Comox Valley REGIONAL DISTRICT

Staff Report

DATE: September 15, 2021

FILE: 5600-03/CVWS

TO: Chair and Directors
Comox Valley Water Committee

FROM: James Warren
Deputy Chief Administrative Officer

Supported by James Warren
Deputy Chief Administrative Officer

J. Warren

RE: **Comox Lake Turbidity Model**

Purpose

To present the results of the Comox Lake turbidity modelling conducted by Tetra Tech Canada Inc.

Recommendation from the Deputy Chief Administrative Officer:

THAT the Comox Valley Regional District continue to work closely with the Village of Cumberland to support initiatives that will decrease sedimentation in Perseverance Creek;

AND FURTHER THAT the Comox Valley Regional District continue to monitor turbidity at the former proposed deep water intake location for one year, along with newly established continuous turbidity monitoring at the new lake intake location, to better understand the extent of the difference in turbidity at these two locations.

Executive Summary

- In 2017, Tetra Tech Canada Inc. (Tetra Tech) completed an assessment of turbidity sources to Comox Lake using available monitoring data, and provided a ranking of the various sources and recommendations regarding next steps and data needs.
- This initial assessment successfully modeled circulation but identified that in order to improve modeling for sedimentation and turbidity, additional data inputs would be necessary.
- Following the initial report, the Comox Valley Regional District (CVRD) installed additional monitoring equipment in the watershed to collect the data necessary to improve calibration of the turbidity model.
- In 2020, Tetra Tech incorporated the additional data into the Comox Lake turbidity model and were able to produce reliable results for sedimentation and turbidity modeling.
- While the model shows the two most significant streams contributing sediment to Comox Lake are Perseverance Creek (36 per cent) and Cruickshank River (24 per cent), the study also reveals that during previously measured high turbidity episodes the percentage of sediment at the deep water intake sampling location originating from Perseverance Creek has been as high as 97-99 per cent.
- Turbidity levels at the new lake intake location are expected to be greater than those at the deep water intake sampling location by a factor of approximately 2-4 during high turbidity events. The newly commissioned Comox Valley Water Treatment Plant is designed to fully accommodate and treat these events.

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Government Partners and Stakeholder Distribution (Upon Agenda Publication)

Village of Cumberland Public Works Department	✔

Background/Current Situation

Comox Lake is the water source for the Comox Valley Water System (CVWS), which supplies drinking water to over 45,000 residents. Elevated turbidity leading to boil water notices was recurrent during the winters of 2014 through 2017, especially after intense rainfall events. The construction of a new water filtration plant has included construction of a new water intake in Comox Lake near the lake outlet. The filtration plant has been designed to comply with provincial surface water treatment objectives and will remove sediment from our drinking water, eliminating the need for boil water notices.

The CVRD engaged Tetra Tech to develop a hydrodynamic model of Comox Lake. The study's objective was to determine the relative contributions of tributary streams to the elevated turbidity periodically observed at the CVRD's drinking water intake.

Tetra Tech began the study in 2017, successfully calibrating the hydrodynamic model for lake circulation and temperature. Calibration for sediment or turbidity was not possible at that time due to a lack of sediment grain size data from the relevant tributaries. Therefore, the study was put on hold while the CVRD collected additional sediment, wind, lake water temperature and other data in the watershed. The collected data has now enabled the completion of this second study.

Three boil water advisory periods in 2017 were selected for detailed modelling analysis. The timing and elevation of turbidity predictions from the model agreed reasonably well with the observed turbidity. While the study found that the two most significant streams contributing sediment to Comox Lake are Perseverance Creek (36 per cent) and Cruikshank River (24 per cent), the elevated turbidity observed at the deep water lake sampling location during three boil water advisories in 2017 was primarily from Perseverance Creek. At the peak of each event, the percentage of sediment at the deep water lake sampling location contributed by Perseverance Creek was in the high 90s. Of note, turbidity levels at the actual lake intake location are expected to be greater than those at the deep water lake sampling location by a factor of approximately 2-4 during high turbidity events.

The CVRD plans to continue monitoring water quality at the deep water lake sampling location for at least one year to determine the extent of the difference in water quality during turbidity episodes between the deep water sampling location and the new lake intake. This information will allow evaluation of the economics of treating water with higher turbidity levels at the current lake intake in comparison with the cost of extending the intake to a deeper location where turbidity levels, and as such water treatment costs, would be lower.

While the source of the turbidity is outside of the CVRD's jurisdiction, another consideration is for the CVRD to support the Village of Cumberland's efforts to mitigate erosion in the Perseverance watershed in order to reduce the amount of sediment entering Comox Lake.

Policy Analysis
The Comox Valley Regional Water Supply Strategy (RWSS) was received by the board in May 2010. The first goal of the strategy is to "deliver safe, high quality drinking water" and listed as a key component of this first goal is an objective to "protect the water sources and watersheds within the region".

Understanding the sediment contribution of the various tributaries of Comox Lake to the turbidity levels experienced at our drinking water intake, and working with stakeholders to reduce sediment loading where possible, is an important part of drinking water source management and protection.

Options
1. The Water Committee support CVRD staff to continue working closely with the Village of Cumberland to support the Village's efforts to address sedimentation in Perseverance Creek.
2. The Water Committee provide alternative direction.

Due to the report's findings that 97-99 per cent of the turbidity at the CVRD's lake intake location comes from Perseverance Creek, staff recommends option 1.

Financial Factors
As part of the planning process for the Comox Valley Water Treatment Plant project, a value engineering exercise was conducted to provide a cost benefit analysis of various aspects of the water treatment plant. One of the components that was analyzed was the location of the lake intake. The value engineering exercise determined that the costs associated with building a deep water intake would exceed the economic benefits provided by the difference in water quality from the deep water intake as opposed to a shallower intake closer to shore. As such, the lake intake has been built closer to shore in shallower water at considerable cost savings. The intake has been designed to be extendable should it be determined in the future that the benefits of a deep water intake would be more economical, for instance if the difference in water quality were determined to significantly affect water treatment costs.

Legal Factors
There are no legal concerns generated by this report.

Intergovernmental Factors
The CVWS supplies water to the City of Courtenay, the Town of Comox, CFB Comox, K'ómoks First Nation and the Comox Valley water local service area.

The CVRD has worked extensively with the Village of Cumberland to analyze the cause of turbidity in Perseverance Creek and to investigate options for remediation of their Lake No. 2 spillway channel. The Village continues to apply for grant funding for the implementation of a long term solution but to date has not been successful.

Interdepartmental Involvement
This work is being led by the CVRD Engineering Services branch.

Citizen/Public Relations
No public engagement or communications plans are currently underway for this report.

Attachments: Appendix A – Comox Lake Turbidity Modelling – Tetra Tech

Comox Lake Turbidity Modelling

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Comox Valley Regional District

DECEMBER 2, 2020
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APPENDICES

Appendix A Limitations on the Use of this Document

ACRONYMS & ABBREVIATIONS

Acronyms/Abbreviations	Definition
CVRD	Comox Valley Regional District
DWI	Drinking Water Intake
MUSLE	Modified Universal Soil Loss Equation
NTU	Nephelometric Turbidity Units
PCSWMM	Personal Computer Storm Water Management Model
TSS	Total Suspended Solids
VIU	Vancouver Island University

LIMITATIONS OF REPORT

This report and its contents are intended for the sole use of Comox Valley Regional District and their agents. Tetra Tech Canada Inc. (Tetra Tech) does not accept any responsibility for the accuracy of any of the data, the analysis, or the recommendations contained or referenced in the report when the report is used or relied upon by any Party other than Comox Valley Regional District, or for any Project other than the proposed development at the subject site. Any such unauthorized use of this report is at the sole risk of the user. Use of this document is subject to the Limitations on the Use of this Document attached in the Appendix or Contractual Terms and Conditions executed by both parties.

1.0 INTRODUCTION

The water that supplies the Comox Valley water system originates in Comox Lake and is taken from the Puntledge River and delivered to approximately 45,000 residents. Elevated turbidity leading to boil water advisories was recurrent during the winters of 2014 through 2017, especially after intense rainfall events in the area as the high turbidity levels at the source interfered with the treatment of drinking water. The anticipated construction of a new water filtration plant will involve construction of a new water intake in Comox Lake.

The Comox Valley Regional District (CVRD) engaged Tetra Tech Canada Inc. (Tetra Tech) to develop a hydrodynamic model of Comox Lake. The study's objective was to determine the relative contributions of tributary streams to the elevated turbidity periodically observed at the CVRD's drinking water intake.

Tetra Tech began the study in 2017, successfully calibrating the hydrodynamic model for lake circulation and temperature. Calibration for sediment or turbidity was not possible at that time due to a lack of sediment grain size data from the relevant tributaries. Therefore, the study was put on hold while the CVRD collected additional sediment, wind and other data in the watershed. The collected data has now enabled the completion of this second study.

1.1 Approach

In 2004, Tetra Tech (formerly Hay and Company Consultants Inc.) developed a hydrodynamic model of Comox Lake for Fisheries and Oceans Canada to examine the potential effects of a deep-water withdrawal on temperatures in Comox Lake and the outflowing Puntledge River. Tetra Tech more recently (May 2017) developed and calibrated a Comox Lake watershed turbidity model for the CVRD. Tetra Tech's approach to the current study involved updating and combining these two models.

The Comox Lake watershed turbidity model was recalibrated for both flow and turbidity based on the most recent data available from BC Hydro, CVRD and other entities. This model predicts flows and turbidities in the lake's tributaries based on rainfall and catchment properties. Predictions from this watershed model were used as inputs to the hydrodynamic model of Comox Lake.

The Comox Lake hydrodynamic model was calibrated for circulation and temperature using the available wind and water temperature observations from 2014-2019. Making use of sediment grain size data recently collected by CVRD, this hydrodynamic model was applied to predict the circulation of sediment (linked to turbidity) during several events of interest.

2.0 COMOX LAKE WATERSHED MODEL

2.1 Objectives

Tetra Tech previously developed and calibrated a PCSWMM watershed model as part of the water quality assessment for Comox Lake in May 2017 to provide estimated turbidity and flow values of tributaries to Comox Lake. These turbidity and flow estimates were used as inputs in the hydrodynamic model to simulate and predict turbidity levels within Comox Lake. The previous watershed model was calibrated mainly using flow and rainfall data of the Cruikshank watershed. New rainfall and turbidity data have since become available. This has allowed Tetra Tech to update the watershed model with the new data to improve the calibration of the model and accuracy of the predicted flow and turbidity values. Tetra Tech has updated the PCSWMM watershed model using the available rainfall, flow and turbidity data collected by BC Hydro, Vancouver Island University (VIU), and CVRD from January 2017 to March 2020. Figure 2.1 presents a screenshot of the updated PCSWMM watershed model detailing the subcatchment delineation as well as the locations of the hydrometric and climate stations referenced in this model update.

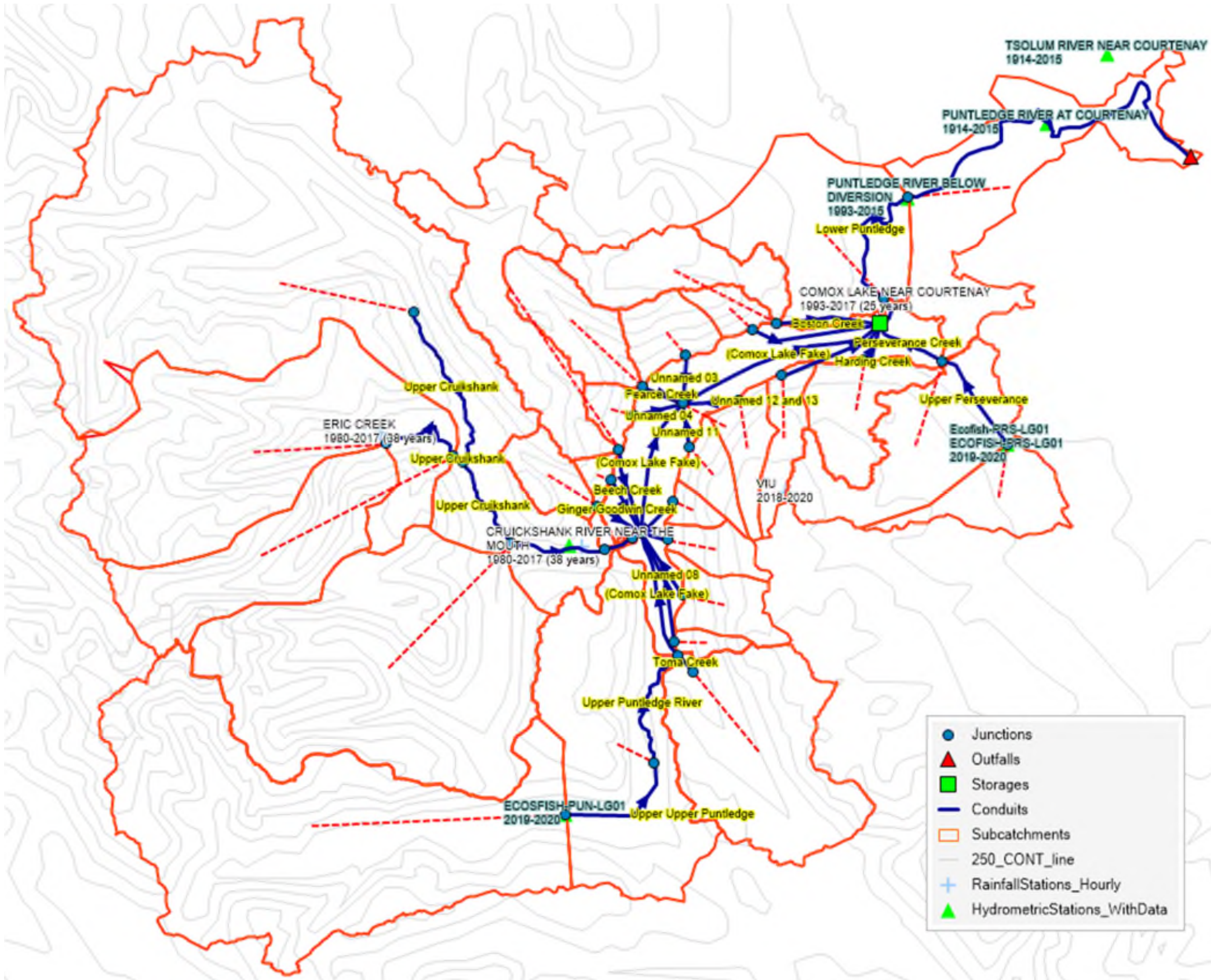

Figure 2.1: PCSWMM Model Screenshot

2.2 Data, Methodology and Assumptions

The following sections describe the types and accuracy of the data available for the model update, as well as the methods and assumptions used in model.

2.2.1 Rainfall and Hydrometric Data

The previous 2017 watershed model was developed and calibrated using climate station data from BC Hydro and hydrometric data from Water Survey Canada (WSC). In this 2020 update, new rainfall and hydrometric data collected by BC Hydro, Ecofish (commissioned by CVRD), and VIU were used to update the watershed model. The following tables summarize the locations, period of records, and data frequencies of the stations available for the model update.

Table 2-1: Rainfall gauge and Climate stations

ID	Station Name	Source	Latitude	Longitude	Elevation (m)	Frequency	Period of Record
08HB082	Comox Lake Near Courtenay	BC Hydro	49.642402	-125.090487	140	Hourly	1993-2020 (27 years)
08HB074	Cruickshank River Near the Mouth	BC Hydro	49.57846	-125.209133	150	Hourly	1980-2020 (40 years)
CMX	Comox Dam Forebay	BC Hydro	49.64305	-125.094421	135	Hourly	1980-2020 (40 years)
ERC	Eric Creek	BC Hydro	49.605351	-125.288171	280	Hourly	1980-2020 (40 years)
Perseverance Creek	Perseverance Creek	VIU	49.593557	-125.131271	970	Hourly	2018-2020 (1.5 Year)

Table 2-2: Hydrometric stations

ID	Station Name	Source	Drainage Area (km^2)	Latitude	Longitude	Frequency	Period of Record
CMC	Comox	BC Hydro	449.32	49.64305	-125.094421	Daily	1990-2020 (30 years)
08HB074	Cruickshank River Near the Mouth	BC Hydro	136.15	49.57846	-125.209133	Daily	1990-2020 (30 years)
PRS-LG01	Perseverance Creek	Ecofish (CVRD)	6.9	49.60502	-125.04364	5 mins	2019-2020 (1 year)
PUN-LG01	Upper Puntledge River	Ecofish (CVRD)	61.79	49.51052	-125.21095	5 mins	2019-2020 (1 year)

The data provided by BC Hydro were from the same stations that were previously used in the 2017 water quality assessment. The new rainfall data from VIU and the flow data from Ecofish provided additional data points within the Comox Lake watershed for model calibration. Tetra Tech reviewed the new data from VIU and Ecofish by comparing their data against BC Hydro's data within the overlapping periods. Tetra Tech concluded that the VIU and Ecofish data are generally consistent with the BC Hydro data, only minor local variances were noted. Based on the completeness of the data and locations of the stations, Tetra Tech has opted to update the PCSWMM model using data from the VIU's Perseverance Creek and BC Hydro's Cruickshank River climate stations. The VIU's Perseverance Creek station dataset includes rainfall as well as wind and temperature data. The additional hourly temperature and wind data were used to simulate snowmelt in the PCSWMM model for a trial run to assess the effects of snowmelt events on flows. The Ecofish flow data was collected at 5-mins interval, which is more discretized than the BC Hydro dataset. With the addition of Ecofish and VIU data, Tetra Tech was able to further calibrate the model using additional simulation tools in the PCSWMM model as described in Section 2.2.3.

2.2.2 Turbidity Data

The CVRD has continued its monitoring program after the water quality assessment in 2017, and has collected handheld turbidity at 12 tributaries of Comox Lake as listed below:

- Upper Puntledge River, Cruikshank River, Pearce Creek, Toma Creek, Boston Creek, Deep Water Intake, Perseverance Creek at Hancock Bridge, Unnamed Tributary, Beech Creek, Ginger Goodwin Creek, Perseverance Creek, and Upper Puntledge River.

The handheld turbidity samplings at these tributaries were carried out approximately every 1 to 2 months. As the handheld turbidity data was not continuous, it does not fully capture spikes in turbidity that were driven by rainstorms, landslides, or other causes. Although the data collected could not be used directly to calibrate the developed models, the collected data, along with site observations, provided insights as to the trends and potential causes of high turbidity events. The handheld turbidity readings collected in 2019 are presented in Figure 2.2 for reference. As shown in Figure 2.2, there appears to be an observable increase in turbidity in the summer month of July. This observable seasonal trend was incorporated in the "Cover and Management Factor" in the Modified Universal Soil Loss Equation (MUSLE) for turbidity simulation, which is described in more details in Section 2.2.3.

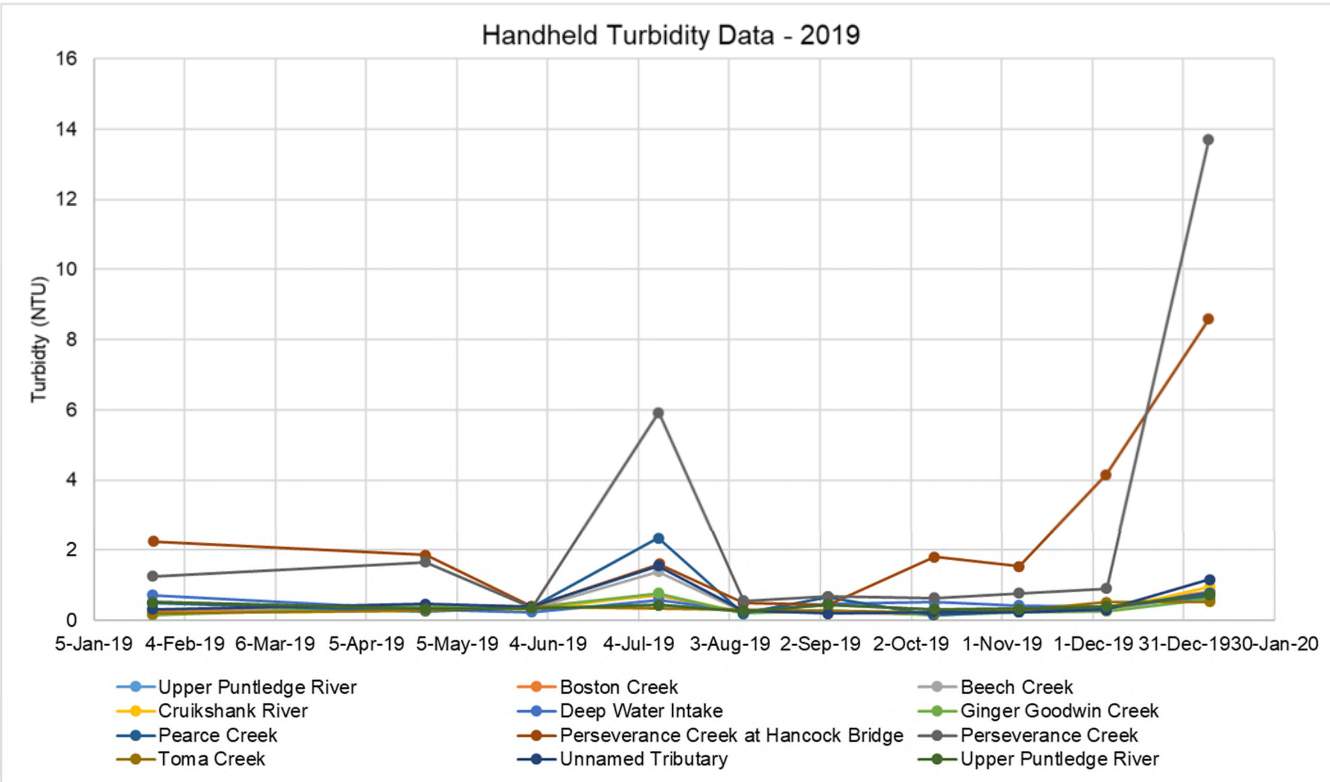

Figure 2.2: 2019 Handheld Turbidity Data

As a continuation of CVRD's 2017 monitoring program, continuous turbidity data was collected at 15 minutes intervals at Perseverance Creek and Cruikshank River, the two (2) tributaries that are believed to be the main sources of sediments and turbidity in the Comox Lake watershed. The continuous turbidity data was used to calibrate the model described in section 2.2.3. The continuous turbidity data of the two stations is plotted with the hourly rainfall data in Figures 2.3 and 2.4. Note the difference in turbidity scale in the figures, indicating that the measured turbidity spikes in Perseverance Creek are roughly 10 times higher than those in Cruikshank River.

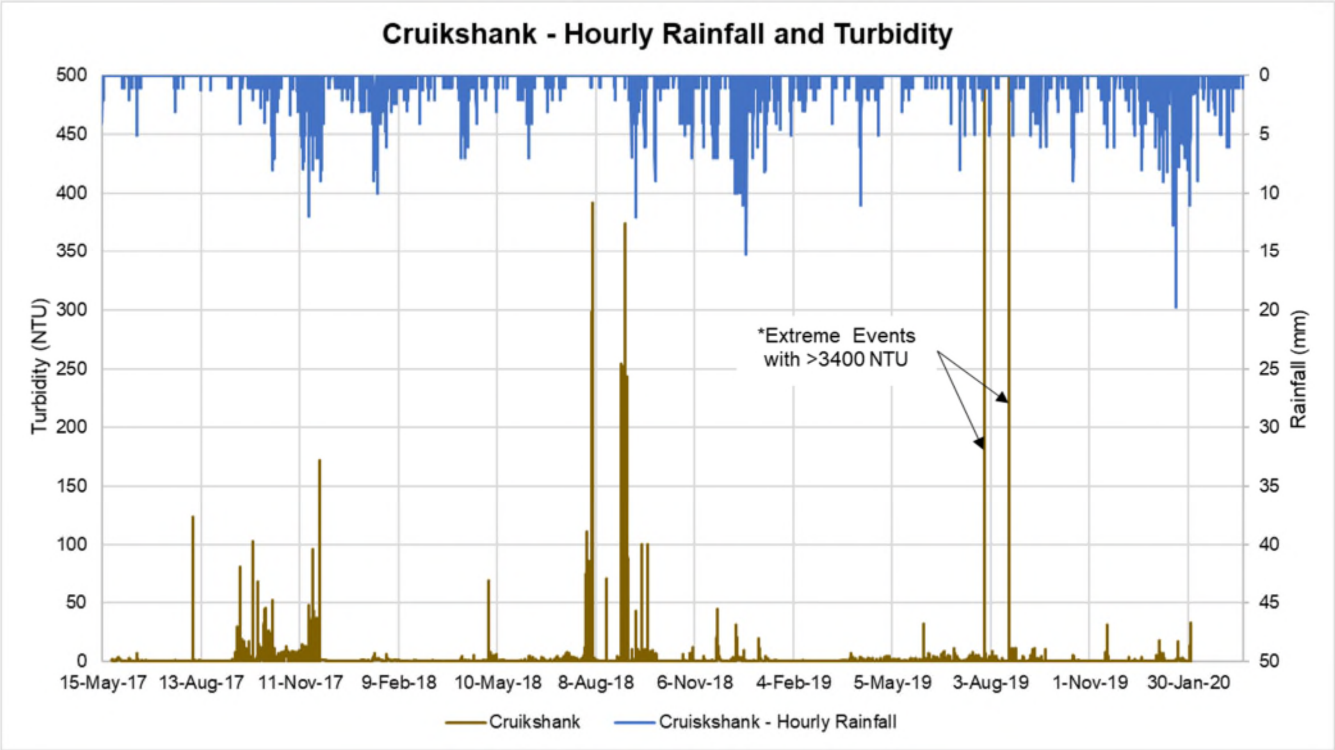

Figure 2.3: Cruikshank River – Hourly Rainfall and Turbidity

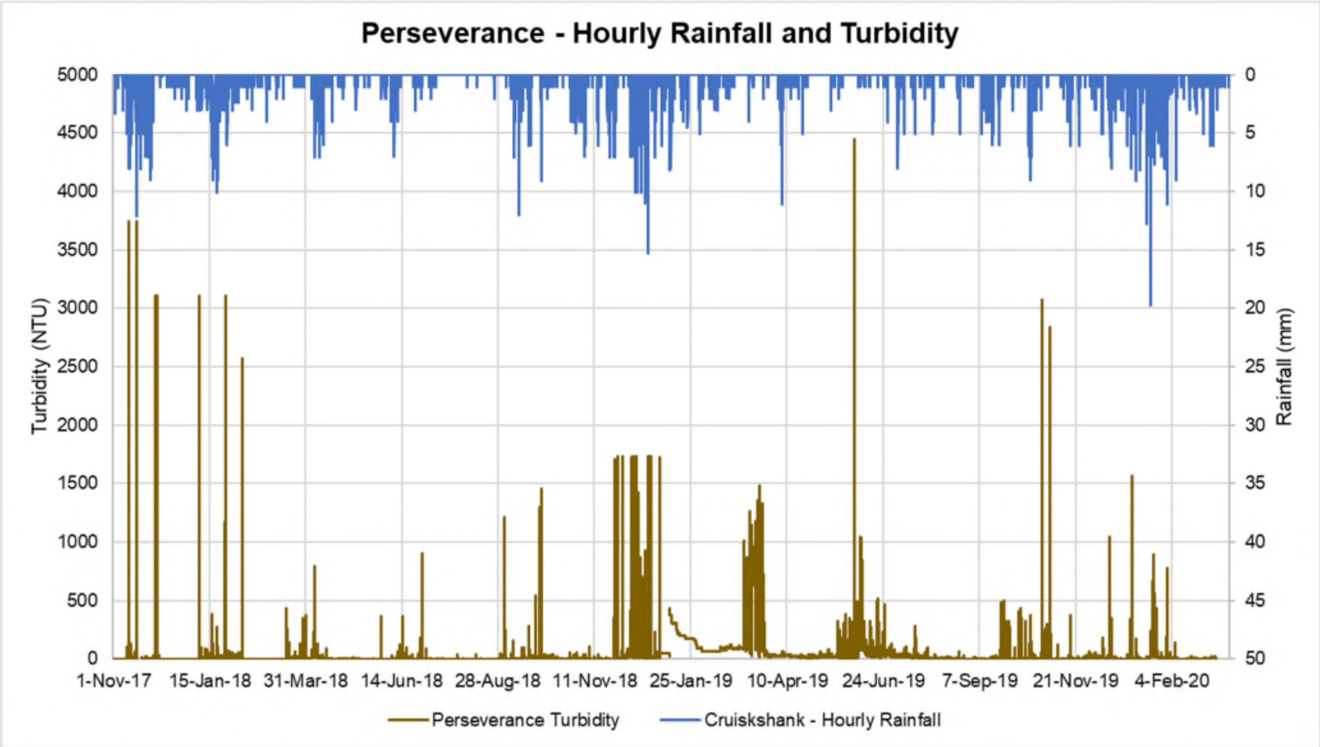

Figure 2.4: Perseverance Creek – Hourly Rainfall and Turbidity

As presented in these figures, high turbidity events are often correlated with large rainfall events; however, some turbidity spikes were observed during summer or low rainfall periods. The spikes could be due to debris obstruction at the sensor; otherwise, these observations suggest that some other causes such as landslides and maintenance or forestry activities may be contributing to these high turbidity events. While the erodibility of the soil in the PCSWMM model can be adjusted based on observed seasonal trends, the model is not able to reproduce sporadic events such as landslides to mimic these spikes in turbidity that are not directly driven by rainfall events. This limitation is discussed further in the methodology and limitation sections.

2.2.3 Methodology

The PCSWMM model was updated and calibrated in a two-step approach. The first step is to update and calibrate the hydrologic model. It is critical to ensure the hydrologic model is accurately representing the hydrology of the watershed prior to the turbidity simulations. This is because the turbidity outputs of the model are largely driven by the flow outputs of the model, which are dependent on the hydrologic components of the model. The hydrologic model components of the model include rainfall, infiltration, and groundwater recharge, which together affect the inflows of the tributaries to Comox Lake. The second step is to update and calibrate the turbidity model, which is based on MUSLE. The following sections describe the parameters and tools used to develop and calibrate these models.

2.2.3.1 Hydrology

In PCSWMM, hydrologic components typically include rainfalls, evaporation, snowmelt, infiltration, and groundwater. With the new climate station data from VIU, hourly temperature and windspeed data can be used to simulate evaporation loss and snowmelt in the PCSWMM Model. As the VIU climate dataset does not cover the full 3-year period from 2017 to 2020, Tetra Tech completed a trial run with the 2019 VIU data to assess if evaporation and snowmelt have significant effects on flow outputs of the model. Tetra Tech concluded that the evaporation and snowmelts do not significantly affect the flow outputs, while the groundwater recharge and infiltration rates have a much stronger influence on baseflows and recessive curves. Considering that discretized temperature and windspeed data are not frequently available, as well as the extensive run time, Tetra Tech believes it is sufficient for our purpose to update the model with the new rainfall data and calibrate the watershed model using only the infiltration and groundwater components in the model for this project. The calibrated results are summarized in Section 2.3.

The infiltration component in PCSWMM simulates the process of rainfall penetrating the ground surface into the unsaturated soil zone of pervious subcatchment areas. The infiltration is simulated based on the Modified Green-Ampt Equation, which require physical based soil parameters, namely suction head, conductivity and initial deficit. Through a cursive review of available soil map and flow calibration, the following infiltration parameters were used in the model:

- **Suction Head:** 90 mm
- **Conductivity:** 1.1 mm/hr
- **Initial Deficit**: 0.3

The groundwater recharge is modeled using the "aquifer" component in PCSWMM. Aquifers are sub-surface groundwater zones used to model the vertical movement of water infiltrating from the subcatchments that lie above them. They also permit the infiltration of groundwater into the channel, or exfiltration of surface water from the channel, depending on the hydraulic gradient that exists. In our watershed model, the aquifers are used to establish baseflow and recession curves that were observed in the flow monitoring data. The groundwater flow equation used in the model is summarized as follows:

$$Q_{GW} = A1(H_{GW} - H^*)^{B1} - A2(H_{SW} - H^*)^{B2} + A3(H_{GW} H_{SW})$$

Where:

Q_{GW}	=	groundwater flow (cfs per acre or cms per hectare),
H_{GW}	=	height of saturated zone above bottom of aquifer (ft or m),
H_{SW}	=	height of surface water at receiving node above aquifer bottom (ft or m)
H^*	=	threshold groundwater height (ft or m)
A1, A2, A3	=	optional coefficients
B1, B2	=	optional coefficients

In our model, each subcatchment has been assigned a unique aquifer to account for its own groundwater movements. Through model runs and review of the flow data, it appears that the baseflow condition and recession curves are relatively similar across all catchments within the Comox Lake watershed. Tetra Tech was able to establish reasonably accurate base flows and recession curves by using uniform aquifer parameters as summarized in Table 2-3 below.

Table 2-3: PCSWMM Aquifer Parameters

Parameter	Value
Receiving Node	Same as Subcatchment Outlet Node
Surface Elevation	Rim Elevation of the Receiving Node
A1 Coefficient	0.01
B1 Exponent	1.1
A2 Coefficient	0.01
B2 Exponent	1.1
A3 Coefficient	Not Used, or 0

2.2.3.2 Turbidity

Turbidity, reported in Nephelometric Turbidity Units (NTU), is a measurement of the degree to which the water loses its transparency due to the presence of suspended particles; however, it is not a direct measurement of the number of suspended particles (reported in mg/L). Some relationship between turbidity and suspended particles is expected, but it may not be linear and is often unique to each instrument and site. Limited Total Suspended Solids (TSS) data was collected at Cruikshank River and Perseverance Creek, but the data was not sufficient to derive any meaningful relationship for the model development. Nonetheless, the erosion (i.e. soil loss) function in PCSWMM still provides a reasonable mean to approximate the turbidity level based on runoff rates. The erosion analysis function in PCSWMM uses MUSLE to estimate daily erosion (i.e. soil loss in mg/l) due to overland flow. The daily erosion is then distributed based on runoff flow rates at the discretization of the model runoff time step. In order to convert soil loss (mg/L) into turbidity (NTU), a fraction of the eroded sediment was assigned as “turbidity”, which is routed through the channels in the model. This is a typical approach used in PCSWMM for water quality modeling, where level of pollutant is tied to the TSS level in the water. The MUSLE parameters and the assigned fraction were used to calibrate the modeled turbidity to the observed turbidity levels. The MUSLE equation and descriptions of the parameters are presented in Table 2-4 below:

$$Sediment\ Yield = 11.8\ (Q_{surf}\ .\ q_{peak}\ .\ Area)^{0.56}\ .K\ .C\ .P\ .LS\ .CFRG$$

Table 2-4: PCSWMM Erosion (MUSLE) Parameters

Parameter	Description	Value
Q_{surf}	Daily surface runoff volume	Model generated based on rainfall
q_{peak}	30-minute peak runoff rate	Model generated based on rainfall
Area	Subcatchment area	Model generated based on measurement
K	Soil erodibility factor	0.011 - 0.03
C	Cover and management factor, due to crop canopy and residue on the soil	Time series based on observed trends on handheld and continuous monitoring data. 0.1 – 0.3
P	Support practice factor, effect of contour tillage/strip cropping, etc.	0.75
LS	Topographic factor	Calculated based on subcatchment length and slope
CFRG	Coarse fragment factor, based on percentage of rock in the upper most soil layer	0.1 – 0.15

The Cover and Management Factor (C-factor) in PCSWMM can be entered as a constant or a time series to simulate crop growth cycle and other management practices that affect the erodibility of the soil. This factor has been used in the model to better match the observed turbidity level during model calibration. The calibrated model results are summarized in the next section.

2.3 Calibration

The following sections summarize the calibration process and calibrated flow and turbidity results of the watershed model.

2.3.1 Flow

In general, the flow calibration was carried out by comparing the outflow hydrographs generated by the model to the monitoring station data. The calibrations focus on runoff volume, response timing, and peak value (i.e. shape of the hydrograph). Infiltration and groundwater parameters were adjusted through trial and error to best mimic the natural flow responses observed in the monitoring data. Because the rainfall data provided by VIU and BC Hydro are reasonably consistent, Tetra Tech concluded that the calibration is not sensitive to which rainfall dataset is used in the model. The calibrated model is able to produce similar results using either VIU or BC Hydro rainfall data. The model calibration was carried out based on the on four (4) hydrometric monitoring stations, namely Comox Lake (CMC), Cruikshank River (08HB074), Perseverance Creek (PRS-LG01), and Puntledge Creek (PUN-LG01). The model calibration began with Perseverance Creek and Cruikshank River stations, and the calibrated hydrological parameters were then transferred to other subcatchments. The Comox Lake station was used to validate the overall flow volume and runoff patterns of the Comox Lake watershed. The calibrated flow results are presented in Figure 2.5 to Figure 2.8.

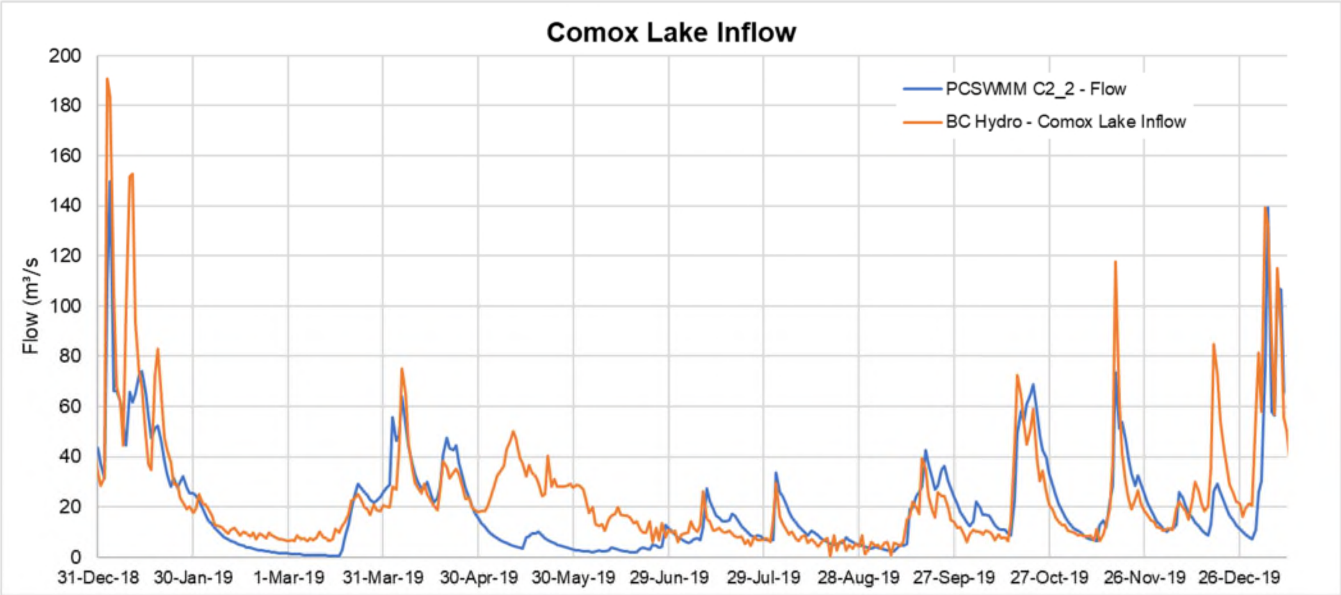

Figure 2.5: Comox Lake Inflow (CMC) - Calibrated Flow Results

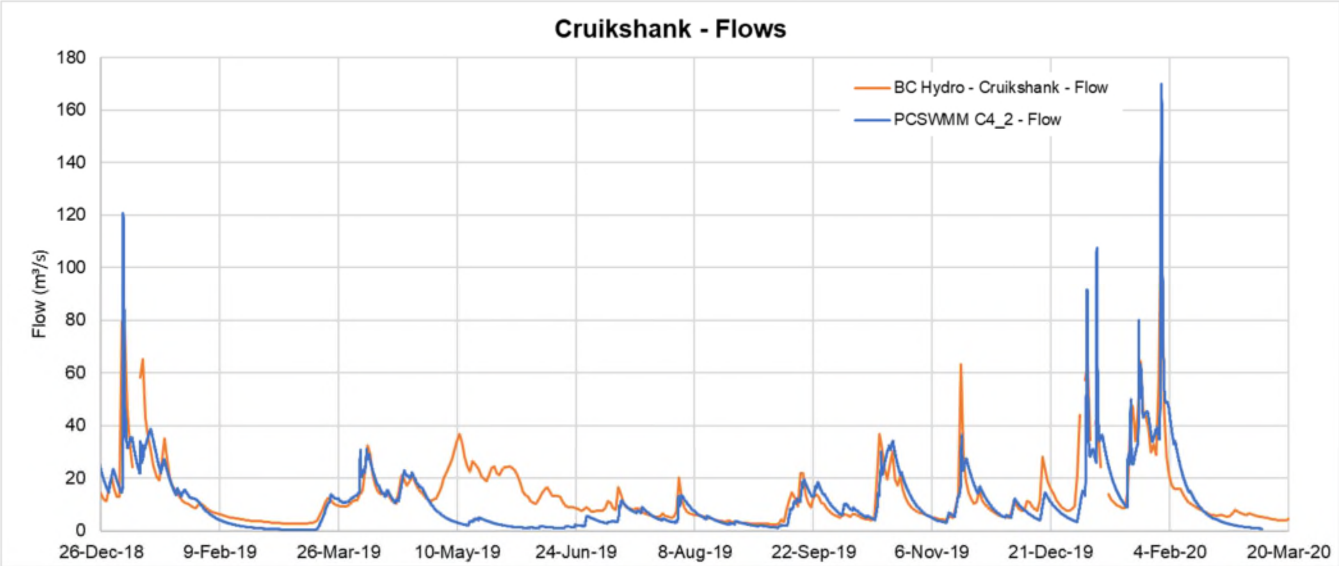

Figure 2.6: Cruikshank River (08HB074) - Calibrated Flow Results

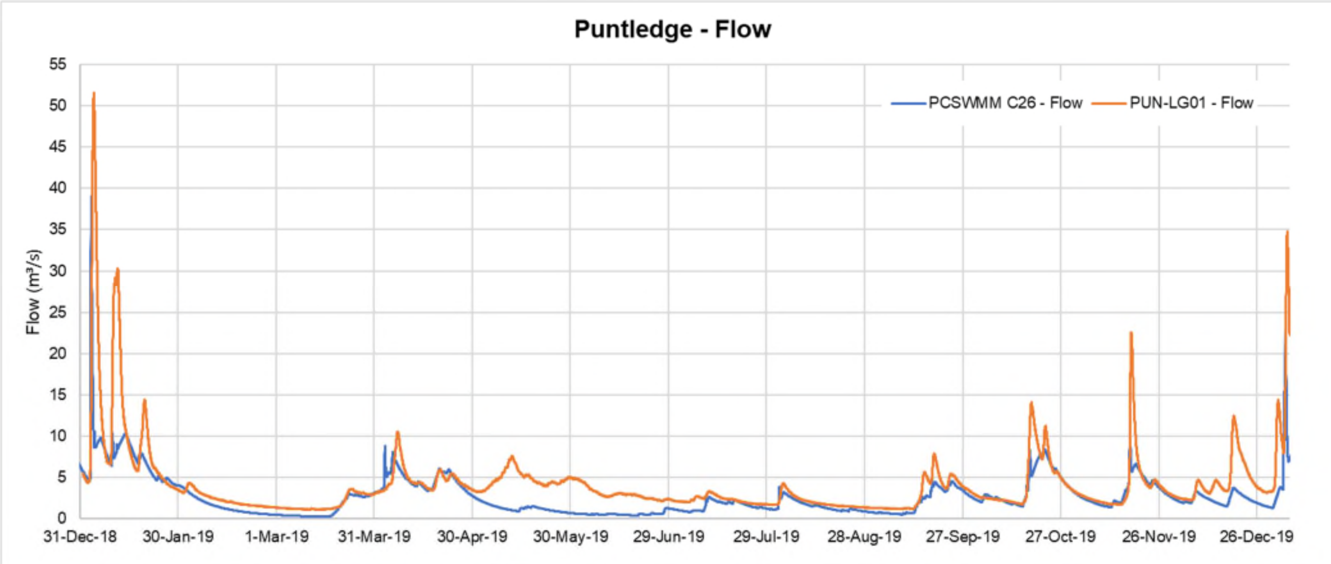

Figure 2.7: Puntledge Creek (PUN-LG01) - Calibrated Flow Results

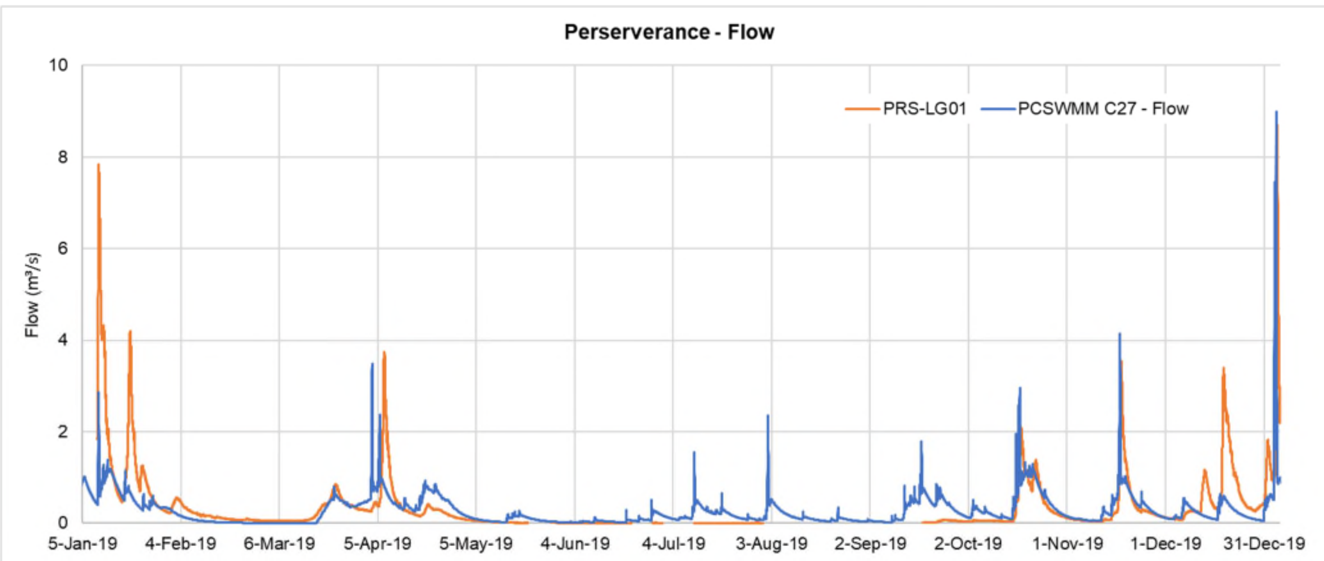

Figure 2.8: Perseverance Creek (PRS-LG01) - Calibrated Flow Results

As presented in Figures 2.5 to 2.8, the calibrated PCSWMM model is generally able to match the runoff patterns and peaks. The accuracy of the model results varies depending on the size and character of the subcatchments. Considering that Cruikshank River and Perseverance Creek are the only tributaries with continuous turbidity data, and they are likely the main sources of turbidity in Comox Lake, the model calibration effort was mainly focused on these two tributaries. The calibrated parameters were then transferred to the other subcatchments, and the overall model performance was validated through comparing the modeled inflows to the observed inflows of Comox Lake. Tetra Tech did not try to match all the observed peaks in other smaller tributaries and did not individually adjust groundwater and infiltration parameters for these smaller tributaries. Tetra Tech believes the level of accuracy the model is providing for the other tributaries is sufficient for the purpose of this assignment. The variations between observed and modeled flow values seen in the above figures are reflective of our calibration approach. The model outputs for Puntledge Creek did not match some of the spikes in September to December in 2019; this suggests the infiltration capacity within the subsoil may be less than what was assumed in the model. The above figure also show that the model did not mimic the increase in flows during the month of May 2019 for Comox Lake (i.e., total inflow), Cruikshank River and Puntledge Creek. This may be due to the spatial distribution or accuracy of the rain gauge data for this period. The rain gauge data used in the model from Cruikshank River and Perseverance Creek did not record an increase in rainfall in May 2019, while Comox Near Courtney Station (08HB082) did record an increase in rainfall in that period. The similar variance in December 2019, where the PCSWMM model underpredicted the outflows, is likely due to variation in rainfall distribution as well. The VIU's Perseverance Creek data used in the model run recorded less rainfall than the Cruikshank River and Eric Creek stations. Overall, despite these variations, Tetra Tech believes the updated PCSWMM watershed model has been improved from the previous version, and it is providing reasonably accurate results for the purpose of estimating turbidity levels in Comox Lake. This is further supported by the turbidity model results presented in the latter sections of this report.

2.3.2 Turbidity

The calibration of the turbidity outputs in the PCSWMM model was carried out by comparing the model results with the observed turbidity data at Cruikshank River and Perseverance Creek. As discussed in the previous sections, the monitoring data suggests that spikes in turbidity during low flow periods may have been caused by human activities or natural forces other than rainfall. For the purpose of the watershed model, Tetra Tech has opted to focus on calibrating to turbidity events or spikes that were driven by rainfall. Figure 2.9 and Figure 2.10 present the modeled turbidity results between August 2019 to February 2020, which Tetra Tech believes is a reasonable period for comparison of rainfall driven turbidity events.

As shown in Figure 2.9, the calibrated model was able to mimic the timing and peak of the turbidity levels observed at Cruikshank River. The calibrated model was also able to reproduce the peak of the high turbidity events (<800 NTU) that are driven by rainfalls at Perseverance Creek as shown in Figure 2.10. However, the model was not able to reproduce the extreme turbidity events (>800 NTU) that were likely not directly caused by rainfalls.

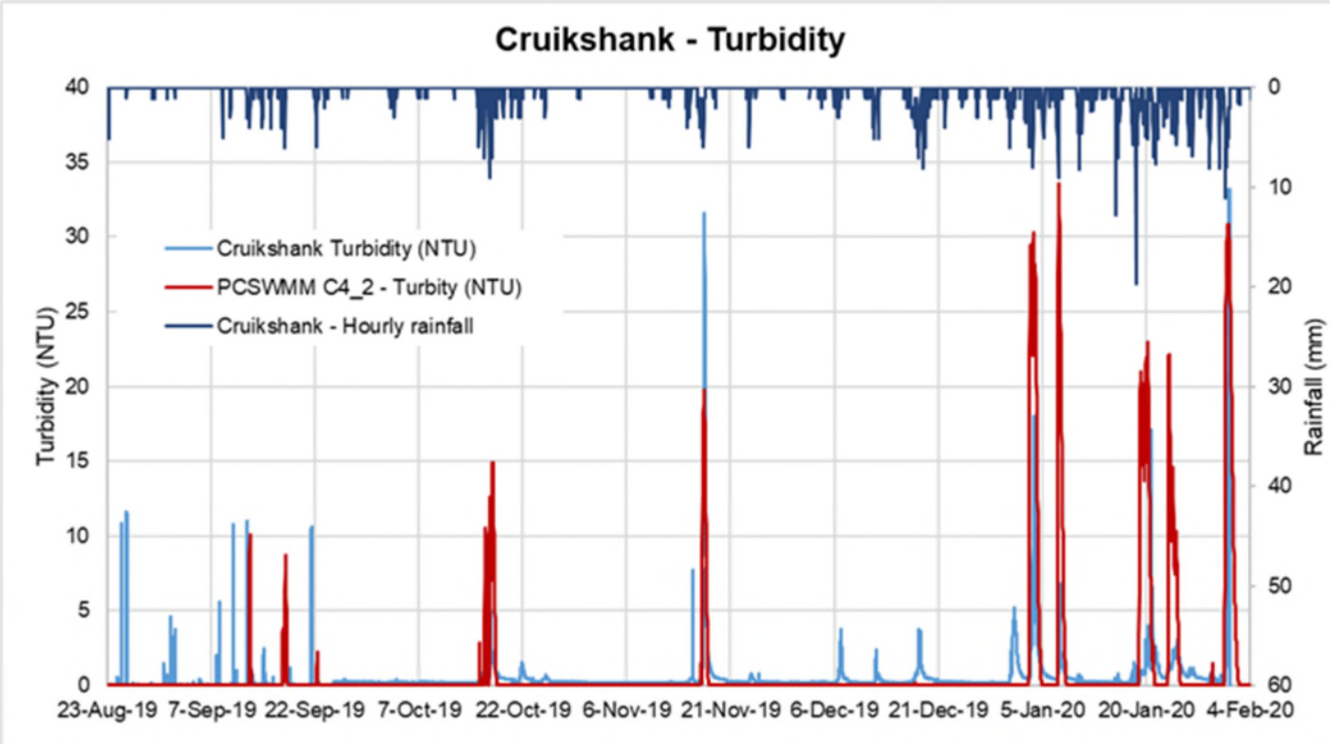

Figure 2.9: Cruikshank River - Turbidity Results

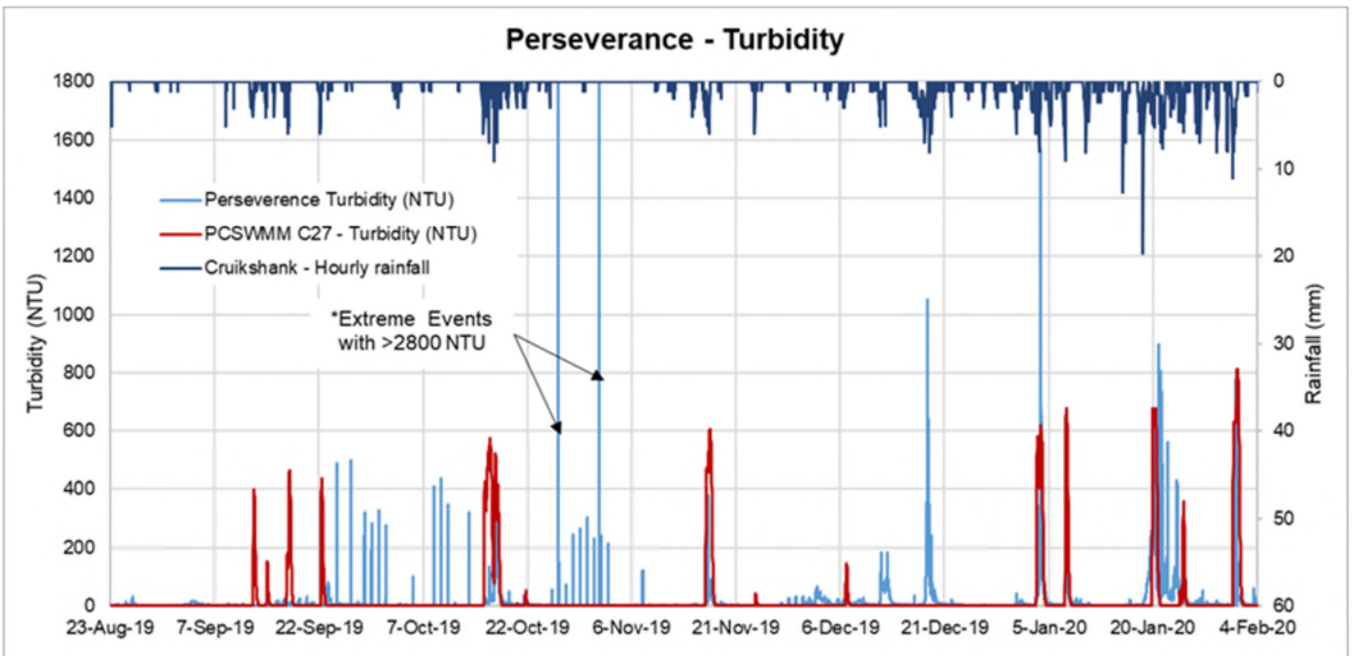

Figure 2.10: Perseverance Creek - Turbidity Results

2.4 Results

The watershed model was run from 1 January 2017 to 9 March 2020 driven by rainfall data from BC Hydro's Cruikshank River Station and from 31 October 2018 to 9 March 2020 driven by rainfall data from VIU's Perseverance

Creek Station. Predicted flow rates and turbidity in each tributary were generated at a 30-minute time step and were used in the hydrodynamic model as described later. Figures 2.11 and 2.12 summarize the flow and turbidity predictions by showing the relative proportions of flow volume and sediment load, respectively, contributed by each stream to Comox Lake from 1 January 2017 to 9 March 2020.

The Cruikshank River is the largest contributor of flow volume to the lake, with a predicted 50% of the total inflow volume. Other major contributors are the Upper Puntledge River (21%), Toma Creek (6%), Perseverance Creek (5%) and Beech Creek (4%).

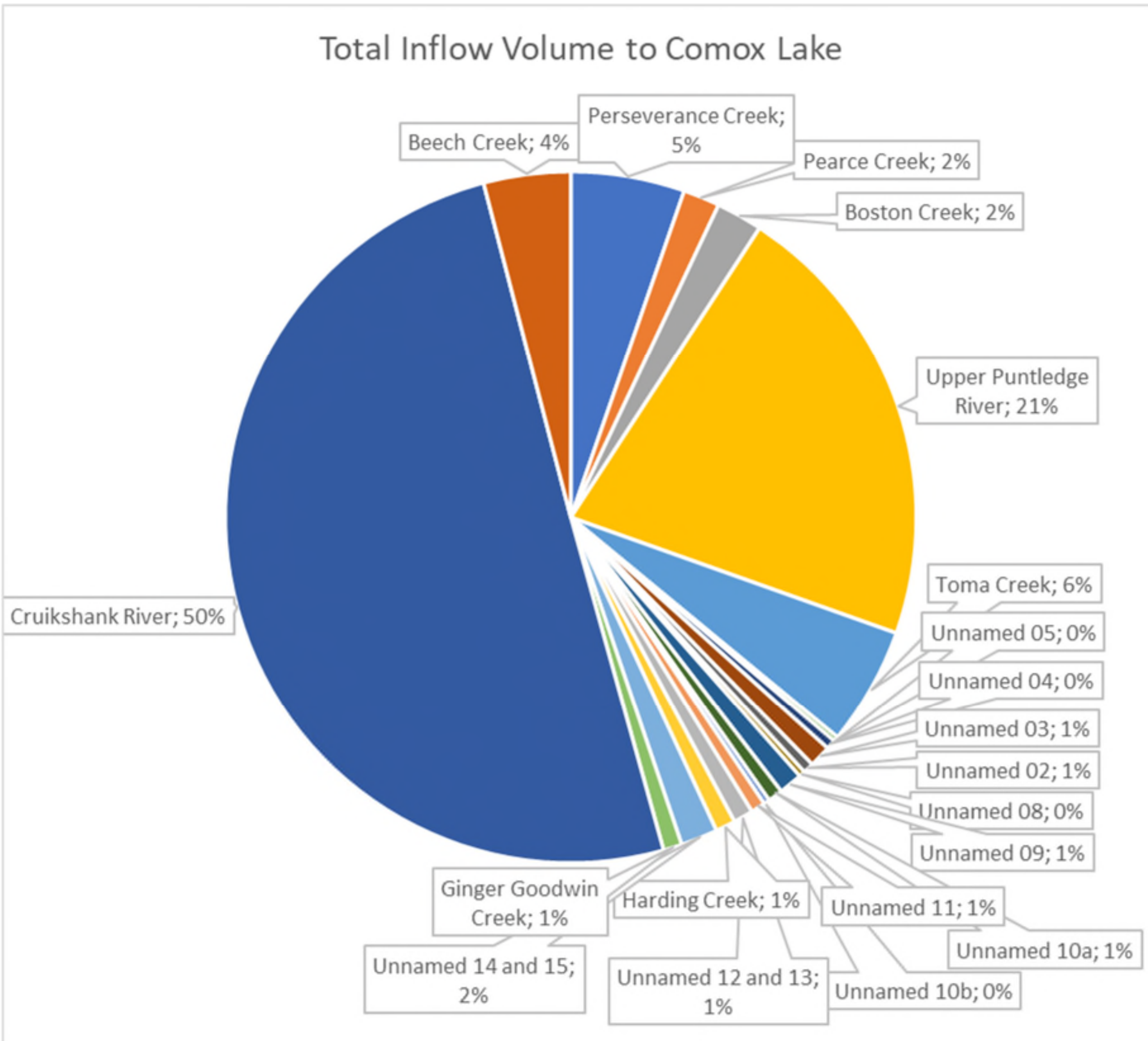

Figure 2.11: Predicted Shares of Total Flow Volume by Tributary

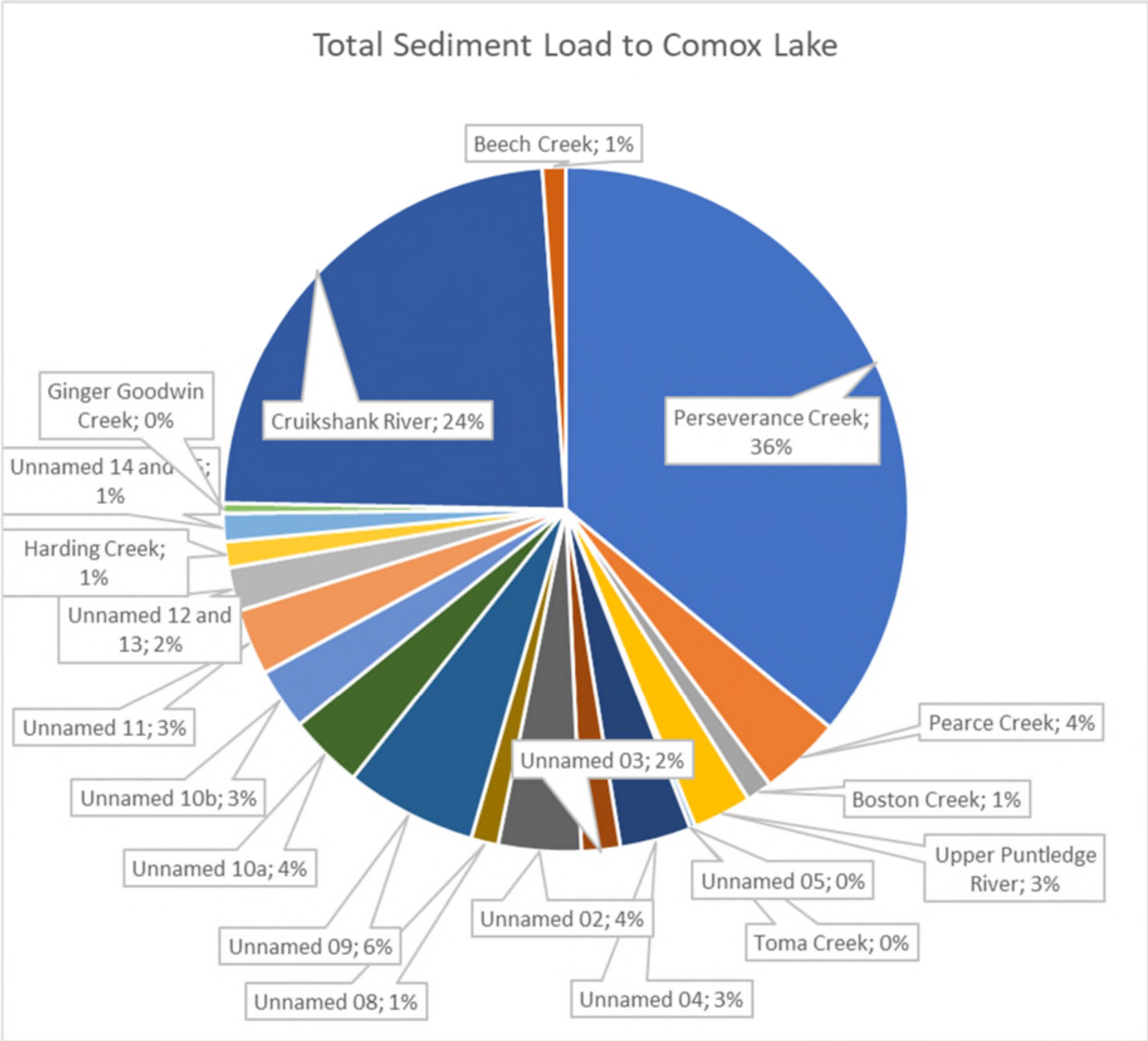

Figure 2.12: Predicted Shares of Total Sediment Load by Tributary

In terms of sediment supply, however, the Cruikshank River is predicted to provide only 24% of the total sediment load to Comox Lake. Due to the settling efficiencies of Willemar and Forbush Lakes, the Upper Puntledge provides only 3%. Perseverance Creek is predicted to be the primary contributor of sediment, providing 36% of the total sediment load. The differences in the sediment and flow volume distributions are reflective of two items. The first is that the unproportionately high turbidity and soil loss outputs of Perseverance Creek have skewed the distribution. The second is that the MUSLE equation used in the model accounts for a topographic factor (LS) based on flow length and slope, which uniquely adjusts the erodibility of each subcatchment based on topography. This means that sediment loading in the model is not only depending on size of the subcatchment (i.e. flow volume), but also the erodibility of the subcatchment based on topography.

2.5 Uncertainty and Limitations

This section briefly outlines the most significant sources of uncertainty in the watershed model.

- Turbidity was derived using a soil loss equation, but a distinct relationship between Total Suspended Solids (TSS) and Turbidity could not be derived based on available data. The soil loss parameters and assigned fraction were adjusted to calibrate to observed data. While this approach could reasonably simulate past events, and also reasonably predict turbidity level based on observed seasonal trend, it may not be able to accurately predict spikes in turbidity due to other causes.
- The turbidity outputs of the model are ultimately driven by rainfall events. The model is not able to simulate spikes in turbidity due to other causes such as landslides or human activities.
- As per email from CVRD on November 16th, 2017, it is suspected that the turbidity data collect between October and November 2017 may not be accurate. It was also noted that the turbidity data collected at Perseverance Creek from January to September 2019 appear to be high in comparison to handheld data. In general, this highlights the inherent challenges of obtaining accurate turbidity data for modeling. This ultimately affects accuracy of the model calibration and predictions.
- Tetra Tech has been provided with a wide range of rainfall and hydrometric data within the Comox Lake Watershed, which are helpful for understanding the overall hydrology of the watershed, as well as for updating and reviewing the model. However, while theoretically possible, it is challenging and not economical to calibrate the model to produce accurate results that match a wide range of observed data. In general, it is more efficient and purposeful to target the model on a certain time period and outputs of key tributaries. This is the approach used in this model update, where Tetra Tech decided to focus on outputs from Cruikshank River and Perseverance Creek where continuous turbidity data is available. Therefore, some model parameters will need to be adjusted and re-calibrated if the CVRD is exploring other objectives or is looking to assess other tributaries within the watershed in details.

3.0 COMOX LAKE HYDRODYNAMIC MODEL

This section describes the Comox Lake hydrodynamic model implemented to simulate the circulation of water and sediment in Comox Lake.

3.1 Objectives

The primary objective of the hydrodynamic model was to predict the relative contributions of the tributaries to the elevated turbidity periodically observed at the CVRD drinking water intake (DWI). To make defensible predictions it was necessary that the model should

- Predict water levels matching those recorded by BC Hydro, as confirmation of the water balance;
- Predict water column temperatures matching those observed by CVRD, as confirmation of heat balance and lake circulation;
- Predict turbidity at the DWI matching observations by CVRD, as confirmation of sediment circulation.

3.2 Data, Methods and Assumptions

3.2.1 Introduction to H3D

The hydrodynamic model developed for Comox Lake is an implementation of H3D. H3D is a proprietary three-dimensional hydrodynamic model maintained by Tetra Tech. The model is derived from GF8 (Stronach et al. 1993) developed for Fisheries and Oceans Canada. H3D has been successfully implemented on several extensive studies along the B.C. coast and inland waters. H3D is a time-stepping numerical model which computes the three components of velocity (u,v,w) on a regular grid in three dimensions (x,y,z), as well as scalar fields such as temperature and sediment. A detailed technical description of the model, and numerous validations, are available on request.

3.2.2 Bathymetry

Bathymetry is the measure of depths throughout a body of water. Bathymetry data were available from Tetra Tech's previous work on Comox Lake. The horizontal resolution of the model is 100 m. The shelf at the mouth of the Upper Puntledge was missing from the previous (2004) model; for the present work, depths in that location were estimated from historical lake elevations and satellite images.

The vertical datum for the old bathymetry was inferred from the shoreline contour by matching the south end shoreline in satellite images and checking lake elevation on the imagery dates. The grid datum is 134.8 ± 0.1 m elevation on the lake level gauge maintained by the Water Survey of Canada. Figure 3.1 shows the model grid bathymetry. The point labelled DWI is the CVRD's deep water intake, where most in-lake observations have been made. The intake is at 30 m depth, though the lake at that location is 43 m deep.

The proposed new intake location is also shown on Figure 3.1. Model depths near the proposed intake were updated based on the 2019 survey by Frontier Geosciences Inc (2019).

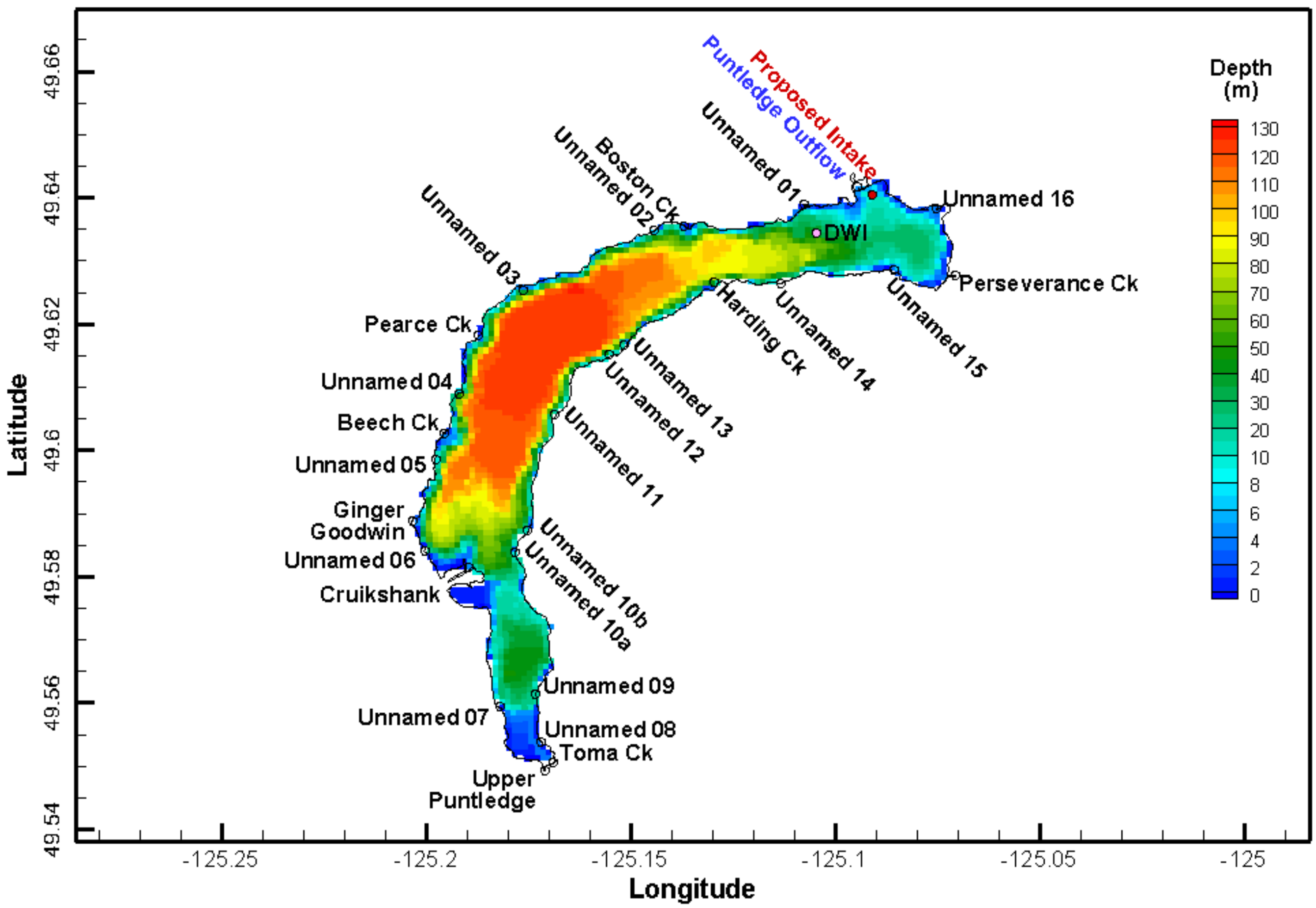

Figure 3.1: Hydrodynamic Model Grid Bathymetry and Rivers

3.2.3 Meteorological Data

Public wind data in the region were available from Comox Airport, Beaver Creek and Mount Washington, stations that also recorded air temperature and humidity. Additionally, in 2019 CVRD installed two anemometers at Comox Lake and in late 2018 VIU installed a weather station in the headwaters of Perseverance Creek. Figure 3.2 shows the locations of these stations.

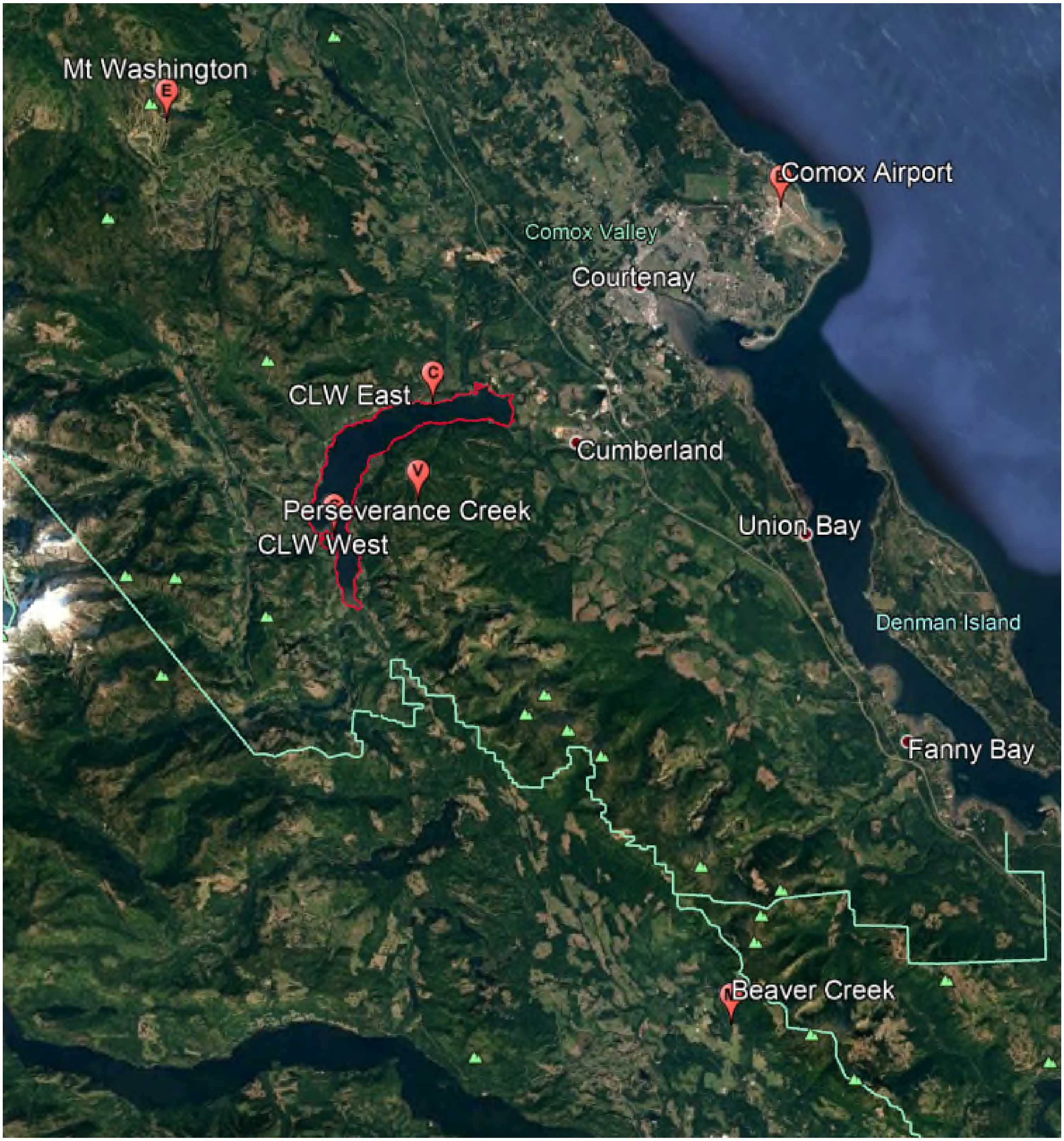

Figure 3.2: Regional Wind Stations

The Comox Airport station is operated by Environment Canada. It is approximately 16 km northeast of Comox Lake, on flat land between the Town of Comox and the Strait of Georgia. Its record runs from 1953 to present, a period of over 67 years. Figure 3.3 presents a wind rose for Comox Airport. The dominant wind direction is southeast, and winds typically align with the Strait of Georgia. Wind speeds are moderate, with about 6% of observed speeds exceeding 9 m/s.

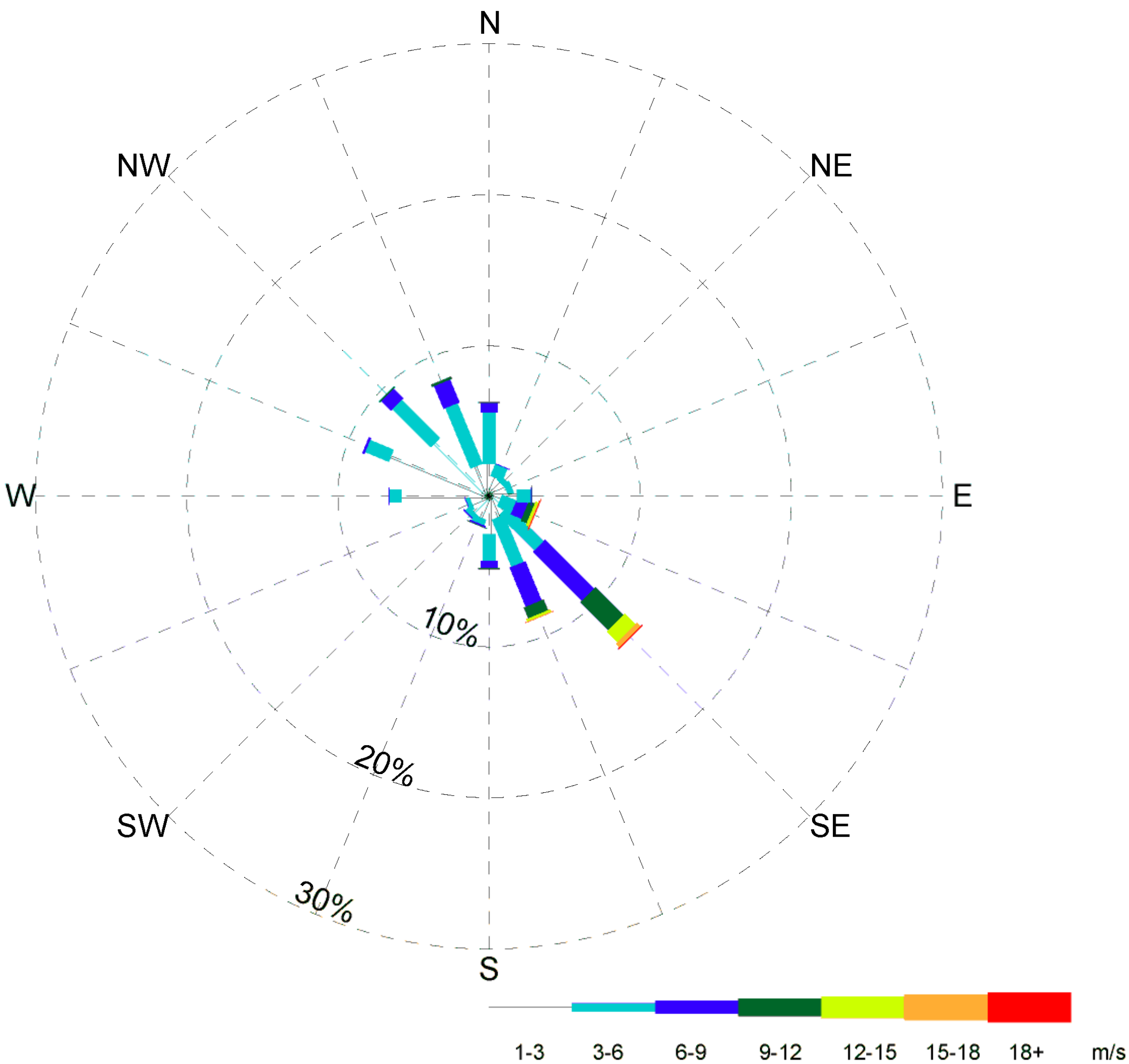

Figure 3.3: Comox Airport Wind Rose

The Beaver Creek station is operated by the Ministry of Forests, Lands, Natural Resource Operations and Rural Development. It is approximately 30 km southeast of Comox Lake near the community of Beaver Creek, in a valley that stretches northwest to the south tip of Comox Lake. Its record runs from 1987 to present, but has intermittent coverage. Figure 3.4 presents a wind rose for Beaver Creek from 2011-2016, years with nearly complete data. The dominant wind direction is southeast, and winds typically align southeast-northwest with the valley. Wind speeds are relatively high, with about 9% of observed speeds exceeding 9 m/s.

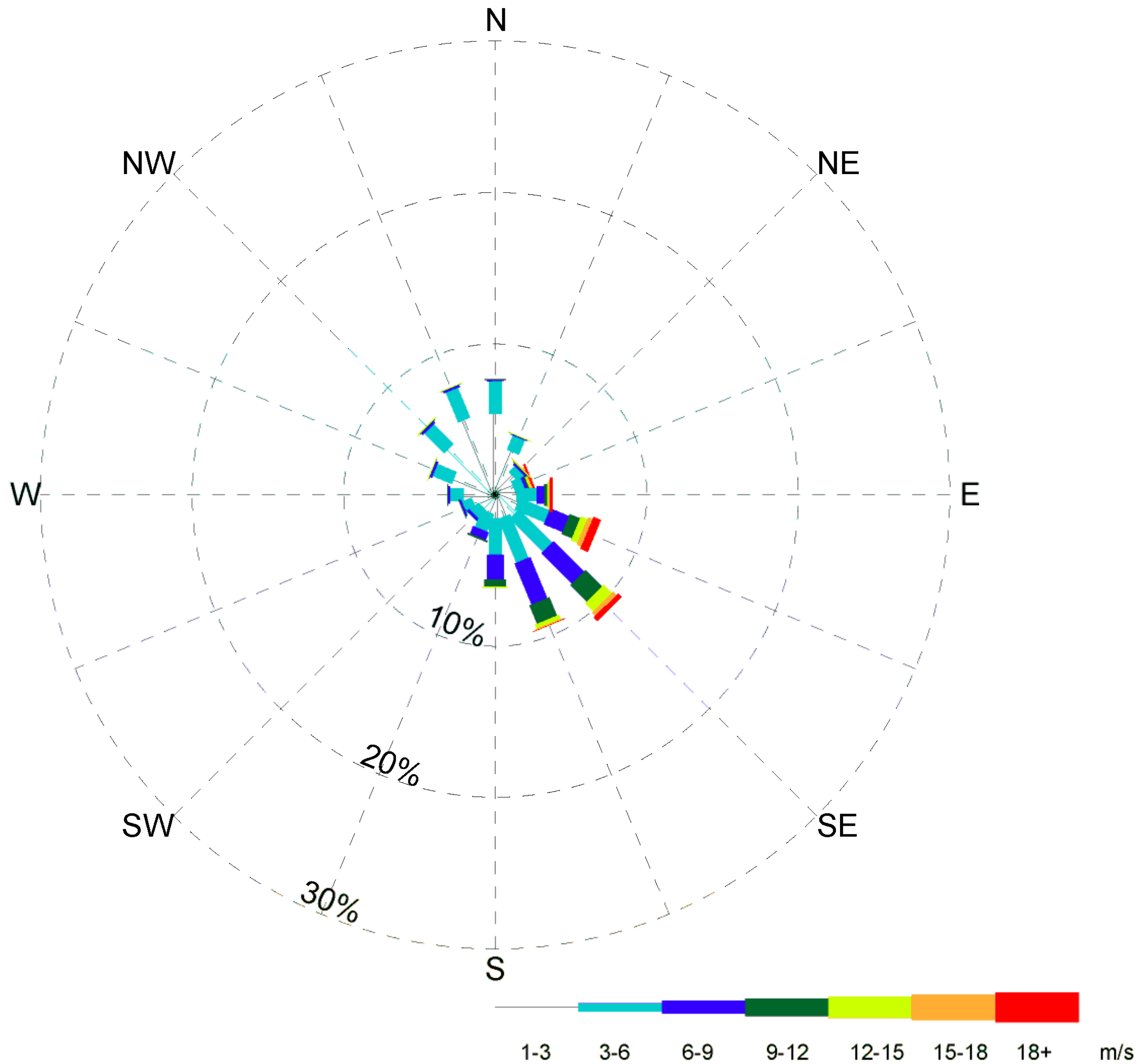

Figure 3.4: Beaver Creek Wind Rose

The Mount Washington station was operated by Environment Canada. It is approximately 17 km northwest of Comox Lake, on the west edge of the southern crest of Mount Washington. Its record runs from October 31, 2007 to September 29, 2010, a period of about 3 years. Figure 3.5 presents a wind rose for Mount Washington. Two dominant directions are evident, southeast and northwest, with northwest winds being generally somewhat stronger but less frequent. Wind speeds were moderate, with about 3% of observed speeds exceeding 9 m/s. Data from this station were not available for the period of interest, so it was not used by the simulations.

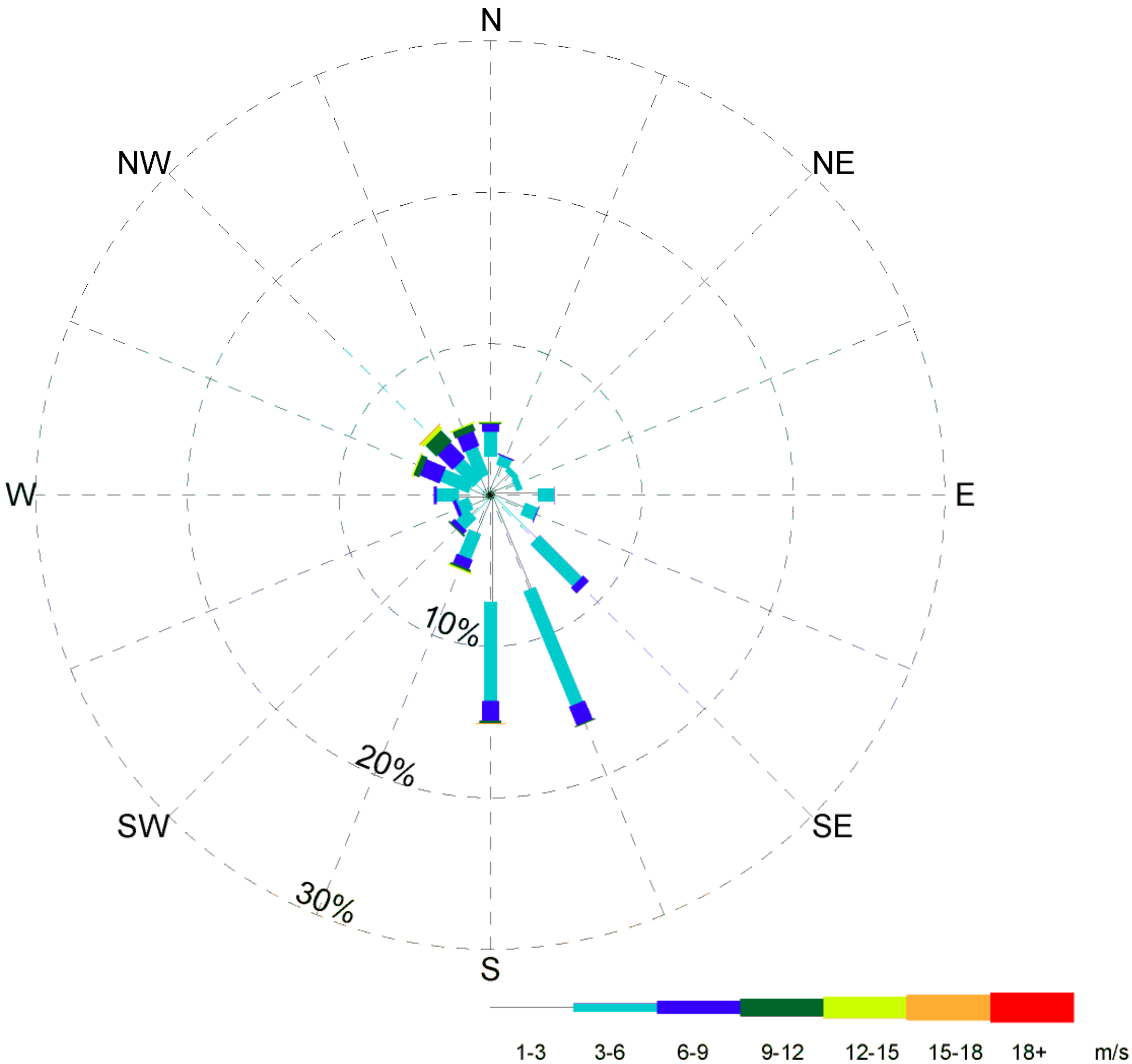

Figure 3.5: Mount Washington Wind Rose

CVRD wind station CLW West (CLWW) has recorded data from 4 February 2019 to present. This station is installed near the shore of the Cruikshank River delta about 300 m south of the river mouth. Figure 3.6 presents a wind rose for CLW West. The observed winds are relatively weak, with 98% of observed speeds being less than 6 m/s. The dominant wind directions are south and north, aligned with the lake and valley.

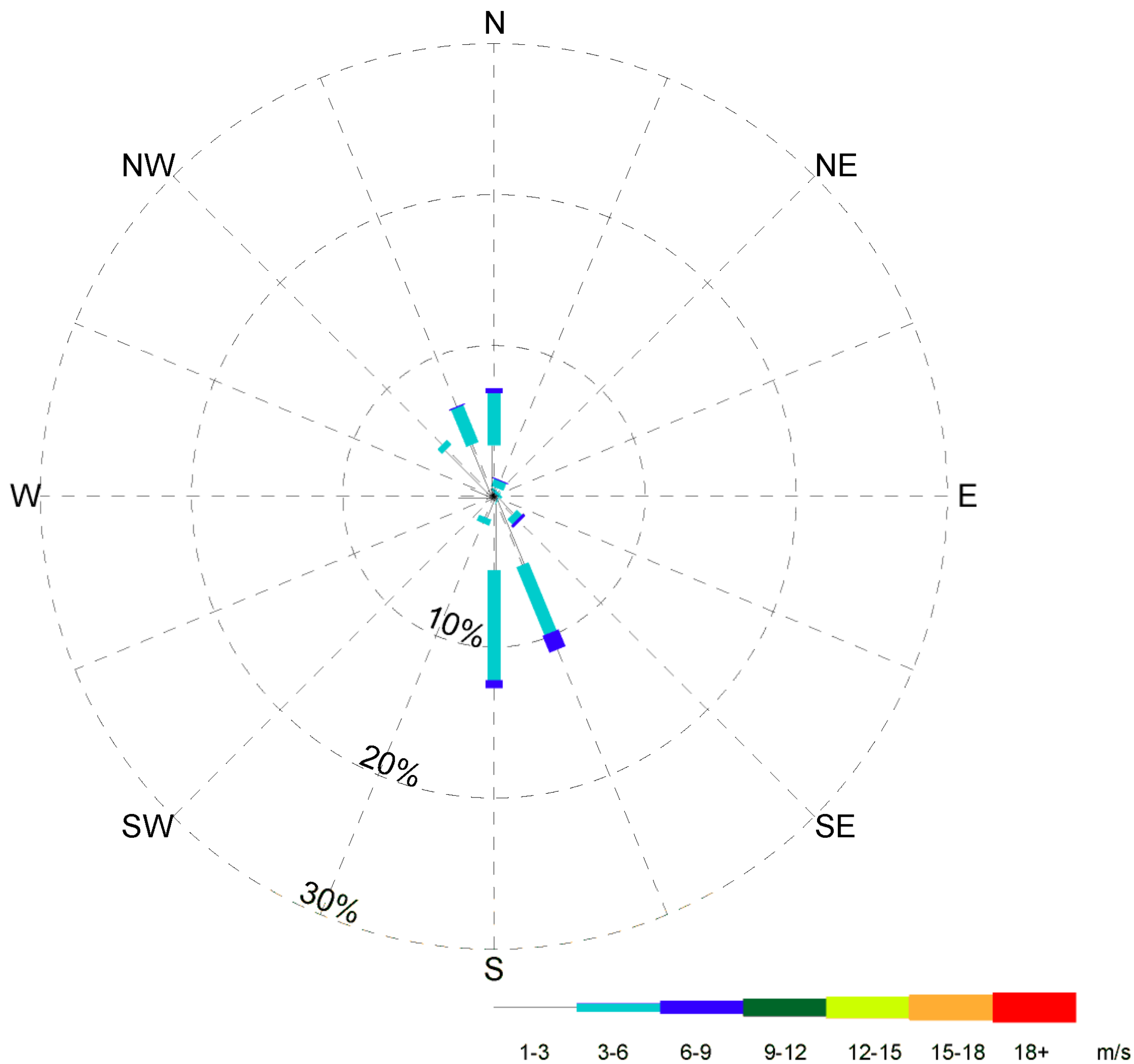

Figure 3.6: CLW West Wind Rose

CVRD wind station CLW East (CLWE) has recorded data from 4 February 2019 to present. This station is installed near the shore of Comox Lake about 1 km east south of Boston Creek. Figure 3.7 presents a wind rose for CLW East. The observed winds are relatively weak, with 96% of observed speeds being less than 3 m/s. The dominant wind directions are east and west, aligned with the lake and valley.

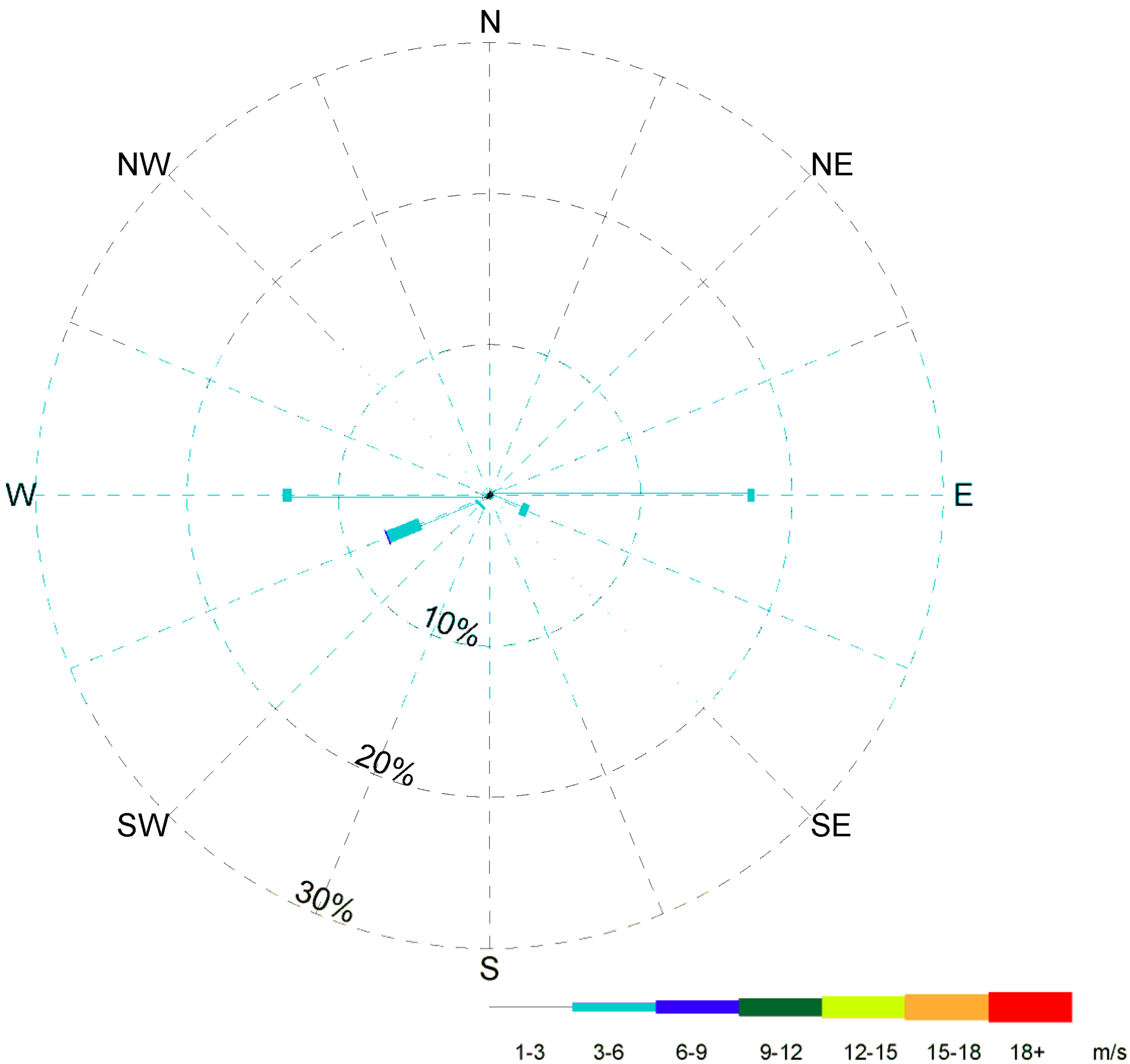

Figure 3.7: CLW East Wind Rose

The Perseverance Creek station operated by VIU has recorded data from 2 November 2018 to present. The station is installed high in the Perseverance watershed at an elevation of about 970 m. Figure 3.8 presents a wind rose for Perseverance Creek. The observed winds are relatively weak, with over 98% of observed speeds being less than 6 m/s. The dominant wind direction is southwest. Since this station is at high elevation and topographically separated from the lake, its data were not used by the hydrodynamic simulations. VIU researcher Bill Floyd remarked that the sensor is affected by trees around the site.

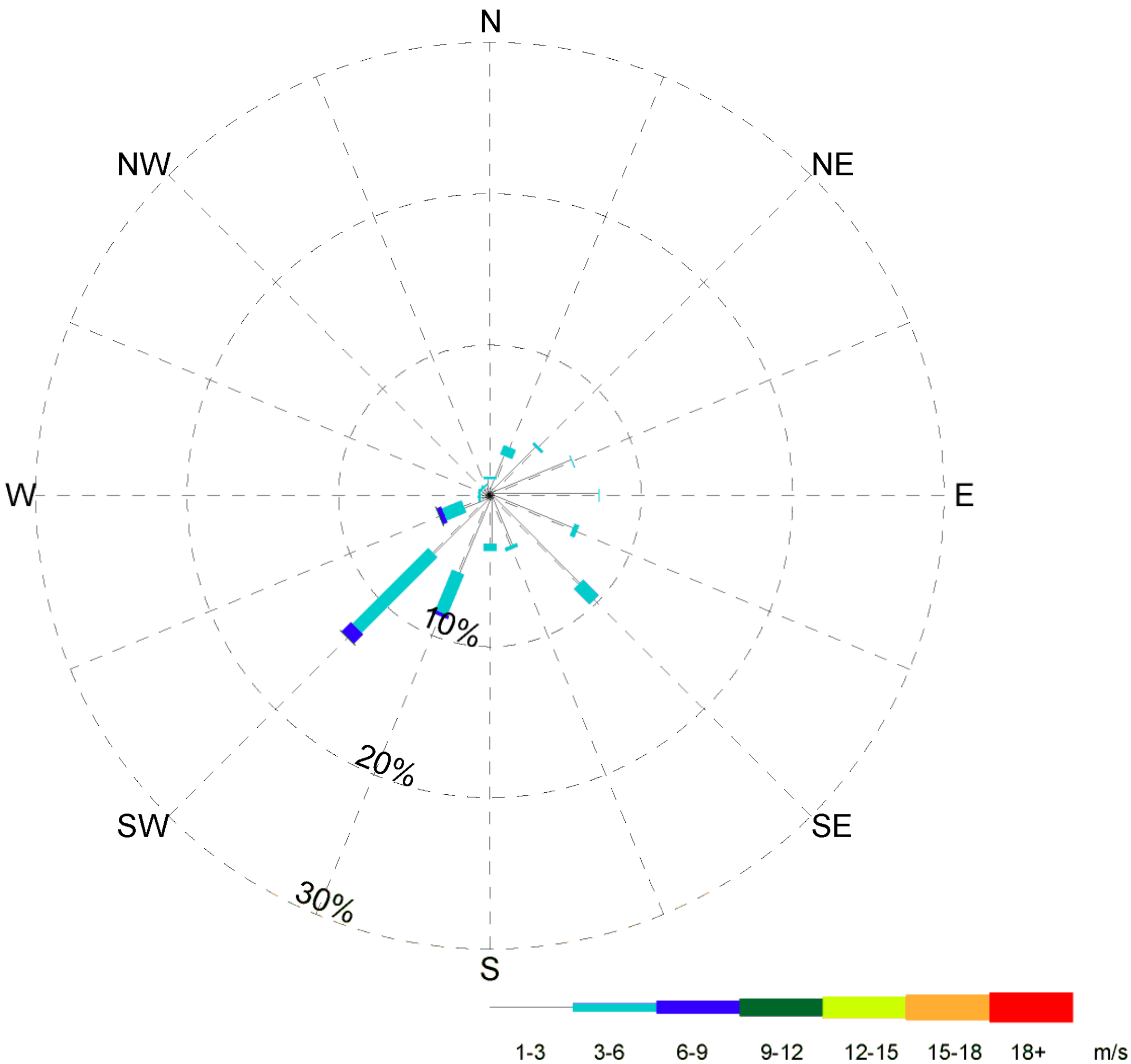

Figure 3.8: Perseverance Creek Wind Rose

In all simulations, temperature and humidity data were taken from Comox Airport and Beaver Creek and combined by averaging. Simulations of years prior to 2019 used wind data from Comox Airport and Beaver Creek, interpolated over the lake. Simulations in 2019-2020 used wind data from the two CVRD stations on Comox Lake, CLWW and CLWE, again interpolated over the lake.

3.2.4 Outflow

Discharge from Comox Lake is through the Puntledge River (Figure 3.1) and is regulated by BC Hydro. BC Hydro provided records of observed daily lake elevation and discharge from 1990 to present.

3.2.5 Inflows

Hydrometric stations recorded stream flows on some of the tributaries to Comox Lake, as described previously. In addition, estimates of inflows to the lake were available from two sources:

1. BC Hydro. Their inflow estimate is a computed parameter, derived based on a water balance with the lake level and measured outflows, and is therefore known with high confidence. The inflow implicitly includes the net contribution of direct rainfall and evaporation at the lake's surface, thus reconciling the lake's water balance by definition. However, the inflow estimate is a total only and does not distinguish between tributaries.

2. Tetra Tech's watershed model, as described above.

For hydrodynamic modelling purposes it is important that inflows and outflows should be reconciled such that the net change in lake storage over the simulation period matches the observed changes in water level. However, it is also important for the individual tributary flows to be estimated so that their contributions to lake turbidity can ultimately be assessed. Therefore, Tetra Tech took a hybrid approach to estimating inflows: the tributary flows estimated by the watershed model were scaled up or down, on a daily basis, as required such that the total daily inflows would match the BC Hydro back-calculated inflows.

3.2.6 Tributary Temperatures

Tributary temperatures were measured and estimated by several methods:

1. Temperature loggers were installed by CVRD in Perseverance Creek (starting 18 October 2016), Cruikshank River (starting 19 October 2016) and Upper Puntledge River (starting 23 December 2017).

2. CVRD measured tributary temperatures with a handheld instrument approximately monthly starting April 2019 at twelve locations.

3. Tetra Tech estimated Perseverance Creek and Cruikshank River temperatures based on air temperatures as described below.

The temperature logger in Upper Puntledge River is installed just within the boundary of Strathcona Park, approximately 10 km and two small lakes upstream of Comox Lake; the observed temperatures (and turbidities) are therefore not representative of the flow entering Comox Lake, and do not agree with the handheld measurements taken near Comox Lake. The temperature loggers on Perseverance Creek and Cruikshank River, however, are installed close enough to Comox Lake to be representative of flows entering the lake, and reasonably match the handheld measurements.

To cover periods in which no observations were available, Tetra Tech generated inflow temperatures using a parameter-based relationship with daily air temperature at Comox Airport and assumed snow pack availability in the Perseverance and Cruikshank catchments. The parameters were adjusted to provide the best match with observed temperatures in Perseverance Creek and Cruikshank River. Figures 3.9 and 3.10 show the estimated and observed temperatures for Perseverance and Cruikshank, respectively; air temperatures from Comox Airport are included for reference. The Cruikshank is colder in summer due to snowmelt from the glacier in its catchment area. The estimated inflow temperatures agree well with observations except for short periods in December 2016, December 2017 and January 2018 when the sensors appear to have been exposed to air. Gaps in the observational data from Perseverance and Cruikshank were filled using these estimates.

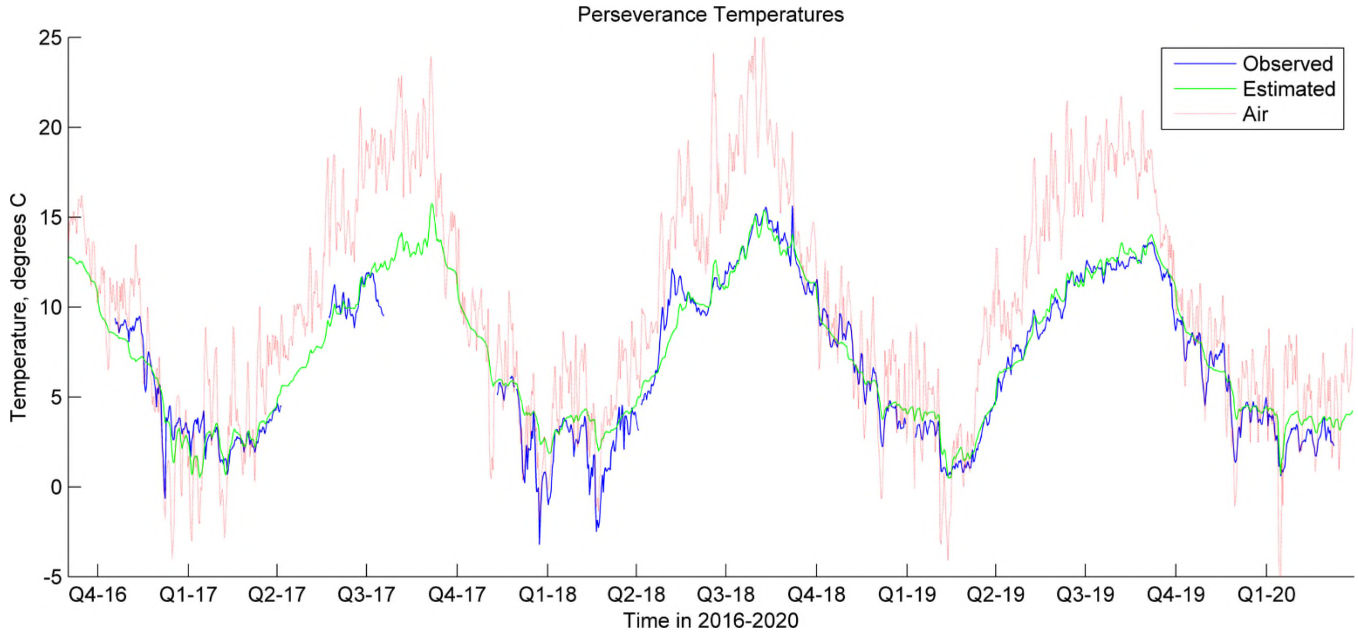

Figure 3.9: Observed and Estimated Temperatures in Perseverance Creek

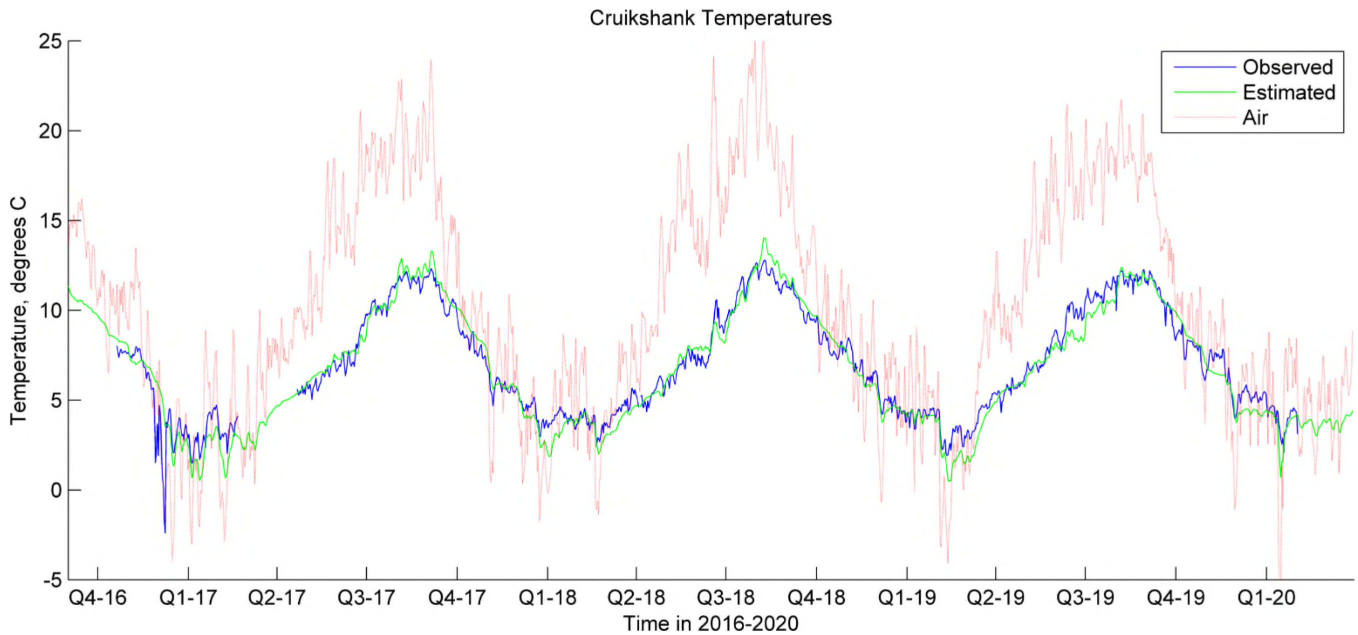

Figure 3.10: Observed and Estimated Temperatures in Cruikshank River

For hydrodynamic simulations up to and including 2017, the observed and gap-filled Cruikshank temperatures were assigned to both the Cruikshank and Upper Puntledge Rivers due to their similarity in catchment elevations. The observed and gap-filled Perseverance temperatures were assigned to all other inflows as they all do not have glacial snowmelt.

For hydrodynamic simulations in 2019-2020, observed Perseverance temperatures were assigned at Perseverance Creek, observed Cruikshank temperatures were assigned at Cruikshank River and Toma Creek, and other tributaries' temperatures were assigned based on the monthly handheld observations at the nearest observation point. Cruikshank River temperatures were assigned to Toma Creek because handheld observations at Toma Creek were missing during summer months and were most similar to Cruikshank River handheld observations in the remaining months.

3.2.7 Tributary Turbidities

Tributary turbidities were measured for the same periods as temperatures, on the same three streams: Perseverance Creek, Cruikshank River and Upper Puntledge River. Handheld turbidity measurements were made approximately monthly at eight to twelve locations beginning in October 2016. Observed hourly turbidities, except for the Upper Puntledge, were assigned to the corresponding streams for periods when data was available. For other periods and tributaries, the turbidities estimated by the watershed model were applied.

3.2.8 Sediment Properties

CVRD took sediment samples at several times and locations:

- Perseverance Creek was sampled three times on the afternoon of 21 September 2018 while turbidity was over 100 NTU. The three samples were very similar, with a median particle size (d_{50}) of 14 microns, a 90th percentile particle size (d_{90}) of 50 microns and approximately 10% clay (under 2 microns). In these samples, the ratio of TSS (mg/L) to turbidity (NTU) was approximately 1.2:1.
- Cruikshank River delta sediment was sampled twice on 11 December 2019, revealing predominantly coarse sand with a d_{50} near 1000 microns. The delta sediment was sampled in a different area on 9 January 2019, showing medium sand with a d_{50} near 200 microns. The delta sediments were not considered representative of suspended sediment in the river since coarser sediments tend to settle near the river mouth and the finer sediments would likely have been missed (dispersing elsewhere in the lake).
- Cruikshank River water was sampled three times on 8 January 2020 while turbidity was below 5 NTU. These samples showed a mix of sand and silt with a d_{50} near 60 microns and around 2% clay. Two more samples were taken on 31 January 2020 while turbidity was over 10 NTU. These samples showed a slightly coarser mix of sand and silt with a d_{50} around 75 microns and around 2-3% clay. The second set of samples was considered better quality data due to its higher sediment concentrations. In these samples, the ratio of TSS (mg/L) to turbidity (NTU) was approximately 3:1.

The objective of the hydrodynamic modelling was to assess which tributaries influence turbidity at the DWI. Preliminary modelling revealed that sediments coarser than approximately 40 microns settled too quickly to reach the DWI. Modelling efforts were therefore focused on the sediment fraction finer than 40 microns.

Based on the detailed grain size distributions of the samples listed above, sediment was represented in the hydrodynamic model as shown in Table 3-1. The tributaries not listed were all assumed to have the same grain size distribution as Cruikshank River.

Table 3-1: Sediment Representation in Hydrodynamic Model

Sediment Size	Model Representation	Perseverance Creek Fraction	Cruikshank River Fraction
Coarser than 40 microns	Not modelled	15.6%	73.2%
10-40 microns	d_{50} = 18 microns	47.7%	19.5%
Finer than 10 microns	d_{50} = 4 microns	36.7%	7.3%

For modelling purposes, the TSS concentrations in the tributaries were estimated from the observed or modelled turbidity (see Section 3.2.7) using the TSS to turbidity ratios seen in the sediment samples. In Perseverance Creek, TSS was estimated as 1.2 times turbidity; in Cruikshank River and all other tributaries TSS was estimated as 3 times turbidity. Preliminary modelling showed that sediment at the DWI was predominantly from Perseverance Creek; therefore, modelled TSS was converted back to turbidity at the ratio corresponding to Perseverance Creek.

Sediment solid volumes were computed in the model using an assumed specific gravity of 2.65.

3.3 Calibration

Calibration of the hydrodynamic model proceeded in three stages:

1. Water balance
2. Circulation and temperature
3. Turbidity

The following subsections describe the calibration effort and results.

3.3.1 Water Balance

In this model implementation, inflow and outflow volumes were both known and specified; therefore, no specific calibration was required for the water balance. Over a one-year simulation, the simulated lake level diverged from the observed lake level about 0.2 m while traversing a range of over 3.5 m. This small divergence represents about 0.5% of the total annual flow and does not introduce any significant uncertainty to the model's predictions.

3.3.2 Circulation and Temperature

Lake circulation is generally controlled by three influences:

1. Atmospheric and solar heating and cooling. These produce an annual cycle of stratification in which a warm, buoyant layer of water in summer overlies a cooler, denser layer below. The difference in densities between the layers creates a resistance to mixing.
2. Wind energy. Wind adds momentum and energy at the surface of the lake, leading to mixing. As the temperature stratification weakens in the fall, wind energy deepens the surface layer and eventually mixes the full water column.
3. Inflows and outflows. These produce a net current along the lake. Depending on stratification and the arrangement of tributaries and underwater sills, not all parts of the lake are equally affected.

In the absence of current meter data, model predictions of lake circulation can be adequately confirmed by comparing observed and predicted profiles of temperature over the seasonal transitions. The availability of temperature profile data therefore determined which periods could be used for model calibration.

One set of temperature profile data is the lake sampling conducted at the DWI between September 2010 and March 2018. Temperatures (and turbidities) were measured at approximately weekly intervals at three depths at the DWI. A second set of temperature profile data comes from the thermistor chains installed by CVRD at three locations in Comox Lake. The available data extend from 7 November 2019 to 4 March 2020 over a range of depths from the surface to 60 m.

The first calibration period was 2014-2016, during which the model was driven by winds and temperatures combined from Comox Airport and Beaver Creek. The model's initial condition was taken from lake sampling observations on 4 March 2014 and tributary temperatures were estimated as described above. Figures 3.11 and 3.12 present temperature calibration results comparing model predictions against the lake sampling observations at the DWI. The two figures show the same data in different forms. Figure 3.11 is a "scroll plot" in which the vertical axis is depth and the horizontal axis is time. Temperature is represented with the colour scale. The three brightly-coloured patches along the top show summer stratification in three consecutive years. The coloured circles are the weekly lake sampling observations. Figure 3.12 is a simpler time series comparison of observed (dots) and modelled (lines) temperatures at the three standard sampling depths.

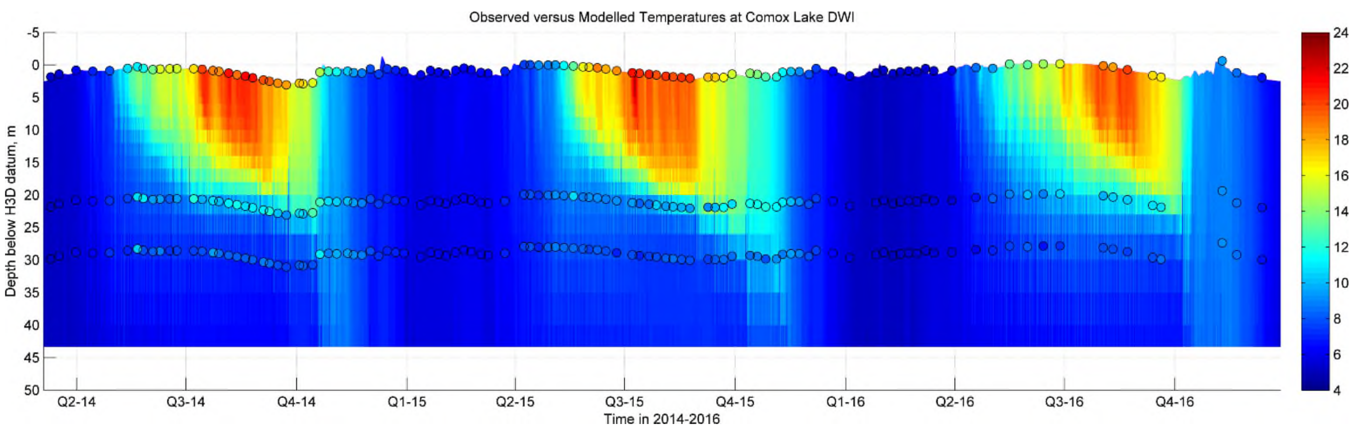

Figure 3.11: Scroll plot of modelled versus observed temperatures at the DWI 2014-2016

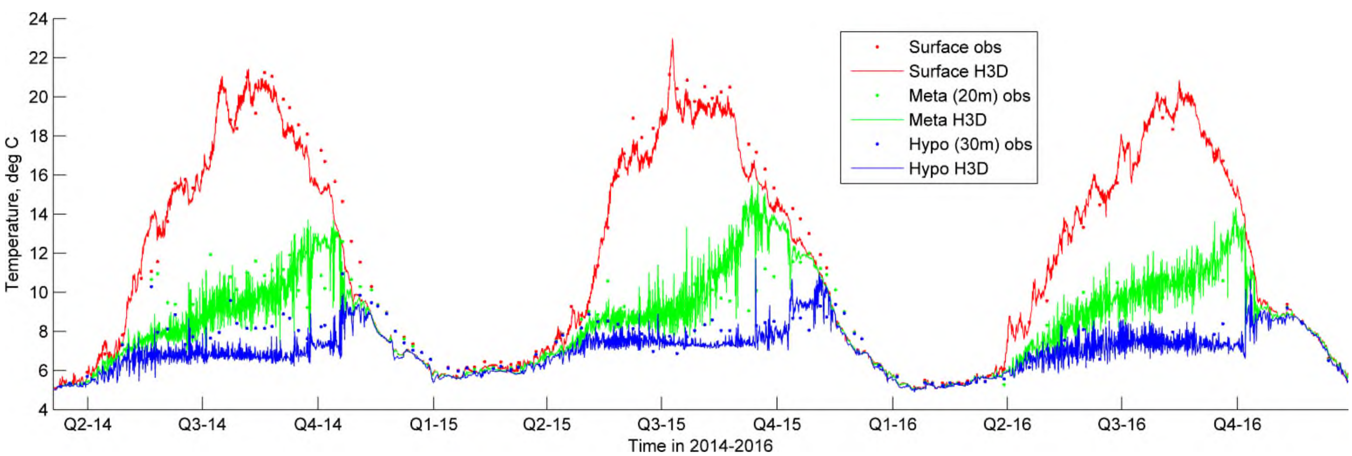

Figure 3.12: Time series plot of modelled versus observed temperatures at the DWI 2014-2016

The model was calibrated using turbulence, vertical diffusion and water clarity parameters. The model's turbulence and vertical diffusion parameters were set based on recent modelling work on Quesnel Lake, which was well validated. The water clarity (Secchi depth) was held constant at 5 m from the 2004 modelling of Comox Lake. With these parameter choices the model successfully reproduced the observed temperature structure over three years.

The model was also run in 2017, which served as a validation. Wind and temperature inputs were taken from the same sources; the model's initial condition was taken from lake sampling observations on 9 January 2017. Figures 3.13 and 3.14 show a scroll plot and time series plot, respectively, of the modelled and observed temperatures. The model successfully reproduced the observed temperature structure in 2017, thus validating the calibration.

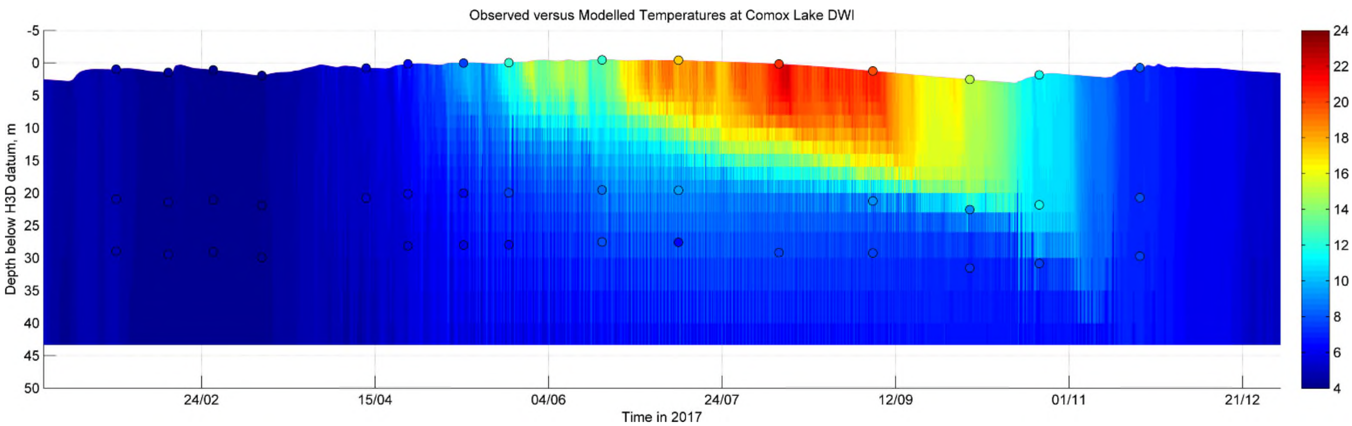

Figure 3.13: Scroll plot of modelled versus observed temperatures at the DWI 2017

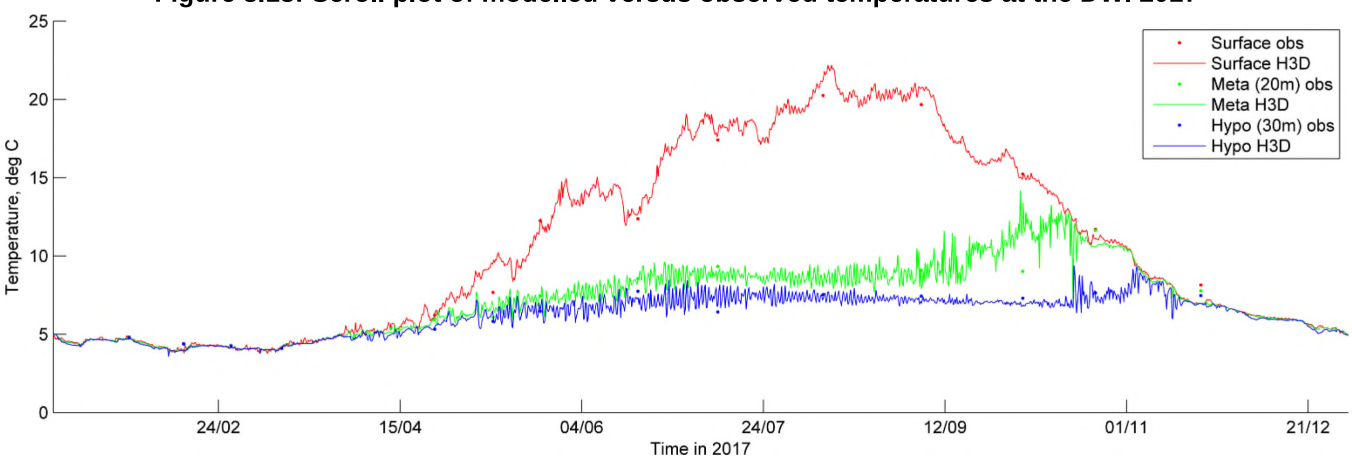

Figure 3.14: Time series plot of modelled versus observed temperatures at the DWI 2017

Since the 2019 modelling used a different set of wind data – namely, the new CVRD stations with much lower observed wind speeds – a second calibration was required for that period. Desiring to use 2019 as a validation, Tetra Tech created a pseudo-calibration scenario by applying the observed 2019 winds at CLW East and West to a 2015 model of Comox Lake (i.e., temperatures and hydrology from 2015). Since the mixing energy provided by wind was much lower, the model's turbulence and vertical diffusion parameters were increased. Additionally, the water clarity (Secchi depth) was increased to 9 m, a value supported by observations (Epps, 2011). Results from this pseudo-calibration (not shown) were satisfactory, considering the transposition of winds from a different year.

The model was also run in 2019-20 with CVRD's observed winds and inflow temperatures. The model's initial condition was set at 5°C on 3 March 2019 based on typical temperature observations from prior years' lake sampling. Observational profile data were available from the CVRD thermistor chains beginning from November 2019. Figures 3.15 and 3.16 show the validation results from the 2019-2020 run in scroll plot and time series form, respectively. The temperature structure at each thermistor chain is closely reproduced by the model, including the timing of the breakdown of stratification (i.e., when the lines converge in Figure 3.16). Tetra Tech considers this validation more than satisfactory for the purposes of this study.

3.3.3 Turbidity

The behaviour of sediment, and associated turbidity, is notoriously difficult to model. In general, a reasonable goal for sediment modelling is to achieve predictions within a factor of two from the observations. The model was not specifically calibrated for sediment, in the sense of adjusting model parameters. However, as discussed above, the modelled grain sizes were chosen carefully to capture the processes of interest. The model's turbidity predictions were validated against observations during two periods, as described below.

The first validation period was 2017, in which observations were available in two forms: continuous sampling at the DWI and intermittent lake sampling. The continuous sampling data are available intermittently in January, February, April and May; the lake sampling measured turbidity at three depths on 12 dates. Perseverance Creek observed turbidity was available in 2017 from 15 February to 5 April, intermittently in June, and intermittently from 10 November to 5 December. Cruikshank River observed turbidity in 2017 was not usable due to data quality problems. Except for the short periods of observational data in Perseverance Creek, the hydrodynamic model relied on the watershed model's turbidity predictions as inputs.

Figure 3.17 shows a comparison of modelled and predicted turbidity in 2017. Note the logarithmic turbidity scale. Predicted turbidity at the DWI moderately matched observed turbidity during the three boil water advisories (bold black bars). During other periods the model generally underpredicted turbidity. These results are presented and discussed at greater length in Section 3.4.

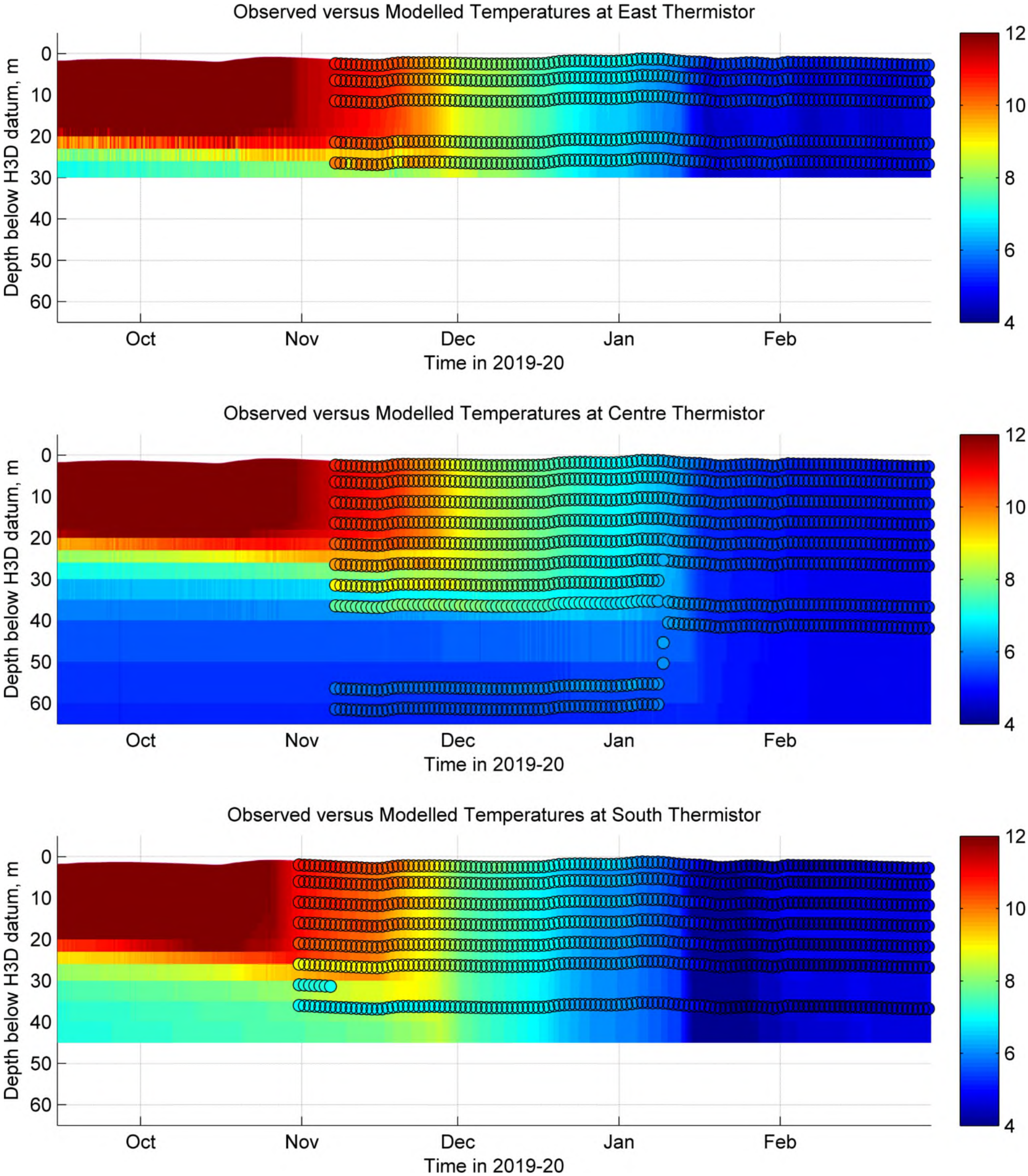

Figure 3.15: Scroll plots of modelled versus observed temperatures at thermistor chains 2019-2020

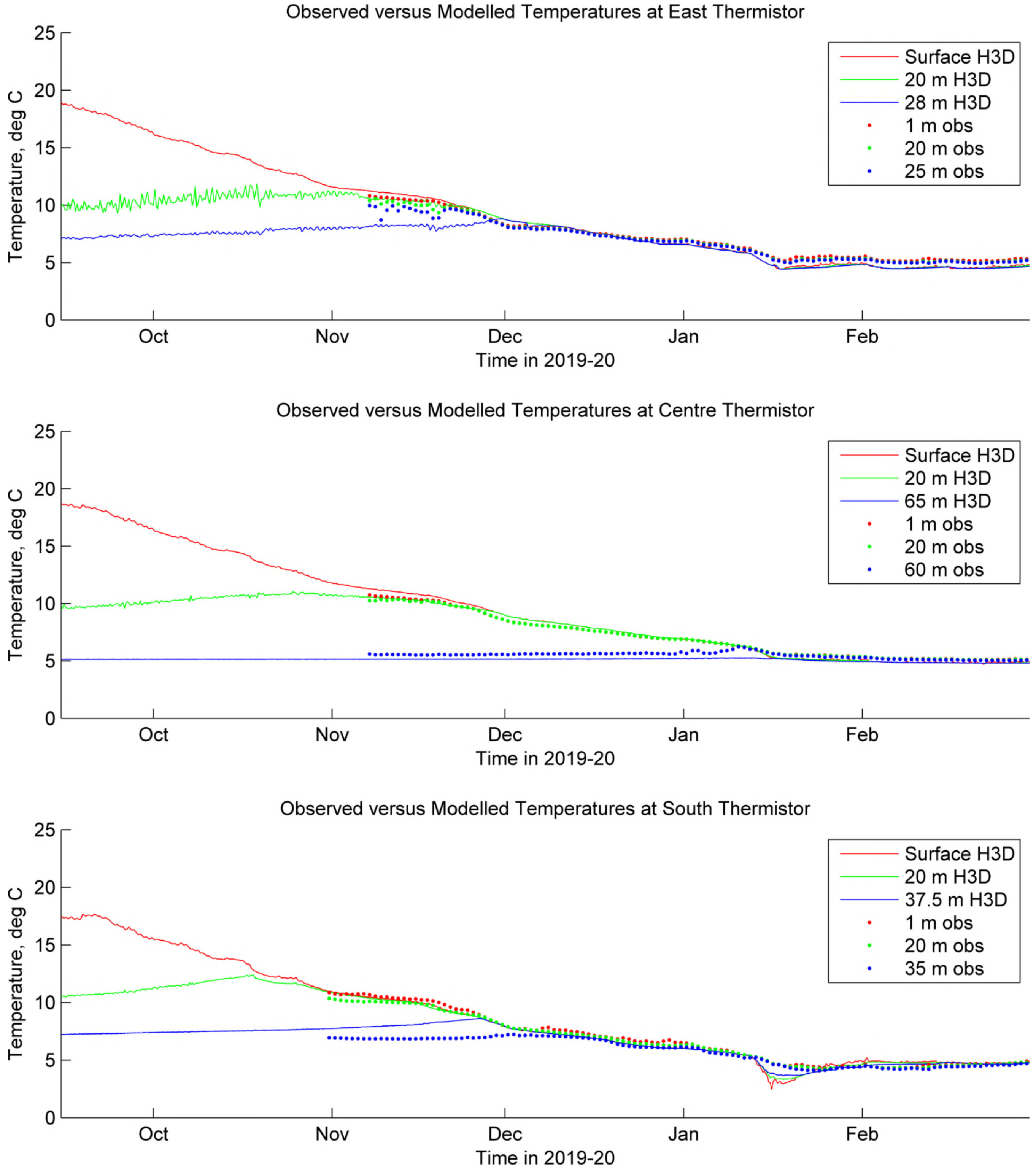

Figure 3.16: Time series plot of modelled versus observed temperatures at thermistor chains 2019-2020

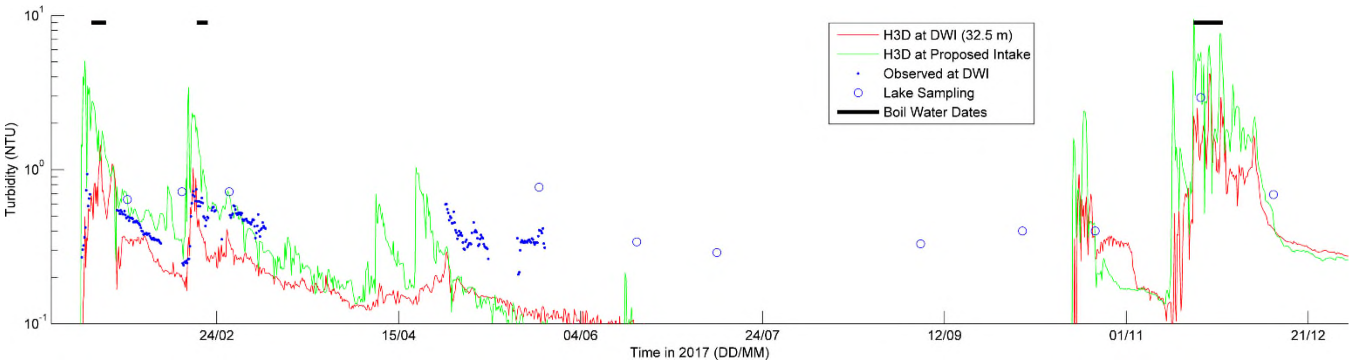

Figure 3.17: Time series plot of modelled versus observed turbidities at the DWI in 2017

The second validation period was 2019, in which observations were available only from continuous sampling at the DWI. The DWI data extend from 24 January 2019 to 9 March 2020 with a gap from 8 September to 7 October 2019. Perseverance Creek observed turbidity was available throughout the modelled period but disagreed significantly with the handheld turbidity measurements through most of the year up to at least early December 2019. For example, on 7 August 2019 the handheld measurements ranged from 0.41 to 0.81 NTU while the corresponding sensor reading was around 4 NTU. Cruikshank River observed turbidity was available throughout the modelled period and reasonably matched the handheld turbidity readings.

Figure 3.18 shows a comparison of modelled and predicted turbidity in 2019-2020. Only the period of reliable Perseverance Creek turbidity data is shown. Model predictions (red line) reasonably match observations (blue dots) including the timing, magnitude and duration of most peaks.

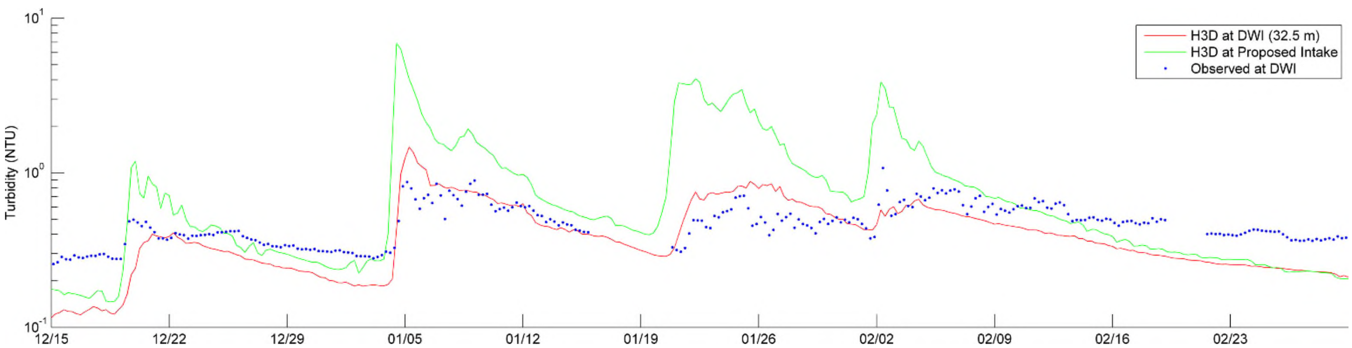

Figure 3.18: Time series plot of modelled versus observed turbidities at the DWI in 2019-2020

Overall, the model's turbidity predictions agreed reasonably with observations subject to reliable turbidity data for Perseverance Creek.

3.4 Results

The principal study objective was to assess the relative contribution of various tributaries to the turbidity observed at the DWI during several events of interest. A secondary objective was to examine the expected turbidity at the proposed intake location for the new water filtration plant.

Events of interest are generally on the dates of the boil water advisories, which were issued intermittently from 2014 to 2017. The turbidity validation of the model showed that observed turbidity data for Perseverance Creek was important for reliable results: this data is available from October 2016 onwards. Therefore, the three boil water advisories from 2017 were selected for detailed modelling analysis: these were issued 20-24 January, 18-21 February and 2 November to 1 December 2017.

Figure 3.19 presents a time series plot of observed and predicted turbidity for the first two boil water advisories of 2017. (This is a zoom-in of the first portion of Figure 3.17.) The timing of the predicted turbidity elevations at the DWI agrees reasonably well with the boil water advisory dates, and with the observed turbidity when available.

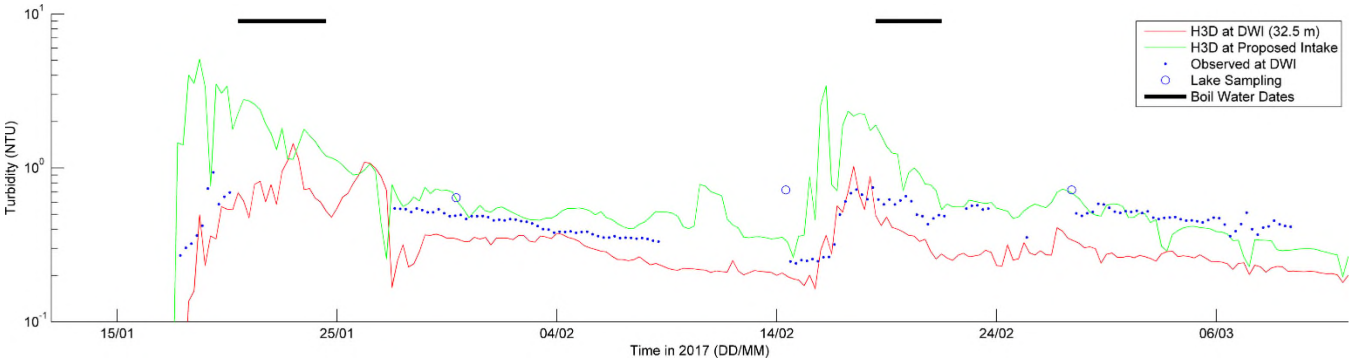

Figure 3.19: Time series plot of modelled versus observed turbidities at the DWI in early 2017

Figure 3.20 shows the simulated percentage contribution of sediment at the DWI from Perseverance Creek, Cruikshank River, and all other sources for the same dates. During the January boil water advisory as much as 99% of the sediment at the DWI is predicted to be from Perseverance Creek, and at the turbidity peak prior to the February boil water advisory, 98%. Off the peaks, the Perseverance Creek contribution is still upwards of 80%.

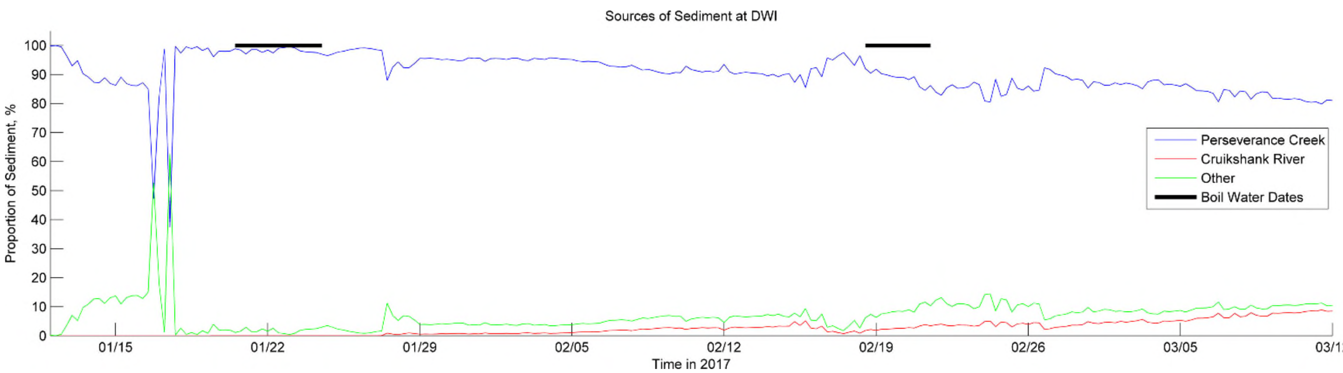

Figure 3.20: Relative contributions to turbidity at the DWI in January to March 2017

Figure 3.21 presents a time series plot of observed and predicted turbidity for the November-December boil water advisory of 2017. (This is a zoom-in of the last portion of Figure 3.17.) The timing of the predicted turbidity elevations at the DWI agrees reasonably with the boil water advisory dates, and with the observed turbidity when available.

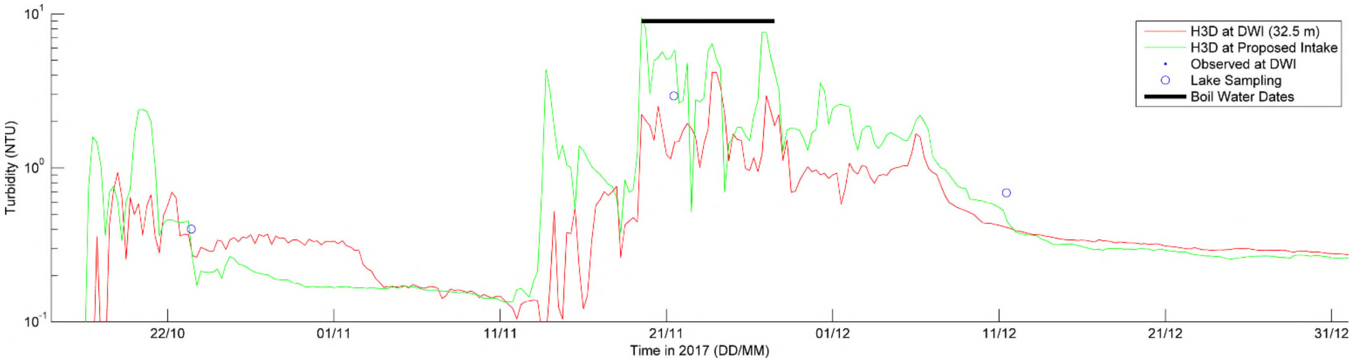

Figure 3.21: Time series plot of modelled versus observed turbidities at the DWI in late 2017

Figure 3.22 shows the simulated percentage contribution of sediment at the DWI from Perseverance Creek, Cruikshank River, and all other sources for the same dates. At the peak of the November boil water advisory as much as 97% of the sediment at the DWI is predicted to be from Perseverance Creek, and off the peaks, the Perseverance Creek contribution is still generally upwards of 80%.

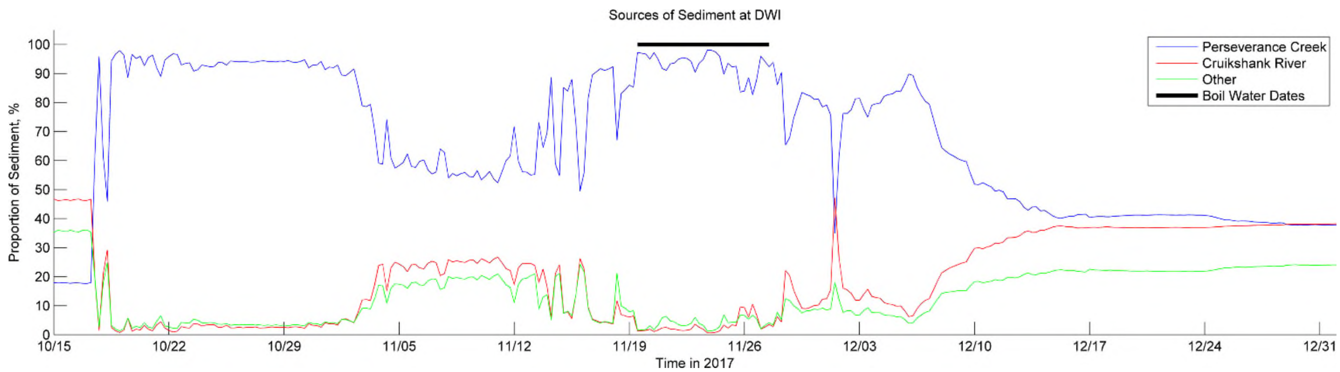

Figure 3.22: Relative contributions to turbidity at the DWI in October to December 2017

Turning to the secondary objective of assessing turbidity at the proposed intake location, predictions were made as part of all model runs and are shown as the green lines in Figures 3.18, 3.19 and 3.21. The general prediction is an increase in turbidity versus the DWI, of approximately 2-4 times. Higher predicted turbidity at the proposed intake is reasonable because the proposed intake location is near the outlet of the lake, on or near the expected route of Perseverance Creek water to the exit, while the DWI is significantly further west, or upstream (Figure 3.1).

3.5 Uncertainty

The most significant sources of uncertainty in the hydrodynamic model are presented below, with brief commentary on how they might impact results.

- Sediment grain size distributions: these were measured in two tributaries on one or two single dates each. This study assumed the samples are representative of the full water column in the streams, on all dates. Naturally, grain size distributions will vary with flow rate and within the water column. The grain size distributions strongly affect how quickly sediment settles or, conversely, how far it travels before settling. Uncertainty in the grain size distributions of the unsampled tributaries could also affect results. Nevertheless, the turbidity predictions reasonably match observations, indicating that the results are accurate enough to be useful.

- Tributary stream sediment loads: these were sampled monthly by handheld instruments in several streams and monitored continuously in the two most important sediment contributing streams. Many streams were neither sampled nor monitored, and the observational data had many gaps. Tetra Tech's watershed model was useful to close the data gaps with estimates but could not perfectly match observations. Nevertheless, the hydrodynamic model's turbidity predictions reasonably match observations, indicating that the results are accurate enough to be useful.
- Conversion between physical (TSS) and optical (turbidity) sediment units: the approximate conversions in Perseverance Creek (1.2:1) and Cruikshank River (3:1) were quite different and illustrate how the conversion may vary with sediment type, grain size and distribution. Model results were interpreted using the Perseverance Creek conversion. Back-calculating turbidity the model's physical units would therefore tend to overestimate the contribution of Cruikshank River.
- Horizontal resolution of model: the Comox Lake hydrodynamic model was based on an existing model with a horizontal resolution of 100 m. While this resolution was adequate to reproduce temperature stratification as well as turbidity at the DWI, it may not have enabled some relevant small-scale features to appear. For example, air photos from 2017 showed the Perseverance Creek plume following the left (south) bank, whereas the model showed only a general forward motion. This shortcoming might affect predictions of turbidity, particularly in locations close to the creek mouth, and possibly including the proposed intake. The model predictions described in this report matched with observed turbidity, giving the predictions a relatively high confidence; however, development of a model with finer resolution has potential to further improve the predictions of the magnitude, timing and distribution of the turbidity signals.

4.0 CONCLUSIONS

The main findings of this turbidity modelling study are as follows:

- The two most significant streams contributing sediment to Comox Lake are Perseverance Creek (36%) and Cruikshank River (24%).
- Some turbidity spikes observed in Perseverance Creek appear to be related to factors beyond rainfall intensity. This is consistent with the episodic erosion events described in the Perseverance Creek Erosion Assessment & Monitoring report by Suavair (Filliter, 2019).
- The Comox Lake hydrodynamic model developed for this study capably reproduced the observed seasonal temperature structure.
- Sediment coarser than approximately 40 microns generally settles before reaching the DWI or proposed intake.
- The elevated turbidity observed at the DWI during three boil water advisories in 2017 was primarily from Perseverance Creek. At the peak of each event, the percentage of sediment at the DWI contributed by Perseverance Creek was in the high 90's.
- Turbidity levels at the proposed intake location are expected to be greater than those at the DWI by a factor of approximately 2-4 during high turbidity events.

5.0 CLOSURE

We trust this report meets your present requirements. If you have any questions or comments, please contact the undersigned.

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APPENDIX A

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LIMITATIONS ON USE OF THIS DOCUMENT

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