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Implications of land disturbance on drinking water treatability in a changing climate: Demonstrating the need for "source water supply and protection" strategies

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ABSTRACT

Forests form the critical source water areas for downstream drinking water supplies in many parts of the world, including the Rocky Mountain regions of North America. Large scale natural disturbances from wildfire and severe insect infestation are more likely because of warming climate and can significantly impact water quality downstream of forested headwaters regions. To investigate potential implications of changing climate and wildfire on drinking water treatment, the 2003 Lost Creek Wildfire in Alberta, Canada was studied. Four years of comprehensive hydrology and water quality data from seven watersheds were evaluated and synthesized to assess the implications of wildfire and post-fire intervention (salvage-logging) on downstream drinking water treatment. The 95th percentile turbidity and DOC remained low in streams draining unburned watersheds (5.1 NTU, 3.8 mg/L), even during periods of potential treatment challenge (e.g., stormflows, spring freshet); in contrast, they were elevated in streams draining burned (15.3 NTU, 4.6 mg/L) and salvage-logged (18.8 NTU, 9.9 mg/L) watersheds. Persistent increases in these parameters and observed increases in other contaminants such as nutrients, heavy metals, and chlorophyll-*a* in discharge from burned and salvage-logged watersheds present important economic and operational challenges for water treatment; most notably, a potential increased dependence on solids and DOC removal processes. Many traditional source water protection strategies would fail to adequately identify and evaluate many of the significant wildfire- and post-fire management-associated implications to drinking water "treatability"; accordingly, it is proposed that "source water supply and protection strategies" should be developed to consider a suppliers' ability to provide adequate quantities of potable water to meet demand by addressing all aspects of drinking water "supply" (i.e., quantity, timing of availability, and quality) and their relationship to "treatability" in response to land disturbance.

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1. Introduction

1.1. Source water protection (SWP)

In 2008, supply and protection of drinking water sources was identified as the top strategic priority of North American water professionals (Runge and Mann, 2008). This is not surprising, given that rapidly expanding demand and associated increased competition over existing water supplies from industrial and municipal development is a major challenge facing water managers globally. This challenge is amplified by changes in water quality, quantity, and timing of availability that are caused by climate change and associated land disturbances. Accordingly, effective and sustainable use and management of water requires integration of water and land management that is specifically linked to characteristics of physiographic regions that supply water. Much of this integrated management has been historically considered in the context of "source water protection". Traditional SWP plans are designed "to control or minimize the potential for introduction of chemicals or contaminants in surface water… that pose a threat to human health as well as aquatic life" (Alberta Environment, 2006). They also state or imply that "watershed protection approaches… safeguard drinking water supplies from potential contamination as a way to ensure the highest quality water and to reduce treatment costs" (USEPA, 1997). Although SWP plans may prevent anthropogenic water quality changes, they often cannot prevent or mitigate the water quality impacts associated with climate change and natural land disturbances (e.g., wildfire, severe flooding) nor are they focused on or able to increase quantity and/or control availability of water supplies.

1.2. Treatment infrastructure design and operation

For surface water supplies of drinking water, the most common treatment approaches are conventional (coagulation, flocculation, clarification, granular media filtration, and disinfection), direct and inline filtration (conventional treatment without clarification), direct microfiltration (screening, microfiltration membranes, and disinfection), and reverse osmosis (RO) (screening, RO membranes, and disinfection) (MWH, 2005). Although treatment process selection, design, and operation are based on numerous factors that are not limited to source water quality, quality-based threshold values and ranges play a significant role in designing new or optimizing existing treatment processes. The basic principles of water treatment process design (Table 1) have been detailed by MWH (2005), who note that conventional water treatment processes are typically used to treat surface waters with high turbidity, color, or total organic carbon (TOC). Direct and inline filtration processes are typically used to treat higher quality surface waters with low turbidity, moderate to low color, and low TOC; while microfiltration processes are typically limited to treating good-quality surface waters with low turbidity, low color, and low TOC. Reverse osmosis is mainly used for desalination of seawater or brackish water and may be used for specific contaminant removal such as NOM (natural organic matter) from surface waters and color from groundwater (MWH, 2005). These process options represent widely differing infrastructure and operations costs that are not proportional to the amount of potable water produced. As a result, many technologies available to large systems may be too expensive or complicated for small systems to consider, sometimes making it difficult to meet all regulatory requirements.

Table 1 – Key water quality thresholds associated with surface water treatment process selection and design (MWH, 2005).

Process	Turbidity (NTU)	Color (color units)	Dissolved Organic Carbon (DOC) (mg/L)
Conventional	high >20 NTU	high >20 c.u.	high >4 mg/L
Direct/Inline filtration	low ≤15 NTU	moderate-low ≤20 c.u.	low <4 mg/L
Microfiltration	low ≤10 NTU	moderate-low ≤10 c.u.	low <4 mg/L

Land disturbance and/or climate-associated changes in source quality may present incremental cost increases for water treatment operations (e.g., increased chemical consumption), while others may necessitate new infrastructure to remove new target compounds (e.g., heavy metals, algae) or treat the associated challenges that they create (e.g., taste and odor compounds, toxic algal by-products). Some changes in source quality may not be significant in magnitude or from a health perspective (e.g., turbidity, DOC, color); however, they may produce shifts in source water quality beyond critical design threshold ranges (Table 1) so that treatment approaches must be modified; resulting in substantial infrastructure, operations, and personnel costs. Accordingly, it is critical to develop strategies that optimize treatment technology use, but also extend beyond technology dependence and traditional SWP to incorporate issues of drinking water supply and treatment.

1.3. Forested watersheds: a clear demonstration of the need to move beyond SWP

In western North America, forested headwaters provide the vast majority of usable surface water supplies to downstream regions. These regions provide approximately 2/3 of all water supplies, including drinking water for ~180 million people in the U.S. (Stein et al., 2005; Stein and Butler, 2004). In Alberta, Canada, the overwhelming majority of useable surface water supplies for communities originate from the forested Eastern Slopes of the Canadian Rocky Mountains.

Ironically, the high quality and quantity of water resources from forested regions makes these source waters particularly vulnerable to impacts of climate change, which creates favorable conditions for catastrophic natural disturbances such wildfire, insect outbreaks and disease (Kurz et al., 2008; Kitzberger et al., 2007; Westerling et al., 2006; Flannigan et al., 2005; Dale et al., 2001). For example, the linkage between increased frequency and severity of large, catastrophic wildfires and climate change is now well established (Westerling et al., 2006; Flannigan et al., 2005). Over the past two decades, longer fire seasons and increased occurrence of large and severe wildfires have been attributable to warmer temperatures, earlier spring snowmelt, and drier vegetation (Westerling et al., 2006). Increases of 74–118% in wildfire season length, fire severity, and area burned in Canadian forests have been projected by the end of the century (Flannigan et al., 2005). Similar trends during inevitable dry years are anticipated in the U.S. (Lenihan et al., 2003; Bachelet et al., 2001). The mid-elevation areas of the northern Rocky Mountains are one of the most vulnerable regions in North America, accounting for as much as 60% of recent increases in large wildfires (Westerling et al., 2006).

Forested landscape disturbances, such as wildfire, can significantly impact both water quality and quantity in headwater streams by a combination of hydrologic processes including dramatic decreases of evaporative losses (interception of precipitation and transpiration) from the forest canopy, increases in soil moisture and runoff generation from hillslopes. These, in turn, can produce greater storm runoff including large peakflows, and increase overall water production from fire-affected landscapes (DeBano et al., 1998). Large changes in physical/chemical stream water quality typically include increased concentration and export of sediments (Silins et al., 2009; Moody et al., 2008), nutrients (Bladon et al., 2008; Mast and Clow, 2008; Silins et al., in review), and some trace metals (Kelly et al., 2006). Thus, wildfires can produce a series of physical, chemical, and biological impacts on downstream river environments that have important design, operating, and cost implications for drinking water treatment processes. No substantive evaluation of how these source water impacts to water quality, which produce subsequent impacts on downstream drinking water treatment, has been reported. Moreover, although the assumption that "source protection = no anthropogenic impacts on source watershed landscapes = water quality stability" describes the essence of many current approaches to developing SWP strategies, it does not acknowledge the climate change-associated increased risk of catastrophic land disturbance that is particularly evident in forested regions.

1.4. *Research objectives*

Here, impairment of water quality by wildfires in forested source water regions was examined as a critical vulnerability of downstream water treatment processes. In 2003, one of the most severe recorded fires (Lost Creek wildfire) occurred in the eastern slopes of the Rocky Mountains of southern Alberta, Canada and impacted several aspects of water quality and streamflow in the upper Oldman River Basin (ORB). Data from source watersheds with varying degrees of wildfire associated land disturbance (reference [unburned], burned, and post-fire salvage-logged) were collected and evaluated during the four years post-fire. Some of the water quality impacts during these recovery years have been reported elsewhere, while others are reported herein. Rather than attempt to predict or demonstrate the impacts of wildfire and salvage-logging on a specific downstream drinking water treatment plant, all of the studied water quality impacts of wildfire in the ORB are synthesized and analyzed to provide a holistic discussion of downstream threats to drinking water "treatability" that can be associated with upstream wildfire and post-fire intervention (salvage-logging). Accordingly, this analysis of water quality impairment resulting from wildfire is used as a case study to demonstrate 1) the impacts of wildfire and post-fire salvage-logging on drinking water "treatability", 2) a general approach for assessing potential drinking water "treatability" implications of land disturbance, and 3) the need for developing strategies for effectively and sustainably managing water resources in anticipation of local climate change and other natural or anthropogenic land disturbances.

2. Methods

2.1. *Study sites and sampling approach*

The Oldman, Crowsnest, and Castle Rivers flow eastward from the Rocky Mountain headwaters of the ORB, which has been closed to the issuing of new water extraction licenses due to a growing imbalance between demand and supply. Hydrologically, the southern Rockies in Alberta are the highest water yielding region of the province. Landscape associated impacts on water quality in the headwaters forests of the ORB are representative of increasing pressures related to land use change in many regions of North America.

During July–September 2003, the Lost Creek wildfire burned more than 21,000 ha in the headwaters of the Castle and Crowsnest Rivers, consuming practically all forest cover and floor organic matter in the burned watersheds. Seven research watersheds were established shortly after the fire. Hydrometric and water quality sampling stations were installed at the outlet of each watershed to document changes in water quantity and quality. Three burned (South York, Lynx, and Drum Creeks) and two unburned (reference) watersheds (Star and North York Creeks) were established prior to the first post-fire spring snowmelt in March–April 2004 and two additional burned and salvage-logged watersheds were added in January 2005 (Lyons Creek East and West). Watersheds selected for study did not have significant historical logging disturbance prior to the fire. A multi-level hydrometric and water quality sampling program was employed to balance measurement of weather, streamflow, and water quality while optimizing the logistical and financial constraints of working in this remote environment. Details regarding the area, elevation, extent of burn, and hydrometric sampling program (categorized into three dominant flow periods: baseflow/non-event [summer and winter], snowmelt freshet, and stormflow [resulting from rainfall in each watershed]) are described in Bladon et al. (2008), Silins et al. (2009, in review).

Water quality sampling involved collection of two separate (overlapping) data sets. The first data set was collected using manual (depth integrated) sampling consisting of instantaneous discharge and water quality measurements every 10 days during snowmelt freshet, every 14 days after the freshet during the ice-free periods, and approximately every 1–2 months throughout winter. Periodic storm events were also sampled. Collection of a second, continuous data set began in the spring of 2005. Automated water samplers were used to collect composite daily samples (four 250 mL sub-samples collected every 6 h) during ice-free periods from May to October in a sub-set of unburned (Star Creek), burned (South York and Drum Creek) and salvage-logged (Lyons Creek East) watersheds.

2.2. Water quality and sediment analyses

Dissolved organic carbon (DOC) concentrations were determined using standard methods (Method 5310B; APHA et al., 2005). Stream turbidity was measured at 10-min intervals during ice-free periods using calibrated multiparameter sondes (YSI Models 6820 and 6920). Turbidity of samples collected by manual and automated sampling was measured with a benchtop turbidimeter (Hach 2100) using Standard Method 2130B (APHA et al., 2005). During the jar tests, turbidity was also measured using a benchtop turbidimeter (VWR Model 66120-200). Laboratory methods for dissolved organic nitrogen (DON) are described in Bladon et al. (2008). Total phosphorus (TP) and periphyton sampling and analysis are outlined in Silins et al. (in review). Microbial community analysis of biofilm formed on sediment collected from reference and wildfire-impacted streams after 2, 7, and 14 days of consolidation in an annular flume was described in Stone et al. (2010).

2.2.1. Jar Testing

Standard jar tests were utilized to evaluate optimal polyaluminum chloride (PACl) (SternPAC, Kemira Water Solutions Inc., Brantford, ON) coagulant doses that would be required to effectively treat the source waters from the various catchments. These tests were conducted five years post-fire. Samples obtained during stormflow were collected on May 24, 2008 after 60–160 mm of rain had fallen during a 3-day period. Samples during baseflow were collected on August 21, 2008 (no precipitation during the preceding 14 days). The first series of jar tests was conducted at ambient conditions, with raw water temperatures of 8.2 °C ± 0.2 °C (mean ± one standard deviation) during stormflow. Each jar was filled with 2 L of raw water and rapid mixing commenced at 300 rpm [i.e., $G \approx 300–400\ s^{-1}$] with PACl addition at varying concentrations to each of the jars. After 30 s, mixing was lowered to 70 rpm (i.e., $G \approx 50–65\ s^{-1}$) for 3 min, followed by 10 min at 35 rpm (i.e., $G \approx 23–28\ s^{-1}$). The particles/aggregates then settled for 15 min. Triplicate samples of supernatant were collected for immediate pH and turbidity analyses and subsequent DOC analyses.

3. Results and discussion

3.1. Turbidity

During the first four post-wildfire years (2004–2007), all of the water sampling programs in the study watersheds indicated that water turbidities were relatively low most of the time. Nonetheless, watersheds affected by wildfire and post-fire salvage-logging did produce markedly higher turbidities on some occasions (Table 2). For example, the combined (manual, daily composite, and 10-min interval) data indicate that even during periods of potential treatment challenge (e.g., stormflows, spring freshet) turbidity typically remained low in reference catchments, with 95th percentile turbidity reaching 5.1 NTU; similar trends in TSS concentrations (Silins et al., 2009) were observed (Table 2). In contrast, discharge from burned and salvage-logged catchments demonstrated more variable water quality and considerable increases in turbidity (e.g., 95th percentile turbidities of 15.3 and 18.8 NTU respectively) (Table 2) that could deleteriously impact treatment by contributing to increased dependency on and/or difficulty in maintaining efficiency of solids removal processes such as coagulation/flocculation/sedimentation (C/F/S), sludge production, oxidant demand, etc. Overall, increased operating costs and compliance concerns could be expected in impacted areas depending on existing treatment approaches and capacities. For example, wildfire and salvage-logging near communities where membrane processes are relied upon would likely necessitate retrofitting of expensive conventional treatment infrastructure to meet such changes in solids treatment needs. Given a "very high confidence" in increased occurrence and severity of wildfire in North America due to climate change (IPCC, 2007), the extent of these impacts on drinking water treatment process performance and costs may likely depend on how infrastructure is adjusted in anticipation of their occurrence.

Fig. 1 is a boxplot of the various water quality parameters measured using manual and daily composite sampling in the study watersheds. The contrast between the turbidity values reported in Table 2 and Fig. 1 underscores the importance of continuous monitoring (every few minutes) of rapidly

Table 2 – Median, mean, 90th percentile, 95th percentile and maximum turbidity and TSS in reference, burned, and salvage-logged watersheds during first four years after wildfire (2004–2007).

Watershed	Turbidity (NTU)				
	Median	Mean	90th percentile	95th percentile	Maximum
Reference	0.7	1.7	3.1	5.1	881
Burned	3.5	7.1	10.4	15.3	1311
Salvage-logged	5.1	7.2	12.6	18.8	1179
	Total Suspended Solids (mg/L)				
Reference	0.8	2.8	5.9	7.7	62.0
Burned	3.1	30.2	43.2	73.2	821.0
Salvage-logged	2.1	22.9	59.5	148.0	260.0

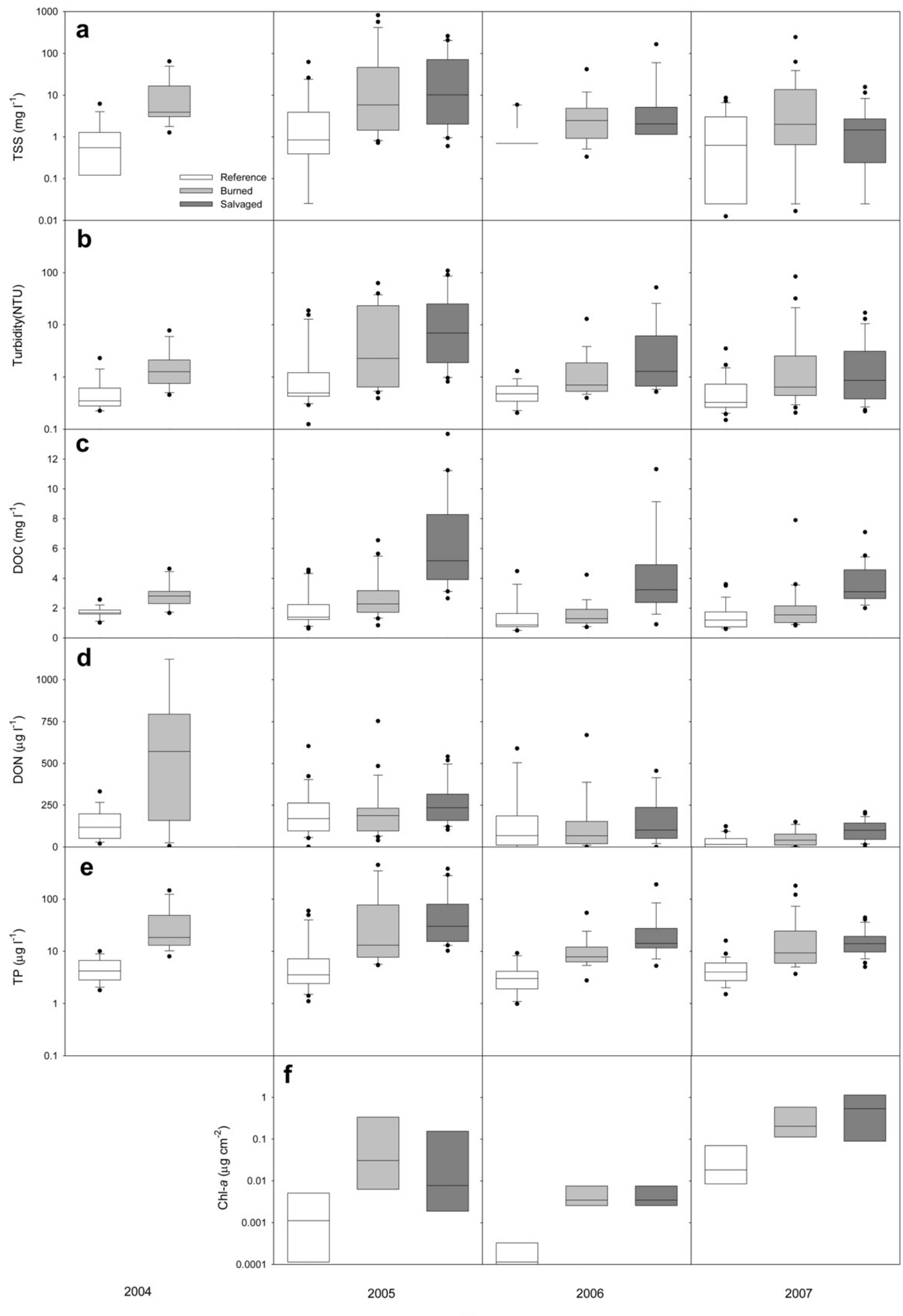

Fig. 1 – Boxplot of (a) TSS (Silins et al., 2009), (b), turbidity, (c) DOC, (d) DON (Bladon et al., 2008), (e) TP (Silins et al., in review), and (f) chlorophyll-a (from attached periphyton) (Silins et al., in review) in concentrations in reference, burned, and salvage-logged watersheds in each of the four years after wildfire. Turbidity data obtained using manual and daily composite sampling only. The whisker indicates the range spanning 1.5 times the interquartile range.

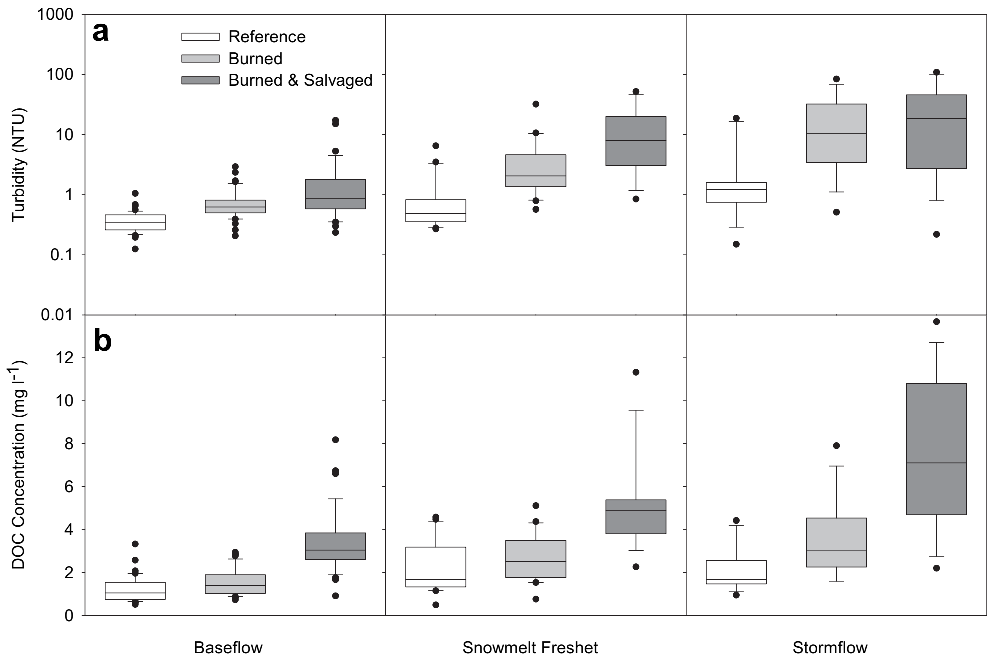

Fig. 2 – Boxplot of (a) turbidity and (b) dissolved organic carbon (DOC) concentration (2004–2007) in streams draining reference, burned, and salvage-logged watersheds during baseflow, snowmelt, and stormflow. Turbidity data obtained using manual and daily composite sampling only.

changing water quality parameters such as turbidity and reporting of extreme values (e.g., maxima, 95th or 99th percentiles) that are critical to treatment process design, but not commonly reported in watershed-scale studies.

3.2. *Dissolved organic carbon (DOC)*

DOC discharge also increased from watersheds impacted by wildfire and post-fire salvage-logging. DOC is a common surrogate for describing aqueous levels of NOM, which is often considered a pollutant that governs coagulant dosing, particularly in low alkalinity and low turbidity source waters such as those flowing from mountain catchments. Elevated levels of NOM can introduce taste and odor-causing chemicals into water supplies because of algal and bacterial activity and can result in increased production of potentially carcinogenic disinfection by-products (DBPs) such as trihalomethanes (THMs) and haloacetic acids (HAAs) when residual organics react with chlorine (Stevens et al., 1990) and other disinfectants (Krasner et al., 2006). NOM/DOC often drives coagulant dosing (O'Melia et al., 1999) and increased levels can deleteriously impact "treatability" by contributing to increased dependency on and/or difficulty in maintaining efficiency of solids removal processes such as C/F/S, sludge production, oxidant demand, etc. As with turbidity, increased source water DOCs can result in overall increases in operating costs and compliance concerns in impacted areas, depending on existing treatment approaches and capacities.

Median DOCs in discharge from watersheds affected by wildfire (3 mg/L) and post-fire salvage-logging (5 mg/L) markedly increased relative to reference levels (1–2 mg/L) in the first two years post-fire and remained elevated in the third and fourth years post-fire (2 and 3 mg/L respectively) (Fig. 1). Similar to turbidity, extreme values of DOC concentrations are relevant to drinking water treatment process performance because they often dictate infrastructure and chemical consumption requirements. The 95th percentile DOC values observed during the study period were 3.8, 4.6, and 9.9 mg/L in the streams draining the respective unburned, burned, and salvage-logged catchments. The maximum DOC concentrations observed in discharge from the reference, burned, and post-fire salvage-logged catchments were 7.9, 8.1, and 19.8 mg/L respectively. Relative to the reference catchments, both turbidity (Fig. 2a) and DOC concentrations (Fig. 2b) remained elevated in discharge from the burned and salvage-logged watersheds during baseflow, snowmelt, and stormflow during the four post-fire years of investigation. In the hydro-climatic setting of the ORB, post-event hydrograph recession conditions can influence water quality for approximately 3–7 weeks over the typical ice-free season; snowmelt freshet flow conditions (rising and falling limbs) occur over approximately 8–10 weeks. Given the high variability in stream discharge in this physiographic setting and the observed increased concentrations of DOC and high turbidity from the legacy of wildfire, it can be expected that there will be significant impacts on water treatability for several years (possibly decades) post-fire.

The changes in source water turbidity and DOC associated with wildfire and post-fire salvage-logging described herein (Table 2, Fig. 1) can clearly contribute to increased dependency on solids removal processes such as C/F/S. Fig. 3a and b respectively present examples of a jar test conducted during baseflow and stormflow five years post-fire. As would be expected, source water turbidities in all of the mountain catchments were relatively low during baseflow sampling. During that period, the source water turbidities were all <1 NTU: mean turbidities (± one standard deviation) were 0.21 ± 0.09, 0.56 ± 0.48, 0.62 ± 0.16 and 0.43 ± 0.15 NTU in discharge from the reference, burned, and Lyons Creek East and West salvage-logged catchments respectively. Fig. 3a shows that low turbidities resulted in non-discernable differences in coagulant dosing requirements in the study catchments. In contrast, during a stormflow event, mean source water turbidities were ~1.1 NTU in reference catchments and ~107, ~247, and ~162 NTU in discharge from the burned, first, and second salvage-logged catchments respectively (Fig. 3b). Although not indicated in Fig. 3b, subsequent jar tests indicated required doses of only approximately 5 mg/L of PACl for effective settling of coagulated water in the reference catchments, whereas 40 and 50–60 mg/L PACl were required for water from burned catchments and salvage-logged catchments respectively. While specific coagulant dosing impacts would likely vary for utilities downstream of wildfire-impacted source watersheds, these results are presented to illustrate the general potential for significant increases in operational costs that may be associated with such source watershed disturbances.

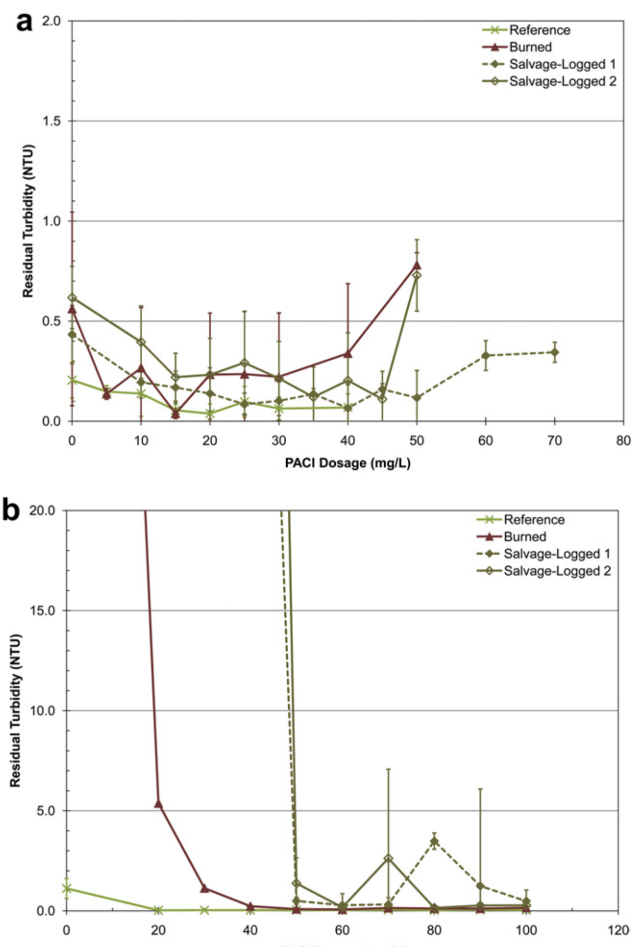

Fig. 3 – Residual turbidity (mean ± one standard deviation) from jar tests of water obtained from reference, burned, and salvage-logged watersheds five years after wildfire during (a) baseflow (mean temperature ± one standard deviation = 17.2 °C ± 0.3 °C and mean pH ± one standard deviation = 8.45 ± 0.10) and (b) stormflow (mean temperature ± one standard deviation = 8.2 °C ± 0.2 °C and mean pH ± one standard deviation = 8.33 ± 0.17; modified from (Emelko et al., 2008)).

3.3. *Nitrogen and phosphorous*

Nutrient releases to source waters can be expected as a result of wildfire because fire causes losses of TN from forest floors and surface soils and the release of inorganic P from soil organic matter. Elevated post-fire concentrations of dissolved and particulate N may decline relatively rapidly within several years post-fire (Hauer and Spencer, 1998); however, the magnitude of wildfire effects on N recovery varies greatly (Bladon et al., 2008; Minshall et al., 1997) and data from severe fires are limited (Turner et al., 2007). The nitrogen concentrations measured in the ORB during the four post-fire years represent some of the highest post-fire N concentrations and subsequent recovery reported by any study (Bladon et al., 2008). Nonetheless, changes in N-species concentrations and composition are important in source watersheds because increases in some species may impact water treatment process optimization, chemical costs, taste and odor formation, and the formation of potentially toxic disinfection by-products (DBPs), including N-containing DBPs (N-DBPs) (e.g., dichloroacetonitrile, trichloronitromethane, and N-nitrosodimethylamine). Moreover, increased nutrient levels may have substantial impacts on water quality in reservoirs with significant residence times.

Here, higher levels of DON were measured in discharge from the post-fire salvage-logged catchments, relative to burned and unburned catchments, even four years post-fire (Fig. 1). The mean concentration of DON over the four post-fire years was 205.3 μg/L (95th percentile: 756.6 μg/L) from the burned watersheds and 166.4 μg/L (95th percentile: 409.7 μg/L) in the salvage-logged watersheds, compared to 120.0 μg/L (95th percentile: 358.5 μg/l) in the unburned. DON promotes the formation of N-DBPs (Lee et al., 2007). Increased levels of ammonia such as those that could be anticipated in conjunction with increases in other N species may also have significant water treatment process impacts. When chlorine is added to water in the presence of ammonia, chloramines can form; in the presence of nitrogenated organic matter, chlorinated organic nitrogen compounds with much less germicidal efficacy than inorganic chloramines can form. The production of monochloramine, dichloramine, and trichloramine is dependent upon pH, the ratio of chlorine to ammonia-nitrogen and, to a lesser extent, temperature and contact time (Wolfe et al., 1984). While monochloramine can be used to provide effective disinfectant residual, dichloramine is a less effective disinfectant and its formation causes taste and odor problems (Suffet et al., 1995). The chlorine demand of organic nitrogen compounds can upset the chlorine to ammonia ratios necessary for maximizing monochloramine formation while minimizing free ammonia available to form dichloramine or be discharged to the distribution system to act as a food source for nitrifying bacteria and contribute to nitrification problems. As a result, wildfire- and salvage-logging-associated increases in both DOC and DON (Fig. 1) may increase water utility challenges associated with providing adequate disinfection while limiting residual chlorine, balancing chlorine to ammonia ratios, and minimizing DBP formation.

Wildfire impacts on phosphorous (P) were also evident with elevated levels observed in discharge from both burned and post-fire salvage-logged catchments (Fig. 1). Mean TP concentrations over the four post-fire years were 42.2 μg/L (95th percentile: 121.0 μg/L) and 41.2 μg/L (95th percentile: 210.0 μg/L) in streams draining the burned and salvage-logged watersheds respectively, compared to 5.7 μg/L (95th percentile: 12.4 μg/L) in streams draining unburned watersheds. In the initial two post-fire years, mean annual TP concentrations were 7–9 times higher in discharge from burned and salvage-logged catchments relative to unburned (Silins et al., in review). In the third and fourth post-fire years, TP concentrations remained 3–8 times higher in the disturbed watersheds, indicating slow recovery. This is likely the result of the strong affinity of P for sediment, which may prolong in-stream TP (Stone and English, 1993). Persistent elevated concentrations of TP are concerning because they have been frequently linked with the presence of microcystins produced by Cyanobacteria (Giani et al., 2005; Kotak et al., 2000), elevated levels of which have been associated with gastroenteritis (Hitzfeld et al., 2000) and, in some cases, liver toxicity and death (Chorus and Bartram, 1999). Increased concentrations of bioavailable phosphorus can increase microbial growth in distribution systems (Miettinen et al., 1997) and also prolong the survival of culturable *Escherichia coli* in water and biofilms (which can also act as a reservoir for microorganisms) in drinking water distribution systems (Juhna et al., 2007). Coagulation, flocculation, and sedimentation (or other clarification processes) may be necessitated for phosphorus removal.

3.4. *Mercury*

Discharge after wildfire also produces pulsed exports of some heavy metals such as mercury (Hg). Two years after the wildfire, mean total Hg concentrations in discharge from post-fire salvage-logged watersheds were ~60% higher than those observed in only burned watersheds; chronic (0.005 μg/L) and acute (0.013 μg/L) total Hg provincial water quality guidelines (Alberta Environment, 1999), established to respectively protect the water body as a whole and to limit lethality to organisms, were exceeded in discharge from both burned and salvage-logged watersheds on 32 and 11 respective occasions during those years (Kelly, E.N., Schindler, D.W., Silins, U., Wagner, M., and Graydon, J., unpublished). Total Hg concentrations observed in these discharges were elevated relative to those in discharge from the reference catchment and notably exceeded both the U.S. EPA Maximum Contaminant Level (MCL) of 2 μg/L and Canadian Maximum Acceptable Concentration (MAC) of 1 μg/L (Health Canada, 2008) on at least one occasion (265 μg/L) after a large flood event during the first two post-fire years. The form of Hg was not determined; regardless, this confirmed result has implications regarding the adequacy of monitoring requirements of Hg sampling every three months if Hg levels that exceed the MCL are observed. Fire characteristics (i.e., fire severity, proportion of catchment burned, and timing and intensity of runoff) influence limiting nutrient and contaminant release from burned catchments, altering the relative importance of Hg accumulation mechanisms (food web restructuring and increased Hg inputs and MeHg production) (Kelly et al., 2006). In such environments, event-associated (e.g., storm event) sampling may be more appropriate to determine if additional treatment is required for effective removal of Hg from source water.

3.5. *Biological impacts*

A clear ecological response in mountain headwater streams was also associated with wildfire (Silins et al., in review). Periphyton-associated chlorophyll-*a* increased as a result of the wildfire, with similar levels observed in burned and salvage-logged catchments (Fig. 1). Periphyton is comprised of a complex mixture of algae and heterotrophic microorganisms that is attached to submerged substrata and represents an important general indication of water quality in lotic waters because community responses to pollutants can be measured at a variety of times scales representing physiological to community-level changes. Increased levels of algae and short-term algal blooms can cause many treatment challenges. The volatile organic compounds geosmin (trans-1,10-dimethyl-trans-9-decalol) and MIB (2-methylisoborneol) are responsible for the majority of reported taste and odor events in surface waters and are secondary metabolites produced by actinomycetes (bacteria) and blue-green algae (Cyanobacteria) (Wnorowski, 1992). Pilot-scale investigations that involved growing sediment-associated biofilm demonstrated that sediments obtained from streams draining burned watersheds yielded increased levels of mid-chain branched saturated structures of phospholipid fatty acids (PLFA; associated with Actinobacteria) as compared to those obtained from unburned watersheds (Stone et al., 2011). In addition to producing taste and odor-causing compounds, algae can also impair coagulation and flocculation processes (Bernhardt, 1984), shorten filter run times because of filter clogging or breakthrough of algae and other particulate matter (Janssens et al., 1989; Bernhardt, 1984), contribute to microbial regrowth in the distribution system (Schmidt et al., 1998), produce microcystins (Chorus and Bartram, 1999), and increase oxidant demand. Algae-excreted metabolic products (which contribute to DOC), as well as the algal cells themselves, can be precursors for DBPs; even in systems that utilize ozonation for primary disinfection rather than chlorination (Plummer and Edzwald, 1998).

3.6. *"Source water supply and protection": integrating SWP and "treatability" assessment*

Many traditional SWP strategies would fail to adequately identify and evaluate many of the significant drinking water treatment implications of wildfire- and post-fire salvage-logging discussed above and summarized in Table 3. For example, it was demonstrated above that turbidity/TSS and DOC, which are critical water quality parameters known to

Table 3 – Water quality parameters impacted by wildfire and their potential implications to 808 drinking water treatability (modified from Emelko et al., 2008).

Impact on Treatment	Parameter					
	Turbidity	TP	DON and TKN	Hg	DOC	Chl.-*a*
Need for solids removal (C/F/S)	✓	✓			✓	✓
↑ Coagulant demand	✓				✓	✓
↑ Sludge production	✓				✓	✓
↑ Oxidant demand	✓		✓		✓	✓
↑ DBPs	✓		✓		✓	✓
↑ Fluence required for UV			✓		✓	✓
↑ microcystins		✓				✓
↑ Taste and odor concerns			✓		✓	✓
Compliance concerns	✓		✓	✓	✓	✓
↑ Operating costs	✓	✓	✓	✓	✓	✓

drive coagulant dosing and can potentially have substantial impacts on it as a result of wildfire and post-fire salvage-logging, (Table 2, Fig. 1), also vary with hydroclimatic conditions. These same water quality data can be presented as exceedance curves (Fig. 4) to highlight differences in the proportion of the time that DOC and turbidity in the study catchments exceeded key design thresholds. In contrast to Fig. 1, the data in Fig. 4 are more extensive and include three overlapping turbidity datasets: manual samples, daily composite samples, and samples collected at 10-min intervals using calibrated multiparameter sondes. The contrast between these figures underscores the need for adequate sampling of extreme water quality conditions (such as those linked to hydroclimatic conditions) that may impact design

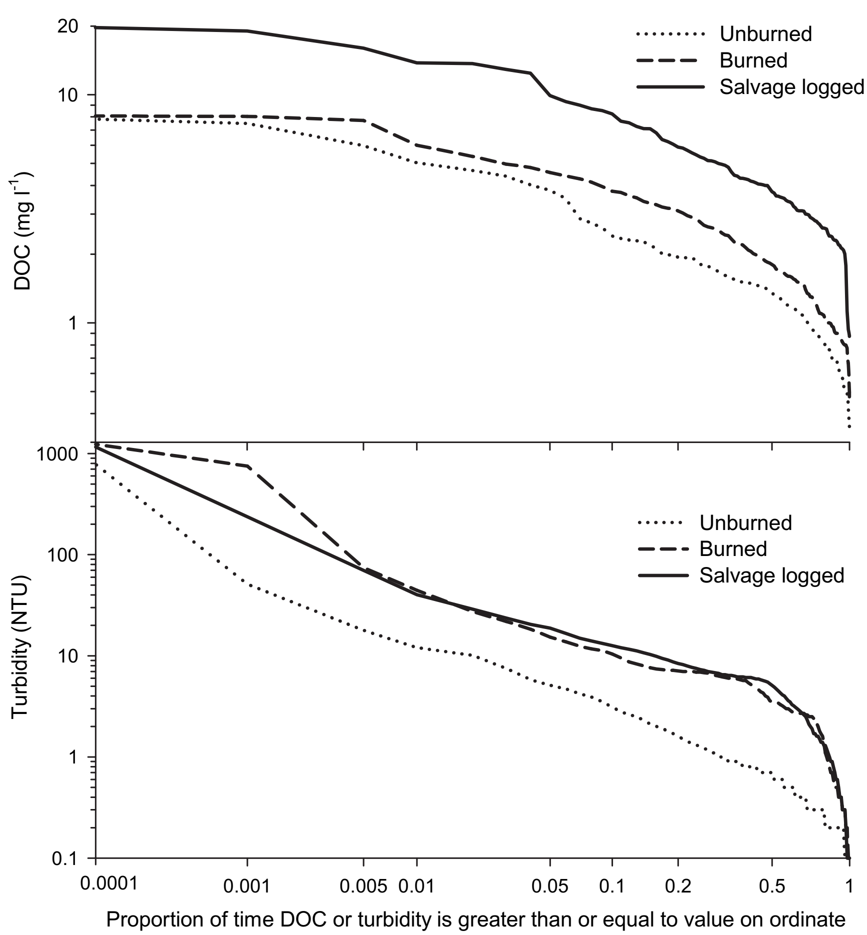

Fig. 4 – Residual DOC and turbidity exceedance curves for water in reference, burned, and salvage-logged watersheds during four post-fire years ($n = 105$ per series). Turbidity data are based on manual samples, daily composite samples, and 10-min interval data obtained using calibrated multiparameter sondes.

and operations decisions. Fig. 4 illustrates that reference catchment source water exceeded 10 NTU of turbidity or 4 mg/L of DOC ~2% and 4% of the time during the study period respectively. In contrast, burned catchment source water turbidities and DOCs respectively exceeded those values 11% and 9% of the time (~1 month per year); these targets were respectively exceeded 16% and 48% of the time in post-fire salvage-logged catchments (Fig. 4).

Many drinking water treatment plants are not designed or equipped to handle extreme water quality variations that exceed design thresholds and potentially necessitate different infrastructure requirements for periods of one month or more per year. Accordingly, plants at reasonable risk of experiencing such changes in source water quality would be faced with significant infrastructure and operational costs and decisions. Moreover, although it is commonly recognized that lower turbidity waters are likely safer from a health standpoint and the potential for harmful DBPs formation is lower when DOC is lower, these and other key water quality parameters discussed herein are not themselves generally considered "contaminants" of significant health risk, often making them relatively insignificant from an SWP standpoint.

Our work demonstrates that changes in water quality that may occur as a result of land disturbances (e.g., wildfire or prescribed fire in forested watersheds) can have catastrophic effects on source water quality and drinking water treatment approach and/or capacity. Accordingly, a more holistic approach to evaluating critical vulnerabilities within source watersheds is necessary for enabling the development of essential adaptation and mitigation strategies to improve drinking water treatment system flexibility and resiliency to respond to the impacts of land disturbance and changing climate. A critical difference between the approach proposed herein and traditional SWP strategies is the necessary consideration of not only "contaminants" that impact human and ecosystem health, but also other water quality parameters (e.g., DOC, turbidity) that may considerably affect the cost of treatment of for potable water production.

We propose that the concept of source water "supply" should be extended to consider not only the amount and quality of water available for potable water production but also the act (and cost) of providing that safe drinking water. Analogously, SWP strategies should be expanded into "source water supply and protection" (SWSP) strategies that also include "treatability" assessments that evaluate the costs and benefits of specific treatment process infrastructure selection, design, and operation as they relate to current and anticipated source water quality, which is governed by climate and the condition of source watershed landscapes. More specifically, "treatability" assessments should evaluate a drinking water suppliers' ability to: 1) treat water to achieve appropriate quality standards, 2) provide adequate quantities of potable water to meet demand, 3) adequately respond to changing water quality conditions by either utilizing robust treatment processes that are resilient to changing water quality conditions and maintain the production of high quality potable water and/or adjusting treatment processes in a timely manner that does not disrupt the supply of high quality potable water, and 4) accomplish all of the above at reasonable cost. Addressing the substantial multi-regional and jurisdictional challenges associated with the implementation of SWSP strategies into policy and governance frameworks is beyond the scope of this work; however, this work provides the scientific basis for justifying the critical need for SWSP or similar strategies.

4. Conclusions

The reported impacts on water quality in Alberta, Canada's ORB are representative of increasing threats to source waters from land disturbances that have been experienced along the entire North American Rocky Mountain range. This evaluation demonstrated that:

1. Turbidity/TSS, DOC, TP, DON, Hg, chlorophyll-*a*, and Actinobacteria-like microbial concentrations were all higher in streams draining burned and salvage-logged watersheds than in those draining reference watersheds and presented important infrastructure and operational challenges for water treatability; most notably, potentially increased dependence on expensive solids and DOC removal infrastructure.
2. TP, DOC, and chlorophyll-*a* remained elevated in the discharge from burned and salvage-logged catchments four years after the wildfire; this result was particularly evident during stormflow. Turbidity/TSS and DON demonstrated some recovery after the wildfire, with levels in the third and fourth post-fire years approaching reference levels. Post-fire recovery of water quality must be evaluated cautiously, however, because it is inextricably linked with hydroclimatic setting. Accordingly, definitive conclusions regarding ecosystem recovery are premature.
3. The "recovery" of water quality parameters to levels observed prior to disturbances must be carefully interpreted because "recovery" is a matter of perspective. Much of the published literature considers recovery from watershed hydrology and ecological perspectives in which "rapid recovery" may occur over time frames of years. In contrast, "rapid recovery" during water treatment requires returns to baseline values within hours, days, or weeks, depending on available water storage capacity. Accordingly, when "rapid recovery" is not possible, robust design and operation of treatment processes is particularly critical.
4. Typically reported watershed-scale data obtained at greater time intervals (e.g., weekly, monthly, etc.) or at conditions that are not representative of periods of greatest treatment challenge (e.g., samples that do not represent extreme values of parameters such as turbidity or DOC), must be interpreted with caution because they are less relevant to water treatment design and practice. Detailed data collection regard extreme values is necessary for evaluating water "treatability".
5. Water "treatability" assessments evaluate a drinking water suppliers' ability to: 1) treat water to achieve appropriate quality standards (i.e., meet regulatory targets for the protection of public health), 2) provide adequate quantities of potable water to meet demand, 3) adequately respond to changing water quality conditions by either utilizing robust treatment processes that are resilient to changing water

quality conditions and maintain the production of high quality potable water and/or adjusting treatment processes in a timely manner that does not disrupt the supply of potable water, and 4) accomplish these at reasonable cost. Therefore, water "treatability" assessments evaluate the costs and benefits of specific treatment process infrastructure selection, design, and operation as they relate to current and anticipated source water quality which, is governed by climate and the condition of source watershed landscapes.

6. Changes in water quality that may occur as a result of land disturbances such as wildfire can potentially have catastrophic effects on source water quality and drinking water treatment approach and/or capacity. Consequently, "Source Water Supply and Protection" (SWSP) or similar strategies that integrate SWP and "treatability" assessments are essential for enabling the development of adaptation and mitigation strategies to improve drinking water treatment system flexibility and resiliency to respond to the impacts of land disturbance and changing climate.

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