M. 2016. Assessing Wildfire Risk to Municipal Waterworks. Western Canada Water Ann. Conf. and Exhibition, Calgary AB, October 4-7, 2016.

Emelko MB, Ruecker NJ, Mayberry P, Cheung M, Bounsombath N, Stalker N, Schmidt PJ, Kundert K. 2016. Evaluating parasite occurrence in source waters: Preventing bias and erroneous interpretation. Western Canada Water Ann. Conf. and Exhibition, Calgary AB, October 4-7, 2016.

Stone M, Krishnapan BG, Silins U, Emelko MB, Williams CHS, Martens AM, Collins AF. 2016. Modelling flow and cohesive sediment transport in wildfire impacted watersheds: Implications for reservoir management. Int. Assoc. Hydrol. Sci. / Int. Comm. Cont. Erosion, ICCE Symposium 2016, North Wyke, Okehampton, UK, July 11-15, 2016.

Stone M, Emelko MB, Silins U, Collins AF, Williams CHS, Martens AM, Bladon KD. 2016. Impact of wildfire on phosphorus speciation and sorption behavior of sediment in Alberta rivers. IAGLR 59th Annual Conference on Great Lakes Research, Guelph, ON, June 6-10, 2016.

Papers by the Graduate Students and Staff HQP at Scientific Conferences and Symposia.

Mueller D, Silins U, Dyck MF. 2019. Impacts of clear-cut harvesting on production and subsurface transport of dissolved organic carbon in the southern Canadian Rocky Mountains. Am. Geophys. Union Fall Meeting, Abst. B13G-2575, December 9-13, 2019, San Francisco, CA, USA.

Baldock RL, Quideau SM, Silins U, Oh SW. 2019 Fire and forest harvesting impacts on soil organic matter and dissolved organic matter composition in the Canadian Rocky Mountains. Am. Geophys. Union Fall Meeting, Abst. B33G-2551, December 9-13, 2019, San Francisco, CA, USA.

Cherlet E, Silins U, Stone M, Herlein K, Williams CHS, Martens AM, Johnston B, Emelko MB, Collins AL, Wagner MJ. 2019. Long-term sediment-phosphorus dynamics in wildfire affected mountain streams in southwestern Alberta, Canada. Am. Geophys. Union Fall Meeting, Abst. H23S-2193, December 9-13, 2019, San Francisco, CA, USA.

Williams CHS, Silins U, Anderson AE, Emelko MB, Stone M. 2019. Seasonality of streamflow response during the decade following wildfire in Canadian Rocky Mountain watersheds. Am. Geophys. Union Fall Meeting, Abst. H23S-2196, December 9-13, 2019, San Francisco, CA, USA.

Spencer SA, Silins U, Anderson AE, Collins AL. 2019. Source water contributions in a steep Rocky Mountain watershed with glacial till and fractured sedimentary bedrock. Am. Geophys. Union Fall Meeting, Abst. H31O-1975, December 9-13, 2019, San Francisco, CA, USA.

Fath KJ, Anderson AE, Silins U, Devito KJ. 2019. Source areas and sediment plumes in the Simonette: A new approach to modelling road-stream connectivity in the Canadian Foothills. Am. Geophys. Union Fall Meeting, Abst. EP51C-2101, December 9-13, 2019, San Francisco, CA, USA.

Decent Q, Stone M, Krishnappan BG, Silins U. 2019.Application of the SIDO (sediment intrusion dissolved oxygen) model to critical trout habitat in gravel bed rivers of the Eastern slopes of the Rocky Mountains, Am. Fisheries Soc. Ont. Chapter Ann. Gen. Meeting, February 28 – March 2, 2019, Orillia, ON.

Williams CHS, Silins U, Wagner MJ, Martens AM, Herlein KD, Spencer SA, Emelko MB, Stone M, Anderson A, Bladon KD, Collins AL. 2019. Snow accumulation, melt and sediment dynamics after wildfire in Rocky Mountain watersheds. AB. Irrigation Districts Assoc. 2019 Conf., Calgary AB.

Greenacre D, Silins U, Dyck M. 2019. Effects of alternative forest harvesting practices on snow and soil water dynamics. 2019 SISCO Winter Workshop, Southern Interior Silviculture Committee, January 21-23, 2019, Kelowna, B.C.

Greenacre D, Silins U, Dyck M. 2018. Spatial and temporal patterns of snowpack accumulation and melt after strip-shelterwood harvesting in the Southern Alberta Rockies. Am. Geophys. Union Fall Meeting, Abst. C42B-08, December 10-14, 2018, Washington DC, USA

Williams CHS, Silins U. 2018. Snowpack accumulation and advancement of melt and catchment runoff after wildfire in Rocky Mountain watersheds, Alberta, Canada. Am. Geophys. Union Fall Meeting, Abst. H23L-2126, December 10-14, 2018, Washington DC, USA.

Spencer SA, Silins U, Anderson A, Collins AL. 2018.The influence of storage and watershed structure on baseflow dynamics and the implication for watershed resilience in the Canadian Rocky Mountains. Am. Geophys. Union Fall Meeting, Abst. H23D-03, December 10-14, 2018, Washington DC, USA

Karpyshin S, Silins U, Dyck M. 2018. Transpiration response of residual Lodgepole pine after strip and partial-cut harvesting in Alberta's southern Rocky Mountains. Am. Geophys. Union Fall Meeting, Abst. H12H-30, December 10-14, 2018, Washington DC, USA.

Cherlet E, Williams CHS, Herlein K, Hawthorn K, Silins U. 2018. Evaluating accuracy of simple winter precipitation overspill systems with tipping bucket gauges for winter precipitation monitoring in remote mountain weather station networks. Am. Geophys. Union Fall Meeting, Abst. H13P-1980, December 10-14, 2018, Washington DC, USA.

Sun X, Emelko MB. 2018. Evaluating the potential impacts of severe wildfire on groundwater supplies Am. Waterworks Assoc. Water Quality Tech. Conf. 2018, November 11-15, 2018, Toronto, ON.

Bahramian S, Emelko MB, Silins U, Stone M, Shams S, Williams CHS. Preliminary assessment of contemporary forest harvesting impacts on NOM and disinfection by-product formation potential. Am. Waterworks Assoc. Water Quality Tech. Conf. 2018, November 11-15, 2018, Toronto, ON.

Robinne FN, Bladon KD, Emelko MB, Parisien MA, Wang X, Silins U, Dupont D, Kienzle SW, Flannigan MD. 2019. A simple, reproducible model to assess regional-scale community water supply hazard from wildfire. IUFRO Joint Forest Water Conference, Nov. 5-8, 2019, Valdivia, Chile.

Karpyshin S, Silins U, Dyck M. 2018. Transpiration response of residual Lodgepole pine after strip and partial-cut harvesting in Alberta's southern Rocky Mountains. 110th Canadian Institute of Forestry Annual Conference and AGM, Sept. 18-20, 2018, Grande Prairie, AB.

Watt C. Stone M. Silins U. 2018. Abiotic control of fine sediment on phosphorus form and mobility in gravel bed rivers: Implications of increasing landscape disturbance pressures. 2018 Joint meeting of the Can. Geophysical Union, Can. Soil Sci. Soc., Comp. Infrastr. Geodynamics, Seismology Soc. of Am., Can. Soc. Ag. For. Met., Niagara Falls, June 11-13, 2018.

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Martens AM, Silins U, Proctor HC, Luchkow E. Williams CHS, Wagner MJ. 2018. Eight years later: Long-term effects of severe wildfire on aquatic ecology in Rocky Mountain streams. Fire Continuum Conf. Forests to flames to faucets. Missoula, MT., USA, May 21-24, 2018.

Williams CHS, Silins U, Anderson A. 2018. Muted streamflow response to increased net precipitation in wildfire-affected headwater catchments. Fire Continuum Conf. Forests to flames to faucets. Missoula, MT., USA, May 21-24, 2018.

Karpyshin S, Silins U, Dyck M. 2018. Transpiration response of residual Lodgepole pine after strip and partial-cut harvesting in Alberta's southern Rocky Mountains. Land Use 2018: Land, Water, Society, Alberta Land Institute, Edmonton, AB, May 30-31, 2018.

Karpyshin S, Silins U, Dyck M. 2018. Transpiration response of residual Lodgepole pine after strip and partial-cut harvesting in Alberta's southern Rocky Mountains. ConforWest 2018, 9th Interdisciplinary Conf. on Natural Resources, Environment, and Forest Science, Canmore, AB, April 6-9, 2018.

Greenacre D, Silins U, Dyck M. 2018. Influence of strip-shelterwood harvesting on snowpack dynamics and seasonal soil moisture in the Southern Alberta Rockies. ConforWest 2018, 9th Interdisciplinary Conf. on Natural Resources, Environment, and Forest Science, Canmore, AB, April 6-9, 2018.

Karpyshin S, Silins U, Dyck M. 2018. Transpiration response of residual Lodgepole pine after strip and partial-cut harvesting in Alberta's southern Rocky Mountains. University of Alberta Graduate Research Symposium, Edmonton, AB, March 14, 2018. *Awarded 3rd place, Best Student Paper Award*.

Greenacre D, Silins U, Dyck M. 2018. Influence of strip-shelterwood harvesting on snowpack dynamics and seasonal soil moisture in the Southern Alberta Rockies. 55th Ann. AB. Soil Sci. Workshop, Edmonton, AB, February 20-22, 2018. *Awarded "Best Student Paper" award*.

Martens AM, Silins U, Emelko MB, Stone M, Bladon KD, Williams CHS, Wagner MJ, Proctor HC, Luchkow E, Herlein KD. 2018. The Lost Creek Wildfire: Long-Term Impacts on Aquatic Ecology. Can. Conf. for Fisheries Res., Edmonton, AB, January 4-7, 2018.

Martens AM, Silins U, Proctor H, Williams CHS, Wagner MJ, Luchkow E, Emelko MB, Stone M. 2017. Long term impact of severe wildfire on macroinvertebrate assemblage structure in Alberta's Rocky Mountains. 2017 Joint Ann. Meeting of ESC/ESM, Winnipeg MB, 22-25 October 2017. *(Awarded 1st runner-up, Best Student Paper Award)*.

Watt C, Stone M, Silins U. 2017. Abiotic controls of fine sediment on the mobility of phosphorus in gravel bed rivers. Abst. B07- 12. Can. Geophysical Union and Can. Soc. Agric. Forest Met. Joint Meeting, Vancouver, BC, May 28-31, 2017.

Corrigan AF, Silins U, Stone M. 2017. Impacts of rapid harvest and subsequent haul road decommissioning on sediment production and ingress, Abst. H11-06. Can. Geophysical Union and Can. Soc. Agric. Forest Met. Joint Meeting, Vancouver, BC, May 28-31, 2017

Stewart DM, Silins U, Emelko MB, Stone M. 2017. Regulation of Post-Logging N Turnover and Mobile N by Solar Insolation in a Steep Mountainous Rocky Mountain Watershed. Abst. P02- B08. Can. Geophysical Union and Can. Soc. Agric. Forest Met. Joint Meeting, Vancouver, BC, May 28-31, 2017

Martens AM, Silins U, Bladon KD, Williams CHS, Wagner M, Luchkow E, Emelko MB, Stone M. 2017. Stable isotope analysis of food web dynamics in aquatic ecosystems following severe wildfire in Alberta's Rocky Mountains. Abst. P02- H11. Can. Geophysical Union and Can. Soc. Agric. Forest Met. Joint Meeting, Vancouver, BC, May 28-31, 2017.

Spencer SA, Silins U, Anderson A. 2017. Temporal variation in precipitation-runoff dynamics and implications for resilience in the eastern slopes of Alberta's Rocky Mountains. Abst. P04- H11. Can. Geophysical Union and Can. Soc. Agric. Forest Met. Joint Meeting, Vancouver, BC, May 28-31, 2017.

Howard M, Silins U, Anderson A, Emelko MB, Stone M. 2017. Quantifying and forecasting erosion from off highway vehicle trails in Front-Range Rocky Mountain watersheds. Abst. P05- H11. Can. Geophysical Union and Can. Soc. Agric. Forest Met. Joint Meeting, Vancouver, BC, May 28-31, 2017.

Greenacre D, Silins U, Dyck, Emelko MB, Stone M. 2017. Influence of alternative forest harvesting strategies on coupled spatial patterns of snowpack accumulation/melt and soil moisture storage. Abst. P06- H11. Can. Geophysical Union and Can. Soc. Agric. Forest Met. Joint Meeting, Vancouver, BC, May 28-31, 2017.

Karpyshin S, Silins U, Dyck, Emelko MB, Stone M. 2017. Transpiration response of residual Lodgepole pine after strip and partial-cut harvesting in Alberta's southern Rocky Mountains. Abst. P07- H11. Can. Geophysical Union and Can. Soc. Agric. Forest Met. Joint Meeting, Vancouver, BC, May 28-31, 2017.

Williams CHS, Silins U, Bladon KD, Anderson A, Wagner MJ, Martens AM, Stone M, Emelko MB. 2017. Muted Runoff Response to Increased Net Rainfall After Wildfire in Mountain Headwaters. Abst. P08- H11. Can. Geophysical Union and Can. Soc. Agric. Forest Met. Joint Meeting, Vancouver, BC, May 28-31, 2017.

Herlein K, Silins U, Williams CHS, Martens AM, Wagner MJ, Stone M, Emelko MB. 2017. Long-term suspended sediment yields in wildfire affected mountain streams in southwestern Alberta. Abst. P09- H11. Can. Geophysical Union and Can. Soc. Agric. Forest Met. Joint Meeting, Vancouver, BC, May 28-31, 2017.

Corrigan AF, Silins U, Stone M. 2017. Sediment impacts during rapid harvest and road-stream crossing decommissioning. ConForW '17, 8th 8th Annual Interdisciplinary Conf. Natural Resources, Canmore, AB, April 21-24, 2017.

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Martens AM, Silins U, Bladon KD, Williams CHS, Wagner MJ, Luchkow E. 2017. Analysis of food web dynamics in aquatic ecosystems following severe wildfire in Alberta’s Rocky Mountains. ConForW ’17, 8th 8th Annual Interdisciplinary Conf. Natural Resources, Canmore, AB, April 21-24, 2017.

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Robinne FN, Miller C, Parisien MA, Bladon KD, Emelko MB, Silins U, Flannigan M. 2017. A spatial evaluation of wildfire-water risks to human and natural systems at a global scale. Spatial Knowledge and Information (SKI) Canada “17, Banff, AB., February 23-25, 2017.

Prescott S. 2017. Off Highway Vehicle Riders in the Crowsnest Pass Area of SW Alberta. Infographic. http://quadsquad.ca/wp-content/uploads/2017/02/OHV_Infographic-3.pdf

Corrigan AF, Silins U, Stone M. 2016. Get in and get out: Assessing stream sediment loading from short duration forest harvest operations and rapid haul road decommissioning. Abst. H43G-1531, American Geophysical Union Fall Meeting, San Francisco, CA, December 12-16, 2016.

Puntenney KC, Bladon KD, Silins U. 2016. Surface Runoff and Sediment Transport Through a Riparian Buffer of a Steep Rocky Mountain Catchment. Abst. H43G-1532, American Geophysical Union Fall Meeting, San Francisco, CA, December 12-16, 2016.

Appiah A, Adamowicz W, Lloyd-Smith P, Dupont D. 2016. Estimating the economic value of drinking water reliability in Alberta. In Canadian Agricultural Economics Society/Western Agricultural Economics Association Joint Meeting. Victoria, BC. June 2016.

Robinne FN, Miller C, Parisien MA, Emelko MB, Bladon KD, Silins U, Flannigan M. 2016. A global index for mapping the exposure of water resources to wildfire, Canadian Water Network, Blue Cities, Toronto, ON.,18-19, May 2016. *Awarded Best Student Poster*.

Prescott S, Adamowicz W, Boxall P. 2016. Modelling of staging area choice for off highway vehicle riders. Alberta Land Institute, Edmonton, AB. May 4-5, 2016.

Shams S, Emelko MB, Stewart DM, Walton T. 2016. Roles of Different Drinking Water Treatment Processes on the Removal and Changes of NOM Fractions and DBP Precursors. OWWA Annual Conference, Windsor ON., May 1-4, 2016.

Appiah A, Adamowicz W, Lloyd-Smith P, Dupont D. 2016. What is the economic value of drinking water reliability in Alberta? Preliminary results. In Resource Economics and Environmental Sociology Graduate Students’ Association/ Alberta Agricultural Economics Association joint conference. Red Deer. April 2016.

Graduate Student Awards

- Sabrina Bedjera (University of Waterloo) was awarded the runner-up for the Policy Award of Excellence at the Canadian Science Policy Conference, Nov. 13-15, 2019.

- Samantha Karpyshin was awarded the Best Student Paper Award at the American Geophysical Union Fall Meeting, Dec. 10-14, 2018, Washington DC, USA.

- Samantha Karpyshin was awarded an Outstanding Student Paper Award at the 110th Canadian Institute of Forestry Annual Conference and AGM, Sept. 18-20, 2018, Grande Prairie, AB

- Dan Greenacre (University of Alberta) was awarded the Best Student Paper Award at the 55th Ann. Alberta Soil Science Workshop Feb. 20-22, 2018.

- Samantha Karpyshin (University of Alberta) was awarded 3rd Place in the Best Student Paper Award. University of Alberta Graduate Student Research Symposium. Mar. 14, 2018.

- Amanda Martens (University of Alberta) was Awarded 1st Runner-up for the Best Student Paper Award at the Ann. Meeting of Ent. Soc. Can. /ESM. Oct. 22-25, 2017.

- Gemma Charlebois (University of Waterloo) was awarded the American Water Works Association's (AWWA's) Academic Achievement Award for Best Master's Thesis (1st Place; 2 awards in North America, 1st 2nd place). 2017.

- Andrew Wong (University of Waterloo) was awarded the American Water Works Association's (AWWA's) Academic Achievement Award for Best Master's Thesis (2st Place; 2 awards in North America, 1st 2nd place). 2017.

- François Robinne (University of Alberta) was awarded the "Best Student Poster Award" at the Canadian Water Network, Blue Cities, Toronto, ON., May 18-19, 2016.

- Shoeleh Shams (University of Waterloo) was awarded the "2nd Place Michael R. Provart Environmental Award for Best Student Presentation" at the OWWA Annual Conference, Windsor ON., May 1-4, 2016.

Completed Graduate Student Theses

Decent Q. 2020. Factors controlling dissolved oxygen in spawning gravels: Evaluation of the Sediment Intrusion and Dissolved Oxygen model (SIDO) for fisheries management. M.Sc. Thesis, University of Waterloo, Jan. 2020, 87 p.

Mukhtarov R. 2020. The Effect of source water quality on water treatment costs: Evaluation of source water protection practices. M.Sc. Thesis, University of Alberta, Jan. 2020, 139 p.

Spencer SA. 2019. Runoff generation in a steep snow-dominated watershed in Alberta's southern Rocky Mountains. Ph.D. Thesis, University of Alberta, Sept. 2019, 138 p.

Karpyshin S. 2019. Transpiration response of residual Lodgepole pine after partial-cut and strip-shelterwood harvesting in Alberta's southern Rocky Mountains. M.Sc. Thesis, University of Alberta, Sept. 2019, 112 p.

Greenacre DME, 2019. Effects of alternative forest harvesting strategies on snowpack dynamics and seasonal soil moisture storage in Alberta's mountain headwaters, M.Sc. Thesis, University of Alberta, Apr. 2019, 117 p.

Martens AM. 2019. Long-term impacts of severe wildfire and salvage-logging on macroinvertebrate assemblages and food web structure in Rocky Mountain headwater streams, M.Sc. Thesis, University of Alberta, Apr. 2019,112 p.

Bahramian S. 2019. Contemporary Forest Harvesting Impacts on Drinking Water Treatability, M.Sc. Thesis – Water Option, University of Waterloo, Oct. 2019, 158 p.

Howard MJ. 2018. Erosion and erodibility from off highway vehicle trails in Alberta's southern Rocky Mountains. M.Sc. Thesis, University of Alberta. Sept. 2018, 112 p.

Yang A. 2018. Fine Sediment Contributions to Cyanobacterial Growth: Potential Threats to Drinking Water Reservoirs, M.A.Sc. Thesis, University of Waterloo, Jan. 2019, 209 p.

Geng X. 2018. Wildfire Impacts on Drinking Water Quality and Treatability, M.A.Sc. Thesis, University of Waterloo, Aug. 2018, 99 p.

Puntenney-Desmond K. 2018. Runoff and Sediment Transport from Harvested Hillslopes to Riparian Buffers of a Rocky Mountain Headwater Catchment. M.Sc.Thesis, Oregon State University, Mar. 2018, 115 p.

Shams S. 2018. Land disturbance effects on source water quality and its implications on drinking water treatability. Ph.D. Thesis, Thesis, University of Waterloo, Jan. 2018, 195 p.

Stewart DM. 2018. Nitrogen Dynamics in a Harvested Rocky Mountain Catchment. M.A.Sc. Thesis, University of Waterloo, Jan 2018, 110 p.

Corrigan AF. 2017. Assessing the Short-term Impacts on Sediment Production following Rapid Harvest and Stream Crossing Decommissioning in Rocky Mountain Headwaters. M.Sc.Thesis, University of Alberta, Jan. 2017, 116 p.

Lloyd-Smith, P. 2017. Fish, time, and water: Essays on environmental resource trade-offs. PhD. Thesis, University of Alberta, 240 p.

Prescott S. 2017. Analysis and Valuation of Off Highway Vehicle Use in Southwestern Alberta. M.Sc.Thesis, University of Alberta, Jan. 2017, 181 p.

Spanjers M. 2017. Biologically active filtration media properties: Practical and mechanistic implications. Ph.D. Thesis, University of Waterloo, Jan. 2017, 628 p.

Allin D. The effect of wildfire on the speciation and sorption behavior of sediment-associated phosphorus in the Oldman River basin. M.Sc. Thesis, University of Waterloo, 2016, 129 p.

Appiah A. 2016. Estimating the Economic Value of Drinking Water Reliability in Alberta., M.Sc. Thesis, University of Alberta, 165 p.

Charlebois G. 2016. Microcystin and microcystis destruction by ozone in drinking water treatment: Constraints and effects. M.A.Sc. Thesis, University of Waterloo, Jul. 2016, 175 p.

Crumb J. 2016. Phosphorus sequestration for control of cyanobacteria growth in drinking water reservoirs. M.A.Sc. Thesis, University of Waterloo, Oct. 2016, 94 p.

H. BENEFITS

Economic Benefits

Our research has contributed to describing the true costs of drinking water treatment in response to climate change-exacerbated landscape disturbances such as severe wildfires in physiographic settings relevant to Alberta. As anticipated, our work has shown that barring unexpectedly unavailability of adequate amounts of water (e.g., as a result of catastrophic post-fire debris flows that alter reservoir raw water storage capacity), even the most severely deteriorated water can likely be treated with the implementation of available treatment technologies and support infrastructure and operational response capacity. An evaluation of the associated costs of emergency preparedness to be able to rapidly achieve such a treatment response was beyond the scope of the present investigation. Nonetheless, these likely costs are consistent with current international consensus of the drinking water supply and treatment community in believing that coupled SWP and enhanced treatment technologies and operational response capacity are likely to be the most cost effective means for ensuring drinking water security in the face of growing climate change-associated threats to drinking water and associated public health protection. Over the next five to ten years, we further expect that the research will lead to tangible economic benefits for industry in Alberta and Canada. These include:

(1) **advancing Alberta technology experts to the international forefront of integration between the water and forestry technology sectors** with specific ground-breaking technical know-how (through the training of HQP and through industry participation in the research) and leadership in integrated development and utilization of “grey” in-plant and “green” natural resource-based infrastructure for climate change adaptation to ensure drinking water security, thereby also **increasing the development and sustainable use of natural resources** (notably, while this is a widely recognized target, tangible demonstrations of this capacity and benefit are relatively scant globally—the SRWP team strives to demonstrate and quantify these relative costs and benefits in Alberta through collaborative research such as that presented herein),

(2) **advancing the bio-economy and clean technologies** in Alberta and by fostering partnerships and opening new markets at the intersection of the industrial forestry and water technology sectors. While the potential for this connectivity has been globally recognized, the benefit of such connectivity has neither been systematically demonstrated nor characterized. The research team PIs are regularly contacted by various global technology developers and government agencies (e.g., Water Services Association of Australia, New York Department of Environmental Protection, Water US Endowment for Forestry and Communities, Water Research Foundation) with requests for guidance on how to build connections to achieve concurrent economic and societal impacts such as those enabled by the present research. The SRWP team is keen support Albertans in being market leaders and/or first to market with that trans-disciplinary capacity,

(3) **avoiding costs associated with potentially catastrophic, natural disturbance-associated disruptions to the provision of safe drinking water** through the development of active SWP policies and integrated green and grey technologies that support the multi-barrier approach to the provision of safe drinking water, prioritize healthy forests, and enable treatment technology resilience for responsiveness in extreme conditions of extreme challenge (e.g., floods, hurricanes, wildfires),

(4) **transferring knowledge to and between industries to identify new markets** by advancing the industrial forestry sector’s knowledge and understanding of drinking water treatability (as opposed to source water quality) implications of landscape disturbance by forestry operations. We expect that in the next five to ten years, that new knowledge will be built upon to co-develop BMPs and technology approaches for minimizing any deleterious effects of forest management on drinking water treatability, thereby justifying BMPs and **opening a new market for forestry services** that would leading to **creating jobs** and **producing spin-off products and/or firms** that specialize in products and services for this new, globally-relevant market, and

(5) **recruiting, retaining and training of highly qualified personnel (HQP)** by providing unique training opportunities and unprecedented opportunities for HQP training that enable development of integrated water and forest management expertise in Alberta and Canada.

Environmental Benefits

Prior to this project, it was believed that in plant drinking water treatment technologies would likely not be able to treat extremely deteriorated (i.e., so-called "black water" with high turbidity and high DOC concentration) after severe wildfire. In this project, post-fire ash was used to create a worst-case scenario source water matrix representative of post-fire ash washing in to either Elbow River or Athabasca River water, representing Calgary and the RMWB's source watersheds, respectively (i.e., the Montane Cordillera and Boreal Plains ecozones, respectively). This work showed that well-operated BSF technology could treat severely deteriorated water post-fire; for especially high levels of post-fire DOC, enhanced coagulation (with pH reduction) or powdered activated carbon (PAC) may be required in combination with BSF. Moreover, the work demonstrated the utility of zeta potential analysis in supporting chemical coagulant dosing requirements. Thus, this research represents a global first in demonstrating best available technology (BAT) approaches for responding to worst-case scenarios in the treatment of severely deteriorated drinking water supplies after wildfire. This advancement in knowledge **improves aquatic environmental systems compared to the industry benchmarks**. Notably, a key question that results from this research is whether or not investment in this level of technological development is financially justified relative to alternative risk mitigation approaches such as forest management-based SWP. This consideration is critical because "black water" events tend to be relatively short-lived (if they happen at all post-fire, as not all wildfires are severe). Thus, the economic trade-offs between investment in technology preparedness must be weighed against forest management-based risk reduction strategies and the known, concurrent ancillary benefits associated with healthy, resilient forests, which include environmental benefits such as carbon sequestration and species diversity (Moore 2007; Naburs et al. 2007; Halpern and Spies 1995).

Social Benefits

The clearest social and health/well-being benefits of the research are broadly associated with new knowledge that enables improved decision-making and policy development regarding trade-offs between SWP in the face of increasing climate change-associated threats to drinking water supplies and investment in expensive, in-plant treatment technologies that may not be required even after source water quality deterioration after severe wildfire. Our team's previous and current analyses show that wildfire impacts on water quality produce perhaps the most severe challenges in provision of drinking water. Thus, strategies to aid in mitigating these impacts will have the clearest social and health benefits for Albertans. Our work demonstrates that the economic trade-offs between investment in technology preparedness must be weighed against forest management-based risk reduction strategies and the known, concurrent ancillary benefits associated with healthy, resilient forests, which include societal benefits such as recreational services and spiritual value (Moore 2007; Naburs et al. 2007; Halpern and Spies 1995). Overall, the outcomes of this project will lead to several tangible **social benefits** for Albertans in the next three to five years. In brief, these include:

(1) **affecting a profound shift in the understanding and leveraging of critical interconnectivities between the drinking water supply and forestry sectors** to inform the development of (i) innovative in-plant treatment optimization and associated analytical support policies and practices (e.g., new frameworks for risk management) and (ii) regionally and culturally appropriate technologies and associated policy frameworks for their implementation (e.g., development of more efficient pathways for demonstrating chemically-assisted filtration or equivalent treatment performance) for rural, remote, and marginalized (including FNIM) communities that may place greater value on "green", natural resource-based approaches to overcome emerging threats to drinking water security including potentially catastrophic disturbance impacts on source water quality and treatability in Ontario, Canada, and globally, and

(2) using that new knowledge and capacity for **improving public policy** related to drinking water treatment and source protection and management by (i) making better informed decisions regarding the relative benefits/costs of managing natural disturbance-associated threats to the provision of safe water; especially with respect to triple bottom line representation of investments in grey in plant treatment technologies,

(3) **improving the health and well-being of Albertans** by (i) ensuring the uninterrupted flow of adequate amounts of safe drinking water and (ii) evaluating current and emerging drinking water treatability and public health threats (e.g., through the use of improved risk management frameworks such as quantitative microbial risks assessment), while achieving <u>known</u> concurrent, ancillary public health benefits associated with healthy, resilient forests (e.g., recreational services, spiritual value) (Moore 2007; Naburs et al. 2007; Halpern and Spies 1995). Notably, the public health sector will gain a new understanding of (1) the public health significance of aligning disturbance response and mitigation strategies related to water supply in disaster preparedness and (2) the societal **public health protection** benefits of reflecting drinking water *treatability* concepts in addition to health-associated water quality as policy targets. The public health significance of this linkage cannot be over-stated. At the start of the 20th century, the newly recognized public health importance of hygiene fueled technology and policy innovation related to water treatment, changing four of the 10 major causes death in Canada, the U.S., and many other parts of the world (Cutler and Miller 2005). The uninterrupted flow of adequate amounts of safe drinking water is <u>integral</u> to ensuring these public health protection outcomes; thus, it is in this way that climate change-exacerbated natural landscape disturbances most threaten public health in association with the provision of drinking water, and

(4) **placing Alberta at the international forefront of the water and forestry technology sectors** with specific ground-breaking leadership and **strengthened stakeholder involvement** in integrated development and utilization of "grey" in-plant and "green" natural resource-based infrastructure for climate change adaptation to ensure drinking water security.

Benefits in Building Innovation Capacity

Two key components of infrastructure were used during the course of this specific project, which also led to the development of unique infrastructure in Alberta. This included:

1. Online and benchtop zeta potential analysis was implemented in the RMWB's Fort McMurray WTP post-fire and contributed to improved control on coagulant dosing and reduction of DOC and aromatic carbon (which contributes to disinfection by-product formation in treated water and is measured by UV_{254}) at the WTP during the period since the wildfire, and

2. A pilot-scale BSF system was used during this project (and will be used in our new project) to evaluate BSF in response to worst-case, severely deteriorated water after wildfire. While the pilot plant exclusively focuses on the BSF process, the City of Calgary decided to build a complete pilot plant that includes BSF treatment and subsequent physico-chemical filtration processes. That pilot plant will be available for use in subsequent investigations.

This project also has enabled the training and retention of highly qualified and skilled professionals (HQSP) to meet current and future needs for water management in Alberta. Over the course of the SRWP (of which this project is a component), 67 HQP have, or are still being trained across a broad spectrum of water science and engineering domains. Many of those trainees are now playing key water management roles in the provincial (AAF, AEP), federal (Water Survey of Canada), municipal (City of Calgary), and for numerous natural resources and engineering consulting organizations serving Alberta's water needs and providing Alberta-based leadership across Canada and globally (through the provision of technical services). As many of the HQSP have spanned multiple projects, they are collectively summarized below. The HQSP denoted with an asterisk (*) are/were direct supervisees or co-supervisees of PI Emelko; of these, a notation of (^{A}) indicates a connection to Alberta (e.g., employment, studies).

Research Associates, Post-doctoral fellows, graduate and undergraduate students

Research Associates

1. Dr. Fariba Amiri*, U Waterloo (2019-present)
2. Sabrina Bedjera*, Waterloo (2019-present)
3. Dr. Phil Schmidt*, Waterloo (2018-present)
4. Dr. Bill Anderson*, U Waterloo (2017-present)
5. Dr. Grant Hauer, U Alberta (2016-*present*)
6. Dr. Jay Anderson, U Alberta (2016)

Post-doctoral Fellows

7. Dr. Yanxi Shao*^{A}, U Waterloo (2020-present)
8. Dr. Sheena Spencer, U Alberta (2019-*presen*t)
9. Dr. Xiaohui Sun*^{A}, U Waterloo (2017-2019)

Graduate students

10. Soosan Bahramian* (Ph.D. U Waterloo; 2019-*present*)
11. Jeremy Fitzpatrick (M.Sc. U Alberta, 2019-*present*)
12. Nik Knezic* (M.A.Sc. U Waterloo, 2019-*present*)
13. Allie Kennington* (M.A.Sc. U Waterloo, 2019-*present*)
14. Rebecca Baldock (M.Sc. U Alberta, 2018-*present*)
15. Erin Humney (M.Sc. U Alberta, 2018-*present*)
16. Jennifer Hall (M.Sc. U Alberta, 2018-*present*)
17. Ravkat Mukhtarov (M.Sc. U Alberta, *completed 2020*)
18. Jesse Skwaruk*^{A} (Ph.D. U Waterloo, 2017-*present*)
19. Derek Mueller (M.Sc. U Alberta, 2017-*present*)
20. Cassio Ishii (M.Sc. U Alberta, *completed 2019*)
21. Liz Hernani (M.Sc. U Alberta, 2017-*present*)
22. Quinn Decent (M.Sc. U Waterloo, *completed 2020*)
23. Soosan Bahramian* (M.Sc., U Waterloo, c*ompleted 2019*)

24. Jared Fath (Ph.D. U Alberta), 2016-*present*)
25. Amy Yang* (M.A.Sc., U Waterloo, 2016-*present*)
26. Dan Greenacre (M.Sc. U Alberta, *completed 2019*)
27. Samantha Karpyshin (M.Sc. U Alberta, *completed 2019*)
28. Amanda Martens (M.Sc. U Alberta, *completed 2019*)
29. David Michael Stewart*^{A} (M.A.Sc. U Alberta/U Waterloo, *completed* 2018)
30. Caitlin Watt (M.Sc. University U Waterloo, *completed* 2018)
31. Milly Corrigan (M.Sc. U Alberta, *completed* 2017)
32. Melissa Howard (M.Sc. U Alberta, *completed 2018*)
33. Kira Puntenney (M.Sc. Oregon State U, *completed* 2018)
34. Patrick Lloyd-Smith (Ph.D. U Alberta, *completed* 2018)
35. Sheena Spencer (Ph.D. U Alberta, *completed 2019*)
36. Kelsey Kundert*^{A} (M.A.Sc. U Waterloo, part-time 2012-*present*)
37. Shoeleh Shams* (Ph.D. U Waterloo, *completed* 2018)
38. Sarah Prescott (M.Sc. U Alberta, *completed* 2017)
39. Xiaoshi Kate Geng*^{A} (M.A.Sc. U Waterloo, *completed* 2017)
40. Mark Spanjers* (Ph.D. U Waterloo, *completed* 2017)
41. Donny Allin (M.Sc. U Waterloo, *completed* 2016)
42. Gemma Charlebois*^{A} (M.A.Sc. U Waterloo, *completed* 2016)
43. Jill Crumb* (M.A.Sc. U Waterloo, *completed* 2016)
44. Alfred Appiah (M.Sc. U Alberta, *completed* 2016)

Undergraduate students

45. Ragdha Said* (URA, Co-Op; U Waterloo, 2019, 2020)
46. Tyler Owl-Scott* (Co-Op; U Waterloo, 2018, 2019, 2020)
47. Nayandeep Maan* (URA, Co-Op; U Waterloo, 2016)
48. Yong Xin Michelle Fan* (URA; U Waterloo, 2016)
49. Shuai Josh Yuan* (URA, Co-Op; U Waterloo, 2016)
50. Adam Schneider* (Co-Op; U Waterloo, 2016)

I. RECOMMENDATIONS AND NEXT STEPS

The recent and continued expansion of wildfire threats to provincial water supplies likely represents the dominant driving force heightening the growing need for potential mitigation options. Against the backdrop of this need, the understanding of potential consequences of growing wildfire threats remains crucial because while this research team is leading this science/engineering effort worldwide, this understanding is based on study of an arguably small cross-section of wildfires and their effects on water supplies. Nonetheless, the present project learnings point directly to key actions that should be undertaken over the next two years to continue advancing innovation in climate change adaptation for public health protection through the continued, reliable provision of adequate amounts of safe drinking water for all Albertans. These key actions are summarized below.

1. This project has demonstrated that severely deteriorated source water (i.e., "black-water") representative of direct "wash-in" of post-fire ash to source water can be treated with well-operated combinations of currently available technologies such as BSF coupled with PAC. A key question that requires further investigation is which technologies are the best for extreme shifts in DOC and DOM aromaticity (UV_{254}), especially for high alkalinity water supplies for which it's difficult to decrease pH. The extent to which these challenges are representative of post-fire conditions rather than artifacts of experimental design must be evaluated. Notably, the widespread consideration of these technology approaches has the potential to put Alberta consulting engineers in global leadership positions regarding resilience in water treatment in wildfire prone areas.
2. Tools for describing and quantifying the resilience of in plant infrastructure and operational response capacity in response to rapidly changing source water quality conditions must be developed so that technology performance can be meaningfully compared.
3. Frameworks for qualitative and quantitative comparison of trade-offs between various technology approaches must be developed and integrated with risk mitigation strategies.
4. Finally, we have to recognize that we have only focused on surface water to date and the impacts of wildfires and other climate change-exacerbated landscape disturbances on subsurface supplies still need to be evaluated—they are likely to be different that those for surface water supplies because subsurface supplies do not typically require as much monitoring and treatment because they are often considered relatively stable supplies.

Notably, #1 and #4 are a focus of our new Alberta Innovates project.

J. KNOWLEDGE DISSEMINATION

In addition to knowledge dissemination to scientific audiences (described in Section G), our team has been regularly and increasingly involved in regional, provincial, national, and international knowledge mobilization activities revolving around wildfire, drinking water, and climate change adaptation. We have received several recognitions for those activities, as well. We expect that the knowledge gained from the project will continue to be disseminated through the formats described below, as well as through new research and knowledge mobilization joint initiatives at the provincial, national, and especially international scales as our team's advice and partnership is being increasingly sought out for guidance, policy development, and research regarding best management practices (BMPs) and best available technologies (BATs) for the management of both grey, in-plant drinking water treatment infrastructure and green, natural-resource-based SWP and drinking water treatment infrastructure for the management of climate change-exacerbated landscape disturbance risks to the provision of safe drinking water. Over the next five to ten years, we further expect that the research will lead to tangible benefits for industry in Alberta and Canada, as discussed in Section H.

International, National, and Provincial Level Knowledge Mobilization

- Team members (Emelko/Stone/Müller/Silins) delivered a utility guidance session entitled "Managing drinking water treatability threats from algal proliferation from the source to plant intake" for the Canadian Water Network (CWN) Webinar: Managing Algal Blooms-Watershed Management Approaches, September 18, 2019.
- Team members (Emelko/Silins/Stone) designed and delivered an invited continuing education operator training session on source water protection strategies at the Western Canada Water Annual Conference, Edmonton, AB, September 17, 2019.
- Team members (Silins/Emelko) served as a members of the City of Calgary multi-agency Wildfire-Source Water Partnership Task Force in 2018/19 leading to the "Calgary Wildfire-Source Water Risk Management. Report from the City of Calgary's Wildfire-Source Water Partnership Task Force, July 2019, 71 p. Report was released for public-stakeholder feedback, July 2019.
- Silins, Williams, & Cherlet provided a detailed analysis and summary report of post-fire climate and flood risk to Parks Canada to assist with their post-fire bridge infrastructure re-construction program, July 2019.
- Team members (Emelko/Silins) provided a synthesis on wildfire impacts to water as input for Health Canada's Climate Change Adaptation Framework, June 2019.
- Emelko delivered an invited commentary at the Canadian Water and Wastewater Association (CWWA) Window on Ottawa national conference, Ottawa, ON, June 3, 3019.
- Emelko delivered an invited webinar presentation to BC's Climate Action Secretariat, April 18, 2019.
- Emelko presented an invited talk and led a panel discussion at the Alberta Water & Wastewater Operators Association Annual Conference, Banff, AB, March 15, 2019.
- Emelko presented an invited talk and participated in a panel discussion for the international Beyond the Textbook: Disinfecting Water and Wastewater in Extreme Conditions webinar coordinated by the Water Environment Federation, March 8, 2019.

- Silins presented and led a discussion with the Board of Directors, Alberta Water Council on wildfire and source water management-based source water protection in Alberta, February 28, 2019.

- Team members (Silins/Emelko/Stone) provided on-going information on wildfire threats and mitigation options to the multi-stakeholder Alberta Water Council Source Water Protection project team to supporting and providing feedback for the AWC Source Water Protection Guidance document, 2018-2019.

- Team members (Emelko/Silins) provided provide technical advice/input to AB, Health Services and AEP staff in southwest AB. on potential contaminant risks to regional water supplies, and potential mitigation options for regional staff and rural residents after the 2017 Kenow Mtn. wildfire, August-September 2018.

- Policy briefing (Silins) for AAF/AEP executive branch (ADM, Exec. Divisional directors) on outcomes of SRWP informing Source Water Projection strategies and policy in Alberta's eastern slopes. High-level strategic summary of key SRWP science outcomes on comparative impacts to eastern slopes headwaters and downstream regions from wildfire, flooding, and industrial forestry operations, March 9, 2018.

- Silins co-organized and served as Assoc. Editor for special issue "Forests to Flames to Faucets" in the Int. Journal of Wildland Fire (published Oct. 2019) based on an international conference workshop he co-organized "Fire Continuum Conf. Forests to flames to faucets". Missoula, MT., USA, May 21-24, 2018.

- Cost Action Policy Brief: Nunes JP, Doerr S, Keesstra S, Pulquério M. 2018. Policy brief: impacts of fires on water quality. Results from the workshop on "fire impacts on water quality", 14-16 February 2018, Lisbon, Portugal. This policy brief was based on discussions among 28 researchers and water resource managers from Europe, USA, Canada, Australia and Israel organized by COST Action ES1306 Connecteur and the H2020 PLACARD project including additional sessions with the public, additional and Portuguese researchers and managers. (Emelko/Stone).

- Silins and Emelko provided emergency assistance as requested by Parks Canada (Waterton Lakes National Park) to provide initial risk assessment, and mitigation advice for staff/public safety (flooding, debris flows, avalanche hazard), water supplies (impacts on water quality and ecosystem services), and water treatment (staff/public health risk, water treatment operations). Ongoing coordinated efforts between WLNP and SRWP have led to development of a weather-flow response based early warning framework for protection of public/staff safety, and coordination between SRWP and WLNP, AEP, and AB Health Services staff on monitoring and public health risk mitigation strategies for both back-country and town site water supplies. This led to a new partnership with Parks Canada, November-December 2017.

- Silins and Emelko provided emergency assistance as requested by the BC Ministry of FLNRORD on early risk assessment on public safety, regional water supply, and water treatment facilities including early emergency mitigation for southern and northern interior regions after the record breaking 2017 wildfire season, Aug. 2017. We delivered a full-day workshop on post wildfire hydrology, water quality, aquatic ecosystem health, and downstream impacts on community drinking water supplies aimed at landscape and water treatment plant mitigation options for provincial, municipal, and indigenous community water managers in Kamloops, B.C., Sept. 12, 2017. This included on-site reconnaissance and discussions of landscape mitigation options, salvage logging policy, and potential forest management regulatory responses in the severely burned Elephant Hill Fire Complex north of Ashcroft B.C. with gov't. management staff (September 13-14, 2017).

- Emelko provided key input into Province of British Columbia: HealthLink BC file review of “Forest Fires and Drinking Water” guidance document (2017), August 2017.
- Emelko participated as Expert Panel member on “Achieving Resilience: Preparation, Response and Recovery from Water Crises” at Canadian Water Network, Blue Cities, Toronto, ON, May 17-18, 2017
- Policy briefing (Emelko/Silins) on Groundwater Under the Influence of Surface Water (GUDI) and flood mitigation for Ronda Goulden (Asst. Deputy Minister, Policy and Planning, AEP) and Cathy Maniego (Exec. Dir. Resilience and Mitigation Branch, AEP), Edmonton, AB, November 11, 2016.
- Team members (Silins / Emelko) were recruited by AEP, AAF, and AB. Municipal Affairs on May 8, 2016 (3 days after evacuation of Fort McMurray) to assist with initial emergency response planning for the city. In the hours-days/weeks-months to follow, our contributions to emergency response planning and reaction for RMWB’s Fort McMurray WTP focused on (1) rapid deployment of support instrumentation (zeta potential analysis) to enable rapid plant operational responsiveness to fluctuating post-fire water quality and treatability challenges, (2) regional post-fire watershed threats assessment for the Athabasca River and tributaries upstream of the RMWB’s WTP, including early strategies for reservoir management response, and (3) broader plant operations coordination (reservoir management, BSF and conventional pre-treatment operations). These contributions were credited as meaningfully contributing to the RMWB’s water treatment operations being able to produce drinking water during and after the wildfire, May-June, 2016.
- Emelko participated on an Expert Panel on “Impacts and Risk Identification for the New Normal” at Canadian Water Network, Blue Cities, Toronto, ON, May 18-19, 2016.

Regional Knowledge Mobilization

- Silins U, Emelko MB, Stone M, Williams CHS, Wagner MJ, Martens AM, Hawthorn K, Spencer SA, Adamowicz W, Anderson A, Collins AL, Dyck M, Krishnappan BG, Mueller K, Quideau S. 2019. Southern Rockies Watershed Project: Wildfire, flooding, and forestry in Alberta’s eastern slopes, Provincially broadcast webinar on Source Water Protection and climate change adaptation for Provincial Government Staff, July 26, 2019. *Internal GOA webinar*
- Emelko delivered an invited plenary talk “Forests for Water” at TU Wien (Technical University of Vienna) on June 21, 2018.
- Silins U, Emelko MB, Stone M, Adamowicz V, Anderson A, Collins AL, Dupont D, Dyck M, Eykelbosh A, Krishnappan BG. 2019. The future of water supply and watershed management in Alberta: Best source-to-tap practices for source water protection in the eastern slopes. Alberta Innovates Water Innovation Program Forum, Edmonton, AB, May 22-23 2019.
- Emelko MB, Silins U, Stone M, Müller K, Cooke C. 2019. Drinking water security after severe wildfire in Alberta: Initial risks and treatment technology resilience, Alberta Innovates Water Innovation Program Forum, Edmonton, AB, May 22-23 2019.
- Emelko MB, Silins U, Stone M. 2019. Water quality and treatability in a changing climate. B.C. Climate Action Secretariat, webinar, April 18, 2019.
- Emelko MB, Silins U, Stone M. 2019. Water disinfection in extreme conditions: Wildfire threats to public health. U.S. Water Environment Federation, Webinar (nationally broadcast), March 8, 2019. (Invited)

- Silins U, Emelko MB, Stone M, Williams CHS, Wagner MJ, Martens AM, Hawthorn K, Spencer SA, Shams S, Geng K, Allin D, Adamowicz W, Flannigan MD, Dupont D, Parisien MA, Bladon KD, Wang X, Robinne FN, Anderson A, Collins AL, Dyck M, Krishnappan BG. 2019. Effects of wildfire on Alberta's water supplies. Alberta Water Council Board of Directors, Edmonton, AB, February 28, 2019.
- Cooke CA, Emmerton CA, Hustins S, Jackson B, Kerr JG, Taube N, Kruk M, Orwin J, Silins U, Emelko MB. 2019. Rapid response and recovery of water quality following the Fort McMurray wildfire. University of Alberta EAS Atlas Seminar, February 15, 2019 Edmonton, AB, February 15, 2019.
- Emelko MB, Stone M, Silins U. 2018. Wildfire Threats to Water Security: Source-to-Tap Case Studies from Western Canada. College of Science Seminar Series, Swansea University, Swansea, UK, May 8, 2018. (Invited)
- Silins U, Emelko, Stone M, Anderson A, Adamowicz V, Dupont D, Flannigan M, Cooke C, Williams CHS, Herlein KD, Martens AM, Hawthorn K, Wagner MJ, Krishnappan BG, Collins AK. 2018. Mine the data – mind the resource: Déjà Vu or grand challenge for Alberta water management? Can. Water Res. Association, Alberta Branch Annual Conference, Red Deer, AB, March 25-27, 2018. (Invited Plenary)
- Silins U, Williams CHS, Emelko, Stone M, Anderson A, Adamowicz V, Dupont D, Herlein KD, Martens AM Hawthorn K, Wagner MJ, Krishnappan BG, Collins AK. 2018. The 2003 Lost Creek wildfire: What happened to the water? Waterton Lakes National Park: Post-Kenow Fire Workshop, Waterton Lakes National Park, January 10-11, 2018. (*Invited*)
- Emelko MB, Silins U, Stone M. 2017. Wildfire impacts on watersheds and drinking water supply and treatment. First Nations Health Authority and Indian and Northern Affairs Canada Ann. Joint Meeting. November 29, 2017.
- Stone M. Climate change land disturbance impacts on water quality and water supply. University of Waterloo Collaborative Water Program for Leadership Retreat, University of Waterloo, Waterloo, ON, October 29, 2017. (*Invited*)
- Silins U, Emelko MB, Stone M., Adamowicz W, Dupont D, Flannigan M, Dyck M, Cooke C, Williams CHS, Herlein KD, Martens AM, Hawthorn K, Wagner MJ, Collins AL, Krishnappan BA, Bladon KD. 2017. Wildfire and other disturbances at the watershed level. fRI Research. Mountain Pine Beetle Breaking News Workshop. Edmonton, AB, October 26-27, 2017.
- Silins U, Emelko MB, Stone M, Adamowicz W, Dupont D, Flannigan M, Dyck M, Cooke C, Williams CHS, Herlein KD, Martens AM, Hawthorn K, Wagner MJ, Collins AL, Krishnappan BG, Bladon KD. 2017. Wildfire impacts on Rocky Mountain source waters in Alberta. Canadian Water Res. Association. Nationally broadcast webinar. September 19, 2017. (*Invited*)
- Emelko, MB. 2017. Wildfire, watersheds, and drinking water. British Columbia Ministry of Health, Health Protection Branch Webinar, June 21, 2017. (*Invited*)
- Silins U, Emelko M, Stone M, Adamowicz V, Anderson A, Collins A, Dupont D, Dyck M, Eykelbosh A, Krishnappan BG, Reid D, Sear D. 2017. The future of water supply and watershed management in Alberta: Best source-to-tap practices for source water protection in the eastern slopes. Alberta Innovates Water Innovation Program Forum, Edmonton, AB, May 24-25, 2017.
- Emelko MB, Silins U, Stone M, Cooke C. 2017. Drinking water security after severe wildfire in Alberta: Initial risks and treatment technology resilience. Alberta Innovates Water Innovation Program Forum, Edmonton, AB, May 24-25, 2017.

- Emelko MB. 2017. Fires, floods, and other natural disasters: Climate change threats to water across Canada. Nature Unleashed Dialogs, The Museum, Waterloo, ON, February 5, 2017. (*Invited*)
- Stone M. 2017. Watershed Science on Fire: Insights from a long-term watershed research platform in southwest Alberta. Woo Water Lecture Series, McMaster University, Hamilton, ON, January 17, 2017. (*Invited*)
- Silins U, Emelko MB, Adamowicz V, Anderson A, Boxall P, Collins A, Dupont D, Dyck M, Krishnappan BG, Sear D, Stone M. 2016. Healthy Forests and Resilient Communities: Source water protection in Alberta and how forest disturbance like fire and harvesting is linked to your glass of water. Alberta Innovates, AIEES Technology Talks, Calgary, AB, November 30, 2016. (*Invited*)
- Silins U. 2016. Shifting climate, fire, and forestry in Alberta's upper eastern slopes. Canadian Forest Products Ltd. Forest Management Advisory Committee, Grande Prairie, AB, October 19, 2016. (*Invited*)
- Emelko MB, Eykelbosh A, Silins U, Stone M. 2016. Adaptation Strategies to Prepare for Climate Change Impacts on Drinking Water Treatability: A Small Systems Approach. CIPHI Annual Education Conference, Edmonton, AB, September 25-28, 2016.
- Eykelbosh A, Emelko MB, Silins U, Stone M. 2016. Fires, floods, and bugs: how climate change may impact drinking water source water quality. CIPHI Annual Education Conference, Edmonton, AB., September 25-28, 2016.
- Silins U, Emelko MB, Adamowicz V, Anderson A, Bladon K, Collins A, Dupont D, Dyck M, Krishnappan BG, Sear D, Stone M. 2016. Water and forests: Linking pressures from source to tap. Alberta Innovates BioSolutions, Impact Innovation 2016, Edmonton, AB, May 11, 2016. (*Invited*)

Awards and Recognitions

- Monica Emelko was named the McMaster Water Week Plenary Keynote and delivered "Re-thinking drinking water security: Are outdated policies and technology concepts precluding scientific advancement and public health protection?" October 29, 2019.
- Monica Emelko was named the Association of Environmental Engineering & Science Professors (AEESP) Distinguished Lecturer at the American Water Works Association (AWWA) Annual Conference and Exhibition, June 10, 2019.
- Monica Emelko was interview by H2O Radio in an interview entitled "Are Water Providers Ready for Climate Change?" (http://h20radio.org/Emelko.html), Denver, CO, June 10, 2019.
- *Letter of appreciation* to Silins and Emelko from Richard Manwaring (Asst. Deputy Minister, BC Ministry of Forests, Lands, Natural Resource Operations, and Rural Development) for post-fire emergency risk assessment assistance and our delivery of a September 2017 workshop to BC government, regional resource managers, Interior Health, and Indigenous agencies supporting post-fire water risk assessment, February 2018.
- *Letter of appreciation and recognition for outstanding service to Albertans, commendation certificate, and medallion for Ft. McMurray wildfire recovery*. Presented to Emelko and Silins from the Premier of Alberta, Hon. Rachel Notley, January 2017.

- Monica Emelko was nominated and selected as a Member of the U.S. National Academies of Sciences, Engineering and Medicine, Water Science and Technology Board’s Expert Committee on New York City’s Operational Support Tool for Water Supply and Response to Climate Change, January 2017.
- *Western Canada Water Exceptional Municipal Project Award.* Presented to the Regional Municipality of Wood Buffalo, Associated Engineering, Stantec Consulting Ltd., Nason Contracting Group Ltd, and the Southern Rockies Watershed Project team for Water/Wastewater Recovery after the 2016 Ft. McMurray fire, October 2016.

K. CONCLUSIONS

Climate change-exacerbated landscape disturbances such as severe wildfires have the capacity to disrupt the provision of adequate amounts of safe drinking water in wildfire prone areas; thus, they are a threat to drinking water security for most Albertans. The main objectives of this project were to (1) characterize the impacts of the 2016 Horse River wildfire on drinking water treatment in Fort McMurray and (2) evaluate ballasted sand flocculation as a potential best available technology for the treatment of severely deteriorated "black-water" representative of the worst-case scenario of post-fire ash washed in to a source water supply. The project demonstrated that, despite burning less than approximately 4% of the large Athabasca River watershed, the wildfire has had a significant and continued impact on drinking water treatment in Fort McMurray—this impact has cost the RMWB at least $9.9 million to date. In addition to increased coagulant dosing requirements (approximately 2.5x increase) associated with more aromatic and variable dissolved organic carbon concentrations post-fire, the potential for membrane fouling (not relevant to the RMWB) and biological regrowth in distribution systems (potentially necessitating more application of chlorine residual and distribution system maintenance was also elevated as a result of the disturbance. While these latter implications of wildfire to drinking water treatability are being reported for the first time globally, the potentially more catastrophic impact of annual cyanobacterial blooms of species that are often toxin formers was recorded for the first time globally. These observed and continued threats to the provision of adequate amounts of safe drinking water underscore the importance of continuing the advancement of innovation in climate change adaptation for public health protection through the continued, reliable provision of adequate amounts of safe drinking water for all Albertans. The potential best available technologies of ballasted sand flocculation and powdered activated carbon very likely have the potential to treat even the most severely deteriorated source water after wildfire; however, the critical question is, is it worth investing in these costly technologies if their use is uncertain potentially only required for a few days periodically if at all? Albertans and many others living on wildfire prone landscapes are necessarily faced with difficult choices regarding investments in drinking water treatment and supply resilience, which can likely be achieved using a combination of forest management-based source water protection approaches and in plant-treatment technologies.

Tangible economic benefits resulting from the project include (1) advancing Alberta technology experts to the international forefront of integration between the water and forestry technology sectors, (2) advancing the bio-economy and clean technologies in Alberta and by fostering partnerships and opening new markets at the intersection of these sectors (3) avoiding costs associated with potentially catastrophic, natural disturbance-associated disruptions to the provision of safe drinking water through the development of active SWP policies and integrated green and grey technologies that support the multi-barrier approach to the provision of safe drinking water, prioritize healthy forests, and enable treatment technology resilience for responsiveness in extreme conditions of extreme challenge (e.g., floods, hurricanes, wildfires), (4) transferring knowledge to and between industries to identify new markets by advancing the industrial forestry sector's knowledge and understanding of drinking water treatability (as opposed to source water quality) implications of landscape disturbance by forestry operations, and (5) recruiting, retaining and training of highly qualified personnel (HQP) by providing unique training opportunities and unprecedented opportunities for HQP training that enable development of integrated water and forest management expertise in Alberta and Canada.

Notably, this project represents a global first in demonstrating best available technology (BAT) approaches for responding to worst-case scenarios in the treatment of severely deteriorated drinking water supplies after wildfire. This advancement in knowledge improves aquatic environmental systems compared to the industry benchmarks. Notably, a key question that results from this research is whether or not investment in this level of technological development is financially justified relative to alternative risk mitigation approaches such as forest management-based SWP. Economic trade-offs between investment in technology preparedness must be weighed against forest management-based risk reduction strategies and the known, concurrent ancillary benefits associated with healthy, resilient forests, which include environmental benefits such as carbon sequestration and species diversity. The clearest social and health/well-being benefits of the research are broadly associated with new knowledge that enables improved decision-making and policy development regarding these trade-offs. The project will further lead to tangible social benefits for Albertans, which include (1) affecting a profound shift in the understanding and leveraging of critical interconnectivities between the drinking water supply and forestry sectors, (2) improving public policy related to drinking water treatment and source protection and management, (3) improving health and well-being by ensuring the uninterrupted flow of adequate amounts of safe drinking water, and (4) placing Alberta at the international forefront of the water and forestry technology sectors with specific ground-breaking leadership and strengthened stakeholder involvement in integrated development and utilization of “grey” in-plant and “green” natural resource-based infrastructure for climate change adaptation to ensure drinking water security.

Work still remains, however. For meaningful analysis of associated trade-offs, best management practices for those approaches must be developed and associated costs must be quantified—tools for describing and quantifying the resilience of these approaches must be developed so that technology performance can be meaningfully evaluated and integrated with risk assessment and mitigation strategies. Continued opportunities for trans-disciplinary and trans-sector partnerships will continue to ensure the advancement of innovative solutions to these challenges.

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