Best practice research on drinking water disinfection protocols

Overview of large unfiltered drinking water systems, and evaluation of organic matter, turbidity, and free chlorine in the drinking water system on the Coquitlam source

Prepared by: Caleb Sinn, UBC Sustainability Scholar, 2025

Prepared for: Vila Goh, Superintendent, Water Services Laboratories, Metro Vancouver

Eileen Butler, Quality Control Coordinator, Water Services, Metro Vancouver

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Disclaimer

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The skʷƛ̓əma:ɬ x̌acaʔ (Coquitlam Lake) watershed is the center of the traditional, ancestral, and unceded territory of the kʷikʷəƛ̓əm (Kwikwetlem First Nation), who continue to live on these lands and care for them along with the waters and all that is above and below. The waters of skʷƛ̓əma:ɬ x̌acaʔ support the needs of people living on the traditional, ancestral, and unceded territories of the kʷikʷəƛ̓əm, qicəy (Katzie), qʷɑ:nƛ̓ən (Kwantlen), máthxwi (Matsqui), xʷməθkʷəy̓əm (Musqueam), qiqéyt (Qayqayt), Semiahmoo, Sḵwx̱wú7mesh (Squamish), scəwaθən məsteyəxʷ (Tsawwassen), and səlilwətaɬ (Tsleil-Waututh) Nations. I am grateful to have lived and worked on the territories of these Nations, where I had the meaningful opportunity to learn about water, which was guided in part by their rich traditional ecological knowledge.

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Cover photo by Caleb Sinn

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Executive Summary

Metro Vancouver is committed to its mandate of ensuring high quality drinking water to 3.0 million residents. To support evidence-based decision-making, Metro Vancouver's Water Services, Interagency Projects and Quality Control division is interested in evaluating and improving disinfection procedures during elevated turbidity events to maintain levels of free chlorine, a secondary disinfectant, in the transmission system on the Coquitlam source. Since the Coquitlam source is unfiltered, turbidity events result in elevated levels of particulates and organic matter in the transmission system. This can lead to increased decay of free chlorine levels and potential risks to water quality and safety for downstream users. To mitigate these risks, chlorine doses are increased at the Coquitlam Water Treatment Plant (CWTP) and at several rechlorination stations on the Coquitlam source. Chlorine setpoints are raised concurrently at CWTP and the rechlorination stations once intake turbidity levels exceed a threshold, and are maintained for 48hrs after turbidity levels are below the threshold. However, managers are interested in critically evaluating the practice of dropping chlorine setpoints concurrently at the CWTP and at the rechlorination stations. Managers are also interested in understanding what leads to variation in free chlorine levels, and are particularly interested in characterizing the influence of water temperature. The purpose of this project is to support Metro Vancouver in improving disinfection response protocols during elevated turbidity events using evidence from historical water quality data from the drinking water system on the Coquitlam source.

First, the drinking water system on the Coquitlam source was contextualized by reviewing publicly available information on six large unfiltered drinking water systems. This review was conducted to determine general approaches of addressing elevated turbidity in unfiltered systems. General system characteristics were considered, as they are critical to understanding differences in how turbidity is managed. Key recommendations from this analysis are: A) Collaboration with Seattle Public Utilities may be beneficial given similarities in system design and management; B) Development of an 'Operations Support Tool' could support a scenario-based decision-making system which leverages real-time system information; C) Continued preparation for potential wildfire-induced changes to natural organic matter.

Next, the relationships between turbidity and metrics indicative of natural organic matter (NOM) in Coquitlam source and treated water were evaluated. This was done because a key assumption is that turbidity, a physical property of water representative of optical transparency, is an adequate proxy of NOM, the key chemical component tied to increased free chlorine decay in drinking water distribution systems. Ten years of daily to weekly samples of turbidity, dissolved organic carbon (DOC), total organic carbon (TOC), and UV transmittance at 254nm (UVT) from intake water and treated water leaving CWTP were analyzed. Findings indicate that turbidity is not a consistently reliable proxy for NOM, since correlations between turbidity and UVT, DOC, and TOC were relatively poor. This implies that some events of elevated turbidity likely do not coincide synchronously with events of elevated NOM. All NOM, either particulate or dissolved, appears to transform into predominantly small, structurally simple dissolved compounds due to ozonation at CWTP. These compounds have the potential to increase chlorine demand throughout the transmission system. Recommendations suggest ways to better characterize NOM to support disinfection protocols during events where particulates and organic matter are elevated in the source water, and to further understand the compositional and temporal relationships between turbidity and NOM in the transmission system on the Coquitlam source.

Finally, free chlorine levels in the transmission system on the Coquitlam source were evaluated during elevated turbidity events. Ten years of hourly water quality measurements upstream and downstream of CWTP and three rechlorination stations, along with measurements at two free chlorine monitoring sites, were analyzed. 34 events of elevated turbidity were identified. From assessing free chlorine levels before, during, and after events, it is evident that response protocols were effective at maintaining adequate levels of free chlorine throughout the transmission system up to 120hrs after the event. Cross-correlation analysis was conducted to estimate the time of water travel during events. Water travel times (2 – 20hrs) being less than the period which elevated chlorine setpoints are maintained after the turbidity events (48hrs) likely explains the effectiveness of the protocol. Analysis of outlier events where free chlorine levels were approaching concerning levels indicates that many measurements of low levels were likely erroneous, but that low levels more frequently occurred towards the beginning of events. Random forest analysis was conducted to describe the relationship between average turbidity, peak turbidity, event duration, event timing, upstream free chlorine levels, and water temperature with median and minimum free chlorine levels upstream of three rechlorination stations. This analysis indicates that increased water temperature and event occurrence between September 1st and January 31st was associated with lower levels of free chlorine in the transmission system. Overall, these results indicate that concurrent adjustment of chlorine setpoints at CWTP and rechlorination stations effectively maintain adequate levels of free chlorine in the transmission system. Key recommendations include swift initiation of elevated chlorine setpoints since the early event period is associated with lower free chlorine, and the inclusion of event timing and transmission system water temperature in decision-making. Future modelling studies could support enhanced protocol development to support resilience to climate change effects.

Project Context

Historically, turbidity levels at the Coquitlam Water Treatment Plant (CWTP) intake on Coquitlam Lake have been low enough such that it qualifies for filtration exemption based on objectives outlined by the Drinking Water Treatment Objectives (Microbiological) for Surface Water Supplies in British Columbia.[1] As such, source water is unfiltered and is treated using disinfection barriers only, specifically ozone, UV, and chlorine. However, intake turbidity periodically increases primarily due to sediment and natural organic matter (NOM) mobilized and transported to Coquitlam Lake during high precipitation events. Elevated turbidity events necessitate increased chlorine dosage to ensure free chlorine concentrations remain at target levels when leaving the CWTP and throughout the transmission system.

To support evidence-based decision-making, Metro Vancouver's Water Services, Interagency Projects and Quality Control division is interested in evaluating and improving Standard Operating Procedures (SOPs) during elevated turbidity events in the transmission system on the Coquitlam source. A key information gap is that managers lack evidence to support decisions guiding when chlorine setpoints should be reduced at the Coquitlam Water Treatment Plant (CWTP) and rechlorination stations on the Coquitlam source. The current SOP states that chlorine setpoints are reduced concurrently at CWTP and the rechlorination stations 48hrs after turbidity levels are below the response threshold. However, since travel times are long throughout the transmission system, there could be increased risks to biological stability in the transmission system with this procedure that could possibly be mitigated through maintaining chlorine setpoints at rechlorintation stations longer than at CWTP. There are also questions surrounding the potential effects of water temperature on free chlorine levels during elevated turbidity events. Additionally, while turbidity is the key physical characteristic of intake water that guides disinfection protocol, there is the recognition that it may not be consistent proxy for NOM.

The objective of this project is to address these key information gaps by evaluating historical water quality in the drinking water system on the Coquitlam source to support evidence-based decision-making during events of elevated turbidity. The primary question, addressed in Section 3, is: *How well are the response protocols maintaining target free chlorine residual levels in the transmission system on the Coquitlam source during elevated turbidity events, and what factors explain their variation?* Prior to addressing this question, it is worth putting the Coquitlam source system in context, given that the necessity of the response protocol is a result of the system design. As such, the first question, addressed in Section 1, is: *How is turbidity managed in other large unfiltered water systems?* Then, the evaluation of turbidity as a proxy of NOM is addressed in Section 2: *How well does turbidity represent natural organic matter in raw and treated water on the Coquitlam source?*

These three questions are addressed in the sections that follow. Each section elaborates further on key concepts: unfiltered drinking water system design and regulation, turbidity, NOM, biological stability in water distribution systems, and Metro Vancouver's response protocols to elevated turbidity events. Section 1 focuses on unfiltered drinking water system design and characteristics with a focus on management of turbidity, places the drinking water system on the Coquitlam source in context with other large unfiltered systems in North America, and provides recommendations based on review of publicly available information from other large unfiltered systems. Section 2 evaluates relationships between turbidity and metrics of NOM from 10 years of discrete samples of raw and treated water on the Coquitlam source. Section 3 evaluates free chlorine levels in the transmission system on the Coquitlam source during elevated turbidity events over the past 10 years with a focus on levels upstream and downstream of rechlorination stations. It also explores the factors that explain variation in free chlorine such as turbidity, water temperature, and seasonal characteristics using a machine learning approach.

Section 1: Review of large unfiltered systems in Canada and the United States with respect to the system on the Coquitlam source

In British Columbia, there are five drinking water treatment objectives that must be followed as outlined by the *Drinking Water Officers Guide*[1] (DWOG), re-published in April 2025. They include:

- 4-log (99.99%) reduction or inactivation of viruses
- 3-log (99.9%) reduction or inactivation of *Giardia* and *Cryptosporidium*
- Two treatment processes for surface water (dual treatment)
- Turbidity is ≤ 1 NTU
- No detectable *E. Coli*, fecal coliform, and total coliform

To meet these guidelines, the conventional treatment approach is filtration and disinfection. The purpose of filtration is to reduce potential pathogens and natural organic matter (NOM). While NOM does not have direct health effects, it affects drinking water quality due to indirect health impacts. It can reduce the effectiveness of disinfection and is a precursor to disinfection byproducts (DBPs) through reactions with chemical disinfection agents such as chlorine, chloramine, chlorine dioxide, and ozone.[2-4] Some DBPs are regulated due to their potential carcinogenicity.[5,6] The presence of NOM alters the biological stability of treated water in transmission and distribution infrastructure and may cause taste and odor issues.[3]

Although rare for large drinking water supply systems, treatment objectives may be met without filtration. The Drinking Water Treatment Objectives (Microbiological) for Surface Water Supplies in British Columbia[1] permits filtration exemption where four conditions are met:

1. Overall inactivation providing 4-log reduction of viruses and 3-log reduction of *Giardia* and *Cryptosporidium* is maintained using two disinfection methods.
2. In raw water, *E. coli* does not exceed 20 CFU/100 mL (or total coliforms are < 100 CFU/100 mL) in at least 90% of weekly samples in the previous six months. Also:
    a. For one sample in 30 days, total coliform objective is 0 CFU/100 mL.
    b. For > 1 sample in 30 days, at least 90% of samples should have 0 CFU/100 mL total coliforms and no sample should have > 10 CFU/100 mL.
3. Average turbidity measured at equal intervals before disinfection is ~1 NTU but does not exceed 5 NTU for more than two consecutive days in a 12-month period.
4. A watershed control program is in effect to minimize the potential for fecal contamination in source water.

There are two large water supplies in British Columbia that operate under filtration exemption criteria, and they are the only large unfiltered water supply systems in Canada. These include the system on the Coquitlam source operated by Metro Vancouver, and the Capital Region District's (CRD) Sooke & Goldstream supply system that serves Greater Victoria. There are several large unfiltered systems in the United States, where filtration avoidance criteria for their systems are generally similar to those in British Columbia, but there are additional criteria that apply to the disinfection system along with watershed protection and overall operations. They include: disinfection redundancy or automatic shut-off if residual disinfection falls below 0.2 mg/L; residual disinfectant concentration must not fall below 0.2 mg/L for more than 4 consecutive hours; residual disinfectant must not be undetectable in 5% of samples taken over a two-month period; annual inspections ensure efficacy of watershed controls and disinfection procedures; no evidence of waterborne disease outbreaks or corrective actions taken in the event of an outbreak; compliance with maximum total coliforms levels in the distribution system; meeting DBPs guidelines.[7] General characteristics of these unfiltered water supplies are listed in Table 1.1.

Table 1.1. Characteristics of large unfiltered water supplies in Canada and the United States

Metropolitan Area	Total Population Served (Million)	Unfiltered Supply & Treatment Facility	Capacity (MLD[a])	Proportion of Total Supply (%)	Treatment System
Vancouver, BC	3.0	Coquitlam; Coquitlam WTP[b]	1,200	33	O_3 – UV – Cl_2
Victoria, BC	0.4	Sooke & Goldstream; Goldstream & Sooke River Road WTPs	625	100	UV – Cl_2 – NH_2Cl
Seattle, WA	1.6	Cedar; Cedar WTP	680	70	O_3 – UV – Cl_2
Portland, OR	1.0	Bull Run; Headworks & Lusted Hill WTPs	850[c]	>95[d]	Cl_2 – NH_2Cl[e]
San Francisco, CA	2.7	Hetch Hetchy; Tesla WTP	1,200	85	UV – Cl_2 – NH_2Cl
Boston, MA	2.5	Quabbin-Wachusett; J.J. Carroll & Brutsch WTPs	1,600	100	O_3 – UV – NH_2Cl & Cl_2
New York City, NY	10.0	Catskill-Delaware; Catskill/Delaware WTP	8,500	90	UV – Cl_2

a: MLD = million liters per day; b: WTP = water treatment plant; c: estimated by the sum of capacity of transmission conduits transporting Bull Run water from the Headworks WTP[9]; d: estimated from the reported groundwater usage10; e: Bull Run supply will be filtered by 2027[9].

The system on the Coquitlam source has the third largest supply capacity, equivalent to the Hetch Hetchy system for San Francisco, after the Catskill-Delaware system for New York City and the Quabbin-Wachusett system for Boston. Most utilities that operate unfiltered water systems also operate filtered or groundwater supply systems that provide redundancy to maintain supply during system maintenance operations, augment supply during dry seasons, and to manage high turbidity events. The exception to this is the water systems for Victoria and Boston, which are currently exclusively unfiltered surface water supplies. Redundancy in disinfection is usually met by a combination of UV and chlorine, with some systems also utilizing ozone for primary disinfection. Most of the unfiltered systems use chloramine for secondary disinfection, except for Seattle, Vancouver, and New York which rely on free chlorine.

In the sections that follow, characteristics of each water supply will be elaborated on, with a focus on general management of high turbidity events for treatment and biological stability of treated water throughout the distribution system. Note that specific standard operating procedures are not publicly available, so descriptions are dependent on information from the utilities' master plans, water quality reports, or other publicly available supply system reports.

1.1 Victoria, BC

The information provided is derived from the CRD's *Regional Water Supply 2022 Master Plan*[7]. The primary water source for the CRD is the Sooke watershed, which is 87 km^2 of forested land, 98% of which is owned and managed by the CRD. The raw water intake is located on Sooke Lake Reservoir, which carries water to the Goldstream Disinfection Facility (GDF), the main water treatment facility for the Greater Victoria region with a capacity of 605 million liters per day (MLD). A second water supply main carries raw water to the Sooke River Road Disinfection Facility (SRRDF) which has a capacity of 20 MLD. Both disinfection facilities are unfiltered, with disinfection achieved by UV and chlorine. The 23 km^2 Goldstream watershed is used as a secondary source of water, 98% of which is owned and managed by the CRD. It consists of a series of smaller reservoirs, the most downstream of which is the Japan Gulch Reservoir, which supplies water to the GDF but not the SRRDF. The CRD is exploring future water supply areas, namely the Leech and Deception Gulch watersheds. A recommendation of the report is that a new filtration plant should be online by 2037 to ensure reliability and resiliency of the system to changes in water quality such as turbidity and organic matter due to climate change and wildfires. In addition, it is implied that filtration will be necessary once the Leech watershed is used for supply, since the Leech River is prone to high colour and turbidity levels during high precipitation events in the fall, and there are significant slope instability and soil erosion concerns. Biological stability in the transmission system is managed through chloramine as the residual disinfectant. Residual levels have remained above target levels throughout the transmission system, and thus rechlorination stations are not in operation (C. Moch, personal communication, May 23, 2025).

Turbidity levels of raw water from the Sooke Reservoir entering the GDF between 2010 and 2019 averaged 0.31 NTU. Average and maximum total organic carbon (TOC) was 1.90 mg/L and 3.9 mg/L, and for dissolved organic carbon (DOC) it was 1.72 mg/L and 3.34 mg/L. The report does not mention details of the management of high turbidity events through alterations in disinfection protocol. However, the CRD does not use water from the Goldstream watershed during the winter due to increased turbidity levels and the risk of landslides in the Goldstream canyon. Generally, the Goldstream supply is reserved for emergency use, or when the Sooke Reservoir supply tunnels are being inspected. Within the distribution system, it was noted that residual consumption rates increase in the late summer and early fall when intake temperatures exceed 15°C, as the reservoir levels are drawn down and the intake begins conveying water from the epilimnion (upper mixed layer) instead of the hypolimnion (deep layer) of the reservoir.

The information gathered from the *Regional Water Supply 2022 Master Plan*[7] implies that the CRD at this time does not encounter significant disinfection challenges with their water supply related to elevated turbidity and temperature events. Their primary water supply, the Sooke watershed and the Sooke Lake reservoir, maintains turbidity levels <1 NTU. However, the CRD is actively planning for capacity to manage high turbidity events in the future given the need to increase supply from sources of higher turbidity (the Leech watershed), and to increase resiliency to high turbidity conditions brought about by climate change, wildfire, and seismic events.

1.2 Seattle, WA

The information provided is from the Seattle Public Utilities' (SPU) *2019 Water System Plan: Volume 1*[8], and from SPU staff (K. Lynn, personal communication, June 5, 2025). The primary water supply is the 370 km^2 Cedar River watershed, which provides 70% of the total supply, with the remainder provided by the South Fork Tolt River watershed which became a filtered supply in 2001. While the water supply system also includes groundwater wells, these have not been in use since 2015 and are reserved for emergencies. The Cedar watershed is publicly owned, and commercial, industrial, and residential development is restricted. The terminus of the Cedar water supply area is the Landsburg diversion which is an intake directly on the Cedar River which conveys water either directly to the Cedar Water Treatment Facility (CWTF) or to Lake Youngs Reservoir. The Landsburg Water Treatment Facility, located at the Landsburg diversion, applies chlorine to minimize microbial growth in the transmission pipeline to Lake Youngs and the CWTF, and to minimize introduction of algae into Lake Youngs. The CWTF uses ozone and UV to ensure adequate primary disinfection, and chlorine is added to ensure secondary disinfection and biological stability in the treated water. The average and typical range of water quality from source and finished water from the Cedar Supply during 2012 – 2017 is listed in Table 1.2.

Table 1.2. Select raw and treated water quality characteristics (average and typical range) from Seattle Public Utilities' Cedar supply from 2012 – 2017.

Parameter	Cedar River at Landsburg (raw)	Lake Youngs Outlet (raw)	Cedar Water Treatment Facility
Turbidity (NTU)	0.6 (0.3 – 1.2)	0.4 (0.2 – 0.6)	0.4 (0.2 – 0.6)
Temperature (°C)	9 (5 – 13)	13 (6 – 20)	13 (6 – 21)
UV_{254} Absorbance (cm^{-1})	0.026 (0.010 – 0.040)	0.017 (0.010 – 0.022)	0.012 (0.008 – 0.016)
Total Organic Carbon (mg/L)	0.78 (0.4 – 1.1)	0.80 (0.7 – 1.0)	Not Reported
Free Chlorine (mg/L)	N/A	N/A	1.5 (1.4 – 1.7)

Algal blooms of the diatom *Cyclotella* have reoccurred in Lake Youngs every year since 2008. These blooms are problematic for the distribution system as they tend to clog water filters in businesses and homes. To manage these events, the Lake Youngs intake is bypassed and the CWTF is supplied with Cedar River water directly from the Landsburg diversion. Bypass operations span from a few days to several months at a time. Water quality during these bypass operations has been acceptable, except during high precipitation events that raise turbidity levels. When turbidity is above 1 NTU, additional chlorine is dosed at the Landsberg diversion. When turbidity is above 2.5 NTU, the Landsberg diversion is shut down.

The range of free chlorine dosage of raw water is 1.5 – 1.7 mg/L. SPU provides additional chlorination (i.e., rechlorination) at some distribution system storage reservoirs to ensure adequate levels of chlorine residuals, at a dose of 1.0 – 1.2 mg/L free chlorine. They have reported a reduction in rechlorination operations since filtration began on the Tolt supply, and since the completion of their reservoir covering program. Monitoring of free chlorine throughout the distribution system informs disinfection operations at the primary water treatment facilities and reservoirs. If free chlorine in the reservoirs is less than 0.6 mg/L, the reservoir is boosted with additional chlorine. Free chlorine setpoints are typically elevated during the summer months, as water temperatures exceeding 15°C are known to accelerate the degradation rate of free chlorine. Where free chlorine is consistently less than 0.2 mg/L in the distribution network, these areas are flushed.

1.3 Portland, OR

The information provided is from the Portland Water Bureau's (PWB) *Bull Run Treatment Projects, Filtration: Project Definition Report*.[9] The purpose of this report was to document the key outcomes from PWB's planning phase for the development of a filtration system for their primary water supply, the Bull Run watershed. Until 2017, the PWB had been operating under a variance for the requirements to treat for *Cryptosporidium* due to limited sources and occurrence within the Bull Run supply. As such, they had been using chlorination as the sole primary disinfection method. In early 2017, several *Cryptosporidium* detections in the Bull Run supply lead the state health authority to revoke the variance, meaning the PWB needed to improve treatment to meet federal regulations. Although UV disinfection was initially considered to maintain the system's status as an unfiltered water supply, the PWB ultimately opted to proceed with a filtration system design. This decision was driven by the need to comply with *Cryptosporidium* removal regulations and to gain additional benefits, such as enhanced biological stability of treated water and improved resilience during prolonged periods of elevated turbidity. The new filtration plant is planned to be operational by 2027.

The Bull Run water supply area, located in Mount Hood National Forest, is a 264 km^2 protected area managed by the United States Forest Service in cooperation with the PWB. Two reservoirs are managed within the watershed, the most downstream of which (Reservoir 2) is where the intake pipe to the Headworks water treatment plant is located. Raw water is screened and chlorinated at Headworks, and then ammonia is added at Lusted Hill water treatment plant to form chloramine for residual disinfection. The PWB also manages a supplemental groundwater supply system with an installed capacity of 360 MLD, sized to meet winter demand during elevated turbidity events in the Bull Run. Between 1985 – 2024, 10% of the days where groundwater was used for water supply was in direct response to turbidity events in the Bull Run, for an average of less than one day per year over the 40-year period.[10] The remaining days where groundwater was used was for supply augmentation and during Bull Run system maintenance. Over the 11 turbidity events that prompted Bull Run shutdowns and the need for groundwater supply usage, the events lasted 12 days on average and ranged 4 – 22 days. A system shutdown is initiated if there is an indication that raw water turbidity will exceed 5 NTU, in accordance with filtration exemption requirements. The maximum daily turbidity during these events ranged from 3.4 to > 25 NTU, but there is uncertainty in the absolute turbidity magnitude when the intake is shutdown. Table 1.3 lists selected water quality characteristics for raw intake and treated water for the Bull Run supply.

Table 1.3. Select raw and treated water quality characteristics (average and min – max) from Portland Water Bureau's Bull Run supply, 2007 – 2018.

Parameter	Reservoir 2 Intake at Headworks (raw)	Finished Water at Lusted Hill Outlet
Turbidity (NTU)	0.6 (0.1 – > 25.0)	0.46 (0.04 – 3.60)
Temperature (°C)	9.8 (2.2 – 18.7)	Not reported
UV_{254} Absorbance (cm^{-1})	0.05 (0.02 – 0.11)	Not reported
Total Organic Carbon (mg/L)	1.1 (0.3 – 4.1)	1.10 (0.66 – 1.90)
Chlorine Residual (mg/L)	N/A	2.0 (0.9 – 3.2)

The target for free chlorine residual varies seasonally at the Lusted Hill Outlet, with a winter-spring target of 2.2 mg/L and summer-fall target of 2.5 mg/L. The dose at Headworks, the chlorination facility, typically ranges from 3.0 – 3.5 mg/L, but may be set to as high as 5.0 mg/L. While DBP levels in the distribution system are generally below maximum contaminant levels (MCL) levels, levels of haloacetic acids at a few points in the distribution system exceed the MCL in November, which is linked to increased free chlorine dose in the fall paired with increased water age (decreased demand) and an increase in NOM in the raw water supply. There is no mention of challenges in maintaining minimum disinfectant residuals in the distribution network, and PWB does not appear to manage rechlorination stations.

1.4 San Francisco, CA

Of the unfiltered systems reviewed, the least information is publicly available for the Hetch Hetchy water supply system for San Francisco, managed by the San Francisco Public Utilities Commission (SFPUC). Information provided is derived from the *Water Treatment Process – February 2023*,[11] *Water Quality Strategic Plan for SFPUC Drinking Water System – 2024 Update*,[12] *Alternative Water Supply Plan*,[13] and *Long-Term Vulnerability Assessment and Adaptation Planning for the San Francisco Public Utilities Commission Water Enterprise – Technical Report 5: Raw Water Quality Model*.[14] About 85% of the SFPUC's water supply is from the Hetch Hetchy system, while surface water reservoirs in the Alameda and Peninsula watersheds represent the remainder of the supply, which is filtered. The Hetch Hetchy system is comprised of the Tuolumne watershed which supplies the Hetch Hetchy reservoir in Yosemite National Park. Water is conveyed from Hetch Hetchy reservoir and is treated for corrosion control at the Rock River Lime Plant, then undergoes UV and chlorine disinfection at the Tesla Treatment Plant (TTP). A chloramine residual is maintained for secondary disinfection. SFPUC operates a series of nine rechlorination stations to meet residual disinfectant targets throughout the distribution system.

If filtration avoidance criteria are not met in the Hetch Hetchy supply due to elevated coliforms, turbidity, or TOC, the water may be treated in the Sunol Valley Water Treatment Plant. The operational objective for turbidity at TTP is < 1 NTU, and if 2 NTU is reached, customer complaints may occur. In addition, the threshold for TOC is 2 mg/L, as TOC above 3 mg/L will likely lead to exceedances of DBP MCLs. The most severe turbidity event occurred in February 1997, which peaked at 6.77 NTU due to a rain-on-snow event. This was considered a 70-year recurrence event. Two other high turbidity events occurred in November of 1996 and 2000, with peak turbidity of 2.50 NTU and 2.65 NTU, respectively, both with recurrence events of about 10 years. Using a machine learning algorithm approach specifically developed to capture the magnitude of outliers for high turbidity events, it was found that antecedent dry days in the previous water year (long-term watershed memory; sediment and NOM accumulation in the Tuolumne watershed due to drought conditions) and current-year cumulative discharge of intake on Hetch Hetchy were the best predictors of turbidity at the Hetch Hetchy reservoir intake.[14] This research demonstrates the vulnerability of water supplies to climate change, and outlines methods for characterizing the primary drivers of turbidity at the raw water intake.

1.5 Boston, MA

The information provided is from the *Massachusetts Water Resources Authority (MWRA) Water System Master Plan*.[15] The only water supply for the region is the Quabbin – Wachusett system, which includes the Quabbin Reservoir (53 % of system yield), the Wachusett Reservoir (34 % of the system yield), and the Ware River (13% of the system yield). Land ownership of the source watersheds is fragmented. While the Department of Conservation and Recreation owns 47% of source watershed areas, up to 75% is regulated under the law. The MWRA monitors land development in the watershed and undertakes land purchases if proposed developments are considered a risk to water quality. They also support local community planning, and work alongside transportation departments to minimize the risk of accidental contaminant release.

The Quabbin is the larger of the two reservoirs, which is filled periodically by transfers from the Ware River. The water quality of the Wachusett Reservoir is managed by periodically transferring water from the Quabbin Reservoir, which has lower NOM and is colder. These transfers create an ‘interflow’ condition when the Wachusett stratifies in the summer months, which effectively moves cold, lower NOM Quabbin water to the intake on the Wachusett Reservoir which conveys water to the treatment plant. This condition improves the disinfection operations. Disinfection of raw water downstream of the Wachusett Reservoir takes place at the John J. Carroll Water

Treatment Plant (JJCTP) which has a maximum capacity of 1,530 MLD. Primary disinfection is ozonation followed by UV, and secondary disinfection is chloramine. The smaller Brutsch Water Treatment Plant (BWTP) has a capacity of 60 MLD and treats water directly from the Quabbin Reservoir. The BWTP utilizes UV and chlorine for primary disinfection and uses free chlorine for secondary disinfection. MWRA has identified that increases in more reactive NOM, as measured by UV absorbance at 254nm (UV254), is related to decreases in chloramine residuals and lead leaching in home plumbing. They describe the primary reason for increases in UV254 is related to the relative contribution of Quabbin Reservoir or Wachusett Reservoir water each year. Management of elevated turbidity events is not directly mentioned in the *MWRA Water System Master Plan*.[15] Rechlorination stations are not operated for water treated by the JJCTP, but a few are operated for the distribution system served by the BWTP.

1.6 New York City, NY

The information provided is from the New York City Department of Environmental Protection's (DEP) *Long-Term Watershed Protection Plan*,[16] the *Watershed Protection Program Summary and Assessment*,[17] and the *2024 Filtration Avoidance Annual Report*.[18] New York City manages an unfiltered drinking water system which supplies 90% of the daily water needs of 10 million residents with the 9,000 MLD capacity Catskill/Delaware Ultraviolet Disinfection Facility. Primary disinfection is carried out by UV and chlorination, and a chlorine residual is maintained through the transmission and distribution systems. The Catskill and Delaware watersheds include a series of 9 reservoirs that flow primarily through a series of tunnels to the Kensico Reservoir, which is the most downstream surface water reservoir prior to disinfection. 40% of the lands in the Catskill/Delaware watersheds are protected by municipal, state, and other authorities. As a result of fragmented land ownership in the source watersheds, the DEP undertakes an extensive watershed protection program that includes an agriculture program, land acquisition activities, development project regulation, wastewater treatment improvements, and stream management programs aimed at improving and maintaining source water quality. Decreases in source water turbidity have been attributed to the effectiveness of these programs.

DEP continues to undertake monitoring and management activities to understand and minimize the sources of turbidity in source watersheds. A major focus has been the levels of turbidity in the Catskill watershed, related primarily to the underlying geology. The design of the interconnected reservoirs facilitates the settling of suspended sediments, which generally reduces turbidity before the water enters the Kensico Reservoir, typically to levels below 5 NTU. During extreme runoff events due to heavy rainfall, high turbidity events have been managed through the addition of a coagulant, aluminum sulfate, to the Catskill Aqueduct inflow to Kensico Reservoir. On average, coagulant addition to the Catskill Aqueduct occurs less than 2 days per year. Connections between reservoirs have been cut-off at times as well, and release channels are opened to discharge high turbidity water out of the system. Turbidity curtains are also maintained in Kensico Reservoir to direct the flow of two tributaries further out into the main basin of the reservoir to increase sediment settling. DEP also operates a system-wide Operations Support Tool (OST) that supports decision making related to reservoir releases and diversions, water quality, and environmental objectives. The OST is capable of simulating system characteristics based on varying environmental and decision scenarios and is used to optimize operations during large storm events to reduce Kensico Reservoir turbidity levels. Through this method, Kensico Reservoir turbidity levels were maintained at <1.5 NTU during multiple storm events in 2023 and 2024. In the distribution system, chlorine residuals are maintained by rechlorination stations and periodic flushing.

1.7 Comparison to the system on the Coquitlam source

This overview of large unfiltered water supplies in Canada and the US demonstrates wide variability in water supply system characteristics including surface water system attributes and disinfection procedures. The CRD surface water system for Victoria is most similar to the system on the Coquitlam source in that a single, large reservoir is the primary hydrological feature that stores and supplies water to the raw water intake of the water treatment plant. However, the CRD utilizes chloramine for secondary disinfection, and does not encounter significant reductions of residual chlorine throughout the system and is less sensitive to storm-induced turbidity increases in the source reservoir. The treatment approach of the Cedar system in Seattle is the most like the system on the Coquitlam source, in that both systems employ ozonation and UV as primary disinfection and maintain a chlorine residual for secondary disinfection. In addition, rechlorination of storage reservoirs is a key aspect of maintaining adequate chlorine residuals in the Cedar system. Unlike the system on the Coquitlam source, the Cedar system has the capacity to alter intake supply from a small surface water reservoir to minimize turbidity levels in the intake, or directly from the Cedar River to minimize intake of algae in the distribution system. While New York City also manages rechlorination stations throughout their distribution system and their secondary disinfectant is chlorine, their turbidity management system focuses on greatly reducing intake turbidity by adjusting reservoir interconnections and applying a coagulant to the raw water system to maintain reservoir turbidity below 1.5 NTU.

The water system for Portland appears to encounter elevated turbidity conditions in their source water reservoir during storm events. With primary disinfection being chlorination only, the chlorine dosage at the water treatment plant is relatively high (3.0 – 3.5 mg/L typical, as high as 5.0 mg/L), and the system will shut down at ~5 NTU and switch to groundwater supply. While the system on the Coquitlam source can encounter similarly elevated levels of turbidity during storm events, the redundancy of ozonation and UV disinfection improves pathogen inactivation, and the reduced chlorine dose (<2.0 mg/L) minimizes DBP formation potential. The San Francisco system can also be exposed to elevated reservoir turbidity but may divert raw water to a filtration facility during storm events. Unlike the system on the Coquitlam source, the systems serving San Franciso, Boston and Portland all use chloramine for secondary disinfection, and only San Francisco appears to operate rechlorination stations among unfiltered systems using chloramine for secondary disinfection.

1.8 Considerations for the system on the Coquitlam source

The overview of unfiltered systems in Canada and the US has revealed general similarities and differences between water supply systems for large metropolitan areas. While standard operating procedures are not publicly available for any of the utilities reviewed, in some cases general disinfection and/or management of high turbidity events can be inferred. In other cases, it is not evident within the documents available. Based on this high-level overview, below are a few useful considerations for the system on the Coquitlam source to improve disinfection protocols and management of high turbidity events:

A. **Continue to connect with Seattle Public Utilities about management of rechlorination operations during turbidity events >1 NTU:** Despite differences in source water attributes, there are considerable similarities between the Cedar system and the system on the Coquitlam source in terms of their disinfection operations. It could be informative to continue discussions about how elevated turbidity events are managed at the Cedar Water Treatment Facility, and how chlorine dosage varies at the treatment plant and the rechlorination stations or reservoirs during these events.
B. **Consider the development of an Operations Support Tool for management of elevated turbidity events:** While Section 3 includes analysis of historical water quality information with the objective of improving operations protocols during elevated turbidity events, the development of an Operations Support Tool (OST) could be a goal to improve evidence-based decision making even further. The OST used by New York City is a modelling algorithm that integrates real-time system characteristics with decision scenarios that simulates water supply system attributes.[16,18] In theory, an OST of this nature could simulate free chlorine levels throughout the transmission system on the Coquitlam source given raw water turbidity levels, variation in chlorine dose scenarios at the treatment plant and re-chlorination stations, along with integrating real-time free chlorine measurements throughout the transmission system. This could help bridge the gap between water quality objectives and disinfection operations during elevated turbidity events.

C. **Continued preparation for wildfire-induced changes to turbidity and organic matter composition:** Climate change is increasing the risk of wildfires, and in Canada, wildfire regimes are increasingly characterized by more frequent larger burns and a longer fire season.[19] Since wildfire has the potential to impact water quality, each of the utilities in western Canada or US managing unfiltered supplies are considering the potential effects of wildfire. The PWB is facing the effects of wildfire directly, as the 2023 Camp Creek fire burned ~2,000 acres of land 2 km from a source water reservoir.[20] Turbidity increases in surface waters immediately post-fire due to the mobilization of burned debris and ash.[21] Sediment delivery may also increase due to change in vegetation cover and watershed geomorphology which can result in and increase in storm flashiness.[22,23] While turbidity may increase, the amount of organic matter mobilized into surface water appears to vary, but the composition of dissolved organic matter appears to become more aromatic, as implicated by post-fire increases in specific UV absorption at 254nm ($SUVA_{254}$).[24] In Boston's drinking water system, increased aromaticity of raw water is thought to increase consumption of disinfectant residuals in the transmission system.[15] Furthermore, wildfire-altered organic matter may become precursors to novel and unregulated DBPs with unknown toxicities.[24] In the event of a wildfire in the Coquitlam watershed, Metro Vancouver could consider if existing protocols to manage elevated turbidity events are adequate to ensure sufficient chlorine residuals while minimizing the formation of DBPs novel to the water supply system. $SUVA_{254}$ could be leveraged as a metric for aromaticity in an assessment of the relationship between raw water organic matter composition and decay of free chlorine in the transmission system.

Section 2: Evaluation of the relationship between turbidity and natural organic matter in raw and treated water on the Coquitlam source

Turbidity is a physical property of water which represents the degree of "optical transparency, cloudiness, or haziness due to the presence of suspended material that blocks the transmission of light".[25] When quantified directly, the amount of suspended solids is usually referred to as 'total suspended solids' or 'non-filterable residue' and is generally reported as a concentration (i.e., mg/L). The concentration of suspended material is usually determined by gravimetric analysis in a laboratory and is time-consuming and not possible for in-line, continuous monitoring applications. As such, turbidity is the preferred proxy metric for monitoring suspended solids as optical techniques that quantify turbidity are cost-effective and can be used in continuous monitoring applications. Turbidity is most often reported in 'Nephelometric Turbidity Units' (NTU), which indicates the linear increase in light scatter proportional to amount of turbidity. Nephelometry refers to the method of detecting light scatter, in which the detector is placed orthogonal (90°) to the light source.

The sources of turbidity can be diverse. Natural sediment mobilization through erosion, landslides, and bed sediment re-suspension within flowing water can increase turbidity.[25] Anthropogenic activities can also increase turbidity through urban runoff, forest management activities, and industrial discharge, and may mobilize novel solid materials such as microplastics. Likewise, the composition of turbidity can be diverse. 'Turbidity causing materials' (TCMs) may be comprised of biological particles such as suspended bacteria and algae, inorganic particles such as clay or silt, or particulate natural organic matter (NOM) such as degraded vegetation.[26] The relevance of turbidity for drinking water treatment is that suspended solids can act as carriers for contaminants such as heavy metals, nutrients, pesticides, and other organic compounds, but most relevant is that TCMs can be a medium for pathogens.[25] In the regulatory context, turbidity serves as a key metric indicating the effectiveness of a water treatment process and the extent to which water is fit for human consumption.[27] Monitoring turbidity is ubiquitous in drinking water systems. Suspended sediments can reduce the effectiveness of UV disinfection by shielding pathogens, which may prevent them from being exposed to enough UV to be eliminated.[26]

NOM is an extremely diverse mixture of organic compounds. Particulate NOM are TCMs, but the primary component of NOM is usually dissolved, except during high flow conditions in aquatic environments where particulate mobilization can be high.[28] The presence of NOM in drinking water systems is crucial because it influences both water treatment processes and potential indirect health impacts. Health Canada[3] lists five effects of NOM in drinking water systems: 1) Alteration of coagulant demand and/or deterioration of pathogen removal; 2) it exerts a chemical disinfectant demand and interferes with UV disinfection; 3) it is a precursor to the formation of disinfectant byproducts (DBPs) through reactions with chemical disinfectants; 4) it stimulates biofilm formation in transmission infrastructure; 5) it promotes lead and copper corrosion in pipes and fittings. Health Canada[3] suggests monitoring of various parameters indicative of NOM characteristics to guide operations of drinking water systems. Parameters which indicate the amount of NOM are total organic carbon (TOC) which is the sum of particulate and dissolved organic carbon, dissolved organic carbon (DOC), and UV transmittance at 254nm (UVT).

The system on the Coquitlam source qualifies for filtration exemption as outlined by the Drinking Water Treatment Objectives (Microbiological) for Surface Water Supplies in British Columbia[1]. Sediments and NOM mobilized in the Coquitlam watershed during storms events are conveyed into the transmission system after being exposed to ozonation, UV, and chlorination treatment. Metro Vancouver follows a set of protocols during these events which include increasing the chlorine dosage at the Coquitlam Water Treatment Plant (CWTP) and at rechlorination stations throughout the transmission system serviced by Coquitlam source water (further described in Section 3). The boosting of chlorine is meant to ensure biological stability throughout the transmission system because elevated sediments and NOM may increase free chlorine decay. A study has indicated that the organic fraction of suspended sediments is usually responsible for the increase in chlorine demand in distributions systems.[29] As such, chlorine demand has been demonstrated to be correlated with both turbidity and TOC when TOC and turbidity are highly correlated. In these cases, turbidity may be a reasonable proxy for TOC. However, NOM has been observed to increase prior to changes in turbidity and may be elevated even after turbidity decreases.[3] It is unclear to what extent turbidity is a reasonable proxy for NOM in water on the Coquitlam source. Furthermore, it is worth assessing how treatment steps alter the composition of sediments and NOM, since post-treatment water quality is most relevant to chlorine demand in the transmission system.

The purpose of this investigation is to explore the relationship between NOM and turbidity in the system on the Coquitlam source. This is important because turbidity is the sole metric used to indicate increased risk of free chlorine decay in the transmission system during events in which particulate and dissolved matter are elevated in the source water. The focus is the raw Coquitlam Lake water entering the CWTP, and the treated water leaving the CWTP. Through characterizing seasonal trends in turbidity and NOM and investigating their relationship, this study tests the assumption that turbidity is a consistently reliable proxy for NOM. This analysis also tests the difference between turbidity and NOM relationships between raw and treated water, since the ozonation treatment process could alter the nature of these relationships. Finally, this analysis tests the extent to which UVT is a reasonable proxy for NOM, since it is the parameter most suited to guiding treatment protocols as it can be measured continuously *in situ* (i.e., online).

2.1 Methods

The water quality dataset includes daily grab samples of turbidity (NTU), sub-weekly grab samples of TOC (mg/L) and UVT (%), and weekly grab samples of DOC (mg/L). If parameters were measured more than once per day, the daily average was calculated. The time span of analysis is January 1, 2015, to December 31, 2024, for water entering the CWTP ('Coquitlam Intake') and treated water leaving the CWTP ('Coquitlam #3 Main'). Within the figures and the sections below, 'Coquitlam Intake' is referred to as 'raw' water, and 'Coquitlam #3 Main' is referred to as 'treated' water. The size of the dataset for daily averages is 3625 and 3639 for turbidity, 1456 and 504 for TOC, 580 and 502 for DOC, and 1435 and 1422 for UVT for raw and treated water, respectively.

Seasonal plots of water quality parameters are ordered by the water year (October 1 – September 31) to align with the hydrological cycle of the watershed where increased precipitation and establishment of high elevation snowpack begins each year approximately in October. Confidence intervals (95%) for data at the monthly scale were calculated using bootstrapping due to the large sample size, non-normality, and unequal variance of the dataset. The R package *boot* was used to execute bootstrap resampling at 1000 replicates.[30] Linear regressions were conducted for TOC, DOC, or UVT as a function of turbidity for 1) the entire dataset, and 2) when turbidity > 0.9 NTU which is the first trigger condition to initiate elevated turbidity response disinfection protocols. Turbidity was transformed by $\log_{10}$ due to the right-skewed tendency of turbidity data (most values around 0.4 NTU with several high outliers). Linear regressions were also conducted for TOC and DOC as a function of UVT for 1) the entire dataset, and 2) when turbidity > 0.9 NTU. For each linear regression, the slope and 95% confidence intervals for the slope were calculated using bootstrapping. Both the range of the confidence intervals of the slope and the fit of the regression model (R^2) were used to assess the strength of the relationship between parameters. All quantitative data analysis and figure production was conducted using R[31] in RStudio[32] using *tidyverse,*[33] *readxl*,[34] and *lubridate*.[35] Figures were arranged as multi-plots using the R package *ggpubr*.[36]

2.2 Results and Discussion

Turbidity was highest between October – April, in line with the months of highest precipitation early in the water year (Figure 2.1). Between September – April was the only period in which turbidity exceeded 0.9 NTU and was also the period with the most variability. TOC and DOC followed a similar trend as turbidity, with each displaying a noticeable peak in November, but were less variable across the water year. UVT was lowest between October – November. These seasonal trends were expected given that in months of highest precipitation is when the greatest mobilization of terrestrial sediments and NOM will occur in the Coquitlam Lake watershed.

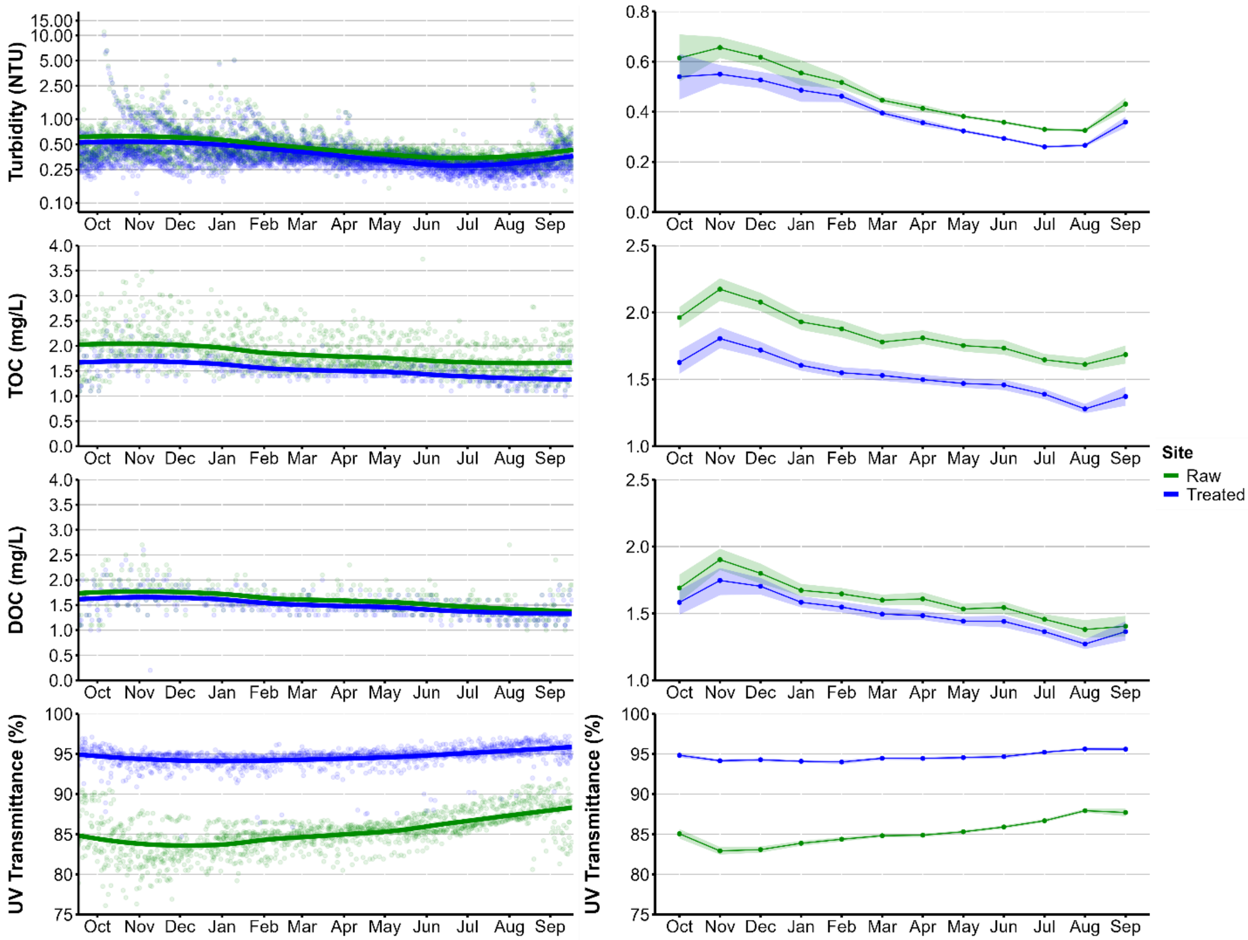

Figure 2.1. Turbidity, TOC, DOC and UV Transmittance at 254nm for raw (green) and treated (blue) water on the Coquitlam source throughout the water year from 2015 – 2024. Daily averages of each parameter and a LOESS trendline are plotted on the left, and monthly averages and 95% confidence intervals are plotted on the right. Note the log-scale y-axis on the top left turbidity plot.

Turbidity was lower in treated than raw water, but more significantly different between March – September (Figure 2.1). The average raw water turbidity was 0.47 NTU, and 0.40 NTU for treated water. TOC in treated water was consistently lower than in raw water, with an average of 1.52 mg/L compared to 1.83 mg/L, respectively. The distance between confidence intervals throughout the entire year indicates the difference in TOC between raw and treated water is statistically significant. Treated water DOC was slightly lower than in raw water, with an average of 1.50 mg/L and 1.59 mg/L, respectively. The difference was only significant between February – August. When all data is pooled together, it is evident that most NOM in raw water is dissolved with a small proportion in particulate form since TOC is slightly greater than DOC (Figure 2.2). In treated water, the NOM pool is predominantly dissolved. UVT was much higher and more stable in treated water than in raw water, with an average of 94.7% and 85.2%, respectively (Figure 2.1).

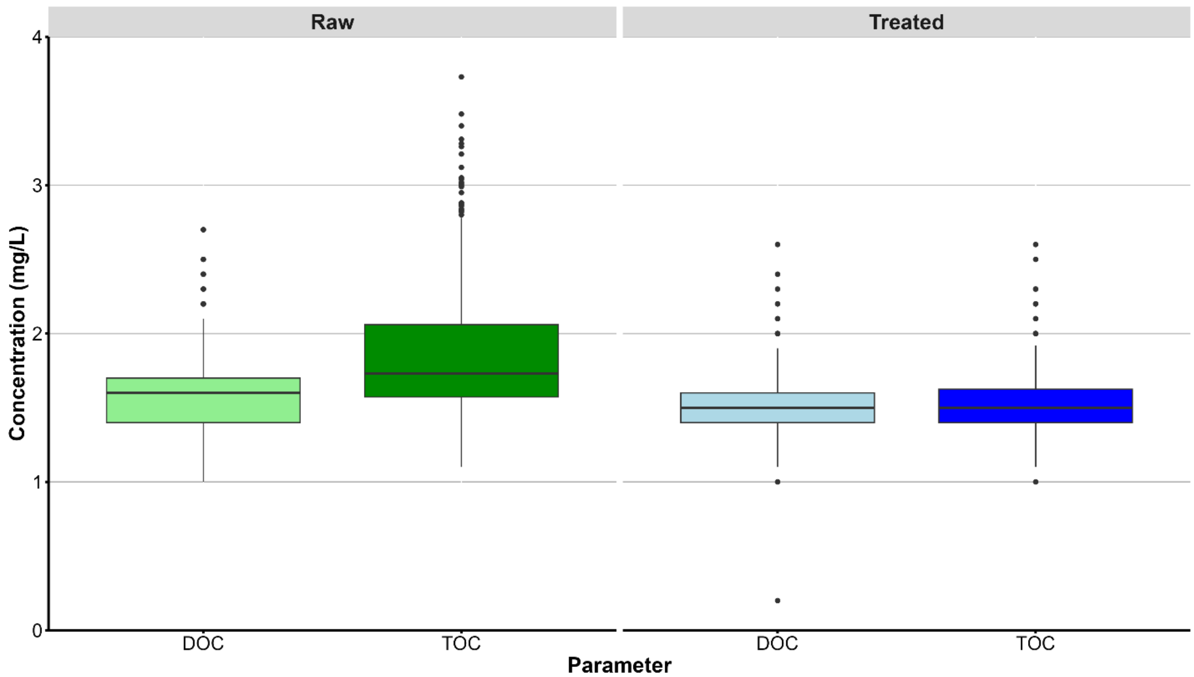

Figure 2.2. Boxplots of DOC and TOC for raw (green) and treated (blue) water on the Coquitlam source from 2015 – 2024.

Regression analysis for the entire dataset indicates that a linear relationship between turbidity and NOM parameters does not capture variation in the dataset well, with R^2 ranging between 0.15 – 0.38 (Table 2.1). Despite the overall poor linear model fit, the 95% confidence intervals for the slopes not overlapping 0 suggests a somewhat real association, where positive slopes of TOC and DOC as a linear function of $\log_{10}$(Turbidity) indicates increasing levels of NOM is somewhat related to increased turbidity. Similarly, the negative slope of UVT as a linear function of $\log_{10}$(Turbidity) indicates decreasing UVT is related somewhat to increasing turbidity. The nature of the relationships in raw compared to treated water do not vary considerably for TOC or DOC, but the slope of the relationship between UVT and $\log_{10}$(Turbidity) is much more negative for raw water (Figure 2.3).

Table 2.1. Results of linear regressions of TOC, DOC, and UVT as functions of $\log_{10}$(Turbidity) including 95% confidence intervals (C.I.) from 2015 – 2024 of raw and treated water on the Coquitlam source.

Water	Parameter	Slope (C.I. Range)	R^2	n
Raw	TOC	0.95 (0.86 – 1.05)	0.17	1455
Treated	TOC	0.74 (0.64 – 0.86)	0.30	504
Raw	DOC	0.85 (0.71 – 1.00)	0.25	580
Treated	DOC	0.70 (0.58 – 0.84)	0.26	502
Raw	UVT	-8.89 (-9.52 –-8.37)	0.38	1435
Treated	UVT	-2.70 (-3.02 –-2.40)	0.15	1422

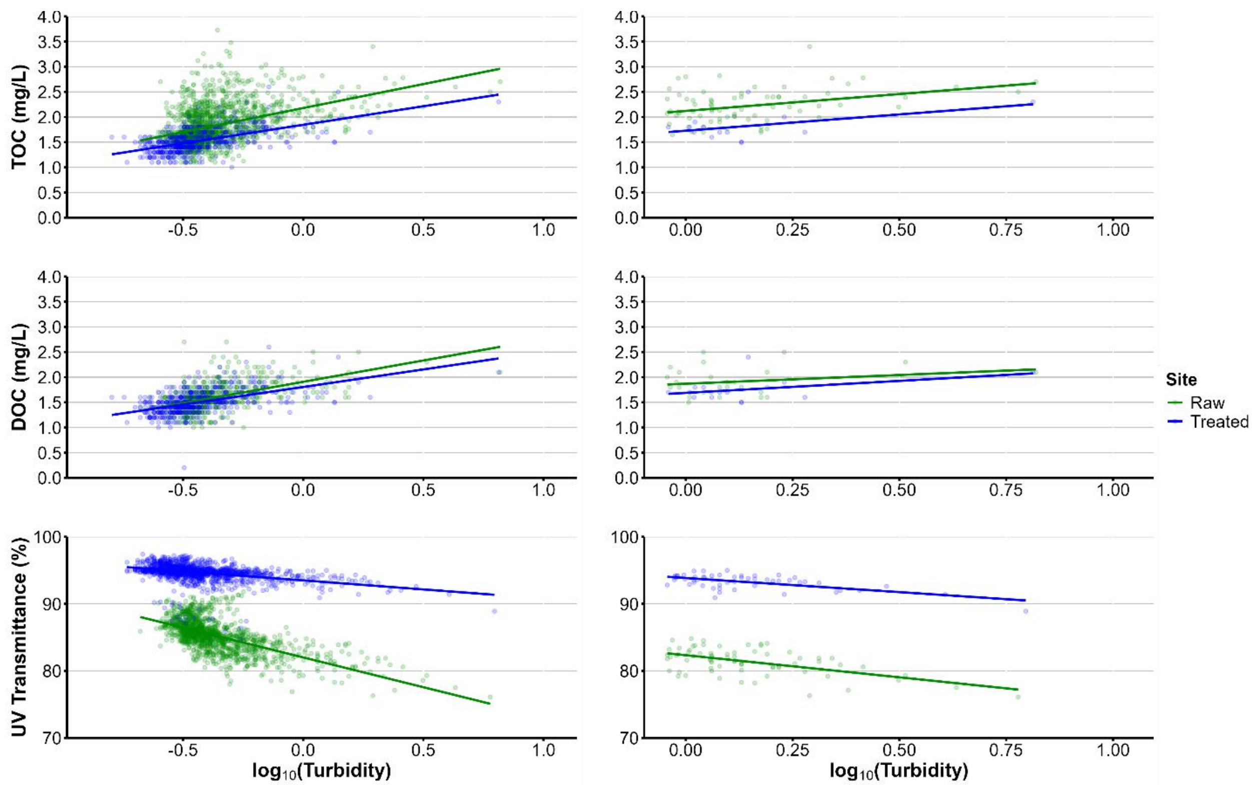

Figure 2.3. Linear regressions for TOC, DOC, and UV Transmittance at 254nm as functions of $\log_{10}$(Turbidity) for the entire dataset (left) and when Turbidity > 0.9 NTU (right) for raw (green) and treated (blue) water on the Coquitlam source from 2015 – 2024.

Levels of NOM and turbidity are not closely related when turbidity is elevated. R^2 values are similarly low across the six model variants (0.05 – 0.38), and the 95% confidence intervals for regressions of DOC in raw and treated water and TOC in treated water overlap with 0, indicating a poor real association with increasing turbidity (Table 2.2). The strongest relationship is UVT as a function of $\log_{10}$(turbidity) in both raw and treated water, with the highest R^2 values and similar magnitudes of slopes which do not overlap with 0, indicating a similar association of decreasing UVT within increasing turbidity in raw and treated water (Figure 2.3).

Table 2.2. Results of linear regressions of TOC, DOC, and UVT as functions of log10(Turbidity) including 95 % confidence intervals (C.I.) when turbidity was > 0.9 NTU from 2015 – 2024 in raw and treated water on the Coquitlam source.

Water	Parameter	Slope (C.I. Range)	R^2	n
Raw	TOC	0.67 (0.35 – 1.03)	0.13	74
Treated	TOC	0.65 (-0.90 – 1.63)	0.23	14
Raw	DOC	0.35 (-0.84 – 0.99)	0.05	27
Treated	DOC	0.48 (-0.58 – 1.62)	0.17	14
Raw	UVT	-6.59 (-8.45 –-4.23)	0.30	72
Treated	UVT	-4.21 (-5.42 –-2.01)	0.38	54

Table 2.3. Results of linear regressions of TOC and DOC as functions of UVT including 95 % confidence intervals (C.I.) for the entire dataset and when turbidity was > 0.9 NTU from 2015 – 2024 in raw and treated water on the Coquitlam source.

Period	Water	Parameter	Slope (C.I. Range)	R^2	n
Entire	Raw	TOC	-0.12 (-0.13 –-0.11)	0.55	1301
Entire	Treated	TOC	-0.09 (-0.14 –-0.06)	0.25	357
Entire	Raw	DOC	-0.09 (-0.10 –-0.08)	0.64	417
Entire	Treated	DOC	-0.08 (-0.13 –-0.06)	0.22	355
> 0.9 NTU	Raw	TOC	-0.13 (-0.17 –-0.10)	0.62	67
> 0.9 NTU	Treated	TOC	-0.07 (-0.16 –-0.13)	0.23	10
> 0.9 NTU	Raw	DOC	-0.12 (-0.16 –-0.09)	0.77	19
> 0.9 NTU	Treated	DOC	-0.04 (-0.13 – 0.16)	0.11	10

DOC and TOC are reasonably linearly related to UVT in raw water but not in treated water (Table 2.3). The range of R^2 for both parameters for all data and when turbidity > 0.9 NTU is much higher for raw water (0.55 – 0.77) than treated (0.11 – 0.25; Table 2.3). This suggests that a UVT reasonably captures variability in TOC and DOC in raw water but not in treated water. Slope confidence intervals for all subsets of relationships appear to indicate that there is a real association between decreases in UVT being linearly related to increases in DOC and TOC, but the linear regression appears to better capture the range of data for raw than treated water (Figure 2.4). There does not appear to be a considerable difference whether all data is included or only when turbidity levels are > 0.9 NTU, but further inference is limited by the small size of DOC and TOC samples during days of elevated turbidity.

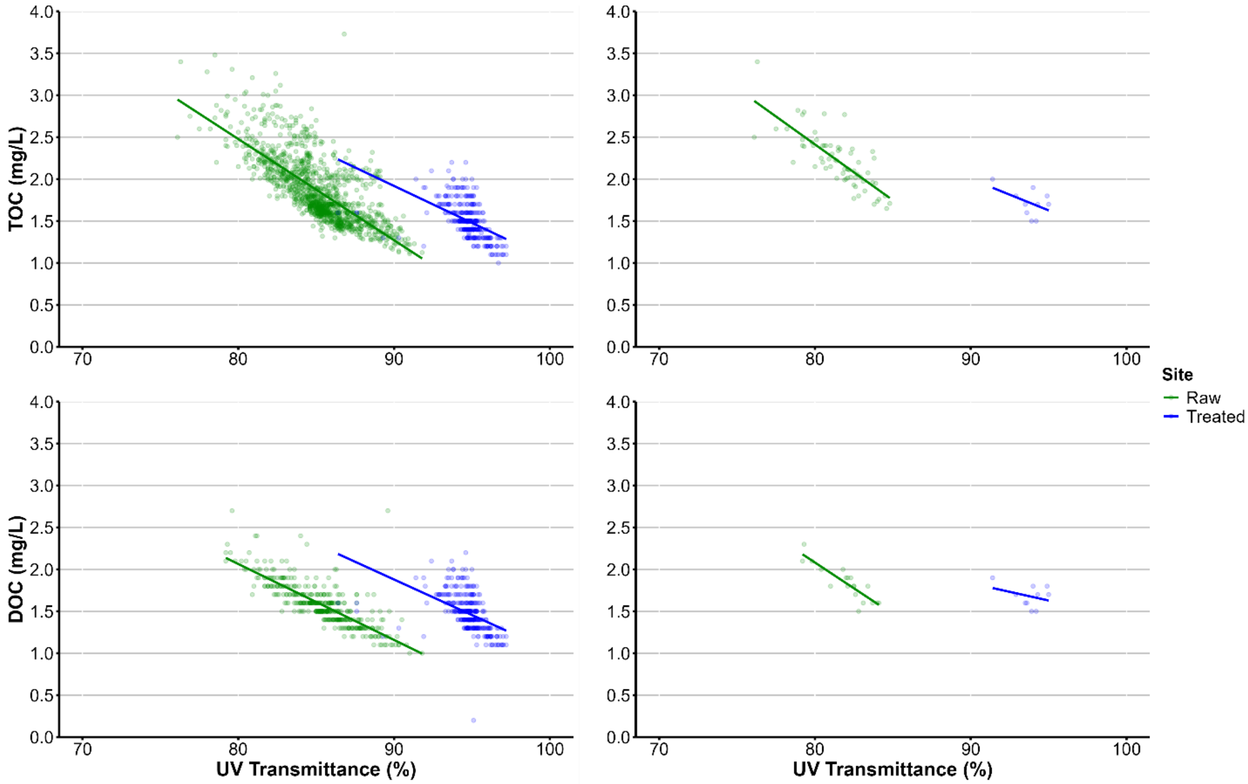

Figure 2.4. Linear regressions for TOC and DOC as functions of UV Transmittance at 254nm for the entire dataset (left) and when Turbidity > 0.9 NTU (right) in raw (green) and treated (blue) water on the Coquitlam source from 2015 – 2024.

Together, these results yield a few important implications for considering the extent to which turbidity represents NOM in raw and treated water on the Coquitlam source. The results show that treatment effectively removes most particulate NOM, leaving primarily dissolved NOM in treated water. This is evident when comparing TOC and DOC in raw and treated water, where TOC was greater than DOC in raw but not in treated water. This can largely be explained by the oxidation of particulate NOM due to ozonation treatment. Furthermore, this indicates that the composition of remaining suspended sediments in treated water is primarily inorganic. The bulk composition of dissolved NOM also appears to be altered due to treatment, despite the difference in DOC between raw and treated water being relatively small. This is evident in the difference in linear relationships between DOC and UVT in raw and treated water. UVT will vary in response to the amount of chromophoric NOM, or organic molecules that have chromophores which will absorb light at 254 nm, which tend to be larger molecular weight and with aromatic structures.[37] The stronger linear relationship between UVT and DOC in raw water indicates an appreciable proportion of dissolved NOM is larger molecular weight with greater aromaticity, but the weakening of this relationship in treated water despite the similar magnitude of DOC suggests that the treatment transforms NOM into compounds that have smaller molecular weight and lower aromaticity. This is likely due to ozonation, which oxidizes larger organic molecules and transforms them into smaller forms with lower structural complexity.[37,38]

Another main implication of these results is that turbidity does not appear to be a consistent proxy for NOM in the system on the Coquitlam source. This is most evident in the poor linear relationships between TOC and DOC with turbidity. There does appear to be a real effect of elevated turbidity being related to increases in TOC and DOC, but the variation in TOC and DOC levels, particularly at their highest, is not well captured by turbidity. This indicates that there are instances where increased dissolved NOM does not coincide with elevated turbidity levels. Health Canada[3] suggests that DOC < 1.8 mg/L should be a target for treated water to ensure biological stability. Between 2015 – 2024 with a sampling frequency of approximately once per week, there were 29 treated water samples where turbidity was < 0.9 NTU but DOC was > 1.8mg/L, while there were only 3 samples where DOC was > 1.8 mg/L when turbidity was > 0.9 NTU. Across the number of weeks between 2015 – 2024, this amounts to an estimated occurrence rate of ~6% compared to ~0.6%. This suggests that in the system on the Coquitlam source, there are events of elevated dissolved NOM in raw water that may not coincide synchronously with elevated turbidity. Furthermore, the form of dissolved NOM in treated water being minimally chromophoric at 254 nm (i.e., does not absorb light at 254 nm) means that instances of elevated dissolved NOM may largely go undetected by online UVT sensors measuring treated water.

2.3 Conclusions and Recommendations

The main purpose of this study was to assess the extent to which turbidity reliably approximates NOM in the Coquitlam source. To fully understand this relationship, it was also necessary to assess turbidity and metrics of NOM in raw and treated water to better understand differences in magnitude, seasonality, and the effects of treatment. Finally, given that chlorine setpoints are adjusted according to online measurements of turbidity in raw water, it was important to assess the extent to which UVT, also measured online, adequately represents NOM in raw and treated water. Analysis of a dataset covering 10 years of historical samples collected daily or weekly for turbidity, DOC, TOC, and UVT indicates that turbidity is not a consistently reliable proxy for NOM. This implies that some events of elevated turbidity likely do not coincide synchronously with events of elevated NOM. All NOM, either particulate or dissolved, appears to transform into predominantly small, structurally simple dissolved compounds due to ozonation. These compounds generated from elevated turbidity and dissolved NOM events have the potential to increase chlorine demand throughout the transmission system. Based on these findings, the following steps are recommended to support further refinement of disinfection protocols during events of elevated turbidity and NOM:

A. **Improve sensitivity of response protocols to elevated natural organic matter.** The protocols that adjust chlorine setpoints at CWTP and at rechlorination stations are best suited to managing events of elevated particulate NOM due to the key response trigger of raw water turbidity levels. These protocols in their current form are not tuned to respond to events of elevated dissolved NOM independent of elevated turbidity, which appear to occur in the Coquitlam source. Given that UVT appears to be adequately sensitive to DOC in raw water, thresholds of online UVT in raw water could be utilized to adjust chlorine doses to manage the increased chlorine demand from events of elevated dissolved NOM. Note that online UVT of treated water would not be as useful in this context given that ozonation appears to alter the composition of dissolved NOM such that a considerable proportion of it is likely undetected by UVT sensors.
B. **Further research is needed to determine the extent to which turbidity and UVT are sensitive to changes in natural organic matter.** A targeted sampling campaign involving hourly sampling of turbidity, UVT, DOC, and TOC could further support the use of raw water UVT to address chlorine dosing protocols during storm events. This could help to refine disinfection protocols during storm events by indicating the relative timing and persistence of dissolved NOM and turbidity peaks, which would inform decision criteria (e.g., even if turbidity is < 0.9 NTU for 48hrs, UVT could still be above a certain threshold indicating the necessity for increased chlorine doses to be maintained).
C. **Further research is needed to characterize asynchrony in elevated particulate and dissolved organic matter.** In future historical analyses, both online turbidity and UVT in raw water could be evaluated for their influence on free chlorine levels across the transmission system on the Coquitlam source, considering the potential for asynchronous turbidity and dissolved NOM peaks to impact free chlorine decay.

Section 3: Assessment of free chlorine levels during elevated turbidity events in the transmission system on the Coquitlam source

The drinking water transmission and distribution system is the last protective barrier before water is used.[39] The extent to which there is minimal change in water quality due to microbial growth throughout water distribution systems is referred to as biological stability. The risks associated with increased microbial growth and poor biological stability relate to health and water aesthetics (i.e., taste, colour, and odor). Numerous factors influence biological stability, which is often contextualized through the concept of the distribution system as a "reactor."[39] Water in the distribution system contains particles, nutrients, and microorganisms which can interact with biofilm, loose deposits, and the piping material and alter treated water quality. Furthermore, reaction rates that decrease biological stability are known to increase with water temperature. The major health risks associated with poor biological stability include exposure to microorganisms but also exposure to metal precipitates and disinfection by-products.[40] The general approach to maintaining biological stability involves minimizing the introduction of biological and chemical constituents that can degrade water quality in the distribution system, and maintaining a disinfectant residual, such as free chlorine, throughout the transmission system.[39] However, increased levels of disinfectants can lead to elevated disinfection by-products, and thus this balance of maintaining adequate residual disinfection while minimizing the potential formation of disinfection by-products in often referred to as a "risk-risk tradeoff."[15]

In Metro Vancouver's drinking water system, the transmission system refers to the series of watermains and reservoirs that convey and store water from the Coquitlam Water Treatment Plant (CWTP) and the Seymour-Capilano Filtration Plant to member jurisdictions within the Greater Vancouver Water District. The distribution system refers to the extension of the transmission system into infrastructure managed by member jurisdictions. It is Metro Vancouver's responsibility to maintain high-quality drinking water throughout the transmission system, and a key component of this is to ensure an adequate level of the residual disinfectant, free chlorine, is maintained.

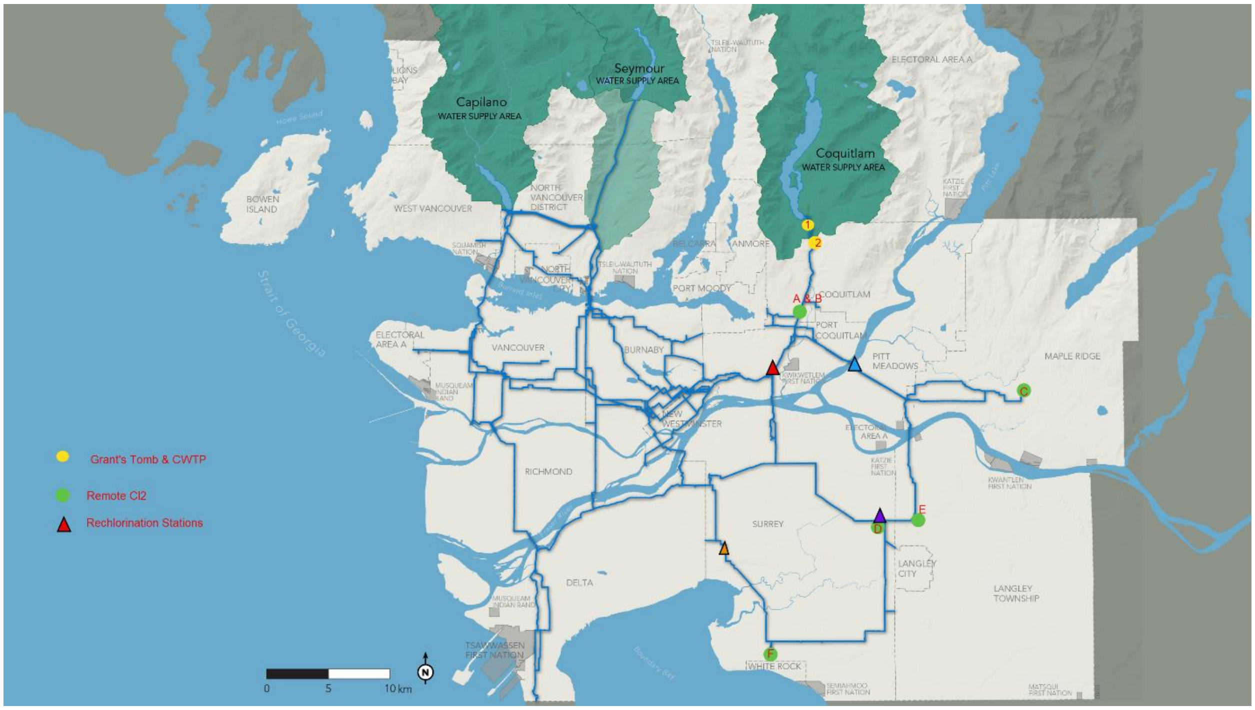

Figure 3.1. Map of the Greater Vancouver Watershed District transmission system, with relevant locations identified in the system on the Coquitlam source: yellow #1 = Coquitlam raw water intake, yellow #2 = treated water leaving Coquitlam Water Treatment Plant, green A+B = Coquitlam Mains at Woodland & Kitchener, green C = Maple Ridge reservoir inlet/outlet, green D = Clayton Reservoir outlet, green E = Jericho Reservoir outlet, green F = Sunnyside Reservoir inlet, red triangle = Cape Horn rechlorination station, blue triangle = Pitt River rechlorination station, purple triangle = Clayton rechlorination station, orange triangle = Newton rechlorination station. Note that this figure was produced by Metro Vancouver.

The lowest acceptable level of free chlorine within the Metro Vancouver transmission system is 0.2 mg/L (Vila Goh, personal communication, July 21, 2025). To maintain adequate levels of free chlorine within the Coquitlam supply system, chlorine is generally dosed at 1.3 mg/L at the CWTP, and 1.2 mg/L at rechlorination stations serviced by the CWTP (i.e., Cape Horn, Pitt River, and Clayton; Figure 3.1).[41] Organic matter and particulates can be mobilized in the Coquitlam watershed during storm events, which increase the risk of biological instability and reduction of free chlorine levels throughout the transmission system on the Coquitlam source. This risk is particularly relevant due to the Coquitlam source being unfiltered, and thus particulate and organic matter will be conveyed into the transmission system after undergoing ozonation and UV treatment (see Section 2 for more details). To maintain adequate free chlorine residuals during these events, chlorine dose at the CWTP and rechlorination stations is increased. The conditions that require adjustments to treatment, such as changes to setpoints and their duration, are outlined in a series of Alarm Response Operations Procedures (hereafter referred to as response protocols). With respect to trigger conditions, dosing, and longevity, the response protocols are as follows:

1. Turbidity levels are above 0.9 NTU in the Coquitlam raw water for a minimum of 30min:[41]
    a. Increase chlorine setpoints to 1.5 mg/L at CWTP and 1.4 mg/L at rechlorination stations.
    b. Go back to default chlorine setpoints at all sites once turbidity is < 0.9 NTU for 48hrs and system attributes are acceptable.
2. Turbidity levels are above 3.0 NTU in the Coquitlam raw water for a minimum of 30min:[42]
    a. Increase chlorine setpoints to 1.7 mg/L at CWTP and 1.6 mg/L at rechlorination stations.
    b. Go back to Protocol 1 setpoints at all sites once turbidity is < 3.0 NTU for 48hrs and system attributes are acceptable.
3. Turbidity levels are above 5.0 NTU in the Coquitlam raw water for a minimum of 30min:[43]
    a. Increase chlorine setpoints to 1.9 mg/L at CWTP and 1.8 mg/L at rechlorination stations.
    b. Go back to Protocol 2 setpoints at all sites once turbidity is < 5.0 NTU for 48hrs and system attributes are acceptable.

Turbidity is the key characteristic in raw water that triggers these protocols, as it represents elevated particulates and organic matter that can increase the free chlorine decay rate in the transmission system (see Section 2 for more information about the degree to which turbidity represents organic matter). Turbidity can be elevated in Coquitlam Lake mainly from heavy rains that mobilize organic matter and particulates in the Coquitlam watershed.[44] However, turbidity events may also result from landslides, or during high wind events when there are low water levels in Coquitlam Lake which leads to mobilization of particulate matter from exposed banks (Vila Goh, personal communication, May 16, 2025). During elevated turbidity events, an aspect of interest within the response protocols is that free chlorine levels in the transmission system are not fully considered when deciding when the free chlorine should be returned to the default setpoints. Since it takes a considerable amount of time for water to travel from the CWTP throughout the transmission system on the Coquitlam source, lowering the chlorine setpoints concurrently at the CWTP and the rechlorination stations has the potential to increase the risk of free chlorine decay. Furthermore, the extent to which seasonality, turbidity characteristics, and water temperature during elevated turbidity events alters the free chlorine levels throughout the transmission system is of interest to support evidence-based decision-making.

The purpose of this investigation is to characterize free chlorine levels in the transmission system on the Coquitlam source during elevated turbidity events to determine the extent to which disinfection protocols maintain adequate free chlorine residuals throughout the transmission system. The focus is on the event scale (n = 34 events) to characterize the levels of free chlorine at multiple points in the transmission system during the event and afterwards. Cross-correlation analysis was performed to assess the temporal lag and alignment of free chlorine between monitoring sites and the nearest upstream location where chlorination occurs – this estimates water travel time. Time series analysis of outlier events where free chlorine levels fell below ideal levels (0.4 mg/L) was conducted to further understand the nature of these instances. Finally, multivariate analysis was conducted to determine which turbidity event characteristics drive variation in free chlorine levels in the transmission system, including magnitude of turbidity, duration of event, upstream free chlorine levels, season, and water temperature. The primary question of this research is: *How well are the response protocols maintaining target free chlorine residual levels in the transmission system on the Coquitlam source during elevated turbidity events, and what factors explain their variation?*

3.1 Methods

The water quality dataset includes hourly averages from January 1, 2015, to December 31, 2024 (n = 87,672). Data analyzed includes online measurements of turbidity (NTU) and water temperature (°C) from Grant's Tomb, representative of turbidity levels and temperature of raw water at the intake of the CWTP. Free chlorine levels leaving CWTP was represented by online measurements in Coquitlam Main No. 3 at the CWTP. Free chlorine levels throughout the transmission system were represented by: 1) Coquitlam Main No. 3 upstream and downstream from the Cape Horn rechlorination station (RCL); 2) Haney Main No. 2 upstream and downstream from the Pitt River RCL; 3) Jericho-Clayton Main upstream and downstream from the Clayton RCL; 4) Whalley-Clayton Main upstream and downstream from the Clayton RCL; 5) remote meters in Coquitlam Main No. 3 at Woodland & Kitchener and Maple Ridge Reservoir Inlet/Outlet. Note that no free chlorine data is available for Maple Ridge Reservoir Inlet/Outlet before March 21, 2021.

Online water temperature data was not available for the transmission system. Water temperature in the transmission system was characterized by periodic grab samples. Water temperature at 'Coq #3 East at Cape Horn' was used to represent water temperature near the Cape Horn RCL; 'Haney Main No. 2' was used to represent Pitt River RCL; 'Clayton – Langley Main' was used to represent Jericho – Clayton Main at the Clayton RCL; and 'Whalley Reservoir' was used to represent Whalley-Clayton Main at the Clayton RCL. If parameters were measured more than once per day, the daily average was calculated.

Turbidity events were classified as the period where turbidity in the raw water was above 0.9 NTU, including any period where turbidity was less than 0.9 NTU for less than 48 hrs. The event selection process removed most turbidity events with missing data (i.e., NA values for turbidity), any events with outlier readings (i.e., if a reading was > 3*quartile 3), any event where the duration was less than 1hr (i.e., a single reading above 0.9 NTU), and any events with substantially elevated turbidity at the beginning or end of the event (i.e., the first or final turbidity values are > 2.0 NTU). Events that contained NAs were visually assessed, and five events appeared to have appropriate data for inclusion, and NA data was linearly interpolated (max gap was < 3hrs) or removed if some NAs were at the beginning of the event (max gap was < 4hrs). Furthermore, turbidity data 6hrs before and up to 120hrs after each event was selected to evaluate event characteristics. In some cases, multiple events overlapped, and these pairs of events were excluded from further analysis. This event selection process yielded 34 elevated turbidity events, and event characteristics such as peak turbidity, average turbidity, average water temperature, event start time, event end time, and event duration in hours were calculated. For further multivariate analysis, the day of year according to an adjusted water year (September 1 – August 31) was calculated to represent the seasonality of the event. This was chosen over the water year described in Section 2.1, as it was observed that elevated turbidity events within September are more closely aligned in character with those in October, and no elevated turbidity events occurred in August.

The timestamps from the selected turbidity events were used to select free chlorine data at sites throughout the transmission system using the R package *fuzzyjoin*.[45] Event characteristics including average turbidity, peak turbidity, and average water temperature in raw water, along with median free chlorine leaving CWTP was calculated for the 6 hour period before the event (i.e., pre-event), during the event, and 48 hours after the event (48hrs), 49 – 72 hours after the event (72hrs), 73 – 96 hours after the event (96hrs), and 97 – 120 hours after the event (120hrs). The median and minimum free chlorine was also calculated for these same time periods at all transmission system sites. Boxplots were produced to assess free chlorine levels before, during, and after events, as well as free chlorine at 48hrs after the event. Water temperature from discrete samples taken in the transmission system were assigned to each event by taking the average value across any sample taken in the pre-event, event, and post-event periods. Outlier events were evaluated to assess the patterns of low free chlorine levels in the transmission system, and time series of any event where minimum free chlorine levels fell below 0.4 mg/L was visualized for further analysis.

Cross-correlation analysis (CCA) was carried out using the *ccf()* function in R.[31] This analysis estimates the water travel time between upstream and downstream sites in the transmission system during events using free chlorine levels. The estimate was determined by identifying the negative lag with the highest Pearson correlation for each event and then finding the most common lag across all events. For Cape Horn, CCA was conducted between the CWTP and upstream of the Cape Horn RCL; for Pitt River, CCA was conducted between the CWTP and upstream of the Pitt River RCL; for Jericho-Clayton, CCA was conducted between the Pitt River

RCL and upstream of Clayton RCL in the Jericho-Clayton Main; for Whalley-Clayton, CCA was conducted between the Cape Horn RCL and upstream of Clayton RCL in the Whalley-Clayton Main; for Woodland-Kitchener, CCA was conducted between the CWTP and at the Woodland-Kitchener monitoring site. Cross-correlation analysis was not conducted for the Maple Ridge monitoring site given the complexity of the reservoir operations.

Random forest analysis was used to assess the relative importance of event seasonality, average turbidity, peak turbidity, water temperature, duration, and median upstream free chlorine levels in explaining variation of median and minimum free chlorine upstream of RCLs. A mixed-effects random forest (MERF) was selected for its flexibility and ability to handle repeated-measures data and nonlinear relationships.[46] The R package *LongituRF*[47] was used to run the models using the function *MERF()*. The variable importance metric 'percent increase in mean standard error' (%IncMSE) was selected as it is a direct representation of each predictor's influence on overall model accuracy.[48] The MERF model was used to produce predictor rankings by %IncMSE using the *importance()* function from the R package *randomForest.*[49] Models were cross-validated with 5 folds using the R package *caret*,[50] and partial dependence plots (PDPs) were produced for each predictor using the R package *pdp*[51] to describe the relationship between event characteristics and free chlorine at sites in the transmission system.

3.2 Results and Discussion

The average peak turbidity across the 34 events was 2.16 NTU, ranging from 0.96 – 16.69 NTU. Average event turbidity was 1.11 NTU, ranging from 0.82 – 2.39 NTU. Average water temperature of raw Coquitlam water during events was 7.6°C, and ranged from 3.9 – 14.5°C. The average event duration was 115 hours, and events ranged from 7 – 826 hours (i.e., up to a month long). Turbidity event characteristics for each event are summarized in Appendix Table A1.

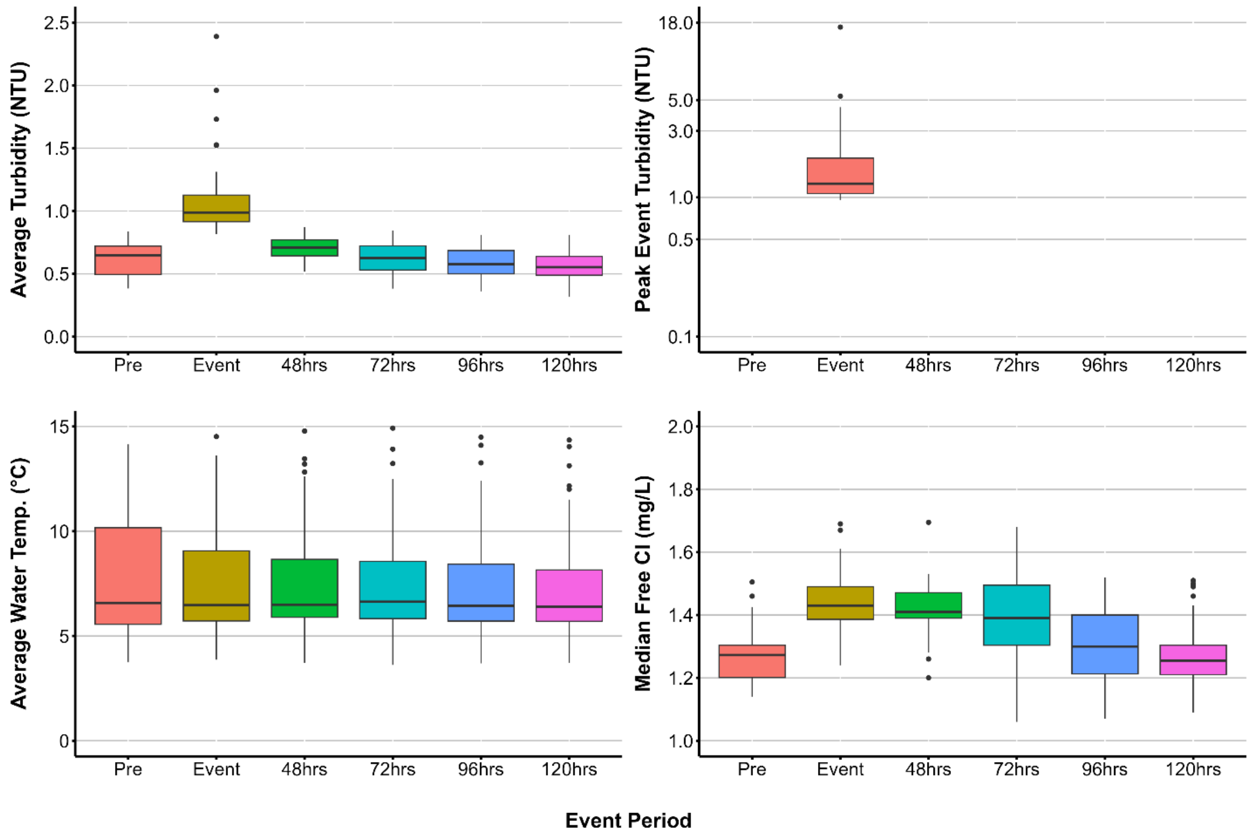

Figure 3.2. Boxplots of average turbidity (NTU), peak turbidity (NTU) and average water temperature (°C) in raw water entering the CWTP, and median free chlorine (mg/L) leaving the CWTP before, during, and after elevated turbidity events between 2015 – 2024 (n = 34 events). Note the log-scale y-axis on the peak event turbidity plot.

While average turbidity of most events was ~1 NTU, there were 4 outlier events with average levels above 1.5 NTU (Figure 3.2). The temporal trend of average turbidity before, during, and after events demonstrates that event classification adequately captured elevated turbidity conditions, and that elevated turbidity conditions largely subsided after 48hrs. Peak turbidity of most events was below 5.0 NTU, with only two events exceeding this threshold. Water temperatures varied greatly between each event, however the extent of the third quartile (i.e., the upper limit of the boxplots) appeared to decrease through pre-event, event, and post-event conditions, suggesting that the event led to the lowering of raw intake water temperatures in some events with elevated pre-event water temperatures. Median free chlorine levels leaving CWTP were variable, but there was a clear pattern of pre-event free chlorine levels at ~1.3 mg/L, increasing generally above 1.4 mg/L during the event, and then decreasing gradually and taking up to 120hrs to return to the pre-event free chlorine levels. These visuals demonstrate the implementation of the turbidity response protocol, where chlorine setpoints were raised when turbidity went above the 0.9 NTU threshold. Furthermore, the application of the elevated setpoint appears to persist between 48 – 120hrs after the event.

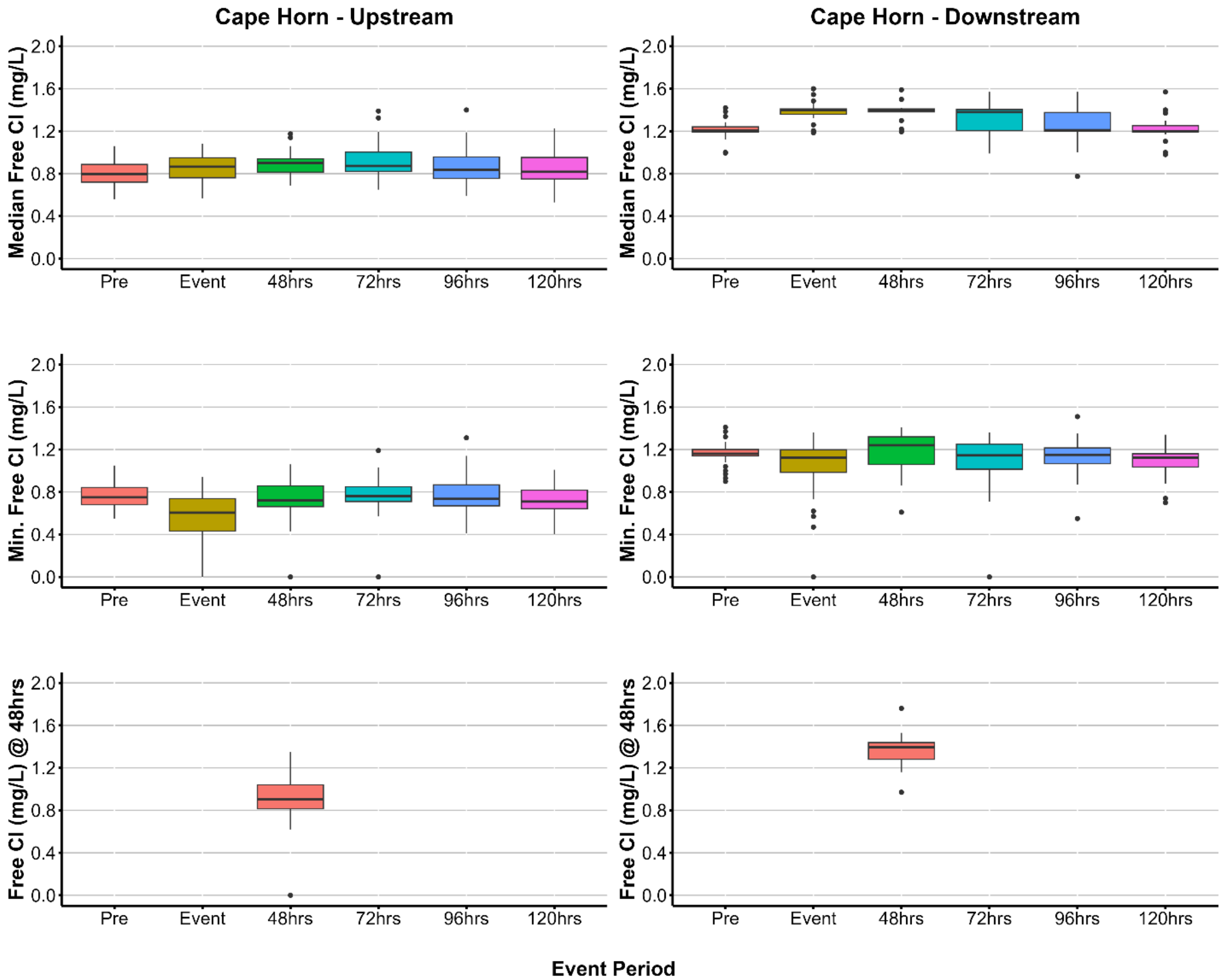

Figure 3.3. Boxplots of median and minimum free chlorine (mg/L) before, during, and after elevated turbidity events, and free chlorine at 48hrs (mg/L) upstream (left) and downstream (right) from the Cape Horn rechlorination station between 2015 – 2024 (n = 34 events).

Median free chlorine upstream of Cape Horn RCL did not change greatly, with levels steady at ~0.8 mg/L (Figure 3.3). Downstream levels were greater and less variable, showing an increasing pattern from ~1.2 mg/L to ~1.4 mg/L between the pre-event and event periods, remaining elevated 48hrs post-event, then decreasing to ~1.2 mg/L by 120hrs post-event. Minimum free chlorine upstream and downstream from the Cape Horn RCL were generally stable throughout the pre-event, event, and post-event periods. The lowest minimum levels were most apparent during the event upstream of Cape Horn RCL. There were some outliers with minimum levels below 0.4 mg/L during the event and post-event periods both upstream and downstream. Free chlorine at 48hrs upstream and downstream were largely consistent at ~0.9 mg/L and ~1.4 mg/L.

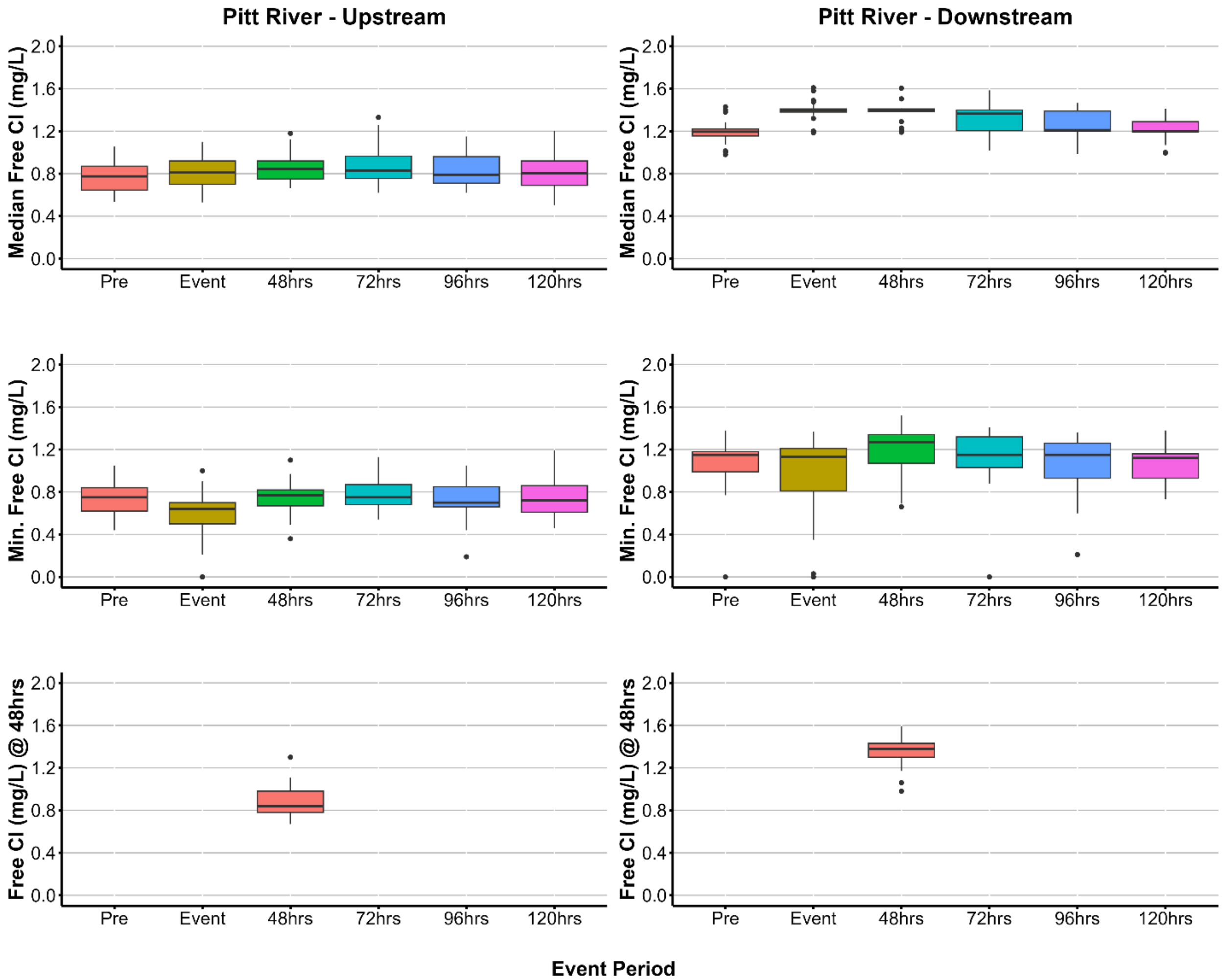

Figure 3.4. Boxplots of median and minimum free chlorine (mg/L) before, during, and after elevated turbidity events, and free chlorine at 48hrs (mg/L) upstream (left) and downstream (right) from the Pitt River rechlorination station between 2015 – 2024 (n = 33 events). Note that one event was filtered out due to missing values.

Median free chlorine upstream of Pitt River RCL did not change greatly, with levels steady at ~0.8 mg/L (Figure 3.4). Downstream levels were greater and less variable, showing a clear pattern of increasing from ~1.2 mg/L to ~1.4 mg/L between the pre-event and event periods, remaining elevated 48hrs post-event, then decreasing to ~1.2 mg/L by 120hrs post-event. Minimum free chlorine upstream and downstream from the Pitt River RCL were generally stable throughout the pre-event, event, and post-event periods, but the lowest minimum levels were apparent during the event upstream and downstream of Pitt River RCL. There were some outliers with minimum levels below 0.4 mg/L both upstream and downstream. Free chlorine at 48hrs upstream and downstream were largely consistent at ~0.9 mg/L and ~1.3 mg/L.

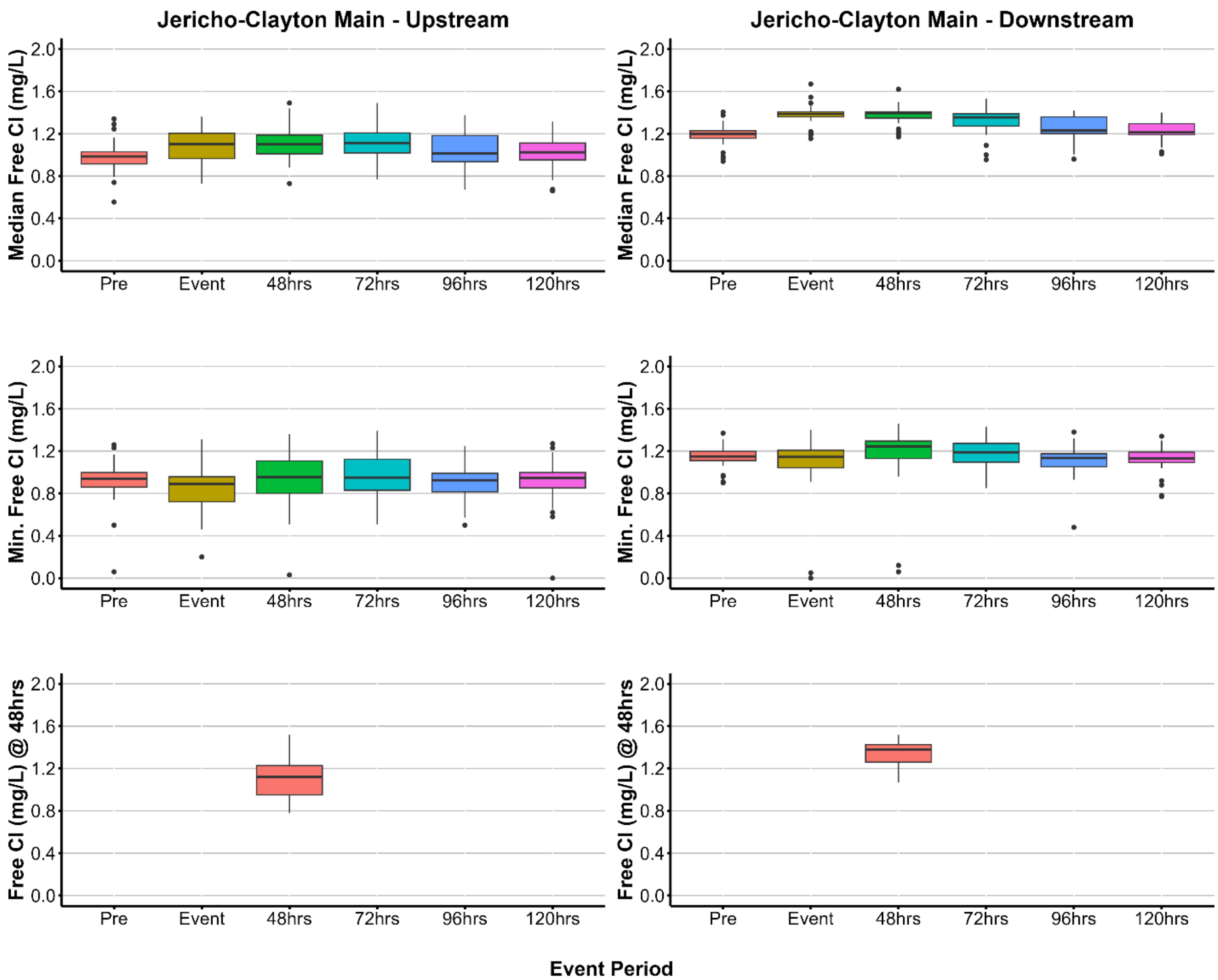

Figure 3.5. Boxplots of median and minimum free chlorine (mg/L) before, during, and after elevated turbidity events, and free chlorine at 48hrs (mg/L) upstream (left) and downstream (right) from the Clayton rechlorination station in the Jericho-Clayton Main between 2015 – 2024 (n = 34 events).

Median free chlorine in the Jericho-Clayton Main upstream of Clayton RCL changed slightly between pre-event and event periods, with levels increasing from ~1.0 mg/L to ~1.1 mg/L (Figure 3.5). Downstream levels were greater and less variable, showing a clear pattern of increasing from ~1.2 mg/L to ~1.4 mg/L between the pre-event and event periods, remaining elevated 48hrs post-event, then decreasing to ~1.2 mg/L by 120hrs post-event. Minimum free chlorine levels upstream and downstream from the Clayton RCL were generally stable throughout the pre-event, event, and post-event periods, but the lowest minimum levels were apparent during the event upstream of Clayton RCL. There were some outliers with minimum levels below 0.4 mg/L both upstream and downstream. Free chlorine at 48hrs upstream and downstream were largely consistent at ~1.1 mg/L and ~1.3 mg/L.

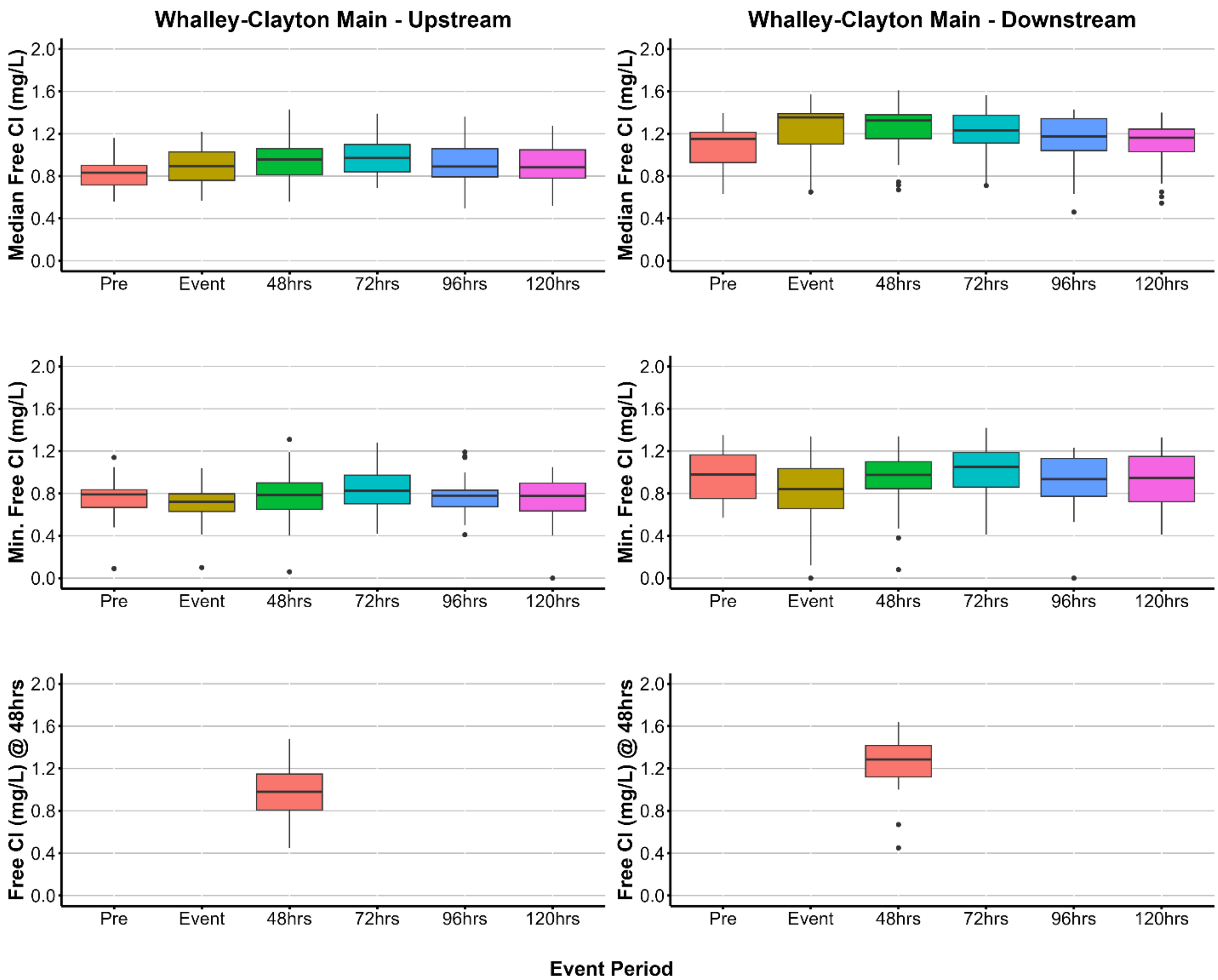

Figure 3.6. Boxplots of median and minimum free chlorine (mg/L) before, during, and after elevated turbidity events, and free chlorine at 48hrs (mg/L) upstream (left) and downstream (right) from the Clayton rechlorination station in the Whalley-Clayton Main between 2015 – 2024 (n = 34 events).

Median free chlorine in the Whalley-Clayton Main upstream of Clayton RCL changed slightly between pre-event and event with levels increasing from ~0.8 mg/L to ~0.9 mg/L, and then to ~1.2 mg/L between 49 – 72hrs post-event (Figure 3.6). Downstream levels were slightly greater, showing a pattern of increasing from ~1.1 mg/L to ~1.2 mg/L between the pre-event and event periods, remaining elevated 48hrs post-event, then decreasing to ~1.1 mg/L by 120hrs post-event. Minimum free chlorine upstream and downstream from the Clayton RCL were generally stable throughout the pre-event, event, and post-event periods, but the lowest minimum levels were apparent during the event upstream and downstream of Clayton RCL. There were some outliers with minimum levels below 0.4 mg/L both upstream and downstream. Free chlorine at 48hrs upstream and downstream were largely consistent at ~1.0 mg/L and ~1.2 mg/L.

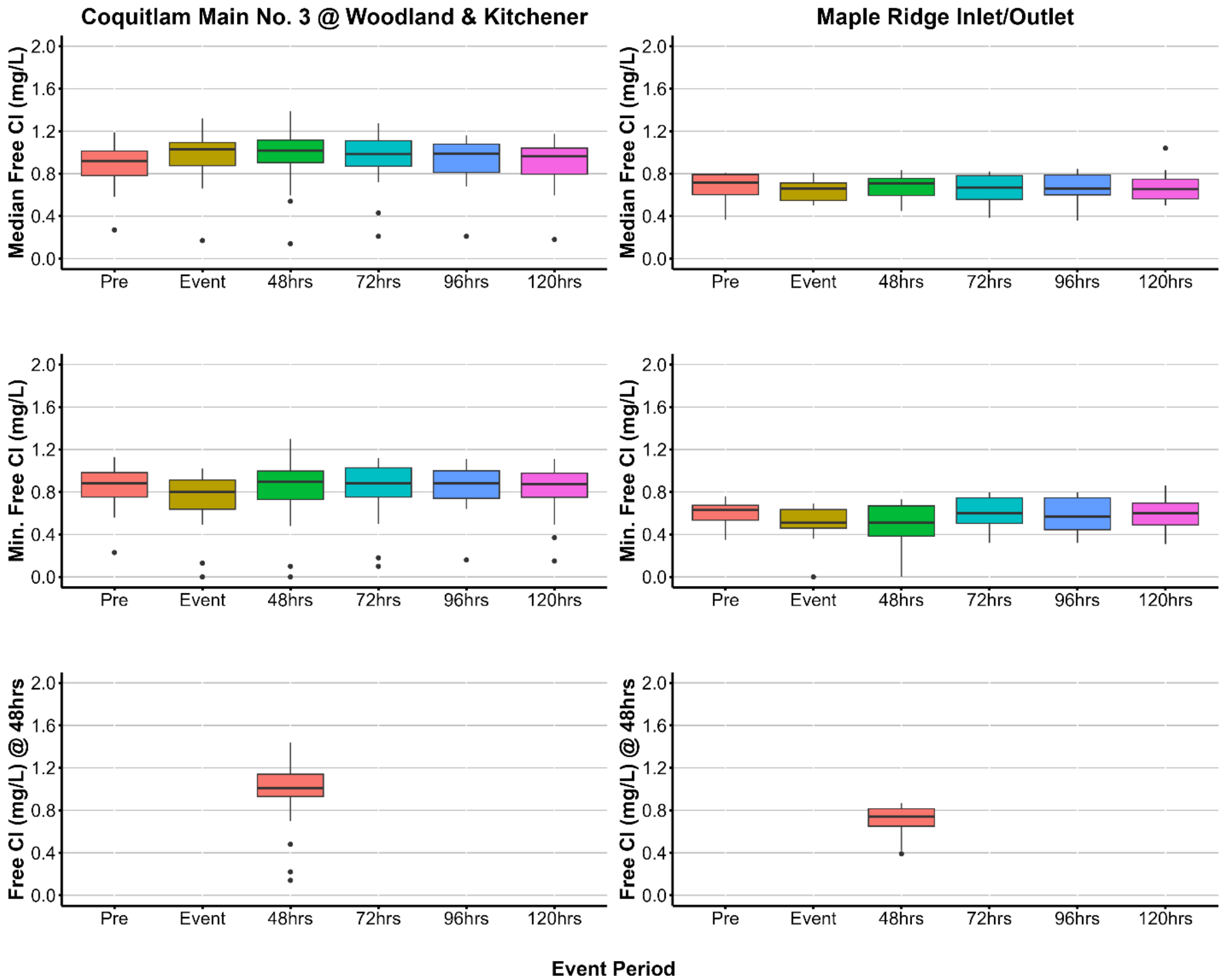

Figure 3.7. Boxplots of median and minimum free chlorine (mg/L) before, during, and after elevated turbidity events, and free chlorine at 48hrs (mg/L) in Coquitlam Main No. 3 at Woodland & Kitchener (left; n = 34 events) and Maple Ridge Reservoir Inlet/Outlet (right; n = 11 events) between 2015 – 2024.

Median free chlorine in Coquitlam Main No. 3 at Woodland & Kitchener changed slightly between pre-event and event with levels increasing from ~0.9 mg/L to ~1.0 mg/L (Figure 3.7). Minimum free chlorine was generally stable, but the lowest minimum levels were apparent during the event, and there were some outliers with minimum levels below 0.4 mg/L. Free chlorine at 48hrs was largely consistent at ~1.0 mg/L, but in two events levels were below 0.4 mg/L. Median free chlorine at Maple Ridge Inlet/Outlet changed slightly between pre-event and event with levels decreasing from ~0.7 mg/L to ~0.6 mg/L (Figure 3.7). Minimum free chlorine was generally stable, but the lowest minimum levels were apparent during the event at 48hrs post-event, and there were some outliers with minimum levels below 0.4 mg/L. Free chlorine at 48hrs was largely consistent at ~0.7 mg/L, but in one event the level was below 0.4 mg/L.

These visuals demonstrate the implementation of the turbidity response protocol at each of the RCLs, where chlorine setpoints were raised during turbidity events and maintained at least until

48hrs post-event. Across most events at each site on the transmission system, median free chlorine remained above 0.4 mg/L. However, in some events, minimum free chlorine dropped below 0.4 mg/L, and this occurred most frequently during the event period. Overall, this demonstrates that the turbidity response protocol is effective at maintaining acceptable levels of free chlorine throughout the transmission system during elevated turbidity events.

A key reason for the effectiveness of the turbidity response protocol is likely due to the water travel time from the CWTP. CCA revealed that free chlorine levels upstream of Cape Horn RCL were generally most highly correlated with free chlorine leaving the CWTP 5 – 9hrs previously, indicating the estimated travel time between the CWTP and Cape Horn RCL (Appendix Table A2). The range in hours likely indicates the variation in flow of the water mains. Using this same method, estimated travel time between CWTP and Pitt River RCL is 6 – 8hrs (Appendix Table A3), 2 – 3hrs from CWTP to Woodland & Kitchener (Appendix Table A6), and 8 – 12hrs from Pitt River RCL to Clayton RCL in the Jericho-Clayton Main (Appendix Table A4). The travel time from Cape Horn RCL to Clayton RCL in the Whalley-Clayton Main could not be estimated with confidence (Appendix Table A5). This indicates that the 48 hour "buffer" period after the event, where chlorine setpoints are maintained at their elevated levels, is much greater than the estimated water travel time throughout the transmission system. This implies that turbidity levels at these transmission system sites are 2 – 20hrs behind the water at Grant's Tomb, which means that intake water with turbidity below 0.9 NTU has already likely been conveyed throughout the transmission system for at least 24hrs prior to return to default chlorine setpoints at the CWTP and each RCL at 48hrs after the event or later.

Time series of outlier events were evaluated to further understand patterns of low free chlorine during elevated turbidity events. 21 different events contained an instance of free chlorine less than 0.4 mg/L. However, there were 5 events where free chlorine levels were low across many (4 or more) locations in the transmission system. These include events 170 (7 locations), 63 (5 location), 17 (4 locations), 36 (4 locations), and 158 (4 locations). The time series figures of these events including raw water turbidity and free chlorine at CWTP, and free chlorine at each of the transmission sites are in the Appendix (Figures A1 – A5). These figures suggest that most instances of the free chlorine levels below 0.4 mg/L appear to be erroneous drops which might indicate sensor maintenance or reduced flow past the sensor which can lead to erroneous readings (Eileen Butler personal communication, July 15, 2025). Another erroneous period is likely at Woodland & Kitchener for events 170 and 158, where free chlorine persisted at ~0.2 mg/L for many days despite acceptable levels upstream (CWTP) and downstream (upstream of Cape Horn RCL; Appendix Figures A1 and A5). Outside of likely erroneous measurements, there are no free chlorine measurements that are below 0.2 mg/L that appear to be realistic. However, there is a noticeable pattern across the outlier events that the lowest free chlorine values, particularly upstream of rechlorination stations, appear to occur near the beginning of each event corresponding with the highest levels of turbidity measured in the raw water.

The random forest model for median free chlorine upstream of Cape Horn RCL yielded a cross-validated model with an average R^2 = 0.79 and percent root mean squared error (%RMSE) of 11.9%, and for minimum free chlorine the cross-validated model had an average R^2 = 0.84 and %RMSE = 10.0%. For median free chlorine, the event seasonality (i.e., Event Date) and water temperature were the most important predictor variables, and event seasonality, event duration, and water temperature were the most important predictor variables for minimum free chlorine (Figure 3.8). The partial dependency plots (PDPs) indicate that an earlier event date, that is, closer to September 1st, is generally associated with lower median and minimum free chlorine levels upstream of Cape Horn RCL. Increased water temperatures are also generally associated with lower median and minimum free chlorine levels. In addition, longer event duration is associated with lower minimum free chlorine levels. While not relatively as important, higher median free chlorine levels at Cape Horn RCL are associated with higher upstream free chlorine from CWTP, peak turbidity, and average turbidity, and lower minimum free chlorine levels at Cape Horn RCL are associated with higher peak and average event turbidity.

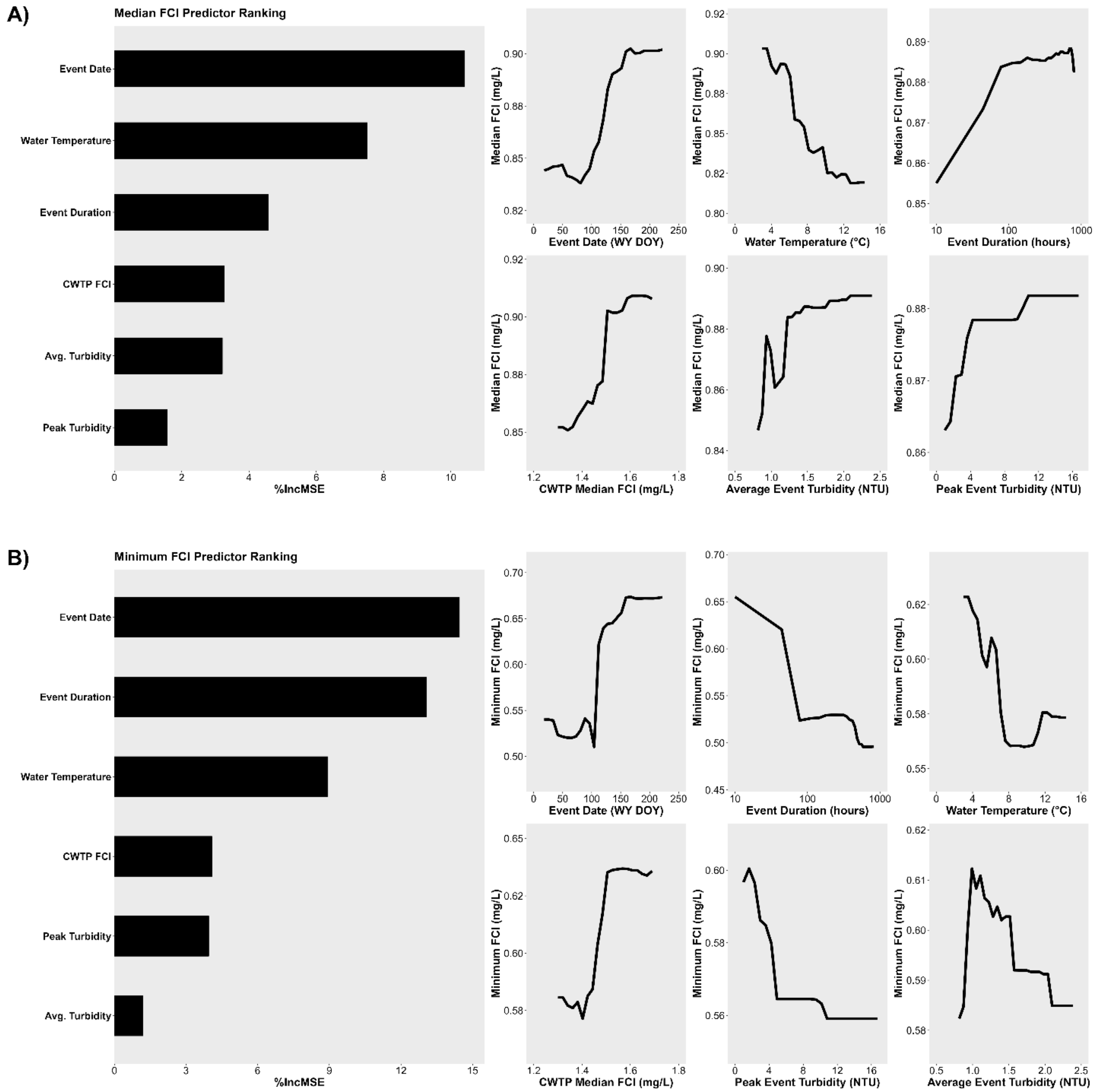

Figure 3.8. Most important variables (left) predicting (A) median and (B) minimum free chlorine (FCl; mg/L) during elevated turbidity events (n = 28) between 2015 – 2024 upstream of Cape Horn rechlorination station (RCL) with bars ranked according to 'percent increase in mean squared error' (%IncMSE), along with partial dependency plots (right) indicating relationships of median or minimum FCl upstream of Cape Horn RCL with event seasonality as 'Event Date' (WY DOY = water year date of year), water temperature (°C), event duration (hours), Coquitlam Water Treatment Plant (CWTP) median FCl (mg/L), peak event turbidity (NTU) and average event turbidity (NTU) measured at Grant's Tomb. Note that some events could not be modelled due to missing water temperature data.

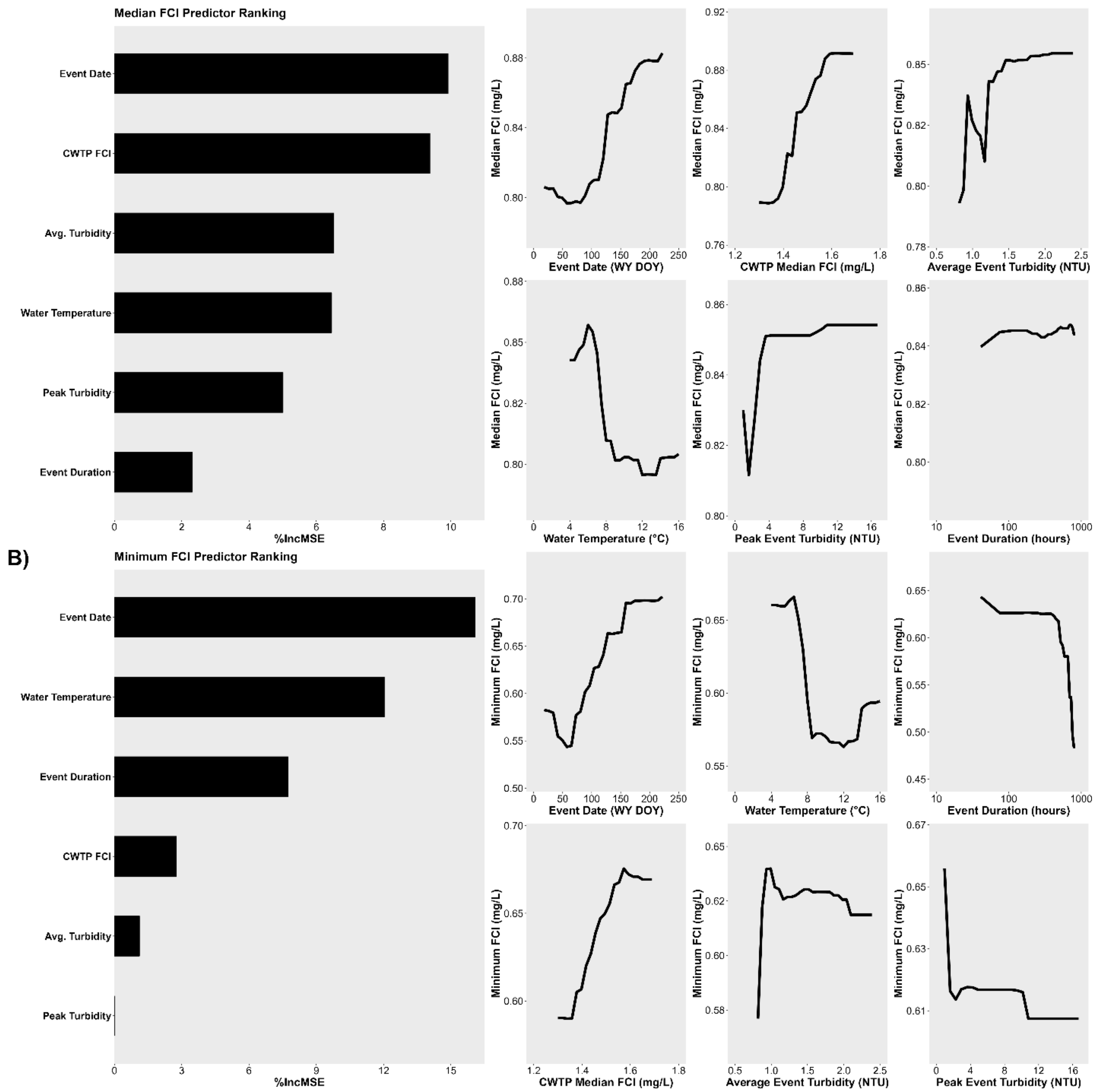

Figure 3.9. Most important variables (left) predicting (A) median and (B) minimum free chlorine (FCl; mg/L) during elevated turbidity events (n = 28) between 2015 – 2024 upstream of Pitt River rechlorination station (RCL) with bars ranked according to 'percent increase in mean squared error' (%IncMSE), along with partial dependency plots (right) indicating relationships of median or minimum FCl upstream of Pitt River RCL with event seasonality as 'Event Date' (WY DOY = water year date of year), water temperature (°C), event duration (hours), Coquitlam Water Treatment Plant (CWTP) median FCl (mg/L), peak event turbidity (NTU) and average event turbidity (NTU) measured at Grant's Tomb. Note that some events could not be modelled due to missing water temperature data.

The random forest model for median free chlorine upstream of Pitt River RCL yielded a cross-validated model with an average R^2 = 0.84 and %RMSE = 10.7%, and for minimum free chlorine the cross-validated model had an average R^2 = 0.83 and %RMSE = 9.3%. For median free chlorine, the event seasonality and free chlorine levels at the CWTP were the most important predictor variables, and event seasonality, water temperature, and event duration were the most important predictor variables for minimum free chlorine (Figure 3.9). The PDPs indicate that an earlier event date and higher water temperature is generally associated with lower median and minimum free chlorine levels upstream of Pitt River RCL. In addition, lower free chlorine levels from CWTP are associated with lower median free chlorine levels upstream of Pitt River RCL. Longer event duration is associated with lower minimum free chlorine levels. Increased average and peak turbidity appear to be associated with greater levels of median free chlorine.

The random forest model for median free chlorine in Jericho-Clayton Main upstream of Clayton RCL yielded a cross-validated model with an average $R^2 = 0.81$ and %RMSE = 11.3%, and for minimum free chlorine the cross-validated model had an average $R^2 = 0.79$ and %RMSE = 10.7%. For median free chlorine, water temperature and free chlorine levels downstream of the Pitt River RCL were the most important predictor variables, and event duration, peak turbidity, and event seasonality were the most important predictor variables for minimum free chlorine (Figure 3.10). The PDPs indicate that higher water temperature and lower free chlorine levels downstream of Pitt River RCL are generally associated with lower median free chlorine levels in Jericho-Clayton upstream of Clayton RCL. In addition, longer event duration and greater peak turbidity are associated with lower minimum free chlorine levels in Jericho-Clayton upstream of Clayton RCL. While not as relatively important, the early the event date, the lower the median and minimum free chlorine levels in Jericho-Clayton upstream of Clayton RCL.

The random forest model for median free chlorine in Whalley-Clayton Main upstream of Clayton RCL yielded a cross-validated model with an average $R^2 = 0.80$ and %RMSE = 11.0%, and for minimum free chlorine the cross-validated model had an average $R^2 = 0.72$ and %RMSE = 12.2%. For median free chlorine, water temperature and free chlorine levels downstream of the Cape Horn RCL were the most important predictor variables (Figure 3.11). Event duration and peak turbidity were the most important predictor variables for minimum free chlorine. The PDPs indicate that higher water temperature and lower free chlorine levels downstream of Cape Horn RCL are generally associated with lower median free chlorine levels in Whalley-Clayton upstream of Clayton RCL. However, PDPs for minimum free chlorine levels at Whalley-Clayton Main upstream of Clayton RCL do not show clear associations with predictor variables.

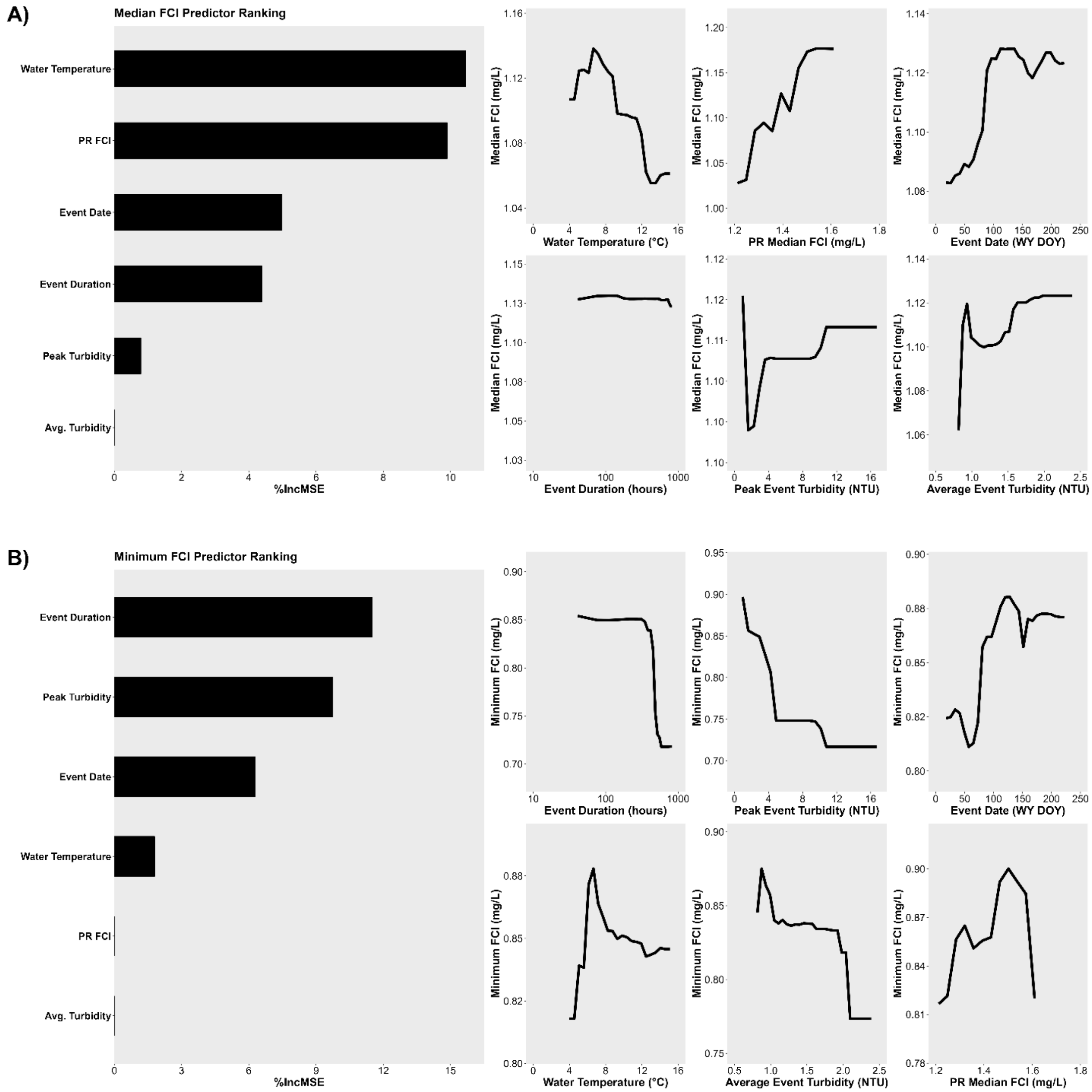

Figure 3.10. Most important variables (left) predicting (A) median and (B) minimum free chlorine (FCl; mg/L) during elevated turbidity events (n = 28) between 2015 – 2024 upstream of Clayton rechlorination station (RCL) in Jericho-Clayton Main with bars ranked according to 'percent increase in mean squared error' (%IncMSE), along with partial dependency plots (right) indicating relationships of median or minimum FCl upstream of Clayton RCL in Jericho-Clayton Main with event seasonality as 'Event Date' (WY DOY = water year date of year), water temperature (°C), event duration (hours), downstream Pitt River (PR) RCL median FCl (mg/L), peak event turbidity (NTU) and average event turbidity (NTU) measured at Grant's Tomb. Note that some events could not be modelled due to missing water temperature data.

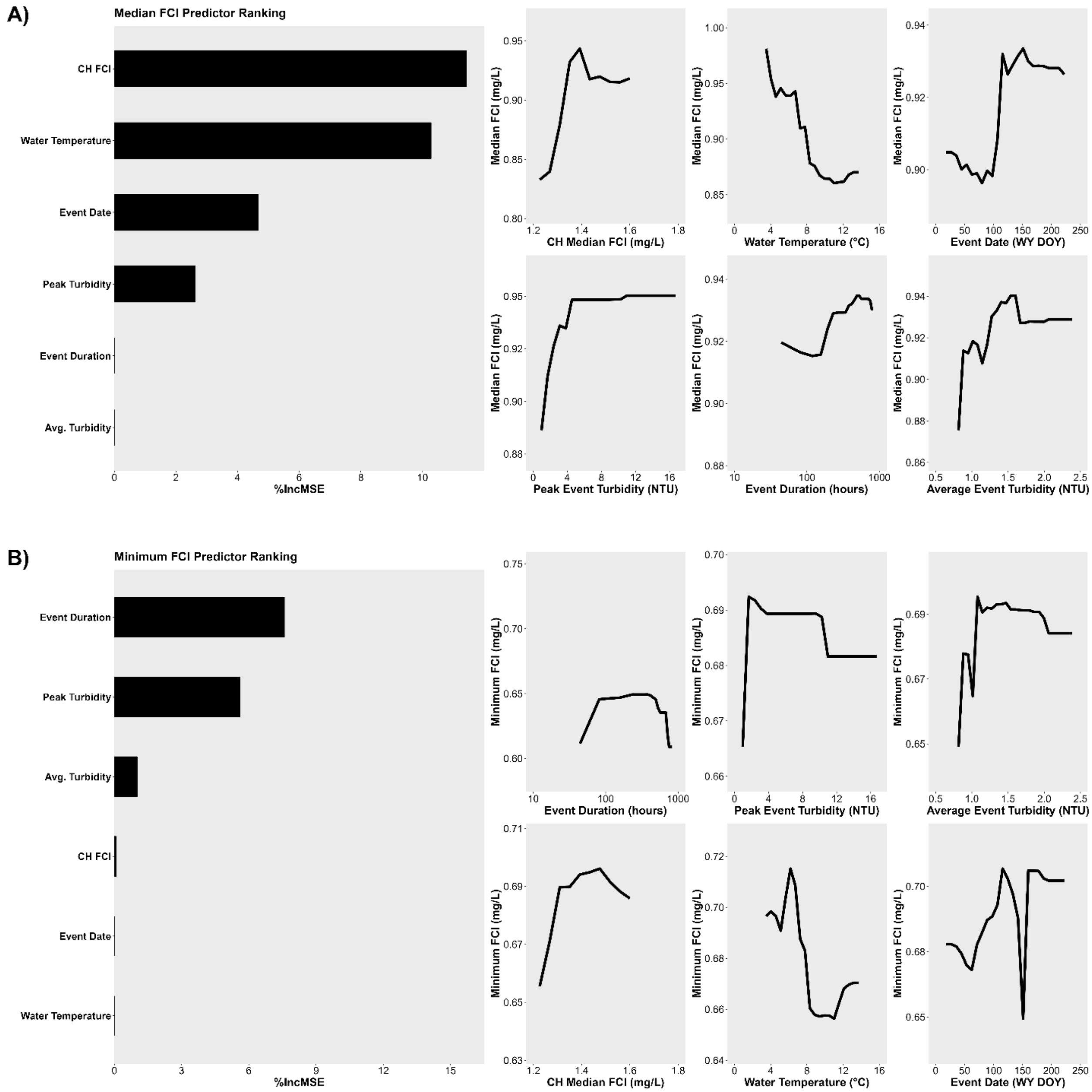

Figure 3.11. Most important variables (left) predicting (A) median and (B) minimum free chlorine (FCl; mg/L) during elevated turbidity events (n = 25) between 2015 – 2024 upstream of Clayton rechlorination station (RCL) in Whalley-Clayton Main with bars ranked according to ‘percent increase in mean squared error’ (%IncMSE), along with partial dependency plots (right) indicating relationships of median or minimum FCl upstream of Clayton RCL in Whalley-Clayton Main with event seasonality as ‘Event Date’ (WY DOY = water year date of year), water temperature (°C), event duration (hours), downstream Cape Horn (CH) RCL median FCl (mg/L), peak event turbidity (NTU) and average event turbidity (NTU) measured at Grant’s Tomb. Note that some events could not be modelled due to missing water temperature data.

Together, the random forest modelling indicates that event seasonality, water temperature, and upstream free chlorine levels best explain variability in median free chlorine levels upstream of RCLs. Event occurrence closer to September 1st, warmer water temperatures, and lower upstream free chlorine levels lead to lower median free chlorine levels upstream of RCLs. Event duration appears to best explain variability in minimum free chlorine levels at all locations. The longer the event duration, the lower the minimum free chlorine, which could be explained by the fact that longer duration events may have prolonged "peak" turbidity conditions at the beginning of the event, as was observed for events 170 and 53 (Appendix Figures A1 and A2). At locations closer to CWTP (i.e., Cape Horn and Pitt River), minimum free chlorine is better explained by event date and water temperature, and at sites further from CWTP (i.e., Jericho-Clayton and Whalley-Clayton), minimum free chlorine is better explained by peak turbidity.

These findings suggest that free chlorine levels during events are generally most sensitive to the seasonal timing of the event, and the water temperature in the water mains. The importance of water temperature for chlorine decay is well known, in that increased water temperature increases microbial activity, reactions with organic matter, and chlorine self-decay rates which result in reduced levels of free chlorine.[40] Greater water temperatures coincide with event timing closer to September 1st (Pearson correlation is -0.83 – -0.85), which likely explains why event seasonality is also important within the random forest models. However, what may also be important is that turbidity events closer to September 1st have greater potential to alter chlorine decay because they are the first to occur after prolonged periods of low precipitation in the summer months. Researchers have observed that the first rainstorm of the season, often called the 'first flush', washes large amounts of dissolved organic matter into aquatic systems.[52,53] This material accumulates in the watershed over the dry summer months and is mobilized with the first large rain storms of the wet season. This increased influx of organic matter is likely to be largely transformed into dissolved fractions (see Section 2), which would then increase the chlorine demand in the transmission system. Importantly, these dynamics appear to be more important for sites closer to the CWTP in terms of the lowest free chlorine values observed, which suggests that there is a greater risk of lower free chlorine levels in the transmission system upstream of the first rechlorination stations (i.e., Pitt River and Cape Horn).

3.3 Conclusions and Recommendations

This study sought to determine how well the response protocol maintains target free chlorine residual levels in the transmission system on the Coquitlam source during elevated turbidity events. From hourly turbidity measurements from the Coquitlam source water, 34 events were selected between 2015 – 2024 to explore patterns of free chlorine levels upstream and downstream of three rechlorination stations, and at two monitoring sites, during periods of elevated turbidity when the response protocol was likely initiated. The results indicate that the response protocol is effective at maintaining free chlorine levels throughout the transmission system both during and up to 120hrs after the event. This is likely explained by the fact that the protocol maintains elevated chlorine setpoints at least until 48hrs after turbidity levels are below 0.9 NTU, and the water travel time to the sites analyzed in this study are between 2 – 20hrs. Instances where free chlorine was below 0.4 mg/L can likely be explained by erroneous readings of the free chlorine meters. However, analysis of outlier events revealed that low levels most often occurred toward the beginning of each event, when turbidity levels were relatively high.

This study also sought to determine what best explains variation in free chlorine levels throughout the transmission system on the Coquitlam source. Random forest analysis was conducted to assess the impact of event peak and average turbidity, event seasonality, event duration, upstream free chlorine levels, and water main temperature on median and minimum free chlorine upstream of rechlorination stations. Water temperature and event seasonality appeared to explain variation best across sites, where increased water temperature and event occurrence closer to September 1st was associated with lower free chlorine levels in the transmission system. Event duration also appeared to be important, along with upstream free chlorine levels. Turbidity characteristics explained variability less.

Below are a few key insights and recommendations to support evidence-based decision making during elevated turbidity events:

A. **Sustaining free chlorine setpoints until 48hrs after the elevated turbidity event at CWTP and rechlorination stations is effective at maintaining adequate levels of free chlorine in the transmission system.** This analysis also provides evidence that concurrent management of free chlorine setpoints at CWTP and rechlorination stations is appropriate for maintaining free chlorine levels in the transmission system.
B. **Swift application of response protocols is just as important as sustaining elevated free chlorine setpoints for 48hrs after turbidity drops below 0.9 NTU.** This analysis demonstrates that occurrence of low free chlorine levels most often occurs at the beginning of the event, concurrent with most elevated levels of turbidity. Therefore, rapid application of the turbidity response protocols is crucial to maintaining free chlorine levels in the transmission system. This may also be especially important for turbidity events which occur between September 1st and January 29th, and when transmission system water temperatures are above 6°C.
C. **Transmission system water temperature and event timing are important factors to consider during elevated turbidity events.** The finding that turbidity characteristics or event duration does not explain most of the variation in free chlorine levels could reflect

what is focused on within the protocol. Since the protocol is responsive to turbidity severity (i.e., different response protocols for levels of turbidity) and event duration, chlorine setpoints are altered accordingly. This analysis suggests that low levels of free chlorine are most likely when transmission system water temperatures are above 6°C, and when the event occurs between September 1st and January 31st. Accordingly, further evidence-based decision-making during elevated turbidity events could consider these factors more explicitly.

D. **Future modelling studies could support enhanced protocol development to support resilience to climate change effects.** The random forest modelling approach was used for description of past elevated turbidity events and may not be a suitable approach to quantitatively predict future conditions, especially for conditions interpolated outside of the range of characteristics quantified by this modelling approach. However, these results suggest that the effects of climate change on water temperature and storm severity particularly for the first storm events of the wet season may increase risks to biological stability in the transmission system on the Coquitlam source. With an appropriate modelling approach, these effects may be quantified and could guide further development of response protocols.

Conclusion

The purpose of this project is to support Metro Vancouver in improving disinfection response protocols during elevated turbidity events using evidence from historical water quality data from the drinking water system on the Coquitlam source. First, the system on the Coquitlam source was contextualized by reviewing information on six large unfiltered drinking water systems. Key recommendations include potential collaboration with other utilities operating similar unfiltered drinking water supply systems, the development of software to support decision making, and to continue preparation for potential wildfire-induced changes to natural organic matter in the Coquitlam watershed. Next, the relationships between turbidity and metrics indicative of natural organic matter (NOM) in raw and treated water on the Coquitlam source were evaluated. Findings indicate that turbidity is not a consistently reliable proxy for NOM, since correlations between turbidity and UVT, DOC, and TOC were relatively poor. Recommendations suggest ways to better characterize NOM to support disinfection protocols during events where particulates and organic matter are elevated in the source water. Finally, free chlorine levels in the transmission system on the Coquitlam source were evaluated before, during, and after elevated turbidity events. From this analysis, it is evident that response protocols, which include concurrent adjustment of chlorine setpoints at CWTP and rechlorination stations, were effective at maintaining adequate levels of free chlorine throughout the transmission system up to 120hrs after the event. Random forest analysis indicates that increased water temperature and event occurrence between September 1st and January 31st was associated with lower levels of free chlorine in the transmission system. Key recommendations include swift initiation of elevated chlorine setpoints since the early event period is associated with lower free chlorine, and the inclusion of event timing and transmission system water temperature in decision-making. Future modelling studies could support enhanced protocol development to support resilience to climate change effects.

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Appendix

Table A1. Elevated turbidity event characteristics in the Coquitlam source (raw) water, measured at Grant's Tomb.

Event ID	Peak Turbidity (NTU)	Avg. Turbidity (NTU)	Avg. Water Temperature (°C)	Event Start Time	Event End Time	Event Duration (hrs)
1	1.23	0.90	5.5	2015-01-05 6:00	2015-01-06 12:00	30
2	5.33	1.96	6.0	2015-01-23 20:00	2015-01-29 3:00	127
4	1.94	0.86	5.8	2015-02-08 0:00	2015-02-12 13:00	109
7	1.05	0.85	6.1	2015-03-15 0:00	2015-03-15 16:00	16
17	1.02	0.85	12.2	2015-09-20 0:00	2015-09-21 1:00	25
18	1.44	0.82	12.1	2015-10-30 13:00	2015-11-02 5:00	64
21	0.96	0.94	6.6	2015-12-13 23:00	2015-12-14 6:00	7
36	2.71	1.53	4.4	2017-01-18 6:00	2017-01-20 17:00	59
48	1.57	0.96	9.6	2017-10-18 19:00	2017-10-21 11:00	64
53	1.71	1.07	6.4	2017-11-23 10:00	2017-12-05 10:00	288
55	1.13	1.02	5.0	2018-01-30 5:00	2018-02-01 1:00	44
58	1.11	0.91	5.2	2018-03-27 21:00	2018-03-28 17:00	20
63	1.98	1.12	8.9	2018-11-01 22:00	2018-12-06 8:00	826
65	1.03	0.92	6.5	2018-12-11 21:00	2018-12-15 8:00	83
67	1.48	1.06	4.8	2019-01-03 19:00	2019-01-05 8:00	37
69	1.33	1.13	3.9	2019-02-09 0:00	2019-02-09 18:00	18
84	1.57	1.13	8.9	2019-11-17 10:00	2019-11-18 12:00	26
88	1.27	1.00	4.4	2020-01-23 23:00	2020-01-25 1:00	26
89	1.84	1.23	4.5	2020-02-01 0:00	2020-02-10 20:00	236
103	1.03	0.90	12.6	2020-09-25 21:00	2020-09-27 11:00	38
109	1	0.91	7.1	2020-12-08 17:00	2020-12-09 18:00	25

Table A1. (continued)

Event ID	Peak Turbidity (NTU)	Avg. Turbidity (NTU)	Avg. Water Temperature (°C)	Event Start Time	Event End Time	Event Duration (hrs)
110	1.08	0.84	6.5	2020-12-19 11:00	2020-12-20 6:00	19
111	1.06	0.97	5.7	2020-12-31 3:00	2020-12-31 13:00	10
123	2.94	1.10	14.5	2021-09-18 7:00	2021-09-19 15:00	32
125	1.12	1.01	11.9	2021-09-30 10:00	2021-10-02 6:00	44
127	4.44	1.31	9.1	2021-11-15 18:00	2021-12-11 18:00	624
132	0.99	0.95	5.7	2022-02-28 16:00	2022-03-01 7:00	15
133	1.24	0.94	6.3	2022-03-14 16:00	2022-03-16 18:00	50
144	2.66	1.52	5.9	2023-02-07 9:00	2023-02-08 18:00	33
147	1.1	0.93	6.7	2023-04-10 10:00	2023-04-11 22:00	36
158	1.19	1.05	13.6	2023-10-18 10:00	2023-10-18 21:00	11
159	4.19	1.73	8.0	2023-12-05 0:00	2023-12-09 11:00	107
162	1	0.94	7.0	2024-01-06 11:00	2024-01-07 10:00	23
170	16.69	2.39	10.5	2024-10-19 9:00	2024-11-19 14:00	749

Table A2. Results of cross-correlation analysis between free chlorine upstream of the Cape Horn rechlorination station and leaving the Coquitlam Water Treatment Plant for 34 elevated turbidity events between 2015 – 2024. Values provided indicate the negative lag (in hours) where the Pearson correlation is the strongest, the count of events with that lag with the strongest correlation, and the average correlation for that group of events.

Lag (hours)	Number of Events	Average Correlation (Pearson's *r*)
5	8	0.70
6	7	0.47
9	4	0.47
7	3	0.61
20	2	-0.02
12	2	0.36
4	2	0.35
1	2	-0.31
19	1	0.63
17	1	0.52
13	1	0.57
10	1	0.38

Table A3. Results of cross-correlation analysis between free chlorine upstream of the Pitt River rechlorination station and leaving the Coquitlam Water Treatment Plant for 34 elevated turbidity events between 2015 – 2024. Values provided indicate the negative lag (in hours) where the Pearson correlation is the strongest, the count of events with that lag with the strongest correlation, and the average correlation for that group of events.

Lag (hours)	Number of Events	Average Correlation (Pearson's *r*)
6	17	0.64
7	7	0.53
8	3	0.22
19	1	0.54
17	1	0.17
14	1	0.45
11	1	0.68
10	1	0.80
9	1	0.40
1	1	0.54

Table A4. Results of cross-correlation analysis between free chlorine upstream of the Clayton rechlorination station in Jericho-Clayton Main and downstream of the Pitt River rechlorination station for 34 elevated turbidity events between 2015 – 2024. Values provided indicate the negative lag (in hours) where the Pearson correlation is the strongest, the count of events with that lag with the strongest correlation, and the average correlation for that group of events.

Lag (hours)	Number of Events	Average Correlation (Pearson's *r*)
8	9	0.50
9	6	0.48
11	4	0.61
10	4	0.58
12	3	0.65
13	2	0.50
6	2	0.50
16	1	-0.15
7	1	0.70
3	1	0.35
1	1	0.44

Table A5. Results of cross-correlation analysis between free chlorine upstream of the Clayton rechlorination station in Whalley-Clayton Main and downstream of the Cape Horn rechlorination station for 34 elevated turbidity events between 2015 – 2024. Values provided indicate the negative lag (in hours) where the Pearson correlation is the strongest, the count of events with that lag with the strongest correlation, and the average correlation for that group of events.

Lag (hours)	Number of Events	Average Correlation (Pearson's *r*)
16	4	0.33
15	3	0.37
14	3	0.39
11	3	0.06
7	3	0.04
20	2	0.16
13	2	0.60
5	2	0.34
1	2	0.13
19	1	0.23
18	1	0.28
17	1	0.38
10	1	0.08
9	1	-0.48
8	1	0.43
6	1	0.82
4	1	0.38
3	1	0.12
2	1	0.30

Table A6. Results of cross-correlation analysis between free chlorine in Coquitlam Main No. 3 at Kitchener & Woodland and downstream of the Coquitlam Water Treatment Plant for 34 elevated turbidity events between 2015 – 2024. Values provided indicate the negative lag (in hours) where the Pearson correlation is the strongest, the count of events with that lag with the strongest correlation, and the average correlation for that group of events.

Lag (hours)	Number of Events	Average Correlation (Pearson's *r*)
3	20	0.57
2	6	0.68
15	2	0.29
1	2	0.06
20	1	-0.17
17	1	-0.12
16	1	-0.63
4	1	0.20

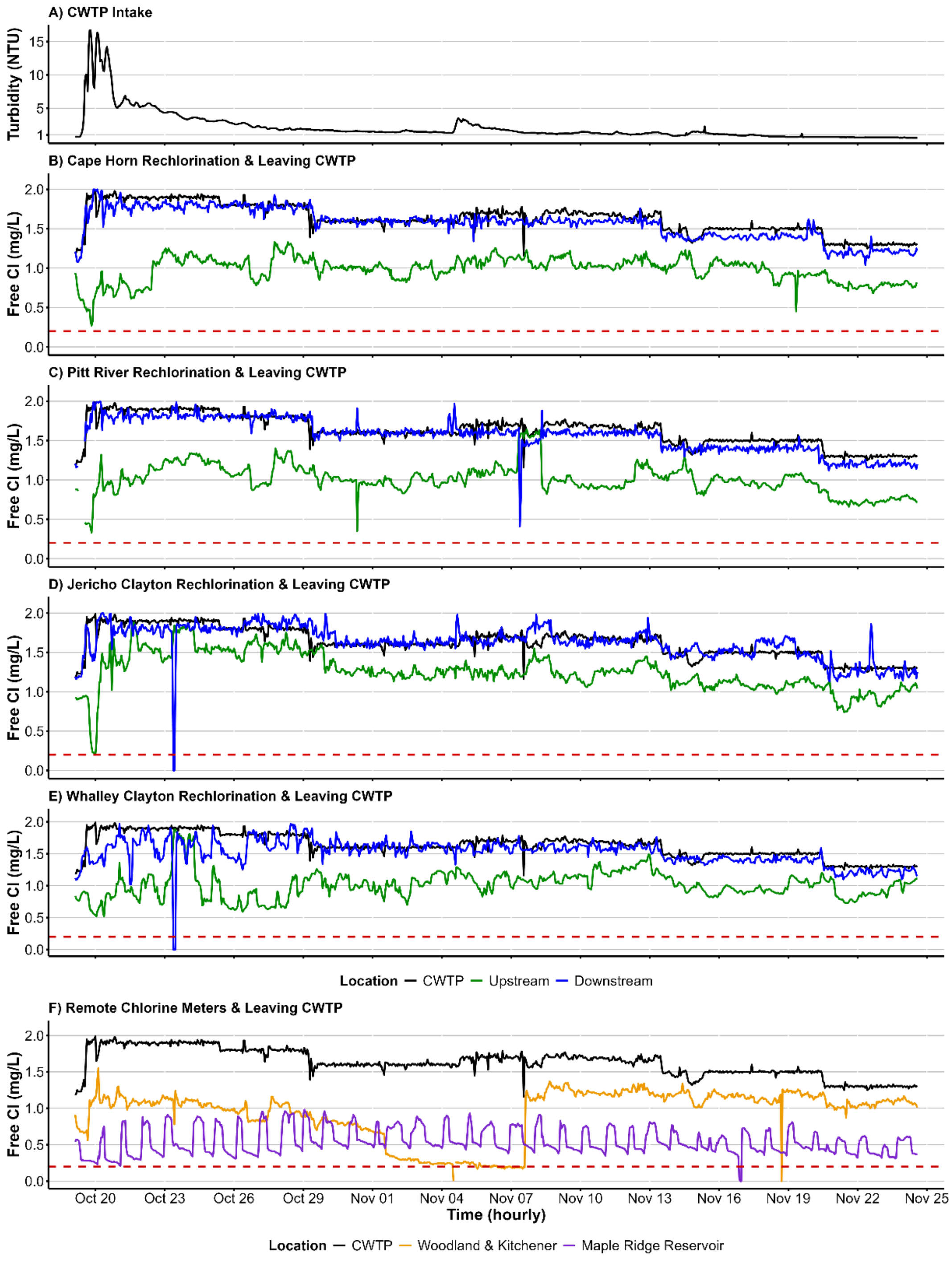

Figure A1. Time series of event 170 (2024-10-19 9:00 – 2024-11-19 14:00) including hourly turbidity (NTU) at Coquitlam Water Treatment Plant (CWTP; A), free chlorine (mg/L) at CWTP (black), and upstream (green) and downstream (blue) of rechlorination stations on the Coquitlam supply (B – E), and at remote chlorine meters in Coquitlam Main No. 3 at Woodland & Kitchener and Maple Ridge Reservoir (F). The red dashed line is free chlorine at 0.2 mg/L, and the period plotted is pre-event, event and post-event.

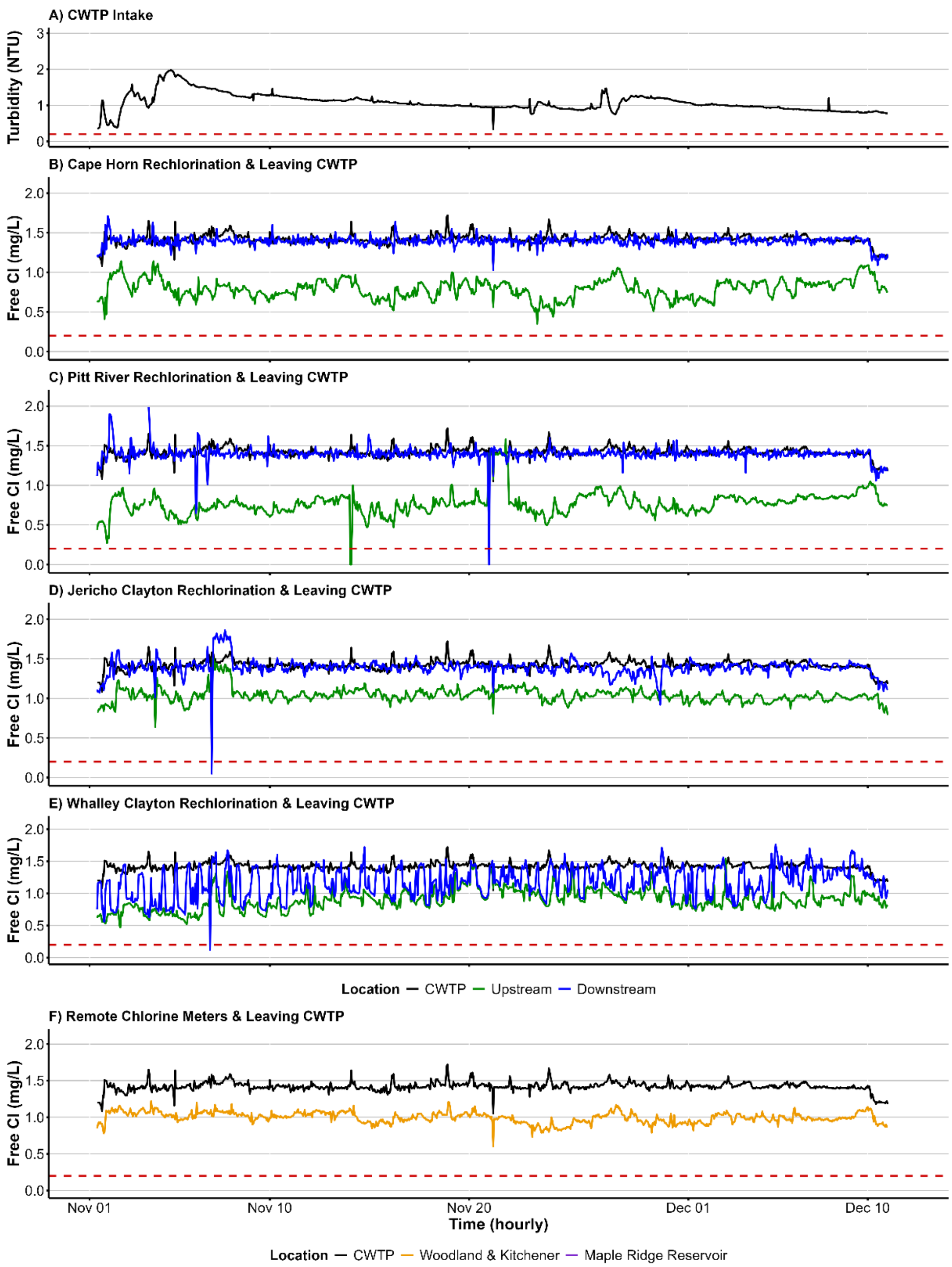

Figure A2. Time series of event 63 (2018-11-01 22:00 – 2018-12-06 8:00) including hourly turbidity (NTU) at Coquitlam Water Treatment Plant (CWTP; A), free chlorine (mg/L) at CWTP (black), and upstream (green) and downstream (blue) of rechlorination stations on the Coquitlam supply (B – E), and at remote chlorine meters in Coquitlam Main No. 3 at Woodland & Kitchener (F). The red dashed line is free chlorine at 0.2 mg/L, and the period plotted is pre-event, event and post-event.

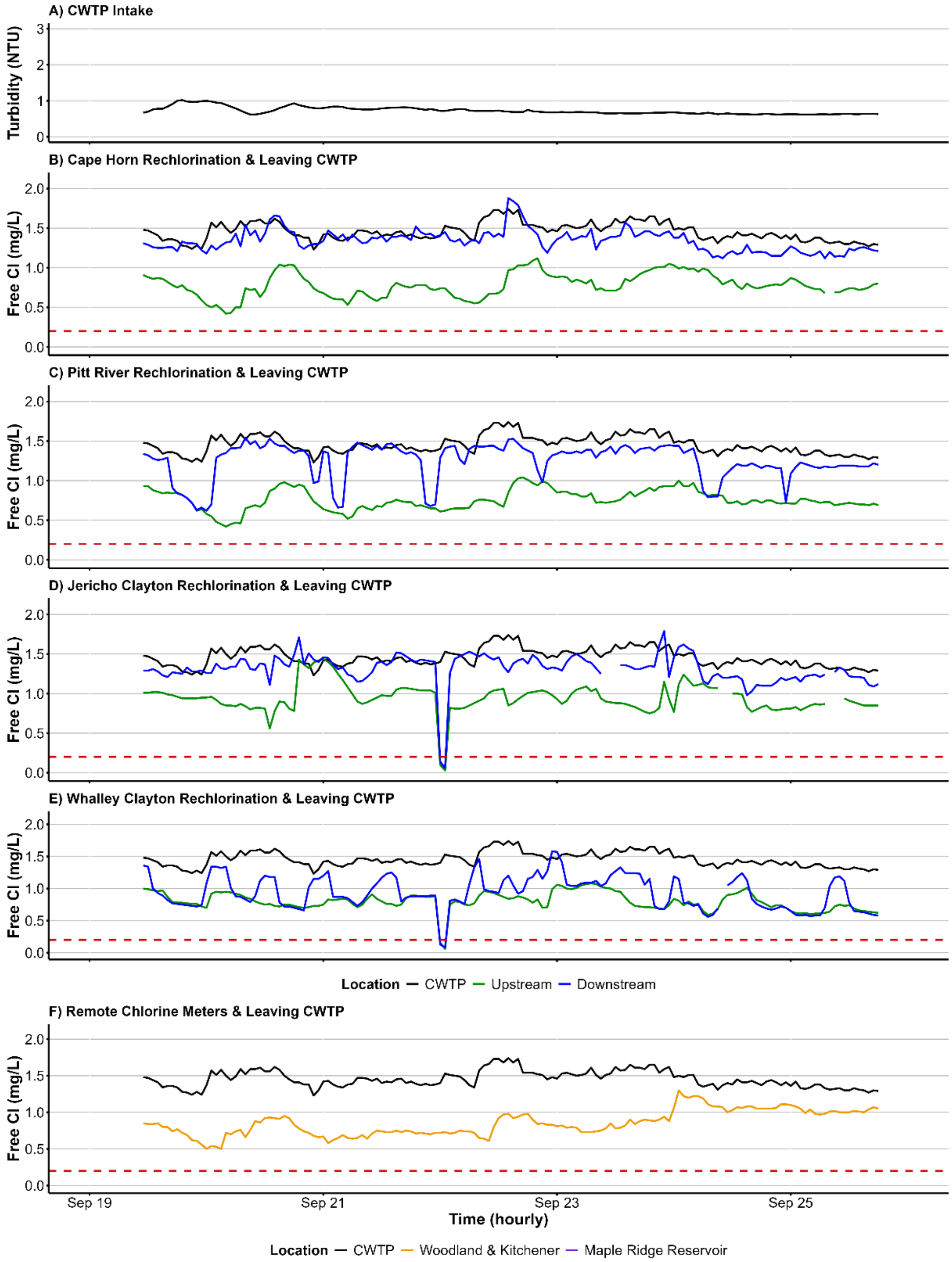

Figure A3. Time series of event 17 (2015-09-20 0:00 – 2015-09-21 1:00) including hourly turbidity (NTU) at Coquitlam Water Treatment Plant (CWTP; A), free chlorine (mg/L) at CWTP (black), and upstream (green) and downstream (blue) of rechlorination stations on the Coquitlam supply (B – E), and at remote chlorine meters in Coquitlam Main No. 3 at Woodland & Kitchener (F). The red dashed line is free chlorine at 0.2 mg/L, and the period plotted is pre-event, event and post-event.

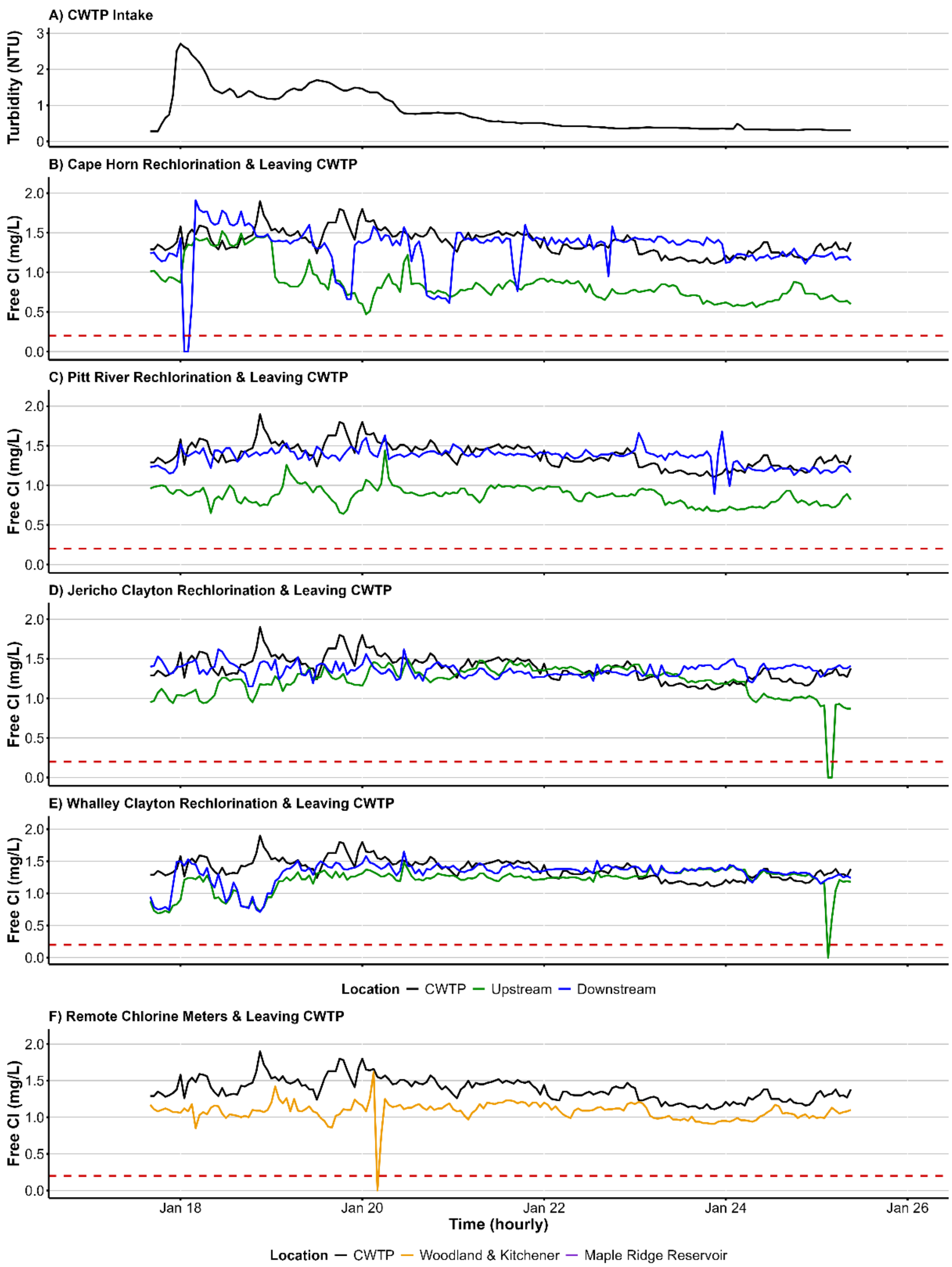

Figure A4. Time series of event 36 (2017-01-18 6:00 – 2017-01-20 17:00) including hourly turbidity (NTU) at Coquitlam Water Treatment Plant (CWTP; A), free chlorine (mg/L) at CWTP (black), and upstream (green) and downstream (blue) of rechlorination stations on the Coquitlam supply (B – E), and at remote chlorine meters in Coquitlam Main No. 3 at Woodland & Kitchener (F). The red dashed line is free chlorine at 0.2 mg/L, and the period plotted is pre-event, event and post-event.

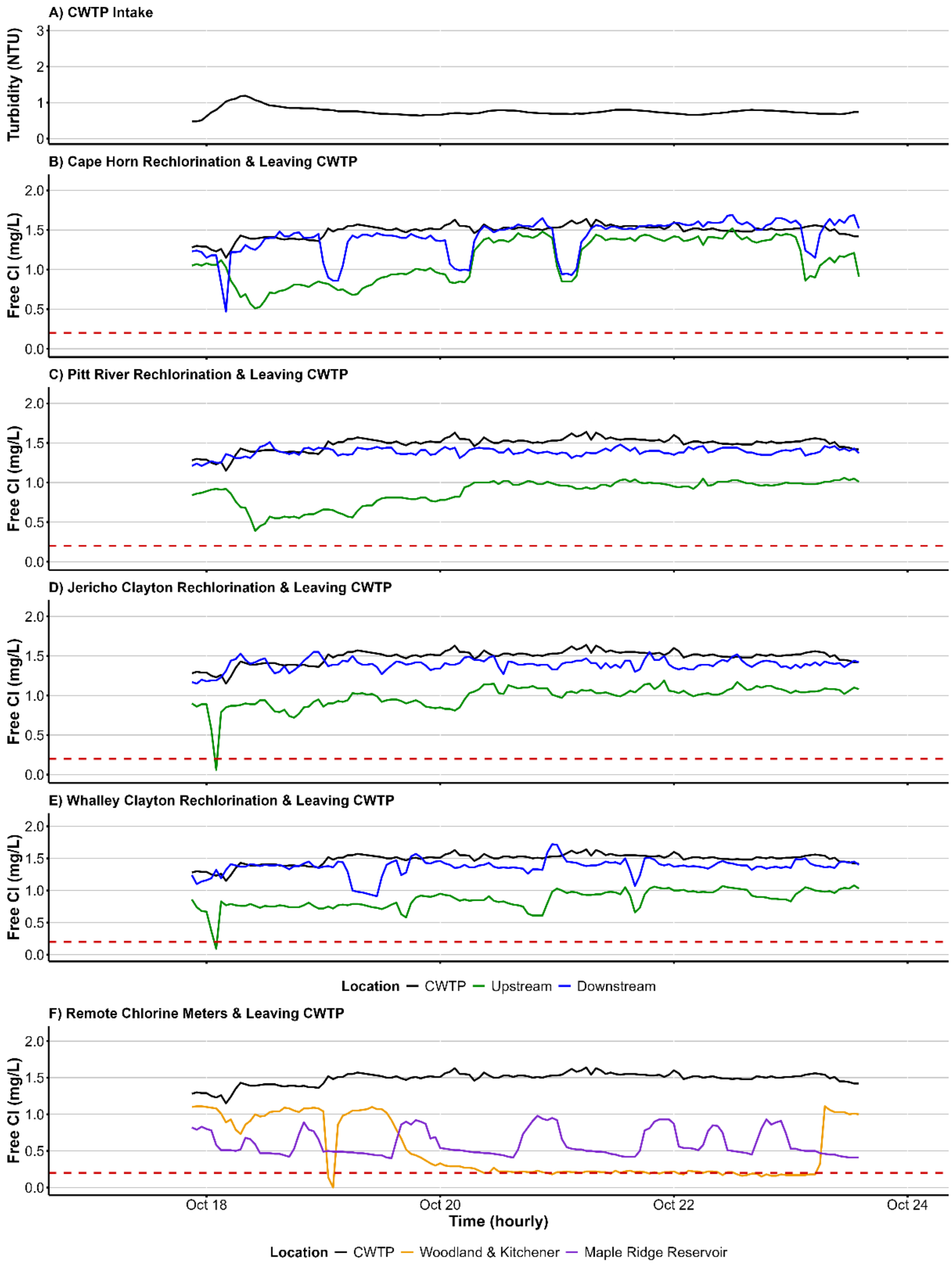

Figure A5. Time series of event 158 (2023-10-18 10:00 – 2023-10-18 21:00) including hourly turbidity (NTU) at Coquitlam Water Treatment Plant (CWTP; A), free chlorine (mg/L) at CWTP (black), and upstream (green) and downstream (blue) of rechlorination stations on the Coquitlam supply (B – E), and at remote chlorine meters in Coquitlam Main No. 3 at Woodland & Kitchener and Maple Ridge Reservoir (F). The red dashed line is free chlorine at 0.2 mg/L, and the period plotted is pre-event, event and post-event.