Truncated MSc Thesis draft

* Intro section only

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# 1 Introduction

## 1.1 Forested source water supplies and drinking water treatment

Surface water is the primary source of drinking water for over 85% of the Canadian population and in the province of British Columbia, approximately 80% of drinking water originates from forested headwaters (Pike et al. [2010](#ref-Pike2010)). Forests offer a variety of ecosystem services (e.g. biodiversity) and also slow and filter runoff, resulting in high quality source water supply (Dudley and Stolton [2003](#ref-Dudley2003)). Surface water quality varies over time and space due to climate, weather, and physical characteristics of the watershed (such as topography, land cover and geology), and runoff processes introduce terrestrial material, sediments, nutrients, and organic matter into surface waters (Pike et al. [2010](#ref-Pike2010); Johnson et al. [1997](#ref-Johnson1997); Delpla and Rodriguez [2016](#ref-Delpla2016); Health Canada [2019](#ref-HealthCanada2019); Yang et al. [2015](#ref-Yang2015); Matilainen, Vepsäläinen, and Sillanpää [2010](#ref-Matilainen2010)).

In Canada, all drinking source water is treated to meet Health Canada drinking water quality guidelines, which specify allowable levels of biological, physical and chemical parameters that are safe for human use and consumption (British Columbia Ministry of Environment ([2017](#ref-BC2019)); HealthLinkBC [2018](#ref-HealthLinkBC2018)). Drinking water treatment processes vary from simple chlorination to combinations of physical filtration, chemically assisted filtration, reverse osmosis, and or advanced oxidative processes (Critten, John C. Trussell, Rhodes. Hand, David. Howe, Kerry. Tchobanoglous [2014](#ref-MWH2014); Emelko et al. [2011](#ref-Emelko2011)). Drinking water treatment technologies differ between communities by infrastructure design and operation, which may be guided by source water quality, infrastructure capabilities, budget, regional size and water quality regulations (Emelko et al. [2011](#ref-Emelko2011)). All drinking water treatment processes share the same goal: ensure public health by providing a continuous supply of pathogen-free water. Therefore, disinfection - the inactivation of potentially harmful microorganisms - is the most important step in the treatment process (Critten, John C. Trussell, Rhodes. Hand, David. Howe, Kerry. Tchobanoglous [2014](#ref-MWH2014)). In BC, chlorination remains the most widely used method of disinfection, whether it is used alone or in combination with other treatment processes (HealthCanada [2006](#ref-HealthCanada2006); HealthLinkBC [2018](#ref-HealthLinkBC2018)).

In addition to treated drinking water quality guidelines, there are source water quality guidelines in place because drinking water treatment requirements vary with source water quality (HealthLinkBC [2018](#ref-HealthLinkBC2018); British Columbia Ministry of Environment [2017](#ref-BC2019)). Stable source water conditions lead to predictable treatment procedures, while fluctuating source water quality creates treatment challenges (Emelko et al. [2011](#ref-Emelko2011)). Treatment effectiveness is influenced, for example, by high turbidity levels (i.e., suspended solids), varying temperature, dissolved oxygen, pH and natural organic matter, which can create aesthetic issues (i.e. taste, odour, colour) and effect coagulation efficiency and oxidative processes (British Columbia Ministry of Environment [2017](#ref-BC2019); Matilainen, Vepsäläinen, and Sillanpää [2010](#ref-Matilainen2010); Health Canada [2019](#ref-HealthCanada2019)). Primarily, colour is an aesthetic concern for drinking water, but the natural organic matter that creates colour can interfere with effective disinfection and treatment, and thus there are water quality guidelines in place for source water colour (British Columbia Ministry of Environment [2017](#ref-BC2019); Health Canada [2019](#ref-HealthCanada2019)).

While objectionable aesthetics (i.e., taste, odour, colour) caused by aqueous natural organic matter (NOM) do not directly impact human health, source water NOM can be problematic for effective drinking water treatment. NOM reduces treatment effectiveness by interfering with ultraviolet (UV) disinfection and/or increasing chlorination demand, and because NOM promotes biological growth, can lead to fouling of treatment and distribution infrastructure (Matilainen, Vepsäläinen, and Sillanpää [2010](#ref-Matilainen2010), Health Canada [2019](#ref-HealthCanada2019); Jacangelo1995). Depending on the infrastructure design and operation of a drinking water treatment plant, elevated levels of NOM in source water can increase coagulant and disinfectant demand which increase the production of sludge (to be disposed of) and creation of disinfection byproducts (Matilainen, Vepsäläinen, and Sillanpää [2010](#ref-Matilainen2010); Health Canada [2019](#ref-HealthCanada2019)).

In addition to operational impediments, NOM is partly responsible for unintended chemical contaminants in treated drinking water. When source water is chlorinated, chemical reactions with NOM can form a variety of chlorinated organic compounds which are broadly classified as disinfection byproducts (DBPs) (Richardson et al. [2007](#ref-Richardson2007); Delpla and Rodriguez [2016](#ref-Delpla2016); Health Canada [2019](#ref-HealthCanada2019); Yang et al. [2015](#ref-Yang2015); Hua, Reckhow, and Abusallout [2015](#ref-Hua2015); Eaton, A. D., Clesceri, L. S., Greenberg, A. E., Franson [2000](#ref-StdMet2000)). A number of chlorinated carbonaceous DBPs are included in Health Canada’s drinking water quality guidelines, and have maximum allowable concentrations in treated water due to their possible or known health affects (i.e., possible genotoxicity or carcinogenicity) (Richardson et al. ([2007](#ref-Richardson2007)); British Columbia Ministry of Environment ([2017](#ref-BC2019)); Health Canada [2019](#ref-HealthCanada2019)).

## 1.2 Aqueous natural organic matter

Natural organic matter (NOM) concentration and character vary widely in source water depending on source material, hydrology, and biogeochemical factors (Aiken, Hsu-Kim, and Ryan ([2011](#ref-Aiken2011)); Abbott et al. ([2018](#ref-Abbott2018)); Zarnetske et al. ([2018](#ref-Zarnetske2018)); Matilainen, Vepsäläinen, and Sillanpää [2010](#ref-Matilainen2010)). Molecular composition and physical structure influence NOM reactivity, therefore different types of aqueous NOM have different disinfection byproduct formation potentials (DBP-FPs) (Delpla and Rodriguez [2016](#ref-Delpla2016); Yang et al. [2015](#ref-Yang2015); Health Canada [2019](#ref-HealthCanada2019); Chow et al. [2008](#ref-Chow2008)). Furthermore, different species of NOM vary in molecular size, structure and charge distribution, which determine requirements for effective treatment and removal (Jacangelo et al. [1995](#ref-Jacangelo1995); Matilainen, Vepsäläinen, and Sillanpää [2010](#ref-Matilainen2010)).

NOM comprises a dynamic collection of molecules from a variety of sources, and aqueous NOM exists in complex and diverse combinations of particulate, colloidal and dissolved fractions. NOM can be introduced to a water body from terrestrial sources or generated through in-stream processes which are often associated with autotrophic organisms like algae and cyanobacteria (i.e., autochthonous NOM). Terrestrial organic matter (allochthonous NOM) includes humic and fluvic acids, tannins, and a wide variety of other compounds (e.g. phenols and lignin, hydrocarbons, proteins, carbohydrates, etc.), which enter fresh water through runoff processes (Zarnetske et al. [2018](#ref-Zarnetske2018); Health Canada [2019](#ref-HealthCanada2019)).

Molecular structures of NOM can contain nitrogen, silica, oxygen and hydrogen and are composed primarily of carbon; thus, organic carbon is often quantified as a proxy for NOM concentration (Health Canada [2019](#ref-HealthCanada2019); Matilainen, Vepsäläinen, and Sillanpää [2010](#ref-Matilainen2010); Critten, John C. Trussell, Rhodes. Hand, David. Howe, Kerry. Tchobanoglous [2014](#ref-MWH2014)). Total organic carbon (TOC) is operationally divided into particulate and dissolved fractions (POC and DOC, respectively) which are typically distinguished based on separation by a 0.45-micron filter (Eaton, A. D., Clesceri, L. S., Greenberg, A. E., Franson [2000](#ref-StdMet2000); Aiken, Hsu-Kim, and Ryan [2011](#ref-Aiken2011)). Generally, DOC is the predominant fraction of aqueous TOC, and the amount of DBPs in treated water is proportional to raw water DOC concentration (Weishaar et al. [2003](#ref-Weishaar2003); Chow et al. [2008](#ref-Chow2008)).

In addition to acting as a precursor for DBPs, DOC has been called a master variable due to it’s terrestrial-aquatic linkages, influence on water chemistry and role in contaminant transport (Zarnetske et al. [2018](#ref-Zarnetske2018)). NOM is an energy source for aquatic heterotrophic microbes, it has the ability to bind and transport contaminants in solution (e.g. metals, hydrophobic organic pollutants, nutrients), can influence stream pH and aquatic light and temperature regimes (which, in turn, effect aquatic microbial communities) (Matilainen, Vepsäläinen, and Sillanpää [2010](#ref-Matilainen2010); Oni et al. [2013](#ref-Oni2013); Aiken, Hsu-Kim, and Ryan [2011](#ref-Aiken2011); Weishaar et al. [2003](#ref-Weishaar2003); LaZerte [1991](#ref-LaZerte1991); Palleiro et al. [2013](#ref-Palleiro2013); Stanley et al. [2012](#ref-Stanley2012)). DOC is an important source water quality parameter to monitor. In fact, guidelines in British Columbia specify that source water TOC should remain below 4 mg/L, primarily to reduce the production of trihalomethanes (e.g., chloroform, a common DBP) in treated drinking water (British Columbia Ministry of Environment [2017](#ref-BC2019)). Aside from DBPs, monitoring source water DOC is important for addressing the other operational issues associated with NOM. Stable source water conditions lead to predictable treatment procedures, while fluctuating source water quality creates treatment challenges. Within a watershed, the characteristics and concentrations of NOM (and therefore DOC) naturally fluctuate over space and through time, creating dynamic treatability conditions (Li et al. [2014](#ref-Li2014); Yang et al. [2015](#ref-Yang2015)).

## 1.3 Watershed processes and water quality

Streams are intrinsically linked to their watersheds through dynamic biotic-abiotic interactions and hydroclimatic relationships; as a result, aqueous biogeochemicals represent an important link between ecosystem processes, hydrology, and water resources. Biogeochemical signatures are useful tracers to better understand catchment processes and regional hydrology, as they are indicative of flow paths, sources, chemical origins and transport pathways (Abbott et al. [2018](#ref-Abbott2018); Meyer and Tate [1983](#ref-Meyer1983); Vidon, Wagner, and Soyeux [2008](#ref-Vidon2008); Rautu [2019](#ref-Rautu2019)). The origins, transport and fate of biogeochemicals in source waters is important for drinking water treatment, because the quality of source water (physiochemical composition and concentrations) governs treatment requirements and, with respect to DBPs, dictates the quality of treated water (Weishaar et al. [2003](#ref-Weishaar2003); Chow et al. [2008](#ref-Chow2008)).

Water quality parameters exhibit natural variability across a river network due to dynamic biotic and abiotic interactions. For example, the river continuum concept (RCC) predicts a temporal shift in DOM character, including seasonal shifts between autotrophic generation of NOM and heterotrophic processing of detritus (i.e. autochthonous to allochthonous DOM) (Vannote et al. [1980](#ref-Vannote1980); Meyer and Tate [1983](#ref-Meyer1983)). The RCC also predicts a spatial reduction in DOM molecular diversity from headwaters (entry point for majority of solutes) to river mouth (i.e., reduced DOM diversity from low to high order streams) (Vannote et al. [1980](#ref-Vannote1980); Mosher et al. [2015](#ref-Mosher2015); Abbott et al. [2018](#ref-Abbott2018); Creed et al. [2015](#ref-Creed2015)). The longitudinal attenuation of DOM diversity can be explained by a combination of hydrological processes; geomorphic variables and physical impoundments; organic matter inputs and sources; sediment transport; solar inputs; and processing by aquatic invertebrates and microbes (Vannote et al. [1980](#ref-Vannote1980); Stanley et al. [2012](#ref-Stanley2012); Aiken, Hsu-Kim, and Ryan [2011](#ref-Aiken2011); Zarnetske et al. [2018](#ref-Zarnetske2018)).

On a finer temporal scale, hydrologic pulses can cause temporal variability in DOM characteristics; for example, the character of DOM has been shown to vary during hydrologic response to precipitation, which indicates a change in DOM source over the course of an event (Vidon, Wagner, and Soyeux [2008](#ref-Vidon2008); Abbott et al. [2018](#ref-Abbott2018)). The Pulse Shunt Concept (PSC) supplements the temporal aspects of RCC by considering how major hydrologic events drive regional DOM metabolism and the magnitude, timing and spatial extent of DOM flux (Raymond et al. [2016](#ref-Raymond2016)). While the link between mobilization of source material and biogeochemical processes govern the character of aqueous NOM, the PSC shows that it is hydrologic processes that govern NOM concentrations in streams (Abbott et al. [2018](#ref-Abbott2018); Creed et al. [2015](#ref-Creed2015); Zarnetske et al. [2018](#ref-Zarnetske2018)). Where the RCC relies on in-stream biogeochemical processing to explain longitudinal alteration of NOM character, intense hydrologic pulses (related to precipitation or melt events) override the rate of biogeochemical processing and force mass transport events. Discharge determines the magnitude of DOC flux (i.e., concentration transport) and under pluvial regime, precipitation and discharge are the primary controls on stream DOC concentrations (Zarnetske et al. [2018](#ref-Zarnetske2018); Vidon, Wagner, and Soyeux [2008](#ref-Vidon2008)). Indeed, brief flood events are often responsible for most of the fluvial DOC transport in a watershed (Raymond et al. [2010](#ref-Raymond2010)).

Through a large and geographically diverse data study in the United States, Zarnetske *et al* ([2018](#ref-Zarnetske2018)) found that increasing flows systematically increased DOC fluxes in 80% of watersheds (n=1006) across ecoregions. Proportional increases in DOC flux and discharge indicates that the flux is not limited by organic matter supply, but rather by hydrologic connectivity and mobilization (Creed et al. [2015](#ref-Creed2015); Zarnetske et al. [2018](#ref-Zarnetske2018)). Watershed size and stream order were determined to be weak indicators of DOC flux-discharge relationship while watershed slope and mean precipitation were strong predictors of DOC flux (Zarnetske et al. [2018](#ref-Zarnetske2018)). Zarnetske *et al* ([2018](#ref-Zarnetske2018)) also found that wetland area exerted non-linear control over whether DOC flux was limited by supply or hydrologic transport.

Aspects of both the RCC and PSC were illustrated in a recent nested catchment study by Abbott *et al* ([2018](#ref-Abbott2018)) which found greater DOM chemical diversity in headwaters relative to downstream, but not greater temporal variance in headwaters biogeochemistry. Despite longitudinal differences in molecular character, solute concentrations varied synchronously among upstream and downstream sites, leading to temporal stability in relative biogeochemical signatures (Abbott et al. [2018](#ref-Abbott2018)). The temporal extent to which water quality changes echo across nested subcatchments depends on the synchrony (i.e. mean covariance) of the hydrologic pulse generation among subcatchments (Abbott et al. [2018](#ref-Abbott2018)).

As our changing climate is likely to lead to increases in hydrologic pulse generation - whether through increased precipitation, earlier or more intense freshet conditions, or changes in subsurface flow conditions and connectivity - it follows that drinking water treatment challenges could arise in response to more variable source water conditions. For forested source water supply areas, developing a better understanding of hydrochemical dynamics and their responses to landscape changes (e.g. wildfire, forest management strategies, mass wasting events) could bolster drinking water security by developing source water protection plans to facilitate more predictable treatment requirements. Understanding water supply area source water quality, variability and response patterns is an important part of the multi-barrier approach to safe drinking water (Canadian Council of Ministers of the Environment [2004](#ref-CCME2004)).

## 1.4 forWater & CRD GVWSA

### 1.4.1 The forWater Network

The forWater NSERC Network for source water protection strategies is a transdisciplinary, cross-Canada, applied research collaboration focused on the connections between treated drinking water quality and land-use impacts of forest management. The majority of source drinking water originates in forested headwaters, so forWater researchers are studying water quality in watersheds across Canada, under a variety of different forest management strategies. Through collaborative analyses, forWater is working to evaluate source water treatability metrics, downstream propagation effects, and resource economic with the ultimate goal of providing a framework for treatment demands of forested source water.

Forest management and landscape disturbances can ultimately effect water treatability by altering material inputs, biogeochemical processes and stream ecology, as well as changing preferential flow-paths and the mobilization, transport and dilution of biogeochemcial components (Meyer and Tate [1983](#ref-Meyer1983)). For example, wildfire combined with post-fire salvage logging in the slopes of Alberta’s southern rockies resulted in higher turbidity and DOC compared to basins that experienced fire without salvage logging, and both disturbed basins had elevated suspended solids and DOC compared to unburned catchments (Emelko et al. [2011](#ref-Emelko2011)). In other studies, it was shown that two to three years post-harvest, baseflow DOC concentrations were higher in forested catchments than in clear-cut catchments; however, these studies also showed variable stormflow DOC responses in harvested and forested catchments (Meyer and Tate [1983](#ref-Meyer1983); Mistick [2019](#ref-Mistick2019)). In the absence of long-term baseline data (i.e., pre- and post-disturbance data sets), the natural variability in fluvial processes complicates land-use studies and anthropogenic climate change can further confound our interpretations. Overall, DOC trends related to land-use seem highly dependent on catchment attributes and hydrologic forces. Understanding the hydrochemistry of a water supply area is key to conducting informed preventative forest management applications.

### 1.4.2 Greater Victoria Water Supply Areas

The Capital Regional District, a forWater Partner, is committed to the multiple barrier approach to clean drinking water and has taken control of source water protection by purchasing and privatizing the water supply areas for Greater Victoria. Located on southeastern Vancouver Island, British Columbia, Canada, the Greater Victoria Water Supply Area (GVWSA) includes 20,549 hectares (205.49 km2) of protected drinking water catchment lands. Currently, Greater Victoria’s water supply is sourced from five surface water reservoirs in the Sooke and Goldstream watersheds. In 2007 and 2010, the CRD purchased and additional 96.28 km2 (9,628 hectares) of land which included the majority of the Leech River watershed (a major sub-catchment of the Sooke River watershed). In anticipation of future water demands, this area was designated as a supplemental water supply for Greater Victoria: the Leech Water Supply Area (LWSA). In the future (possibly by 2050), inter-basin transfer will supplement the primary drinking water supply by moving Leech River water through a diversion tunnel to Sooke Reservoir. Approximately 92% of the Leech River watershed above the point of diversion (Leech Tunnel) is protected as WSA.

Overall, the hydrology of the LWSA is poorly understood, as are water quality dynamics. In the mid-1980’s, some water was transfered from the Leech River into Deception Gulch and Reservoir (adjacent to but physically separated from Sooke Reservoir), and the mixing resulted in biological water quality problems that included odour and raised concerns about the operational usage of the existing tunnel. The Leech River Tunnel and anticipated inter-basin transfer will provide many interesting research opportunities. Before work is done on inter-basin transfers, the hydrology and water quality of the Leech River system need to be better understood.

#### 1.4.2.1 Forest management

The LWSA was privately managed forest land which was extensively harvested over the past 70 years (nearly 96% clearcut); as a result, a large portion of the WSA is densely forested with softwood stands less than 35 years of age. The second growth forests of the LWSA are no longer managed for timber supply, they are now managed to improve drinking source water quality and to reduce the risk of landscape level wildfire. Due to harvest, reforestation and active fire suppression, forest fire fuels have accumulated and pose a threat in the event that a fire occurs. In the Sooke WSA, the CRD implements forest treatments designed to foster healthy forest stands capable of reducing fire intensity, such as reducing fuel hazards and creating conditions that are safe for crews to action a fire. Similarly, preventative fire treatments will be applied in the LWSA prior to inter-basin transfers. Developing an understanding of baseline water quality dynamics and hydrologic forces in the LWSA will help to inform forest management strategies by evaluating the effects of fire fuel management on water supply.

#### 1.4.2.2 Greater Victoria Drinking Water Treatment

Island Health is the Vancouver Island Health Authority which oversees drinking water systems regulated under the provincial Drinking Water Protection Act and Drinking Water Protection Regulation frameworks. In keeping with Health Canada’s drinking water quality guidelines, the Act sets out requirements for drinking water operators & suppliers to ensure the provision of safe drinking water. The CRD complies with all drinking water requirements as well as several that are not enforced in the province of BC. Treatment of source water from the Greater Victoria Water Supply Area consists only of disinfection: raw water (unfiltered) is treated with ultraviolet light as primary disinfection, chlorination is secondary, and finally ammonia is added to produce chloramine (NH2Cl, a long-lasting disinfectant that persists throughout the distribution system). Understanding dynamics and variability of hydrochemistry in the LWSA is needed to anticipate possible treatment challenges that may accompany future inter-basin transfer from the LWSA.

## 1.5 Research Objectives

As a member of the Watershed Science and Forest Management Theme of forWater, this research was conducted in partnership with the CRD to contribute to their pursuit of characterizing the Leech Water Supply Area, while contributing to our understanding of “natural” variations in source water quality (primarily with respect to DOM and DOC) across nested catchments in a second growth forested watershed. The objectives of this research were to quantify spatial and temporal patterns in DOC concentrations, and to explore the hydrochemical synchrony of nested catchments across the LWSA. Ideally, results of this research will contribute to baseline understanding for further exploration of forest management strategies, such as fire fuel management, and their impacts on source water quality and supply. Understanding source water quality, as well as the timing and magnitude of flows, is an essential component to multiple barrier approach to ensuring clean drinking water.

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