Final Technical Report

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1. Executive Summary

Because the majority of Alberta's water supplies are produced in forested regions along the eastern slopes of the Rocky Mountains, this project was designed to deliver the science necessary to enable and inform the development of integrated source water protection (SWP) strategies in Alberta. Specifically, while forest management has the potential to reduce risk of catastrophic natural disturbances such as wildfire, the role of forestry in broader source water protection efforts is unclear because the specific impacts of forest harvesting operations on the full scope of water values has not been previously evaluated.

The broad objective of this project was to study the comparative impact of three alternative forest harvesting strategies on headwaters hydrology, water quality, and aquatic ecology, and to sequentially link these impacts to their downstream propagation at increasingly larger river basin scales, including their effects on drinking water treatment, and lastly to evaluate the economic implications of these effects. Three sub-catchments of the Star Ck. watershed were harvested using 3 contemporary alternative harvesting strategies (clear-cutting with retention, strip-shelterwood cutting, and partial cut harvesting) in 2015 and the impacts of harvesting were evaluated in 2015 and 2016 and compared to pre-disturbance research in the same watersheds by the Southern Rockies Watershed Project (2004-2014) and compared to results of research on older harvested areas in the upper Oldman River basin and previous research on impacts of both wildfire and the 2013 flood.

The three forest harvest strategies produced no detectable effects, or small effects close to the margin of careful scientific detection on hydrology, water quality, and aquatic ecology with little if any detectable downstream effects including effects on drinking water treatability. Results from this component of the study are preliminary because a minimum of 4-6 years is typically needed to support meaningful conclusions on watershed scale impacts. However, forest harvesting did produce detectable effects on water quality with subsequent impacts to key drinking water treatability in a retrospective study of areas harvested -20, and -40 years earlier. In contrast, the 2013 flood produced catastrophic impacts resulting in extreme sediment and phosphorus loading, while the 2003 Lost Ck. wildfire produced similar impacts on sediment, phosphorus, and organic carbon loading into streams and rivers. The impacts of these two severe natural disturbance events was an order of magnitude greater than that of either logged watersheds or loading from undisturbed watersheds. The relative impacts of these two broad categories of land disturbance were also generally paralleled in results on downstream water quality and impacts to drinking water treatability. While Alberta's public is willing to invest in initiatives for further protect drinking water supplies, willingness to pay for such improvements is modest.

Results from this project constitute the 1st solid quantitative comparison of the comparative impacts from severe natural disturbances such as flooding and wildfire with those of both historic and contemporary forest harvesting practices illustrating the risk to Alberta's water supplies from increasing occurrence and severity of these natural disturbances because of climate change. While the study suggests forest management is an important component of broader source water protection strategies, additional economic analyses of avoided impacts and relative benefits/costs will help further inform the best suite of forest management strategies for source water protection in the critical Rocky Mountain source water region.

2. Project Description

2.1. Introduction/Challenge

Because the majority of Alberta's water supplies are produced in forested regions along the eastern slopes of the Rocky Mountains, this project is designed to deliver the science necessary to enable the government of Alberta (GOA) to streamline its policies related to integrated water and forest management or "integrated source water management" in that region. Both natural (wildfire, mountain pine beetle, etc.) and manmade landscape disturbances (resource extraction by forestry and petrochemical sectors, recreational activity, etc.) in these regions have the potential to increase pollutant loads and significantly impact many water "values" necessary to sustain ecosystem integrity and the diverse water needs of Albertans. Accordingly, source water protection (SWP) policies have been developed to minimize or eliminate those impacts by preventing or minimizing landscape disturbances and associated water quality deterioration. While such policies may be effective for minimizing the deleterious impacts of human activity on water quality, they cannot protect against natural disturbances such as wildfire. Ironically, SWP policies can significantly increase the risk of natural disturbances such as wildfire or flooding impacts on water because the landscape structure of older mature forests can promote greater vulnerability to these potentially catastrophic natural disturbance agents. As a result, land managers may develop what appear to be contradictory strategies because SWP policies aim to minimize anthropogenic disturbances such as forest harvesting to protect water quality while broader allied forest management goals for landscape resistance and resilience to natural disturbance contribute to protection for communities and water supplies from potentially catastrophic effects of the most prevalent natural disturbances (wildfire) that pose very real threats to Alberta.

2.2. Technology Description

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) are often 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 research on forest management impacts to water has been conducted in other forested regions worldwide, little if any of this knowledge is specifically useful in developing SWP strategies 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) are unknown. Thus, the comparative risks and benefits to water associated with forest management including costs/avoided impacts from catastrophic natural disturbances are unknown. This information is needed to develop truly integrated landscape SWP strategies in Alberta.

2.3. Project Goals/Objectives

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 trans-disciplinary 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 SWP strategies.

3. Approach and Results

3.1. Literature Review

Compared to plot scale or stand scale studies, relatively few experimental watershed studies exist due to the high financial costs, necessary manpower and the difficulty of working at the catchment scale. Though limited in number and scope, other catchment-scale experiments in Alberta and elsewhere have contributed a foundation of knowledge regarding the effects of forest management activities on water. However, none of this previous research has explored the linkages (headwaters, regional scaling, drinking water, economic cost-benefit analysis) necessary to support evaluation and development of integrated SWP strategies for Alberta's critical eastern slopes water supply region.

The most closely aligned research in Alberta is the Marmot Creek Research Basin, which is focused on a single catchment in the Rocky Mountain eastern slopes (9.4 km^2 split into 3 sub-basins). Early research at Marmot Creek (1962-1986) was established to assess the potential for clear-cut harvesting to maximize water production within the Saskatchewan River headwaters (Swanson *et al*., 1986). Recent research at Marmot Creek (2004-Present) has focused on understanding and predicting climate change impacts on energy balance, snowpack dynamics, snowmelt, streamflow generation, and hydrologic modeling (Pomeroy *et al*., 2012). The Tri-Creeks Experimental Watershed was another important watershed scale study in Alberta. It was established in 1965 to assess the impact of forest harvesting on the effectiveness of forest harvesting ground rules on protecting the water resources and to determine the effects on population dynamics of fish and aquatic invertebrate populations. Specifically, research at Tri-Creeks focused on measurements of snow accumulation, streamflow, suspended sediment, nutrients (N, P), and stream temperature (Nip 1991). Two noteworthy forest watershed-scale studies in British Columbia are both located in the dry, southern interior. The Upper Penticton Creek Watershed Experiment (1984-present) is a paired basin study which was designed to quantify changes in hydrologic processes due to forest harvesting and regeneration (Winkler, 2010). That study has measured a broad range of parameters at the catchment scale (4-5 km^2), including streamflow, precipitation, snow accumulation and melt, interception, evapotranspiration, soil moisture, groundwater, stream chemistry, soil chemistry, stream morphology, suspended sediment, and aquatic ecology. The objective of the Cotton Creek Experimental Watershed (2004-present) was to conduct intensive monitoring and process studies of precipitation, snowpack dynamics, stream discharge, stream temperature, soil moisture, and groundwater dynamics in a single watershed (17.4 km^2) to provide data for testing modeling tools that could be used to assess the effects of forest harvesting and disturbance (Moore, 2010).

Similarly, there is a long history of forest watershed research in the United States, dating back to the Wagon Wheel Gap Project (1909-1935) in the central Rocky Mountains of Colorado (Bates and Henry, 1928). This study compared the time and amount of streamflow, erosion, and sediment transport before and after forest harvesting. Coweeta Long Term Ecological Research (North Carolina; 1934-Present) and Fernow Experimental Forest (Appalachian Mountains of West Virginia; 1951-Present) have both studied the effects of forest management of deciduous forests on hydrologic processes (Ice and Stednick, 2004). Work at Fraser Experimental Forest (Colorado; 1937-Present) investigated how different silvicultural prescriptions (e.g., overstorey thinning, patch cuts) in subalpine forest across four watersheds impacted water storage (snow), runoff, nutrient cycling, and linkages between riparian areas and streams (Troendle and King, 1985; Stottlemyer and Troendle, 1992). H.J. Andrews Experimental Forest (Oregon; 1948-present) is a paired watershed study in the Pacific Northwest (maritime climate with wet, mild winters and dry, cool summers) of alternative harvesting and road practices impacts on peak flows and water quality (sediment, nutrients) (Duncan, 1999). Hubbard Brook (New Hampshire; 1955-Present) researched the effects of forest harvesting and herbicide treatments (to prevent vegetation regrowth and not representative of commercial forest harvesting) on nutrient cycling processes (Likens *et al.*, 1970; Hornbeck *et al.*, 1997). Beaver Creek (Arizona; 1956-present) has studied the impacts of vegetation manipulation (e.g., forage, timber harvest, and wildfire) on water yield in pinyon pine and ponderosa pine forests. Alsea (Oregon; 1958-1973) – first long-term watershed study (clearcut and patch cut) to consider the effect of forest harvesting on water quantity, water quality (e.g., temperature, dissolved oxygen), and impacts on fish (habitat, populations) (Stednick, 2008). Studies at Caspar Creek (California; 1961-present) documented road and harvest impacts on water quantity, erosion, and sediment yield in two coastal watersheds (Rice *et al.*, 1979).

Surprisingly, virtually no information exists that meaningfully links the general understanding of headwaters disturbance impacts to water (timing of flows, quantity, quality) to potential downstream impacts on key water metrics needed to assess if or how such disturbances might affect provision of downstream drinking water. While a number of researchers have attempted syntheses based on existing published literature on water quality impacts from forestry operations (Ryan 2000, Scatena 2000, Stednick 2000, Binkley & Brown 1993) none of these works provides meaningful linkages to evaluate how forest harvest disturbances affect drinking water treatability or treatment operations.

While all of the studies outlined above have/are providing key information to help manage forested watersheds, most of this research is not applicable to forest management in the eastern slopes of Alberta because of differences in climate, physiography, forest type, geology, etc. that govern the impacts on water. More importantly, none of this previous research provides information on forest management effects on water quality applicable to Alberta's Rocky Mountain source water region which is a keystone requirement in the assessment of forest management as an important component of SWP in Alberta.

3.2. Research Approach and Methods

Research providing insight into the key linkages spanning source water protection and management from "source to tap" necessarily spans a very broad range of science, engineering, economic, and management domains. Accordingly, the general approach used in this project focused on linking research among four primary research themes from the source headwaters landscapes through to downstream drinking water. Because of the diversity of expertise required to appropriately address these issues, our research plan was organized around specific research tasks associated with the major disciplinary components of the problem. The project includes four major themes or nodes:

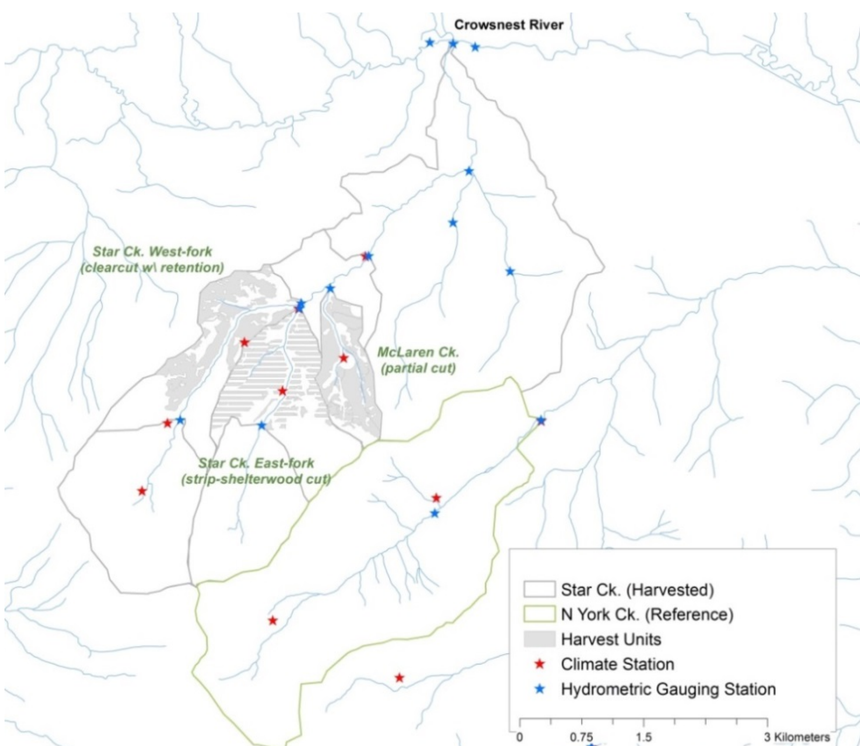
1. Effects of alternative forest management strategies on headwater resources
2. Propagation of headwaters impacts to produce regional-scale impacts
3. Impacts on downstream drinking water treatment (vulnerabilities)
4. Economics evaluation of cost/benefit implications of alternative source water strategies

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 built upon the foundation of previous research (10 years) on the Southern Rockies Watershed Project (SRWP) studying the effects of a large wildfire in the southwest Alberta's Rocky Mountains. This prior research provided the necessary information to evaluate the implication of source water protection using un-managed landscapes (undisturbed and wildfire affected forests). Two of the previously instrumented SRWP watersheds (North York and Star Cks.) served as the necessary platform to assess impacts of alternative forest management practices on water resources (SRWP Phase II) for the current research. One watershed (North York Ck.) would remain undisturbed while three sub-catchments in North York Ck. were each be harvested using three alternative harvesting strategies including a) conventional green-tree retention, b) strip-shelterwood, and c) partial cut harvesting strategies in the fall-winter of 2013/14. Nine years of prior data (hydrology, water quality, ecology) from these watersheds enables the powerful before/after;control/impact design needed for the comprehensive evaluation of these impacts. Thus the work plan for this program necessarily included all of the major components needed to meet program objectives; i) planning/execution of the forest harvest treatments, ii) monitoring/maintenance of distributed climate/streamflow monitoring stations, and iii) research specific tasks needed to evaluate these impacts across a range of scales/sectors including linking these effects to the comparative cost/benefits of alternative source water management for both unmanaged and managed landscapes.

3.3. Installation and Commissioning

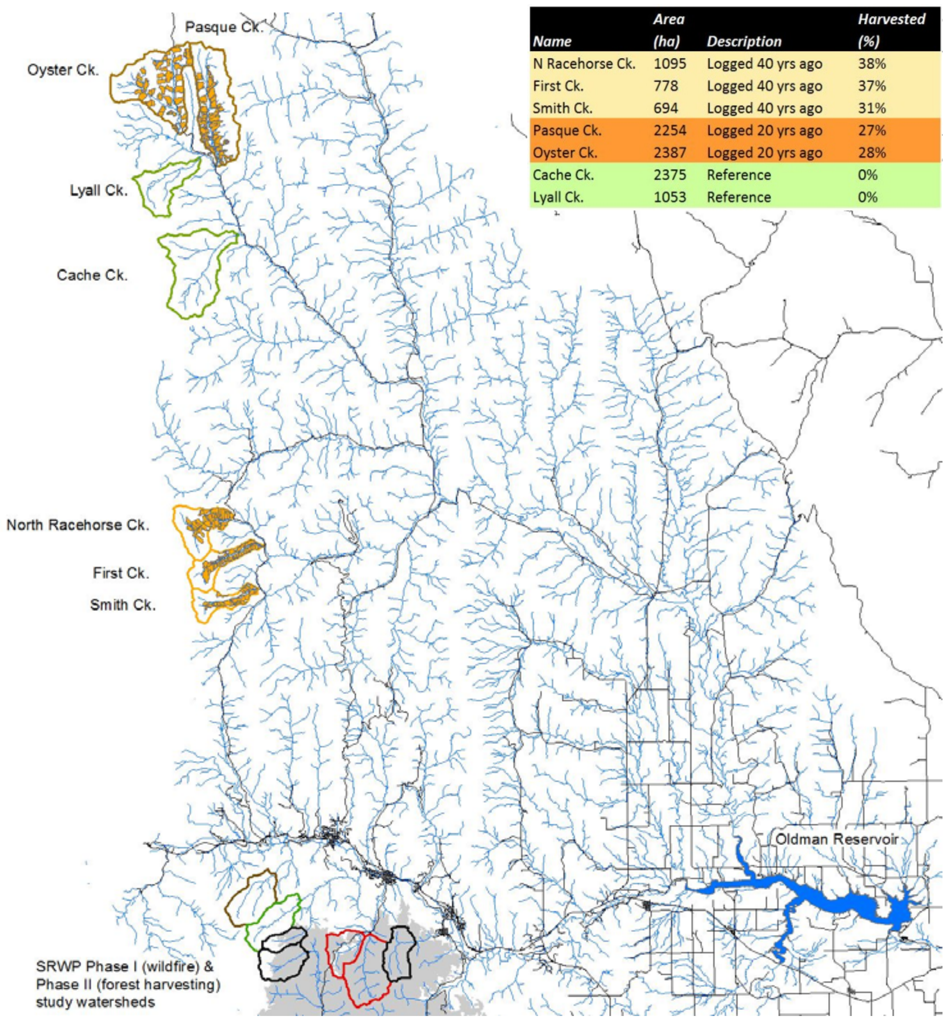
While planning for the harvesting needed for this study led by Government of Alberta and industrial partners began in 2009/10 with a target of having the harvesting completed in the fall/winter of 2013/14, the planning process required significantly longer than anticipated pending completion of the final harvest plan, contractors, and approvals. Canadian Forest Products Ltd. conducted the harvesting which commenced in late Dec. 2014 with road construction followed by harvesting activities in each of the 3 sub-catchments in Star Ck. (clear-cutting, strip-shelterwood, and partial cutting). All harvesting, silvicultural treatments, log hauling, road and road-stream crossing decommissioning were completed by late Oct. 2015 (Figure 1).

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



While the original research plan (2013-2015) specified 1 additional year of pre-harvest research in 2013 followed by two additional years of research during both the harvest (2014) and in the 1st full post-harvest year (2015), a delay in completing the harvest for this study necessitated revision and extension of the research plan to include two additional years of pre-harvest research (2013 & 2014) followed by the 2015 harvesting year, and one full post-harvesting measurement year (2016). In an effort to minimize the impact of this delay in meeting overall project goals for evaluating impacts of forest management on water, a new study element was added in 2013/14 to provide insight into the longevity of harvesting impacts on water quality and drinking water treatability. This study was focused on legacy effects from historic harvesting encompassing 7 new large study watersheds in the upper Oldman river sub-basin. These catchments included historic harvesting operations in two regions with differing harvesting history (harvested ~20 yr. and 40 yr. ago) along with 2 reference catchments in the Beehive Natural Area (Figure 2). Hydrometric and water sampling stations were instrumented and lower frequency sampling for key water quality and drinking water treatability parameters were 4-6 times during the ice free season of 2014-2016.

Figure 2 – Historic (legacy harvesting) study watersheds in the upper Oldman R. sub-basin



The catastrophic flooding in June 2013 that affected the City of Calgary also produced major flooding in the Crowsnest Pass study region. Thus the harvesting delay unintentionally (serendipitously) enabled the characterization of the largest flood on record along with one full post-flood recovery year in both study watersheds. The unintended outcome of this natural disturbance event enabled additional comparisons between harvesting impacts with those of two major natural disturbance events: a) the 2013 flood, and b) 2003 Lost Ck. wildfire from SRWP Phase I research.

3.4. Approach and Methods

The research was organized around major research components (research tasks) focused on addressing key knowledge gaps in each of the four research themes to enable establishing linkages among themes needed to evaluate the comparative impacts of alternative forest harvesting strategies.

Table 1 – Major research components across four research themes

Installation & commisioning	Downstream Propogation of Effects	Economic Implications
1) Harvest treatment application Star Ck. subcatchments	**5) Regional Effects** – quantify effects on:	**9) Potential economic consequences of management**
partial cut (McLaren Ck.), strip-shelterwood (Star Ck.	Task 5.1 – Flow dynamics Crowsnest R.	**alternatives**
fork), variable retention clear-cut (Star Ck. west-fork)	Task 5.2 – Sed. loading in Crowsnest R.	Task 9.1 – Benefits/incremental costs of
Effects on headwaters resources	Task 5.3 – Nutrient loading Crowsnest R.	management alternatives on water supply
2) Hydrology – *quantify effects on* :	Task 5.4 – Sediment/nutrient interactions	interruptions and “advisories” (reliability)
Task 2.1 – snowpack & melt rate	**6) Contaminant source tracing**	Task 9.2 – Impact of change in supply reliability (8.1)
Task 2.2 – evaporative losses (ET)	Task 6.1 – Regional scale source tracing of long distance downstream	of management alternatives on treatment
Task 2.2.1 rain/snow interception	transport of contaminants from three alternative harvest strategies	operating & infrastructure costs
Task 2.2.2 transpiration in reserves	**7) Contaminant transport modeling**	**10) Cost of ecosystem service provision for water**
Task 2.2.3 ET in harvested units	Task 7.1 – Regional contaminant transport model calibration/performance	Task 10.1 – Costs analysis of management alternatives
Task 2.2.4 soil moisture & runoff	evaluation for changes in water quality	incremental & opportunity costs (loss of
Task 2.2.5 hillslope-stream linkages	Task 7.2 – Quantify downstream regional water quality from upstream	ecosystem services)
Task 2.3 – volume/timing of flows	management alternatives (natural disturbance & forest management)	**11) Future cost/benefits of management alternatives**
3) Water quality – *quantify effects on:*	**Drinking water treatment impacts assessment**	Task 11.1 – Evaluation of shifting costs/benefits
Task 3.1 – sediment, turbidity, nutrients (N P),	Task 8.1 – Infrastructure/ design/ operations assessment of	from management alternatives in a dynamic forest
organics (DOC), base cations / anions, metals,	regional impacts of forest management across range of scales	source water region
& water temperature	Task 8.1.1 – solids removal/handling	**Knowledge Mobilization**
Task 3.2 – sediment/nutrient interactions	Task 8.1.2 – disinfection by-product	**12) Partner/Stakeholder Workshop**
4) Stream health – *quantify effects on* :	Task 8.2 – Comparative infrastructure/ design/operations	Outline and workshop 1st post-harvest year results
Task 4.1 – Algal communities	assessment of regional impacts from un-managed & managed landscapes	including preliminary comparative outcomes of
Task 4.2 – Invertebrate communities	Task 8.2.1 – solids removal/handling	source water protection & management alternatives
Task 4.3 – West-Slope Cutthroat trout	Task 8.3 – Technology evaluation for mitigating impactson treatability	

Completing the application of the three alternative forest harvesting strategies in each of the three sub-catchments in Star Ck. (task 1) was a foundational milestone which enabled all the other research elements. The importance of completing these alternative harvesting treatments in a fully instrumented study watersheds with > a decade of prior water resources research meeting this keystone component of this study cannot be understated.

Research in theme 1 was focused on evaluating headwaters impacts of alternative harvesting strategies on hydrology (task 2), water quality (task 3), and stream health (task 4). These effects are linked to the downstream effects at larger river basin scales in theme 2 (task 5) including exploring contaminant source tracing techniques as generalized approach for cumulative watershed effects assessment (task 6) and development of regional modeling framework (task 7) for such assessments. This in turn, is linked to research needed for assessment of impacts to drinking water treatment (task 8) and evaluation of economic consequences (costs/benefits) and implications. This was accomplished in components including economic consequences of management alternatives (task 9), evaluating costs of ecosystem service provision (task 10, and evaluation of likely future costs/benefits of management alternatives (task 11).

3.5. Results

3.5.1. Early initial effects of harvesting on hydrology, water quality, and stream health

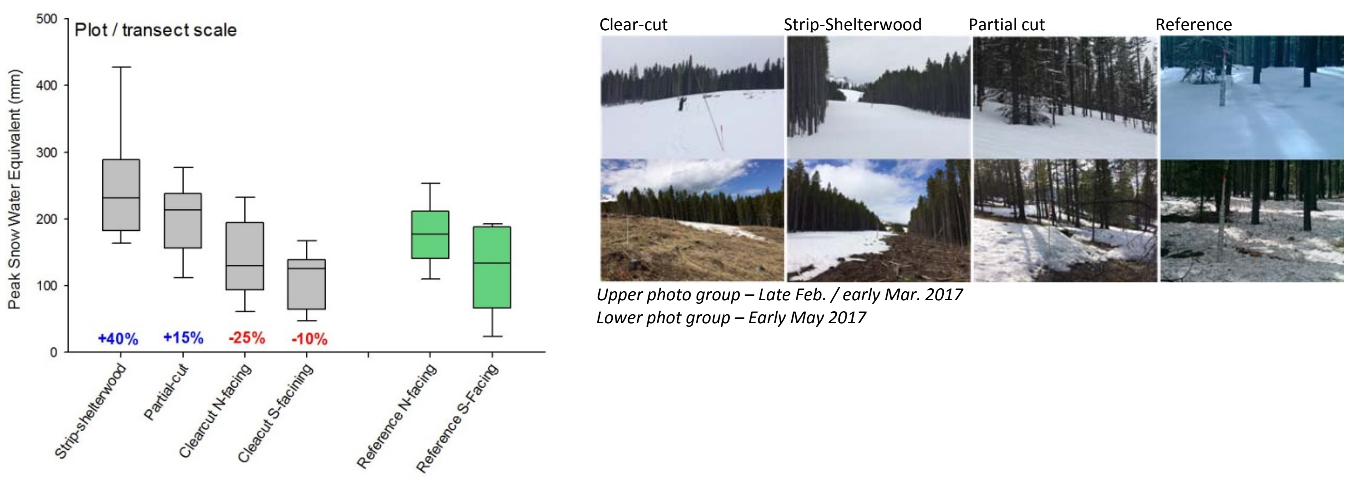
Hydrology (task 2)

Precipitation and climate – Harvest effects on headwaters hydrology, water quality, and stream health depend on both the comparative disturbance footprints from the 3 alternative harvesting strategies and climatic conditions during the evaluation period. Precipitation varied considerably among wet/dry years during the pre-harvest calibration period (2004-2014) with mean annual precipitation of 864 and 1169 mm/yr in Star Ck. (harvest) and N. York Ck. (reference), respectively. However, snowfall which represents ~40-60% of total annual precipitation was the lowest on record during the 2015 harvest year and below normal during 2016, while summer precipitation was only 12% below average. Both the very low snowpacks and slightly below average summer precipitation played an important role in the magnitude of initial early effects on hydrology, water quality, and stream health observed after the harvest.

Snowpack accumulation and melt (task 2.1) - Because undisturbed forest canopies regulate snowpack accumulation through interception and subsequent evaporative losses of snow, and limit ground-level solar radiation, harvesting in Star Ck. affected both snowpack accumulation and melt dynamics during the winters of 2015 & 2016. This component also provides insights into snowpack interception losses (task 2.2.1).

A MSc. student project (Dan Greenacre, Sept 2016) is exploring the effects of all three harvesting strategies on plot scale peak snow water equivalent (SWE; maximum liquid water equivalent of snowpacks) during the winter of 2016/17. Compared to reference plots, peak SWE was increased by 40% and 15% in strip-shelterwood and partial cut areas, while SWE was decreased in clear-cut transects. Differences in peak SWE among harvesting strategies along with greater radiation in more heavily harvested transects produced substantial differences in melt rate and timing of disappearance of snow cover among the harvesting treatments. Thinner snowpacks disappeared earliest in the clear-cut transects followed by unharvested reference transects while deeper snowpacks persisted longer in partially harvested, and much longer in strip-shelterwood harvested transects.

Figure 3 – a) Peak SWE, and b) comparative melt rates of three harvesting strategies in 2016/17



However, strong effects of the three harvesting strategies evident at transect scales were generally not reflected in overall sub-catchment and catchment scale differences in peak SWE among harvested and reference watersheds because catchment scale mean snowpack conditions include both harvested and unharvested regions of each watershed. While a full paired catchment ANCOVA was not possible with only 3 yr. of harvesting data, 95% confidence intervals from the pre-harvest calibration between N. York Ck. (reference) and Star Ck. (harvested) peak SWE was used as an interim approach to assess the impact of harvesting strategies on peak catchment scale snowpacks (Table 2).

Table 2 – Change in peak catchment scale SWE for 3 harvest strategies (sig. shown in brackets)

Watershed	Harvest Strategy	Post-harvest change in mean SWE (mm) 2014/15	2015/16	2016/17
Star West-fork	Clearcut	-9.8 (*ns*)	-48.2 ($p<0.05$)	-7.6 (*ns*)
Star East-fork	Strip-Shelterwood	-20.6 (*ns*)	+2.0 (*ns*)	+16.6 (*ns*)
Star McLaren	Partial cut	+41.3 ($p<0.05$)	+9.8 (*ns*)	+0.6 (*ns*)
Star Ck. sub-basin	Entire drainage	-11.0 (*ns*)	-22.9 ($p<0.05$)	4.0 (*ns*)

While broader inferences on effects of these harvest strategies from these analyses should be interpreted cautiously, overall catchment scale changes in peak SWE (both + & -) were generally not significant or were otherwise small across the winters of 2014/15-2016/17.

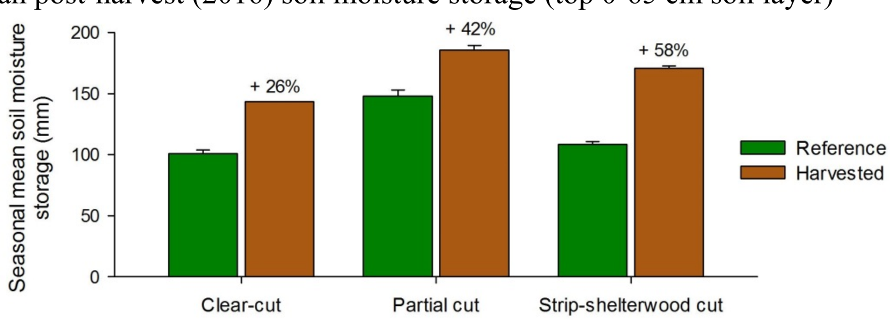
Rain interception (task 2.2.1), transpiration (2.2.2), ET in harvested units (task 2.2.3) - An M.Sc. student project (Samantha Karpyshin, Sept. 2016) is currently exploring the effects of harvesting on transpiration, rainfall interception, and overall evaporative losses. Field research on this component began in Apr. 2017 with a focus on catchment scale changes in evaporative process after harvesting; interim results are reported on in the progress report for the companion 2016-2019 AI project.

Soil Moisture (task 2.2.4) - Networks of soil moisture transects in all three harvested sub-catchments were established and measured monthly during the 2016 1st full post-harvesting summer season. Measurements are continuing through the 2017 and 2018 field seasons as part of the two M.Sc. projects described for tasks 2.1 and 2.2.2 above. Because of the steep reduction in evaporative losses by the canopy after harvesting, soil moisture storage increased during the 1st full post-harvest snow-free season (May-Oct 2016) in all three harvested treatments. Mean soil moisture increased most strongly in the surface 0-20 cm soil layers which contain the vast majority of fine root biomass for water uptake by vegetation, with substantial but smaller increases of soil moisture in the 45cm layer beneath the surface layer (Table 3). Harvesting in clear-cut, partial cut, and strip shelterwood strategies increased the mean seasonal hydrologically important (to 0-65 cm deep) soil moisture storage by 26-, 42-, and 58%, respectively (Figure 4). Changes to water storage in this 65 cm thick surface layer are likely the main driver of post-harvest responses in hillslope runoff dynamics and streamflow after harvesting.

Table 3 – Mean post-harvest (2016) soil moisture storage of 3 soil layers

	Depth								
	0-20 cm			20-65 cm			0-65 cm		
Sub-catchment	Reference	Harvested	% increase	Reference	Harvested	% increase	Reference	Harvested	% increase
West-fork (clear-cut)	34.1	48.2	41%	66.8	95.2	43%	100.9	143.4	42%
McLaren (partial cut)	47.8	59.0	23%	100.0	127.3	27%	147.8	185.6	26%
East fork (strip-shelterwood cut)	36.9	64.7	76%	71.5	106.0	48%	108.4	170.7	58%

Figure 4 – Mean post-harvest (2016) soil moisture storage (top 0-65 cm soil layer)



Thus, while mean seasonal soil moisture storage was increased by all three harvesting strategies, the magnitude of post-harvesting soil moisture increases were somewhat consistent with differences in peak snow water equivalent (Figure 2) among harvesting treatments. However, because changes in soil moisture storage after harvesting reflects the combined effects of decreased evaporative loss (interception & transpiration), differences in the strength of these effects is more of an indication of overall post-harvest changes in evaporative losses among these three harvesting strategies.

Hillslope-stream linkages & runoff generation (task 2.2.5) - A Ph.D. student project (Sheena Spencer, Jan. 2014) has been exploring the complex interaction of groundwater and surface runoff flow pathways in Star Ck. to enable understanding how this watershed and its sub-catchments respond to disturbance. Climatic and hydrometric data (2005-2014) from the 5 nested watersheds in the larger Star Ck. drainage were used to evaluate groundwater inputs to-, and losses from streams, long-term sub-catchment scale water storage dynamics, precipitation-runoff responses, and their linkage with seasonal-annual variation of stream water chemistry. This work demonstrates that variation in streamflow within sub-catchments of Star Ck. is partially regulated by catchment scale "memory" of previous year(s) precipitation because of time lags in soil and groundwater recharge and storage contribution to flow. Surface streamflow and shallow groundwater responses to precipitation show that variation in landscape topography and relief are not good indicators of runoff generation or flow responses at the hillslope or sub-catchment scale likely due to complex flow pathways created by glacial features (e.g., lateral moraines) and relic streams. Shallow hillslope groundwater responses indicate that precipitation infiltrates vertically most of the year; perched water tables and lateral flow occurs only during snowmelt or during large storms later in the summer. Fractured bedrock produces preferential flow pathways for precipitation but it is unlikely that this water contributes to stormflow. This body of research shows that Star Creek is hydrologically resilient to disturbance because of 1) permeable bedrock and deep surficial glacial tills with high storage capacity and 2) dominant subsurface flow pathways linked to groundwater. An important outcome of this work confirms that interpreting streamflow responses from the three harvesting strategies is not straight forward but requires careful evaluation of both seasonal and multi-year climate patterns.

For example, a common assumption is that because harvesting reduces evaporative losses by transpiration and snow/rain interception resulting in increased soil moisture, the balance between surface/sub-surface pathways becomes more dominated by surface runoff after harvesting resulting in "flashier" streamflow response to precipitation or increased peak flows. However, potassium:silica ratios (geochemical tracer indicating relative dominance of surface runoff) showed no evidence of increased surface runoff in either clear-cut or strip-shelterwood harvested sub-catchments in 2015 or 2016, while increases in this ratio were observed in the partial cut harvesting sub- drainage(both 2015 & 2016).

Retrospective analysis of precipitation-runoff relationships from SRWP phase I data (Chris Williams, SRWP lead staff field hydrologist) is focused on identifying key catchment scale runoff indicators of severe land disturbance from the 2003 Lost Ck. wildfire. This work is confirming the significant hydrological resistance and resilience to disturbance in this region and the metrics being developed from this work will be directly applied to evaluation of post-harvesting changes in runoff in the coming years after several addition years or streamflow monitoring are complete.

Volume/timing of streamflows (task 2.3)
Streamflow during 2013 flood. The delay in harvesting enabled collection of 2 additional years of pre-harvest calibration data on streamflows and the power of the calibration relationships depend to a large extent on the variability of flow conditions captured during the calibration period. The 2013 flood in S. Alberta produced record precipitation and streamflows in the Crowsnest Pass region surpassing the previous maximum flood of 1995 as the largest event on record in 106 years. The storm produced > 235mm of precipitation in 24 hr. resulting in extreme flows in the SRWP

catchments resulting in major streambed, bank, and channel erosion and channel reconfiguration (Figure 5). Seven hydrometric stations were lost during the peak of the flood, however, all of the instrumentation was subsequently recovered downstream with all of the data still stored in data loggers enabling reconstruction of the full streamflow record from the flood event. This event produced peak streamflows 2-6x greater than previous peak streamflows measured in the study watersheds over the previous 9 years. These data from the 2013 event along with associated water quality measurements provide powerful insights on the comparative effects of this flood.

Figure 5 – Deposition in lower reach of Star West-fork after 2013 erosion from upstream reaches

Effects of 3 harvesting strategies on streamflows. Results from 2.2.5 suggest early assessment of streamflow responses to the three harvest strategies requires considerably more than 2 years of post-harvest data to evaluate. While the paired catchment (before/after;control/impact) design serves as a powerful foundation for evaluating these effect, such analyses depend on a *minimum* of 5-6 years of post-harvest data to support any meaningful inferences supported by analysis of covariance (ANCOVA) on sub-catchment scale streamflow observations. However, *for purely illustrative purposes*, 95% confidence intervals on the pre-harvest calibration between N. York Ck. (reference) and Star Ck. (harvested) annual streamflow was used as an early indication of the 1st two years of post-harvesting effects on streamflow (Table 4).

Table 4 – Early changes in annual streamflow for 3 harvest strategies (% change & sig. in brackets)

		Post-harvest change in streamflow (mm/yr)	
Sub-catchment	**Harvest Strategy**	**2015**	**2016**
Star West-fork	Clearcut	+124.2 (+22.2%, *p<0.05*)	+30.4 (+5.5%, *ns*)
Star East-fork	Strip-Shelterwood	+84.9 (+22.2% *p<0.05*)	+50.6 (+15.0%, *p<0.05*)
Star McLaren	Partial cut	+37.9 (+24.1%, *ns*)	-29.0 (-19.3%, *ns*)

Early assessment of streamflow after harvesting showed variable responses to harvesting in clear-cut and partial-cut harvested watersheds with early indications of elevated runoff evident in the clear-cut sub-catchment in 2015 only. However, more consistent indications of a potential for greater streamflow after strip-shelterwood harvesting was evident with increased streamflow observed in both 2015 & 2016. A general trend of slightly greater flow from Oct-June with no change or slightly lower flows during Aug-Sept appeared evident in all three harvested sub-catchments.

Water Quality (task 3)

Sediment, nutrients, and other water quality parameters (task 3.1)

Evaluation of the 2013 flood on water quality - The 11 yr. pre-harvesting calibration data enabled evaluating the effects on key water quality parameters. While the flood had only a moderate impact on many water quality parameters, the flood produced extreme sediment and nutrient loading (particularly nutrients such as phosphorus that are associated with sediment) in all SRWP study watersheds including both North York and Star Cks. However, Star Ck. was more strongly affected by the storm than was N. York Ck. producing extreme instantaneous water quality values during the flood. However, very high production of sediment and total phosphorus persisted for months afterwards into the following 2014 runoff season as reflected in the strong legacy of effect of the flood in our pre-harvest calibration record (Table 5). Mean annual concentrations for these parameters, mean annual TSS, turbidity, and TP increased 51-, 67-, and 13-fold respectively during 2013 compared to the previous 9 years. Flow weighed TSS and TP exports were even more strongly increased by 104x, and 25x respectively during 2013 than over the previous 9 years.

Table 5 – Mean annual total suspended solids (TSS), turbidity. & total phosphorus (TP) 2004-2014

Year	Total suspended solids (mg/L)	Turbidity (NTU)	Total phosphorus (µg/L)
2004	1.32	0.58	4.56
2005	4.61	1.55	7.03
2006	1.18	0.40	2.06
2007	1.62	0.43	4.17
2008	3.56	0.83	6.20
2009	1.29	0.35	4.55
2010	0.78	0.48	4.17
2011	8.78	3.43	9.05
2012	1.33	0.99	5.47
2013	**137.98**	**66.88**	**70.93**
2014	16.54	9.35	11.33

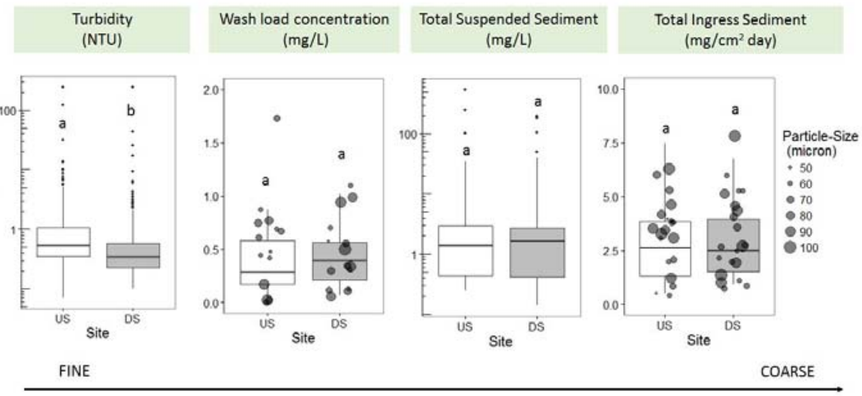
Flooding effects were still evident in 2014 when TSS, turbidity, and TP remained 6x, 9.4x, and 2.2x greater (respectively) than pre-flood concentrations because the flood exposed extensive areas of new sediment sources. Similarly, mean annual sediment and total phosphorus production in from the three uppermost sub-catchments in Star Ck. in 2013 were 8-52x greater than over the 6 previous years of pre-flood monitoring. Among those sub-catchments, 68% of the total sediment export during 2013 was produced by the West-fork sub-drainage with 27% from the East-fork and only 5% from the McLaren Ck. sub-drainages. The total sediment export from the 2013 flood in these 3 sub-catchments (3462 tonnes/yr) was 141x greater than in the previous 6 years (mean 24.5 tonnes/yr).

Evaluation of harvesting or other human associated changes to water quality - Assessment of early post harvesting changes in water quality was evaluated at two spatial scales; a) detailed site-scale or hillslope scales (by 3 M.Sc. students) and b) at sub-catchment and larger basin scales (see task 5).

An M.Sc. student project (Milly Corrigan, Sept. 2015) assessed the impact of road-stream crossings on stream sediment using paired upstream (US) and downstream (DS) measurement of 3 crossings (1 in each sub-catchment).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 installed into streambeds both upstream and downstream of each road-stream crossing were used to measure the intrusion (fate) of sediment into streambeds which is considered one of the primary impacts of sediment on stream health. 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) nor the 1st year following road-stream crossing decommissioning in 2016

(Figure 6). Because a series of significant storms were captured in these data (2015 in particular), this lack of impact likely reflects the outcome of the suite of "best management" erosion control practices employed during construction, hauling, and crossing decommissioning phases.

Figure 6 – Distribution of suspended and settled sediments above/below stream crossings (2015/16)



Another M.Sc. student project (Melissa Howard, 2014) is evaluating erosion and sediment production from regional trails used for off-highway vehicles (OHVs) and modelling frameworks such as the "Universal Soil Loss Equation" (USLE) framework for regional evaluation of sediment loading water quality risk from OHV trail networks. Results of field-based rainfall simulation (device to control rainfall amount/intensity) show higher sediment erodibility (0.001-0.125 t/ha/hr/per unit P energy) from trails with steeper slopes and greater intensity of traffic compared to those with lower slopes/low traffic intensity (0.001-0.02). Despite broad use for erosion prediction, and the fact that USLE accurately predicted observed erosion from low traffic trails, prediction of actual erosion on high use trails (measured as 10x greater / unit slope than low use trails) was poor. However, approaches using erosion-precipitation relationships may provide resource managers with simpler approaches to predict erosion from broader OHV trail networks. This project is also linked with a companion OHV project in Node 4 (task 10.1) and provides the road/trail erodibility characterization needed to support the regional road erosion research in Node 2.

A third M.Sc. student project (Michael Stewart, Sept. 2016) is focused on hillslope-stream linkages governing nitrogen production (NH_4^+ and NO_3^-) in the clear-cut harvested sub-catchment as regulated by slope position and radiation (north/south facing aspect). Early results suggest clear-cut harvesting had little impact on nitrogen turnover and mobile nitrogen one year following harvest due largely to uptake by herbaceous vegetation and microbial immobilization. Stream nitrogen appears more tightly coupled to sub-surface/groundwater water N sources in riparian areas than with upslope areas..

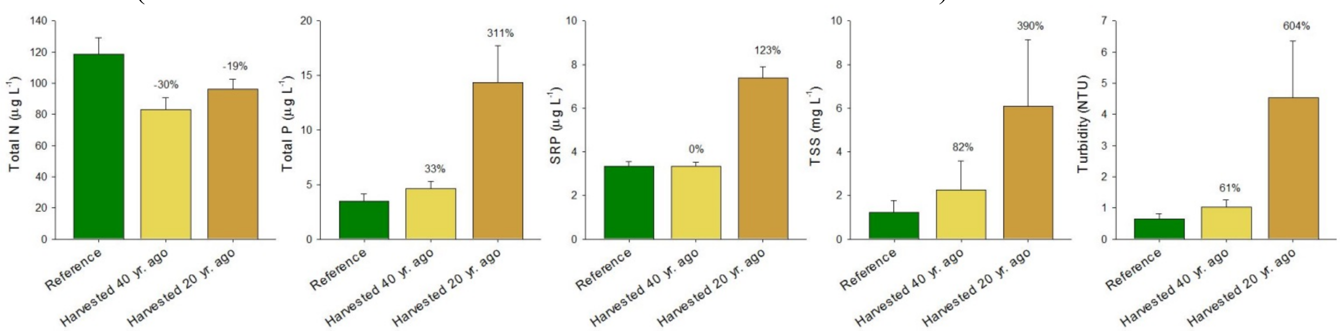
Evaluation of 3 harvesting strategies on water quality - The three harvesting strategies generally produced weak to no initial effects on the concentration of most physical and chemical water quality parameters during 2015 and 2016. In some cases, mean post-harvest concentrations of some water quality parameters decreased (McLaren Ck.) while more consistent increases in soluble reactive phosphorous (SRP) was evident in all harvested sub-catchments in 2016 (and Star East-fork in 2015). Again, while a full paired catchment ANCOVA is not possible with only 2 yr. of harvesting data, 95% confidence intervals on the pre-harvest calibration between N. York Ck. (reference) and Star Ck. (harvested) were used to illustrate early post-harvesting changes in key water quality parameters that should be interpreted cautiously (Table 6).

Table 6 – Early changes in key water quality parameters in harvested sub-catchments in 2015-2016

Parameter	Star West-fork (clear-cut)	Star East-fork (strip-shelterwood)	Star McLaren (partial-cut)
Total nitrogen	no change	↓ 2015 & 2016 (–11–17%)	↓ 2015, ↑ 2016 (–32%, +25%)
Total phosphorus	no change	no change	↓ 2015 (–60%)
Soluble reactive phosphorus	↑ 2016 (+19%)	↑ 2015 & 2016 (+15–17%)	↑ 2016 (37%)
Total suspended solids	no change	no change	↓ 2015 (–95%)
Turbidity	no change	no change	↓ 2015 (–83%)
Dissolved organic carbon	no change	no change	no change

Evaluation of historic harvesting effects on water quality - While no pre-disturbance streamflow or water quality data existed for catchments in this sub-study (section 3.2) preliminary evaluation of whether legacy effects of watersheds harvested ~20-, and ~40 yrs. ago is based on comparing mean flow and water quality responses across a wide range of flow conditions (early pre-melt, snowpack melt freshet, post-peak melt freshet, and summer-fall baseflow conditions) over 3 full years (2014-2016). Total nitrogen was notably lower than reference watersheds largely due to the N uptake by early and late juvenile forests established after harvesting with the greatest reduction in N evident in the younger, most rapidly growing juvenile forests in the 20 yr old harvested watersheds. A manuscript reporting on the same finding after wildfire and salvage harvesting is currently in the latter stages of preparation for publishing. However, a very large signature of elevated sediment and turbidity was evident in watersheds harvested 20 yrs. ago and smaller but still

Figure 7 – Mean (2014-2016) TN, TP, SRP, TSS, turbidity from reference and harvested catchments (values above bars indicate % increase over reference catchments)



clearly evident signature of sediment production was observed in watersheds harvested >40 yrs. ago. Similarly, nutrients such as phosphorus (total P and SRP) were strongly elevated in watersheds harvested 20 yrs. ago, while some impacts of harvesting 40 yrs. earlier were still evident for total P (not for SRP). Dissolved organic carbon (DOC) production from these watersheds (2014-2016) is outlined in section 3.5.3 because it is closely associated with many of the drinking water treatability parameters associated with these water quality results.

While the water quality impacts from these old harvested watersheds were much larger than those observed for the SRWP Phase II watersheds in Star Ck., the most likely reasons for these differing results is a combination of factors reflecting differing requirements/application of best management practices for erosion control from harvested areas and roads from historic harvesting practices compared to contemporary practices, and the fact that old roads and legacy harvesting trails still exist in these older harvested areas which would promote persistence of disturbance effects on sediment and associated nutrients such as phosphorus.

A closely allied M.Sc. student project (Kirk Hawthorn, completed 2013) showed that while no effects of historic harvesting on elevated soluble reactive phosphorus concentrations were evident in Smith

Ck. (harvested ~40 yr. prior), legacy harvesting effects were still detectable on particulate phosphorus in association with suspended sediments. Furthermore, chronic post-harvesting sediment production over the previous 40 yr. resulting in sediment intrusion into streambeds subsequently served as the primary sources of phosphorus through desorption of P from streambed sediments into the water column. The research demonstrated this was the mechanism responsible for elevated aquatic productivity (algal production) that was still clearly evident > 4 decades after harvesting.

Sediment-nutrient-trace element interactions (task 3.2)

Preliminary evaluation of harvesting effects on sediment associated trace elements in the three sub-catchments is based on comparison of pre- and post-harvesting sediment geochemical analyses for > 70 sediment associated trace compounds. While changes in the concentrations of these compounds prior to- and after-harvesting was variable between the three harvested sub-catchments, more consistent post-harvesting decreases in Chromium, Thallium, and Selenium were notable along with increases in sediment associated Mercury (Hg).

This latter finding is not unexpected given prior research on forest disturbance impacts on mercury production by both wildfire and harvesting (Garcia & Carignan 2005). While these data are highly preliminary and will require additional years of study to confirm, it should be noted that the post-harvesting sediment Hg concentrations were over 3x lower than the Canadian Council of Ministers of the Environment (CCME) "Canadian Sediment Quality Guidelines for the Protection of Aquatic Life" Interim Sediment Quality Guidelines (ISQG).

Stream health (task 4)

Effects of harvesting on algal communities (task 4.1).

Early evaluation of 3 harvesting strategies on algal communities – The three harvesting strategies resulted in smaller or variable effects on productivity of algal communities as reflected in two measures of algal productivity; ash-free dry mass (AFDM) or chlorophyll-a content of algae (Chlor-a). While a full paired catchment ANCOVA is not possible with only 2 yr. of harvesting data, 95% confidence intervals on the pre-harvest calibration between N. York Ck. (reference) and Star Ck. (harvested) were used to illustrate early post-harvesting changes in algal productivity (this should be interpreted cautiously). While algal AFDM declined in the Star Ck. East-fork drainage in both 2015 & 2016, AFDM was not significantly affected by harvesting in the Wast-fork sub-drainage. However, a large increase in AFDM was evident downstream of all three harvested sub-drainage at the Star. Ck. main gauging station (Table 7).

Table 7 – Early changes in algal productivity (AFDM) during 2015 & 2016

		Post-harvest change in algal AFDM (mg/cm^2)	
Watershed	Harvest Strategy	2015	2016
Star West-fork	Clearcut	-37% (*ns*)	+21% (*ns*)
Star East-fork	Strip-Shelterwood	-72% ($p<0.05$)	-67% ($p<0.05$)
Star McLaren	Partial cut	*NA*	*NA*
Star Ck. sub-basin	Entire drainage	-0.2% (*ns*)	+52% ($p<0.05$)

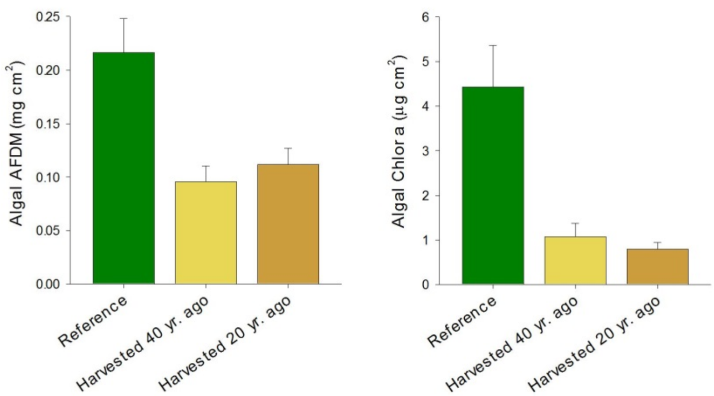
Chlor-a estimates of algal productivity closely paralleled those of AFDM. Chlor-a declined after harvesting in the East-fork (strip-shelterwood harvested) drainage while no change was observed in West-fork. However, a substantial increase (116%) in Chlor-a was observed downstream of all three harvested sub-drainage at the Star. Ck. main gauging station (Table 8).

Table 8 – Early changes in algal productivity (Chlor-a) during 2015 & 2016

		Post-harvest change in algal Chlor a (µg/cm²)	
Watershed	Harvest Strategy	2015	2016
Star West-fork	Clearcut	-32% (*ns*)	-29% (*ns*)
Star East-fork	Strip-Shelterwood	-88% ($p<0.05$)	-76% ($p<0.05$)
Star McLaren	Partial cut	*NA*	*NA*
Star Ck. sub-basin	Entire drainage	+10% (*ns*)	+116% ($p<0.05$)

Evaluation of historic harvesting on algal communities – Contrary to the finding of strongly to moderately elevated sediment and nutrient production from 20- and 40 yr. old harvested watersheds, both algal AFDM and Chlor-a were much lower in both groups of previously harvested watersheds. Phosphorus is the primary limiting nutrient for plant and biofilm growth in these oligotrophic Rocky Mountain streams. Thus while this finding is inconsistent with our other data on differences in water quality among these catchment groups, it is possible that some other limiting element may be associated with the strong differences in algal productivity between reference and harvested watersheds.

Figure 8 – Mean (2014-2016) algal AFDM and Chlor-a reference and harvested watersheds



Invertebrate communities (task 4.2)

Evaluation of 3 harvest strategies on invertebrate communities -An M.Sc. project (Amanda Martens, Jan. 2016) has been focusing on characterizing the effects of physical and chemical water quality, terrestrial, and aquatic food sources and their relationship to macroinvertebrate community structure to identify disturbance sensitive taxa and their sensitivity to specific environmental changes after disturbance (water quality, temperature, food source, etc.). Preliminary results have identified 7 families of Ephemeroptera, Pleocoptera, Trichoptera, Diptera, Coleoptera, and Turbellaria that may serve as indicators of watersheds disturbance. Canonical discriminant analysis and principle components analysis is underway to describe the specific watershed factors associated with either positive or negative shifts in abundance of these taxa after disturbance. This component will be reported on further in progress reports for the 2016-2019 AB. Innovates grant supporting this research program.

West-slope Cutthroat trout (task 4.3)

Evaluation of 3 harvest strategies on West-slope Cutthroat trout - West-slope Cutthroat trout was listed under the "Canada Species At Risk Act" (SARA) in 2013 after this project began which necessarily limited the direct study of impacts of harvesting to West-slope Cutthroat trout populations. However, while other research in this project (hydrology, water quality) is directly relevant to habitat requirements for this fish species, an additional study element focus on disturbance impacts to spawning habitat was added to the 2016-2019 AB. Innovates grant supporting this research program is reported on in reports for that grant.

3.5.2. Downstream propagation of harvesting effects

Regional Propagation of Harvest Effects (task 5)

Effects on flow dynamics in the Crowsnest River (task 5.1)

Effects of 3 harvesting strategies on flow in the Crowsnest R. - Based on preliminary assessment of harvesting effects on streamflow, an early estimate of how those changes in streamflow affected the total annual streamflow at increasing downstream spatial scales was conducted (Table 9).

Table 9 – Estimated post-harvest contributions to downstream streamflow volume

	Watershed Area (ha)	% harvested in SRWP Phase II	Historic pre-harvest flow contribution from Star Ck harvested sub-basins (%)	Estimated change in flow in 2015 from Star Ck. harvesting (%)	Estimated change in flow in 2016 from Star Ck. harvesting (%)
Star Ck. Main Gauging Stn.	1030	17.5%	84.6%	23.8% (*ns*)	25.2% (*ns*)
Star Ck. Willow	1855	9.7%	86.0%	21.9% (*ns*)	25.8% (*ns*)
Crowsest R. below Star Ck.	18272	1.0%	4.6%	1.2% (*ns*)	1.2% (*ns*)
Crowsest R. at Frank, AB	40600	0.4%	3.1%	0.8% (*ns*)	0.9% (*ns*)

Prior to harvesting, the West-fork, East-fork, and McLaren sub-drainages of Star Ck. contributed 84.6-, 86-, 4.6-, and 3.1% of the historic annual flow volume gauged downstream of these sub-drainages at 3 SRWP hydrometric gauging stations in Star Ck. and on the Crowsnest R., and the Water Survey of Canada gauge in Frank, AB. The post harvesting changes in flow along this gradient of increasing downstream spatial scale indicates the additional streamflow generated in the three harvested sub-catchments of Star Ck. contributed approximately 25% additional flow volume at downstream stations within Star Ck., but only approximately 1% additional flow volume into the Crowsnest R. While these are highly preliminary analyses, none of these estimated changes in flow downstream at larger spatial scales were statistically meaningful.

Effects on sediment loading in the Crowsnest River (task 5.2)

Effects of the 2013 flood on sediment loading into the Crowsnest R. - Flow and sediment monitoring above-, and below the confluence of Star Ck. with the Crowsnest river (2012-2016) enabled direct documentation of the effects of the 2013 flood on sediment production from the Star Ck. basin prior to harvesting. The flood produced extreme erosion and sediment production from Star Ck. which

Table 10 – Total sediment export and mean annual turbidity in the Crowsnest R. above-, and below the confluence with Star Ck.

Year	Sediment export (tonnes/yr)		Mean annual turbidity (NTU)	
	Crowsnest R. above Star Ck.	Crowsnest R. below Star Ck.	Crowsnest R. above Star Ck.	Crowsnest R. below Star Ck.
2012	3809	4220	4.6	4.6
2013	5410	257768	6.5	26.7
2014	8536	10082	12.7	13.0
2015	2489	3295	4.3	4.8
2016	1403	1402	11.7	11.3

increased annual sediment export into the Crowsnest river in excess of 250,000 tonnes in 2013 which represents >46-fold increase in sediment loading into the river from just above-, to below the confluence with Star Ck. While measurement in the Crowsnest River began in the Crowsnest R in 2012, previous estimates of sediment export from the Star Ck. basin ranged from 400-1800 tonnes/yr. prior to the flood. Thus, sediment loading into the Crowsnest River from Star Ck. in 2013 would represent a stunning 140-630-fold increase over average pre-flood sediment contributions to the river. Similarly, while total production of fine sediments that constitute turbidity (measure of optical light scattering), average annual turbidity downstream of the confluence of Star Ck. with the Crowsnest R. was 311% greater during 2013 compared to turbidity immediately above Star Ck. We are unaware of any documented natural disturbance event producing impacts of this magnitude.

Effects of 3 harvesting strategies on sediment loading into the Crowsnest R. As no meaningful increase in total suspended solids concentration nor turbidity was evident in any of the three harvested sub-catchments of Star Ck., no downstream propagation of sediments or turbidity in the larger Star Ck. basin or into the Crowsnest River was evident.

Effects of nutrient and trace element loading in the Crowsnest River (task 5.3)

Effects of the 2013 flood on nutrient loading into the Crowsnest R. – The project study design including historic and current monitoring enabled direct documentation of the effects of the 2013 flood on nutrient production from the Star Ck. basin prior to harvesting. Because the flood produced extreme sediment loading and nutrients such as phosphorus which are strongly associated with sediment production, the flood produced extremely high total phosphorus (TP) loading into the Crowsnest River (Table 11).

Table 11 – Total phosphorus export into the Crowsnest River

Year	Total P export (tonnes/yr)	
	Crowsnest R. above Star Ck.	Crowsnest R. below Star Ck.
2012	5.8	5.9
2013	9.6	116.8
2014	9.4	9.8
2015	2.8	3.0
2016	2.4	2.4

The flood increased annual TP export into the Crowsnest river in excess of 107 tonnes in 2013 which represents >11-fold increase in sediment loading into the river from just above-, to below the confluence with Star Ck. Again, while measurement in the Crowsnest river began in the Crowsnest R in 2012, previous estimates of TP export from the Star Ck. basin ranged from 0.3-0.4 tonnes/yr. prior to the flood. Thus, TP loading into the Crowsnest River from Star Ck. in 2013 would represent a 135-163-fold increase over average pre-flood TP contributions to the river.

Effects of 3 harvesting strategies on nutrient loading into the Crowsnest River. The only nutrient affected by harvesting in the three sub-catchments of Star Creek was soluble reactive phosphorus (SRP, Table 6). However, analyses based on pre-harvest calibration between N. York Ck. and Star Ck. indicated only a very minor (non-significant) increase of 0.2 (+1.1%) and 0.17 (+1.5%) kg/yr. SRP at the Star Ck. main gauging station downstream of the three harvested catchments. Thus, no downstream propagation at this downstream location of nutrients within the larger Star Ck. drainage or into the Crowsnest River was observed in 2015 or 2016.

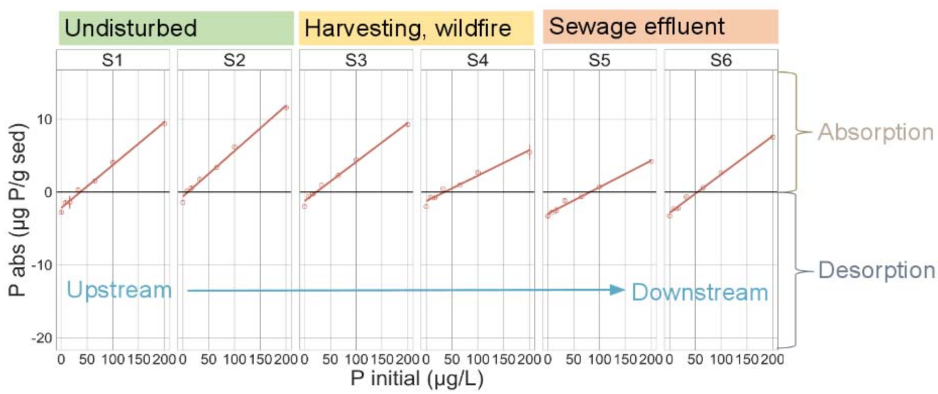
Effects of 3 harvesting strategies on trace element loading into the Crowsnest River. The decreases in Chromium, Thallium, and Selenium, along with increases in sediment associated Mercury (Hg) observed in the headwaters sub-catchments after harvesting were also evident in downstream sediments at the Star Ck. Main gauging station (1035 ha, 17.5% upstream harvested). However, upstream harvesting effect on these trace elements were not evident further downstream at the mouth of Star Ck. (1855 ha, 9.7% upstream harvested) or below the confluence of Star Ck. with the Crowsnest River (18272 ha, 1.0 % upstream harvested).

Effects on sediment nutrient interactions (task 5.4)

A longitudinal study is underway by a M.Sc. student (Caitlin Watt) across a 50 km reach of the Crowsnest River to evaluate the differential land disturbance effects of harvesting, wildfire and urbanization on the form and bioavailability of particulate phosphorus (P). Six study sites along a downstream gradient in the Crowsnest River with multiple land uses (reference – forested, harvested, burnt, and urban sewage outflow) were instrumented to evaluate the vertical distribution of soluble reactive P (SRP), redox conditions (dissolved oxygen and temperature), and P release potential (equilibrium P concentration EPC_0) of sediment. The distribution of dissolved P in the river bed and water column was measured with porewater peepers and physico-chemical characteristics of the sediment and environmental conditions in the stream bed and water column were assessed to identify factors regulating P release.

Early results show that sediment pore water concentrations varied with depth and landscape disturbance. Notably higher dissolved P concentrations were observed downstream of a wastewater treatment facility. Measurements of EPC_0 indicate that bed sediments were acting as a source of dissolved P to the water column. The P sorption characteristics of sediment from harvested tributaries and an upstream reference site were not significantly different. However, the effects of wildfire and sewage effluent on the potential release of P from sediment to the water column (i.e. EPC_0) were considerably higher (Figure 9).

Figure 9 – The effect of land use on the P sorption characteristics of sediment in the Crowsnest River



Contaminant source tracing (task 6)

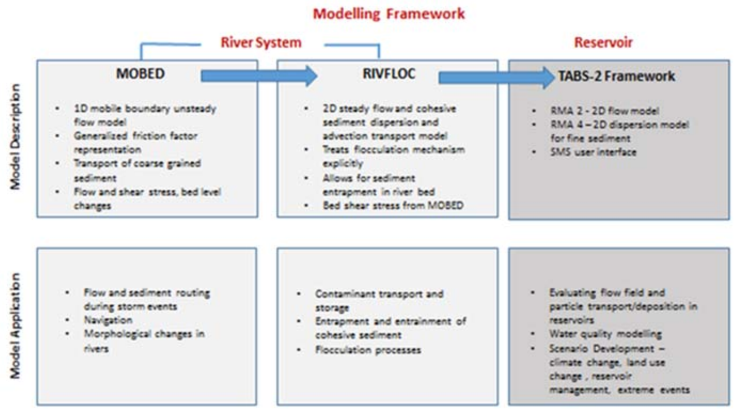
Regional scale tracing of contaminants from harvesting (task 6.1)

To evaluate and compare the effects of harvesting on sediment efflux from Star Creek, a series of Phillips samplers were deployed above and below the three harvest treatments as well as above and below the tributary inflow in Crowsnest River in 2013-2016 before- and after harvesting. Additional sediment samples were collected from harvest roads, stream bank and bed sediments to characterize sediment fingerprint sources. The physical and geochemical composition of sediment from these sources has been determined and this summer (2017) the data will be incorporated into a composite geochemical fingerprinting procedure to evaluate the differential effects of three harvest treatments on sediment source and transport in the Crowsnest River basin. This component will be reported on in progress reports for the 2016-2019 AB. Innovates grant supporting this research.

Regional contaminant transport modeling (task 7)

In 2014, a modelling framework was developed and used to evaluate the large scale land disturbance effects of wildfire on the source, transport and fate of sediment and associated contaminants in wildfire impacted headwater streams of the Oldman River and Oldman Reservoir. The framework integrates four existing models (MOBED, RIVFLOC, RMA2, RMA4) to route sediment from tributary inflows through the Crowsnest River and into the Oldman Reservoir (Figure 10).

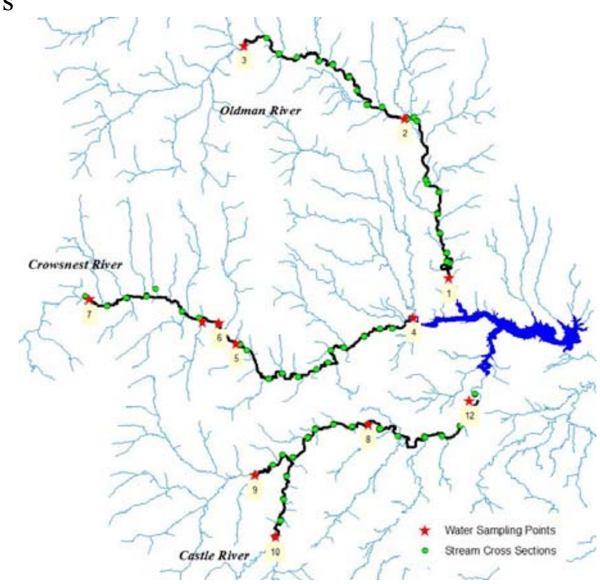
Figure 10 – Flow and sediment transport modelling framework



Regional contaminant transport model calibration (task 7.1)

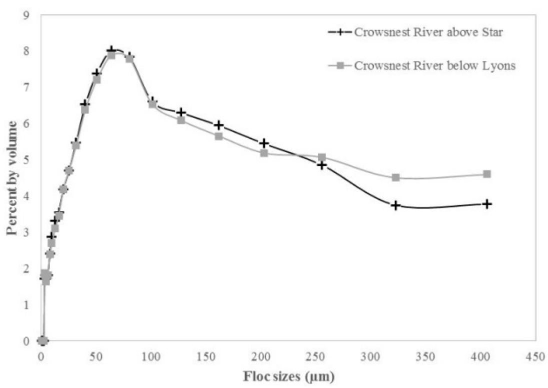
The models were parameterized and calibrated using a series of hydrometric and sediment surveys. Cross-section surveys were conducted at ~ 2 km intervals along 54, 46 and 46 km reaches of the Crowsnest, Castle and Oldman Rivers, respectively (Figure 11). Hydrometric data collected at Water Survey of Canada gauging stations were used to set the boundary conditions of the models. The physical characteristics (slope, width, substrate) of the Castle, Crowsnest and Oldman study reaches were determined. Suspended sediment concentrations were determined for high, medium and low flow conditions. Particle size distributions of suspended sediments were measured using a laser particle size analyzer (LISST) at several locations in the upper part of the Crowsnest River near the confluences of three of its tributaries (Star Creek, York Creek and Lyons Creek). At each confluence, discharge, particle size distribution and suspended sediment concentrations were measured in each tributary, above and below the confluence of each tributary with the Crowsnest River. The flow data as well as the concentration and particle size distribution were used in the modelling framework to simulate flow conditions in late spring and summer and to calibrate MOBED and RIVFLOC.

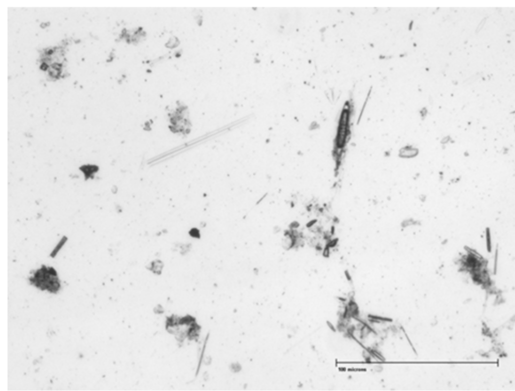
Figure 11 – Location of cross-section surveys and gauging stations in the Crowsnest, Castle and Oldman Rivers



Spatial and temporal variability in particle size distributions of suspended solids in the study reaches is a necessary requirement for model calibration with RIVFLOC. Representative particle size distributions of suspended sediment were measured directly in the water column using a LISST and the data for two stations (upstream of Star Creek confluence and downstream of Lyons Creek confluence) in the Crowsnest River (Figure 12 - left panel). At these two stations, the particle size distributions are similar for smaller size ranges, but the distributions deviate from each other as the size increases. For example, for particles > 200 µm, the distribution corresponding to the station above Star Creek is slightly smaller in comparison to the distribution corresponding to the station below the Lyons Creek. This is because or flocculation of the suspended sediment as it is transported between these two stations is confirmed by direct measurement (Figure 12 - right panel) showing that the sediment population in the Crowsnest R. does include flocculated materials.

Figure 12 – Particle size distributions of suspended solids (left) and floc characterization (right) in Crowsnest River





Quantify downstream regional water quality from natural disturbance & harvesting (task 7.2)

In 2017, the modelling framework will be used to compare the effects of wildfire and harvesting on sediment propagation to the Oldman River. Discharge and sediment data (concentration and particle size) were collected during periods of snow melt and storm flow in Star Creek (harvested watershed) and Lyons Creek (burned watershed). These historical data sets are currently being incorporated into the modelling framework to quantify and compare the relative differences in sediment loading from these watersheds and quantify the downstream propagation of these materials in the Crowsnest River to the Oldman Reservoir. Final results of the modelling are expected to be compiled in a manuscript by November 2017. This component will be reported on in progress reports for the 2016-2019 AB. Innovates grant supporting this research program.

Early assessment operational sediment assessment models - Research was initiated with close cooperation with Canfor and Government of Alberta (GoA) to test tools used to assess erosion and sedimentation hazards at the site and watershed scale. TerrainWorks is a U.S. based that calibrated and delivered data for NetMap at a test watershed the Simonette R. area south of Grande Prairie. NetMap is a GIS toolset that is used for watershed assessments. Preliminary field survey data on erosion surfaces and sediment deposition areas were collected in 2016. Preliminary assessments of existing models identified several barriers for application in Alberta including a) lack of baseline data on erosion and sedimentation processes in Alberta, b) poor quality of input data such as road condition, surface type and other attributes, and c) the density of roads/linear disturbances presents significant barriers to field assessment. Subsequent phases of this work will include 3 targeted graduate student projects to explore the first order controls on erosion and sedimentation processes in the foothills / boreal (with Canfor) and east slopes (with GoA, West Fraser and Spray Lake

Sawmills). Model testing will employ LiDAR remote sensed data. Our objective is not to predict the erosion rates with LiDAR and modelling, but rather use a risk framework to identify the high risk road and linear features that need to evaluated with field crews to collect the specific data needed for restoration planning. This latter component will be reported on further in progress reports for the 2016-2019 AB. Innovates grant supporting this research program.

3.5.3. Drinking water treatment impacts assessment

There are different approaches for evaluating drinking water treatability. The most directly useful treatability metrics are 1) coagulant demand via jar testing (Emelko et al., 2011) to assess turbidity/suspended solids and dissolved organic carbon (DOC) reductions and 2) disinfection by-product formation potential (DBP-FP); specifically, for trihalomethanes (THMs; Method 6232B; APHA, AWWA, & WEF, 2005) and haloacetic acids (HAAs; Method 6251B; APHA, AWWA, & WEF, 2005) because they are regulated DBPs. In addition to these metrics, several proxies for treatability can also be evaluated; while they may not be as directly informative of in plant challenges as the aforementioned list of metrics, these proxies are typically much easier and less expensive to evaluate. At a minimum, assessment of the treatability proxies involves quantification of turbidity and DOC because they are the main water quality drivers of treatment infrastructure and operational requirements/costs (MWH, 2005; 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 (O'Donnell et al, 2010; Aiken et al, 2011; Emelko and Sham, 2014). Increases in DOC may necessitate the use of complicated and costly chemical pretreatment (MWH, 2005; Emelko et al., 2011) or increase chemical coagulant demand (Edzwald & Tobiason, 1999; O'Melia et al, 1999; MWH, 2005; Emelko et al., 2011). Hydrophobic natural organic matter (NOM), for which DOC is a surrogate (Kaplan & Newbold, 1995), is a reactive precursor of regulated carbonaceous DBPs (Singer, 1999; Kitis M et al. 2002). Hydrophilic NOM is more difficult to remove by conventional treatment (Kitis M et al., 2002; Chow et al., 2004) and forms unregulated DBPs of emerging health concern (Liang & Singer, 2003; Ates et al, 2007; Chen & Westerhoff, 2010). Thus, proxies include FEEM, UV254, specific UV absorbance (SUVA) and resin fractionation or LC-OCD. Other treatability challenges associated with changing DOC include increased distribution system regrowth of bacteria (Kaplan et al., 1993); increased disinfectant demand (Amy et al, 1987; Jacangelo et al, 1995); adverse taste/odor/color (Amy et al, 1987; Jacangelo et al, 1995); membrane fouling (Lee et al., 2004; Kwon et al., 2005); and increased heavy metal complexation (Wu et al., 2004; Waples et al., 2005).

Infrastructure/ design/ operations assessment of harvest impacts (task 8.1)

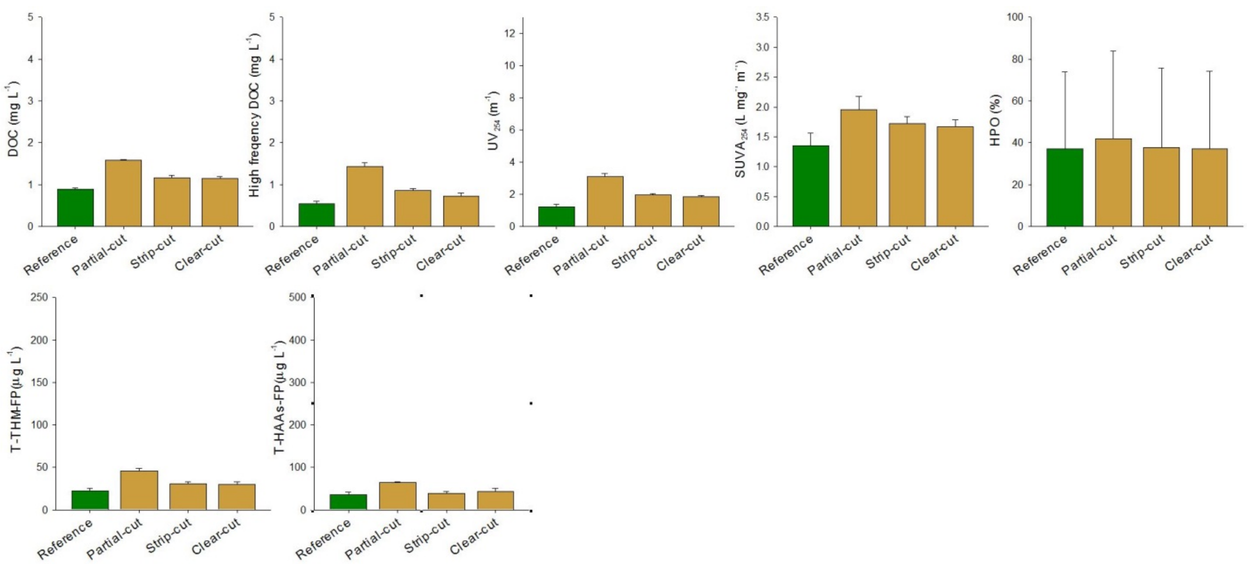
Early effects of 3 alternative harvesting strategies - The 11 years of pre-harvesting turbidity data were discussed above as part of Task 3.1. Notably, the 2013 flood produced significant turbidity loading that persisted for months into the following 2014 runoff season (Table 5). In contrast, the three harvesting strategies did not have an appreciable impact on mean annual turbidity production during 2015 and 2016, except for McLaren Ck. (partial cut) where mean post-harvest turbidity decreased (Table 6); however, these data are preliminary and longer term data are required for a full paired catchment ANCOVA to be conducted. An evaluation of legacy effects ~20 and ~40 years of after harvesting (2014-2016) indicated that mean turbidity remained significantly elevated (604% > reference) ~20 years after historic harvesting and somewhat elevated (61% > reference) ~40 years after historic harvesting (Figure 7).

Mean DOC, UV254, SUVA, hydrophobicity (HPO %), TTHM-FP, and THAA-FP from reference and contemporary harvested sub-catchments across both 2015 and 2016 is presented in Figure 13.

None of the three harvesting strategies had an appreciable impact on any of these parameters during these two years. Notably, it should be emphasized that the observed DOC concentrations during this period (evaluated both concurrently evaluated with the treatability metrics and proxies and those observed at higher frequency as part of the routine water chemistry monitoring program) were very low and at concentrations typical of these types of high quality headwaters supplies. Similarly, UV254, SUVA, hydrophobicity (HPO %), TTHM-FP, and THAA-FP were also low. Notably, any differences between catchments observed (at such low levels) in these parameters likely would be operational insignificant (even if the differences in the parameters were statistically significant) because they were below key thresholds for typical surface water treatment operations (i.e., plants with chemically-assisted filtration or equivalent treatment). As discussed above, longer term results are required for a full paired catchment ANCOVA to be conducted.

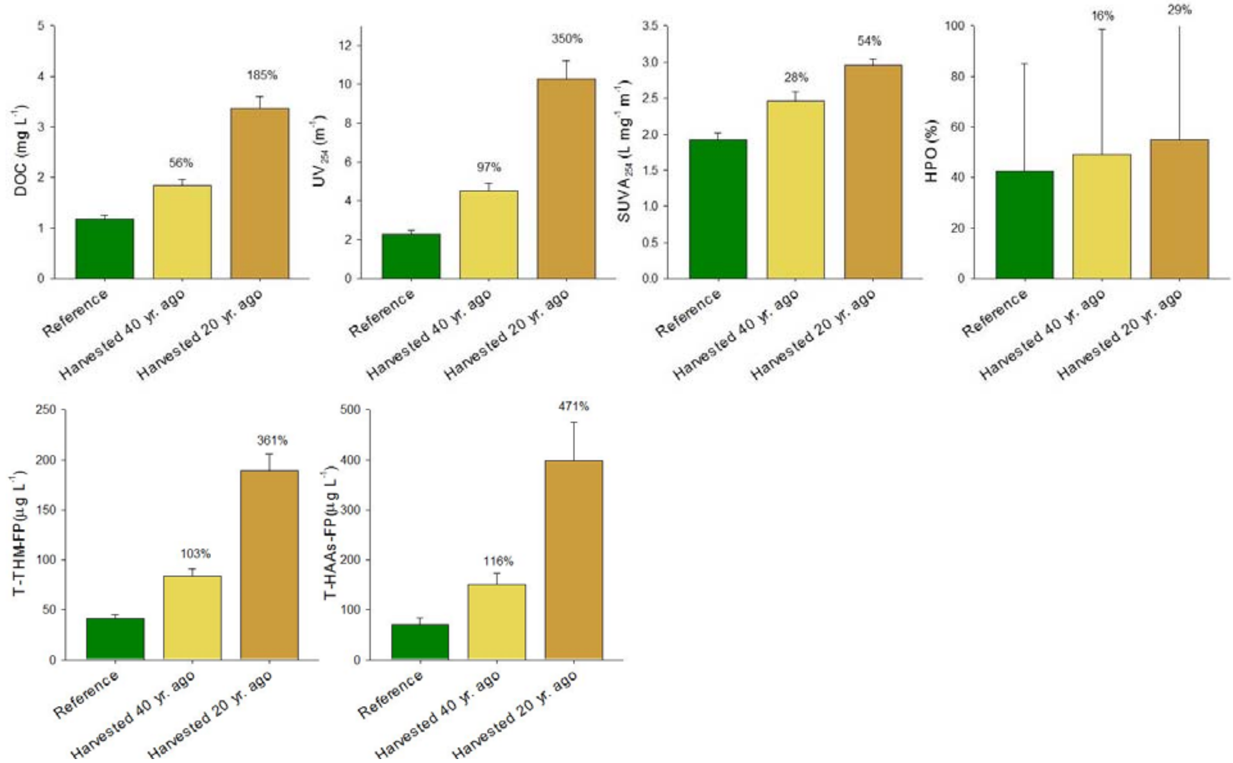
It should be noted that the data presented in Figure 13 are mean values over two full harvest/post-harvest years. Of course, drinking water treatment needs are not driven by mean values, but rather by extreme values because of the need to avoid service disruptions. The mean values and standard errors presented in Figure 13 further demonstrate that the range of water quality that was observed in 2015-2016 does not suggest any substantial challenges to drinking water treatability for most types of surface water systems, especially those with chemically-assisted filtration or equivalent treatment.

Figure 13 – Mean DOC, UV_{254}, SUVA, hydrophobicity (HPO %), TTHM-FP, and THAA-FP from reference and contemporary harvested catchments (bars indicate standard error of the mean; values above bars indicate % increase over reference catchments) in 2015 and 2016.



Evaluation of historic harvesting effects - The water quality and treatability impacts from the historic harvested catchments (Figure 14) were more substantive than those from the contemporary harvested catchments (note: Figures 13 and 14 have the same scales on the ordinate). Notably, the DOC, UV_{254}, SUVA, TTHM-FP, and THAA-FP data from the historic harvested catchments (Figure 14) did suggest potential treatability challenges (MWH, 2005; Emelko et al., 2011)—these would be site (treatment typology) specific and would also depend on the rate of water quality change and operational response capacity. Overall, this comparative analysis suggests that erosion control measures associated with contemporary harvesting practices may offer significant mitigation of impacts (i.e., coagulant demand [indicated by turbidity and DOC], TTHM-FP, THAA-FP) on drinking water treatability (Figures 13 and 14), however longer term investigation of the contemporary harvesting treatments is required to support these early inferences.

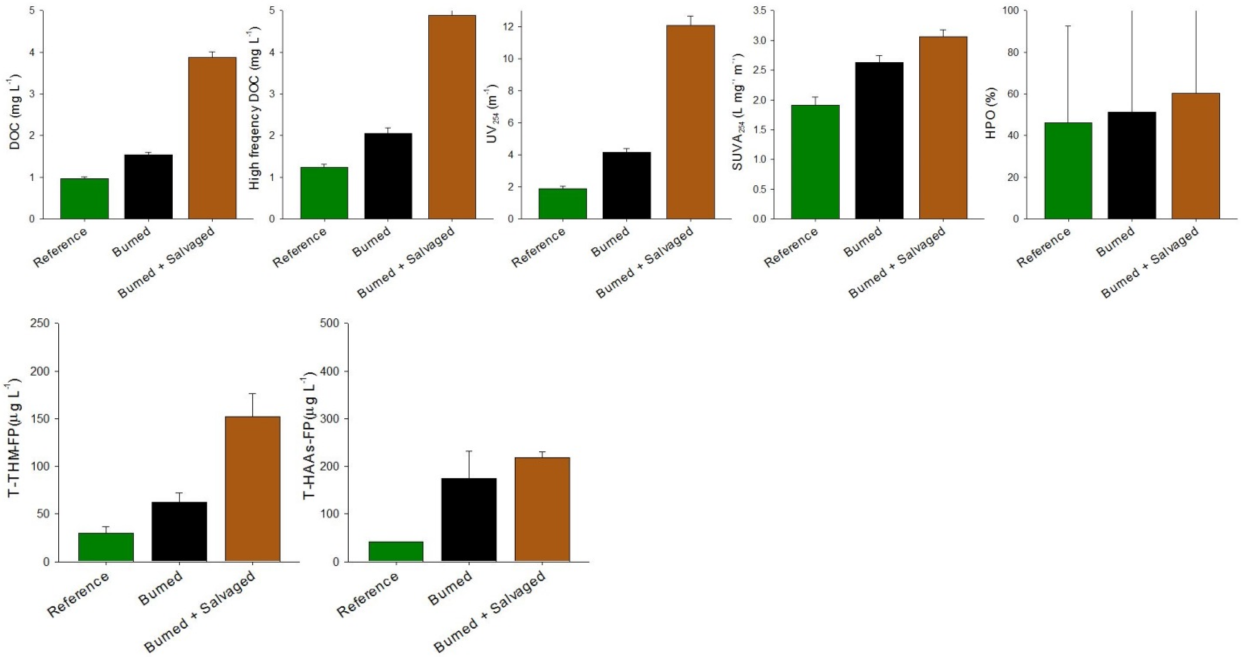
Figure 14 – Mean DOC, UV_{254}, SUVA, hydrophobicity (HPO %), TTHM-FP, and THAA-FP from reference and historic harvested catchments (bars indicate standard error of the mean; values above bars indicate % increase over reference catchments) from 2014 to 2016.



Comparative infrastructure/design/operations – managed and unmanaged landscapes (task 8.2)

While the initial water quality and treatability impacts from contemporary harvesting relative to the reference were essentially inconsequential (Figure 13), the impacts from the historic harvested catchments (Figure 14) and burned and salvage-logged catchments 10 and 11 years after fire (Figure 15) were more substantive and similar. The DOC, UV_{254}, SUVA, TTHM-FP, and THAA-FP data from these harvested, burned, and burned and salvage logged catchments suggest potential treatability challenges (MWH, 2005; Emelko et al., 2011). As mentioned above, these challenges would be site (treatment typology) specific and would also depend on the rate of water quality change and operational response capacity. For example, systems with conventional chemically-assisted filtration might be more challenged than systems with high throughput solids contact units such as ballasted sand flocculation. Overall, this comparison of impacts (Figures 13-15) suggests that the longer term impacts of erosion (regardless of its origin) and associated implications to nutrient release, bioavailability, and transformation may have longer term consequences for water quality and associated challenges and costs of treatability.

Figure 15 – Mean DOC, UV_{254}, SUVA, Hydrophobicity (HPO %), TTHM-FP, and THAA-FP from reference, burned, and burned and salvage logged catchments (bars indicate standard error of the mean) over 2013-2014.



Technology evaluation for minimizing impacts on treatability (task 8.3)

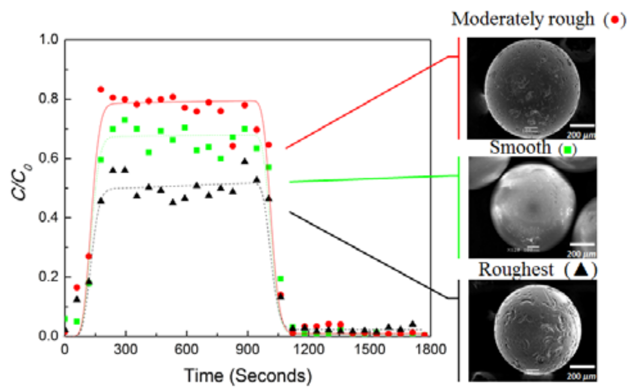
Several strategies for understanding and mitigating the impacts of disturbance-associated changes in water quality and treatability have been evaluated. These can generally be described as focusing on 1) improved turbidity/solids removal, 2) improved DOC removal, 3) improved cyanobacterial bloom mitigation and 4) cyanotoxin treatment.

Chemically-assisted filtration remains a critical treatment process for turbidity/solids reduction during drinking water treatment (MWH, 2005). In the past few decades, numerous experimental and theoretical studies have been conducted to investigate the effects of multiple factors affecting particle deposition during physico-chemical filtration. These include: particle and filtration media properties (Bradford et al., 2007; Johnson et al., 2010), physico-chemical (or biological) interactions between particles and media (Elimelech et al., 1998; Tufenkji and Emelko, 2011; Bradford et al., 2013), and system operational conditions (Amirtharajah et al., 1993; Huck et al., 2002). Among these, the morphology of media/collector surfaces (i.e. roughness) is an important factor that has been recognized for decades; however, literature on this topic has been, for the most part, contradictory, non-mechanistic, and non-quantitative (Hoek et al., 2003; Morales et al., 2009; Huang et al., 2010; Henry et al., 2011; Shen et al., 2014).

A Ph.D. student project (Chao Jin, completed 2014) investigated media roughness impacts on particle deposition in absence of an energy barrier (i.e., high ionic strength, conditions generally consistent with chemically-assisted filtration). In contrast to conventional expectations of increased collector surface roughness leading to improved particle removal, media/collector surface roughness consistently influenced colloid deposition in a non-linear, non-monotonic manner such that a critical roughness size associated with minimum particle deposition could be identified (Figure 16); this was confirmed using a convection-diffusion model. The results demonstrated that media surface roughness size alone is inadequate for predicting media roughness impacts on particle deposition;

rather, the relative size relationship between the particles and media/collectors must also be considered. A model that quantitatively considers media surface roughness was developed that described experimental outcomes well and consistently with classic colloid filtration theory (CFT) for smooth surfaces. These outcomes were further investigated in a parallel plate system and it was observed that the critical roughness size effect was more significant for nanoparticles (<1µm) than for colloids. It was numerically simulated using a Convective-Diffusion model and experimentally validated. Inclusion of flow field and hydrodynamic retardation effects explained particle deposition profiles better than when only the DLVO force was considered. The work provided 1) a first comprehensive framework for describing the hydrodynamic impacts of nano-scale surface roughness on particle deposition by unifying hydrodynamic forces (using the most current approaches for describing flow field profiles and hydrodynamic retardation effects) with appropriately modified expressions for DLVO interaction energies, and gravity forces in one model and 2) a foundation for further describing the impacts of more complicated scales of deposition surface roughness on particle deposition and improving the prediction of particle removal by physico-chemical filtration processes.

Figure 16 – Representative observed (symbol) and simulated (line) colloid breakthrough curves obtained using 4.5 µm colloids on smooth, moderately rough, and rough media (0.707 to 0.841 mm).



Biologically active filtration [BAF] was investigated by a Ph.D. student (Mark Spanjers, completed 2017) because it can be used to concurrently remove particles and natural organic matter (DOC) during drinking water treatment. The selection of a given media type for use in BAF can impact filter performance, capital costs, and operating costs. BAF performance using different media types has been previously compared; however, no single media type has been found to consistently provide the best performance. Notably, no comparisons of BAF with various media types have been reported where the same grain size distribution was used for all media types; precluding observed differences in performance from being attributed solely to media type. Furthermore, mechanisms affecting BAF performance (especially DOC removal) have not been well understood historically. Here, pilot-scale biologically active filters [biofilters] were filled with coal-based granular activated carbon [GAC], anthracite, rough engineered ceramic media [REC], or wood-based GAC; critically, the media grain size distributions were closely matched. The biofilters were fed water that was flocculated, settled, and ozonated at a full-scale water treatment plant and operated continuously for 660 days. Dissolved organic carbon [DOC] removal, turbidity removal, headloss, and filter run time were monitored and compared. It was found that the GACs provided better DOC removal than either REC or anthracite (Table 12), even though the coal-based GAC had been used for seven years in full scale filters prior to these experiments. It was further demonstrated that the adsorptive property of GAC is critical for enhancing DOC removal during BAF relative to other media over the long-term, even for GAC that has been used for many years. The results also implied that mechanisms related to a medium's adsorptive properties (e.g. bioregeneration, adsorption of organic matter spikes) are significant to DOC removal during BAF in the long-term. Thus, the investigation demonstrated the importance of adsorptive filtration media for BAF, and the potential of BAF application (and further optimization) as an adaptation strategy to increase treatment resilience to mitigate the impacts of landscape disturbances on drinking water treatability.

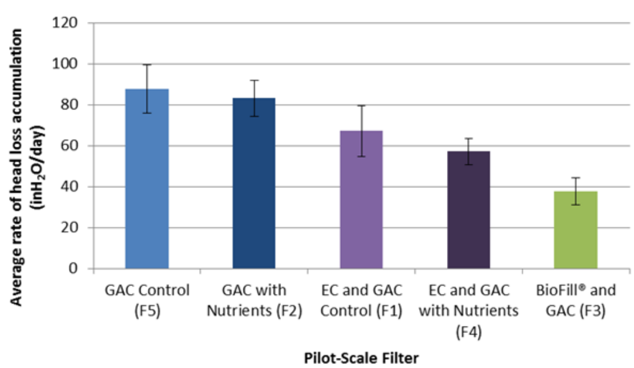
Table 12 – Overview of DOC removal by filtration

Summary Statistic	DOC removal (mg/L)[1] Filter 1 Coal-based GAC	Filter 2 Anthracite	Filter 3 REC	Filter 4 Wood-based GAC	Filter 5 Coal-based GAC (declining-rate)
Mean	0.619	0.478	0.502	0.826	0.713
Standard Deviation	0.242	0.196	0.201	0.266	0.288
Max	1.168	0.844	0.884	1.280	1.248
Min	0.245	0.177	0.174	0.409	0.241
n	22	23	25	24	21

1. All filters operated in constant-rate mode unless otherwise noted

To further enhance BAF performance, an M.A.Sc. student project (Andrew Wong, completed 2015) conducted further pilot-scale BAF investigations. Here, the impact of 1) capping material (EC: engineered ceramic or Biofill®) selection to enhance turbidity removal while extending run times and 2) nutrient amendments for increasing DOC removal by BAF were investigated. The capping materials delayed terminal head loss by 10-40 hours, compared to a control GAC filter, and significantly reduced the rate of head loss accumulation at all temperature ranges without negatively impacting filter effluent turbidity or DOC removal. There were no significant differences in filter run time at cold water conditions between each of the filter configurations; however, both capping layers extended filter run time at warm water conditions by decreasing the rate of headloss accumulation (Figure 17). Replacing a relatively small layer of media with one that has a larger effective size can lead to more resilient filter operation. In contrast to reports from the southern U.S., amending the influent stoichiometric C:N:P ratio of the GAC biofilters to either 100:10:1 or 100:20:2 did not yield any improvements in DOC removal, regardless of operational season/water temperature. Thus, nutrient enhancement strategies may not be suitable for biological filters that operate in climates that experience short, or no periods of warm water conditions (such as all of Canada).

Figure 17 – Mean rate of head loss accumulation (± one standard deviation) at warm water conditions with the influent of Filters 2 and 4 nutrient-amended to a C:N:P ratio of 100:20:2.

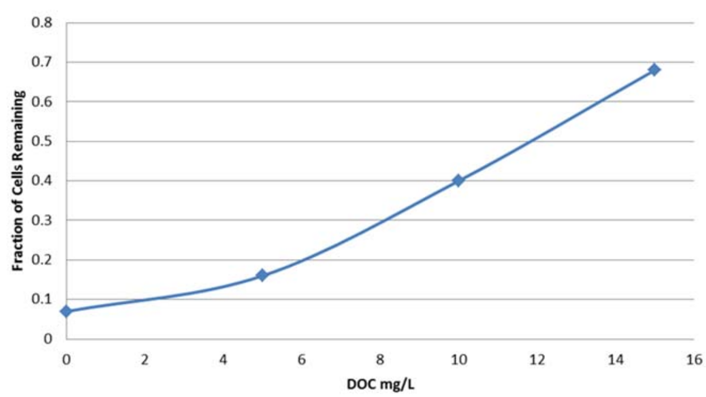


Increased nutrient runoff into water supplies may create favourable conditions for the growth of cyanobacteria and the harmful toxins that they may produce. While ozone is generally understood to effectively destroy many toxins during drinking water treatment, its efficacy can be adversely impacted by the presence of natural organic matter, often measured as dissolved organic carbon (DOC). As discussed above, the conditions that create favourable growth conditions for cyanobacteria, can also increase the concentrations of DOC in source waters.

A M.A.Sc. graduate student (Gemma Charlebois, completed 2016) investigated ozone's efficacy as a cyanobacterial toxin elimination technology in the presence of high DOC (~10 mg/L). The investigation included an assessment of the destruction of intracellular (within cells) toxin and extracellular (within water matrix) toxin. Bench-scale experiments were conducted. Both extracted toxin and cyanobacterial cells were added to coagulated/flocculated/clarified water from the Mannheim Water Treatment Plant in Kitchener, Ontario. Microcystin concentrations were measured by the ELIZA method and by liquid chromatography-mass spectroscopy-mass spectroscopy (LC-MS-MS). The study confirmed ozone could destroy extracellular Microcystin-LR to below 1.5 ppb at ozone residuals above 0.3 mg O_3/L when aqueous DOC concentration was below 5 mg/L. Notably, when *Microcystis aeruginosa* cells were present, an amount equivalent to only 50% of the concentration of extracellular Microcystin-LR was destroyed by ozone, demonstrating that significant oxidative capacity is required to lyse the cells before ozone can destroy intracellular toxin and the need to reassess operational requirements for ozonation for the treatment of cyanobacterial toxins when intact cells are present as opposed to extracellular toxin, which is used in most performance assessments.

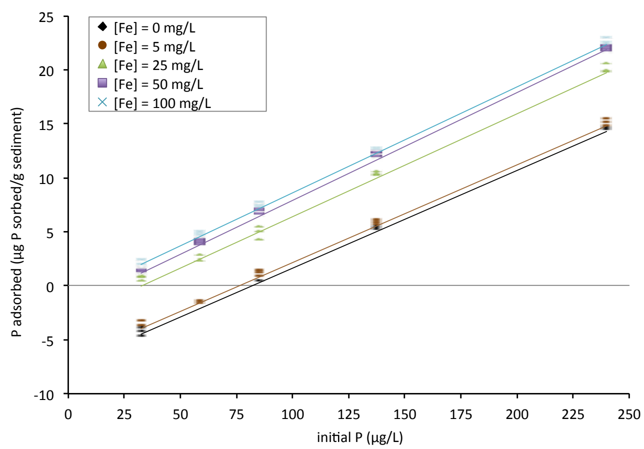
Critically, as the aqueous DOC concentration increased, the proportion of live cells present following ozonation (as measured by intercellular toxin concentrations) also increased (Figure 18). This showed that, not only does DOC decrease the efficacy of ozone in destroying toxin, it decreases its oxidative capacity to lyse cells; moreover, the rate is not directly proportional to the aqueous DOC concentration. As a result, a minimal effect of increases in ozone residual concentration on toxin destruction was demonstrated in these cases. Stated more simply, the levels of toxin destruction that would have been expected for comparable ozone residuals in absence of DOC (or when only low levels of DOC were present) were not achieved because of the significant oxidant/ozone demand of DOC when present at high aqueous (~10 mg/L) concentrations. This work further demonstrated that not all cyanobacterial cells were destroyed following ozonation; thus, they were described as "Damaged and Potentially Viable (DAPV)" cells. These cells were present at ozone residuals less than 0.45 mg O_3/L, logically suggesting that incomplete oxidative treatment occurs at lower ozone residual concentrations. Notably, these DAPV cells may have the potential to reproduce; given this and the common assessment of treatment performance using extracellular toxin, the efficacy and operational requirements of oxidative treatment of cyanobacterial and algal cells by ozonation may need to re-evaluated for situations in which live cells are being treated. These observations also underscored the need to more fully assess the significance of DAPV cells.

Figure 18 – Cell lysis by ozone according to DOC present in water matrix at all ozone residuals investigated (points are connected only to improve visualization of results)



The in-plant treatment of cyanobacteria and the toxins that they produce can be costly and challenging, particularly when source water quality has deteriorated (and DOC in particular is elevated). The capacity to prevent cyanobacteria proliferation in source water reservoirs is an attractive alternative to in plant treatment of cyanobacteria and their toxins. Given that fine cohesive sediment particles can carry significant loads of adsorbed phosphorus (P) that can desorb into the water column and enable the proliferation of cyanobacteria, strategies for mitigating rapid CB proliferation through sequestration of P were investigated by M.A.Sc. student Jill Crumb (completed 2016). The research examined the impact of managing dissolved and sediment-associated P for controlling CB growth and the utility of sequestering soluble reactive P (SRP) with a common metal salt coagulant, ferric chloride ($FeCl_3$) was investigated. Adsorption/desorption experiments demonstrated that a dose as low as 25 mg/L was effective in precluding SRP desorption from the sediment over a relatively wide range of solution SRP concentrations (Figure 19). Thus, such does offer a simple form of mitigating the risk of cyanobacteria blooms and toxin production in reservoirs where coagulant application is feasible during risk periods.

Figure 19 – Impact of $FeCl_3$ on P sorption dynamics in reservoir water and sediments



3.5.4. Economic implications

Potential economic consequences of management (task 9)

-Benefits/ costs of management alternatives on water supply interruptions & advisories (task 9.1)
-Impact of change in supply reliability of on treatment operating & infrastructure costs (task 9.2)
-Benefits/ costs of management alternatives on water supply in a water-short region (task 9.3)

A major component of Tasks 9.1 to 9.3 is the estimation of the benefits of improved water management. The benefits of source water protection include reduced chances of "water outages" associated with turbidity issues or other water quality problems that resulted in a water outage. Similarly a benefit of improved source water protection could include reduced numbers of communities with boil water advisories. Both issues were investigated by a M.Sc. graduate student (Alfred Appiah, completed 2016) outlined below.

Benefits of supply reliability
A province wide survey (including questionnaire development, focus groups, survey pilots) was used to assess the economic benefits of improved water reliability. A total of 1250 completed responses to the internet based survey were recorded. We oversampled rural communities given that these communities were more prone to water reliability problems than larger urban centres. The final set of respondents (weighted to adjust for over-sampling rural residents) is reasonably representative of Alberta's population in terms of observable characteristics (age, education, gender, etc.).

An important component of the benefits of water reliability improvements is that water outages are probabilistic, thus the analysis focused on the probability of water outages, and reductions in this probability. This necessitated an assessment of experiences with water outages (historical risk and perceptions of future risk. These perceptions typically drive behavior and are important elements of the analysis. The majority of Albertans experienced no water problems the year of the survey. Some experienced restrictions for construction projects, water shortages, or other short term activities. Table 13 outlines Albertan's experiences with outages in the past ten years. The low frequency of water outages or boil water advisories is remarkable and indicative of the quality of infrastructure and management of water resources in the province. However, as expected, a test of short term outages between rural and urban households indicated a significantly higher rate in rural Alberta.

Table 13 – Water outages experienced by Albertans in the past 10 years

Type of water outage	Number of times experienced			
	0	1-10	>10	Mean
Short-term unexpected water outage	63.84%	35.20%	0.16%	**0.97**
Longer-term unexpected water outage	84.92%	14.83%	0.24%	**0.38**
Boil water advisory	81.42%	18.25%	0.32%	**0.57**

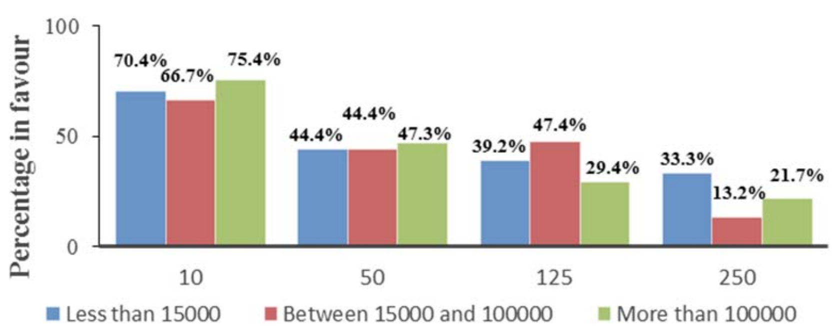
Respondents were also asked about their perceptions of the risk of water outages in the future (Table 14). Somewhat surprisingly given the low rate of historical outages Albertans are pessimistic about the future in terms of water reliability. There are no significant differences between rural and urban Albertans in terms of water reliability risk perceptions.

Table 14 – Perception of water outages in Alberta over the next 10 years (percent chance)

Water Outage /Expectation (%)	0	1-20	>20	Mean%
Short-term water outage	22.50%	48.67%	28.81	**24.40**
Longer-term water outage	45.56%	44.68%	9.76%	**8.37**
Boil water advisory	45.88%	41.47%	12.64%	**9.74**

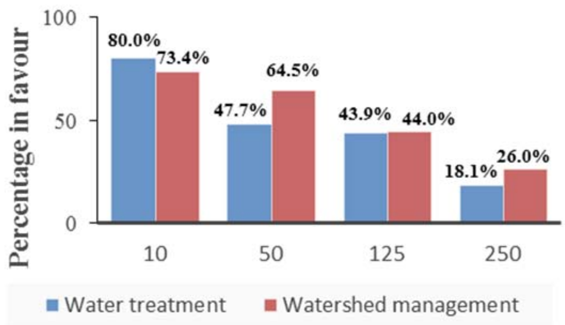
To construct an economic value of reducing the risk of water outages respondents were presented with a stated preference question framing the issue as a referendum on water infrastructure improvements. These are carefully designed and tested questions that attempt to minimize hypothetical bias and strategic behavior. The statistical analysis also incorporates a "spike' in the distribution associated with individuals who are not willing to pay anything for improved services (e.g. current services are sufficient). Figure 20 illustrates the proportion of Albertan's who are willing to pay various amounts of money for a program that reduced the probability of water outages by at least 50% (relative to their current perceived risk of outages). The proportion of those in favour of the program drops off considerably at amounts higher than 10% per year.

Figure 20 - Percentage of respondents' votes in favour of the proposed program in the CV scenario by bid amounts (increased water bill per year) and community size



Resident's preferences on the how increases in supply reliability could be achieved through use of "green" infrastructure (watershed management) versus "grey" infrastructure for water treatment was tested. There was no significant difference between the percentage in favour of either watershed management or technological (engineering) approaches (Figure 21).

Figure 21 – Percentage of respondents' votes in favour of the proposed program in the hybrid valuation scenario by bid amount and method of reliability improvement



Econometric analysis of the responses was conducted to reveal the public's willingness to pay for programs to reduce water reliability risks (Table 15). A number of different econometric methods were used to assess endogeneity of the risk perceptions, the potential difference between respondents who voted no even at low or zero cost, and other factors.

Table 15 – Mean willingness to pay (WTP) ($ / household / year) computed using parameter estimates from random effects probit models that used exogenous measures of risk reduction

	Short-term risk reduction	Joint risk reduction of short-term, longer-term and BWA
Full sample Mean WTP	$71.07	$98.99
	(10.65)	(10.60)
Respondents with >20 risk perceptions	$119.38	$156.88
	(24.88)	(25.69)
Rural Sample only	$89.84	$103.84
	(19.32)	(19.33)
Urban Sample only	$67.72	$98.11
	(13.26)	(13.05)

When extrapolated to a provincial level the lower bound estimates of the willingness to pay is approximately $100M/year (maximum willingness to pay to reduce the risk). These values can be used with reasonable accuracy to assess willingness to pay at the community level. For example, the annual economic benefits of improved reliability for the city of Edmonton would be approximately $20M per year. These values can be put into context by comparing them with the costs that would be required to achieve the outcome of reducing water outages by at least 50%.

Cost of ecosystem service provision for water (task 10)

The costs of ecosystem service provision in the context of this project can be categorized in two ways; a) directs costs of ecosystem service provision as an outcome of land management, and b) indirect costs associated with provision of non-market ecosystem services.

a) Forest management – The direct costs of ecosystem service provision are associated with the forest management costs of the different harvesting treatments. The differences in water provisioning services across different forest management regimes can be evaluated by comparing the water impacts (research Nodes 1-3) with the costs of the different forest management costs. These costs were tracked during the harvest operations in Star Ck. by Canadian Forest Products Ltd. and provided to the project team to enable these analyses and reformulated to enable an evaluation of comparative costs for each of the 3 alternative forest harvesting strategies applied in Star Ck. in 2015.

Because each of the three harvesting approaches required differing density access/haul roads, landings, along with differing requirements for felling, skidding, and de-limbing operations, harvesting costs varied considerably among clear-cut with retention, strip-shelterwood, and partial cut harvesting strategies. Because conventional clear-cut harvesting operations require the lowest road density and harvest operational time, clear-cut harvesting strategies result in the lowest cost per unit volume of wood ($\$/m^3$). Harvest costs were 17% higher for the strip- cut treatment (relative to a clear cut treatment) and 39% higher for a partial cut (50% removal) treatment (costs were measured in $/m3 and actual costs will be used in the on-going research but are not reported here due to confidentiality concerns. Note that the costs for the strip cut and partial cut treatments could be expected to decrease as equipment operators become more familiar with these harvest systems. This information is currently being used in the forest management model (task 11).

b) *Non-market ecosystem services*. The more challenging costs associated with the use of forest management in these regions for source water management are those associated with non-market ecosystem services. Forest management may have positive effects on non-marketed ecosystem services or negative effects. For example, forest management may provide access to recreationists for hiking, hunting or OHV use. Such actions may also result in erosion, congestion, or have other impacts on ecosystems and people (e.g. impacts on fishing quality or other recreational activities). However, forest management may also reduce water treatment costs if management results in improved water quality. The section below summarizes the analysis of the ecosystem service effects which focused on OHV use in the region.

Cost/benefits of management; incremental/opportunity costs (loss of ecosystem services)- (task 10.1)

Typical non-market activities potentially affected by changes in forest management include recreational activities such as hiking, hunting and fishing because the indirect outcome of harvesting operations on access to forests (scenery / surroundings) provided by forestry roads and trails. While some associated economic benefits and costs to environmental quality has been evaluated Alberta and Canada, the local-regional economic benefits/costs of off-highway vehicle (OHV) use in Alberta is largely unstudied. Two M.Sc. projects evaluated economic benefits (Sarah Prescott, completed 2017; results detailed below) and environmental costs to erosion and sediment production (Melissa Howard, detailed in task 3.1).

Regional field (in-person) and mail surveys indicate respondent's made 12,817 single- and multi-day trips to the Crowsnest Pass region for OHV based recreation with average per trip economic value ranging from $258/trip with a total economic value of $3,306,786 by the respondents in 2014 (Table 16). Of prime importance is the impact of forest management on OHV values.

Table 16 – Count model economic value measures: Per-trip values in 2014 (Canadian dollars)

Model	$/trip/household, (SE)
All individuals, all trip types	$258 ($29)
Individuals who prefer day trips	$211 ($40)
Individuals who prefer overnight trips	$314 ($55)

Two key findings arose from our research. First, historical forest harvesting (age since harvest) appeared to have no statistically significant impact on recreational values. This may be because of the particular harvesting pattern in the region, or because forest harvesting can create both positive and negative features for OHV users. Second, closures of areas to OHV use, depending on the area can have substantial economic impacts (Table 17).

Table 17 – Predicted economic impact ($/trip) of changes to staging areas in the Crowsnest Pass

	Large campsites near town	North C5	South C5	Porcupine Hills
Closure of Area	$38.18 ($5.39)	$6.66 ($2.82)	$7.73 ($1.54)	$2.00 ($1.07)
Closure of 50% of trails within 5 km of staging area	$18.97 ($2.09)	$2.57 ($1.01)	$4.53 ($0.88)	$1.26 ($0.67)

The benefits of improving water quality through forest management actions, as proxied by reductions in area burned and improvements in turbidity, were also examined by measuring water treatment

Elbow River case study on the impacts of wildfire on water treatment costs – A combination of water treatment plant operations data provided by Calgary Water Services and a water treatment plant operator survey across Alberta was used to estimate a cost function for the Glenmore Water Treatment Plant in Calgary for prediction of operational costs for water treatment related to variation in source water quality in the Elbow River. While there are numerous factors affecting treatment cost, this cost model was based on costs of chemical coagulants consumed during drinking water treatment. A land disturbance model developed by our team as part of allied wildfire research was used to predict the downstream change in source water turbidity from a range of upstream wildfire scenarios in the Elbow R. drainage. This framework was used to evaluate both the economic costs of water treatment from a range of potential wildfire scenarios, but also the potential avoided costs of drinking water treatment of potential forest management fuel-reduction treatments as a means of avoiding wildfire-related water treatment costs. Results from this evaluation suggest that a 1% increase in turbidity in the Elbow River increases water treatment costs by 0.11% and that if a fire were to burn 100% of the forested area in the Upper Elbow River Watershed, the additional water treatment cost over a 10-year period would be $491,170. However, these cost estimates reflect only the cost of coagulant consumption as predicted by our cost function on the existing high quality infrastructure and thus must be interpreted in that light.

Future cost/benefits of management alternatives (task 11)

The information above (forest management costs, water treatment costs, non-market benefits and costs) are being integrated into a model for forest dynamics to construct an analysis of alternative dynamic management strategies. While the delay in harvesting created delays in completing this component of the research, evaluation of these data and model development is underway and progress is reported on further in progress reports for the 2016-2019 AB. Innovates grant supporting this research program.

3.5.5. Knowledge Mobilization

Partner/Stakeholder Workshop (task 12)

A full-day field workshop on was held in the backcountry Star Ck. watershed on August 25, 2017 focused on SRWP Phase II and implications of early results (1st 1.5 yr. after harvesting) for source water protection and management in Alberta (Figure 22). Senior members 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, and 2 executive directors of companion divisions from AB. Environment and Parks and AB. Agriculture and Forestry along with senior management staff from participating agencies.

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 SWP 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 workshop in bringing together policy, governance, and professional public and private domains leading development of SWP initiatives in Alberta.

Figure 22 – Field workshop on source water protection and management.

Partner/Stakeholder Forum and SWP "white" paper (task 13/14)

While the scope of this project builds on the research teams prior research on wildfire, the project deliverables expanded well beyond the deliverables originally proposed to now include nearly the full scope of land management pressures being experiences in Alberta's critical Rocky Mountain source water region including catastrophic natural disturbance by both wildfire and extreme wildfire along with evaluation of both legacy effects of historic forest harvesting and the alternative contemporary harvesting practices that were originally proposed. Given the particularly high public, municipal, industrial and policy focus on source water protection in Alberta, the research team believes the early-preliminary results from harvesting research do not yet fully support the strong, science-based inferences needed for a "white" paper which would likely have significant implications on the future trajectory of source water protection strategies in this critical region. As the work reported on herein is continuing with support from Alberta Innovates in a companion grant (2016-2019), we expect that more robust science-based inferences needed to support a "white" paper on source water protection in Alberta will be possible near the end of this companion project.

4. Relevance and Impact

While this project has delivered an exceedingly broad spectrum of science, engineering, and economic research producing both significant impact to the science and management knowledge in each of the four research domains and to the broader research objectives in each of the four research themes needed to provide the transdisciplinary insights to inform SWP in Alberta. An abstracted listing of some of the more important insights are outlined below.

4.1. Three most important lessons learned from each of the four research themes

Disturbance effects in Rocky Mountain source water landscapes

1. The hydrologic resistance of Alberta's Rocky Mountain source water landscapes to changes in streamflow after land disturbance is much greater than previously thought. Perhaps the most severe land disturbance possible in this region, the 2003 Lost Ck. wildfire, produced almost no detectable change on streamflow including the occurrence of large peakflows. Initial results show the effects of forest harvesting produced either no detectable changes in flow or smaller changes in flow closer to the margins of detection for three different harvesting strategies under the most carefully gauged research conditions. None of these produced any detectable changes in flow downstream at larger watershed scales. Science-based observations of the hydrologic resistance to disturbance in this region by this study and others have important for land management and policy where likelihood of these impacts has been previously assumed.
2. Impacts of land disturbance on water quality in the Rocky Mountain region are highly variable ranging from little to no effect on some water quality parameters (i.e. water temperature) to very large effects on others (sediment, phosphorus). Natural disturbances from both wildfire and floods produce impacts on key water quality parameters an order of magnitude greater than both undisturbed watersheds and those disturbed by forest harvesting. This finding very clearly illustrates the risks to source water quality from climate change associated increases in these types of natural disturbance. Compared to undisturbed forests, forest harvesting impacts on water quality can range from moderate to no evidence of detectable impacts when harvest operations are conducted with a suite of best management practices for erosion control.
3. Land disturbance effects on the aquatic ecology of mountain streams are affected by phosphorus associated with sediment. Because phosphorus limits aquatic productivity in Alberta's mountain streams which are typically very nutrient poor, smaller changes in sediment production can increase phosphorus thereby increasing stream productivity as reflected in increased growth of algae. This, which in turn, affects other organisms such as aquatic insects and fish by increasing growth of abundance of these organisms which also causes some shifts in species/taxa present at the community level. While these effects were very large after wildfire, preliminary results suggest no effect or effects near the margin of detection 2 years after forest harvesting. This was because harvesting produced essentially no or very small effects on sediment and phosphorus.

Downstream propagation of disturbance effects

4. Land disturbance in Alberta can have substantially longer-term impacts on water quality than in many other regions of Canada or elsewhere in North America. This is because many of the water quality constituents of concern are associated with fine sediment which is abundant in Alberta because of its sedimentary geology and glacial history. Because of this, land disturbance impacts on the storage and transport of fine sediments along with their impacts on water quality can be much greater than in other regions of North America. Furthermore, storage of fine sediments in river beds can also cause these effects to persist much longer and be transported much further downstream than other regions.

5. Current frameworks to evaluate cumulative watershed effects from multiple, overlapping land use pressures do not provide the quantitative cause and effect linkages to guide policy or improve practice. However, the sediment/contaminant modeling framework developed in this project provides a powerful, transferrable, and quantitative approach to support the evaluation and management of cumulative watershed effects assessment platform for broader, strategic regional planning (e.g. Land Use Framework).
6. Many of the water treatment challenges experienced by drinking water treatment systems are closely related to phosphorus associated with deposition of fine sediments in water supply reservoirs. This has enabled the potential for developing reservoir management strategies that municipalities did not previously recognize as part of a suite of strategies available to them to manage reservoir water quality to mitigate changes in broader source water quality. Research on evaluating several of these strategies (intake management, dredging others) is on-going.

Drinking water treatment

7. Land disturbance can produce impacts to water quality that can create additional challenges to drinking water treatment processes. In particular, wildfires increase both turbidity and DOC which are primary drivers of drinking water treatment. However, wildfire associated changes in the chemical character of DOC has the potential to further increase treatment challenges with respect to solids removal, disinfection by-product formation potential, and other processes important in drinking water treatment. Moderate to large increases in treatability parameters were in burned and burned + salvaged logged watersheds (respectively) were still evident >10 years after the Lost Ck. wildfire suggesting impacts from fire on drinking water treatability may be very long lasting.
8. Effects of forest harvesting on drinking water treatability was quite variable. Impacts of historic harvesting on treatability were surprisingly similar to wildfire despite the fact that the harvesting occurred 20-40 years earlier. In contrast, contemporary forest harvesting practices investigated in this project were found to have effectively no impact on the treatability parameters studied. The reasons for the longevity of historic harvesting impacts are not known.
9. Despite the finding of variable impacts of land disturbance to drinking water treatability, drinking water treatment processes in Alberta are generally resilient to fluctuating source water quality. However, numerous options have been explored and developed in this project to further improve drinking water treatment resilience including enhanced chemically assisted solids removal and disinfection processes. Other potentially promising technologies related to reservoir management including ferric chloride coagulation to mitigate the risk of cyanobacteria blooms and toxin production in reservoirs appear to be feasible options during higher risk periods.

Economic implications of source water protection strategies

10. Albertans have generally had very reliable drinking water supplies in the past, yet their expectation is that drinking water supply will be less reliable in the future. This suggests Albertans are willing to invest in market goods or programs that will avoid water reliability challenges (supply outages) in the future.
11. Albertans have no preferences on how improvements in reliability are achieved through either investment in treatment technology (grey infrastructure) or investments in source water protection (green infrastructure) but their willingness to pay to improve reliability is modest (average $70/yr per household). If water quality impacts were to differ strongly among forest management strategies, the incremental costs of some strategies such as partial cutting are substantially greater than conventional clear-cut harvesting with retention. These incremental

management costs that would require broader evaluation of total benefits to society (water, recreation, etc.). However, because grey infrastructure in our case study was resilient to water quality change (using turbidity), the marginal cost of water treatment with changing source water turbidity was relatively low.

12. One non-market value indirectly affected by forest management (OHV use by the public) generates significant economic value for local economies in S. Alberta and these recreational values do not appear to be affected by historical harvesting patterns or their locations. However the economic impact of OHV closures in the Crowsnest Pass region would likely be an order of magnitude greater than in other areas such as the Porcupine Hills. Corollary research on erosion and sediment impacts of OHV trails has developed models for the broader regional evaluation of sediment risk from OHV trail and road networks.

4.2. <u>Implications of this project to source water protection in Alberta</u>

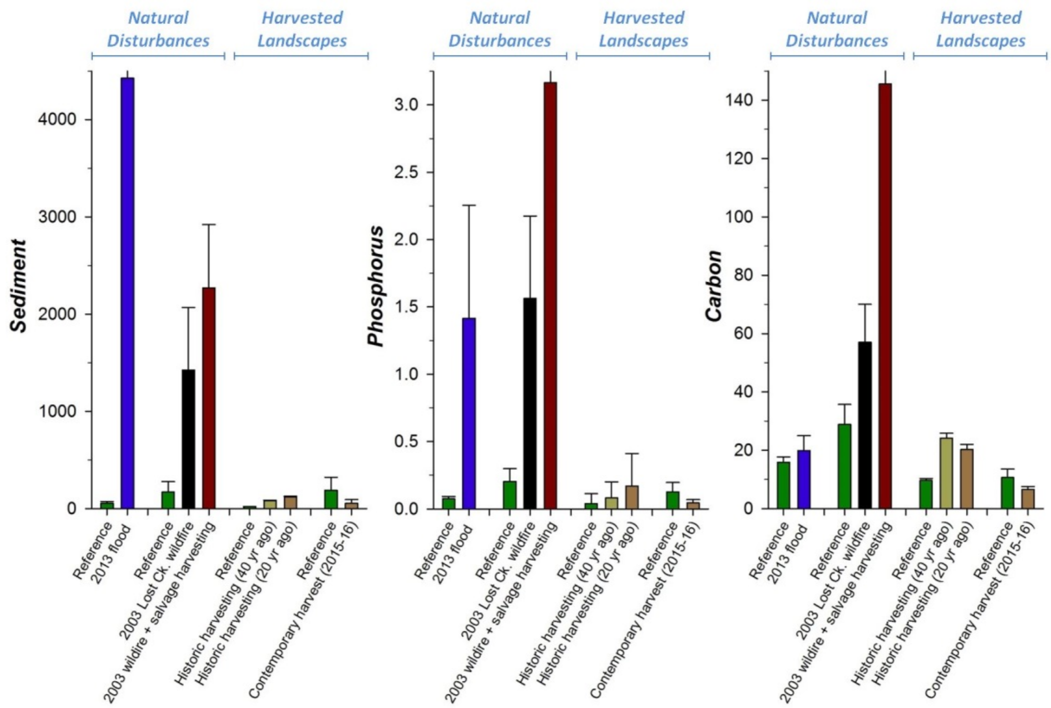
The implications of this project to informing source water protection policy and practice is reflected in the broader transdisciplinary insights across the four research themes spanning the diversity of governance, policy and practice domains that need to be integrated in provincial source water protection strategies. The concept at the foundation of our project approach is the recognition that the majority of water supply supporting Alberta's environmental, social, and economic sustainability originates from the forested regions of Alberta's Rocky Mountains while a common perception of source water protection strategies is to prevent or exclude land disturbance thereby protecting supplies, an important paradox is that protection strategies that minimize land disturbance over decades promote older forest landscape structures that are more vulnerable to catastrophic land disturbances from wildfire, forest insects, etc. Moreover, the potential severity of such natural disturbances may be greater where old forests with greater fuel loading (in the case of wildfire) with potentially more severe impacts to water. Increasing natural forest disturbance because of climate change is amplifying this risk in Alberta.

While more ecologically resistant and resilient forest conditions reflecting a more diverse forest age class distribution (with potentially positive implications for water resources) is typically an allied strategic outcome of integrated forest management, comparative impacts of forest management through harvesting on key water values in this region were not well known, thus the comparative risks and benefits to water resulting from "active", integrated source water protection strategies involving forest management could not be evaluated.

By building upon the investments and information generated from our previous research, the additional insights enabled by this project provide the first solid scientific data available anywhere world-wide on this problem. These integrated insights are effectively captured in Figure 22.

Sediment, phosphorus, and dissolved organic carbon play keystone roles regulating stream/river health, and human uses of water such as drinking water, thus these water quality constituents can be considered parsimonious proxies for the importance of water quality to Alberta's environment, society, and economy. For example, phosphorus is a keystone regulator of aquatic health with strong social and economic implications, while sediment and carbon govern production of safe drinking water supplies supporting Alberta's population and economy. Thus, this effectively captures our project results with respect to risks, trade-offs, and strategies for effective source water protection in the critical water supply region as follows;

Figure 22 – Impact of natural disturbance from floods, fire, and forest harvesting on three primary water quality attributes important for Alberta's environment, society, and economy. Values reflect mean flow-area-weighed production of sediment, phosphorus, and carbon (kg/ha/yr) from affected streams over 2 full years after disturbance.



a) Firstly, this is the 1st quantitative, comparative summary of risk to water from climate associated impacts from floods and wildfire showing that severe natural disturbances can produce catastrophic impacts to water orders of magnitude greater than what is typical from undisturbed forest landscapes. These risks are real and it is particularly notable that our study documented the breadth of water impacts from both of these climate associated natural disturbances in a small region of southwest Alberta in relatively short 11 yr. period.

b) Secondly, these natural disturbances do not affect water supplies in the same way; floods producing extreme impacts on sediment, moderate effects on phosphorus, and little if any impact to carbon, whereas fires have large impacts on sediment with somewhat larger impacts on phosphorus and carbon. Thus, these two natural disturbances would have meaningfully different implications for Alberta's environment, social outcomes, and economy..

c) Lastly, while the impacts to water from natural disturbances can be catastrophic, impacts of forest management through harvesting on water is an order of magnitude lower.

This, along with the more detailed project results, and the broader scientific literature provide the scientific basis for the following implications for source water protection strategies in Alberta's Rocky Mountain region.

d) Higher risks from natural disturbances because of the combination of both vulnerable source water landscape forest structure and climate driven increases in frequency/severity of disturbance is well established in the scientific literature. Resistant and resilient landscape structure (structure and diversity of forest age classes) mitigate some of that risk, but it is unlikely that these risks can be entirely avoided.

    i. While it is unclear if landscape resilience would mitigate some of the initial impacts from flooding, resilient landscapes are likely to promote more rapid or effective post-disturbance recovery
    ii. The reduction in fire risk in more resistant-resilient landscapes is much better established in the in the scientific literature.

e) Forest management through forest harvesting can produce impacts on water (though much smaller) or alternatively, no detectable impacts on water. This means that best management practices can meaningfully reduce or avoid those impacts.
    i. A surprisingly long lasting legacy of water impacts from historic harvesting was observed > 40 yr. after harvesting with larger effects from comparatively more recent, but still > 20 yr. old. These may be a reflection of variable or uncertain application of best practices for erosion control measures at the time of these historic forest harvesting operations.
    ii. The impact of the three alternative contemporary harvesting practices evaluated in this project produced effectively no impact on water quality. However, caution in drawing broad conclusions based on only 2 years of post-harvest study is warranted. Additional years of study are needed to support such conclusions
    iii. This supports the initial conclusion that effective policies, operating ground rules for forest harvesting operations, and careful application of best management practices for erosion control can be successful in minimizing or reducing the impact of forest harvest to below detection limits.

f) 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 rapid water quality change

5. Overall Conclusions

Prior to this project, while the risks to water from wildfire were well understood from our earlier work on the Lost Ck. wildfire, impacts of flooding to the diversity of water values being investigated in this study were largely unknown. Furthermore, the comparative impacts of several alternative strategies for forest harvesting on key water values had also not been comprehensively documented in this critical source water supply region.

This work has conducted a full comparative study of how multiple land disturbances affect key water resource values (hydrology, water quality, aquatic ecology) in both source headwater regions, evaluated the differential prorogation of these effects downstream, and evaluated the effect of these changes on drinking water. Some of the key economic implications, costs, and benefits of alternative source water protection strategies have also been explored.

Developing integrated source water protection strategies in Alberta presents a formidable challenge because of highly 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 insights into the many of the most challenging unanswered questions that served as important knowledge gaps prior to this project.

6. 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.

Most importantly, the assessment of comparative impacts of the three contemporary harvesting practices evaluated herein (clear-cut, strip-shelterwood, and partial cut harvesting) cannot reasonably be evaluated in only two years because disturbance effects on the full scope of water values vary strongly in response to fluctuating weather and climate from year to year. A minimum of 4-6 years is required to support meaningful inferences on the comparative effects of these disturbances. While the watershed study design employed in this study (before:after, control:impact) is the most powerful approach to evaluate these effects, several additional years of measurements are needed to produce the defendable scientific insights needed to evaluate these effects. Secondly, the development of effective forested SWP strategies will be meaningfully advanced with the parallel evaluation or development of best practices to minimize adverse impacts of forest management based SWP strategies.

Both of these components along with continued research on the same suite of research tasks as the present project are being researched in the companion AI research project (2016-2019).

7. Communications Plan

The research team has remained in close communication with project partners throughout this project and this will continue in the next phase of the research.

Given the particular importance of SWP to both AB. Environment and Parks / AB. Agriculture and Forestry, as a follow-up to last year's field based workshop we are planning 1-2 meetings with GoA partners contingent on schedule and availability of key members of the executive branch of both ministries. Meetings will provide a high level, shorter briefing of key project results to the executive branch and a longer workshop reporting on the full scope of the project results to management staff from both ministries and Calgary Water Services. This will occur in late summer / early fall 2017.

We also anticipate the submission of several refereed scientific publications that are in the latter stages of preparation including:

Three publications focused on nutrient, carbon, and sediment production after forest land disturbance, 1 focused on post-disturbance metal toxicity after forest land disturbance, and 1 reporting on results of the coupled sediment transport modeling framework. These will be followed by 2 additional manuscript submissions that are well under way, but not yet at late stages for manuscript submission - both of these are focused on hydrologic resilience after forest land disturbance

8. **Scientific Achievements** (student names bolded)

8.1. Important scientific, knowledge mobilization events, and distinctions

8.1.1. Significant knowledge mobilization activities

- 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, 2017.
- Participated as Expert Panel member (Emelko) on "Achieving Resilience: Preparation, Response and Recovery from Water Crises" at Canadian Water Network, Blue Cities, Toronto, ON., May 17-18, 2017.
- Participated on Expert Panel (Emelko MB) on "Impacts and Risk Identification for the New Normal" at Canadian Water Network, Blue Cities, Toronto, ON., May 18-19, 2016.
- Co-organized and delivered a nationally broadcast Webinar ("Changing climate, watershed disturbance and potential risks to municipal waterworks systems in Canada") hosted by the Canadian Water Network on Nov. 3, 2015. This sold out webinar included approximately 100 participants from across Canada.
- Co-organized and co-delivered a full day national training workshop on water utility preparedness responding to extreme events (including wildfire, flooding, etc.) at the Canadian Water & Wastewater Association, National Water & Wastewater Conference in Whistler, B.C., Oct. 22-18, 2015. Continuing education units (CEU's) for utility operators were offered for participants.
- Co-organized and co-delivered a full day practitioner workshop entitled "Fires, Floods and Other Extreme Events: Is Your Utility Ready?". Alberta Water and Wastewater Operators Association Conference, Banff, AB, March 9, 2015.
- Held a major partner/stakeholder workshop – "Southern Rockies Watershed Project - a decade of integrated water science and engineering research". Hosted by the City of Calgary, this meeting was attended by 85 government and industrial partners/stakeholders from 4 GOA Ministries, City of Calgary, Municipality of Crowsnest Pass, Stantec Eng., Associated Eng., Spray Lk. Sawmills, West Fraser Sundre, Oldman and Bow R. Basin Watershed Councils, and Parks Canada. June 2014.
- Co-organized a Wildfire-Water Experts' Workshop on state of knowledge on wildfires, water supplies, and the potential for mitigation of the impacts of wildfire on the provision of safe drinking water. Canadian Water Network and American Water Works Association: Water Research Foundation, Kananaskis, AB., Sept. 18-19, 2013.
- Co-organized an American Geophysical Union Chapman Expert Conference on Wildfire, Erosion, & Sedimentation, Estes Park, Colorado, USA., Aug. 25-31, 2013

8.1.2. Research Team Awards and Recognition

- *Letter of appreciation and recognition for outstanding service to Albertans, commendation certificate, and medallion for Ft. McMurray wildfire recovery.* Presented to Monica Emelko and Uldis 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.
- *2014 Canada Council of the Federation – Excellence in Water Stewardship Award.* Presented to the Southern Rockies Watershed Project team by Hon. Kyle Fawcett, Minister of Alberta Environment and Sustainable Resource Development, Edmonton, AB, Nov. 2014.
- *2014 Alberta Emerald Award – 2014 Challenge Award: Water.* Presented to the Southern Rockies Watershed Project team. Alberta Emerald Foundation, Calgary AB, June, 2014.

8.1.3. Graduate Student Awards

- 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.
- Sheena Spencer (University of Alberta) was awarded the "Most Innovative Student Presentation Award" at the IUFRO 4th International Conference, Forests and water in a changing environment, Kelowna, B.C., July 6-9, 2015.

8.1.4. Field based workshops

- Field workshop on SRWP Phase II and implications of early results (1^{st} 1.5 yr. after harvesting) for Source Water Protection and Management. AB. Agriculture and Forestry, AB. Environment and Parks, AB. Innovates, City of Calgary Water Services, and Canadian Forest Products Ltd. Workshop participants included Deputy Minister AB. Environment and Parks and three Assistant Deputy Ministers from AB. Environment and Parks and AB. Agriculture and Forestry along with members of executive/senior management staff from participating agencies. August 25, 2017.
- Field tour for Municipality of Crowsnest Pass councilors on Southern Rockies Watershed Project Phase II, August 27, 2015.
- Field tour for AB. Environment and Parks Regional Biologists on Southern Rockies Watershed Project Phase II, August 26, 2015.
- Field tour for AB. Environment and Parks Planning Branch on Southern Rockies Watershed Project Phase II, August 12, 2015.
- Field tour for the Oldman Watershed Council on Southern Rockies Watershed Project Phase II, July 15, 2015.

- Field tour for AB. Environment and Sustainable Resource Development executive (Asst. Deputy Minister, Exec. Director Forest Management Branch) and senior regional managers on Southern Rockies Watershed Project Phase II, April 24, 2015
- Field tour for AB. Environment and Sustainable Resource Development regional management staff on Southern Rockies Watershed Project Phase II, April 24, 2015

8.2. Refereed Publications

Price J, Renzetti S, Dupont D, Adamowicz W, & Emelko MB. 2017. Production costs, inefficiency, and source water quality: A stochastic cost frontier analysis of Canadian water utilities. Land Economics 93:1-11.

Jin C, Zhao W, Normani S, Zhao P, Emelko MB. 2017. Synergies of media surface roughness and ionic strength on particle deposition during filtration. Water Research. 114: 286-295.

Emelko MB, Stone M, Silins U, **Allin D**, Collins AL, **Williams CHS**, **Martens AM**, & Bladon KD. 2016. Sediment-phosphorus dynamics can shift aquatic ecology and cause downstream legacy effects after wildfire in large river systems. Global Change Biology 22:1168-1184.

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.

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

Jin C, Ren CL, & Emelko MB. 2016. Concurrent Modeling of Hydrodynamics and Interaction Forces Improves Particle Deposition Predictions. Environ. Sci. Technol. 50:8:4401-4412.

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.

Mahat V, Anderson A, & Silins U. 2015. Modelling of wildfire impacts on catchment hydrology applied to two case studies. Hydrological Processes 29: 3687-3698.

Kazemzadeh F, **Jin C**, Molladavoodi S, Mei Y, Emelko MB, Gorbet MB, & Wong A. 2015. Lensfree Spectral Light-field Fusion Microscopy for Contrast- and Resolution-enhanced Imaging of Biological Specimens. Optics Letters. 40:16:3862-3865.

Jin C, Normani S, Emelko MB. 2015. Nano-scale roughness impacts on granular media filtration at favorable conditions. Environ. Sci. Technol. 49:13:7879–7888.

Bladon KD, Emelko MB, Silins U, & Stone M. 2014. Wildfire and the future of water supply. Environmental Science & Technology 48:8936–8943. (*Feature article w/cover*)

Emelko MB and Sham CH. 2014. Wildfire impacts on water supplies and potential for mitigation. Synthesis of state of science from "2014 Expert Workshop on Wildfire Impacts on Water Supplies", Kananaskis, AB, Sept. 18-19, 2013. 33 p. Canadian Water Network and Water Research Foundation, June 2014.

Glasbergen K, Stone M, Krishnappan B, Dixon J, & Silins U. 2014. The effect of coarse gravel on cohesive sediment entrapment in an annular flume. IAHS Redbook Series 367:157-162.

Wagner MJ, Bladon KD, Silins U, **Williams CHS**, Boon S, **MacDonald RJ**, Stone M, Emelko MB, **Martens AM**, & Anderson, A. 2014. Catchment-scale stream temperature response to land disturbance by wildfire governed by surface-subsurface energy exchange and atmospheric controls. Journal of Hydrology 517:328-338.

Silins U, Bladon KD, Kelly EN, **Esch E**, Spence JR, Emelko MB, Boon S, **Wagner MJ**, **Williams CHS**, & **Tichkowsky I**. 2014. Five-year legacy of wildfire and salvage logging impacts on nutrient runoff and aquatic plant, invertebrate, and fish productivity. Ecohydrology 7:1508-1523.

MacDonald, RJ, Boon S, & Byrne JM. 2014. A process-based stream temperature modelling approach for mountain regions. Journal of Hydrology 511:920–931

MacDonald, RJ, Boon S, Byrne JM, & Silins U. 2014. A comparison of surface and subsurface controls on summer temperature in a headwater stream. Hydrological Processes 28:2338-2347

Dixon D, Boon S, & Silins U. 2014. Watershed-scale controls on snow accumulation in a small montane watershed, southwestern Alberta, Canada. Hydrological Processes 28:1294-1306.

MacDonald, RJ, Boon S, Byrne JM, Robinson MD, & Rasmussen JB. 2014. Potential future climate effects on mountain hydrology, stream temperature, and native salmonid life history. Can. J. Fish Aquat. Sci. 71:189-202.

Stone M, Collins AL, Silins U, Emelko MB, & Zhang YS. 2014. The use of fingerprints to quantify sediment sources in a wildfire affected landscape, Alberta, Canada. Science of the Total Environment 473-474:642-650.

8.3. Papers at Scientific Meetings, Conferences, & Symposia

8.3.1. Papers at by principal research team

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.

Silins U, Emelko MB, Bladon KD, Stone M, **Williams CHS**, **Martens AM**, & Wagner MJ. 2015. Longer-term Stream Nitrogen Dynamics after Wildfire and Salvage Harvesting: Implications for Management Concepts based on Trajectories of Post-disturbance Watershed Recovery, Abst. H31D-1439, American Geophysical Union Fall Meeting, San Francisco, CA, Dec. 13-16, 2015.

Emelko MB, Silins U, & Stone M. 2015. Wildfire examples: What we wish we'd known and what we've done, Can. Water & Wastewater Assoc., National Water & Wastewater Conference, Whistler, B.C., Oct. 22-18, 2015.

Silins U, Emelko MB, Stone M, Bladon KD, & Anderson A. 2015. Extreme events: Is this really the new normal?, Can. Water & Wastewater Assoc., National Water & Wastewater Conference, Whistler, B.C., Oct. 22-18, 2015.

Stone M, Silins U, Emelko MB, **Allin D**, Collins AL, Krishnappan B, **Williams CHS**, **Martins AM**, & Bladon KD. 2015. Does what happens on the pile of rocks really affect me?, Can. Water & Wastewater Assoc., National Water & Wastewater Conference, Whistler, B.C., Oct. 25-28, 2015.

U Silins, Emelko M, Flannigan M, Dupont D, Bladon K, Wang X, **Robinne F**, Parisien MA, Adamowicz W, Renzetti S, Tymstra C, Schroeder D, Thompson D, de Groot B, Kienzle S, Reid D, Wolford D, Stone M, Waddington M, Devito K, & Wotton M. 2015. Mitigating the impacts of events 1: Active source water protection through watershed management, Can. Water & Wastewater Assoc., National Water & Wastewater Conference, Whistler, B.C., Oct. 25-28, 2015.

Emelko MB, Silins U, Stone M, **Shams S**, **Williams CHS**, **Martens AM**, **Geng K**, & Wagner MJ. 2015. Fires and Floods: Expected and Unexpected Differences and Impacts on Treatability, Can. Water & Wastewater Assoc., National Water & Wastewater Conference, Whistler, B.C., Oct. 25-28, 2015.

Stone M, Silins U, Emelko MB, Bladon KD, **Martens AM**, **Williams CHS**, & Collins AL. 2015. Exploring the linkage between fine sediment, phosphorus and stream ecology in wildfire impacted watersheds, 9th International SedNet conference, Krakow, Poland, Sept. 23-26, 2015.

Bladon KD, **Puntenney KC**, & Silins. 2015. Runoff and sediment transport through riparian buffers following forest harvesting of a Rocky Mountain headwater catchments. NCASI Forest Watersheds Science Symposium, Vancouver, USA, Sept. 23, 2015. (***Invited***)

Emelko MB, **Shams S**, Silins U, **Williams CHS**, & **Martens AM**. 2015. Approaches for characterizing landscape disturbance impacts on NOM: A wildfire case study. International Water Assoc. Specialist Conf. on Natural Organic Matter in Water, Malmö, Sweden, Sept. 7-10, 2015.

Bladon KD, Silins U, Wagner MJ, **Williams CHS**, **Martens AM**, Stone M, & Emelko MB. 2015. On the complexity of catchment-scale stream temperature response to land disturbance by wildfire and post-fire salvage logging in the Rocky Mountains. Am. Fisheries Soc., 145th Annual Meeting, Portland, Oregon, Aug. 16-20, 2015.

Diiwu J. 2015. Decision framework for post-wildfire salvage logging to protect watershed values in Alberta. IUFRO 4th Int. Conf., Forests and water in a changing environment, Kelowna, B.C., July 6-9, 2015.

Stone M, Silins U, Emelko MB, **Martens AM**, **Williams CHS**, Bladon KD, & Collins AL. 2015. Long term impacts of severe wildfire and post-fire salvage logging on sediment production in the Rocky Mountain headwaters of the Oldman River Basin, Alberta. International Union of Geodesy & Geophysics, 26th General Assembly, Prague, Czech Republic, June 22-July 2, 2015.

Anderson A, Wagner MJ, **Hirshfield F**, **Howard M**, Silins U, Benda LE. 2014. Combining field and modeling tools as an approach to assess cumulative surface erosion in Alberta eastern slopes and foothills. Abstract H51G-0687, AGU 2014 Fall meeting, San Francisco, CA, USA, Dec. 15-19, 2014.

Silins U, Bladon KD, **Williams CHS**, **Martens AM**, Wagner MJ, Emelko MB, & Stone M. 2014. Impacts of wildfire and salvage harvesting on stream nitrogen across nine years of watershed research. Abstract H51I-0729, American Geophysical Union 2014 Fall meeting, San Francisco, CA, USA, Dec. 15-19, 2014.

Bladon KD, Silins U, Emelko MB, Flannigan MD, Dupont DP, **Robinne F**, Wang X, Parisien MA, Stone M, Thompson DK, Tymstra C, Schroeder D, Kienzle SA, & Anderson A. 2014. Assessing the impact of active land management in mitigating wildfire threat to source water supply quality. Abstract H54D-04, American Geophysical Union 2014 Fall meeting, San Francisco, CA, USA, Dec. 15-19, 2014.

Silins U, Stone M, **Hawthorn K**, **Allin D**, Emelko MB, Bladon KD, **Martens AM**, **Williams CHS**, Anderson A, Collins AL. 2014. Channel storage of sediment-phosphorus governs legacy forest disturbance effects on stream benthos decades after wildfire and forest harvest. ICCE/IAHS 2014 Symposium, New Orleans, LA, USA, Dec. 11-14, 2014.

Emelko MB, Stone M, Silins U, & Bladon KD. 2014. Wildfire impacts on sediment and nutrient storage and downstream delivery to drinking water treatment plants. Int. Commission on Continental Erosion / Int. Assoc. of Hydrologic Sciences 2014 Symposium, New Orleans, LA, USA, Dec. 11-14, 2014.

Emelko MB, Silins U. 2014. Forests, wildfire, and drinking water security: A mandate for active source water protection. Wildland Fire Canada: 2014 Conference, Halifax, NS, Oct. 7-9, 2014. (Invited Plenary)

Silins U, Bladon KD, **Wang X**, **Robinne F**, Emelko MB, Flannigan M, Dupont D, Parisien MA, Renzetti S, Tymstra C, Schroeder D, Thompson D, de Groot B, Kienzle S, Wolford D, Stone M, Waddington M, Devito K, Wotton M. 2014. Management of wildfire risk to downstream municipal drinking water treatment in Alberta. Wildland Fire Canada: 2014 Conference, Halifax, NS, Oct. 7-9, 2014.

Silins U, Emelko MB, Bladon KD, & Stone M. 2013. Assessing wildfire impacts on water quality and treatability: Which effects are attributable to wildfire? Water Quality and Technology Conference 2013, American Water Works Association, Long Beach, CA, November 3-7, 2013.

Emelko MB, Silins U, Bladon KD, & Stone M. 2013. Post-fire DOC, DBPs and nutrients: Justifying and achieving robust treatment. Water Quality and Technology Conference 2013, American Water Works Association, Long Beach, CA, November 3-7, 2013

Bladon KD, Silins U, Flannigan MD, Emelko MB, Dupont DP, de Groot B, Kienzle SW, Parisien MA, **Robinne F**, Schroeder D, Stone M, Thompson DK, Tymstra C, Wang X, Waddington JM, Woolford DG, & Wotton BM. 2013. Minimizing wildfire risk to municipal water works by active source water protection. Water Quality & Technology Conf. 2013, American Water Works Assoc., Long Beach, CA, November 3-7, 2013.

Stone M, Silins U, Emelko MB, Krishnappan BG, Collins AL, Bladon KD, & **Williams CHS**. 2013. Assessing downstream propagation of wildfire impacts on water quality. Water Quality and Technology Conference 2013, American Water Works Association, Long Beach, CA, November 3-7, 2013.

Emelko MB, Geng X, Shams S, Bladon KD, Silins U, Stone M, **Williams CHS**, Wagner MJ, & **Martens AM**. 2013. Forested catchment fire and post-fire management: Implications to NOM character and treatability. NOM 2013 - Natural Organic Matter Specialist Conf. Int. Water Assoc., Perth, Australia, October 1-4, 2013.

Silins U, Flannigan MD, Waddington JM, Devito KJ, Stone M, and Bladon KD. 2013. High latitude post-wildfire response domains: Montane, Boreal, and Taiga. Synthesizing empirical results to improve predictions of post-wildfire runoff and erosion response, American Geophysical Union: Chapman Conference, Estes Park, CO, August 25-31, 2013. (invited)

Stone M, Silins U, Emelko MB, Bladon KD, Krishnappan BG, Collins AL, & Droppo IG. 2013. Biological modification of sediment transport processes in wildfire impacted river systems. Synthesizing empirical results to improve predictions of post-wildfire runoff and erosion response, American Geophysical Union: Chapman Conference, Estes Park, CO, August 25-31, 2013.

Silins U, Bladon KD, Wagner MJ, **Williams CHS**, **Martens AM**, Stone M, Emelko MB, Anderson A, Collins AL, & Krishnappan BG. 2013. Shifting disturbance regimes in forested source waters in Alberta: Long-term impacts of wildfire on water quantity, quality, & stream ecology. Healthy Forests = Healthy Waters specialty conference, Am. Water Res. Assoc., Hartford, CT, June 27-28, 2013.

Emelko MB, Silins U, Stone M, Bladon KD, Wagner MJ, **Williams CHS**, & **Martens AM**. 2013. Long-term implications of wildfire to drinking water treatment. Healthy Forests = Healthy Waters specialty conference, Am. Water Res. Assoc., Hartford, CT, June 27-28, 2013.

Stone M, Krishnappan BG, Silins U, Emelko MB, Collins AL, & Bladon KD. 2013. Modeling flow and sediment transport in three rivers and a reservoir in the upper basin of the Oldman River in Alberta. Healthy Forests = Healthy Waters specialty conference, Am. Water Res. Assoc., Hartford, CT, June 27-28, 2013.

Bladon KD, Silins U, Flannigan MD, Emelko MB, Dupont DP, Kienzle KW, Parisien MA, Schroeder D, Stone M, Thompson DK, Tymstra C, Waddington MJ, Wang X, Woolford DG, and Wotton BM. 2013. Management of wildfire risk in forested regions of Alberta to downstream municipal drinking water treatment. Healthy Forests = Healthy Waters specialty conference, Am. Water Res. Assoc., Hartford, CT, June 27-28, 2013.

8.3.2. Papers by graduate student and staff HQP

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.

Spencer SA, Silins U, Anderson A, Collins AL, & **Williams CHS**. 2015. Understanding Groundwater-Surface Water Interactions Using a Paired Tracer Approach in Alberta's Rocky Mountains, Abst. H31K-08, American Geophysical Union Fall Meeting, San Francisco, CA, Dec. 13-16, 2015.

Herlein K, Silins U, **Williams CHS**, Wagner MJ, & **Martens AM**. 2015. Evaluating the Impacts of Unexpected Forest Disturbances on Paired Catchment Calibrations of Sediment Yield and Turbidity Abst. H31D-1432, American Geophysical Union Fall Meeting, San Francisco, CA, Dec. 13-16, 2015.

Williams CHS, Silins U, Bladon KD, **Martens AM**, Wagner MJ, & Anderson A. 2015. Rainfall-Runoff Dynamics Following Wildfire in Mountainous Headwater Catchments, Alberta, Canada, Abst. H34B-06, American Geophysical Union Fall Meeting, San Francisco, CA, Dec. 13-16, 2015.

Martens AM, Silins U, Bladon KD, **Williams CHS**, Wagner MJ, & Luchkow E. 2015. Stable isotope analysis of energy dynamics in aquatic ecosystems suggests trophic shifts following severe wildfire. Abst. H34B-06, American Geophysical Union Fall Meeting, San Francisco, CA, Dec. 13-16, 2015.

Puntenney KC, Bladon KD, & Silins U. 2015. Forest Harvesting of a Rocky Mountain Headwater Catchment: Assessing the Impacts on Runoff and Sediment Transport Into and Through Riparian Buffers. Abst. H31D-1429, American Geophysical Union Fall Meeting, San Francisco, CA, Dec. 13-16, 2015.

Charlebois G, Emelko MB, & **Mesquita MMF**, Westrick J. 2015. The Relationship between *Microcystis* Sp. And Microcystin Destruction by Ozone in Water Treatment. AWWA Water Quality and Technology Conference, Salt Lake City, UT., November 15-19, 2015.

Wong AWT, Emelko MB, & **Walton T**. 2015. Optimizing Biological Filtration Performance with Innovative Capping Material Designs and Nutrient Amendments. AWWA Water Quality and Technology Conference, Salt Lake City, UT., November 15-19, 2015.

Prescott, S., Adamowicz, W.L., Boxall, P. Off Highway Vehicle Use in the Crowsnest Pass of Alberta, Canada: Valuation using Count Data and Random Utility Travel Cost Model. Presentation for the Resource Economics and Environmental Sociology Brown Bag Workshop Seminar Series; 2015, Nov 16; University of Alberta, Edmonton, Alberta.

Shams S, Emelko MB, **Stewart DM, Walton T, Kundert K**, & Scott D. 2015. Evaluation of NOM Characterization Techniques as Methods of Detecting THM Formation. 6th IWA Specialist Conference on Natural Organic Matter Research, Malmö, Sweden, September 7-10, 2015.

Prescott, S., Adamowicz, W.L., Boxall, P. Modelling of Staging Area Choice for Off Highway Vehicle Riders. Poster presented at: Land Use 2016 Conference; 2016, May 4-5; Edmonton, Alberta.

Spencer SA, Anderson A, Silins U, Bladon KD, & Collins AL. 2015. Groundwater-surface water interactions in a Rocky Mountain catchment in Alberta, Canada, IUFRO 4th Int. Conf., Forests and water in a changing environment, Kelowna, B.C., July 6-9, 2015.

MacDonald RJ, Anderson A, Silins U, & Craig JR. 2015. Application of process-based modelling to assess peak and low flow response to timber harvest scenarios in a mountain watershed. IUFRO 4th Int. Conf., Forests and water in a changing environment, Kelowna, B.C., July 6-9, 2015.

Puntenney KC, Bladon KD, & Silins U. 2015. The role of antecedent soil moisture conditions in erosion and sediment transport to streams in managed, headwater catchments. 5th Annual Hydrophiles Water Research Symposium. Apr. 26-28, 2015. Corvallis, OR.

Charlebois G, Emelko MB, **Mesquita MMF**, & Westrick J. 2015. Destruction of Microcystin-LR and Anatoxin-a by Ozone in Drinking Water Treatment. OWWA/OMWA Joint Annual Conference, Toronto, ON., April 26-28, 2015.

Charlebois G, Emelko MB, **Mesquita MMF**, Westrick J. 2015. Destruction of Microcystin-LR and Anatoxin-a by Ozone in Drinking Water Treatment. 50th Central Canadian Symposium on Water Quality Research, Burlington, ON, Canada, February 18, 2015.

Puntenney KC, Bladon KD, & Silins U. 2015. Assessing riparian buffer effectiveness: The role of antecedent moisture conditions in predicting erosion and sediment transport. Western Forestry Graduate Research Symposium. Apr. 27-28, 2015. Corvallis, OR.

Williams CHS, Silins U, Wagner MJ, Bladon KD, **Martens AM**, Anderson A, Stone M, & Emelko MB. 2014. Impacts of wildfire on interception losses and net precipitation in a sub-alpine Rocky Mountain watershed in Alberta, Canada. Abstract H51I-0721, American Geophysical Union 2014 Fall meeting, San Francisco, CA, USA, Dec. 15-19, 2014.

MacDonald RJ, Anderson A, Silins U, & Craig JR. 2014. Applying physically representative watershed modelling to assess peak and low flow response to timber harvest: Application for watershed assessments. Abstract H51G-0690, AGU 2014 Fall meeting, San Francisco, CA, USA, Dec. 15-19, 2014.

Glasbergen K, Stone M, Krishnappan B, Dixon J, & Silins U. 2014. The effect of coarse gravel on cohesive sediment entrapment in an annular flume. Int. Commission on Continental Erosion / Int. Assoc. of Hydrologic Sciences 2014 Symposium, New Orleans, LA, USA, Dec. 11-14, 2014.

Jin C, **Glawdel T**, Ren C, & Emelko MB. 2014. Surface Roughness Impacts on Particle Removal by Granular Media Filtration. AWWA Water Quality and Technology Conference, New Orleans, LA., November 16-20, 2014.

Charlebois G, Emelko MB, McDermott L, & **Walton T**. 2014. Identifying Operational Constraints for Microcystin Destruction by Ozonation. AWWA Water Quality and Technology Conference, New Orleans, LA., November 16-20, 2014.

Kundert K, Emelko MB, Mielke L, Elford T, Ruecker N. 2014. Alberta Flood 2013–City of Calgary Water Treatment System Resiliency. 16th National Conference on Drinking Water, Gatineau, QC., Canada, October 26-29, 2014.

Shams S, Emelko MB, Silins U, Bladon KD, Stone M, **Williams CHS**, & **Martens AM**. 2014. Long-term wildfire impacts on THM formation potential. 248th American Chemical Society National Meeting, San Francisco, CA, USA, August 10-14, 2014.

Jin C, **Glawdel T**, Emelko MB, & Ren C. 2014. Non-Linearity Impact of Nano-scale Surface Roughness on Particle Deposition in Parallel Plates. American Society of Mechanical Engineers (ASME) 4th Joint US-European Fluids Engineering Division Summer Meeting and 12th International Conference on Nanochannels, Microchannels and Minichannels, Chicago, IL, USA, August 3-7, 2014.

Wong AWT, Emelko MB, & **Walton T**. 2014. Enhancing Biologically Active Filtration Performance with Innovative Capping Material Designs. AWWA Annual Conference, Boston, MA, USA, June 8-12, 2014.

Chik AHS, Emelko MB, Stone M, Silins U, Dixon J, Mielke L. 2014. Linking source water quality to treatment impacts: Evaluating phosphorus as a source water and treatment vulnerability indicator. American Waterworks Assoc., Annual Conference & Exposition, Boston, MA, USA, June 8-12, 2014.

Robinne FN, Flannigan MD, Parisien MA, Bladon KD, Wang X, Silins U, & Emelko MB. 2014. A spatial analysis of wildfire risk to Alberta's drinking-water supply. Large Fire Conference, Missoula, MT. May 19-23, 2014.

Charlebois G, Emelko MB, & McDermott L. 2014. Optimization of Microcystin Removal by Ozone. OWWA/OMWA Joint Annual Conference, London, ON., Canada, May 4-7, 2014.

Wong AWT, Emelko MB, & **Walton T**. 2014. Enhancing Biologically Active Filtration Performance with Innovative Capping Material Designs. OWWA/OMWA Joint Annual Conference, London, ON., Canada, May 4-7, 2014.

Spencer SA, Anderson A, Silins U, Bladon KD, & Collins AL. 2014. Towards understanding the spatial and temporal characteristics of stream, hillslope, and groundwater runoff processes in a Rocky Mountain headwater catchment in Alberta, Canada. Abstract EGU2014-4576, European Geophysical Union, Vienna, Austria, Apr. 27- May 2, 2014.

Chik, AHS, Emelko, M.B., Stone, M., Silins, U., Dixon, J., Mielke, L. Extending the Phosphorus Transfer Continuum Concept: An Innovative Framework for Linking Source Water Quality and Drinking Water Treatability. 49th Central Canadian Symposium on Water Quality Research, Niagara-on-the-Lake, ON, Canada, March 5-7, 2014.

Wong AWT, Emelko MB, & **Walton T**. 2014. Enhancing Biologically Active Filtration Performance with Innovative Capping Material Designs. 49th Central Canadian Symposium on Water Quality Research, Niagara-on-the-Lake, ON., Canada, March 5-7, 2014.

Charlebois G, Emelko MB, & McDermott L. 2014. Optimization of Microcystin Removal by Ozone. 49th Central Canadian Symposium on Water Quality Research, Niagara-on-the-Lake, ON., Canada, March 5-7, 2014.

Macdonald RJ, Boon S, Byrne JM, & Silins U. 2013 Changes in snowmelt runoff timing: Potential implication for stream temperature and native Salmonid habitat. Abstract GC23C-0958, American Geophysical Union Fall Meeting, San Francisco, CA., Dec. 7-13, 2013.

Ho J, Stone M, Norwood W, & Silins U. 2013. Toxicity and bioaccumulation of sediment-associated metals in wildfire impacted streams of Alberta. 40th Ann. Aquatic Toxicity Workshop, Moncton, NB, Oct. 6-9, 2013.

8.4. Knowledge mobilization for professional and public audiences

8.4.1. Presentations to professional and public audiences

Emelko, MB. 2017. Wildfire, watersheds, and drinking water. British Columbia Ministry of Health, Health Protection Branch Webinar, June 21, 2017. (*Invited*)

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*)

Appiah A, & Adamowicz W. 2016. How much are Albertans willing to pay to have drinking water all the time?" In University of Alberta Faculty of Graduate Studies and Research 3-minute thesis competition. Edmonton, Alberta. April 2016

Emelko MB. 2015. Implications of forest disturbance to drinking water supply treatability. Sustaining Alberta's Forested Headwaters: Science Symposium., AB. Agriculture and Forestry, Calgary, AB, Nov. 26, 2015. (*Invited*)

Stone M. 2015. Linking downstream river condition to disturbance in the headwaters. Sustaining Alberta's Forested Headwaters: Science Symposium., AB. Agriculture and Forestry, Calgary, AB, Nov. 26, 2015. (*Invited*)

Silins U. 2015. Coupled sediment, nutrient, and stream ecological responses to disturbance in the headwaters. Sustaining Alberta's Forested Headwaters: Science Symposium., AB. Agriculture and Forestry, Calgary, AB, Nov. 26, 2015. (*Invited*)

Silins U, Emelko MB, & Stone M. 2015. Extreme Events: Is this really the new Normal? Canadian Water Network Webinar (nationally broadcast) - Changing climate, watershed disturbance and potential risks to municipal waterworks systems in Canada, November 3, 2015. *Note: Webinar was sold out (86 participants from across Canada).* (*Invited*)

Stone M, Silins U, & Emelko MB. 2015. Does what happens up in the pile of rocks really affect me? Canadian Water Network Webinar (nationally broadcast) - Changing climate, watershed disturbance and potential risks to municipal waterworks systems in Canada, November 3, 2015. *Note: Webinar was sold out (86 participants from across Canada).* (*Invited*)

Emelko MB, Silins U, & Stone M. 2015. Fires, floods and other disturbances: Are treatment challenges the same? Canadian Water Network Webinar (nationally broadcast) - Changing climate, watershed disturbance and potential risks to municipal waterworks systems in Canada., November 3, 2015. *Note: Webinar was sold out (86 participants from across Canada).* (*Invited*)

Silins U, Emelko MB, Flannigan M, Dupont D, Bladon KD, Wang X, **Robinne FN**, Parisien MA, Adamowicz W, Renzetti S, Tymstra C, Schroeder D, Thompson D, de Groot B, Kienzle S, Reid D, Wolford D, Stone M, Waddington M, Devito K, & Wotton M. 2015. Management of wildfire risk to downstream municipal drinking water treatment in Alberta. AB Environment & Parks, Drinking Water Data Summit, Sept. 3, 2015.

Prescott, S. Conference call reviewing general research results on the OHV component of the project to representatives of the Oldman Watershed Council, Red Key Communications, the University of Manitoba, the Environmental Law Centre, and the Government of Alberta. June 4, 2015.

Stone M., Silins U, Emelko MB, Flannigan M, Dupont D, Bladon KD, Wang X, **Robinne FN**, Parisien MA, Renzetti S, Tymstra C, Schroeder D, Thompson D, de Groot B, Kienzle S, Reid D, Wolford D, Waddington M, Devito K, & Wotton M. 2015. Management of wildfire risk to downstream municipal drinking water treatment in Alberta. Global Water Research Coalition, Ottawa, ON., March 13, 2015. (*Invited*)

Stone M, Silins U, Emelko MB, Bladon KD. 2014. Large scale landscape disturbance by wildfire on water quality in the Oldman River Basin, Alberta, Water Institute, University of Waterloo, March 12, 2014. (*Invited*)

Silins U, & Emelko MB. 2014. Impact of forest fires on local watersheds: An Alberta case study. Surface water quality and watershed protection – What you need to know. Western Canada Water & Western Canada Water Env. Association Workshop, Red Deer, AB., Nov. 4, 2014. (*Invited*)

Silins U, & Emelko MB. 2014. Impact of forest fires on local watersheds:An Alberta case study. Surface water quality and watershed protection – What you need to know. Western Canada Water & Western Canada Water Env. Association Workshop, Red Deer, AB., Nov. 4, 2014. (*Invited*)

Emelko, Silins U, Bladon KD, Wang X, Robinne F, Flannigan M, Dupont D, Parisien MA, Renzetti S, Tymstra C, Schroeder D, Thompson D, de Groot B, Kienzle S, Wolford D, Stone M, Waddington M, Devito K, & Wotton M. 2014. Analysis of avoided water utility costs from wildfire risk mitigation. SSHERC Water Economic Policy & Governance Network AGM, St. Catherines, ON., May 30, 2014.

Emelko MB, Silins U, Bladon KD, Stone M. 2014. Linking upstream watershed activity to downstream treatment performance (This month's DOC may not be last month's DOC). OWWA Spring Treatment Seminar, Etobicoke, ON, Mar. 27, 2014. (*Invited Plenary*)

8.4.2. Popular articles/books

Struzik E. 2017. "Firestorm: How wildfire will shape our future" / Chapter 5 – "Water on Fire". Two day field tour of the 2003 Lost Creek wildfire and Southern Rockies Watershed Project instrumented watersheds (Silins / Emelko) with author Ed Struzik for his upcoming book "Firestorm: How wildfire will shape our future". Outcome of these tours led to development of a new chapter in the book "Chapter 5 - Water on Fire" outlining wildfire water research in North America and showcasing the Southern Rockies Watershed Project. This book is scheduled for release October 2017 by Island Press.

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

8.4.3. Media interactions

CBC News. Live interview with Monica Emelko, Uldis Silins, and Travis Kendle (RMWB treatment plant manager) on how the Ft. McMurray wildfire affected water quality in the Athabasca, and how this in turn, created treatment challenges leading to increases water treatment costs. Article "Fort McMurray seeing big spike in water-treatment costs", Feb. 9, 2017.

Water Today. Interview with Uldis Silins by on the Ft. McMurray wildfire and how this fire is likely to affect water quality in the Athabasca River. Article by Jessica Lemieux, July 10, 2016.

CTV2 Alberta Primetime. Live interview with Monica Emelko on how the Ft. McMurray wildfire is likely to affect water quality and drinking water in Ft. McMurray. July 4, 2016.

CBC NewsNet. Live interview with Monica Emelko on how the Ft. McMurray wildfire is likely to affect water quality and drinking water in Ft. McMurray. July 3, 2016.

Blacklock's Reporter. Interview with Monica Emelko and Uldis Silins on how the Ft. McMurray wildfire is likely to affect water quality and drinking water in Ft. McMurray. Article "Fire's fallout may last years" by Jason Unrau appeared June 27, 2016.

Canadian Water Network "Quick Facts" – "Wildfire and Water Supply: what you need to know" Interview with Monica Emelko leading to "Fact Sheet" on wildfire effects on water. June 26, 2016.

University of Waterloo. "Is Fort McMurray's water supply contaminated by the wildfire?" by Brian Caldwall based on an interview with Monica Emelko on how the wildfire is likely to produce effects on both river water quality and potential water treatment challenges that may last for years.

Globe and Mail. Interview (Monica Emelko and Uldis Silins) and article by Leyland Cecco "Fire and Water" on how wildfires affect water quality and how the Ft. McMurray wildfire is likely to affect drinking water in the Ft. McMurray. June 17, 2016.

CJOB Winnipeg live interview by Geoff Currier with Monica Emelko and Uldis Silins on how the Fort McMurray wildfire might impact regional water resources and drinking water treatment at the Regional Municipality of Wood Buffalo water treatment facility for the city of Fort McMurray. May 20, 2016. Podcast URL: http://www.cjob.com/2016/05/20/currier-fort-mcmurray-fire-could-contaminate-water/

CBC Edmonton (740 AM) "Radio Active" live interview by Portia Clark with Uldis Silins on how the Fort McMurray wildfire might impact regional water resources and drinking water treatment at the Regional Municipality of Wood Buffalo water treatment facility for the city of Fort McMurray. May 19, 2016.

CBC Kelowna (88.9 FM) "Daybreak South" live interview by Chris Walker with Uldis Silins on how wildfires affect regional water resources, river ecology, and human uses of water. May 18, 2016. (no podcast available).

Huffington Post Alberta article "Fort McMurray Fire: Rain Could Be A Double-Edged Sword For Wildfire-Stricken Area" by Sarah Rieger based on interview with Uldis Silins and Monica Emelko on how the Fort McMurray wildfire might impact regional water resources and drinking water treatment at the Regional Municipality of Wood Buffalo water treatment facility for the city of Fort McMurray. May 17, 2016. URL: http://www.huffingtonpost.ca/2016/05/17/fort-mcmurray-rain_n_10011296.html

University of Alberta News article "Rain would be mixed blessing for Fort McMurray" by Bev Betkowski based on interview Uldis Silins and Monica Emelko on how the Fort McMurray wildfire might impact regional water resources and drinking water treatment at the Regional Municipality of Wood Buffalo water treatment facility for the city of Fort McMurray. May 16, 2016. URL: https://uofa.ualberta.ca/news-and-events/newsarticles/2016/may/rain-would-be-mixed-blessing-for-fort-mcmurray

8.5. Student and Staff Training

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

Research Associates

1. Dr. Jay Anderson, U Alberta (2016)
2. Dr. Grant Hauer, U Alberta (2016-*present*)

Post-doctoral Fellows

3. Dr. Xiaohui Sun, U Waterloo (2017-*present*)
4. Dr. Chao Jin, U Waterloo (2014-2015)
5. Dr. Maria Mesquita, U Waterloo (2013-2015)

Graduate students

6. Cassio Ishii (M.Sc. U Alberta, 2017-*present*)
7. Liz Hernani (M.Sc. U Alberta, 2017-*present*)
8. Soosan Bahramian (M.Sc., U Waterloo; 2016-*present*)
9. Amy Yang (M.A.Sc., U Waterloo, 2016-*present*)
10. Dan Greenacre (M.Sc. U Alberta, 2016-*present*)
11. Samantha Karpyshin (M.Sc. U Alberta, 2016-*present*)
12. Amanda Martens (M.Sc. U Alberta, 2017-*present*)
13. David Michael Stewart (M.Sc. U Waterloo/U Alberta, 2015-*present*)
14. Caitlin Watt (M.Sc. University U Waterloo, 2015-*present*)
15. Milly Corrigan (M.Sc. U Alberta, 2015-*present*)
16. Melissa Howard (M.Sc. U Alberta, 2014-*present*)
17. Kira Puntenney (M.Sc. Oregon State U, 2014-*present*)
18. Sheena Spencer (Ph.D. U Alberta, 2014-*present*)
19. Kelsey Kundert (M.A.Sc. U Waterloo, part-time 2012-*present*)
20. Shoeleh Shams (Ph.D. U Waterloo, 2011-*present*)
21. Sarah Prescott (M.Sc. U Alberta, *completed* 2017)
22. Xiaoshi Kate Geng (M.A.Sc. U Waterloo, *completed* 2017)
23. Mark Spanjers (Ph.D. U Waterloo, *completed* 2017)

24. Donny Allin (M.Sc. U Waterloo, *completed* 2016)
25. Gemma Charlebois (M.A.Sc. U Waterloo, *completed* 2016)
26. Jill Crumb (M.A.Sc. U Waterloo, *completed* 2016)
27. Alfred Appiah (M.Sc. U Alberta, *completed* 2016)
28. Andrew Wong (M.A.Sc. U Waterloo, *completed* 2015)
29. Chao Jin (Ph.D. U Waterloo, *completed* 2014)
30. Ken Glassbergen (M.Sc. U Waterloo, *completed* 2014)
31. Kirk Hawthorn (M.Sc. U Alberta, *completed* 2014)
32. Ryan Macdonald (Ph.D. U Lethbridge, *completed* 2014)
33. Alex H.S. Chik (M.E.S. in Planning, U. Waterloo, *completed* 2013)

Undergraduate students

34. Nayandeep Maan (URA, Coop; U Waterloo, *completed* 2016)
35. Yong Xin Michelle Fan (URA; U Waterloo, *completed* 2016)
36. Shuai Josh Yuan (URA, Coop; U Waterloo, *completed* 2016)
37. Tianyi Huang (Coop; U Waterloo, *completed* 2015)
38. Adam Schneider (Coop; U Waterloo, *completed* 2016)
39. David Michael Stewart (URA, Coop; U Waterloo, *completed* 2015)
40. Shehryar Khan (Coop; U Waterloo, *completed* 2014)
41. Deesha Nayeck (Coop; U Waterloo, *completed* 2014)
42. Jiaqi Qian (Coop; U Waterloo, *completed* 2014)
43. Simon Liu (URA; U Waterloo, *completed* 2013)
44. Stanley Cheng (URA, Coop; U Waterloo, *completed* 2013)

Incoming Graduate students (Sept. 2017)

45. Derek Mueller (M.Sc., U Alberta)
46. Camille Chalifoux (M.Sc. U Alberta)

8.5.2. Technical staff

Hydro-meteorological field staff

Fulltime Personnel (> 9 months)

47. Kalli Herlein (2014-*present*)
48. Chris Williams (2006-*present*)
49. Amanda Martens (2011-2016)
50. Kirk Hawthorn (2014)
51. Evan Luchkow (2013)

Seasonal field staff

52. Michael Pekrul (2017- *present*)
53. Erin Cherlet (2017- *present*)
54. Amber Becker (2016-2017)
55. Shauna Strack (2015-2016)
56. Chrystyn Skinner (2015-2016)
57. Aryn Sherritt (2015)
58. Eric Lastiwka (2014-2015)
59. Veronica Martens (2014)
60. Evan Esch (2013)
61. Melaina Weiss (2013)

Engineering science staff

Fulltime Personnel

62. Dr. Bill Anderson, U Waterloo (2016-*present*)
63. Dr. Maria Mesquita, U Waterloo (2013-*present*)

8.5.3. Graduate Theses Completed

Geng X. 2017. Wildfire Impacts on Drinking Water Quality and Treatability, M.A.Sc. Thesis, University of Waterloo, August 2017, 115 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.

Wong A. 2015. Investigating the enhancement of biological filtration with capping material designs and nutrient amendments. M.A.Sc. Thesis, University of Waterloo, Sep. 2015, 274 p.

Glassbergen K. 2014. The effect of coarse gravel on cohesive sediment entrapment in an annular flume. M.Sc. Thesis, University of Waterloo, Jan 2014, 87 p.

Jin C. Describing and evaluating media roughness contributions to granular media filtration. Ph.D. Thesis, University of Waterloo, Sep. 2014, 278 p.

Hawthorn K, 2014. The role of fine sediment in phosphorus dynamics and stream productivity in Rocky Mountain headwater streams: Possible long-term effects of extensive logging. University of Alberta, Jan. 2014, 126 p.

MacDonald RJ. 2013. Stream temperature drivers and modelling in headwater catchments on the eastern slopes of the Canadian Rocky Mountains. University of Lethbridge, Dec. 2013, 122 p.

Chik AHS. 2013. Assessing the role of phosphorus as a source water and treatment vulnerability indicator: Implications for planning, management and operations. MES.Thesis, University of Waterloo, Oct.. 2013, 192 p.

Ho J. 2013. Toxicity and bioaccumulation of sediment-associated metals in wildfire impacted streams of southern Alberta, M.Sc. Thesis, University of Waterloo, September 2013, 134 p.

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