ALBERTA **INNOVATES**

CLEAN ENERGY FINAL PUBLIC REPORT TEMPLATE

1. PROJECT INFORMATION:

Project Title:	**The future of water supply and watershed management in Alberta: Best source-to-tap practices for source water protection in the eastern slopes**
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2. PROJECT PARTNERS

The research team would like to acknowledge the strong partnerships and support, including both funding and staff involvement in the research. Without these strong partnerships, this project would not have been possible.

- Alberta Agriculture and Forestry
- Alberta Environment and Parks
- Alberta Innovates
- Calgary Water Services
- Canadian Forest Products Ltd.
- National Collaborating Centre for Environmental Health
- National Science and Engineering Research Council
- VAST Resource Solutions

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A Executive Summary

The majority of Alberta's water supplies are produced from forested regions of the Rocky Mountain eastern slopes, but climate change driven increases in natural disturbances such as rapidly growing threats from wildfires is increasingly threatening provincial water supplies from this region. While wildfire threats cannot be eliminated, forest management-based source water protection strategies are being employed to help mitigate this threat elsewhere. However, unlike historic forestry practices which are well studied, the impacts of more current contemporary forest harvesting on a broad range of water resource values important to Albertans had not been evaluated. Thus, the potential alignment of current forest management practices with strategic objectives for source water protection in critical water regions remains unclear in Alberta.

The broad objectives of this project were to provide key information on the broad scope of impacts from several alternative, contemporary forest harvesting strategies on water from "Source to Tap" including water quantity, quality, stream health, downstream cumulative watershed effects, drinking water treatability, and economic evaluation of trade-offs between source water protection-based, and technology-based investments in drinking water protection. Development of tools and assessment procedures for both addressing source water protection and pressing drinking water treatment challenges allied research priorities.

Results of this study demonstrated surprisingly consistent alignment in findings across the breadth of these water domains showing that contemporary forest harvesting practices produced effectively no detectable impacts to water quality, or stream health both in smaller headwaters catchments or further downstream. Similarly, no meaningful effects to key drinking water treatability were also evident. While we expected to find important differences in harvesting impacts to water between very different forest harvesting strategies (clear-cut, strip-shelterwood, partial-cuts), the suite of best management practices employed during and after harvesting effectively prevented these impacts to water, regardless of harvesting strategy employed. It is notable that these studies were conducted under rigorously controlled, paired-catchment (before:after/control:impact) watershed research design with the power to detect even subtle impacts, had they occurred. Similarly, a broad suite of comprehensive best practices tools and assessment frameworks were developed to both enable land and water managers to address challenging source water protection problems, and allow drinking water treatment managers to address pressing treatment challenges with a similar suite of tools and assessment frameworks.

The most important strategic outcome of this project was the rigorous science, engineering, economics/policy evidence showing that contemporary forest management practices can be in much closer alignment with broad source water protection objectives than many water managers and policy makers might currently perceive. Furthermore, our analyses show forest management-based source water protection coupled with development of enhanced drinking water treatment resilience are likely to be both cost-efficient and effectives strategies for both protection of provincial water supplies and potential climate change adaptation strategies to address threats to Alberta's critical forested source water regions.

It is particularly noteworthy that similar evaluations involving even a small fraction of the scope reported on here do not presently exist anywhere worldwide. However, it is precisely this broad, transdisciplinary scope that has enabled this project to produce the key science, engineering, and economic/policy insights on integrated municipal and forested source water protection options enabling Alberta to develop science-informed climate change adaptation strategies.

B Introduction

The vast majority of water supplies supporting Alberta's social, economic, and environmental health are produced from the eastern slopes of the Rocky Mountains, where forested regions of the province supply drinking water for ~ 2 out of 3 Albertans (Robinne et al. 2019). However, while land disturbance from resource development and other human pressures has significant potential to impact these supplies, climate change is exerting rapidly increasing pressure on forested landscapes and sustainability of water resources from this region. Indeed, our previous and on-going research from several recent wildfires (2003 Lost Ck., 2012 Milk River, 2016 Horse River, 2017 Elephant Hill/Thuja Ck. B.C., and 2017 Kenow Mtn. wildfires) has shown that wildfire impacts to water resources can be orders of magnitude greater and last longer than those of other types of forest landscape disturbances. While little can be practically done to manage the inertia of climate change associated increases in severity of fire weather conditions driving these fires, forest management is being used in other regions world-wide to aid in managing these threats as part of integrated forest source water protection strategies.

Broader strategic forest management strategies attempt to balance economic, social, environmental benefits to sustainability, while minimizing environmental impacts and conflicts among competing/non-complimentary forest and social values. While more ecologically resistant and resilient forest conditions (with positive implications for water resources) can be a strategic outcome of integrated forest management, forest disturbance from management activities also produces impacts on water including potential impacts to water quality, water quantity, stream health, and the condition of downstream water supplies. While much historic research on forest management impacts to water has been conducted in other forested regions worldwide, very little of that information reflects contemporary practices which have changed substantially in the past 40 years. Furthermore, little if any of this knowledge is specifically useful in evaluating potential alignment of strategic forest management objectives with those of source water protection in Alberta's critical Rocky Mountain source water region because the key connections between disturbance effects on water quality across spatial scales (cumulative watershed disturbance effects) remain unknown. Thus, the comparative risks and benefits to water associated with forest management including costs/avoided impacts from catastrophic natural disturbances are not known. This information is needed to develop truly integrated landscape source water protection strategies to help mitigate and adapt to climate change impacts to Alberta's forests and the water they provide.

Accordingly, the broad objectives of this project are to provide key information on the broad scope of impacts from several alternative, contemporary forest harvesting strategies on water from "Source to Tap" including water quantity, quality, stream health, downstream cumulative watershed effects, drinking water treatability, and economic evaluation of trade-offs in provision of ecosystem goods and services provided by water.

C Project Description

The broad objective of this program is to provide key information needed to develop integrated source water management strategies to ensure the protection and sustainability of water resources and associated water values for Albertans. This research was designed to provide information on both the ecological, water treatment, and economic outcomes (both impacts/benefits) of three alternative contemporary forest management strategies (variable retention clear-cut harvesting [most common current practice], strip-shelterwood cutting, and a partial-cut selection harvest) to provide insight into the initial-early and long-term impacts of source water management on water resource values at a range of spatial scales from headwaters downstream to larger river basin scales (cumulative watershed disturbance effects). The demonstrably unique feature of this research is the transdisciplinary approach linking multi-scale evaluation of landscape disturbance to downstream impacts on critical human water use; provision of safe drinking water and technology/operations options to improve treatment resilience along with the overall economic evaluation of costs/benefits involved in integrated landscape source water protection strategies.

The most notably unique feature of our project is that the research team spans the diversity of practice domains and expertise required to appropriately address these issues, our research plan is organized around specific research tasks associated with the major disciplinary components of the problem. The project will include four major themes or nodes:

- Effects of alternative forested management strategies on headwater resources,
- Propagation of headwaters impacts to produce downstream regional-scale impacts,
- Impacts on downstream drinking water treatment (vulnerabilities), and
- Economics evaluation of the cost/benefit implications of alternative source water strategies

D Approach and Methods

Because this program is focused on integrating a broad range of biophysical, socio-economic, and engineering impacts from varied headwaters land disturbances on downstream regional water values including drinking water treatment utility operation, this research could not be accomplished without building on prior research and partner-stakeholder investment. Accordingly, this project is built upon the foundation of previous research (11 previous years) on the Southern Rockies Watershed Project (SRWP) studying the effects of the 2003 Lost Ck. wildfire in the southwest Alberta's Rocky Mountains. This prior, and more recent research provides the necessary information on comparative impacts to water from severe wildfire. Two of the previously instrumented SRWP watersheds (North York and Star Cks.) served as the necessary platforms to assess impacts of alternative forest management practices on water resources (SRWP Phase II) for the current research. This project was also only possible because very strong partnerships with Alberta Agriculture and Forestry (AAF) and Canfor who undertook the forest management plan development and conducted the harvest operations for this study. One watershed (North York Ck.) remained undisturbed while three sub-catchments in North York Ck. were harvested using three alternative harvesting strategies including a) conventional clear-cut harvesting with green-tree retention, b) strip-shelterwood, and c) partial cut harvesting strategies in 2015 (Fig. 1). A suite of best management practices to control runoff and erosion from the road network (haul road and in-block roads) were employed during the harvest with road-stream crossings and roads decommissioned and rolled-back in after harvesting was complete in the fall of 2015. Eleven years of prior data (climate, hydrology, water quality, stream ecology) from these watersheds enabled the powerful before/after;control/impact (BACI) design used in the comprehensive evaluation of these impacts.

The research was organized around major research components (research tasks) focused on addressing key knowledge outputs (Milestones) in each of the four research themes (Table 1) to enable establishing linkages among themes needed to evaluate the comparative impacts of alternative forest harvesting strategies. Furthermore, research tasks and milestones were devoted to broader scientific knowledge generation, and practical application of that knowledge in evaluation or development of best practices (Table 1). Research in theme 1 was focused on evaluating headwaters impacts of alternative harvesting strategies on hydrology (milestone 1), water quality (milestone 2), and stream health (milestone 3), evaluation of tools and best practices for sediment management (milestone 4), and evaluation of downstream flow/water quality effects (milestone 5). These were linked to the broader regional downstream effects at larger river basin scales in theme 2 including contaminant source tracing (milestone 6), development of a generalized modelling framework for

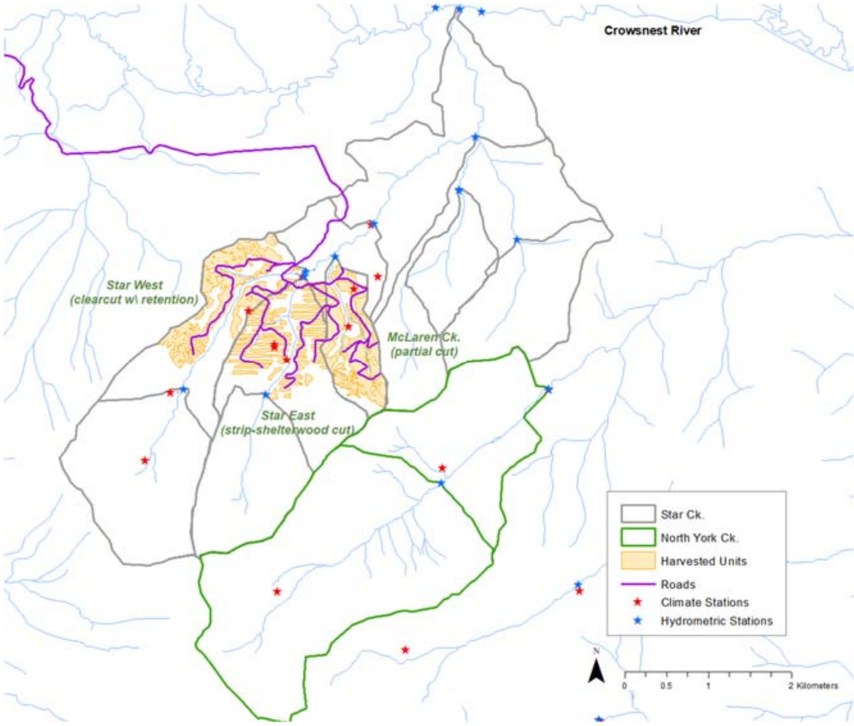
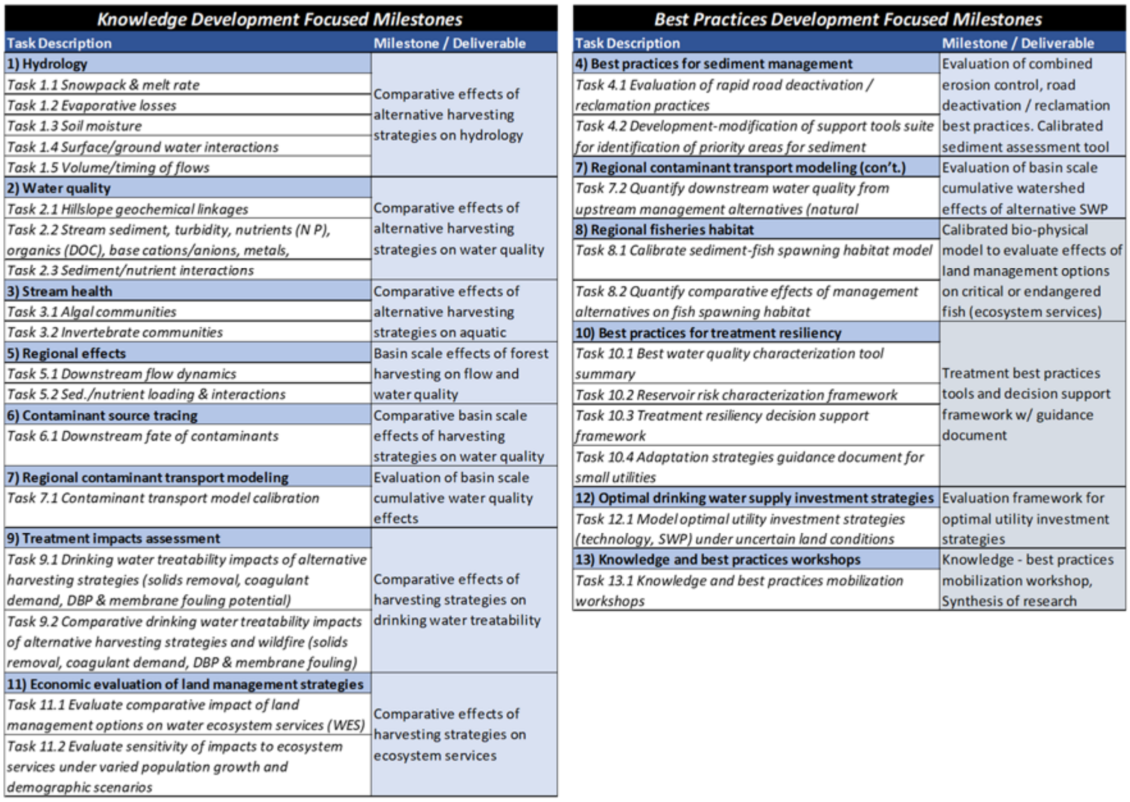


Figure 1 – Star Ck. (harvested 2015) and North York Ck. study watersheds

cumulative watershed effects assessment (milestone 7). These in turn, were linked to research needed for assessment of impacts to drinking water treatment (milestone 10) and evaluation of economic consequences (costs/benefits) and implications for ecosystem services provision (milestone 11) and evaluation of likely future costs/benefits of management alternatives (milestone 12).

Table 1 – Major research components across four research themes



Knowledge Development Focused Milestones	
Task Description	**Milestone / Deliverable**
1) Hydrology	Comparative effects of alternative harvesting strategies on hydrology
Task 1.1 Snowpack & melt rate	
Task 1.2 Evaporative losses	
Task 1.3 Soil moisture	
Task 1.4 Surface/ground water interactions	
Task 1.5 Volume/timing of flows	
2) Water quality	Comparative effects of alternative harvesting strategies on water quality
Task 2.1 Hillslope geochemical linkages	
Task 2.2 Stream sediment, turbidity, nutrients (N P), organics (DOC), base cations/anions, metals,	
Task 2.3 Sediment/nutrient interactions	
3) Stream health	Comparative effects of alternative harvesting strategies on aquatic
Task 3.1 Algal communities	
Task 3.2 Invertebrate communities	
5) Regional effects	Basin scale effects of forest harvesting on flow and water quality
Task 5.1 Downstream flow dynamics	
Task 5.2 Sed./nutrient loading & interactions	
6) Contaminant source tracing	Comparative basin scale effects of harvesting strategies on water quality
Task 6.1 Downstream fate of contaminants	
7) Regional contaminant transport modeling	Evaluation of basin scale cumulative water quality effects
Task 7.1 Contaminant transport model calibration	
9) Treatment impacts assessment	Comparative effects of harvesting strategies on drinking water treatability
Task 9.1 Drinking water treatability impacts of alternative harvesting strategies (solids removal, coagulant demand, DBP & membrane fouling potential)	
Task 9.2 Comparative drinking water treatability impacts of alternative harvesting strategies and wildfire (solids removal, coagulant demand, DBP & membrane fouling)	
11) Economic evaluation of land management strategies	Comparative effects of harvesting strategies on ecosystem services
Task 11.1 Evaluate comparative impact of land management options on water ecosystem services (WES)	
Task 11.2 Evaluate sensitivity of impacts to ecosystem services under varied population growth and demographic scenarios	

Best Practices Development Focused Milestones	
Task Description	**Milestone / Deliverable**
4) Best practices for sediment management	Evaluation of combined erosion control, road deactivation / reclamation best practices. Calibrated sediment assessment tool
Task 4.1 Evaluation of rapid road deactivation / reclamation practices	
Task 4.2 Development-modification of support tools suite for identification of priority areas for sediment	
7) Regional contaminant transport modeling (con't.)	Evaluation of basin scale cumulative watershed effects of alternative SWP
Task 7.2 Quantify downstream water quality from upstream management alternatives (natural	
8) Regional fisheries habitat	Calibrated bio-physical model to evaluate effects of land management options on critical or endangered fish (ecosystem services)
Task 8.1 Calibrate sediment-fish spawning habitat model	
Task 8.2 Quantify comparative effects of management alternatives on fish spawning habitat	
10) Best practices for treatment resiliency	Treatment best practices tools and decision support framework w/ guidance document
Task 10.1 Best water quality characterization tool summary	
Task 10.2 Reservoir risk characterization framework	
Task 10.3 Treatment resiliency decision support framework	
Task 10.4 Adaptation strategies guidance document for small utilities	
12) Optimal drinking water supply investment strategies	Evaluation framework for optimal utility investment strategies
Task 12.1 Model optimal utility investment strategies (technology, SWP) under uncertain land conditions	
13) Knowledge and best practices workshops	Knowledge - best practices mobilization workshop, Synthesis of research
Task 13.1 Knowledge and best practices mobilization workshops	

E Project Results

KNOWLEDGE DEVELOPMENT FOCUSED MILESTONES

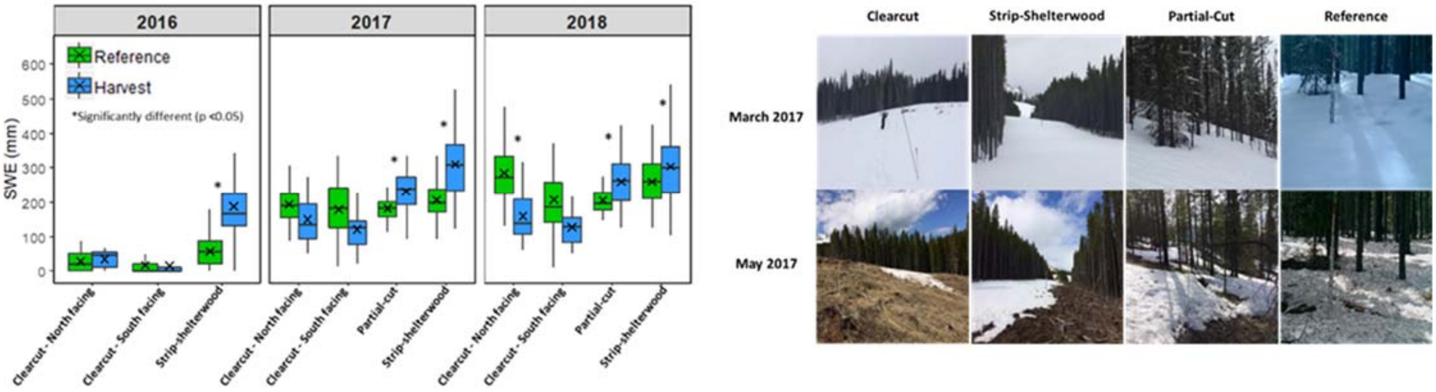
E.1 *Milestone 1 - Comparative Effects of Harvesting Strategies on Hydrology*

E.1.1 *Task 1.1 Snowpacks*

Forest canopies regulate snowpack accumulation by a) intercepting (catching) and subsequently evaporating snow which reduces snow accumulation, and b) limiting ground-level solar radiation which regulates timing of snowmelt. Thus, harvest effects on snowpack accumulation and melt are important drivers regulating harvest impacts on hydrology. Our results (MSc D. Greenacre) showed all three harvesting strategies employed in Star Ck. had substantial impacts on both snowpack accumulation and melt dynamics during the winters of 2016-2018.

While peak snowpack accumulation (Snow Water Equivalent; SWE - liquid water equivalent of snowpacks) was variable from year to year because of differences in winter snowfall, general pattern of effects of the three harvesting strategies on peak SWE were consistent over the winters 2016/17 - 2018/19 (Fig. 2).

Figure 2 – a) Peak snowpack SWE and b) comparative melt of 3 harvesting strategies (2016-2018)



Despite strongly reduced snow interception losses after clear-cut harvesting, we observed consistently lower snowpacks (compared to reference stands) after clear-cut harvesting. This finding is in strong contrast to the vast majority of studies where increased snowpacks after harvesting are typically reported. This novel finding likely reflects the particularly dry, continental snowpacks of Alberta's Rockies where increased solar radiation and wind scouring of dry snow strongly reduced snowpack accumulation in our clear-cut sites (particularly on south-facing clear-cuts). Average peak SWE in north-facing clear-cuts was reduced by 17% compared to reference stands, whereas the very strong increase in solar radiation on south-facing clear-cuts resulted in a 28% reduction in average peak SWE. Effects of cut-block orientation on solar radiation was a key factor regulating harvest effects on melt dynamics where greater solar radiation on south-facing clear-cuts advanced the onset of melt by two weeks compared to north facing clear-cuts (Table 2).

Table 2 – Overall effect of harvest strategies on snowpack accumulation and melt (2016-2018)

Harvesting Strategy	*Effect on peak accumulation (SWE)*	*Effect on timing of melt*
Clearcut south-facing	-28%	Much earlier
Clearcut north-facing	-17%	Earlier
Partial-cut	+28%	Delayed
Strip-shelterwood	+43%	Strongly delayed

In contrast, snowpack accumulation was strongly increased in areas harvested using partial-cut and strip-shelterwood harvesting where the sheltering effect of these harvest patterns on solar radiation and wind resulted in 28% and 43% increases in peak SWE, respectively. Greater snowpack accumulation with moderate sheltering of radiation/wind in the partial-cut and a stronger sheltering effect in the strip-shelterwood also produced substantial differences in melt rate and timing of disappearance of snow cover. The melt was substantially delayed in the partial-cuts and very strongly delayed (3-4 weeks) in the strip-shelterwood harvested areas.

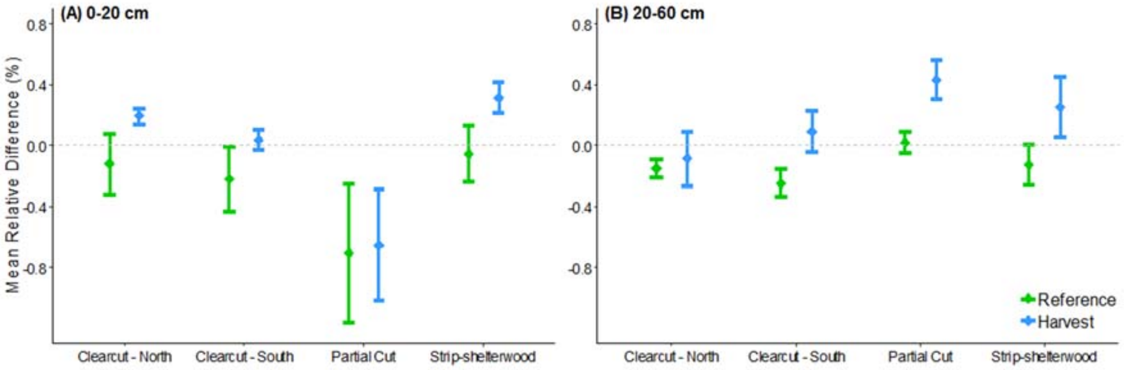
E.1.2 Task 1.3 Soil Moisture

Removal of forest canopies during harvesting can result in increased soil moisture because of reduced interception of rain and snow, and reduced evaporative losses by the canopy. Extensive soil moisture monitoring was conducted beginning after snowpack disappearance to the late fall (2016-2018) to characterize the effects of all three alternative harvesting strategies on soil moisture storage in both shallow (0-20 cm) and deeper (20-60 cm) soil layers. These two layers would reflect potential harvest effects on a) plant/tree growth regulating evaporative losses and b) broader hydrologic responses to precipitation, respectively.

Total soil moisture storage increased substantially across harvested areas of all three harvest strategies where average total seasonal increases in soil moisture (0-60 cm depth) were greatest after strip-shelterwood cutting (39%), followed by clear-cut harvesting (25% across south and north-facing clear-cuts), and partial-cut harvesting (19%). While the magnitude of increases in soil moisture generally reflected the snowmelt legacy of harvest effects in regulating growing season soil moisture (strip-cut and partial-cut), strongly increased soil moisture was evident in both north and south facing clear-cuts despite the strong reduction in snowpacks after clear-cutting (see E.1.1 above).

The effects of harvesting on increased soil moisture of both shallow and deeper soil layers were generally similar (Fig. 3), however seasonal patterns highlighted some important differences. In particular, soil moisture was strongly increased post-harvest in deeper soil layers during the exceedingly dry mid- and later growing seasons of both 2017 and 2018. However, soil moisture reserves in the more sheltered (lower wind and solar radiation) partial-cut and strip-shelterwood harvests were slightly less susceptible to these exceptionally dry conditions. While soil moisture reserves in shallow layers were strongly depleted, soil moisture remained strongly elevated in deeper layers of harvested areas compared to unharvested reference sites suggesting greater potential for hillslope hydrological connection with streams. Increased soil moisture reserves in deeper soil layers may also limit impacts of severe drought conditions for vegetation after harvesting.

Figure 3 – Relative (normalized) effects of harvest strategies on a) shallow, and b) deep soil moisture

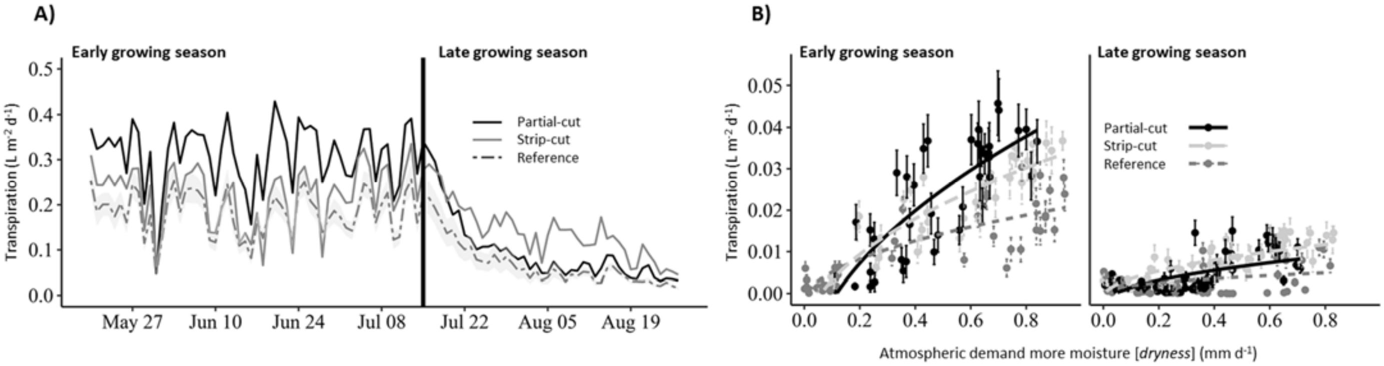


E.1.3 Task 1.2 Evaporative Losses

In addition to the harvest effects on evaporative losses from snowpacks described in E.1.1, reduction in the total evaporative loss through transpiration of forest canopies during the growing season is often considered the dominant process by which forest disturbance can affect streamflow. However, such changes are rarely studied directly; thus, the effects of altered post-harvest microclimate and soil moisture on transpiration losses remain unknown. The effect of these factors on post-harvest transpiration of unharvested residual trees/stands were studied (MSc student, S. Karpyshin) during the 2017 / 2018 growing seasons to determine if post-harvest changes in microclimate and soil moisture resulted in changes in transpiration of the remaining forest.

Transpiration of residual trees after partial-cut and strip-shelterwood harvesting were found to be highly responsive to increased soil moisture reserves (see E.1.2 above) and changes in micro-meteorological conditions (increased radiation, wind, etc.). Transpiration of residual trees was 60% greater in the partial-cut stand and 40% greater in the strip-shelterwood stand compared to reference (unharvested) stands (Fig. X). While transpiration was greatest during the moister, early growing season compared to the drier, late season for both 2017 and 2018, which were exceptionally dry years in south-west Alberta. Increased post-harvest rooting zone soil moisture enabled residual trees to maintain much higher transpiration rates despite increased atmospheric demand for moisture (atmospheric dryness)..

Figure 4 – A) Mean early and late season canopy transpiration, and B) transpiration per unit atmospheric moisture demand



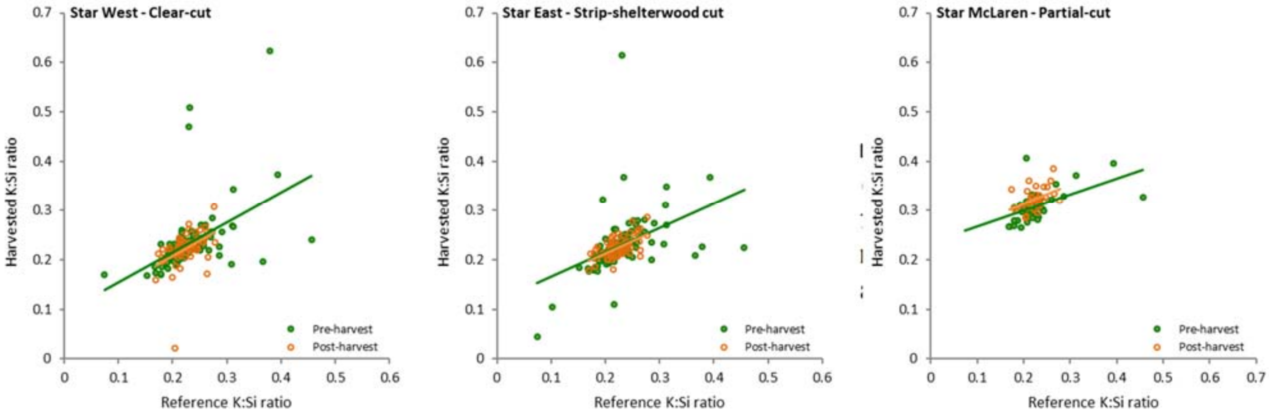
While harvesting removed trees from 44 ha (30%) and 55 ha (58%) of the lower forested watersheds in Star East (strip-shelterwood) and Star McLaren (partial-cut), respectively, the increased transpiration of residual trees was scaled-up to estimate the net effect of harvesting on sub-watershed scale evaporative losses. Results suggest if the transpiration rate of residual trees had remained unaffected by the harvest, total evaporative losses in the lower forested watersheds from transpiration would have been expected to decline by -31% and -38% in Star East and Star McLaren watersheds, respectively. In contrast, the elevated transpiration rates of residual trees almost fully compensated for the reduction in evaporative fluxes in after strip-shelterwood harvesting (only -1% less than pre-harvest), and actually increased evaporative losses in the partial-cut watershed (3% greater than pre-harvest). This finding is notable because it shows that the hydrologic impact of various harvesting strategies is not proportional to the disturbance footprint (% harvested) and has direct application in forest management planning procedures designed to manage disturbance impacts on water resources (i.e. Equivalent Clear-cut Area analysis, Alberta & B.C.).

E.1.4 Task 1.4 Surface Water / Groundwater Interactions

Runoff from undisturbed forested watersheds is often dominated by sub-surface flow generation pathways. Indeed, our previous research in Star Ck. suggested that prior to harvesting, approximately 74% of the total annual streamflow was generated through slower, sub-surface and groundwater runoff pathways (Wagner et al. 2014). However, numerous watershed studies have reported that disturbances such as harvesting can increase generation of surface runoff and peakflows from large storms, potentially causing deterioration of water quality and the destabilization of streambanks. In contrast, there is also a growing body of research suggesting the Rocky Mountain region may be more hydrologically resistant to disturbance (Harder et al. 2015) likely because of the dominance of groundwater contributions to streamflow in association with the large storage capacity of glacial tills and fractured, permeable sedimentary bedrock. Thus, changes in surface water / groundwater interactions provide important mechanistic insights into potential land disturbance impacts on hydrology.

Potential changes in surface water / groundwater after harvesting were evaluated using several approaches. Firstly, sub-catchment scale water quality response of potassium:silica ratios (geochemical tracer indicating relative dominance of surface:subsurface flow pathways) were evaluated to explore if this indicator of surface runoff generation was affected by any of the three harvesting strategies. A fully controlled paired catchment ANCOVA was used to evaluate if the relationship of this ratio in the harvested watersheds compared with the reference watershed (N. York Upper) had changed between the period prior to and after the 2015 harvest in Star Ck. These results show that based on this proxy indicator, no change ($p>0.59$) in the fraction of surface:sub-surface runoff occurred between the period prior to and after any of the 3 harvests were conducted (Fig. 5).

Figure 5 – Effect of the three harvest strategies on K:Si ratio (*proxy indicator of surface runoff*)

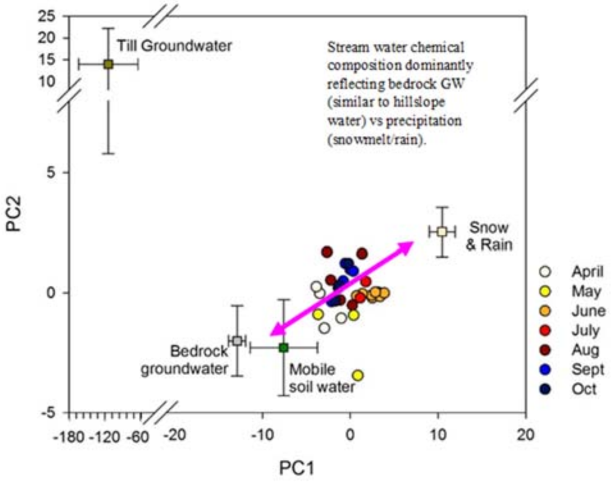


It is also noteworthy that this analysis using geochemical tracers suggests 76% of the streamflow generated in the headwaters sub-watersheds of Star Ck. is likely from sub-surface or groundwater sources which is in surprisingly close agreement with our previous estimate of 74% (Wagner et al. 2014) based on completely independent hydrograph separation techniques.

A comprehensive series of studies (Ph.D. student, S. Spencer) also provided important additional insights on groundwater / surface water interactions in Star Ck. to evaluate the first order controls governing runoff generation to help assess watershed responses to disturbance. For example, while streamflow in upper alpine stream reaches contributed approximately half the stream discharge for the watershed as a whole, streams in forested lower elevation watersheds were poorly coupled to the hillslopes and produced little contribution to streamflow. Indeed, much of the lower watershed contributed to groundwater recharge rather than storm runoff for much of the year. This preferential groundwater recharge could reduce the hydrologic impact of forest harvesting in the forested, lower elevation areas.

Groundwater storage was an important factor governing variation in total annual runoff across multi-year historic dry (2008-12) and wet periods (2013-14), but showed no notable influence on storm runoff responses. This provides important insights into potential impacts of forest disturbance because larger runoff responses would be expected following disturbance. Instead, shallow sub-surface storage (soil and surface glacial till), in conjunction with spring snowmelt, appeared to control hillslope connectedness and magnitude of storm runoff response. Deeper bedrock groundwater appeared to regulate broader overall annual flow because of the dominance of vertical percolation and groundwater recharge and high annual groundwater contribution to streamflow (Spencer et al. 2019).

Figure 6 – Stream water chemical composition in relation to surface- / sub-surface water sources



Dominance of groundwater contributions to streamflow were also explored by chemical source tracing that showed groundwater dominated the composition of streamflow much of the year, but was diluted by spring/early summer meltwater when snowmelt saturated the landscape connecting hillslopes to the streams (Fig. 6). Water level responses in the glacial till well suggested slow release of till groundwater to the stream. Similar to other studies, this suggests that glacial till groundwater contributes to late season or overwinter baseflows. This series of studies illustrated that large storage capacity of glacial till and slow release of groundwater is likely a key factor governing watershed resistance to disturbance that has been observed in front-range Rocky Mountain watersheds in Alberta (Spencer et al. 2019).

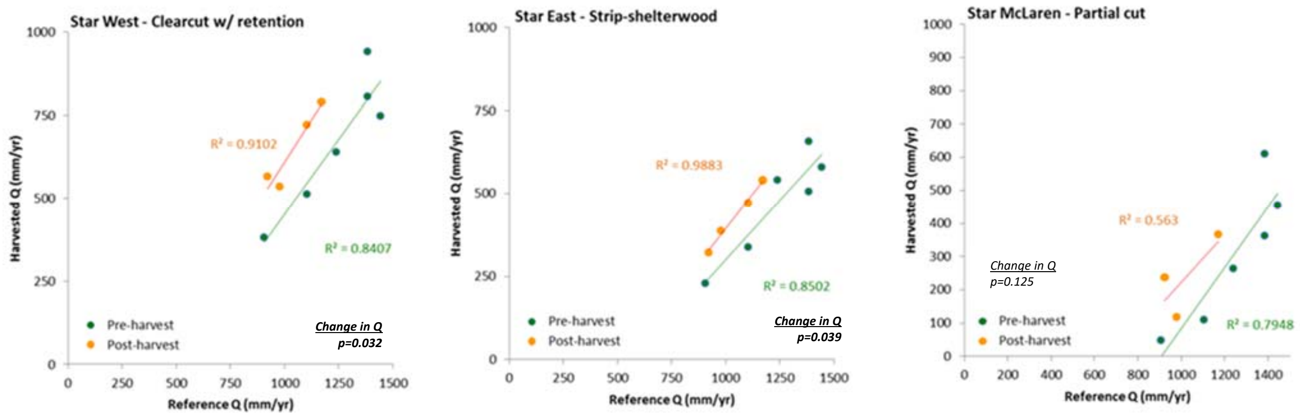
E.1.5 Task 1.5 Volume and Timing of Streamflow

The paired catchment (before/after; control/impact) study design serves as a powerful platform for assessing the impact of the three alternative harvest strategies on total annual volume and timing of streamflows. However, because of strong governing role of weather and climate in governing streamflows, a minimum of 5-7 years of post-harvesting flow observations are required to support definitive conclusions on harvest effects to streamflow. Because these data represent interim results, they should be interpreted cautiously.

Harvesting began in Star Ck. in Jan. 2015 and the majority of harvest operations were progressively completed in the clear-cut unit (Star West) by Feb/March, the strip-shelterwood unit (Star East) by June, and the partial-cut (McLaren Ck.) by late August. These were followed by completion of associated silvicultural, and road/stream crossing decommissioning operations by late Sept. 2015. Thus, for the early assessment of harvesting impacts on streamflow, we include the 2015 harvest year along with 3 additional full years (2016-2018) of flow data after the clear-cut and strip-shelterwood cutting. In contrast, only 3 years (2016-2018) were analyzed for the partial-cut as McLaren creek is ephemeral, typically flowing only from late spring to early July. Harvest operations were still only partially completed by the time McLaren Ck. had already stopped flowing in 2015.

Despite comparatively low total disturbance footprints and only 4 years post-harvest flow measurements, total annual area-weighted flow was significantly increased after both clear-cut (179 mm/yr, p=0.032) and strip-shelterwood (130 mm/yr, p=0.039) harvests in Star West and East, respectively (Fig. 7). This represented a mean (climate adjusted) increase in flow over pre-disturbance streamflows of 29.8% and 27.1%, respectively. While visual comparison of pre- and post-harvesting relationships between the reference watershed (N. York Upper) and McLaren Ck. suggest harvesting likely resulted in increased flow, 3 years of post-harvest flow data do not enable any initial quantification of these effects (r^2=0.56, p=0.46). More definitive evaluation of harvest impacts will be possible with several additional years of streamflow monitoring.

Figure 7 – Preliminary effects of three harvesting strategies on total annual streamflow



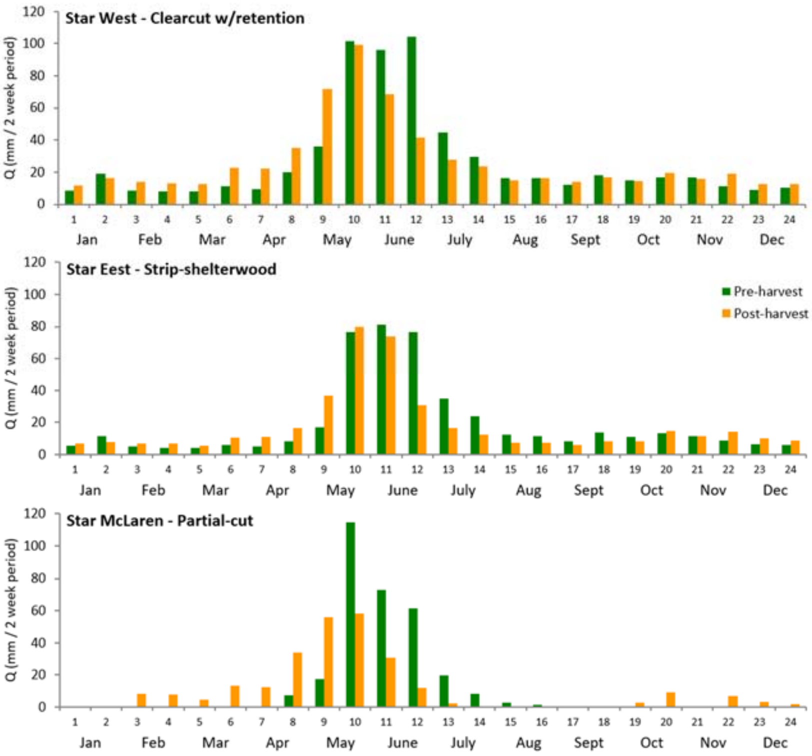
Similarly, preliminary assessment of harvest effects on seasonal timing of flows can only be preliminarily assessed with this flow record. Furthermore, the very short record of seasonal distribution of post-harvest flows does not yet enable evaluating the climate-adjusted change in flows which would correct the data for subtle changes in monthly weather/climate between the pre-harvest (2005-2014) and post-harvest (2015-2018) periods. Raw un-adjusted mean seasonal flows are presented here for illustrative purposes and should not be interpreted as fully climate adjusted results.

The seasonal distribution of streamflow was compared across 24- two-week periods to enable summarizing flows for the front and back halves of each month (Fig. 8). For both Star West and Star East, the distribution of bi-weekly streamflows associated the rising and falling limb of the spring snowmelt freshet hydrograph appear to have been shifted forward in time by approximately 2 weeks. However, harvesting does not appear to have influenced either the timing or total runoff during the peak snowmelt period. Advanced onset and early progression of the spring snowmelt freshet in April and May, also appear coupled with a decline in post-peak flow recession in June and July. Consistent with our snowpack results, and the findings from earlier watershed studies in the Colorado Rockies (Troendle and King 1985), these preliminary results suggest that by exposing deeper, post-harvest snowpacks to early spring solar radiation, earlier onset of snowpack melt was associated with early initiation of the snowmelt freshet in harvested watersheds. However, in contrast to impacts of harvesting in Colorado, these results also suggest that the effective catchment scale melt contributions may be exhausted earlier in harvested watersheds similar to recent results reported by Winkler et al. (2017) in the B.C. interior.

Seasonal timing of flows may have been somewhat differently affected in the more extensive partial-cut harvesting (Star McLaren). Consistent with Star West and East Cks., the timing of snowmelt freshet runoff appears to be advanced by > 2 weeks, however streamflow during the peak snowmelt period appears substantially diminished. In particular, the streamflow regime of this small ephemeral creek appears to be extended into the early spring and late fall periods whereas this stream was flowing only from mid-April to late-July prior to harvesting.

Furthermore, preliminary analysis of the association of increased total annual streamflow in Star West and East with peakflows or stormflows showed no evidence of increased instantaneous peakflows or total event stormflows after harvesting for either small or large stormflow events (some interim indication of peakflow actually declining after harvesting). However, these data are highly

Figure 8 – Preliminary effects of three harvesting strategies on seasonal timing of streamflows



preliminary (thus not presented here) and should be considered very cautiously. However, they are strongly consistent with several lines of evidence from the analysis shown in E.1.4 and additional downstream analysis of base geochemistry suggesting the increased streamflows after harvesting are likely driven by deeper sub-surface or groundwater flowpaths not associated with increased surface flows or stormflows.

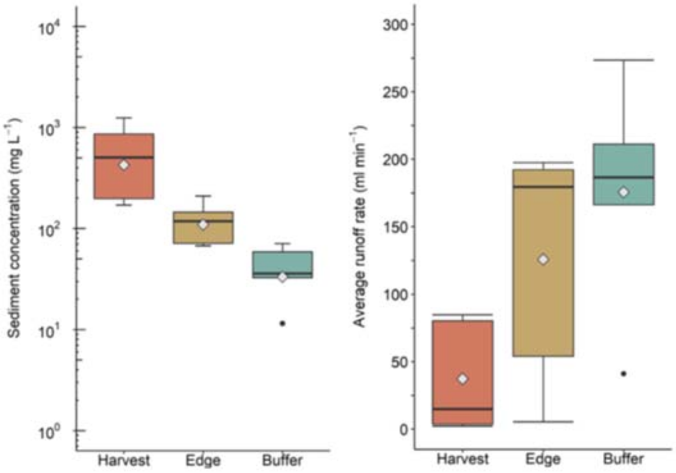
E.2 *Milestone 2 - Comparative Effects of Harvesting Strategies on Water Quality*

E.2.1 *Task 2.1 Hillslope geochemical linkages*

Two graduate student projects evaluated harvesting effects on a) hillslope erosion and sediment production, and b) hillslope nitrogen production.

The objective of the first study (MSc. student, K. Puntenney) was to characterize erosion and delivery of sediment from the clear-cut harvest in Star West under the worst-case conditions of extreme intensity (1:100 year) rainfall events using a portable rainfall simulator. Consistent with expectations, results showed greatest sediment concentrations in runoff water from the interior of harvested / scarified cutblocks compared to cutblock edges, or adjacent riparian buffers. However, contrary to expectations, much lower runoff was generated from cutblocks during these high intensity rainfall events because of both high rainfall infiltration rates in scarified cutblocks and naturally occurring water repellency in undisturbed riparian stands (Fig. 9). As a result, there was no evidence of sediment transport from cutblocks into, let alone through riparian buffers and into receiving streams. Ground surface roughness after scarification promoted vertical water infiltration in cutblocks making sediment transport to-, and through riparian buffers highly unlikely in physiographic settings similar to Star Creek (Puntenney-Desmond et al. 2020).

Figure 9 – Sediment concentration and runoff from cutblocks, block edges, and riparian buffers



The objective of the second project (MASc student, M. Stewart) was to explore post-harvest nitrogen (N) dynamics on clear-cut harvested hillslopes to identify nitrogen delivery pathways to streams. It was expected that harvesting effects on factors controlling N cycling such as soil moisture and temperature would produce effects on soil and porewater ammonium (NH_4^+) and nitrate (NO_3^-). While soil NO_3^- and total N were greater on south-facing compared to north-facing hillslopes, no harvest effects on spatial patterns of soil or soil porewater N were evident among clear-cut harvested and reference hillslopes.

Figure 10 – Rapid post-harvest vegetation establishment after clear-cut harvesting in Star West

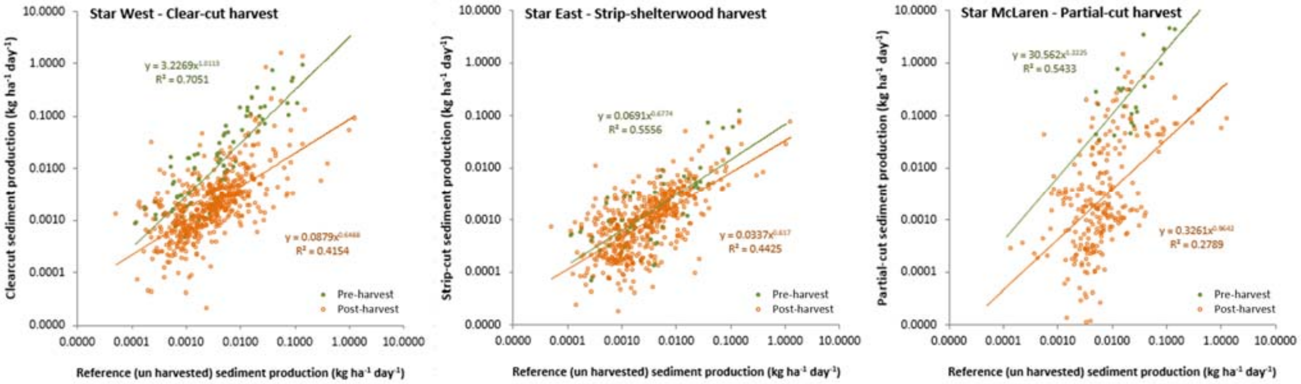
Rapid uptake by vegetation and microbial immobilization (Fig. 10) were likely responsible for these findings. However, this study provided a clear mechanistic explanation for the lack of a catchment-scale water quality response in Star West (see E.2.2 below) and further support the notion of high potential ecosystem and watershed resilience to disturbance to N regimes in this region.

E.2.2 Task 2.2 Catchment-scale water quality

Key water quality parameters were measured using a combination of continuous monitoring with water quality probes, automated daily sampling with ISCOs, and routine manual sampling every 10-14 days (+ storm sampling). Results from a broad range of water quality parameters (sediment, nutrients, base ions) showed a high degree of consistency across the three alternative harvesting strategies. These included parameters for which a) no detectable effect was observed, or b) a strong decline (*improvement* of water quality) was observed after harvest.

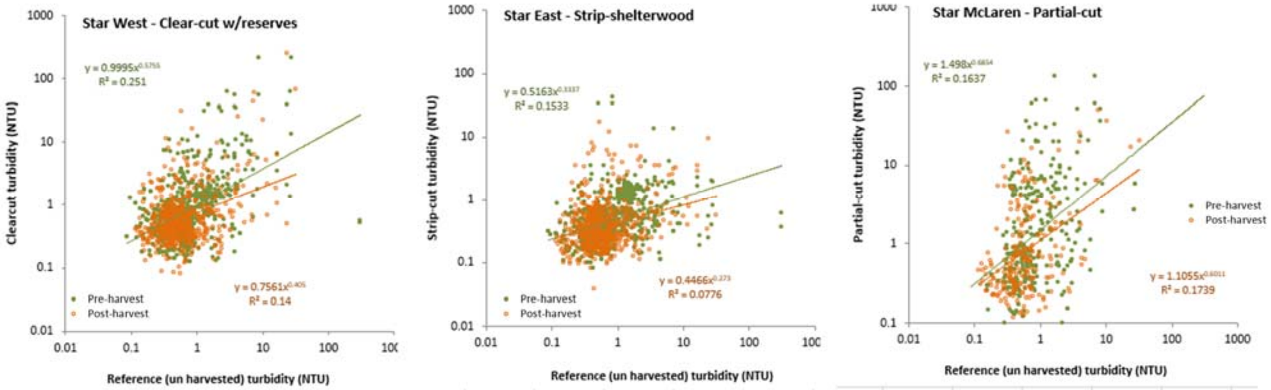
Sediment concentration (TSS) declined strongly (80-90%) for the 4-year period (2015-2018) after clear-cut and partial-cut harvesting ($p<0.001$). While a smaller 9% reduction in mean sediment concentrations were also evident after strip-shelterwood harvesting, these reductions were not statistically significant ($p=0.64$). Similarly, total sediment production (flow weighted yield) declined strongly after all three harvest strategies ($p<0.001$, Fig. 11) where sediment production was 15%, 73%, and 95% lower after strip-shelterwood, clear-cut, and partial-cut harvesting, respectively.

Figure 11 – Sediment production (yield) from three watersheds before-, and after harvesting



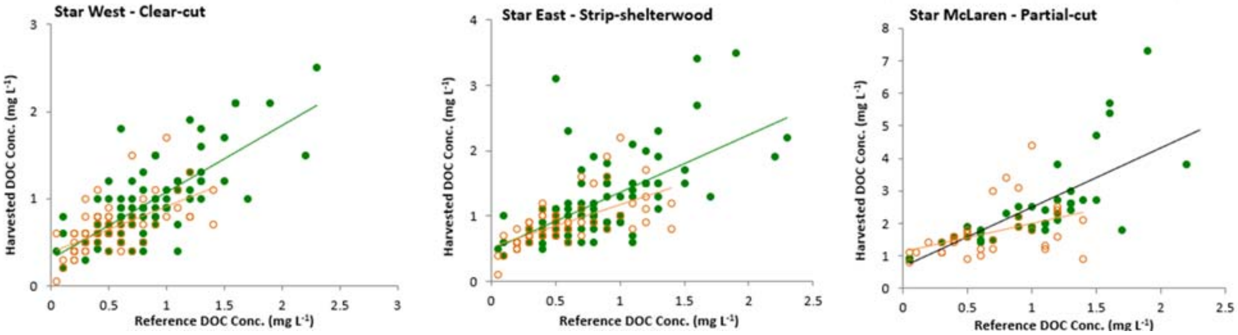
While sediment production indicated by total suspended solids (TSS, above) include the entire spectrum of sediment particle sizes (fine to coarse), TSS is more responsive to variation in coarse sediment particles. In contrast, turbidity (measure of optical clarity) can serve as a better indicator of finer sediments. Similar to results for TSS, fine sediments as indicated by turbidity were reduced by 18% to 25% during the 4 years after harvesting ($p<0.001$, Fig. 12).

Figure 12 – Turbidity from three watersheds before-, and after harvesting



The concentration and total production of key dissolved nutrients (total N, total dissolved N, NH_4^+, NO_3^-, total P, total dissolved P, soluble reactive P, dissolved organic carbon) were similarly either unaffected or were reduced after harvesting. For example, while weaker, 8% to 9% decreases in DOC concentration were evident in Star West and Star East, these decreases were not statistically significant ($p>0.26$). However, a stronger 17% decline in DOC concentration after harvesting was observed in Star McLaren (Fig. 13).

Figure 13 – DOC concentration from three watersheds before-, and after harvesting



However, despite the lower DOC concentrations after harvesting, the total flow-weighted production (yield) of DOC remained unchanged because the decreased concentrations were balanced against increased post-harvest streamflow (see E.1.5). Thus, the increased streamflow evident in all three watersheds produced similar patterns of either a) decreased nutrient concentrations but no change in total yield, or b) no change in nutrient concentrations but increased nutrient production (Table 3).

Table 3 – Significance of observed harvesting effects on total nitrogen (TN), phosphorus (TP), and dissolved organic carbon (DOC) concentrations and yield

	Nutrient concentation			***Nutrient production (yield)***		
	TN	**TP**	**DOC**	**TN**	**TP**	**DOC**
Star West - Clearcut w/ reserves	*no effect*	*lower (-6%)*	*no effect*	*higher +19%*	*no effect*	*higher +37%*
Star East - Strip-shelterwood	*no effect*	*lower (-7%)*	*no effect*	*no effect*	*no effect*	*higher +27%*
Star McLaren - Partial-cut	*no effect*	*lower (-2%)*	*lower (-17%)*	*no effect*	*no effect*	*no effect*

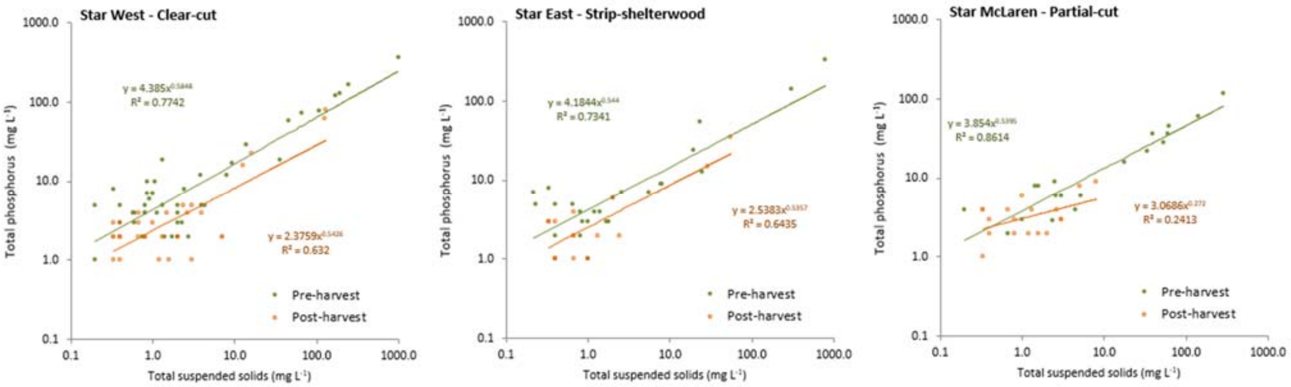
Similarly, while variable effects on concentration of base ions were observed, the yield of many ions potentially indicating harvest effects on sub-surface or groundwater inputs to streams (Ca^{2+}, Mg^{2+}, Si) were marginally increased after harvesting (consistent with results shown in E.1.4).

E.2.3 Task 2.3 Sediment / Nutrient Interactions

Key nutrients such as carbon, and phosphorus can be stored and transported in association with fine sediments. For example, phosphorus and fine sediment production are well known to be closely coupled (Emelko et al. 2016) which is particularly important in this region because phosphorus is the key nutrient limiting aquatic productivity in this study area (Silins et al. 2014, Martens et al. 2019).

Forest harvesting in 2015 did affect the relationships between sediment and these key water quality factors. Not only did suspended sediment concentrations and turbidity (finer sediments) decline after harvesting in all three sub-catchments, relationships between sediment (TSS) and total phosphorus (TP) show that phosphorus production per unit sediment concentration also declined by 40% to 48% during the 4-year period after harvesting (Fig. 14). These changes were particularly notable in the clear-cut and partial-cut watersheds (p<0.001 and p=0.025, respectively) with marginally weaker decreases evident in the strip-shelterwood cut watershed (p=0.065).

Figure 14 – Relationship of total phosphorus with suspended sediment for three watersheds before-, and after harvesting



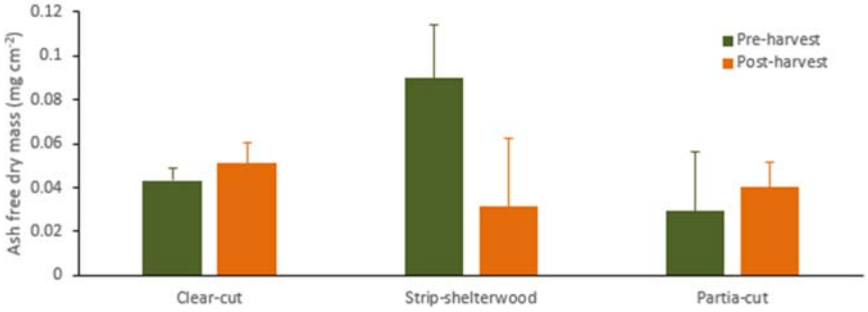
While potential harvest effects on specific forms of phosphorus were not studied (i.e. biologically reactive, organic, or geological forms), these results establish the broad explanation for why ecologically limiting nutrients associated with sediment (such as phosphorus) declined after harvesting; reduced post-harvest phosphorus concentration and production (Table 3) reflected the combination of lower absolute sediment production (Fig. 11; hence less phosphorus), plus lower phosphorus concentrations per unit sediment after harvesting (Fig. 14). Additional insights into this and other sediment / nutrient interactions including the association of carbon with sediment oxygen demand in downstream regions are reported on for Milestones 6 and 8.

E.3 Milestone 3 - Comparative Effects of Harvesting Strategies on Stream Health

E.3.1 Task 3.1 Algal Communities

Algal productivity was assessed monthly by scraping algae from replicate unglazed porcelain tiles deployed in harvested and reference streams, before (2004-2014), and after harvesting (2015-2018). Algal productivity was assessed using two measures; a) ash-free dry mass (AFDM) of monthly algal growth, and b) chlorophyll-a concentration (Chlor-a) of algae (not shown). While mean monthly algal production was highly variable over this long record, the paired catchment (BACI) design using ANCOVA enabled controlling for variability in climate/weather (removing the effect) over this long period. While climate adjusted mean algal growth varied from the pre-harvest period by -12% (Star East) to +2.5% (Star McLaren), no change in algal productivity based on either AFDM or Chlor-a was evident in any of the harvested watersheds (p=0.26, 0.11, and 0.40 for the clear-cut, strip-shelterwood, and partial-cut watersheds, respectively; Fig. 15).

Figure 15 – Mean monthly algal productivity (+ 1 se) from 3 watersheds before-, and after harvesting



E.3.2 Task 3.2 Invertebrate Communities

Our previous research confirmed the strong hydro-ecological linkages between sediment/phosphorus production and algal productivity as key controls driving subsequent changes in benthic macroinvertebrate communities in this region (Silins et al. 2014, Martens et al. 2019). However, because interim results showed no effect of harvesting on key a) nutrient regimes or b) algal productivity that would be needed to affect a change in these communities, our findings indicated characterizing invertebrate communities was not warranted and they were not evaluated as originally planned.

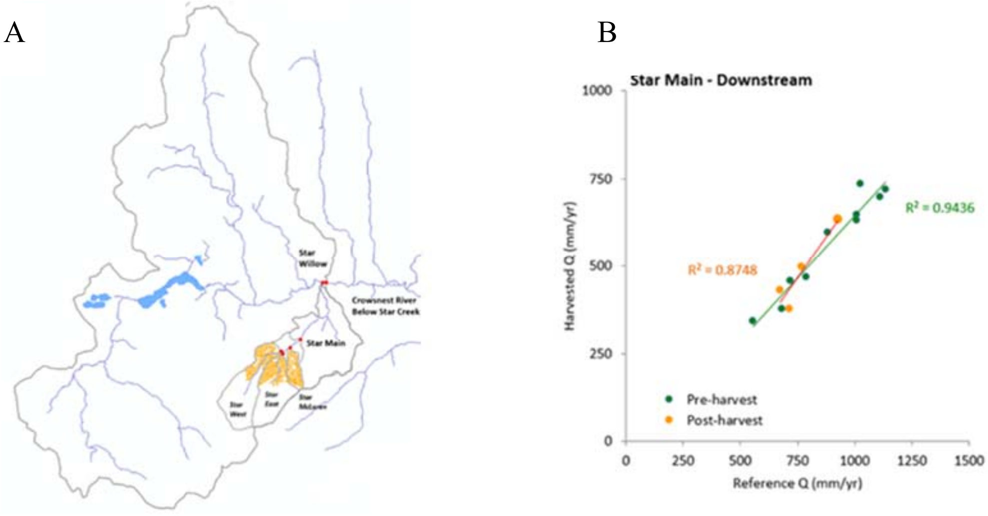
E.4 Milestone 5 - Downstream Effects of Upstream Harvesting on Flow and Water Quality

E.4.1 Task 5.1 Downstream Effects on Streamflow from Upstream Harvesting

Detection of hydrologic or water quality effects downstream of headwaters disturbances is difficult because of a) strong scale-dependence of streamflows, and b) broader cumulative watershed effects from other factors at larger downstream spatial scales (Reid 1993, Blöchl et al. 2007). While this often results in watershed impacts becoming undetectable as watershed scale increases downstream, the fully controlled (pre-, post-disturbance) paired-catchment design of this study imparts far greater power to detect these effects than the vast majority of studies. Moreover, no previous studies on forest harvesting anywhere world-wide include the downstream monitoring to enable this analysis.

Effects of upstream harvesting on streamflow at larger, downstream spatial scales were evaluated using the nested watershed design of this study (Fig. 16A). Despite considerable harvesting effects on streamflow for individual sub-catchments, the combined effects on total annual streamflow became undetectable only a short distance downstream of all three headwaters sub-catchments (p=0.83, Fig 16B). However, a weak effect on the timing of seasonal flows (E.1.5) still appeared downstream at the Star Main gauge (not shown here).

Figure 16 – A) Nested catchments to monitor downstream effects of harvesting, and B) harvest effects on streamflow at Star Main



Analysis of headwaters catchment harvest effects on streamflow downstream to the confluence with the Crowsnest River (Table 4) was consistent with this finding. As the spatial disturbance footprint (% area disturbed) decreased downstream, the change in streamflow (both mm/yr and %) declined rapidly and remained undetectable below the Star Main stream gauge and further downstream. While upstream harvesting appeared to produce a very small increase in average annual flow in the Crowsnest River below Star Ck. of approximately 1.5%, this change was not statistically meaningful (p=0.47).

Table 4 – Downstream effect of upstream harvest on average unit area (mm/yr) and % total flow

Watershed	Area (ha)	Area disturbed (ha)	Area disturbed (%)	Δ Q (mm yr^{-1})	Δ Q %
Star West	463	71.7	15.5%	178.5	29.8%
Star East	389	45.1	11.6%	113.2	27.1%
McLaren	95	42.3	44.4%	106.8	45.3%
Star Main	1035	164.3	15.9%	21.6	4.0%
Star Willow	1855	165.1	8.9%	19.3	4.9%
Crowsnest R. below Star*	18269	165.1	0.9%	8.7	1.5%

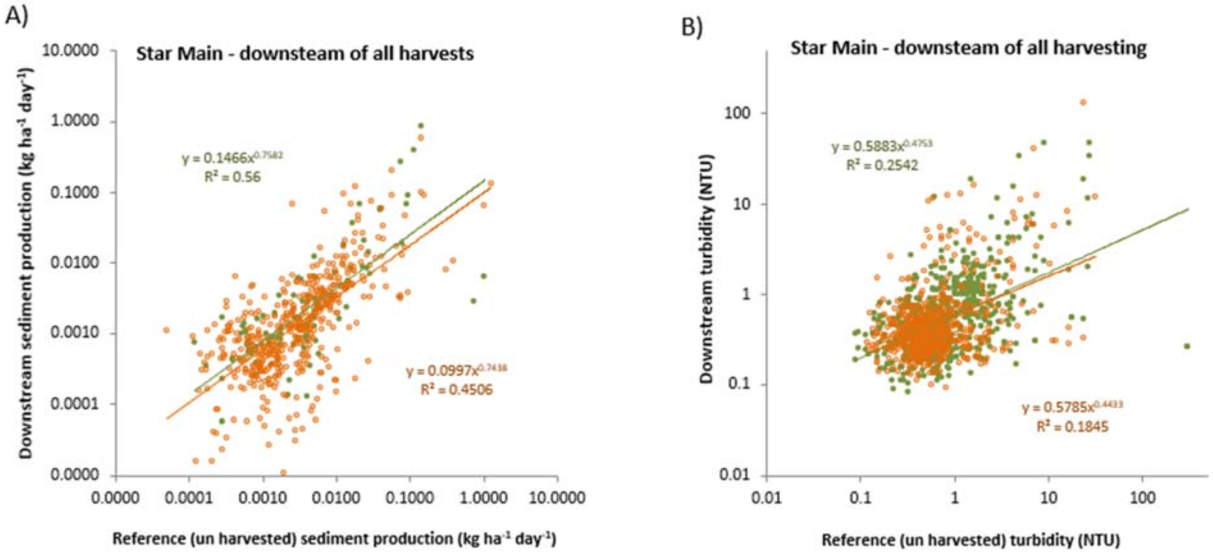
Red indicates significant at a=0.05
** due to gauging errors for this station, Δ Q estimated from upstream volumes*

While these findings are consistent with expectations, no previous studies to our knowledge have directly measured such downstream scale-dependent changes. More broadly however, the streamflow responses to harvesting in small headwaters catchments observed here are notably greater than have been previously reported in Rocky Mountain settings where a ~15% disturbance footprint has been suggested as the lower limit of detectable hydrologic change (Stednick 1996), whereas harvested effects on flow from Star West and East with 12-16% disturbance produced a considerable ~27-30% increase in streamflow. Provincial forest hydrology staff (AAF) indicate these findings will have a significant impact on refinement of forest watershed management procedures including Equivalent Clear-cut area modeling frameworks.

E.4.2 Task 5.2 Downstream Effects on Water Quality from Upstream Harvesting

As with downstream effects of harvesting on streamflow, assessment of potential downstream water quality impacts were evaluated using paired-catchment (before-, and after-) relationships of downstream watersheds with reference watersheds. Despite findings of lower post-harvest sediment concentrations in clear-cut and partial-cut harvested headwaters watersheds (E.2.2), only a minor 1.4% decline in sediment concentration was observed a short distance downstream at the Star Main stream gauge which was not statistically meaningful (p=0.83). However, a 9% reduction in sediment production (yield) and 6% reduction in turbidity were still evident at this lower gauge after harvesting (Fig. 17, $p<0.001$ and $p=0.002$, respectively). No meaningful changes in sediment or turbidity were observed at gauging sites further downstream to the Crowsnest River.

Figure 17 – Downstream sediment production A) and turbidity B) before-, and after harvesting



Additionally, no changes in nutrient concentrations or nutrient production (TN, TP, or DOC) were evident downstream of the headwater's catchments at the Star Main gauge, or gauges further downstream to the confluence of Star Ck. with the Crowsnest River. Most notably, these findings clearly illustrate that upstream harvesting in Star Ck. produced no downstream deterioration of water quality (sediments or nutrients) in strong contrast to common narratives that forest harvesting causes deterioration of downstream water quality. Again, these results are highly novel as no fully controlled studies of this type have been conducted anywhere to our knowledge.

E.5 Milestone 6 - Downstream Fate of Contaminants from Upstream Harvesting

E.5.1 Task 6.1 Contaminant Source Tracing from Upstream Harvesting

Knowledge of changes in both sediment source and supply resulting from landscape disturbance is necessary for practitioners to target sediment source problems at the watershed scale. Sediment fingerprinting is a powerful tool that is widely used to inform sediment management decisions because it can link tracer properties (mineralogical, bio-geochemical and contaminant composition) of sediment to its source (Pulley and Collins, 2018). We used this approach to evaluate the effects of wildfire on sediment source and downstream propagation to reservoirs (Stone et al., 2014) and showed that ~80% of post fire sediment deposited in the Oldman reservoir originated from ~14% of the upstream landscape that was burned. This study demonstrated that runoff after severe wildfire can transfer significant quantities of sediment to rivers and that these fine-grained pyrogenic materials can be propagated downstream for decades at large basin scales.

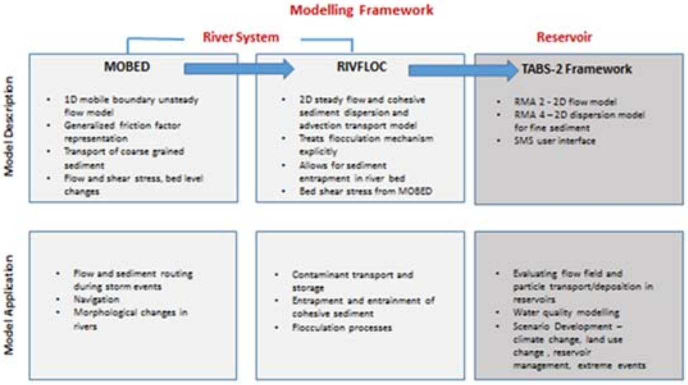
Building on our previous source apportionment work, we used sediment fingerprinting to evaluate the effect of harvesting on sediment sources in Star Creek and its downstream propagation in the Crowsnest River. Results of the sediment fingerprinting study showed there was no difference between pre and post-harvest mineralogical and geochemical tracer properties of sediment in Star Creek. This finding is consistent with results from Milestones 2 and 5.

E.6 *Milestone 7 - Regional Contaminant Transport Modelling*

E.6.1 *Task 7.1 Contaminant Transport Model Calibration*

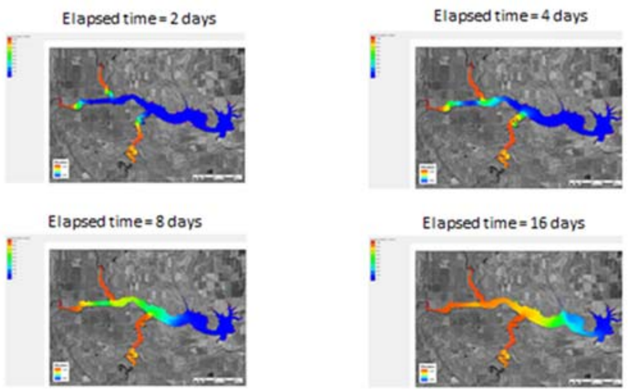
Landscape disturbance in critical forested source water regions can alter the flux of fine sediment and associated contaminants in rivers to downstream environments such as reservoirs and tools are needed to understand the transport and fate of these materials. A modelling framework (Fig. 18) was evaluated as a tool to simulate fine sediment transport in three main tributaries of the Oldman watershed (Castle, Crowsnest, Oldman).

Figure 18 – Contaminant transport modelling framework



Detailed hydrometric and sediment monitoring surveys were conducted for a range of flow conditions and the data were used to calibrate flow (MOBED) and sediment transport (RIVFLOC) models. Longer term flow and sediment data (2005 to 2009) from tributary inflows to the Crowsnest River were used to route sediment into the Oldman Reservoir and provide estimates of sediment loading from each landscape disturbance. The flow and sediment transport models were calibrated using measured flow and sediment concentration data in the study reaches for high, medium and low flow conditions. MOBED and RIVFLOC were used to route sediment to the reservoir and reservoir models (RMA2 and RMA4) were used to simulate flow and sediment dynamics in the Oldman reservoir. An example of RMA4 output illustrating sediment dispersion in the reservoir over time (Fig 19).

Figure 19 – Simulation of sediment dispersion predicted using the RMA4 model



E.7 Milestone 9 - Treatment Impacts Assessment

E.7.1 Task 9.1 Drinking Water Treatability Impacts from Three Forest Harvesting Strategies

Forest harvesting can affect hydrology and deteriorate source water quality (Feller 2005; Ice & Binkley 2003; Binkley & Brown 1993); thus, it is possible—and likely—they could impact on drinking water treatment. While natural and anthropogenic landscape disturbance effects on hydrology and water quality have been widely studied, forest management impacts on drinking water treatment by the full range of possible conventional and emerging in-plant treatment typologies (i.e., *treatability*); to date, they have never been reported globally outside of the presentations of work associated with this project.

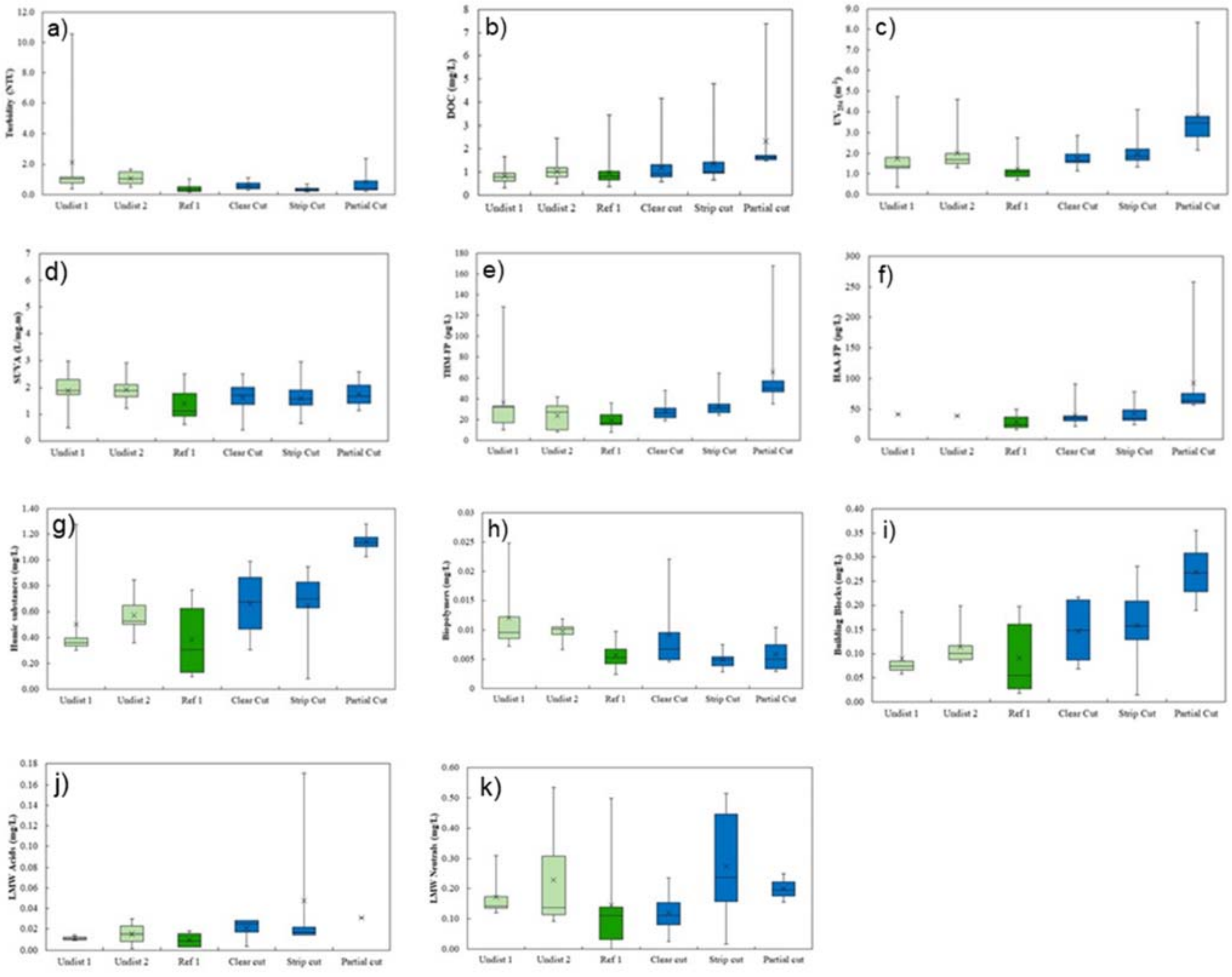
It is commonly recognized that turbidity (i.e., microns-sized and smaller suspended solids) and dissolved natural organic matter (NOM) are the main water quality drivers of drinking water treatment infrastructure and operational requirements/costs (MWH 2012; Emelko et al 2011). There are many different approaches that are used to evaluate shifts in these aspects of source water quality to inform drinking water treatability. The most useful *direct* metrics of drinking water treatability are (1) coagulant demand via jar testing (MWH 2012; Emelko et al 2011) to assess coagulant dose requirements and coagulation/flocculation/clarification infrastructure needs (as well as the potential need to implement advanced pre-treatment technologies such as powdered activated carbon [PAC] or enhanced coagulation [which includes pH adjustment]) to achieve turbidity and dissolved organic carbon (DOC) reductions and (2) disinfection by-product formation potential (DBP-FP); specifically, for trihalomethanes (THMs) and haloacetic acids (HAAs) because they are regulated, but also to more broadly signal the potential formation of undesirable DBPs of potential chronic risk concern.

Water quality measurements can be somewhat relied upon as general *proxy indicators* of drinking water treatability. While turbidity is typically directly evaluated, there are different approaches that are used to evaluate differences in dissolved NOM aspects of source water quality to inform drinking water treatability. At a minimum, assessment of the treatability proxies involves quantification of turbidity and dissolved organic carbon (DOC) because they are the most widely understood water quality drivers of treatment infrastructure and operational requirements/costs (MWH 2012; Emelko et al 2011). While increased turbidity loads to treatment plants result in obvious solids removal needs, DOC has several less obvious implications. It is typically present at low concentrations in forested watersheds and increases and/or changes in character (e.g. hydrophilicity/hydrophobicity, aromaticity) as a result of land disturbance (Emelko & Sham 2014; Shams 2018). Increases in DOC may necessitate the use of complicated and costly chemical pretreatment or increase chemical coagulant demand (Emelko & Sham 2014; Emelko et al 2011; Edzwald & Tobiason, 1999). Hydrophobic natural organic matter NOM, for which DOC is a surrogate, is a reactive precursor of regulated carbonaceous DBPs (Kitis et al 2002). Hydrophilic NOM is more difficult to remove by conventional treatment (Chow et al 2004) and forms unregulated DBPs of emerging health concern (Chen & Westerhoff 2010). Thus, NOM-associated treatability proxies include UV_{254}, specific UV absorbance (SUVA), fluorescence emission-excitation matrices [EEMs] in general, resin fractionation of hydrophobic and hydrophilic constituents, and further fractionation using liquid chromatography with organic carbon detection (LC-OCD). As UV absorbing compounds and aromatic carbon within NOM are generally understood to be primary sources of precursor materials for unknown and unregulated DBPs, SUVA is considered a good general indicator for their formation. Beyond coagulation needs and DBPs, further treatability challenges associated with shifts in NOM/DOC include increased distribution system regrowth of bacteria (Kaplan et al 1993); increased disinfectant demand (Jacangelo et al 1995); adverse taste/odor/color (Jacangelo et al 1995); membrane fouling (Kwon et al 2005); and increased heavy metal complexation—one of the biggest challenges in treatability assessment is to *reliably* link these various water quality-based proxy indicators to treatability impacts.

Drinking water treatability impacts of the three harvesting strategies (clear-cut, strip-shelterwood, and partial-cutting) were evaluated using a synoptic sampling approach (PhD Student S. Shams; MASc

Student S. Bahramian; PDF Dr. F. Amiri). It should be noted that care was taken to ensure that the analysis included a representative range of streamflow conditions (melt freshet stormflow and baseflow). Reference and harvested stream water turbidity, DOC, aqueous NOM proxies (UV_{254}, SUVA, and NOM fractions LC-OCD), and DBP-FPs were evaluated during the forest harvesting period and over the first three years following harvesting. These data are summarized in Fig. 20 where the undisturbed reference watershed is referred to as Ref 1. To the extent possible, additional pre-disturbance treatability data (i.e., collected prior to harvesting and previously reported in earlier SRWP investigations) were also included in this analysis. Specifically, these data were obtained from samples collected during the 2013-2015 period prior to harvesting at (1) a second order stream downstream of the reference sample collection point (denoted Undist 1) and (2) a second order stream downstream of harvesting (denoted Undist 2). The inclusion of these data is not intended to suggest that comparison of water quality and treatability at headwaters and downstream locations is directly informative of disturbance impacts on water; rather, these data are provided for the sole purpose of providing a snapshot of natural variability in these parameters in the broader region (Fig. 20).

Figure 20 – Turbidity (a), DOC (b), UV254 (c), SUVA (d), THM-FP (e), (HAA-FP (f), humic substances (g), biopolymers (h), building blocks (i), LMW acids (j), and LMW neutrals (k) levels in streams draining adjacent undisturbed, reference and harvested watersheds. Green represents undisturbed sites (light green is pre-harvesting, dark green is during and post- harvesting). Blue represents harvested sites. The horizontal bars reflect medians, boxes are 25th and 75th percentiles, crosses represent the mean, and whiskers reflect max/min values.



Turbidity. Although focused examination of forest harvesting impacts on stream suspended solids and turbidity was conducted as a component of Milestone 2, it was also evaluated with other drinking water treatability analyses that were focused on aqueous NOM-associated impacts of forest harvesting because turbidity is critical to optimizing and evaluating overall treatment system performance, especially in conventional surface water treatment plants (MWH, 2012).Turbidity observed in the study watersheds were all very low (Fig 20a). Forest harvesting disturbances have been widely reported to increase turbidity in streams draining impacted watersheds. The turbidities observed over a range of flow conditions in the streams draining strip cut-, and partial cut-impacted watersheds were not statistically different than those draining the reference watershed ($U = 112$, $p = 1$; and $U = 41.5$, $p = 0.238$ respectively). Although a statistically significant difference was observed between the stream turbidities in the reference and clear cut-impacted watersheds ($U = 57.5$, $p = 0.012$), this difference was not practically relevant because they were less than 0.5 NTU. The very low stream turbidities (regularly below 10 NTU, and most frequently well below 5 NTU) that were observed across all of the study watersheds (Fig. 20a) are consistent with the more exhaustive data reported for Milestone 2. Collectively, these data clearly indicate that none of the forest harvesting practices meaningfully degraded stream turbidities and would not likely result in additional challenges to conventional surface water treatment (MWH, 2012).

Dissolved Organic Carbon (DOC). DOC concentrations in the study watersheds were all very low (i.e., below 2 mg/L; Fig. 20b). Here, the DOC concentrations observed over a range of flow conditions in the stream draining the clear cut-impacted watersheds were not statistically different from those draining the reference watershed ($U = 82.5$, $p = 0.140$). Although statistically significant differences were observed between DOC concentrations in the reference and both the strip cut- and partial cut-impacted watersheds ($U = 63.5$, $p = 0.041$; and $U = 7$, $p < 0.001$ respectively), they were *likely* not practically relevant because they were less than 1 mg/L, which would not be expected to pose any challenges to conventional surface water treatment, especially when the DOC concentrations were generally below 2 mg/L. However, a doubling in DOC concentration would likely necessitate increased coagulant usage. Moreover, it is possible that associated shifts in DOC character (e.g., aromaticity) could possibly pose treatment challenges, especially if they occurred relatively rapidly. The range of DOC concentrations after harvesting was generally consistent with stream DOC concentrations in the undisturbed watersheds at slightly downstream locations several years prior to harvesting. Accordingly, results indicate that stream DOC concentrations were generally very low in all of the study streams and the forest harvesting disturbances would not be expected to pose significant challenges to conventional surface water treatment (MWH, 2012).

UV_{254} and Specific UV Absorbance (SUVA). UV absorption by organic compounds is one of the simplest and most useful methods that enable real-time monitoring of organic matter, specifically aromaticity; to date, UV_{254} has been demonstrated as the best proxy indicator for total THM- and HAA-FPs after wildfire in the eastern slope of the Rocky Mountains (Shams 2018). Although, significant differences between Ref 1 and each of harvested sites were observed ($U = 33.5$, $p < 0.001$; $U = 31$, $p = 0.000$; and $U = 4$, $p < 0.001$ for clear cut, strip cut, and partial cut watersheds, respectively), the UV_{254} values were very low (i.e., typically below $5 m^{-1}$ and most frequently below $2 m^{-1}$) and consistent with undisturbed watersheds in the region (Fig. 20c). Given that significant differences were observed in UV_{254} between the reference and harvested watersheds, differences in DBP-FPs would also be expected. It should be noted, however, that the observed values were all quite low; thus, while significant differences would likely be expected in DBP-FPs between the reference and harvested watersheds, high levels of total DBP formation (e.g., in excess of 100 and 80 µg/L regulatory targets for respective total THM and HAA concentrations in treated water) would not be expected, even at hyper-chlorinated conditions that are non-representative of typical disinfection during drinking water treatment. It should be further noted that UV_{254} values in the partial cut watershed were higher than those observed in the other watersheds, consistent with observations of relatively higher DOC concentrations in the same watershed. Thus, SUVA values were similar across all of the study watersheds (as would be expected given the UV_{254} and DOC concentration data)—the stream SUVA values were not significantly different between Ref 1 and each of the clear cut, strip cut, and partial cut watersheds ($U = 95$, $p = 0.22$; $U = 85$, $p = 0.22$; and $U = 33.5$, $p = 0.08$; respectively), as evident in Fig. 20d. Given that the ratio of UV_{254} to DOC concentration (i.e., SUVA) was so consistent between the streams draining the reference and harvested watersheds across a range of hydrologic conditions, it is reasonable to speculate that natural variation in carbon cycling processes in the partial cut sub-watershed may also be a factor in these findings. Indeed, considerable variation in study watersheds existed prior to harvesting where long-term average DOC concentrations were 0.9, 1.2, and 2.6 mg L^{-1} for clear-cut, strip-cut, and partial-cut watersheds before they were logged. Thus, it is reasonable to assume some natural variation in carbon character would also have been present prior to harvesting. The generally low SUVA values observed in all of the study watersheds suggest the presence of lower molecular weight organic compounds that are not easily removed by coagulation and are more consistent with treated/finished waters; thus, it would be expected that only a small fraction (if any) of the DOC in these systems would likely be removed during conventional coagulation in absence of advanced treatment (e.g., enhanced coagulation, activated carbon). Notably, however, these materials are less likely to lead to DBP formation relative to higher molecular weight organics.

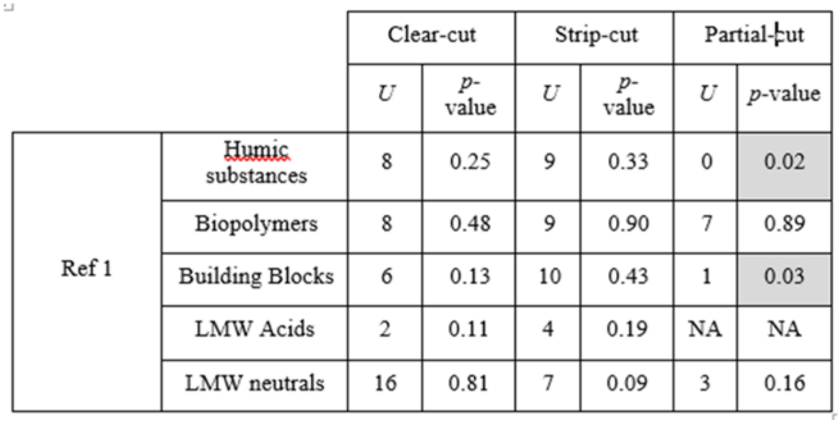
Disinfection By-product Formation Potentials (DBP-FPs). The mean total THM-FP and HAA-FP concentrations in the source waters are presented in Fig. 20e and 20f, respectively. It should be underscored that true DBP-FPs were evaluated at hyper-chlorinated conditions to evaluate any potential shifts in FPs that might be attributable to harvesting, as opposed to estimating DBP formation that might occur under typical operational (i.e., uniform) formation conditions. Chloroform, bromodichromethane (BDCM), dibromochloromethane (DBCM), and bromoform are the most abundant groups of THMs in drinking water. As only trace concentrations of bromide are present in the study watersheds, THMs primarily consisted of chloroform across the study sites and concentrations of DBCM and bromoform were typically below detection limits. Thus, stream THM concentrations were comprised of 98±3% chloroform and 98±3% BDCM across the study locations. Similarly, brominated HAAs were not formed, and HAAs were comprised of 63±7% of trichloroacetic acids and 35±2% of dichloroacetic acids across the study locations

Similar to UV_{254}, significant differences in total THM-FPs between Ref 1 and each of the disturbed (i.e., clear cut, strip cut, and partial cut) watersheds were observed, with $U = 43$, $p = 0.01$; and $U = 20$, $p < 0.001$, and $U = 1$, $p < 0.001$, respectively—as discussed above, this was expected given the observed differences in UV_{254} between the study watersheds. The HAA-FP results were similar to those observed for DOC; specifically, HAA-FPs in the stream draining the clear cut-impacted watersheds were not statistically different from those draining the reference watershed ($U = 57$, $p = 0.065$; though they would be significant at the 10% significance level) whereas statistically significant differences in HAA-FPs were observed between the reference and both the strip cut- and partial cut-impacted watersheds ($U = 43$, $p < 0.001$, and $U = 0$, $p = 0.01$, respectively). These observations were consistent with the differences in DOC concentrations and UV_{254} values observed between reference and harvested streams. Overall, slight differences in stream DBP-FPs could likely be attributed to forest harvesting, like other parameters (e.g., DOC concentration, UV_{254}); notably, however, these differences in total DBP-FPs were relatively small (i.e., less than ~10-15 µg/L) and not of practical concern, especially when considering that hyper-chlorination associated with the FP analysis that would result in greater DBP formation than what would be observed at operationally relevant applied chlorine doses. Like the DOC and UV_{254} data, the THM-FP data (Fig. 20e) also further underscore that the range of THM-FP concentrations observed after harvesting was generally consistent with stream THM-FPs in the undisturbed watersheds at locations slightly downstream locations before harvesting. Accordingly, the collective data generally indicate that stream DBP-FPs were generally low in all of the study streams and the forest harvesting disturbances would not be expected to pose significant challenges to conventional surface water treatment (MWH, 2012).

Carbon Fractionation by Size using LC-OCD. Relatively new LC-OCD technology enables carbon fractionation by size and direct quantification of several constituents of aquatic NOM that are particularly relevant to drinking water treatability. For example, elevated concentrations of some fractions of dissolved NOM may promote taste and odour problems, greater risks of bacterial regrowth in distribution systems, pipe corrosion, and higher concentrations of disinfection by-products (DBP) after disinfection with chlorine, and can be used to assess the organic removal efficiency of pretreatment and membrane filtration processes.

The concentrations of the humic substances, building blocks, LMW acids, and LMW neutrals **(**low-molecular weight weakly charged hydrophilic or slightly hydrophobic [amphiphilic] compounds such as alcohols, aldehydes, ketones, amino acids**)** fractions of DOC that were observed during the study period Fig. 20g to 20k, respectively. The concentrations of these fractions of DOC observed over a range of flow conditions in the streams draining the clear cut- and strip-cut impacted watersheds were not statistically different from those draining the reference watershed (Table 4). Only the concentrations of the humic substances and building blocks fractions of DOC in the partial-cut watershed were statistically different from those in the reference/unharvested watershed (Table 4). Although key concentration threshold values for the various fractions of DOC have not been identified and universally agreed upon, the observed concentrations of each of these fractions were low (because overall DOC concentrations were very low), thereby indicating high quality and relatively little risk for challenges to conventional surface water treatment and distribution resulting from forest harvesting in the study watersheds

Table 4 – Comparison of stream concentrations of humic substances, biopolymers, building blocks fractions, LMW acids, and LMW neutrals fractions of DOC in reference and harvested watersheds.



		Clear-cut		Strip-cut		Partial-cut	
		U	*p*-value	*U*	*p*-value	*U*	*p*-value
Ref 1	Humic substances	8	0.25	9	0.33	0	0.02
	Biopolymers	8	0.48	9	0.90	7	0.89
	Building Blocks	6	0.13	10	0.43	1	0.03
	LMW Acids	2	0.11	4	0.19	NA	NA
	LMW neutrals	16	0.81	7	0.09	3	0.16

E.7.2 Task 9.2 Comparative Drinking Water Treatability Impacts from Harvesting and Wildfire

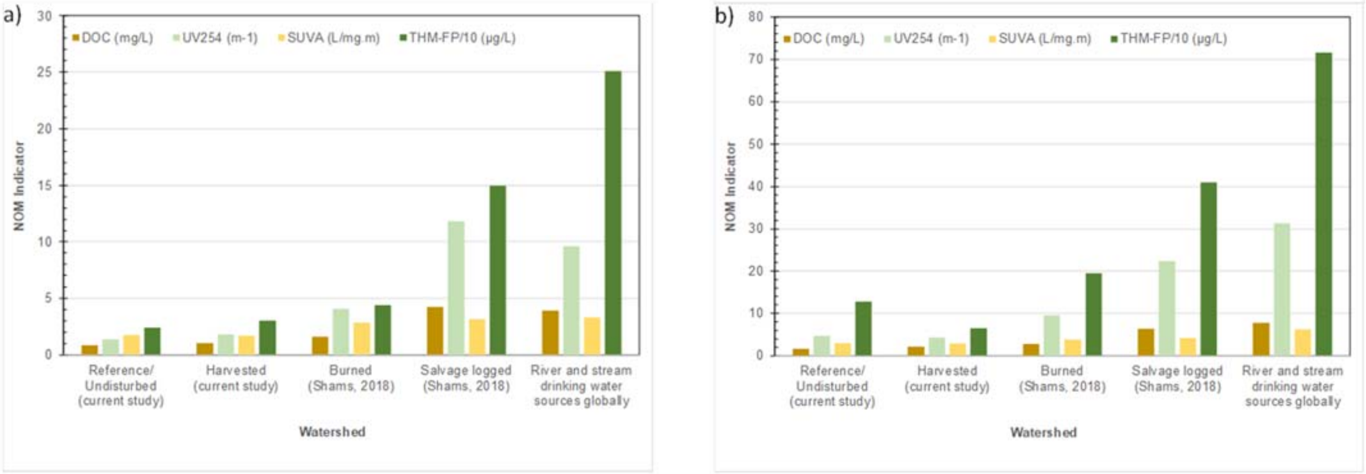
To contrast the drinking water treatability implications of wildfire, post-fire salvage logging, and contemporary forest harvesting on NOM, changes in dissolved organic carbon (DOC) concentration and character (UV254 and SUVA) and their relationships to regulated DBP-FPs (THM-FPs) were characterized using samples collected during two years (2013 and 2014; n = 64) following Lost Creek wildfire and three years (2015-2018; n = 69) during and after forest harvesting in the Star Creek watershed. Samples were collected during all of the dominant regional streamflow regimes (baseflow, snowmelt freshet, and stormflow) (MASc Student S. Bahramian). These values were contrasted to characteristic values reported in streams and rivers serving as drinking water sources globally (Table 5). While average water quality values are most frequently reported when source water quality is characterized, it is the extreme values that most challenge drinking water treatment.

Table 5 – Trihalomethane formation potentials (THM-FPs) reported in streams and rivers serving as drinking water sources globally.

Study	Location	Source	DOC	UV254	THM-FP	HAA-FP	Test conditions
Collins et al 1985	Canton, NY, US	Grasse River	7.71	31.4	716	-	pH= 7; reaction time= 7 days; temperature= 20 °C
	Las Vegas, NV, US	Colorado River	3.02	4.5	167	-	
	LaVerne, CA, US	Colorado River	3.15	4.3	164	-	
	Orange Co., CA, US	Colorado River	3.13	4.4	167	-	
	Anaheim, CA, US	Colorado River	3.42	4.5	152	-	
	Oceanside, CA, US	Colorado River	3.28	4.5	142	-	
Chadik & Amy 1987	MS, US	Pearl River	5.62	13.6	284	-	pH= 7; reaction time= 7 days; temperature= 20 °C
	NY, US	Grasse River	6.56	28.8	475	-	
Rathbun 1996	US	Mississippi River	5.9		576	-	pH= 7; reaction time= 7 days; temperature= 25 °C
		Missouri River	5.3		468	-	
		Ohio River	5		460	-	
Martin-Mousset et al 1997	France	Charente	2.8	5.7	109	-	pH= 7.5; reaction time= 3 days; temperature= 20 °C
		Loire	3.9	8.4	211	-	
		Mayenne	4.2	14	155	-	
		Sevre Nantaise	5.3	15	170	-	
Garvey & Tobiason 2003	Boston, MA, US	Cadwell Creek	2.05	6.1	188	-	pH= 7; reaction time= 7 days; temperature= 20 °C
		Purgee Brook	1.73	4.3	131	-	
		Atherton Brook	2.63	8.6	246	-	
		West Branch Swift River	2.92	9.4	257	-	
		Dickey Brook	3.86	14.5	365	-	
		Prescott Breek	2.89	9.8	256	-	
		Underhill Brook	3.08	10.5	291	-	
		Hop Brook	3.18	10.8	251	-	
		Middle Branch Swift River	4.93	17.3	436	-	
		West Branch Fever Brook	7.74	28.3	659	-	
		East Branch Fever Brook	5.8	20.9	537	-	
		East Branch Swift River	4.72	16.1	447	-	
Kim et al 2003	South Korea	Han River	2.35	7.3	56	11	pH= 5.5, 7, raw water pH; reaction time= 2 days; temperature= 20 °C
		Youngsan River	2.35	7.2	59	19	
		Nackdong River	5.12	11.6	103	9	
van Leeuwen et al 2005	Australia	Middle River	13.77	-	99	-	pH= 5 (HAA-FP), 7 (THM-FP); reaction time= 7 days; temperature= 25 °C
Xu et al 2007	Shanghai, China	Huangpu River	6.45	14.55	433	312	pH= 7; reaction time= 7 days; temperature= 25 °C
Hong et al 2008	China	Dongjiang River	3.82	4.44	15	17	pH= 5 (HAA-FP), 7 (THM-FP); reaction time= 7 days; temperature= 20 °C
Jung & Son 2008	South Korea	Nakdong River	2.86	6.35	111	112	pH= 8; reaction time= 1 days; temperature= 20 °C
Lantagne et al 2008	Kenya	Not specified	3	-	92	-	pH= 7; reaction time= 7 days; temperature= 20 °C
Chen & Westerhoff2010	USA	11 Rivers	6.98	13	244	282	pH= 8.2; reaction time= 1 days; temperature= 25 °C
Bush, 2008; Chowdhury et al 2008	KamloopsBC, Canada	South Thompson River	2.6	2.6	26	65	pH= 5 (HAA-FP), 7 (THM-FP); reaction time= 7 days; temperature= 25 °C
Zhao et al 2013	China	Songhua River	4.1	12.3	164	382	pH= 7; reaction time= 7 days; temperature= 25 °C

Thus, the median and maximum DOC concentrations, UV254, SUVA, and THM-FP levels in streams draining (1) adjacent undisturbed and reference, (2) harvested, (3) burned, and (4) post-fire salvage logged SRWP watersheds characterized by synoptic sampling and contrasted to characteristic values from river and stream drinking water sources globally are presented in Fig. 21a and 21b, respectively. It should be underscored that although the data from the SRWP watersheds represent extensive discrete sampling, they do not necessarily reflect the true maximum values that were experienced in these systems because DBP-FPs could only be evaluated in a subset of the collected samples. Moreover, it should be noted that THM-FPs on this figure are scaled for convenience of presentation.

Figure 21 – Median (a) and maximum (b) DOC concentrations, UV254, SUVA, and THM-FP levels in streams draining (1) adjacent undisturbed and reference, (2) harvested, (3) burned, and (4) post-fire salvage logged SRWP watersheds characterized by synoptic sampling and contrasted to characteristic values from river and stream drinking water sources globally (Table 5). Note: THM-FPs are scaled down 10-times for convenience of presentation.



The data presented in Fig. 21 demonstrate several key points. First, the eastern slopes of the Rocky Mountains provide high quality source water with relatively low aromaticity and concentrations of dissolved NOM. Second, the contemporary forest harvesting practices investigated herein did not appear to deteriorate either median or maximum observed DOC concentrations, UV254, SUVA, and THM-FP levels in the watersheds, while wildfire and post-fire salvage logging resulted in somewhat elevated median values and substantially elevated extreme values that could pose significant challenges for drinking water treatability—notably, the higher/maximum THM-FP values observed in the post-fire salvage-logged watersheds are approaching some of the highest values that have been reported for water supplies with moderately high DOC concentrations (i.e., 5-8 mg/L).

E.8 Milestone 11 - Economic Evaluation of Land Management Strategies

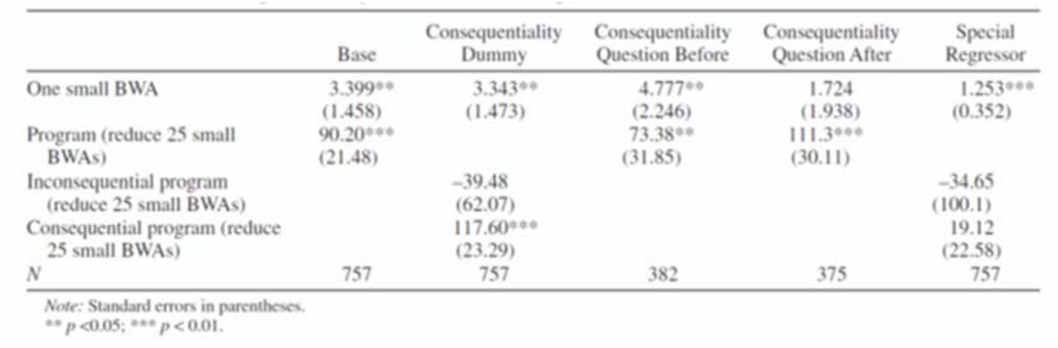
E.8.1 Task 11.1 Comparative Impacts of Land Management Options on Ecosystem Services

The economic analysis component of the project is examining the economic benefits and/or costs associated with land use changes and water ecosystem services (WES) arising from forest disturbances (natural / managed). A range of WES can be investigated including those associated with water quantity (e.g. potentially positive for irrigation, negative for flooding) and water quality (impacts on recreation; impacts on drinking water) (Holmes et al, 2017). Previous analysis suggests the most significant potential impacts on WES values arise from drinking water impacts (as those potentially affect human health and wellness) and from reduced flood risk (Price et al, 2019). Recreational values depend on the alternatives and if significant substitutes are available, water quality impacts can be small. For any of these economic values, a key component is the human population affected by the WES, thus analysis of long-term impacts must take population growth rates into account. In addition, impacts on drinking water quality are related to thresholds associated with water treatment infrastructure: if thresholds are exceeded and result in boil water advisories or water outages, economic impacts are significant. Previous research on the economic value of water quality changes has tended not to examine such thresholds, and thus may significantly underestimate the value of water quality improvement. In this section we report on research on the economic values of WES with a focus on a novel approach to examining drinking water value in the context of population growth, water treatment costs, infrastructure thresholds, and health/wellness impacts.

This element of the project built on previous AI research that examined measures of the economic value of changes (positive and negative) on recreational use (upstream impacts) and measures of the economic value of changes in water quality and WES associated with water quantity reliability (potential outages) and water quality (e.g. avoidance of boil water advisories).

Building on the earlier analysis of water outages at a household level, we examined Alberta provincial willingness to pay for reducing the frequency (probability) of boil water advisories (BWA) (Lloyd-Smith et al. 2019). This analysis employed a public good framing and assessed province wide economic value for BWAs by community size. Novel survey and econometric techniques were used to acquire valid (consequential) estimates of economic value. The results show the value of reduction of BWA risk for small communities (Table 6). The values were not statistically significant for medium and larger communities. This does not mean that households do not place an economic value on water quality, rather they perceive relatively low risks of BWA, given treatment plant infrastructure, for medium and large communities and given a choice they would prefer investment in small communities.

Table 6 – Mean annual willingness to pay for 10 years for programs to avoid boil water advisories



	Base	Consequentiality Dummy	Consequentiality Question Before	Consequentiality Question After	Special Regressor
One small BWA	3.399**	3.343**	4.777**	1.724	1.253***
	(1.458)	(1.473)	(2.246)	(1.938)	(0.352)
Program (reduce 25 small BWAs)	90.20***		73.38**	111.3***	
	(21.48)		(31.85)	(30.11)	
Inconsequential program (reduce 25 small BWAs)		–39.48			–34.65
		(62.07)			(100.1)
Consequential program (reduce 25 small BWAs)		117.60***			19.12
		(23.29)			(22.58)
N	757	757	382	375	757

Note: Standard errors in parentheses.
** $p < 0.05$; *** $p < 0.01$.

There was no significant economic value difference if the improvement in water quality arose from the use of forest management or improved infrastructure. This finding illustrates that the public is not opposed to forest management alternatives to improve water quality and this analysis illustrates the economic importance of improving water quality and avoiding quality shocks in small communities.

In a complementary project with WEPGN funding and employing the same design as Appiah et al (2019; AI funded)), Price et al (2019) investigated the value of both the improvement of water reliability (reduction of outages, BWAs) as well as flood risk reduction. This analysis was national in scope but included separate valuation for Prairie Provinces. The survey design used in the analysis included features to enhance validity and consequentiality as in Appiah et al. (2019). The results for Prairie province residents indicate a per household value of a 50% reduction in water reliability risks of between \$99 and \$120 / year ($p<0.05$) with the larger value associated with forest management and the smaller value for grey infrastructure. The value of flood risk reductions were of similar magnitude at \$111- \$116 / household for a 50% reduction in flood risk. These findings are significant as drinking water ecosystem services and flood protection ecosystem services are separate values arising from improve management of land resources or avoidance of land disturbances. Furthermore, this analysis also showed that forest management is viewed as at least as desirable, or in this case preferred to, grey infrastructure investments. These estimates can also be used to project the economic value associated with alternative forest harvesting methods via their relative contributions to changes in water quality and flood risk.

The economic analyses discussed above produced values per person or per household thus the projections of populations of affected households is required. In addition, the assessment of impacts of water quality on drinking water treatment costs and water infrastructure thresholds requires analyses of population growth. Thus, Task 11.2 (*assessment of population growth scenarios*) was integrated into Milestone 12 / Task 12.1 (see E.13.1 *below*) which focuses on the Calgary region as it is the basis for the examination of treatment costs and cost thresholds, and the focal area for WES assessments.

BEST PRACTICES EVALUATION AND DEVELOPMENT FOCUSED MILESTONES

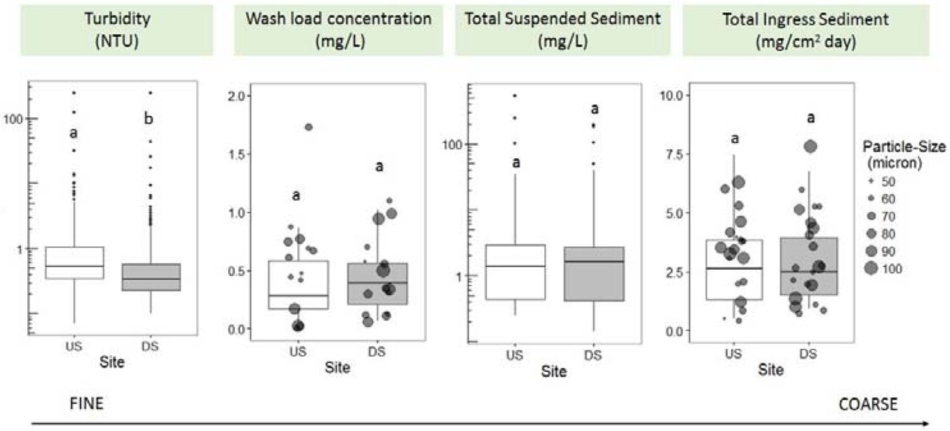
E.9 Milestone 4 - Best Practices for Sediment Management

E.9.1 Task 4.1 Evaluation of Rapid Road De-activation / Reclamation

A graduate student (MSc. M. Corrigan) assessed the impact of road-stream crossings on stream sediment using paired upstream (US) and downstream (DS) evaluation of 3 road-stream crossings (1 in each sub-catchment) after bridge installation. A series of best management erosion control practices were employed during installation and operational road use. All crossings were removed, with erosion control measures applied after decommissioning. Three measures of suspended sediment were used to assess the impact of crossings on very fine (turbidity), fine (washload), and coarser (total suspended) sediment. Sediment traps were used to measure the intrusion (fate) of sediment into streambeds which is considered one of the primary impacts of sediment on stream health (Luce and Black 2001).

There was no detectable impact of the three road-stream crossings on any of the measures of suspended or settled sediments assessed during either the harvest year (2015) or the 1st year following road-stream crossing decommissioning in 2016 (Fig. 22).

Figure 22 – Impact of 3 road-stream crossings on distribution of suspended and settled sediments



Because a series of significant storms were captured in these data (2015 in particular), the finding of no detectable impact of the road-stream crossings on suspended or settled streambed sediments was likely a strong reflection the efficacy of the suite of "best management" erosion control practices employed during construction, hauling, and crossing decommissioning phases. Road de-commissioning and right of way roll-back in particular, likely played a major role in both the results of this assessment on road-stream crossings, and lack of the broader, negative catchment-scale impacts of from forest harvesting outlined in E.2.2 above.

E.9.2 Task 4.2 Support Tools to Identify Priority Areas for Sediment Management

This task included two components focused on 1) evaluating tools to identify priority areas for sediment management of back-country off-highway (OHV) trails, and 2) an extensive program spearheaded by Dr. Axel Anderson on calibrating/refining GIS based tools to manage sediment from developed road networks.

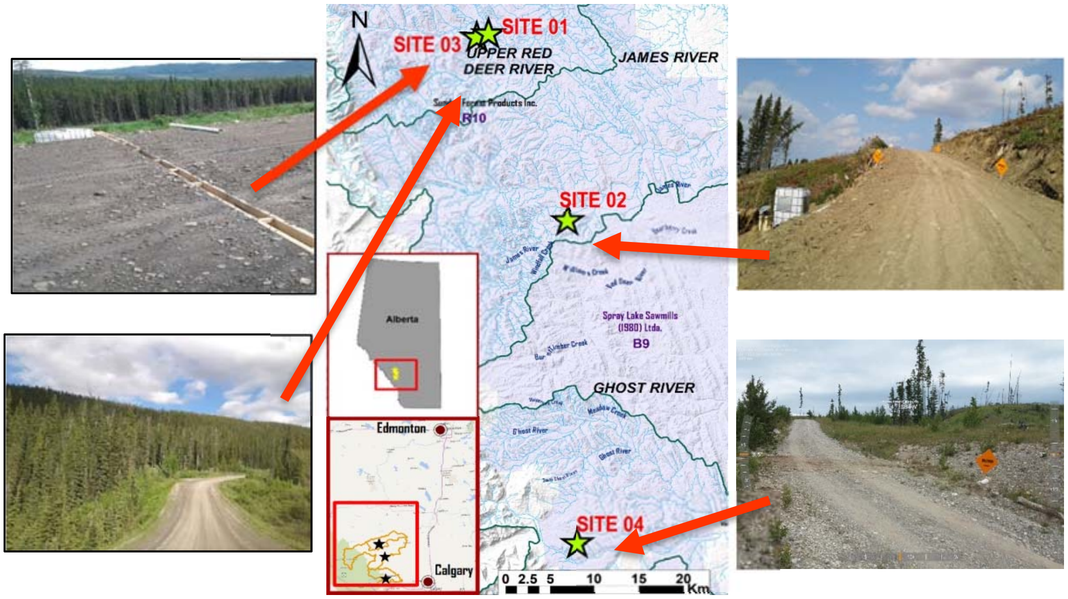
1) A graduate student project (MSc M. Howard) characterized both erodibility and total erosion from OHV trail networks to explore the potential use of common soil erosion modelling frameworks (Universal Soil Loss equation; USLE) for broader provincial use as tools to identify priority areas for sediment management. Sediment production from moderate intensity rainfall simulation on small plots ranged from 0.01-6.4 tonnes ha^{-1} of trail surface while erosion from larger trail segments produced by natural storm events (36-146 mm) caused much greater erosion (0.9-43 tonnes ha^{-1}). Both controlled rainfall simulation and natural rainfall erosion studies showed that trail use intensity was a chief factor governing both runoff and erosion with approximately 10x greater erodibility (Fig. 23) and total erosion from trails with high intensity of OHV use compared to low use trails.

Figure 23 – Comparison of measured and predicted erodibility for high and low use intensity trails

While sediment availability and erodibility from trails were strongly affected by OHV use, soil properties commonly used to predict erodibility using a broad suite of erosion models (including USLE) substantially under-predicted actual erodibility and total erosion (Fig. 23) particularly on higher intensity use trails responsible for the majority of trail erosion. Other types of erosion prediction tools are likely needed (see *below*).

2) The broader program on support tools for developed road networks (Dr. A. Anderson led, MSc's. C Ishhii and LH. Hernani, PhD J. Fath) included monitoring of erosion plots on road sections using methods presented by Luce and Black (2001) (Fig 24). Over 700 road stream crossings were surveyed in the southern east slopes to measure the connectedness between the roads and streams.

Figure 24 – Plot locations in 2017-19. Site 2 a temporary road was deactivated late 2018 and another site installed in 2019. Sites 1 and 3 are on a West Fraser temporary road that is gated. Site 2 was on a Spray Lake Sawmills temporary road (newly constructed) without access control. Site 4 is a long term TransAlta road that is heavily used by the public.



These data provide regional science that directly supports government and forest industry initiatives. The goal is to implement a suite of GIS and field-based tools that can identify priority stream crossings for sediment management. We have been working closely with consultants and others to implement a regional version of the Road Erosion and Delivery Index (READI) model (Benda et al 2019). In its current form the model can rank sedimentation potential at stream crossings based on the erosion potential and the connectivity. However, without regional data this tool only provides a relative scale for road segments within a given watershed (Fig 25). To be useful as a monitoring tool we need to move beyond the relative index to predict a nominal amount of sediment delivery (kg/yr).

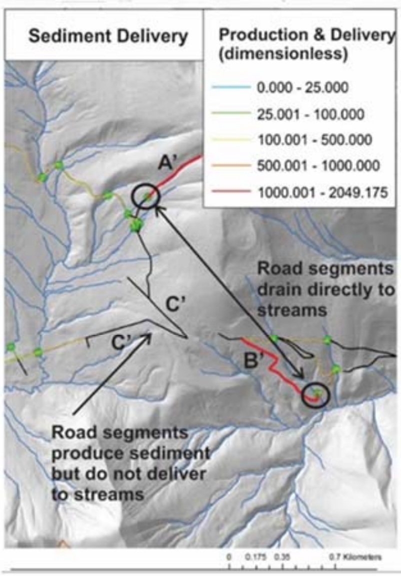


Figure 25 - Relative road sediment delivery from READI model. Figure produced by TerrainWorks for FRIAA

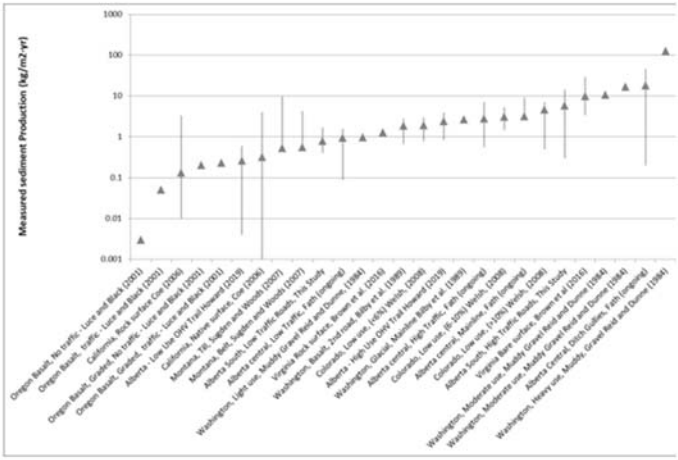


Figure 26 - Comparison of measured erosion rates kg/m^2*yr, for this study, Howard (2019), Fath (ongoing), and select published results. Results are grouped based on level of use. Preliminary results show almost a magnitude difference in erosion rate between high and low use roads/trials. Note the gully ditch erosion rates surveyed by Fath are 2nd highest in published literature.

To achieve this goal we collected erosion and connectivity data on a range of road and trail features found in the east slopes. Collectively, we have data on recreation trails (M. Howard *see above*), temporary forestry roads, longer term gated and ungated access (this project, data collected by C. Ishii MSc 2019, L. Huayta Hernani MSc 2019 and fRI Research staff), and resources roads typically found in the northern east slopes (Canfor funded, J. Fath, PhD ongoing, Fig. 26.

Key findings:

1) Measured seasonal erosion rates are within the range of those found in the literature (Fig. 26). Not surprisingly, erosion rates are on the higher end of the rates reported in the literature.

2) Results show erosion rates are significantly lower on trails and roads with low traffic levels. This is broadly supported in the literature and provides support for closing (or limiting) access to reduce sedimentation hazard.

3) Only 34% of the road drain points surveyed were not connected to a watercourse. The road drain points are points that were predicted to have concreated water leaving the road or trail surface (Fig. 27). 50% of these points were directly connected to a watercourse (usually at stream crossings, e.g. Fig. 27b) and the remaining 16% had a partial connection during rain events.

4) Preliminary findings show that the road stream crossing density (#/km^2) may be a better predictor of the amount of fine sediment intruded into the stream bed. This is significant because road density (km/km^2) is currently the indicator most often used in Alberta. We used several indicators, model outputs and field verification to classify sub-watersheds of the Simonette into Low, Medium and High road sedimentation pressure. Instream sediment attributes were measured on a subset of sub-watersheds to relate them to model predictions.

Next Steps and applications: We continue to modify the model to move beyond an index and provide measures of sediment delivery (publication expected late 2020). In its current form government and fRI Research staff are using the model to prioritize remediation of un-owned stream crossings under the federally funded native trout recovery program. Government Forestry staff are planning a pilot project to use the tool to risk rank stream crossings and focus forest officer inspections on high risk forestry roads.

Figure 27 – Two road drain pour points on a cutline in the Waiparous Watershed, west of Calgary. Left panel disconnected water and sediment from the road surface goes onto the forest floor far from a watercourse. Right panel directly connected road surface and watercourse.

E.10 Milestone 7 (con't) - Regional Contaminant Transport Modelling

E.10.1 Task 7.2 Quantify Downstream Water Quality/Cumulative Effects from Harvesting & Fire

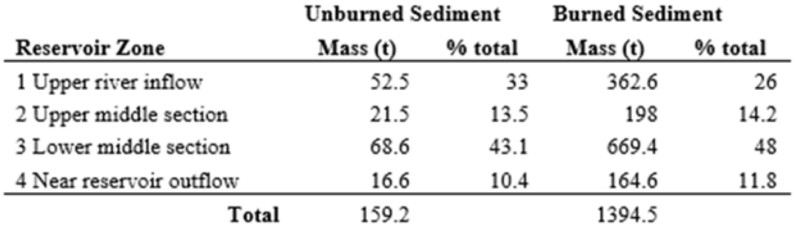
While significant advancements have been made in fine sediment transport models, they are based primarily on results of laboratory studies and are very seldom verified under field conditions particularly at large basin scales. One of the primary values of the modelling framework described herein, is its potential use to explore risks of landscape disturbance (i.e. wildfire, harvesting) on the propagation and fate of fine sediment from upstream sources to reservoirs. In the present study, a five year historical hydrometric and sediment data set (Table 7) was used to route sediment from tributary inflows draining into the Crowsnest River downstream into the Oldman Reservoir.

Table 7 – Sediment export in tonne/yr from SRWP watersheds used in the modelling framework

	2005	2006	2007	2008	2009
Star Creek	3.3	26.7	13.0	14.4	5.9
Drum Creek	3.8	28.8	9.4	17.1	13.5
South York	2.6	21.8	80.7	71.6	27.3
Lyons Creek	298.9	16.7	19.4	1406.9	46.1

These long term (5 year) simulations provided 1) estimates of the mass of sediment entering the reservoir from each of the upstream tributary inflows and 2) the amount of sediment deposited within sections of the reservoir. According to the model, about 16% of the sediment deposited in the reservoir was from reference tributary inflows (Star Creek and South York). These data were collected prior to the harvest in Star Creek but since harvesting had no effect on sediment dynamics these data are used here in the modelling exercise to represent sediment dynamics that would have occurred during the harvest. In contrast, ~84% of the post fire sediment mass deposited in the reservoir originated from burned landscapes (Drum Creek and Lyons Creek) and based on the output of the RMA4 model ~60% of these pyrogenic materials were deposited in two deeper sections (3 and 4 below) of the reservoir near the dam and reservoir outflow (Table 8). The presence of significant quantities of pyrogenic materials and associated bioavailable phosphorus (non-apatite inorganic phosphorus) deposited in the reservoir may represent an important internal loading source of phosphorus to the water column and that could proliferate algal blooms. Accordingly, the flushing frequency of the reservoir may have to be increased due to the enhanced fine sediment loading from impacted landscapes upstream to avoid the proliferation of algal blooms. However, this practice may also have implications for water quality and the ecology of the Oldman River in reaches downstream of the reservoir. A manuscript describing the modelling framework and its implication for reservoir management is in preparation and will be submitted for review by September 2020.

Table 8 – Sediment mass deposited in four depositional zones of the Oldman Reservoir from burned and unburned tributary inflows Forested reference (Star Creek and South York), Burned (Drum Creek), Burned and post fire salvage logged (Lyons Creek)



	Unburned Sediment		Burned Sediment	
Reservoir Zone	**Mass (t)**	**% total**	**Mass (t)**	**% total**
1 Upper river inflow	52.5	33	362.6	26
2 Upper middle section	21.5	13.5	198	14.2
3 Lower middle section	68.6	43.1	669.4	48
4 Near reservoir outflow	16.6	10.4	164.6	11.8
Total	159.2		1394.5	

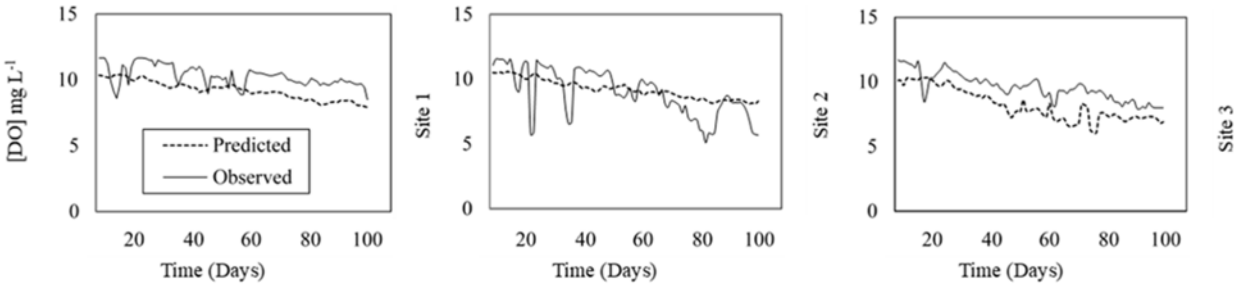
E.11 Milestone 8 - Regional Fisheries

E.11.1 Task 8.1 Calibrate Sediment-Fish Spawning Habitat Model

The delivery of sediment to sensitive high-quality streams from harvested landscapes in forested watersheds is a key concern for watershed managers because it can strongly affect water quality, stream biota and stream bed composition. Accumulation of fine sediment in spawning gravels can block intra-gravel flow and decrease gravel permeability which decreases the availability of oxygen supply and cause egg mortality. Existing approaches for management of sensitive high-quality streams draining forested landscapes are currently based on crude/coarse filter proxies such as road density or equivalent clear-cut area. However, these approaches are not directly or meaningfully connected to specific habitat conditions that govern critical spawning habitat conditions (i.e. DO, incubation and alevin survival).

The applicability of a sediment-fish spawning Sediment Intrusion Dissolved Oxygen Model (SIDO) was evaluated as a potential tool for fisheries managers to evaluate the effect of fine sediment accumulation on dissolved oxygen (DO) concentrations in spawning gravels of the Crowsnest River in southwestern Alberta by MSc student Quinn Decent. The magnitude of oxygen demand imposed by fine sediment infiltrating spawning gravels was measured every 15 minutes over a period of 90 days using oxygen probes inserted in the gravel bed and these data were subsequently used to calibrate SIDO. A comparison of modelled and measured oxygen concentrations in spawning gravels at three transects of the Crowsnest River are presented in Figure 28. The data show that dissolved oxygen concentrations in spawning gravels varied within and between the three investigated transects. Despite the observed variability in measured dissolved oxygen concentrations, SIDO produced similar trends to the measured data but was not sensitive to observed fluctuations in DO over short time periods. However, the model in its present form can be used as a coarse proxy to model dissolved oxygen concentrations within spawning gravels and model sensitivity could be improved if terms to describe microbial activity, the type and amount of dissolved and particulate carbon and groundwater surface water interactions were included in the model.

Figure 28 – Comparison of modelled and measured dissolved oxygen concentrations



E.11.2 Task 8.2 Quantify Comparative Effects of Harvesting and Wildfire on Spawning Habitat

Based on the initial results of this research conducted at the reach scale, the SIDO model may represent an important fisheries management tool for rivers draining forested watersheds on the eastern slopes of the Rocky Mountains in the southern Alberta. Our initial study showed that measured and simulated dissolved oxygen concentrations in relatively pristine headwater reaches of the Crowsnest River were in general agreement. Based on our field experience and knowledge of the literature, sediment inputs from wildfire are expected to be more pronounced but this hypothesis will have to be further evaluated. A manuscript regarding the applicability of SIDO as a fisheries management tool for rivers draining forested watersheds on the eastern slopes of the Rocky Mountains in the southern Alberta is currently in preparation.

E.12 Milestone 10 - Best Practices for Water Treatment Resiliency

E.12.1 Task 10.1 Best Water Quality Characterization Tool Summary

While the treatment of pathogens to management acute risks to public health is the paramount objective of drinking water treatment, they can be readily treated as long as physical and chemical water quality is adequate so that disinfection via chemical oxidation (e.g., chlorination, ozonation) and/or UV irradiation can be efficiently achieved. The associated treatment is typically referred to as "chemical pre-treatment" prior to filtration and includes coagulation, flocculation, and clarification (i.e., typically sedimentation) during conventional treatment (i.e., chemically-assisted filtration [CAF]) of surface water. Chemical pre-treatment further serves to destabilize suspended colloidal particles (including microorganisms), thereby enhancing their removal during filtration, which is a physico-chemical particle removal process, as opposed to a size exclusion-based process. Thus, chemical pre-treatment literally provides the "chemically-assisted" component that is critical to enabling efficient and resilient water treatment (including removal of colloidal particles and pathogens) by CAF. A key goal of CAF is to reduce source water turbidity and DOC concentrations so that matrix oxidant demand is reduced and UV transmittance, if relevant, is maximized (i.e., pathogen shielding by particulate material is reduced), thereby enabling efficient disinfection with minimal formation of undesirable DBPs, some of which are unregulated, but of potential health concern.

As discussed for Task 9.1, it is commonly recognized that turbidity and dissolved NOM are the main water quality drivers of drinking water treatment infrastructure and operational requirements/costs, especially the need for CAF. Turbidity can be directly and inexpensively measured in real time, and its contributions to coagulant demand can be evaluated with relatively inexpensive, though laborious, jar tests, which can be used to inform coagulant dose requirements and coagulation, flocculation, clarification, and subsequent filtration (i.e., chemically-assisted filtration [CAF]) infrastructure needs, including the potential need to implement advanced pre-treatment technologies such as PAC or enhanced coagulation to achieve both turbidity and NOM/DOC reduction targets. Turbidity can be further relied upon to provide real-time information on particle and pathogen removal by CAF.

While turbidity removal can be directly assessed online, real- (e.g., online UV254 absorbance) or near real-time proxy indicators for DBP formation are not as quantitative. In Task 10.1, the linear relationship between THM-FP and the aromatic fractions of DOC (which are generally understood to be a directly proportionality) was investigated to identify opportunities to improve their performance as THM-FP predictors/proxy indictors (PhD Student S. Shams; MASc Student S. Bahramian; PDF Dr. F. Amiri). THMs are formed because of chemical reactions between disinfectants and different constituents/fractions of DOC and THM concentrations are directly proportional to precursor concentrations. Accordingly, least squares linear regression analysis has been widely used to describe relationships between DBPs and potential proxy indicators such as DOC concentration (Ates et al 2007; Singer 1999). Here, hydrophobicity (HPO) measured by resin fractionation of the humic substances fraction (HS) obtained from size-based fractionation with LC-OCD were evaluated as relative (fractions) and absolute (mass-based concentration) quantities. While both approaches to data reporting are found in the literature, specific guidance regarding optimal approaches for reporting these data is lacking. These data were then compared based on their potential to predict regulated THM-FPs. These relationships were also compared to those obtained using other common proxies (UV254 and SUVA) of NOM aromaticity. Recognizing that it is unlikely that a single, directly-measured universal precursor for DBP-FP will ever be identified based exclusively on one descriptor of the structural characteristics of NOM, it is critical that the metrics that are utilized and reported as proxy indicators for DBP-FP describe as much of the response variability as possible (i.e., highest possible coefficient of determination [R2]) because these will correspond to most precise predictions. Accordingly, the concurrent evaluation of multiple metrics of NOM character was conducted to (1) provide the most precise simple predictors of NOM reactivity and (2) enable the most efficient development of multivariate models to better predict NOM reactivity. This comparative analysis is critical to identify the most useful metrics for prediction of THMs and optimization of strategies to limit water treatment challenges associated with their formation.

An initial evaluation of data collected over two years (2013 and 2014) was conducted to reflect a wide range of THM-FP and proxy indicator values. Data collected during previous SRWP evaluations of wildfire and post-fire salvage logging effects on water quality and treatability during dominant regional streamflow regimes (baseflow, snowmelt freshet, and stormflow) were utilized. Regression significance (p value) and prediction precision (R2) between THM-FP and DOC, UV254, SUVA, and HPO are presented in Table 9. As would be expected, the correlation between THM-FP and each of the proxy indicators was significant. The fraction of variability in the observed data that was explained by regression (i.e., the precision of the simple linear model), varied considerably, however. For example, DOC concentrations only somewhat explained the variability in THM-FP (R2 = 0.47)—the other indicators also had similar, lower precision. UV254 offered the most precise prediction of THM-FP (R2 = 0.60)—this was not surprising because it is a surrogate for NOM aromaticity and its utility in generally signaling DBP-FPs has been historically demonstrated. While investigation of the mechanisms that might explain why the relationships between DBP-FPs and proxy indicators such as DOC concentration are site specific and often change temporally is beyond the scope of this work, it is reasonable to expect that the catastrophic flood event of 2013 contributed to some of this variability. Good correlations between TOC and THM-FP for individual source waters have been reported previously; however, the correlations are frequently imprecise when comparing water from different sources—such differences likely also extend to flood events which may have introduced and/or removed different types/sources of NOM to/from the study watersheds.

Table 9 – Regression significance (p value) and THM-FP prediction precision (R2) of NOM aromaticity indicators (HPO, HS, UV254, and SUVA) ($p < 0.01$ in all cases; $n = 38$).

	HPO (mg/L)	**HPO** (%)	**HS** (mg/L)	**HS** (%)	**UV_{254}** (m^{-1})	**SUVA** (L/mg.m)
THM-FP (µg/L)	0.89	0.83	0.88	0.26	0.90	0.39

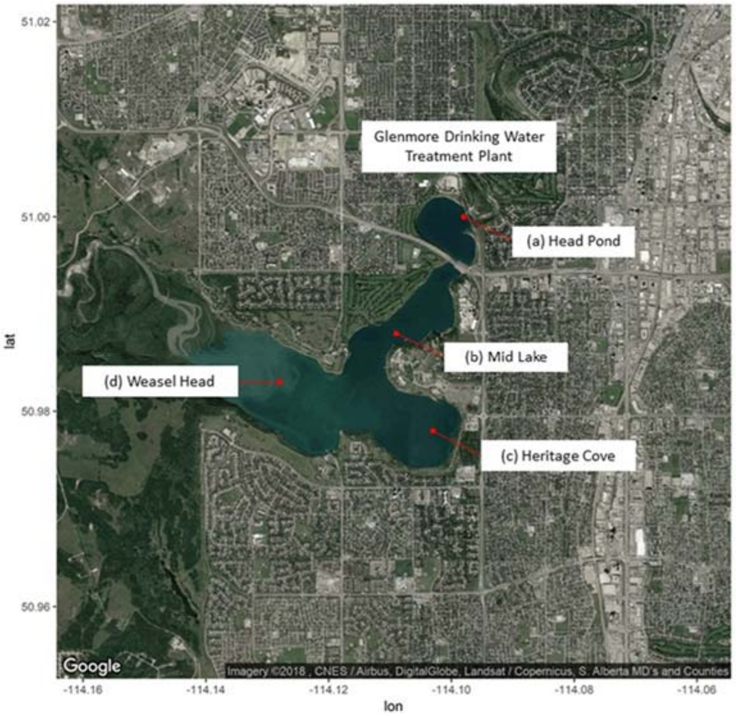
Several DOC characterization metrics were compared and their direct relationship to THM-FP was examined. THM formation potential- (THM-FP), DOC-, and aromaticity-associated parameters including UV254, SUVA, and hydrophobic (HPO) and humic substances (HS) fractions were evaluated. As expected, metrics indicative of aromatic compounds were good predictors of THM-FP in general; however, the prediction precision of HS and HPO fractions was enhanced (especially HS) when expressed as mass-based parameters (absolute quantities) as opposed to fractions or ratios of DOC (relative quantities). Thus, the use of a mass-based weighting approach for reporting NOM fractionation data is recommended for further exploration and use in discussing and evaluating NOM-related implications to drinking water treatability.

E.12.2 Task 10.2 Reservoir Risk Characterization Framework

Increasing loading of fine sediment-associated phosphorus (P) is widely recognized as a risk factor that causes changes in algal activity and promotes algal proliferation in reservoirs. In many parts of Alberta, such as the Elbow River watershed that provides source water to Calgary, relatively little is known about the form and mobility of fine sediment-associated P across the transfer continuum from headwaters regions to downstream reservoirs. In the case of Calgary, no information linking fine sediment to P dynamics and algal growth in the Glenmore Reservoir is currently available. The goal of this reservoir risk characterization study was to (1) assess the P form and mobility of fine river and reservoir sediment and (2) to conduct “proof-of-concept” bench-scale experiments to assess the potential of fine reservoir bottom sediment in promoting the proliferation of toxin-forming M. aeruginosa suspended in the Glenmore Reservoir water matrix (M.A.Sc. Yang).

Suspended solids were collected over nine weeks (from July 3 to August 18, 2015) with passive sediment samplers deployed at four stations over a 103 km reach of the Elbow River from its headwaters to the reservoir inflow. The stations include the upper most station is Cobble Flats (ER-CF), Highway 22 (ER-HWY22), Twin Bridges site (ER-TB) and Weasel Head Footbridge site (ER-WFB) located 8 km downstream of ER-TB and immediately above the inflow to Glenmore. Reservoir bottom sediment was collected using a Ponar Sampler at four locations: Weasel Head (WH), Heritage Cove (HC), Mid Lake (ML), and Head Pond (HP) (Fig. 29).

Figure 29 – Fine sediment sampling locations in the Glenmore Reservoir, Calgary.



Physical characteristics and geochemical composition of Elbow River and Glenmore Reservoir sediments were analyzed according to standard methods at an accredited commercial laboratory. Analyses included grain size distribution, specific surface area, major elemental composition, and particulate P speciation. Particulate P forms (non-apatite inorganic P [NAIP], apatite P [AP], and organic phosphorus [OP]) were determined by sequential extraction according to the method described by Pettersson et al. (1988). Fractionation of particulate P forms can be used as a proxy to estimate the bioavailability of particulate P and its contributions to cyanobacterial growth in aquatic systems. The equilibrium phosphate concentration (EPC_0) is a measure of sediment potential to adsorb or desorb sediment-associated P to/from the water column (Froelich, 1988). Batch experiments were conducted to determine the EPC_0 of sediment samples collected in the Elbow River the Glenmore Reservoir according to the method of Stone and Mudroch (1989). A protocol for culturing Microcystis aeruginosa in natural waters was developed and microcosm bench scale experiments were conducted to assess the role of sediment-associated nutrients, specifically P, in the proliferation of the non-axenic cyanobacteria Microcystis aeruginosa (Yang, 2018).

It is widely acknowledged that changes in flow velocity due to changes in river gradient cause downstream sediment fining to occur. Because suspended solids settle according to size and density (selective sorting), larger particles are generally more prevalent in upstream reaches whereas finer grained materials are transported further downstream and settle in reservoirs. The median diameter (D50) of suspended solids in the Elbow River ranged from 243 μm in the headwater reaches to 33μm at the downstream locations before entering the Glenmore Reservoir. In contrast the median grain size diameter of bottom sediment ranged from 7.23 μm in the outer reservoir to 3.16 μm at the inner reservoir near the dam. Accordingly, the data show that selective sorting of sediment by size is prevalent in the Elbow River and Glenmore Reservoir.

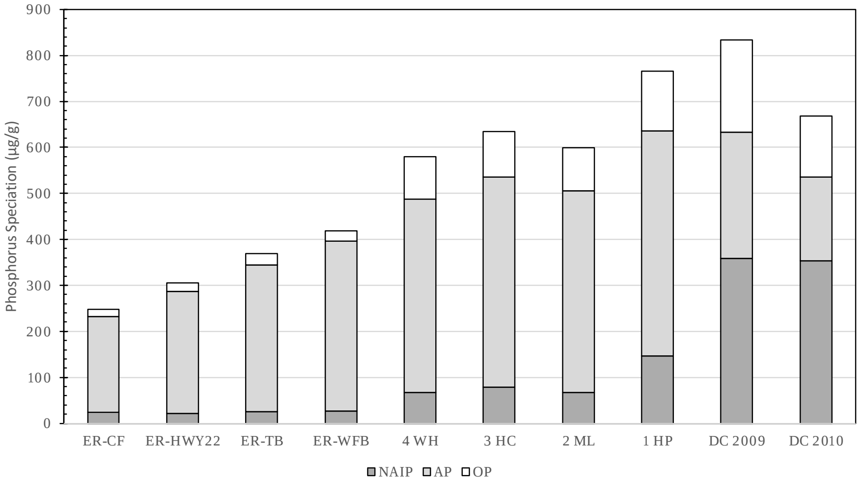
Spatially, the D50 in the Elbow River sediments decreased with distance downstream. Elbow River D50 ranged from 100 to 243 μm in the upper reaches (ER-CF and ER-HWY21, respectively), to 33 to 46 μm in the lower reaches (ER-TB and ER-WFB, respectively). This general trend of decreasing sediment grain size observed in the Elbow River and Glenmore Reservoir is consistent with the general understanding that as rivers flow downstream, most natural river bed sediments progressively become finer grained. This phenomenon is referred to as downstream fining, a fluvial process by which finer particles are preferentially transported and deposited downstream. Two main mechanisms are typically attributed to downstream fining: abrasion, where larger particles break into smaller ones, and selective deposition, which describes hydraulically driven sediment fractionation. Larger particles generally deposit upstream, while smaller ones (i.e., fine grained sediments, typically <63 μm) travel further downstream. Thus, these analyses demonstrated that downstream fining in which suspended solids settle according to size and density (selective sorting) is occurring as water enters the Glenmore Reservoir from the Elbow River.

The major element composition of river sediment varied in a downstream gradient from the headwaters of the Elbow river to the Glenmore Reservoir, in which sediments were primarily composed of the same geochemical elements as Elbow River of: $SiO2$ (40.03% to 42.80%), LOI (20.49% to 22.97%), CaO (14.28% to 17.33%), and $Al2O3$ (9.28% to 11.51%). Levels of $Al2O3$, $Fe2O3$, MnO, $TiO2$, and $P2O5$ were generally observed to have increased with distance downstream from the uppermost site in the Elbow river to the Glenmore Reservoir. This observed increase in Al, Fe, and Mn is typical of downstream increases of clay mineral content that is attributed to selective sorting of sediment in rivers. In contrast, levels of $Na2O$ decreased with distance downstream. The higher fractions of $Al2O3$, $Fe2O3$, and MnO may be of importance, as dissolved P can bind strongly to Fe and Al oxides and oxyhydroxides, while Mn can also form hydroxide coated surfaces, indicating potentially greater bioavailability of P in the reservoir compared to upstream locations.

Total particulate phosphorus (TPP) and particulate phosphorus forms (NAIP, AP, OP) of fine sediment were assessed to determine the relative abundance of particulate P forms along a downstream gradient from the headwaters of the Elbow River to the Glenmore Reservoir. The data show that total particulate P increased with distance downstream (Figure 4) and that fine-grained sediments preferentially deposited in the reservoir contain relatively higher levels of TPP compared to the larger materials that settle upstream. TPP concentrations in the reservoir ranged from 579 to 765 μg P/g sediment, with the highest concentrations occurring in the deepest portion of the reservoir near the dam. In contrast, TPP levels in the Elbow River ranged from 247 to 418 μg P/g. Concentrations of the most bioavailable particulate P form (NAIP) gradually increased with distance downstream within the Elbow River and Glenmore Reservoir. The results show that higher levels of NAIP are associated with the finest grained sediment and that there is an accumulation of the most bioavailable particulate P form (NAIP) in the deepest section of the reservoir near the dam.

Globally, TPP concentrations may range from <300 μg/g to >6000 μg/g depending on surrounding land use, grain size, and other parameters. The TPP of sediment collected from the Elbow River and Glenmore Reservoir ranged from 247.81 μg/g to 304.9 μg/g in the upper reaches (ER-CF and ER-HWY21, respectively), to 368.5 μg/g to 418.1 μg/g in the lower reaches (ER-TB and ER-WFB,

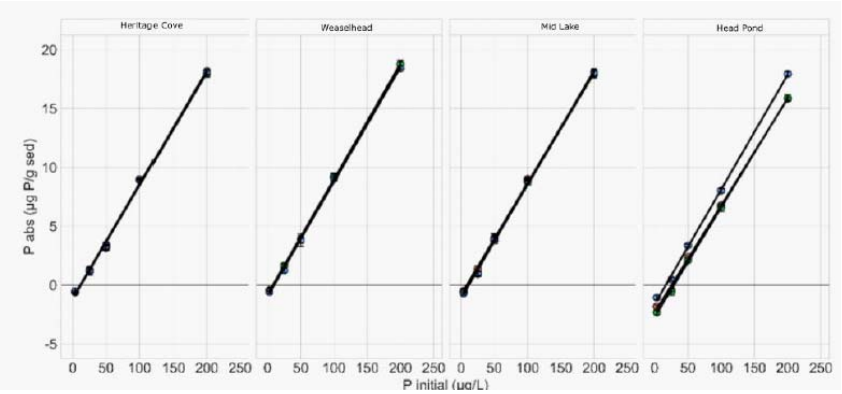
Figure 30 - Phosphorus speciation of fine sediment from the head waters of the Elbow River watershed (Elbow River to the Glenmore Dam).



respectively), and 579.7 µg/g to 765.1 µg/g in the Glenmore Reservoir. These results are consistent with previously reported investigations that have demonstrated that finer particle size fractions have higher concentrations of TPP (Allin 2015).

The equilibrium phosphorus concentration (EPC_0) of the fine sediment was determined using a series of batch tests. The extent to which fine sediments act as sources or sinks of soluble reactive phosphorus (SRP) to the water column was examined. Sediments release SRP to the water column when aqueous P concentrations are below the EPC_0. In the Glenmore Reservoir, the fine sediment EPC_0 ranged from 8.8 µg P/L to 23.7 µg P/L. Given that the SRP concertation in the reservoir can exceed 20 µg P/L, the data presented in Fig. 31 show that sediments preferentially deposited in Glenmore have a high potential to act as an internal loading source of P to the water column, with the highest concentrations occurring at the farthest distance from the reservoir inlet.

Figure 31 - Sediment sorption behaviour of bottom sediment collected from the Glenmore Reservoir.

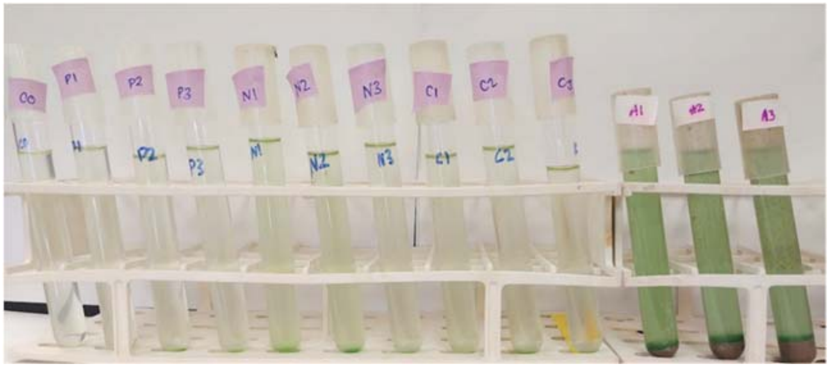


The impacts of sediment source, and nitrate amendment on *M. aeruginosa* proliferation were investigated using a factorial design experiment. Sediments were collected from two watersheds and were also impacted by different surrounding land uses. Drum Creek (DC) sediments were collected from a wildfire impacted region in the Crowsnest watershed, and Head Pond sediments (HP) were collected from a relatively urban reservoir compared to upstream waters in the Elbow River watershed. Nitrate amendment was also investigated - it has been suggested that *M. aeruginosa* outcompete other organisms like green algae when adequate, but not necessarily when excess N is available. Pigment analyses were conducted at the end of the 60-day factorial design microcosm experiments following the approach of Thomas et al. (2013). Cell densities were measured at least every 2 to 3 days, for a total over the course of the 60-day experiments. Each reported cell density was based on the average count obtained from three replicates.

The presence of fine sediment in the microcosms (A1, A2, A3) clearly enhanced *M. aeruginosa* cell proliferation (Fig. 32). This photograph suggests that the sediment provided a sufficient mixture of macro- and micro-nutrients to support cyanobacterial growth. Notably, microcosms containing sediment (A1, A2, A3) were the only treatments that promoted noticeable growth and cell densities similar to those that would be expected during bloom conditions.

This study illustrates that benchtop microcosm investigations can be conducted to investigate the proliferation of potentially toxin-forming cyanobacteria (here *M. aeruginosa*) in modified natural waters with the addition of natural reservoir (or other) sediments to investigate reservoir management, natural disturbance, and other water quality and environmental impacts on the potential proliferation of cyanobacteria. While the microcosm investigations detailed herein are by no means predictive, they are easy and inexpensive to conduct relative to other approaches (such as the use of limno-corrals). Moreover, they offer a relatively rapid means for providing insights and direction for further investigation and consideration of landscape disturbance and reservoir management impacts on source water quality and drinking water treatability.

Figure 32 - *M. aeruginosa* proliferation in Elbow River water on Day 27 of 60-day microcosm experiments. Samples containing fine sediment from Glenmore Reservoir exhibited significantly higher *M. aeruginosa* proliferation.



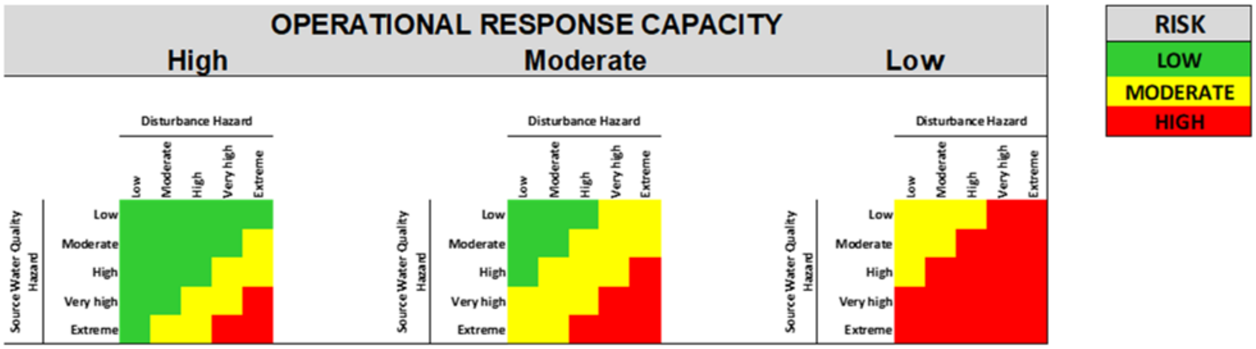
The proof-of-concept investigation presented herein demonstrates that reservoir sediment can significantly promote *M. aeruginos*a proliferation in low nutrient, mesotrophic-oligotrophic waters. This work emphasizes the need to evaluate and better understand the contributions of various fine sediment sources during drinking water reservoir risk management. Notably, drinking water reservoirs are typically managed to ensure water availability. When reservoirs are used as equalization basins for dampening rapid changes in water quality, the contributions of the relatively small amounts of fine sediment present within them—and the associated potential for that sediment to serve as an internal source of bioavailable P—are not typically considered. This work suggests fine sediment and its potential contributions to the proliferation of cyanobacteria and algae should be considered as part of regular reservoir management and source water protection planning in the drinking water industry.

It should also be underscored that both anthropogenic (e.g., development, agriculture, and resource extraction) and natural (e.g., wildfire and flooding) landscape disturbances can significantly increase fine sediment availability and transport to downstream receiving waters, including drinking water reservoirs. Thus, these results have significant implications for both climate change adaptation and the management of drinking water reservoirs, especially in systems that receive high quality source water. High quality source waters are more likely to be sensitive to relatively small shifts in sediment-associated nutrient availability. Moreover, it is critical to note that reservoirs such as the one investigated herein may already contain sediments that can significantly enhance cyanobacterial proliferation if the system conditions (e.g., turbulence, light levels, etc.) favour their growth. Thus, an improved understanding of ecosystem dynamics is still needed. Regardless of whether or not such shifts occur due to landscape disturbance or reservoir management, the potential for fine sediment-associated proliferation of cyanobacteria should be a critical component of drinking water treatment risk management. Cyanobacterial blooms can challenge treatment infrastructure and lead to service disruptions that threaten public health. Critically, as fine sediment characterization is not a typical component of most source water protection programs, this type of watershed characterization and associated water quality analysis may be useful for drinking water utilities in identifying both current threats to water supply and treatment and future threats associated with potential or anticipated watershed disturbances.

E.12.3 Task 10.3 Treatment Resiliency Decision Support Framework

While drinking water treatment is what occurs in plants, drinking water “treatability” is related to key attributes of untreated (source) water quality that drive the need for and performance of different water treatment technologies and operational strategies (Emelko et al. 2011). The treatment capabilities of various types of treatment infrastructure are generally understood and can be described as infrastructure response capacity. The ability to recover quickly from challenges (i.e., resilience) is a characteristic of both the infrastructure type and the ability to operate the infrastructure optimally (or near to optimally) during periods of significant operational challenge (i.e., operational response capacity). A generalized framework was developed to characterize operational response capacity and associated risk of treatment system failure for a given infrastructure typology in response to a landscape disturbance hazard and associated consequence to source water quality that may subsequently result in a drinking water treatability hazard (Fig. 33). This figure underscores that high operational response capacity can substantially decrease the risk of system failure, thereby leading to treatment resilience.

Figure 33 – Generalized framework for characterizing operational response capacity and associated risk of treatment failure for a given infrastructure typology in response to a landscape disturbance hazard and associated consequence to source water quality that may subsequently result in a drinking water treatability hazard.



High	Low	Moderate	High	Very high	Extreme
Low	🟩	🟩	🟩	🟩	🟩
Moderate	🟩	🟩	🟩	🟩	🟨
High	🟩	🟩	🟩	🟨	🟨
Very high	🟩	🟩	🟨	🟨	🟥
Extreme	🟩	🟨	🟨	🟥	🟥

Moderate	Low	Moderate	High	Very high	Extreme
Low	🟩	🟩	🟩	🟨	🟨
Moderate	🟩	🟩	🟨	🟨	🟨
High	🟩	🟨	🟨	🟨	🟥
Very high	🟨	🟨	🟨	🟥	🟥
Extreme	🟨	🟨	🟥	🟥	🟥

Low	Low	Moderate	High	Very high	Extreme
Low	🟨	🟨	🟨	🟥	🟥
Moderate	🟨	🟨	🟥	🟥	🟥
High	🟨	🟥	🟥	🟥	🟥
Very high	🟥	🟥	🟥	🟥	🟥
Extreme	🟥	🟥	🟥	🟥	🟥

RISK
🟩 LOW
🟨 MODERATE
🟥 HIGH

Several key support analyses and practices that can increase operational response capacity in managing drinking water treatability threats from large, rapid shifts in source water turbidity and/or DOC concentration/character are provided in Table 10. Notably, the operational practices that are highlighted in this table are consistent with and build upon the “know your system” approach of drinking water safety plans by not only encouraging source water monitoring and characterization, but also regular treatability assessment and trend analysis. Systems that regularly implement operational response practices such as those listed in Table 10 are more likely to have high operational response capacity and thus lower risk of system failure as a result of landscape disturbance-associated turbidity and/or DOC threats to drinking water treatability. It should be mentioned that this table is not intended to serve as an emergency preparedness or response plan; rather, it is designed to highlight good practices associated with recognizing and responding to source water quality shifts that can compromise treatment responsiveness and the associated provision of adequate amounts of safe drinking water.

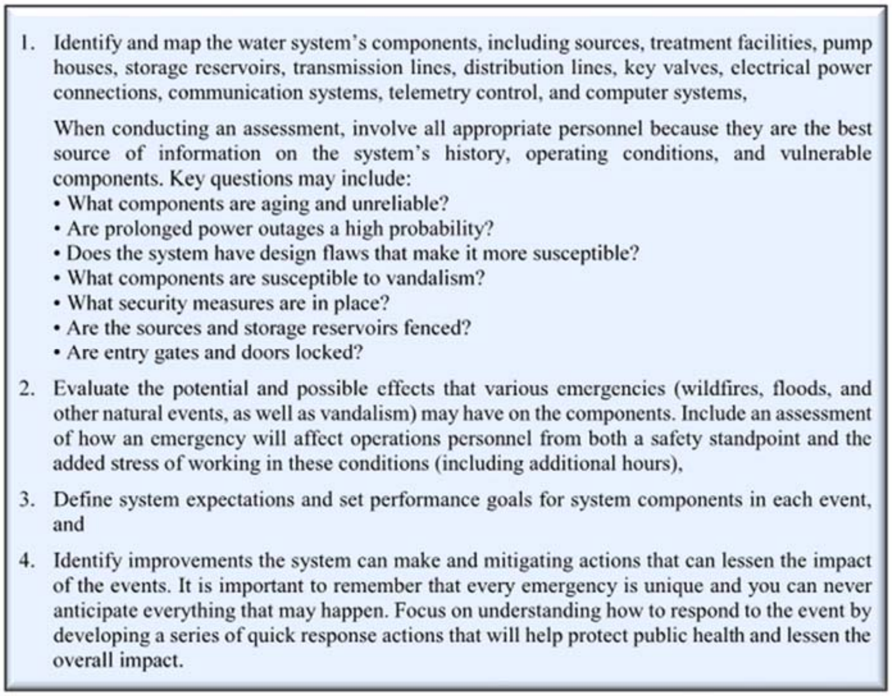
Table 10 - Approaches for Increasing Operational Response Capacity in Managing Treatability Threats from Turbidity and DOC

Approaches for Increasing Operational Response Capacity in Managing Treatability Threats from Turbidity and DOC	Suggested Frequency
online monitoring of source and clarified (if relevant) water turbidity	online
regular monitoring of source and filtered water DOC	weekly and during events
regular monitoring of source and filtered water UV_{254}	daily and during events
regularly analyse trends in source and filtered water turbidity, DOC, UV254, applied chlorine doses, and DBP formation	ongoing
regularly conduct/practice jar testing	monthly
regular evaluation of DBP formation at different DOC and UV_{254} conditions	monthly and during events
evaluate zeta potential analysis for informing coagulant dosing	confirmatory trial and daily analysis (if relevant)

E.12.4 Task 10.4 Adaptation Strategies Guidance Document for Small Utilities

A simple set of guidance criteria were developed for small utilities to (1) inform them about how land disturbances and extreme events affect drinking water quality, (2) assess vulnerabilities in their drinking water treatment systems, and (3) increase treatment resiliency. Landscape disturbance effects on water quality and treatability were generalized based on Emelko et al. (2011) and summarized using a tabular format. In brief, they highlighted the impacts of turbidity, DOC, phosphorus, algae, and heavy metals on drinking water treatability and public health for surface- and groundwater-based supplies.

“Vulnerability Assessment” was described as a process that is conducted to evaluate each component of the water supply, treatment, and distribution system for weaknesses or deficiencies that may make it susceptible to damage or failure during periods of high operational challenge and emergency situations. A simple 4-step process for conducting vulnerability assessment was detailed. It advises:



1. Identify and map the water system’s components, including sources, treatment facilities, pump houses, storage reservoirs, transmission lines, distribution lines, key valves, electrical power connections, communication systems, telemetry control, and computer systems,

   When conducting an assessment, involve all appropriate personnel because they are the best source of information on the system’s history, operating conditions, and vulnerable components. Key questions may include:
   - What components are aging and unreliable?
   - Are prolonged power outages a high probability?
   - Does the system have design flaws that make it more susceptible?
   - What components are susceptible to vandalism?
   - What security measures are in place?
   - Are the sources and storage reservoirs fenced?
   - Are entry gates and doors locked?
2. Evaluate the potential and possible effects that various emergencies (wildfires, floods, and other natural events, as well as vandalism) may have on the components. Include an assessment of how an emergency will affect operations personnel from both a safety standpoint and the added stress of working in these conditions (including additional hours),
3. Define system expectations and set performance goals for system components in each event, and
4. Identify improvements the system can make and mitigating actions that can lessen the impact of the events. It is important to remember that every emergency is unique and you can never anticipate everything that may happen. Focus on understanding how to respond to the event by developing a series of quick response actions that will help protect public health and lessen the overall impact.

The treatment resilience framework developed in Task 10.3 is utilized to provide infrastructure typology examples and identify strategies for increasing operational response capacity to increase treatment resilience and decrease the risk of system failure when faced with severe treatability threats from turbidity and DOC. An additional, non-exhaustive module (Table 11) was developed to facilitate discussion regarding reservoir management strategies for managing algal bloom risks that can be exacerbated by internal loading of bioavailable phosphorus from fine sediments. These materials have been effectively combined with case study examples in the delivery of operator training workshops.

Table 11 - Reservoir management strategies to manage algal bloom risks

Reservoir Management Strategies to Manage Algal Bloom Risks	**Suggested Frequency**
evaluate release of bioavailable phosphorus from fine sediment	every few years and after major events
flush out or remove fine sediment from raw water storage reservoirs	yearly
remove vegetation and woody debris (if relevant)	yearly
apply aeration to reduce algal blooms (if relevant)	seasonally
install reservoir cap to reduce algal blooms (if relevant)	seasonally as relevant
regularly flush settling basins to remove sludge build-up	yearly

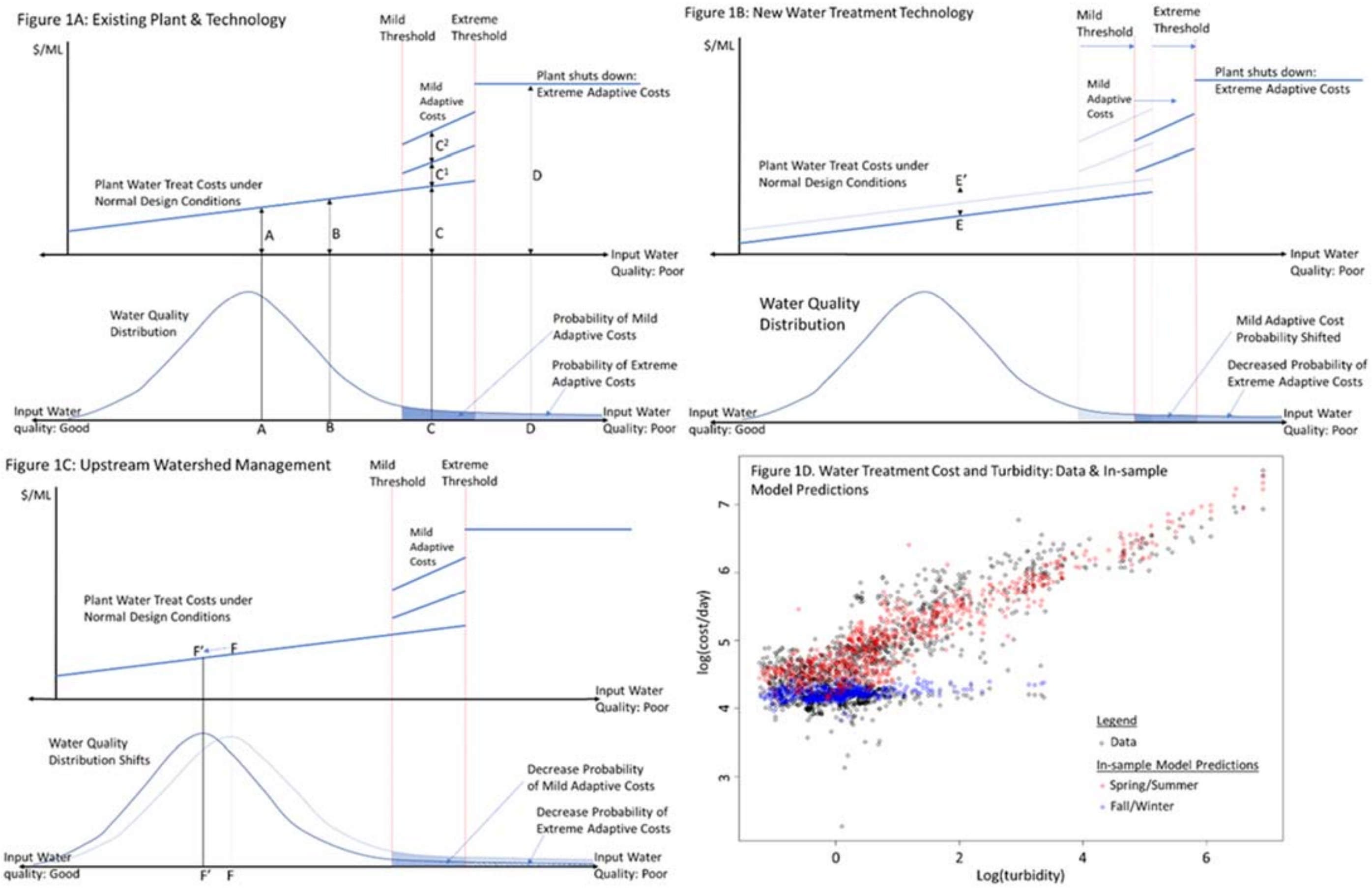
E.13 Milestone 12 - Model Optimal Utility Investment Strategies

E.13.1 Merger of a) *Task 11.2 Evaluate Sensitivity of Impacts to Water Ecosystem Services under Varied Population Growth and Demographic Scenarios* with b) *Task 12.1 Model Optimal Utility Investment Strategies (technology, source water protection) under Changing or Uncertain Land Conditions*

A novel conceptual framework for considering trade-offs between investment in upstream watershed management strategies and investment in water treatment plant infrastructure was developed (Fig. 34). To the best of our knowledge, no similar framework has been developed and tested in a case study as described below. The conceptual framework begins with an assumption that the source water quality (as measured by various indicators such as turbidity, TOC, pH, and temperature) for a drinking water plant varies over time on various time scales (daily, seasonally, annually) which may be represented as a statistical distribution. The water treatment costs, shown in the upper part of Fig. 34-1A, are assumed to be based on a fixed existing plant and technology, water output quality standards, and servicing a relatively fixed population. Fig. 34-1A shows, conceptually, what happens to costs when water quality varies across four different levels (A, B, C and D) ordered from best quality to worst. Water quality level A is closest to the center of the water quality distribution and falls within the normal design thresholds. When water quality decreases to B, quality is still within design thresholds allowing the plant to process the water to the desired standards but the cost of processing increases.

However, if water quality decreases (to the right) sufficiently, design thresholds are crossed (Mild & Extreme) and additional adaptive costs are incurred by the community serviced by the water plant. There are three cost zones defined by the thresholds: 1) Water treatment costs under normal design conditions; 2) mild adaptive costs; 3) extreme adaptive costs and possibly costs associated with increased morbidity/mortality. Water quality level C crosses the mild threshold and results in adaptive costs resulting from additional in-plant costs (C1) and adaptive community wide costs(C2). Additional in-plant costs may include additional staff time and energy consumption, or in some cases additional expensive actions such as dredging. In this scenario the plant still operates, however, output water quality does not meet standards resulting in warnings to the community such as boil water advisories. Mild adaptive costs result from adaptive or defensive actions of community members in the form of additional time and energy costs of boiling water or purchasing bottled

Figure 34 – Illustration of a framework for economics analysis of water treatment. Details are explained in the text. Panel 1D shows data used to estimate chemical costs of water treatment within normal operating conditions and in-sample model predictions for chemical costs as a function of turbidity, TOC, in-plant water flow, and seasonal dummy variables



water. There may also be mild increases in risks of water-borne diseases. At point D, water quality crosses the extreme threshold resulting in possible plant shut-down and extreme community wide adaptive costs such as trucking in large quantities of water and further increases to risks of disease.

Cleary it is desirable to design the water treatment plant so that the probabilities of crossing these thresholds is low (in the right tail of the water quality distribution). Fig. 34-1B shows the effect of investing in new in-plant technology. Mild and extreme thresholds are shifted to the right decreasing the probability of incurring adaptive costs. However, these benefits must be weighed against the cost of the investment. In addition, in-plant water treatment costs may rise or fall as illustrated by point E and E'. Obviously, it is desirable for the new technology to have lower processing costs and so one might question why a potentially higher cost is shown here. However, this may be economically beneficial if the technology significantly reduces the risk of incurring adaptive costs - especially high costs. Processing costs may also increase if output water quality standards increase. Risk preferences or risk aversion of those planning future upgrades will also play a role in how these tradeoffs are made.

Conceptually, Fig. 34-1C shows the effect of improving water quality by managing upstream water quality. The water quality distribution is shifted left which decreases median water quality and water treatment costs from F to F'. Adaptive costs are decreased by thinning the tail of the poor water quality end of the distribution. Again, the benefits of reducing adaptive costs must be weighed against the net-costs of improving the management of the upstream water source.

Population growth is another consideration that drives both new in-plant investments and upstream water management decisions. For example, if heightened population growth threatens to exceed plant capacity earlier than expected then new investment decisions designed to reduce risks of adaptive costs from extreme events and increase output water quality may be combined with investments decisions oriented towards increasing output capacity. Finally, both in-plant ("grey infrastructure") and upstream land-water management investments ("green infrastructure") may be weighed against each other and balanced or optimized jointly. It is impossible, a-priori, to say definitively what the balance of investments between in-plant and source water management should be and it is likely that this will depend on specific unique characteristics of the source watershed and the community being served.

Analysis Approach

The framework described above was used to develop and inform an empirical case study. Costs, under normal operating costs as defined above, were calculated for the period 2011-2015 from daily records of treatment plant operations acquired from the Glenmore Water Treatment Plant in Calgary, Alberta. Additional description of these costs, calculation of water quality thresholds, and adaptive costs for risks of illness, costs of reservoir dredging, costs of plant shut down, and population growth estimates / scenarios used in these analyses are described in the Appendix to this report.

Modelling Direct Costs of Water Treatment and Risks of Incurring Adaptive Costs

Water quality indicators (TOC and Turbidity) for the water intake at the Calgary, Glenmore were modeled based on analysis of 11 years of data obtained from the plant. The aim of the analysis was to create a model that simulates variability in water quality accounting for seasonal averages, seasonal differences in variability. The water quality and population models were used to simulate turbidity, TOC and population for a period of 20 years. The simulated values were then used as inputs to estimate total costs of in-plant chemical treatment costs plus community costs incurred from adaptive/averting behaviors due to boil water advisories, plant shut-downs, and probability adjusted morbidity/mortality cost scenarios. Two community cost scenarios were created using the lowest and highest costs for each cost component (Appendix Table M-1) for boil water advisories, shutdown costs and illnesses. As an initial assumption, the outside costs were triggered when turbidity exceeded 4000NTUs. Dredging costs are large but were left out of the simulation because of difficulties determining how to properly condition the probability of incurring dredging costs[1]. The net present value of 10,000 twenty-year scenarios were calculated using an annual discount rate of 3.5%. This created a distribution of net present values for both the low and high outside cost scenarios. Preliminary results for these distributions are shown in Fig. 35.

In comparison to community ("outside") costs, the net present value of plant chemical costs changes very little from the lowest (1st percentile) to highest (99th percentile) costs, with the caveat that variation of in-plant cost is likely underestimated here because energy, labor and maintenance costs are not included. There is more variation in the present value of outside costs especially if these costs are high (see Fig. 35). The costs of boiled water advisories make up the majority of outside costs. There is an order of magnitude of difference in outside costs depending on whether we use the low or

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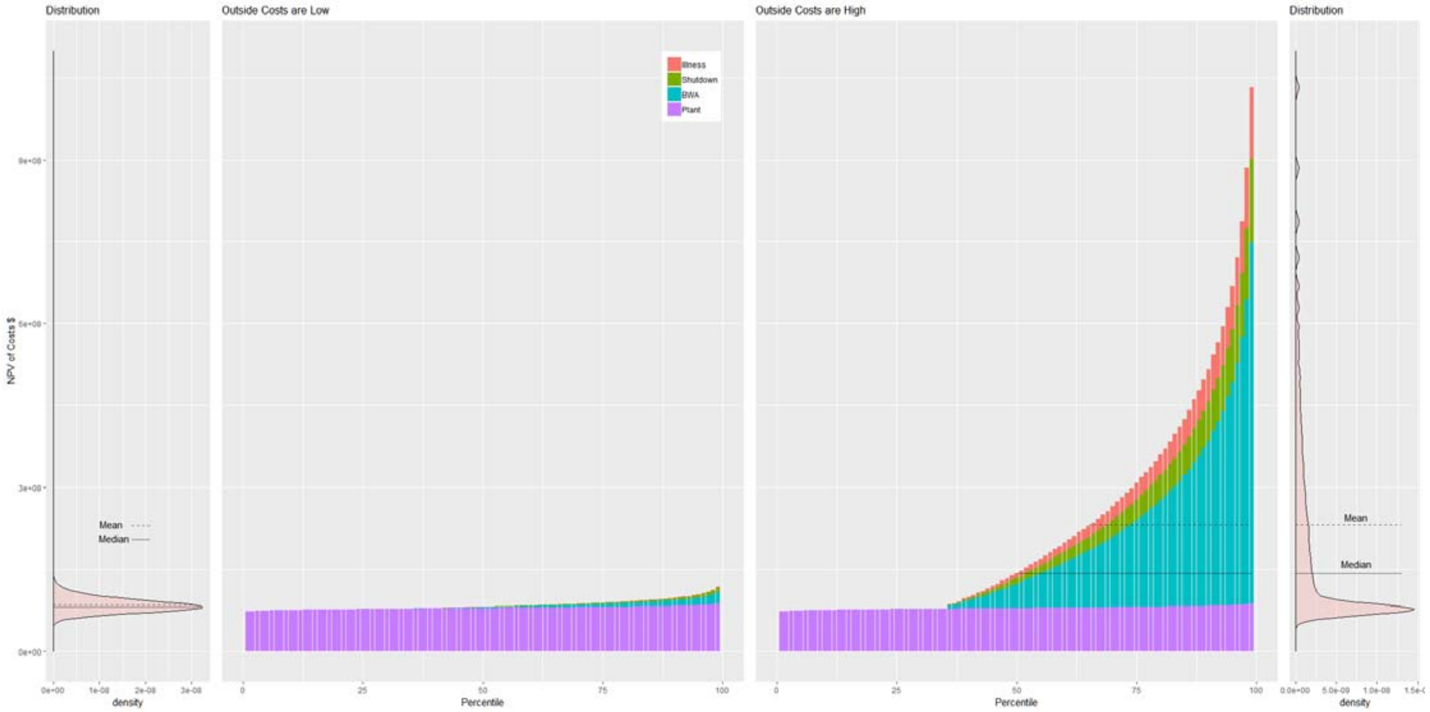
[1] It would be desirable to estimate a conditional probability or to simply use a higher threshold for dredging costs since not all breaches of the thresholds would result in the need for dredging. It was difficult to find data that would allow us to estimate a probability and no doubt the probability or threshold would be site specific. In addition, the need for dredging may be the result of an accumulation of deposition from both normal and extreme conditions over time. Thus, dredging costs were left out of the cost estimates for now. Clearly, including them, with appropriately set probabilities or thresholds, would increase the costs.

Figure 35 - Distribution of chemical treatment costs and two assumed levels of outside costs.



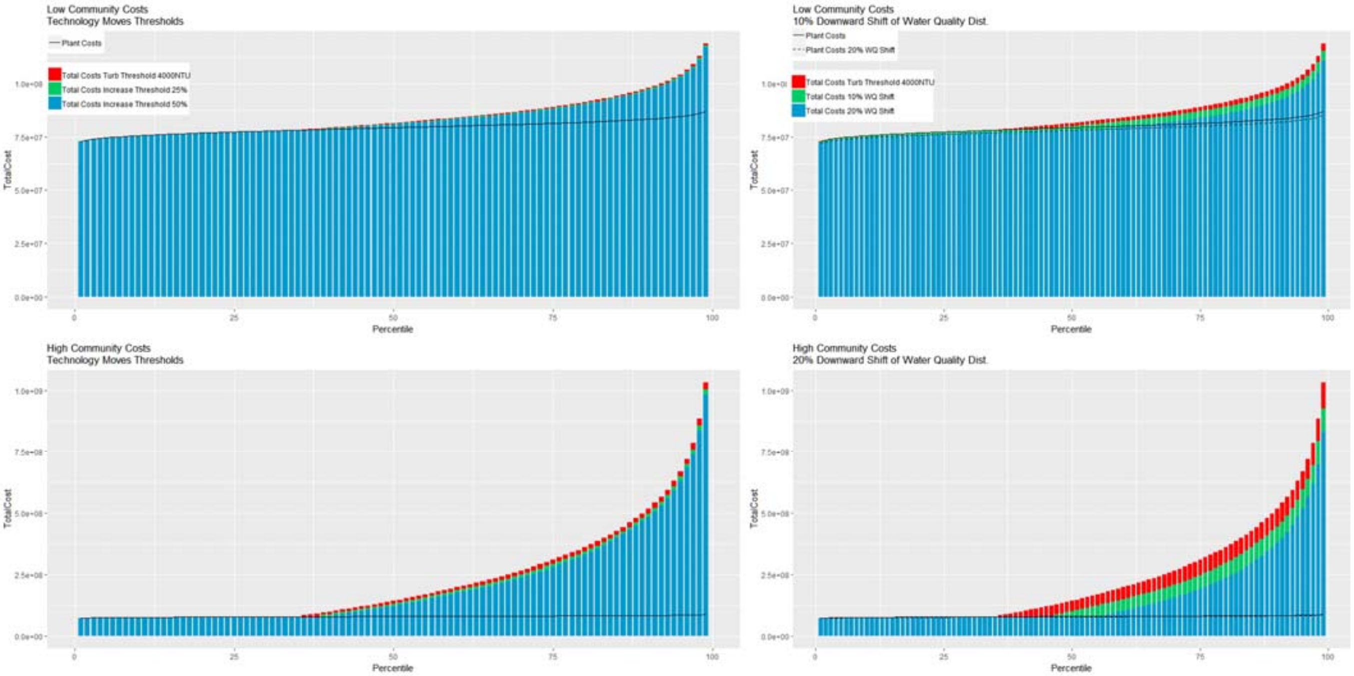
high costs estimates. If outside costs are assumed low (see middle-left pane in Fig. 35) then in-plant chemical costs make up the majority of total costs in terms of expected costs (mean), median costs and even maximum costs (99th percentile). However, if outside costs are assumed to be high, then median costs are roughly doubled while mean or expected costs are approximately 3.5 times higher. Maximum costs are more than ten times higher. Since the outside costs are triggered only if the 4000NTU threshold is exceeded the distribution of outcomes is highly skewed especially in the high cost scenario (see outside panes of Fig. X3). Proper inclusion of dredging costs, would skew the distribution further.

Potential Changes in Costs due to Technology or Changes in the Distribution of Water Quality

The effect of changes in the in-plant technology, that increases the threshold at which community costs are incurred, was explored by increasing the 4000 NTU threshold by 25 and 50% which will obviously decrease the number of simulated occurrences of community costs. Fig. 36 shows the effect of this change on the NPV of total costs (plant, boiled water advisories, shutdowns and illnesses combined). The 25% increase in threshold decreases median NPV of costs from $81.51-142.7 million (low/high outside costs) at the base assumption to $81.1-131.4 million (the red portion of the bars in the graph in the two left panes) or by <1% and 8%. The 50% increase in threshold decreases median NPV of costs further to $80.8-121.8 million (the green portion of the bars in the left two panes) or 1% and 15%. There is also a small effect on the number of simulated outcomes with positive community wide costs. In the base scenario the outside costs are zero up until the 36th percentile. This shifts to the 39th and 41st percentiles for the 25% and 50% threshold changes respectively.

The effect of changes in the water quality distribution were modelled by reducing each simulated water turbidity and TOC over 20 years by a fixed proportion of 10% and 20%. The effect of this for both low and high outside costs is shown on the right side of Fig. 36. In this case, the outside costs drop more substantially than they do for changing the in-plant thresholds. The 10% decrease in

Figure 36 - Cost changes due to shifting of thresholds that trigger community wide costs and shifting the water quality distribution – illustration of investments of “grey versus green” infrastructure.



turbidity and TOC reduces costs to $80-100.4 million at the median or by 2% and 30% for low and high community costs respectively, while the 20% decrease reduces costs to $78.2 million for both or by 4% and 45%. There is also a large change in the percentile at which community wide costs appear for the simulated shifts in the water quality distribution. The changes are from 36 to 47 for the 10% shift and 36 to 57 for the 20% shift.

Interpretation of Findings

While community costs decrease more under our improved ecosystem services case (shift the water quality distribution) than they did for changing the in-plant thresholds (improve grey infrastructure technology), it is impossible to draw immediate conclusions about which or what combination is the best investment. The answer to that question will require more information about the relative (economic) efficacy of an investment in upstream management versus investment in-plant technology. However, the framework presented here can incorporate this information and could be the focus of future investigations. Such investigations will likely reveal that the relative effect sizes of improved grey infrastructure and improved upstream water management will be very site specific.

Recent high-profile extreme events have revealed that costs of water treatment failures can be high but it is important to realize that these are *ex-post* costs. The current investigation attempts to incorporate these potential costs up-front and does reveal that outside community-wide costs as a result of water treatment plant failure can be substantial in an *ex-ante* sense. The heavy skewness of the cost distribution due to the small but significant probabilities of plant failure combined with potentially high costs of failure significantly separates the median and mean (expected) estimates of water treatment costs. While the expected or mean total cost, estimates add significantly to in-plant water treatment costs and provide an important benchmark, relying on minimizing expected cost alone implies risk neutral decision makers. Water treatment decision makers are likely to be (justifiably) risk averse (high preference to avoid the extreme costs) and therefore it is important to display the full distribution of costs as shown in Fig. 35 and 36. Relative to expected values, a careful accounting of risk aversion in a cost minimization framework places more weight on extreme cost outcomes and combined with a full description of cost outcomes may provide economic rationale for improved management of upstream water supply. This will be especially true if it can be shown that shifts in the water quality distribution attributable to upstream management significantly shifts the tail of the poor end of the water quality distribution. If upstream management does shift the water quality distribution but without significantly reducing extreme poor-water quality events, then increased costs will be largely confined to the water treatment plant. In this case, there may not be enough cost reduction to provide a convincing rationale for improved upstream water source management[2] even for risk averse decision makers. However, if source water management reduces the probability of extreme events (i.e. extreme natural disturbances) then these costs may be justified.

To the best of our knowledge the approach used here is novel and has not been applied to cost or investment analysis. This research, while still preliminary in nature, suggests that previous studies have (potentially significantly) underestimated cost impacts of water quality improvements. A real options framework together with improvements in calibration of outside costs, water quality distributions, technology and water management effects could be used to consider both the timing and balancing of new water treatment investments in plant and water source management. This research has attempted to lay the groundwork for such a study.

E.14 Milestone 13 - Knowledge and Best Practices Workshops

E.14.1 Task 13.1 Knowledge and Best Practices Mobilization Workshops

In addition to numerous smaller meetings and workshops with project partners and practitioner stakeholders (see Section J), two major field-based workshops were held during the project.

1) The first was a very large, full-day field workshop held in the backcountry Star Ck. watershed on August 25, 2017 focused on SRWP Phase II and implications of early results (first 1.5 yr. after harvesting) for forested source water protection and management in Alberta (Fig. 37). Executive and senior staff of AB. Agriculture and Forestry, AB. Environment and Parks, AB. Innovates, City of Calgary Water Services, and Canadian Forest Products Ltd. staff participated including Deputy Minister AB. Environment and Parks, 3 Assistant Deputy Ministers (AAF/AEP), and 2 executive directors of companion divisions from AAF/AEP, along with senior management staff from all participating agencies.

Figure 37 – Field workshop on forest management-based source water protection (Aug. 2017)

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[2] We note that other considerations such as reduction of property damage derived from reducing extreme fire events may provide sufficient rationale for upstream management that would include water ecosystem service benefits.

A particularly important element of this workshop was enabling the interaction of senior participants from government environmental protection and forestry sectors, the industrial forestry sector, and the municipal drinking water treatment engineering sector that had not previously had the opportunity to discuss and share highly diverse perspectives on forested source water protection in Alberta. Feedback on this workshop was universally positive (including a letter from Andre Corbould, Deputy Minister, Alberta Environment and Parks) reflecting the impact of the workshop in bringing together policy, governance, and professional public and private domains leading development of source water protection initiatives in Alberta.

2) A second major field-based workshop on forested source water protection spanned 2 full days on July 31– Aug 1, 2018 (Fig. 38). This field workshop was held in both the harvested sub-watersheds of Star Ck. (day 1) and in the 2017 Kenow Mtn. Wildfire in Waterton Lakes National Park (day 2). The workshop built on workshop 1, but expanded the scope of participating agencies to include land-water managers from *both* provincial and federal agencies responsible for management of *both* protected and managed landscapes. After hearing about our workshop, four B.C. government land-water managers (geomorphologists/hydrologists) from two regions in the B.C. interior were also invited to participate.

The result was a highly unique, and particularly powerful workshop that brought together highly diverse perspectives from across agencies with diverse management missions which included B.C. Ministry of FLNRO (4 staff), their counterpart land-water managers from AAF/AEP (3 staff), Alberta Parks (2 staff), and Parks Canada (8 staff).

We received exceedingly positive feedback from all participants (i.e. "*I have never before participated in such a meeting of the minds over a common issue like source water protection in the face of growing wildfire threats … the workshop was fantastic and I've never heard of anyone attempting such a thing*"). This particular workshop has led to significant new and on-going provincial-federal collaborations between these agencies since Aug. 2018.

Figure 38 – Two-day workshop on forested source water protection (July-Aug. 2018)

F Key Learnings

This project has delivered an unparalleled, and exceedingly comprehensive evaluation of impacts to water from contemporary forest management strategies that reflect the highly diverse “values” society places on water including supply, quality, ecosystem health, regional downstream effects, implications for drinking water, along with full economic analysis of implications of source water protection strategies on water ecosystem goods and services. This includes development and preliminary analysis of optimal investment strategies to both better protect municipal drinking water supplies and the forested landscapes furnishing these supplies through both technological (”Grey”) infrastructure and landscape source water protection-based (”Green”) infrastructure investments.

It is particularly worth noting that similar evaluations involving even a small fraction of the scope reported on here do not presently exist anywhere worldwide. However, it is precisely this broad, transdisciplinary scope that has enabled this project to produce the key science, engineering, and economic/policy insights on integrated municipal and forested source water protection options to enable Alberta to develop science-informed climate change adaptation strategies. A high-level summary of 3 key insights from the four major project domains are outlined below.

Three high-level learnings from each of the four research themes

Effects of contemporary forest management/harvesting on water from the eastern slopes

- Hydrologic resistance of Alberta’s upper eastern slopes to changes in streamflow after disturbance is greater than previously thought. Common perceptions are that disturbance increases streamflow leading increased peakflows and with risk of downstream flooding. However, while annual flows increased in small watersheds after harvesting by a greater amount than expected based their disturbance footprint, these effects on flows appeared to result from deeper sub-surface delivery of water that did not affect storm runoff or peakflows. Furthermore, while harvest effects on snowpacks also appeared to shift flows into early spring seasons, none of these harvest effects on flow were detectable even a short distance downstream. Science-based observations of the hydrologic resistance to disturbance in this study are important in informing land management regulations and policy where likelihood of these impacts has been previously assumed.
- Contemporary forest management strategies involving harvesting do not always (or may not actually) produce any negative impacts on water quality. This is highly contrary to common narratives, but not only was there no meaningful degradation of water quality from any of the harvest strategies studied, paradoxically, the water improved for four years after harvesting. Furthermore, because water quality is a key regulator of stream productivity, there were also no impacts to aquatic health. While much historic research documents considerable impacts of harvesting on water quality, this research does not reflect contemporary forest practices and current forestry sector best practice. Practically, this means that careful application of best management practices for minimizing impacts of forestry operations can absolutely be effective in minimizing (or preventing as in this case) negative impacts on water. This outcome is crucial because it advances the management focus and attention towards careful application of best practices for both industrial and government land managers.
- Results of this research also challenges common perceptions by the public and even policy makers that forestry practices produce negative downstream effects on water. This study showed harvest effects on water (whether they might be positive or negative) could not be detected even a short distance immediately downstream of harvested sub-catchments. In this regard, our study design enabled the most powerful ability to detect such effects, but these were not were evident across a broad range of downstream spatial scales. These insights are very important to regional water

managers and policy makers where such impacts might be routinely assumed, but are highly unique findings because no prior studies have enabled this type evaluation.

Regional downstream cumulative effects of land disturbance

While the interim results did not show any meaningful downstream effects of forest harvesting, characterizing downstream cumulative watershed effects remains a daunting challenge for water managers in Alberta. Because fine-sediments are the primary vector for most of the contaminants of concern, our research on contaminant transport and tools to model these over broad spatial scales represent powerful cumulative watershed effects assessment methodologies that are applicable to a broad range of regional water management challenges in Alberta.

- Sediment fingerprinting is a powerful tool that has been used globally to identify problem sediment source areas at the catchment scale. When appropriate tracers for robust source discrimination are used, this approach provides another component of a weight-of-evidence approach to assess and compare the relative effects of landscape disturbance such as wildfire, harvesting, flooding and resource extraction. The utility of source fingerprinting procedures within a weight-of-evidence framework for a BACI experimental design is that by providing a direct link between sampled target sediment and landscape sources, the results of these methods are one of the most sensitive indicators of the impacts of land management interventions.
- Sediment transport modelling: Although the data requirements of these physically based models are costly, once calibrated flow these models can be used as a management tool to quantify the downstream propagation of sediment, evaluate sediment and flow dynamics in reservoirs and simulate a range of conditions to assess a range of possible climate driven scenarios. The modeling framework evaluated herein represents a useful simulation tool for informing landscape and reservoir management in the context of disturbances driven by climatic or anthropogenic pressures.
- Phosphorus form and mobility: Our work demonstrated that fractionation methods can be used to assess the effect of landscape disturbance on the phosphorus composition of sediment at the large basin scale. This approach enabled the relative effects of sewage effluent, harvesting and wildfire to be compared and to evaluate its potential as an internal loading source of phosphorus in rivers and reservoirs. Accordingly, particulate phosphorus forms are useful tracers in watersheds at the basin scale and can be used in cumulative effects studies to link nutrient supply from various land disturbance types to ecosystem response.

Drinking water

- Contemporary forest harvesting practices did not meaningfully impact the drinking water treatability of water supplies from Alberta’s upper eastern slopes. This was in stark contrast to severe wildfire and post-fire salvage logging, which can compromise drinking water treatment by causing THM-FPs that approach some of the highest values that have been reported for water supplies with moderately high DOC concentrations. Thus, forest management-based forested source protection shows great promise if the outcome of these strategies reduce or mitigate these climate change-associated disturbances posing risks to drinking water treatability.
- Despite extensive efforts to identify advanced metrics for characterizing dissolved NOM concentrations and character, UV254 remains a simple indicator of THM formation potential. Hydrophobicity (HPO) measured by resin fractionation and the humic substances fraction (HS) obtained from size-based fractionation with LC-OCD are also excellent indicators when evaluated as absolute (mass-based concentration) quantities.

- While it is generally understood that fine sediment can serve as a source of internal loading of bioavailable phosphorus that can promote potentially toxin forming algal blooms, the proof-of-concept investigation presented herein incontrovertibly demonstrated that very small amounts of fine sediment can significantly promote the proliferation of toxin-forming M. aeruginosa, even in low nutrient, mesotrophic-oligotrophic Alberta water supplies, such as those serving Calgary. This observation has critical implications for reservoir (and flood) management in Alberta because drinking water reservoirs are typically managed to ensure water availability, not water quality. When reservoirs are used as equalization basins for dampening rapid changes in water quality, the contributions of the relatively small amounts of fine sediment present within them—and the associated potential for that sediment to serve as an internal source of bioavailable P—are not typically considered. This work suggests fine sediment and its potential contributions to the proliferation of cyanobacteria and algae should be considered as part of regular reservoir management and source water protection planning in the drinking water industry. Given Alberta's reliance on raw water storage reservoirs for meeting summer demands, this work demonstrates an urgent need to further develop reservoir risk assessment and management strategies so that they reflect water quality and treatability targets in addition to supply targets.

Economic implications of source water protection to water ecosystem services

- Assessment of the economic value of reducing the risks of water outages (from boil water advisories and/or other causes) are positive (approximately $75 /household / year) and illustrate the public's willingness to support investments to reduce risks to water supplies. These values, while modest relative to household water bills, when aggregated provide an indication of a sizable economic value for water reliability. Interestingly there is little evidence of any preference for risk reduction arising from source water protection versus traditional infrastructure. People prefer greater reliability, regardless of how this achieved.
- Economic benefits arise from source water protection that improves water quality (e.g. lowers turbidity) or avoids reductions in water quality. Using unique data and methods we explored benefits that focused on water treatment costs alone, however, these understate the economic values by up to 50%. Economic analysis that probabilistically incorporates extreme events and possibilities of boil water advisories (or similar water reliability challenges) shows considerably higher economic benefits from source water protection. This illustrates the importance moving beyond the assessment of "average" impacts and carefully examining the most challenging, extreme "tails" of the water quality distributions (i.e. storms). Given concerns over climate change, severe natural disturbances and potentially more extreme events, this type of analysis is particularly timely and important.
- A novel economic framework developed to assess "green" versus "grey" infrastructure shows that the relative efficacy of these approaches will lie in the ability of the approaches to reduce or mitigate the likelihood or impacts of extreme events such as those known to be produced from wildfires or floods. Grey and green infrastructure affect treatment plant intake water quality and costs in different ways, thus investments in green infrastructure through careful forest management that reduce the probabilities of extreme water quality events and reduce the tails of the water quality distribution will result in comparable economic benefits to grey investments.

G Outcomes and Impact

The most important strategic outcome of this project is the rigorous science, engineering, economics/policy evidence showing that contemporary forest management practices can be in very close alignment with broad source water protection objectives for both protection of provincial water supplies and potential development of climate change adaptation strategies to address threats to Alberta's critical forested source water regions. Our project's highly unique objectives were to assess forest management impacts across the full scope of key water resources values from "source-to-tap", and the inferences supported by our results showed surprisingly clear, and consistent alignment across these highly diverse science, engineering, and economic domains. This type of information does not exist anywhere else world-wide.

This is particularly important for provincial land and water managers because this project shows that that potential landscape level outcomes of forest management involving forest harvesting by the industrial forestry sector can be in much closer alignment with water management objectives than many land and water manager's, or policy makers may currently perceive. For example, our research showed that contemporary forestry practice can not only minimize, but also prevent negative impacts to water. There was no meaningful difference in impacts from three very different harvest strategies because the best management practices employed effectively removed any difference in impacts that might otherwise have been observed.

However, effective source water strategies by themselves cannot entirely reduce the impacts of natural disturbances to Alberta's drinking water. A range of strategies are available to increase drinking water treatment and operational resilience to land disturbance and rapid water quality change. Strategies and tools to assess integrated land-water management, and resiliency of water treatment operations are needed. This project has delivered a comprehensive and powerful suite of best practices tools and assessment frameworks that are both directly applicable to land or water managers to address challenging source water protection problems, and a similar suite of tools and frameworks to address pressing treatment challenges. These span the breadth of landscape road network sediment management, cumulative watershed effects evaluation modelling frameworks, to drinking water treatment resilience decision support and operations response capacity assessment frameworks.

Notably in reference to the central objectives of this project, a comprehensive framework for evaluating strategic investments in upstream source water protection strategies and investment in water treatment plant infrastructure was developed and employed to both demonstrate the power of the framework, but also shed initial light on the cost implications of these choices. While these estimated the cost implications to society of protecting provincial water supplies through forest-management based "green" infrastructure or technologically-based "grey" infrastructure might be comparable, we know the actual costs of treatment were significantly underestimated. Thus, while additional work is needed to fully evaluate these policy choices, this outcome currently supports the pressing need to advance provincial source water protection efforts for critical forested water source supply regions.

We also expect this project will support development of future outputs through meaningful contributions to the body of knowledge in scientific, engineering, and land-water policy and economics disciplines underpinning this issue. A listing of these contributions appears below;

Refereed Publications

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*, Jan. 28, 2020)

Cooke CA, 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, Jan. 23, 2020)

Wang D, Kundert KL, Emelko MB. 2020. Optimisation and improvement of in-line filtration performance in water treatment for a typical low turbidity source water. Environ. Tech. 41:181-190

Puntenney-Desmond KC, Bladon KD, Silins U. 2020. Runoff and sediment production from harvested hillslopes and the riparian area during high intensity rainfall events. J. of Hydrology, 582:124452, http://DOI: 10.1016/j.jhydrol.2019.124452

Spencer SA, Silins U, Anderson AE. 2019. Precipitation-runoff and storage dynamics in watersheds underlain by till and permeable bedrock in Alberta's Rocky Mountains. Water Res. Res. 55(12):10690-10706. http://DOI: 10.1029/2019WR025313

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Kirisits MJ, Emeko MB, Pinto AJ. 2019. Applying biotechnology for drinking water biofiltration: advancing science and practice. Current Opinions. in Biotech. 57:197-204.

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Collins AL, Stone M, Horowitz A, Foster I. *Editor(s)* IAHS Redbook. 2017. Integrating monitoring and modelling for understanding, predicting and managing sediment dynamics ICCE Symposium 2016. – Proceedings of the IAHS ICCE meeting "Integrating monitoring and modelling for sediment dynamics" held at Okehampton, UK, 11–15 July 2017 PIAHS Volume 375, 39 pp.

Devito KH, Hokanson JK, Moore PA, Kettridge N, Anderson AE, Chasmer L, Hopkinson C, Lukenback MC, Mendoza CA, Morissette J, Peters DL, Petrone RM, Silins U, Smerdon B, Waddington JM. 2017. Landscape controls on long-term runoff in sub-humid heterogeneous Boreal Plains catchments. Hydrological Processes 31:2737-2751.

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Silins U, Anderson A, Bladon KD, Emelko MB, Stone M, Spencer SA, Williams CHS, Wagner MJ, Martens AM, Hawthorn K. 2016. Southern Rockies Watershed Project. Forestry Chronicle 96:39-42.

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.

Jin C, Mesquita M, Emelko MB, Wong A. 2016. Computerized Enumeration and Bio-volume Estimation of the Cyanobacteria Anabaena flos-aquae. 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.

Papers by the Principal Research Team at Scientific Conferences and Symposia.

Silins U, Emelko MB, Stone M, Williams CHS, Cherlet E, Wagner MJ, Collins AL, Dyck MF, Anderson AE, Spencer SA, Quideau SM, Hawthorn K, Krishnappan BG, Bladon KD. 2019. The Canadian Southern Rockies Watershed Project Observatory; Natural Disturbance and Land Management Effects on Watersheds from "Source to Tap", Am. Geophys. Union Fall Meeting, Abst. PA13B-1018, Dec. 9-13, 2019, San Francisco, CA, USA.

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, July8-18, 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. *Keynote*.

Emelko MB, 2019. Modeling Critical Infrastructure Interdependencies. CWWA's Window on Ottawa, Ottawa, ON, Canada, June 3. *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., Mar. 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, Feb. 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, Dec. 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, Dec. 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, Nov. 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, Sept. 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, 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, Apr. 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, Mar. 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, Dec. 11-15, 2017.

Stone M. 2017. Watershed Science on Fire: Insights from a long-term large-scale watershed research platform in southern Alberta. 2017 Woo Water Lecture, McMaster University, Hamilton, ON, November 18, 2017. (*Plenary keynote*).

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, B.C., 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, U.K., 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, Dec. 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, Dec. 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, Dec. 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, Dec. 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, Dec. 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, Dec. 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, Feb. 28 – Mar. 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, Jan. 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, Dec. 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, Dec. 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, Dec. 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, Dec. 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, Dec. 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.

Herlein KD, Silins U, Williams CHS, Martens AM, Wagner MJ, Hawthorn K, Stone M, Emelko MB. 2018. Long-term suspended sediment yields in wildfire affected mountain streams in southwestern Alberta, Canada. Fire Continuum Conf. Forests to flames to faucets. Missoula, MT., USA, May 21-24, 2018.

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, Mar. 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, Feb. 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, Jan. 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 Oct. 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, B.C., 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, B.C., 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, B.C., 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, B.C., 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, B.C., 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, B.C., 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, B.C., 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, B.C., 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, B.C., 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, B.C., 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.

Greenacre D, Silins U, Dyck M. 2017. Influence of alternative forest harvesting strategies on coupled spatial patterns of snowpack accumulation/melt and soil moisture storage. ConForW '17, 8th 8th Annual Interdisciplinary Conf. Natural Resources, Canmore, AB., April 21-24, 2017.

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.

Stewart MD, 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. ConForW '17, 8th 8th Annual Interdisciplinary Conf. Natural Resources, Canmore, AB., April 21-24, 2017.

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, Dec. 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, Dec. 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

Environmental Benefits

Our research shows that forest management-based source water protection strategies contemporary forest harvesting practices by the industrial forestry sector may not always produce negative impacts on water quality and thus would produce no impacts to stream health or downstream water quality. More practically, this means that careful application of best management practices for erosion control can be highly effective at minimizing or eliminating negative impacts on water.

Economic Benefits

Our research similarly shows that while the costs to society from forest management-based source water protection or investments in water treatment plant infrastructure to be comparable, our estimates likely underestimated treatment costs by at least 50% suggesting source protection strategies are cost effective means to protect drinking water supplies. While source water protection along is not likely to be fully effective at mitigating landscape threats, the foregoing suggests that coupled source water protection and enhanced treatment processes are highly likely to be cost effective means to protect provincial drinking water supplies in the face of growing climate associated threats. Furthermore, considerable additional economic benefits would be clear outcomes of provincial industrial forestry sector contributions to provincial source water protection efforts.

Social Benefits

The clearest benefit to social health and well-being of Albertans from enhanced source water protection in the face of increasing climate associated threats to drinking water supplies is the avoidance or more likely, the minimization of those impacts. Our teams 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.

Benefits in Building Innovation Capacity

This project has enabled the training and retention of highly qualified professionals to meet current and future needs for water management in Alberta. Indeed, a large number of prior highly qualified personnel (HQP) are 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. Over the course of this project, 67 HQP have, or are still being trained across a broad spectrum of water science and engineering domains;

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

Research Associates

1. Dr. Fariba Amiri, U Waterloo (2019-present)
2. Dr. 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, Waterloo (2020-present)
8. Dr. Sheena Spencer, U Alberta (2019-*present*)

9. Dr. Xiaohui Sun, 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 (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, co*mpleted 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, co*mpleted 2019*)
27. Samantha Karpyshin (M.Sc. U Alberta, *completed 2019*)
28. Amanda Martens (M.Sc. U Alberta, *completed 2019*)
29. David Michael Stewart (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 (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 (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 (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. Rahda Said, (URA, Coop; U Waterloo, 2019, 2020)
46. Tyler Owl-Scott, Coop; U Waterloo, 2018, 2019, 2020)
47. Nayandeep Maan (URA, Coop; U Waterloo, 2016)
48. Yong Xin Michelle Fan (URA; U Waterloo, 2016)
49. Shuai Josh Yuan (URA, Coop; U Waterloo, 2016)
50. Adam Schneider (Coop; U Waterloo, 2016)

Technical staff

Hydro-meteorological field staff

Fulltime Personnel

51. Erin Cherlet (U Alberta, 2018-*present*)
52. Kalli Herlein (U Alberta, 2014-*2018*)
53. Amanda Martens (U Alberta, 2011-2016)
54. Chris Williams (U Alberta-2006-*present*)

Seasonal field staff

55. Kaegan Finn (U Alberta, 2019)
56. Emma Hawsworth (U Alberta, 2019)
57. Daniel White (U Alberta, 2019)
58. Jaimie Forest (U Alberta, 2018)
59. Kathyrn Purdon (U Alberta, 2018)
60. Caitlin Tomaszewski (U Alberta, 2018)
61. Mia Stratton (U Waterloo, 2018)
62. Michael Pekrul (U Alberta, 2017)
63. Erin Cherlet (U Alberta, 2017)
64. Amber Becker (U Alberta, 2016-2017)
65. Shauna Strack (U Alberta, 2015-2016)
66. Chrystyn Skinner (U Alberta, 2015-2016)

Engineering science staff

Fulltime Personnel

67. Dr. Maria Mesquita, U Waterloo (2013-2019)

I Next Steps

While there are numerous research domain specific research questions that would contribute important additional knowledge supporting development of integrated approaches to source water protection in Alberta, two primary categories of information needs are likely the most important in the short term.

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. Yet, increasingly extreme wildfire behavior continues to appear almost each new fire season in fire-prone regions world-wide with unknown impacts to water resources (i.e. B.C./Alberta, south-west U.S., Australia). To help fill this knowledge gap, our new study of extreme severity wildfire impacts to water from the 2017 Kenow Mtn. wildfire is already producing critical new insights where early indications are that impacts to water from this fire are meaningfully different than what we have observed from four other wildfires we have studied.

Similarly, while this study has already provided extensive, important insights into the potential suitability of forest management-based source water protection strategies, many of the findings reported here are not yet fully conclusive. The before-after;control-impact (BACI) watershed study design provides likely the most powerful approach to such conclusions, however at least 5- 7 years of post-disturbance data (three additional years) of study are needed to establish the conclusive science/engineering basis for forest management-based source water protection approaches to help mitigate potentially significant impacts of climate associated wildfires on provincial water supplies.

Both of these components are a priority focus of our new companion AI research project (2020-2023). This new project has also led or is leading to significant new partnerships with land-water management agencies in Alberta (Parks Canada, Alberta Parks).

J Knowledge Dissemination and Mobilization

In addition to knowledge dissemination to scientific audiences outlined in section G, here we list a) particularly notable or high impact knowledge dissemination activities – in particular, those that *reflect actionable mobilization of knowledge*, and b) knowledge dissemination activities specifically aimed at practitioner, professional, and public stakeholder audiences, and c) team awards or recognition for noteworthy impacts from our work.

Notably High Impact Knowledge Mobilization Activities

- Team members (Emelko/Stone/Muller/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, Sept. 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, Sept. 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 British Columbia'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, Feb. 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. Aug.-Sept. 2018
- Policy briefing (Silins) for AAF/AEP executive branch (ADM, Exec. Divisional directors), March 9, 2018 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.
- 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).
- In Nov./Dec. 2017, emergency assistance (Silins/Emelko) was 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.
- Similarly, in Aug. 2017 emergency assistance was requested from Silins/Emelko 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. 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//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 (Sept. 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, AB. Env. Parks) and Cathy Maniego (Exec. Dir. Resilience and Mitigation Branch, AB. Env. Parks), Edmonton, AB., November 11, 2016.
- Team members (Silins / Emelko) were recruited by AB. Environment and Parks, AB. Agriculture and Forestry, and AB. Municipal Affairs on May 8, 2016 (3 days after evacuation of Ft. McMurray) to assist with initial emergency response planning for the City of Ft. McMurray by AB. Environment and Parks, AB. Agriculture and Forestry, and AB. Municipal Affairs. In the hours-days/weeks-months to follow our contributions to emergency response planning and reaction for the Municipality of Wood Buffalo Water Treatment plant focused on a) rapid deployment of instrumentation (zeta sizer) and to enable rapid plant operational responsiveness to fluctuating post-fire water quality challenges, b) regional post-fire watershed threats assessment for the Athabasca R. and tributaries upstream of the RMWB water treatment plant including early strategies for reservoir intake response during early post-fire events, and c) broader plant operations coordination (reservoir, ballasted sand flocculation, and filtration operations). These contributions were credited as meaningfully contributing to the municipalities' water treatment operations being able to produce drinking water during and after the disaster. May-June, 2016.
- Emelko participated on Expert Panel on "Impacts and Risk Identification for the New Normal" at Canadian Water Network, Blue Cities, Toronto, ON., May 18-19, 2016.

Knowledge mobilization for practitioner, professional, and public stakeholder audiences

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 BB. 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, May 22-23 2019, Edmonton, AB

Emelko MB, Silins U, Stone M, Mueller K, & Cooke C. 2019. Drinking water security after severe wildfire in Alberta: Initial risks and treatment technology resilience, Alberta Innovates Water Innovation Program Forum, May 22-23 2019, Edmonton, AB

Team members (Emelko/Stone) delivered a distinguished lecture series seminar at Swansea University, UK, May 8, 2018.

Emelko MB, Silins U, & Stone M. 2019. Water quality and treatability in a changing climate. B.C. Climate Action Secretariat, webinar, Apr. 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), Mar. 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. Feb. 28, 2019. Alberta Water Council Board of Directors, Edmonton, AB.

Stone, M Road Salt Presentation Ontario Good Roads Association Meeting, Sheraton Hotel, Toronto. February 25, 2019 (*Invited*)

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, Feb. 15, 2019, Edmonton, AB.

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, Mar. 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, Jan. 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. Nov. 29, 2017.

Stone M. 2017. 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. Oct, 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 BA, Bladon KD. 2017. Wildfire impacts on Rocky Mountain source waters in Alberta. Canadian Water Res. Association. Nationally broadcast webinar. Sept. 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 B, 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., Jan. 17, 2017. (*Invited*)

Silins U, Emelko MB, Adamowicz V, Anderson A, Boxall P, Collins A, Dupont D, Dyck M, Krishnappan B, 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., Oct. 19, 2016. (*Invited*)

Anderson A. Planning frameworks for assessing and modeling sediment production from forest road networks. Canadian Forest Products Ltd. Forest Management Advisory Committee, Grande Prairie, AB., Oct. 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 Conf, 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 Conf, Edmonton, AB., September 25-28, 2016.

Adamowicz W, Appiah A, Lloyd-Smith P, Simpson S, Dupont D. 2016. Putting a price on how much Albertans value the reliability of their drinking water supply. Canadian Water Network / Water Economics Policy and Governance Network. 5 pp. http://www.cwn-rce.ca/assets/End-User-Reports/Municipal/Adamowicz/CWN-EN-Adamowicz-WEPGN-2016-5Pager-Web.pdf

Silins U, Emelko MB, Adamowicz V, Anderson A, Bladon K, Collins A, Dupont D, Dyck M, Krishnappan B, 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*)

Adamowicz W, Appiah A, Lloyd-Smith P, Dupont D. 2016. Putting a price on how much Albertans value the reliability of their drinking water supply. Canadian Water Network Knowledge Mobilization Report" May 2016.

Impacts and Research Team Awards and Recognitions

- Our 2018 publication on water contamination risks from wildfires (Nunes et al. 2018, pg. 57 *above*) received recognition as "*one of the top cited journal articles in recent publication history*" from the Wiley scientific journal; Hydrological Processes (Jan 2020).
- 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?" Oct. 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.
- *Letter of appreciation* from Richard Manwaring (Asst. Deputy Minister, B.C. FLNRORD) for post-fire emergency risk assessment assistance from Silins Emelko (including our delivery of a Sept. 2017 workshop) to government of B.C., regional resource managers, Interior Health, and Indigenous agencies supporting post-fire water risk assessment. Feb. 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

Developing integrated source water protection strategies presents a formidable challenge because of diverse environmental, social, and economic realities in Alberta. While the outcome of this project does not by itself, lead seamlessly to developing effective source water protection strategies, this project has provided fundamental, science founded insights into the many of the most challenging unanswered questions that served as important knowledge gaps prior to this project.

Results of this study demonstrated exceedingly strong alignment in findings across the breadth of these water domains showing that contemporary forest harvesting practices produced effectively no detectable impacts to water quality, or stream health both in smaller headwaters catchments or further downstream. Similarly, no meaningful effects to key drinking water treatability were also evident. In particular, these findings highlighted the efficacy of contemporary forestry best practices in preventing impacts to water supporting the potential important role of the provincial forestry sector in source water protection of forested regions under a warming climate.

Thus, project results provide rigorous science, engineering, economics/policy evidence showing that contemporary forest management practices can highly consistent with strategic source water protection objectives for protection of crucial provincial water supplies from Alberta's eastern slopes region.

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M Appendix – Summary of Costs (*Milestone 12*)

Water Treatment Costs under Normal Operating Conditions

Costs, under normal operating costs as defined above, are represented in an equation estimated using daily plant operating data for the Glenmore Water Treatment Plant for 2011-2015. The estimated equation relates daily costs of the main chemicals used in drinking water treatment to water quality indicator variables at the plant intake: turbidity and TOC. Daily water flow into the plant is also included. All three of these variables contribute positively to chemical cost. However, cost responses vary seasonally so the equation also includes seasonal dummy variables for fall/winter and spring/summer which are interacted with turbidity and TOC. Fig. 34-1D (inset to Fig. 34 pg. 46) is a plot of the logged cost data on the log of turbidity. In-sample model predictions are also plotted and show that positive cost responses for turbidity and TOC are larger in the spring/summer period than in fall/winter period. Data on daily variations in energy costs, labor, and maintenance costs were not available so the in-plant cost model likely does not fully capture the full variation of costs.

Thresholds for Adaptive Costs

Defining the thresholds discussed above is difficult and presents uncertainties. A 2015 survey of Alberta plant managers conducted by the research team suggests that operating thresholds depend on the overall quality of source water, the water treatment technology, and risk perceptions of those making the decisions about managing the water supply. In terms of turbidity, drinking water quality guidelines define a range of 1-5 NTU as fair, and boiled water advisories are issued when turbidity exceeds 5 NTUs (Guidelines for Canada Drinking Water Quality cited in TNRD, n.d. and SEKID, n.d.). But these thresholds are defined based on output water quality and the relationship between input and water output quality is not deterministic but rather the outcome of a complex treatment process with a (conditional) distribution of outcomes. Given this uncertainty, and the fact that data on output water quality was not available for this study means that an assumption must be made. The 2015 survey provides a useful starting point as it elicited the value of turbidity beyond which a plant would have to shut down temporarily. A turbidity level of 4000 NTUs or greater was a response to this question for water treatment plants similar to the Calgary plants. Therefore, 4000NTUs was chosen as a starting point for both the mild and extreme thresholds for outside WTP adaptive costs. Sensitivity analysis on the thresholds reveals how costs would change if the thresholds are different.

Adaptive Costs vs Costs of the Risk of Illness or Death

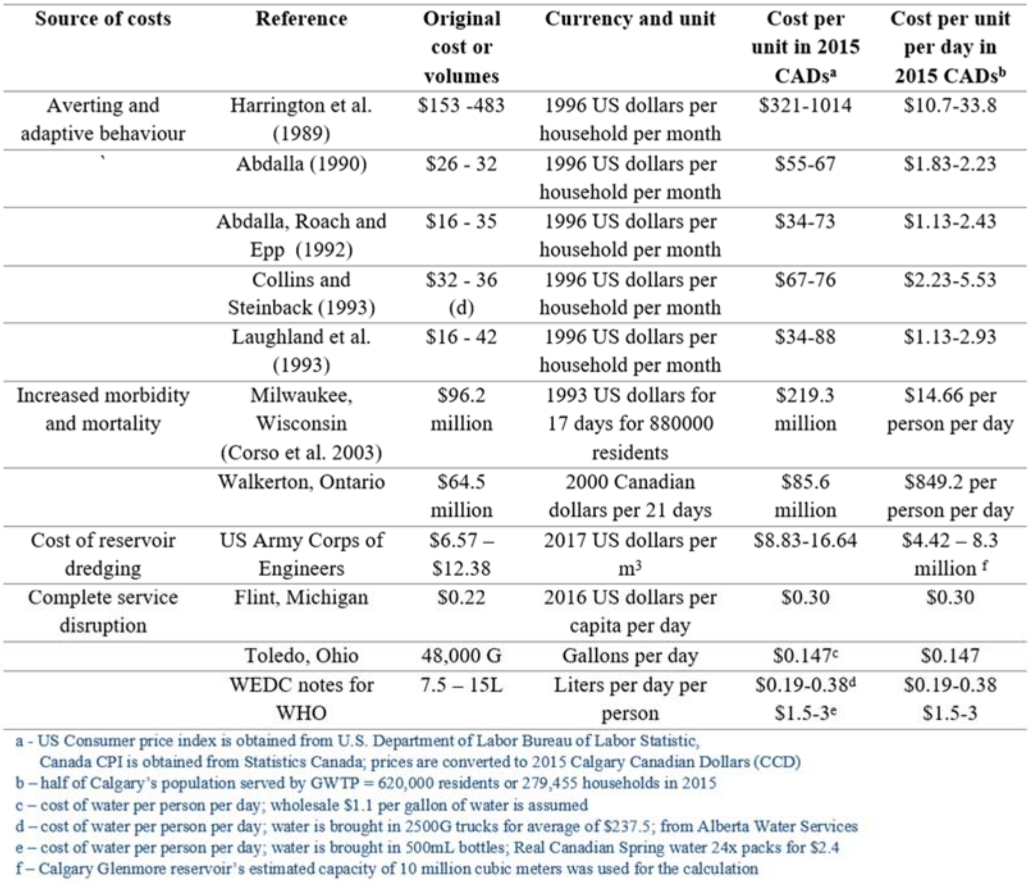
Ultimately, if a large population of people are exposed to untreated water there is a risk of illness or even death. Adaptive costs may be described as those resulting from averting, adapting, or defensive behaviour to reduce these risks (Cropper and Oates, 1992, p. 680). These costs may be incurred at both an individual and a community level. Individuals avoid drinking contaminated water by switching to clean water sources such as bottled water, boiling or filtering water. In extreme cases, communities may use trucks to bring in large quantities of water. In this case study, costs were based on a series of cost estimates in Whitehead et al. (1998). A summary of these estimates is provided in Table M-1, inflated and converted where needed to 2015 CAN$.

Costs due to increased morbidity and mortality risks are difficult to estimate, partly because it is difficult to value mortality risk increases but also because of a dearth of relevant cases to study. However, there are two cases where plant failures lead to the exposure of the surrounding population to water-borne disease, one in Milwaukee, Wisconsin and the other in Walkerton Ontario. Cost estimates of the damage due to increased risk of illness or death are available for both of these cases based on studies by Corso et al. (2003), and Woo and Vincente (2003). The Walkerton case must be considered an upper bound, because the usual problems of response to reduction in water quality were compounded by a lack of technical sophistication of plant staff and a delay in warning the community with a boil water advisory (O'Conner, 2002). These cost estimates are one to two orders or magnitude larger than averting and adaptive costs (see Table M-1 – last column). This is due to both high medical costs and estimates of the value of mortality risks. However, not all cases in which boiled water advisories arise result in sickness and disease. Therefore, it is necessary to multiply the costs by a conditional probability. Estimating such a probability is difficult due to a sparsity of data, however, a rough estimated may be constructed. In Canada, 48 cases of illness due to drinking inadequately treated water were reported between 1993 and 2007 (Moffat and Struck, 2011) while there have been an average of 1084 boil water advisories per year of over the same period. Therefore, an initial estimate for the conditional probability that the damage costs will be incurred given that water quality threshold is exceeded is 0.002952.

Costs of Sedimentation and Reservoir Dredging
Events such as forest fires or unusually heavy rains may lead to soil erosion and the formation of additional sediment in reservoirs and water treatment plant, sediment-settling ponds. This may lead to the need for additional dredging which is a very costly activity (see Table M-1).

Costs of Shutting Down a Water Treatment Plant
When a water treatment plant shuts down the same types of costs are incurred as described above but on a larger scale. Complete water supply shutdown certainly implies that water must be brought in on a large scale by the affected community instead of being left entirely to individuals. Again, there is a dearth of sources to estimate these costs. In this study, we provide bounds based on water provision costs from two cases of complete shutdown (Toledo, Ohio in 2014 and Flint, Michigan in 2016) and upper bound estimates are provided by the World Health Organization (Table M-1).

Table M-1 – Community costs incurred when water quality is beyond assumed the quality threshold for portion of Calgary population that is served by the Glenmore WTP in 2015 CAN$.



Source of costs	**Reference**	**Original cost or volumes**	**Currency and unit**	**Cost per unit in 2015 CADs[a]**	**Cost per unit per day in 2015 CADs[b]**
Averting and adaptive behaviour	Harrington et al. (1989)	$153 -483	1996 US dollars per household per month	$321-1014	$10.7-33.8
`	Abdalla (1990)	$26 - 32	1996 US dollars per household per month	$55-67	$1.83-2.23
	Abdalla, Roach and Epp (1992)	$16 - 35	1996 US dollars per household per month	$34-73	$1.13-2.43
	Collins and Steinback (1993)	$32 - 36 (d)	1996 US dollars per household per month	$67-76	$2.23-5.53
	Laughland et al. (1993)	$16 - 42	1996 US dollars per household per month	$34-88	$1.13-2.93
Increased morbidity and mortality	Milwaukee, Wisconsin (Corso et al. 2003)	$96.2 million	1993 US dollars for 17 days for 880000 residents	$219.3 million	$14.66 per person per day
	Walkerton, Ontario	$64.5 million	2000 Canadian dollars per 21 days	$85.6 million	$849.2 per person per day
Cost of reservoir dredging	US Army Corps of Engineers	$6.57 – $12.38	2017 US dollars per m^3	$8.83-16.64	$4.42 – 8.3 million [f]
Complete service disruption	Flint, Michigan	$0.22	2016 US dollars per capita per day	$0.30	$0.30
	Toledo, Ohio	48,000 G	Gallons per day	$0.147[c]	$0.147
	WEDC notes for WHO	7.5 – 15L	Liters per day per person	$0.19-0.38[d] $1.5-3[e]	$0.19-0.38 $1.5-3

a - US Consumer price index is obtained from U.S. Department of Labor Bureau of Labor Statistic,
Canada CPI is obtained from Statistics Canada; prices are converted to 2015 Calgary Canadian Dollars (CCD)
b – half of Calgary's population served by GWTP = 620,000 residents or 279,455 households in 2015
c – cost of water per person per day; wholesale $1.1 per gallon of water is assumed
d – cost of water per person per day; water is brought in 2500G trucks for average of $237.5; from Alberta Water Services
e – cost of water per person per day; water is brought in 500mL bottles; Real Canadian Spring water 24x packs for $2.4
f – Calgary Glenmore reservoir's estimated capacity of 10 million cubic meters was used for the calculation

Population Growth

Water treatment plants are designed to serve a particular population, allowing for variations in daily and seasonal demands as well as long term changes in drinking water demand caused by changing population. If population growth and accompanying demand for water is still within the plant's capacity, in-plant treatment costs may increase as a result of having to increase water supply that meets quality standards. However, perhaps more importantly, costs of surpassing quality thresholds increase because averting/adaptive behaviors and morbidity/mortality costs scale-up with population. Obviously, if populations increase to the point where capacity to meet demand is insufficient, investments in increased capacity will be required. This may provide decision makers opportunities to make decisions about new technologies that shift mild/extreme thresholds and balance/optimize these decisions with upstream watershed management options as illustrated in Fig. 34-1B and 34-1C (insets to Fig. 34, pg. 46).

Population growth was simulated using an ARIMA model derived from a time series analysis of Calgary population data from 1880 to 2016. Fig. M-1 shows the median population projection together with the City of Calgary's forecast to 2025 (City of Calgary, 2019). The ARIMA model's median simulation is slightly higher but also shows uncertainty in population growth projections by showing percentiles of the simulated populations levels from the 1st to 99th percentiles. These simulated increases in population were integrated into the estimates of cost discussed in the next section. The approximate population that the water treatment plants in Calgary can adequately serve is also overlain on the population projections.

Figure M-1 – Historical population of Calgary and simulated populations for 2016-2035 derived from a time series model estimated from Calgary population data from 1880-2016. A forecast by the City of Calgary is also plotted