The Scale of Ecological Restoration: Restoring Steelhead Habitat in the Oktwanch Watershed, Vancouver Island, B.C.

by

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Declaration of Committee

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Abstract

Forestry practices are thought to be the major cause of degraded salmonid habitat and declining steelhead populations in the Oktwanch River on Vancouver Island. Large woody debris installations and channel modifications were completed in Reach 1 of the Oktwanch River and adjacent side channels in 2001 to provide spawning and rearing habitat for multiple salmonid species and prevent further degradation, but were ultimately unsuccessful. This study investigated if watershed-scale restoration, rather than reach-scale, is necessary to restore this habitat for steelhead in the Oktwanch River indefinitely. This was achieved through an assessment of fish habitat in Reach 1 of the Oktwanch River and adjacent side channels and spatial analysis of the Oktwanch watershed using Landsat historical aerial imagery and i-Tree Canopy. The findings from this study suggest watershed-scale changes to forestry practices are required to restore steelhead populations in the Oktwanch River.

Acknowledgements

I would like to acknowledge that this research was conducted on the traditional, ancestral and unceded territory of Mowachaht/Muchalaht First Nation. I am thankful to the Nootka Sound Watershed Society for giving me the opportunity to pursue this research and for providing funding. I am grateful to Kent O’Neill (Nootka Sound Watershed Society President) and Roger Dunlop (Lands, Resources and Fisheries Manager Mowachaht/Muchalaht First Nation) for their knowledge and support throughout. Thanks to Danica Rogers for her help with data collection.

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List of Acronyms

COSEWIC	Committee on the Status of Endangered Wildlife in Canada
CWHvm	Very Wet Maritime Coastal Western Hemlock Biogeoclimatic Zone
DO	Dissolved Oxygen
ER	Electromagnetic Radiation
FHAP	Fish Habitat Assessment Procedures
FI	Forest Vegetation Index
FRPA	Forest and Range Practices Act
LWD	Large Woody Debris
NDVI	Normalized Difference Vegetation Index
NSWS	Nootka Sound Watershed Society
PNW	Pacific Northwest
RMA	Riparian Management Area
SWD	Small Woody Debris
VRI	Vegetation Resource Inventory
YOY	Young of the Year

1.0. Introduction

Oncorhynchus mykiss is a pacific salmonid that has two distinct life history strategies. Steelhead are the anadromous (ocean-going) phenotype of *O.mykiss*, while rainbow trout spend their life cycle entirely in freshwater. Steelhead typically spawn between March and May but can migrate upstream in summer or winter. Populations of both runs can be supported in the same stream, with summer runs often spawning earlier and further upstream (Roberge et al. 2002). Steelhead are unique as the only iteroparous anadromous salmonid, although only small percentages survive to repeat spawn. Historically on Vancouver Island, approximately 10% of steelhead were return spawners in the Keogh River (Ward & Slaney 1988) and winter-run and summer-run steelhead in the Somass River had return spawning rates of 9.2% and 3.3% respectively (Horncastle 1981). Following a three to four week egg incubation, juveniles generally remain in freshwater for two to three years before ocean bound migration and smoltification occurs (Maher & Larkin 1955; Peven et al. 1994).

Steelhead populations have been declining in the Pacific Northwest (PNW) for decades; over 80% of sampled populations in Washington, Oregon, and British Columbia have declined since 1980 (Melnychuk et al. 2007; Kendall et al. 2017). The Thompson River and Chilcotin River populations of steelhead have been identified by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) as endangered and are under consideration for Schedule 1 protection under the Species at Risk Act (COSEWIC 2020). Population declines have been attributed to habitat degradation associated with forestry operations that alter geophysical and hydrological characteristics of watersheds, in addition to other pressures.

Forestry practices have been identified as a major contributor to declining salmon populations in the PNW (Hicks 2002). Mass wasting events increase in frequency and intensity following logging activity. This is predominantly due to the creation of a network of logging roads and loss of coniferous root cohesion (Schmidt et al. 2001; Guthrie 2002). Areas of clear-cut and actively managed forests have significantly lower lateral root cohesion compared with old-growth coniferous forests, resulting in mass wasting events being triggered more frequently (Schmidt et al. 2001). Landslides in

Clayoquot Sound on Vancouver Island rose ninefold following logging, with most attributed to road fill failures (Jakob 2000). Landslides in the Artlish River and Macktush Creek watersheds increased by 3 and 11 times respectively after logging occurred (Guthrie 2002). Weakened root cohesion can persist for more than a century relative to undisturbed areas (Schmidt et al. 2001). Subsequent increased debris flow frequency introduces large volumes of sediment and woody debris to stream networks (Slaymaker 2000) and degrades salmon habitat quality.

Logging alters hydrological processes through modification of the relationship between soil, vegetation, and precipitation. Between 10 and 30 percent of rainfall is typically intercepted by coniferous trees in the PNW (Moore & Wondzell 2005). Canopy interception and evapotranspiration are reduced following logging which causes peak flows to increase in magnitude (Jones 2000). This effect increases sediment yields and may result in aggradation that contributes to poor spawning substrate and dewatering during low flow periods (Moore & Wondzell 2005). Additional disturbance occurs by way of soil compaction from machinery associated with logging, resulting in reduced infiltration of precipitation that increases surface runoff and erosion (Winkler et al. 2010). Soils in the PNW generally have poor water retention capacities (Sanborn et al. 2011), but this may be further reduced when precipitation falls on disturbed ground, dislodging fine sediment that then clogs soil pores (Moore & Wondzell 2005). Soil disturbance and reduced canopy interception have been shown to raise the groundwater table, leading to increased overland flows and greater peak flows in streams (Dhakal & Sidle 2004). Logging of mature forest vegetation in the riparian zone in particular can drastically alter the biotic and abiotic characteristics of streams.

A functional riparian zone positively influences channel morphology and fish habitat quality. Mature trees in the riparian zone improve channel stability and rates of bank erosion by providing both a stabilizing root network and large woody debris (LWD) inputs that deflect flows away from banks (Young 2000). LWD is also important for fish habitat creation as it promotes local scour and hydrological complexity. In the PNW, riparian zones predominantly comprised of conifers have greater root network cohesion compared to disturbed areas and more effectively stabilize streambanks during high flow periods (Schmidt et al. 2001). Characteristics important to fish habitat suitability such as stream temperature, allochthonous nutrient input, and habitat heterogeneity are also influenced by the riparian zone (Mellina & Hinch 2009). In British Columbia, the Forest and Range Practices Act (FRPA) determines the size of the riparian buffer that must be maintained around streams according to stream width and fish presence. This riparian buffer ranges from 50 m in fish bearing streams wider than 20 m, to no buffer in fish bearing streams less than 1.5 m in width and non-fish bearing streams. Streams in the upper reaches of watersheds are often topographically underrepresented and logged to their banks in spite of these regulations (Benda et al. 2005). The loss of a functional riparian zone can lead to channels widening to many times their natural width and alteration of stream morphology (Tripp 1997; Tschaplinski 2008).

The cumulative effects of increased mass wasting events, hydrological change, and loss of coniferous riparian vegetation leads to more fine sediment deposition within streams (Gomi et al. 2005). The amount of fine sediment recruitment to a stream network because of logging changes depending on where the vegetation disturbance occurs within a watershed. As headwater streams constitute the majority of the stream network, when logging occurs in headwaters more fine sediment enters streams and may cause aggradation in valley bottoms and higher order rivers (Slaymaker 2000). Consequences of continuous aggradation can include rivers switching from a single channel to a braided or wandering channel morphology and dewatering during low flow periods (Hoffman & Gabet 2007). Logging also reduces structural features in streams such as LWD and boulders that can retain fine sediment (Benda et al. 2005).

Fine sediment suspended in the water column has negative physiological effects on all fish life stages, as well as lowering habitat quality for fish and their benthic invertebrate food sources. Fine sediment suspended in the water column can have deleterious effects on juvenile salmon, damaging their gills and reducing respiratory capacity (Berg & Northcote 1985; Lake & Hinch 1999; Kjelland et al. 2015). Excessive fine sediment accumulation on stream beds reduces interstitial space within the substrate, lowering metabolite and oxygen availability for eggs and alevins (Kemp et al. 2011). This sediment accumulation also removes habitat for benthic invertebrates and decreases prey availability for juvenile salmonids (Kaller & Hartman 2004). Furthermore, suspended sediment reduces prey visibility, thus raising the metabolic cost of predation for salmon (Kemp et al. 2011). Chronic and acute stress has negative impacts on *O.mykiss* fecundity by lowering sperm count, reducing egg size, and delaying ovulation (Campbell et al. 1993).

In the Nootka Sound watershed on Vancouver Island, logging is thought to have contributed to the decline of salmon populations in the area. Steelhead populations in particular have decreased drastically in recent years, with no more than four winter-run steelhead observed in annual Gold River snorkel counts since 2017 (Damborg 2020). Logging began in this region in the 1960s (Tripp 1997) and many watersheds were logged without any consideration of impacts to fish habitat as relevant protective legislation was not in effect. The Nootka Sound region is activity logged as part of tree farm license (TFL) 19 by Western Forest Products Inc. and unvegetated clear-cuts are present throughout the watershed, as well as an extensive logging road network. To address the decline in salmon populations, the Nootka Sound Watershed Society (NSWS) was established with the mission “to protect, restore and enhance pacific salmonids and their habitat in Nootka Sound…through sustainable, science-based practices” (Nootka Sound Watershed Society 2022).

This research project was instigated by NSWS because of the declining steelhead population in the region and the failure of previous salmon habitat restoration efforts in the Oktwanch River and adjacent side channels. There is also an indigenous-led movement supported by the Nuu-chah-nulth Tribal Council on the west coast of Vancouver Island to establish a “Salmon Park” in the traditional and unceded territory of Mowachaht/Muchalaht First Nation (Nuu-Chah-Nulth Tribal Council 2022). This movement aims to restore wild salmon populations by protecting fish habitat at a watershed-scale, in contrast to provincial regulations that rely on fish presence/absence at a stream level. It is hoped this research identifies an appropriate spatial scale for restoration activities in the Oktwanch watershed and will help inform the Salmon Parks initiative.

1.1. Goals and Objectives

- Goal 1- Determine if any channels are suitable candidates for instream or riparian restoration to improve spawning and rearing habitat quality for steelhead in Reach 1 of the Oktwanch River.
    - Objective 1.1- Assess quality of steelhead spawning and rearing habitat in the mainstem and side channels of Reach 1 of the Oktwanch River.
- Goal 2- Investigate if watershed-scale restoration could improve steelhead spawning and rearing habitat within the Oktwanch watershed.
    - Objective 2.1- Develop forest vegetation indices for the Oktwanch watershed to highlight change in forest vegetation coverage over time.
    - Objective 2.2- Apply i-Tree Canopy software to assess changes in precipitation runoff in the Oktwanch watershed following vegetation change as the result of logging activity.
    - Objective 2.3- Repeat spatial analysis in the Carnation Creek watershed as a demonstration of long-term biotic and abiotic responses to the absence of forestry activity.

1.2. Study Area

This project occurred in the Oktwanch watershed in central Vancouver Island (Figure 1). This is in the traditional and unceded territory of Mowachaht/Muchalaht First Nation. The watershed covers an area of approximately 131 km^2 and the mainstem of the Oktwanch River is 19.3 km in length (Walsh 2001).

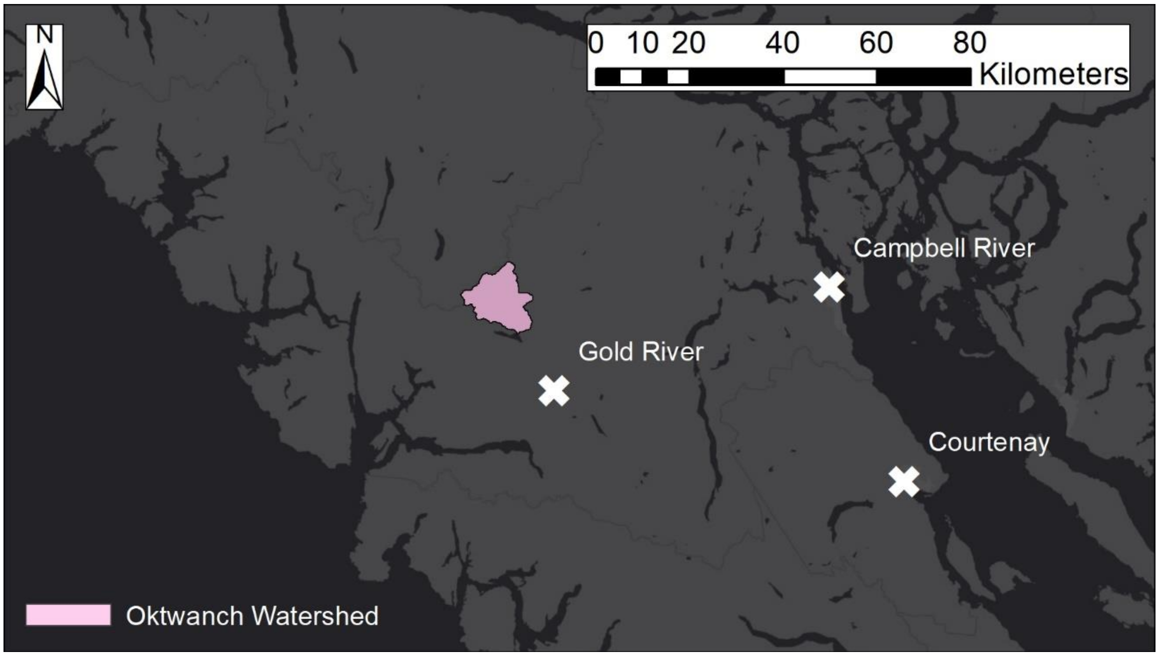

Figure 1. The Oktwanch watershed (pink shaded area) is located approximately 14.5 km northwest of the village of Gold River, Vancouver Island.

The Oktwanch watershed is located within the very wet maritime Coastal Western Hemlock biogeoclimatic zone (CWHvm). Prior to industrial forestry activity, the forest was dominated by Western hemlock (*Tsuga heterophylla*), Amabilis fir (*Abies amabilis*), and Western redcedar (*Thuja plicata*) (Pojar et al. 1991). Logging commenced within the Oktwanch watershed during the 1950s and the riparian area surrounding fish bearing streams was logged to the banks by 1975 (Walsh 2001). Loss of the riparian zone and erosion control from the associated root network (Hartman et al. 1996) resulted in the banks of Reach 1 of the Oktwanch River widening by one to two metres annually between 1978 and 1995 (Walsh 2006). The active channel of the Oktwanch River has transformed from a single channel to the multichannel wandering stream observed today (Figure 2). Following the introduction of Coastal Fisheries Forestry Guidelines that required riparian buffers to be maintained around fish bearing streams in

1988, most logging activity moved to high elevations where stream gradient becomes a barrier to fish passage.

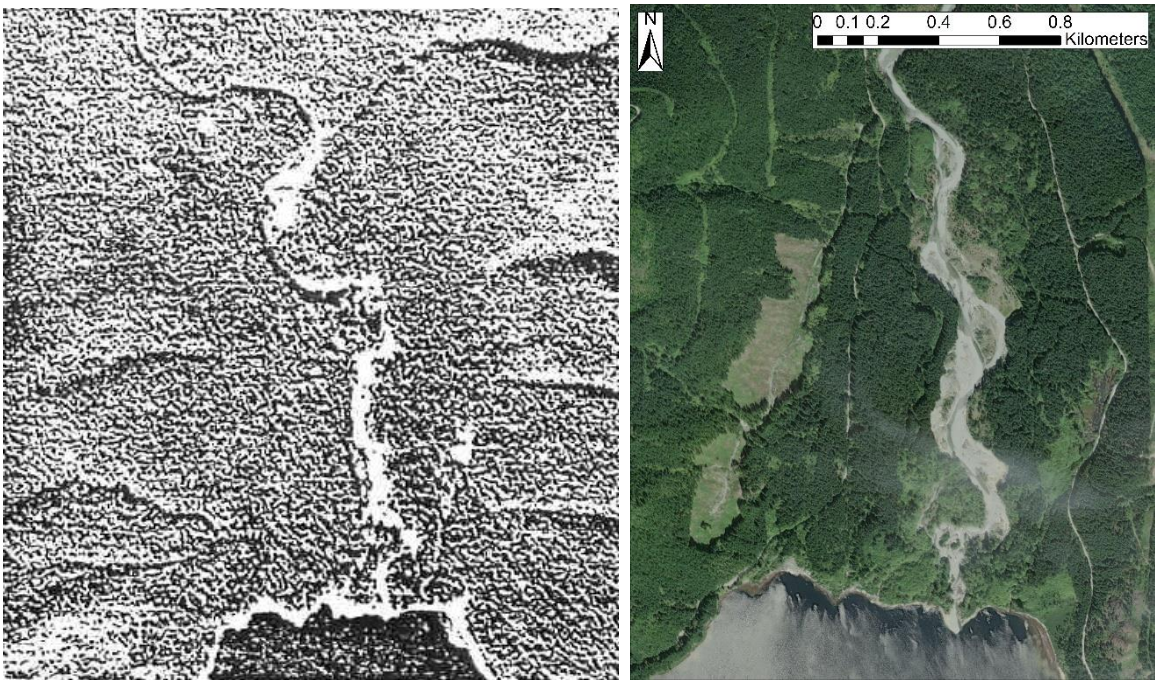

Figure 2. Left: Reach 1 of the Oktwanch River in 1957 prior to logging activity in the Oktwanch watershed (Tripp 1997). Right: Reach 1 of the Oktwanch river in 2019. Logging of the riparian zone has caused bank instability and channel widening. Aggradation in Reach 1 has resulted in morphological change and annual dewatering.

Following a review of potential sites in need of fish inventory and habitat restoration in the Oktwanch watershed, ten sites were identified for restoration in Reach 1, or the lower 2 km, of the Oktwanch River in 1997 (Tripp 1997). From 2000 to 2001, eight LWD installations were placed in the mainstem of the river to slow the rate of lateral erosion and protect groundwater side channels east of mainstem (Walsh 2006). Concurrent to the installation of the mainstem LWD structures, groundwater and backwater channels were constructed to the east and west of Reach 1 to develop spawning and rearing habitat for coho, sockeye (*O.nerka*), steelhead, rainbow trout, cutthroat trout (*O.clarkii*), and Dolly Varden (*Salvelinus malma*). These side channel engineering projects were assessed five years later and deemed a success, having created approximately 10600 m^2 of wetted area west of Reach 1 of the Oktwanch River, and 5350 m^2 to the east. (Walsh 2006). No assessment of the structures has been conducted since a routine effectiveness evaluation by Northwest Hydraulic Consultants in 2006.

Extensive dewatering occurs in the mainstem of Reach 1 and adjacent side channels annually (Figure 3). The restructuring of the main channel causes the LWD installations in the mainstem to be outside of the wetted width and non-functioning during the low flow period (Figure 4). In the mainstem, log jams mostly range between tens and hundreds of logs in size and are predominantly outside of the wetted width of the stream. Only side channels with groundwater influence maintain a wetted area during low flow periods, and there is no connectivity between side channels and the mainstem.

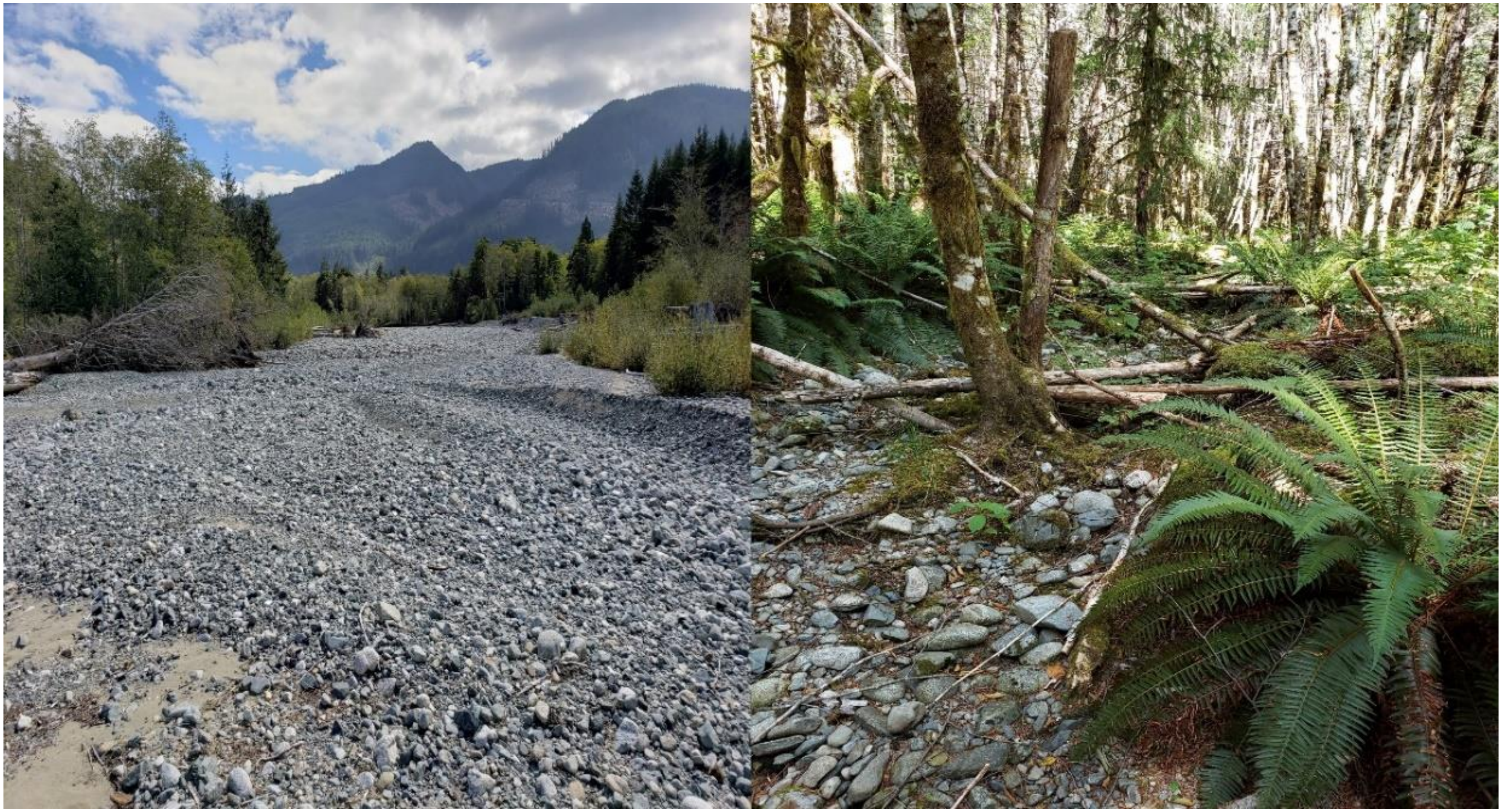

Figure 3. Left: Dewatering in the mainstem of Reach 1 of the Oktwanch River. Photograph was taken August 18th 2021. Right: Dewatering in a side channel to the east of Reach 1 of the Oktwanch River. Photograph was taken on August 17th 2021.

Figure 4. **LWD installations along the right bank of the mainstem of Reach 1. The structures were created to armour the bank against lateral erosion and prevent side channels being engulfed by the widening mainstem. Aggradation has caused the channel to migrate away from the LWD structures, rendering them non-functional. Photograph was taken August 2nd 2021.**

2.0. Methodology

2.1. Fish Habitat Assessment

An assessment of fish spawning and rearing habitat was conducted along Reach 1 of the Oktwanch River and all adjacent side channels (Figure 5) during the low flow period in August 2021. The surveyed area included the entire length of the main channel within the reach and a 100 m sample site in all side channels. Fish Habitat Assessment Procedures in British Columbia (FHAP) were used to inform methodology (Johnston & Slaney 1996). Benchmarks for habitat assessment sites in each side channel were established at randomly generated start points representative of the characteristics of the overall channel. UTM coordinates were recorded at each start point (Appendix A). Data was collected at two benchmarks in east side channel 1 as two reaches were identified in this channel.

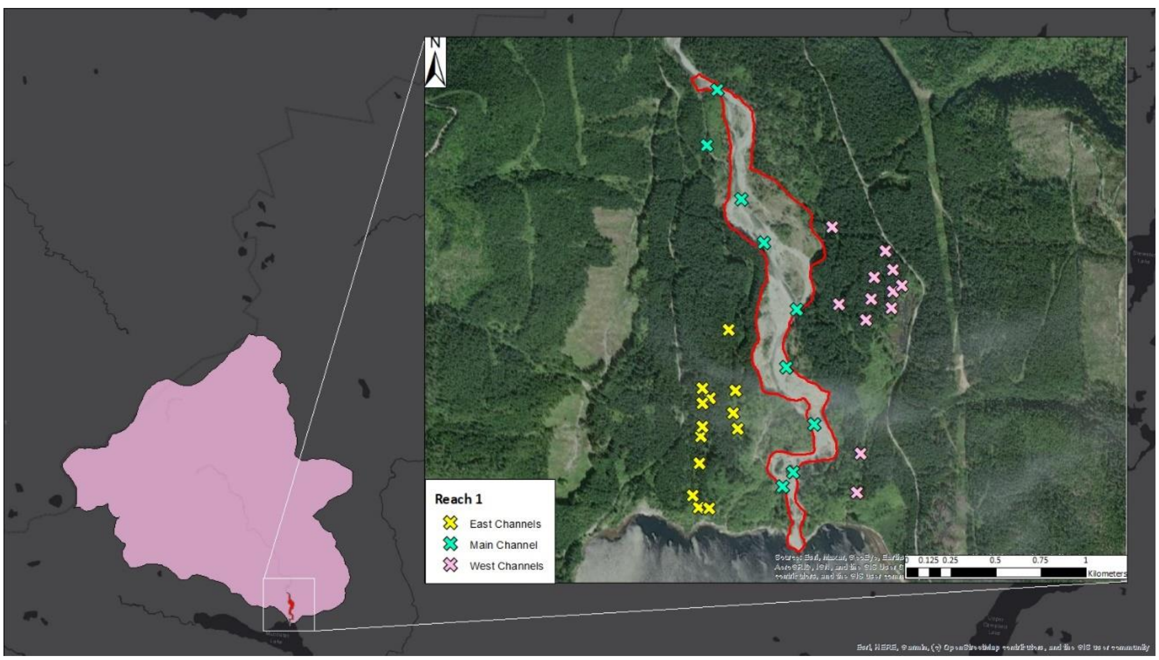

Figure 5. Location of Reach 1 of the Oktwanch River within the Oktwanch watershed. Inset: Location of sample sites within Reach 1 of the Oktwanch River.

Bankfull and wetted widths were measured at 20 m intervals along the length of the sample site in each side channel. To adequately represent variation in the main channel, width measurements were taken at 200 m intervals. The gradient of each channel was recorded using a clinometer.

2.1.1. Substrate

Wolman pebble counts (Kondolf 1997) were conducted to assess substrate size. To represent variation at sites, pebble counts were conducted at 200 m intervals in the mainstem and 20 m intervals in side channels. Ten substrate particles were sampled from the bed at increments of 10% bankfull width and measured along the B-axis using a gravelometer (Kondolf 1997; Bunte & Abt 2001). Each substrate particle was classified as fines (<2 mm), gravels (2-64 mm), cobbles (64-256 mm), boulders (256-4000 mm), or rock (>4000 mm). Averages of pebble counts for each channel were calculated to determine the dominant and subdominant substrate. General substrate suitability for salmonid spawning was assessed using FHAP, and literature review was used to further define suitability for steelhead (Appendix B) (Kondolf & Wolman 1993; Johnston & Slaney 1996; Roberge et al. 2002).

2.1.2. Pool Frequency

According to FHAP a pool is defined as an area of “slower, deeper water with a concave bottom profile, finer sediments, and a water surface gradient near 0%”. FHAP also requires that pools have minimum area and residual depth measurements dependent on the bankfull channel width. Residual depth is the difference between maximum pool depth and depth at pool outlet, allowing for measurement of pool depth regardless of flow conditions. The number of pools that met the minimum residual depth criteria according to FHAP within the survey area in each channel was recorded. This number was divided by the length of survey area to determine pool frequency. Habitat quality with respect to pool frequency was determined by comparison with FHAP diagnostics (Appendix B) (Johnston & Slaney 1996).

2.1.3. Dissolved Oxygen and Water Temperature

Dissolved oxygen (% DO) and water temperature were recorded using a YSI Pro Plus Multiparameter at the surface of the head of pools that met the minimum residual depth criteria outlined in FHAP. Measurements were also collected in pools that did not meet the minimum residual depth but contained juvenile salmon (henceforth referred to as small pools). The % DO was subsequently converted to mg/L using the altitude of sample site and climate data from the Tahsis Village North climate station. Measurements were taken on the 12th and 13th of August in the west side channels, on the 17th and 18th of August in east side channels, and between the 18th and 20th of August in the main channel. Results were compared to provincial water quality guidelines in B.C. for juvenile salmon and ranges of DO and temperature associated with physiological effects specific to steelhead rearing and growth (Oliver & Fidler 2001; Richter & Kolmes 2005; Carter 2008). As provincial guidelines for single DO measurements are based on an instantaneous minimum, the maximum temperature on the day of data collection was used to calculate DO (mg/L). DO and temperature measurements in small pools were compared with pools that met FHAP residual depth criteria to determine if there was a significant DO and temperature difference between the two that could reduce rearing habitat quality for juvenile steelhead in small pools.

2.1.4. Functional LWD

All functional LWD was tallied in each channel. Functional LWD is defined as dead wood pieces that intrude into the bankfull channel and promote scour, with minimum dimensions of 10 cm in diameter and 2 m in length. The effect of functional LWD on fish habitat quality within a channel was defined by the number of pieces per bankfull width. Less than one piece per bankfull width of stream length was deemed poor, between one and two pieces fair, and more than two pieces good (Johnston & Slaney 1996).

2.1.5. Instream Cover

Instream cover, defined as a structural element within 1 m of the water's surface, was estimated for the entire 100 m site length in the side channels, and at 200 m intervals in the mainstem. Cover types recorded were:

- Small woody debris (SWD; <10 cm diameter and 2 m in length)
- LWD
- Boulder
- Undercut bank
- Deep pool (>1 m deep)
- Overhead vegetation
- Instream vegetation

These were visually estimated to be absent, present in trace amounts (<5%), present in moderate amounts (5-20%), or abundant (>20%).

2.1.6. Statistical Analysis

Kruskal-Wallis tests were used to investigate if there were significant differences in substrate size, DO, and water temperature in the mainstem and adjacent side channels of Reach 1. This was to identify if any areas within the study site were more suitable candidates for instream or terrestrial restoration activities to improve steelhead spawning and rearing habitat. The Kruskal-Wallace non-parametric test was selected as collected data was not normally distributed, likely due to the limited sample size available for analysis. As data for each variable in the east side channels, mainstem, and west side channels had a different distribution, this test ranks the stochastic dominance of each location. One-tailed t-tests were used to determine if DO and temperatures were greater in small pools compared to pools that met FHAP residual depth criteria.

2.2. Spatial Analysis

2.2.1. Logging Disturbance

To compare logging disturbance in the watershed and interpret how logging and deforestation may have contributed to steelhead habitat degradation in Reach 1, a forest vegetation index (FI) was created using historical aerial imagery of the Oktwanch watershed from 1985, 1990, 1995, 2002, 2007, and 2021. Landsat 5 satellite imagery was used to analyze images for 1985-2007 and Landsat 8 satellite imagery was used for 2021.

The Landsat satellite program gathers images of specific bands of electromagnetic radiation (ER) within the visible light spectrum as raster images. Raster images have a value assigned to each individual pixel that determines its colour. Using the raster calculator tool in ArcMap, a multiband spectral image can be created to gather information such as vegetation distributions, location of active fires, and soil types (Boettinger et al. 2008; Schroeder et al. 2016).

A common technique to distinguish between vegetation and non-vegetation in remote imagery is to create a normalized difference vegetation index (NDVI). The equation:

$$NDVI = \frac{(\rho_{NIR} - \rho_{red})}{(\rho_{NIR} + \rho_{red})}$$

can be used to generate an image that shows variety in the concentration of chlorophyll in each pixel, where ρ_{NIR} represents the reflectance of ER in the near-infrared spectral band (0.77-0.90 μm) and ρ_{red} represents the reflectance of ER in the red spectral band (0.63-0.69 μm; Figure 6).

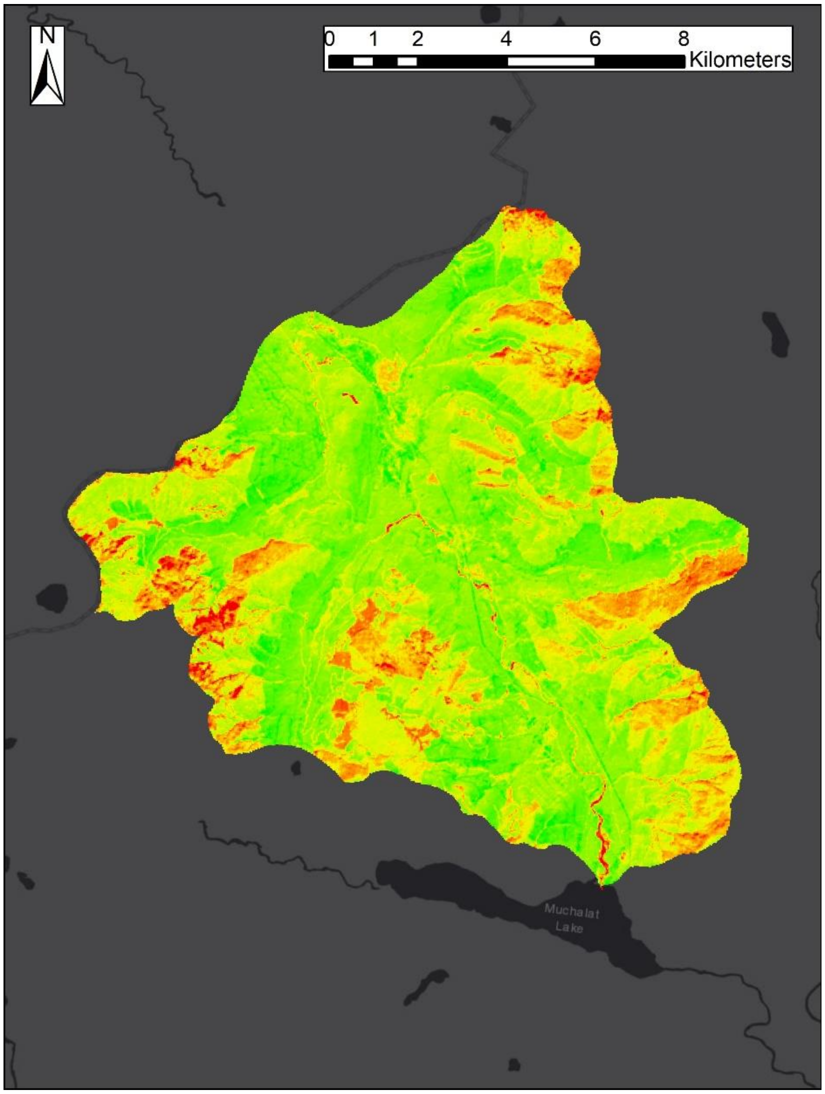

Figure 6. **A NDVI showing vegetated and non-vegetated areas in the Oktwanch watershed during the low flow period on July 30th, 2021. Red represents areas that have low concentrations of chlorophyll and are associated with impervious surfaces and clear-cuts. Yellow represents vegetation with low concentrations of chlorophyll. Green represents vegetation with higher concentrations of chlorophyll.**

A basic NDVI lacks sensitivity to identify different types of vegetation, such as shrubs or forest. To address this limitation, a FI that better highlights forest vegetation, was created using the equation:

$$FI = \left(\frac{\rho_{NIR} - \rho_{red} - 0.01}{\rho_{NIR} + \rho_{red}}\right)\left(\frac{1 - \rho_{NIR}}{0.1 + \rho_{green}}\right)$$

where ρ_{NIR} represents the reflectance of ER in the near-infrared spectral band (0.77-0.90 μm). ρ_{red} represents the reflectance of ER in the red spectral band (0.63-0.69 μm), and ρ_{green} represents the reflectance of ER in the green spectral band (0.52-0.60 μm; Figure 7) (Ye et al. 2014).

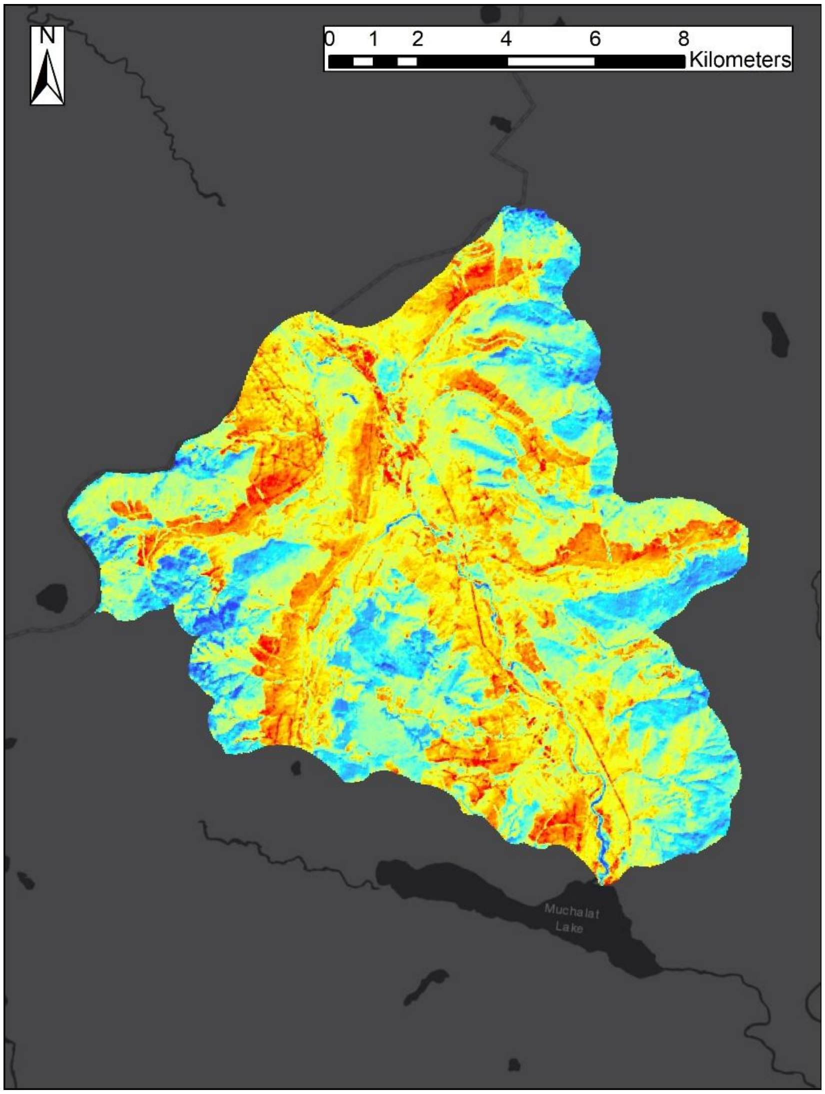

Figure 7. **A FI that shows different vegetation types and non-vegetated areas in the Oktwanch watershed during the low flow period on July 30th, 2021. Red represents areas that have low concentrations of chlorophyll and are associated with impervious surfaces and clear-cuts. Yellow represents areas that have higher abundance of shrubs or deciduous vegetation associated with recent disturbance and the early stages of succession towards a forest community. Green represents forest vegetation with higher concentrations of chlorophyll. Blue represents areas that have the highest coverage of mature forest or water.**

2.2.2. Vegetation Analysis

Vegetation Resource Inventory (VRI) data for the Oktwanch watershed (available between 1996 and 2017) was obtained from the B.C. data catalogue. Maps showing tree species composition and tree age within polygons in the Oktwanch watershed were created using VRI data in ArcMap to demonstrate how vegetation species composition differs when compared to watersheds in the CWHvm that have not been commercially logged. These maps and a literature review were then used to infer how transpiration rates and slope stability may have changed as the result of logging.

2.2.3. i-Tree Canopy Analysis

Change in precipitation runoff into streams following rain events and potential evapotranspiration following logging was analyzed to infer how sediment contribution into the stream network in the Oktwanch watershed may have changed over time. This analysis was conducted using i-Tree Canopy software that calculates hydrological characteristics of an area based on estimates of tree coverage and geographic location (Wang et al. 2008; Hirabayashi & Endreny 2016). The intent of this analysis was to investigate if changes in hydrological characteristics in the Oktwanch watershed correlated with observed dewatering and aggradation in Reach 1 of the Oktwanch River. The i-Tree suite of tools was developed in collaboration between the USDA Forest Service and other institutions to inform urban forest management and advocacy and is supported by peer-reviewed applied research (Wang et al. 2006, 2008; Yang et al. 2011; Yang & Endreny 2013). i-Tree Canopy is easily accessed through a web browser and may provide an opportunity for land managers to quickly assess physical characteristics of a watershed remotely and identify areas to focus restoration activities.

Landsat satellite imagery from 1985 and 2021 was analyzed to determine change in percentage cover of different land cover classes within a subsection of the watershed with logging activity during this period. Land cover classes identified using i-Tree Canopy were:

- Clear-cuts
- Non-tree vegetation
- Road
- Soil/ bare ground

- Tree
- Water

i-Tree canopy analysis was completed for two different spatial scales within a tributary watershed to the Oktwanch River that was logged between 1985 and 2021 (Figure 8). The entire tributary watershed (28.45 km^2) was analyzed to investigate the relationship between the area of tree coverage change and hydrological change in the watershed. A 100 m buffer surrounding streams (11.63 km^2) was also analyzed as this represents the maximum size for a riparian management area (RMA) that can be applied under current FRPA provincial legislation. The percentage change in avoided runoff and evapotranspiration was estimated for both years (Hirabayashi 2013) to allow comparison between the two spatial scales.

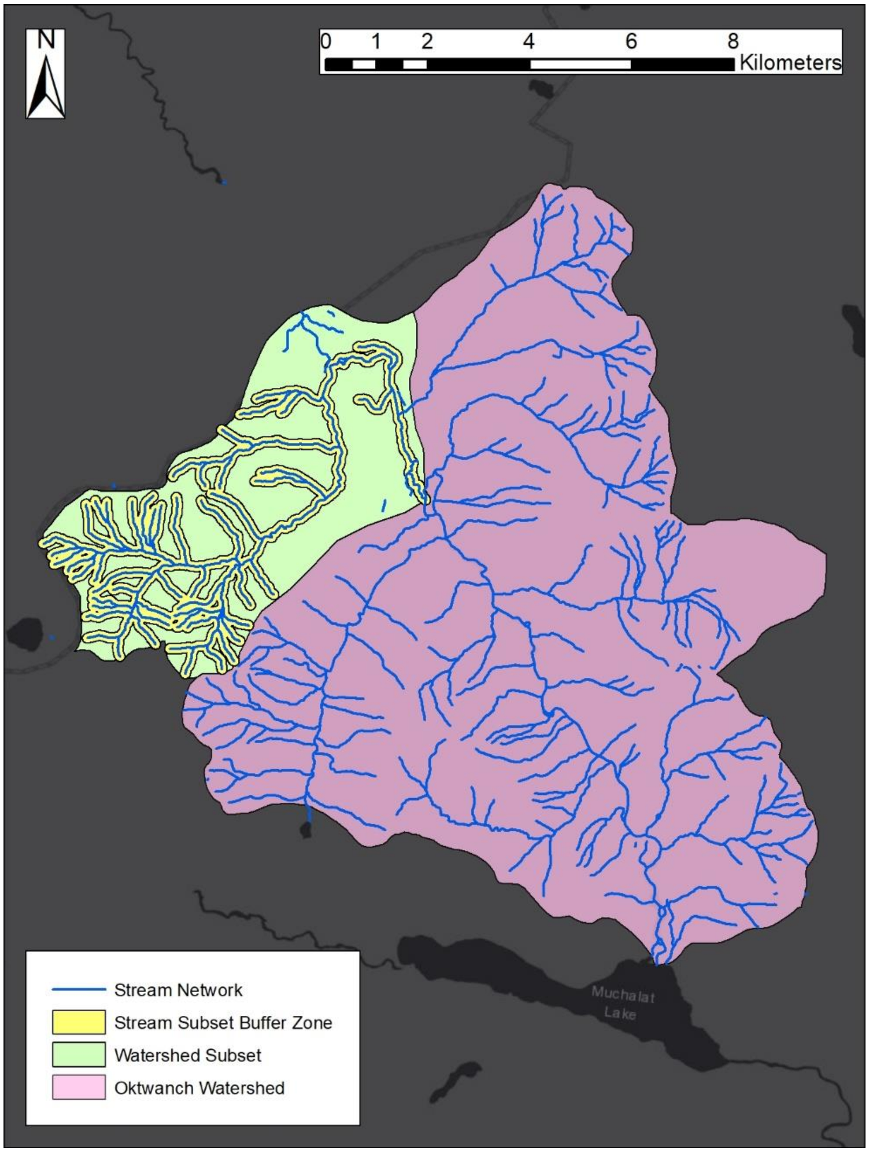

Figure 8. The green and yellow areas show the subset of the Oktwanch watershed and the 100 m buffer zone that were considered in i-Tree analysis to assess the change in avoided runoff and evapotranspiration due to the change in tree coverage between 1985 and 2021.

Landsat and i-Tree Canopy analysis was also completed for the 11.26 km^2 Carnation Creek watershed on the southwest coast of Vancouver Island (Figure 9), also within the CWHvm. In 1970, the Carnation Creek watershed was selected as the subject of a series of experiments to improve understanding of the biological and physical consequences of forestry practices (Tschaplinski 2008). From 1976 to 1981, 41% of the watershed was logged and an additional 42% was logged between 1987 and 1994

(Hartman et al. 1996). Approximately 61% of the length of headwater streams were logged to the banks between 1976 and 1994 (Hartman et al. 1996). The Carnation Creek watershed has been subject to similar harvesting practices as have occurred in the Oktwanch watershed, but with continuous monitoring of the impacts to salmonid populations and subsequent restoration (Tschaplinski & Pike 2017). As a result, Carnation Creek was selected to demonstrate the recovery of biotic and abiotic characteristics in the absence of logging, and may help inform necessary restoration measures to restore a steelhead population in the Oktwanch watershed.

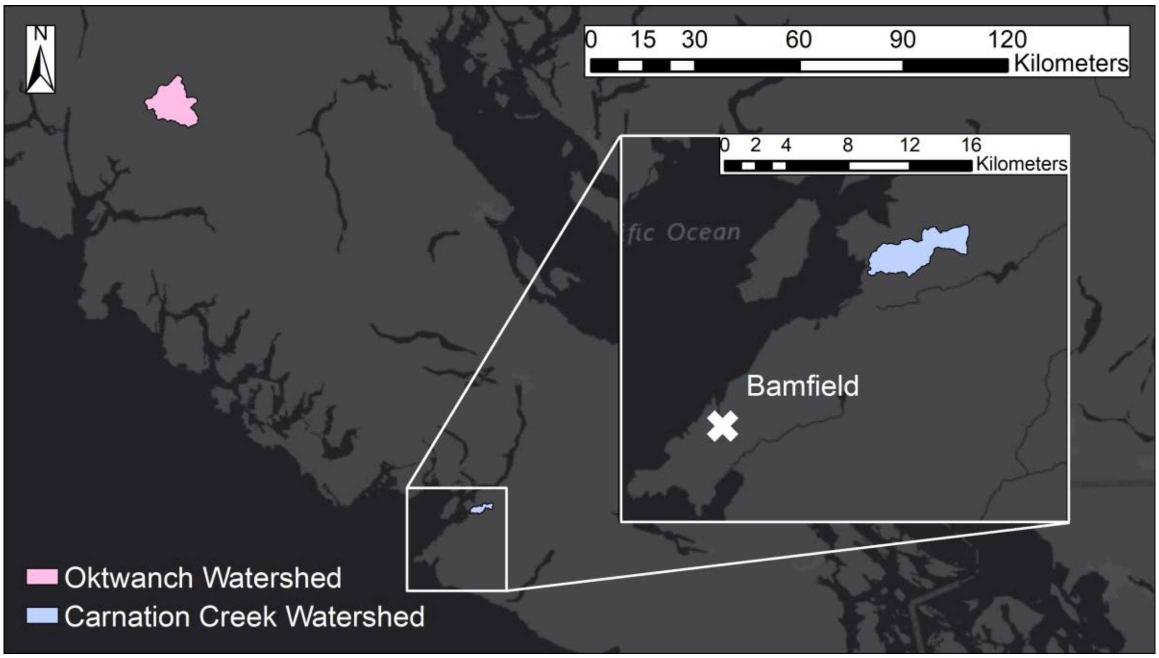

Figure 9. **The Carnation Creek watershed (shaded in blue) is located approximately 14 km northeast of Bamfield on Vancouver Island. This watershed is located in the CWHvm and has a history of forest harvesting and subsequent habitat restoration for salmon.**

3.0. Results

3.1. Fish Habitat Assessment

3.1.1. Substrate

Fines were dominant in the east and west side channels at 65.6% and 58.2% coverage respectively. Gravels were dominant in the main channel at 50.4% and cobbles and fines were subdominant (Figure 10). There was no statistically significant difference between substrate particle sizes in the mainstem or side channel networks ($H_{(1)} = 1.38$, $p = 0.50$).

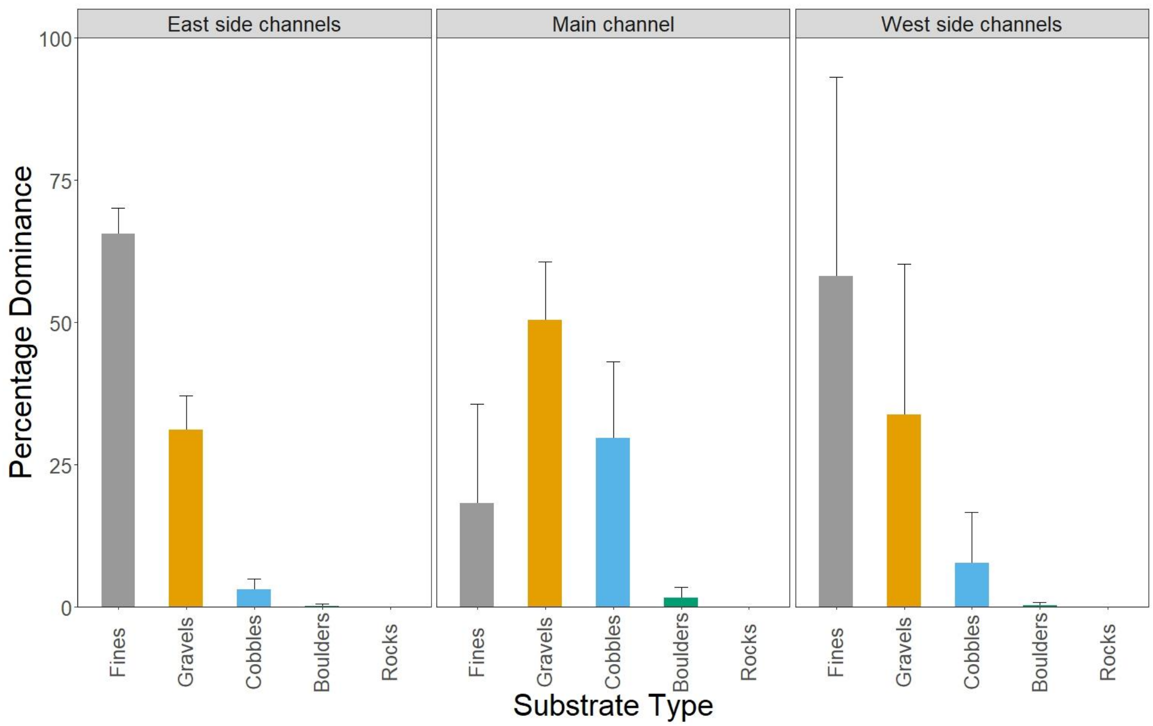

Figure 10. Percentage dominance of substrate types in Reach 1 of the Oktwanch River and side channels. There was no significant difference between substrate particle sizes in the mainstem or side channel networks ($H_{(1)} = 1.38$, $p = 0.50$).

3.1.2. Dissolved Oxygen

Average DO in pools in the main channel was 4.84 mg/L. The inclusion of small pools in the calculation increased average DO to 4.96 mg/L. Pools in the east and west side channels contained an average of 6.37 mg/L and 4.75 mg/L of DO respectively (Figure 11). No significant difference was observed between DO in any channel network ($H_{(2)} = 3.78$, $p = 0.15$), nor between pools and small pools ($H_{(1)} = 0.0054$, $p = 0.94$). DO in small pools was not significantly greater than pools deeper than the minimum residual depth for FHAP ($t_{(46)} = 0.06$, $p = 0.47$).

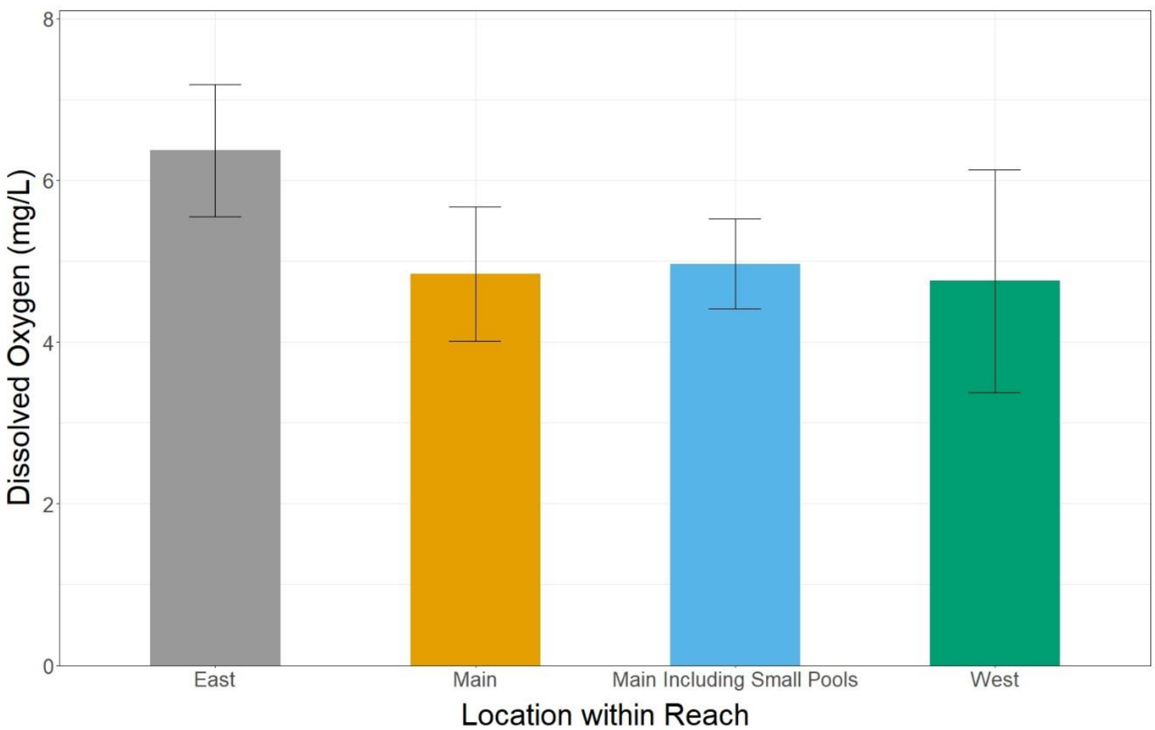

Figure 11. Dissolved oxygen levels in pools in Reach 1 of the Oktwanch River. There was no significant difference in DO levels in pools in the main channel of Reach 1 and side channels ($H_{(2)} = 3.78$, $p = 0.15$).

3.1.3. Water Temperature

Water temperature within pools averaged 12.0˚C in east side channels, 11.7˚C in west side channels, and 13.0˚C in the main channel. The inclusion of small pools in the calculation increased the average water temperature to 14.8˚C (Figure 12). Pool water temperature was not significantly different between east side channels, west side channels, and the main channel ($H_{(2)} = 2.98$, $p = 0.23$). Water temperature in small pools was found to be significantly warmer than pools as defined by FHAP ($t_{(46)} = 5.16$, $p = <0.001$).

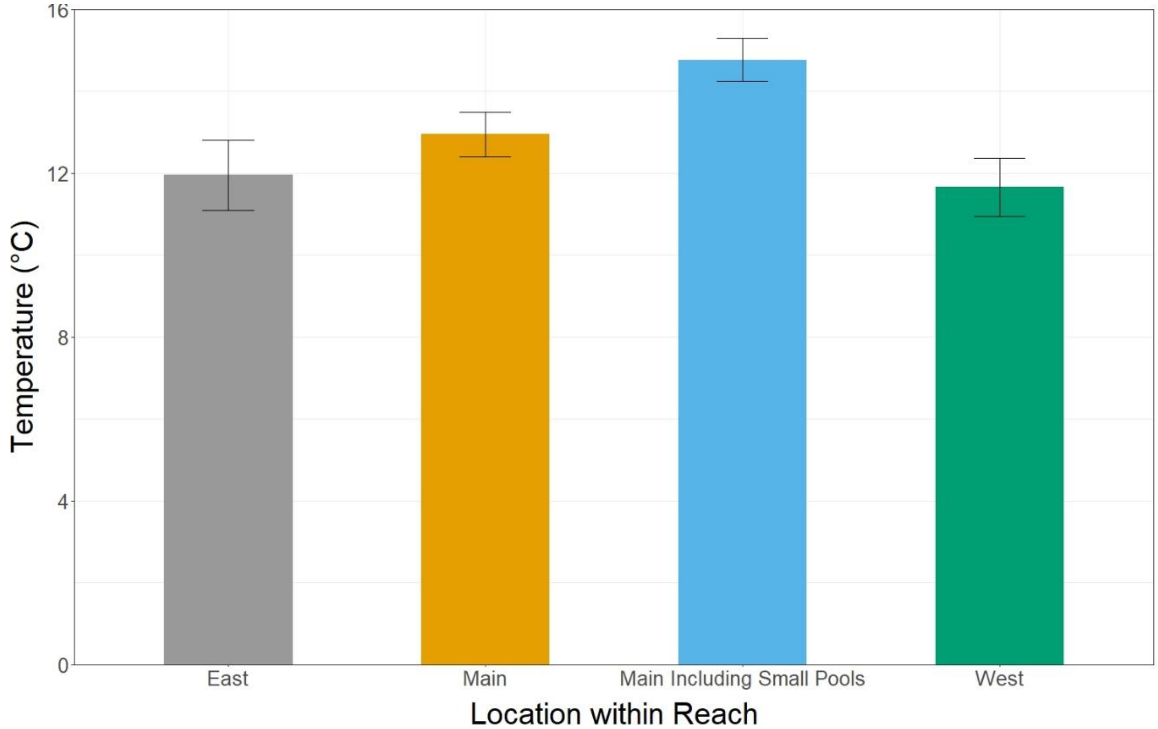

Figure 12. Average water temperature of pools in Reach 1 of the Oktwanch River. There was no significant difference in temperature in pools in the main channel of Reach 1 and side channels ($H_{(2)} = 2.98$, $p = 0.23$).

3.1.4. Pool Frequency

Seven channels contained pools that met the minimum residual depth criteria for FHAP. One channel in the west side channel network had fair pool frequency between 2 and 4 channel widths per pool. All other side channels were categorized as poor (Table 1). The main channel was rated as good according to FHAP diagnostics (Appendix B).

Table 1. Quality of pool frequency for salmonids according to FHAP diagnostics, defined by the number of channel widths per pool.

Channel Location	Poor (>4)	Fair (2-4)	Good (<2)
Main	0	0	1
East Side Channels	2	0	0
West Side Channels	3	1	0

3.1.5. Instream Cover

A low percentage of all cover types was observed in the main channel of Reach 1. The only cover type that was present in more than trace amounts was instream vegetation, which was found to have a moderate coverage of 11% (Figure 13). East side channels had more varied cover, with SWD, LWD, instream vegetation, and overhead vegetation occurring in moderate or abundant amounts. West side channels had the most varied cover of the three surveyed areas, with moderate deep pool and undercut bank coverage. Boulder coverage was the least represented cover class present in trace amounts in the main channel and west side channels. This was followed by undercut bank cover, which was moderate in 11% of sampling sites in the west side channels and absent or trace in all other channels.

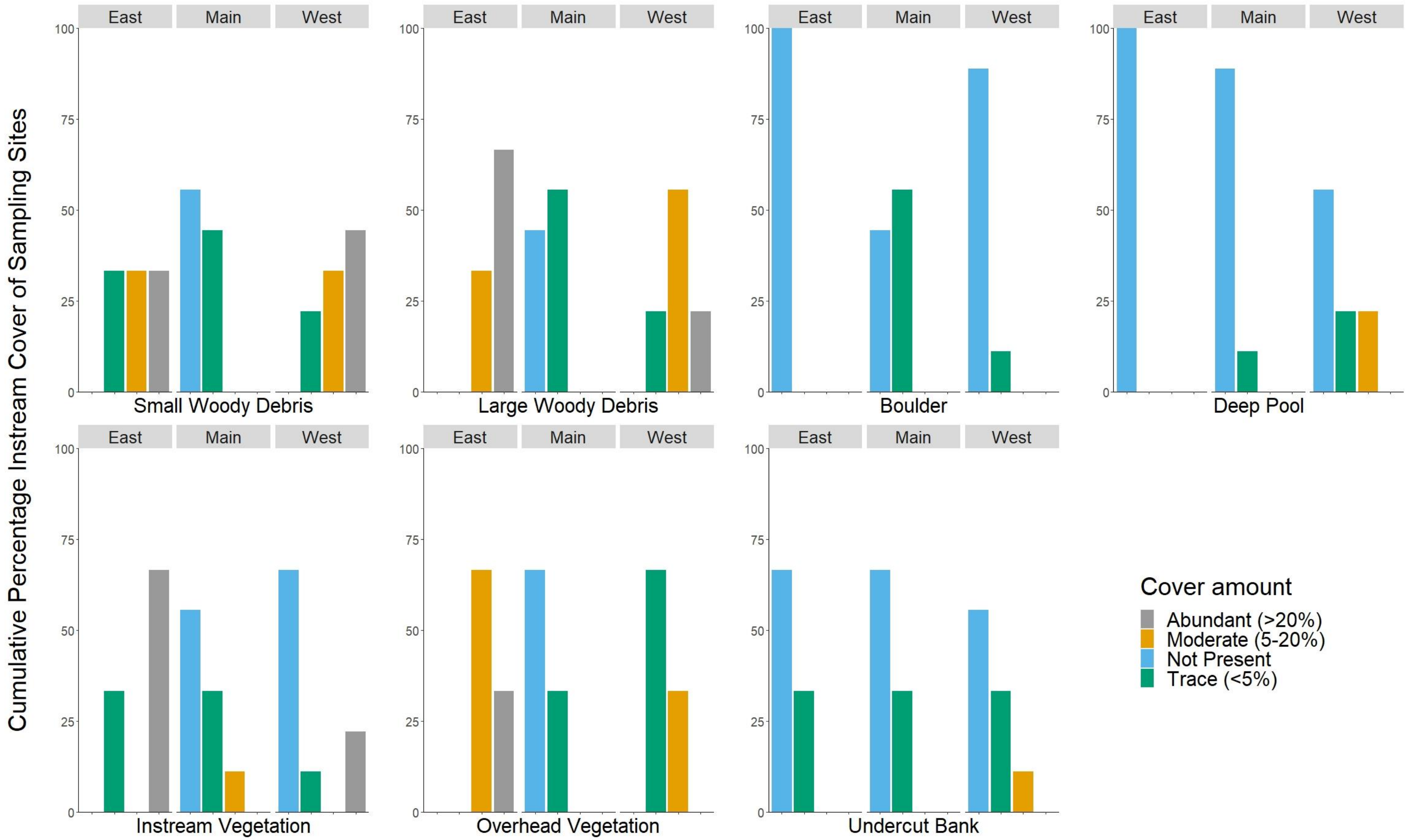

Figure 13 **The cumulative percentage of instream cover types within Reach 1 and adjacent side channels of the Oktwanch River.**

3.1.6. Functional LWD

Functional LWD content in Reach 1 and adjacent side channels was good in four channels, fair in two, and poor in four channels (Table 2). Channel 5 in the west side channel network had the highest amount of LWD while the lower section of Channel 1 in the east side channel network and the mainstem had the least amount.

Table 2. Functional LWD content in streams containing fish habitat within Reach 1 of the Oktwanch River.

Location	Channel ID	LWD Tally	LWD per Bankfull Width	Quality
west	1	10	0.74	Poor
west	2	16	1.70	Fair
west	3	12	1.83	Fair
west	4	14	2.15	Good
west	5	13	2.74	Good
west	6	1	0.19	Poor
east	1-lower	0	0.00	Poor
east	1-upper	13	2.00	Good
east	7	19	2.94	Good
main	mainstem	2	0.02	Poor

3.2. Spatial Analysis

3.2.1. Logging Disturbance

An analysis of historical forest indices using Landsat imagery showed a change over time of the areas most disturbed by logging within the Oktwanch watershed (Figure 14; Figure 15). In 1985, the most disturbed area of the watershed was the riparian zone surrounding the Oktwanch River and the adjacent valley bottom. The upper watershed and headwaters were relatively undisturbed. Vegetation coverage remained similar in 1990, with increases in the amount of clear-cut area in the riparian zones of lower order streams. In 1995, there was a decrease in the amount of clear-cut area in the riparian zone of the Oktwanch River and an increase in the shrub layer and young forest from regrowth. All new clear-cuts during this time occurred in the upper watershed. There was also a decrease in the vegetation coverage in the riparian zone surrounding the mainstem in 1995. This pattern of growth and disturbance continues in 2002, 2007, and 2021. By 2021, the valley bottom of the Oktwanch Watershed had mostly revegetated with shrub or young forest. The upper watershed exhibited ongoing logging activity and clear-cut areas.

The 1985 forest index in Carnation Creek watershed showed areas that were logged between 1976 and 1981 in the northwest region of the watershed (Figure 16). During this time the rest of the watershed was undisturbed, as demonstrated by historical aerial imagery. The 2021 forest index showed how the northwest region has revegetated following disturbance but that vegetation structure in this area is not equal compared to areas that were undisturbed.

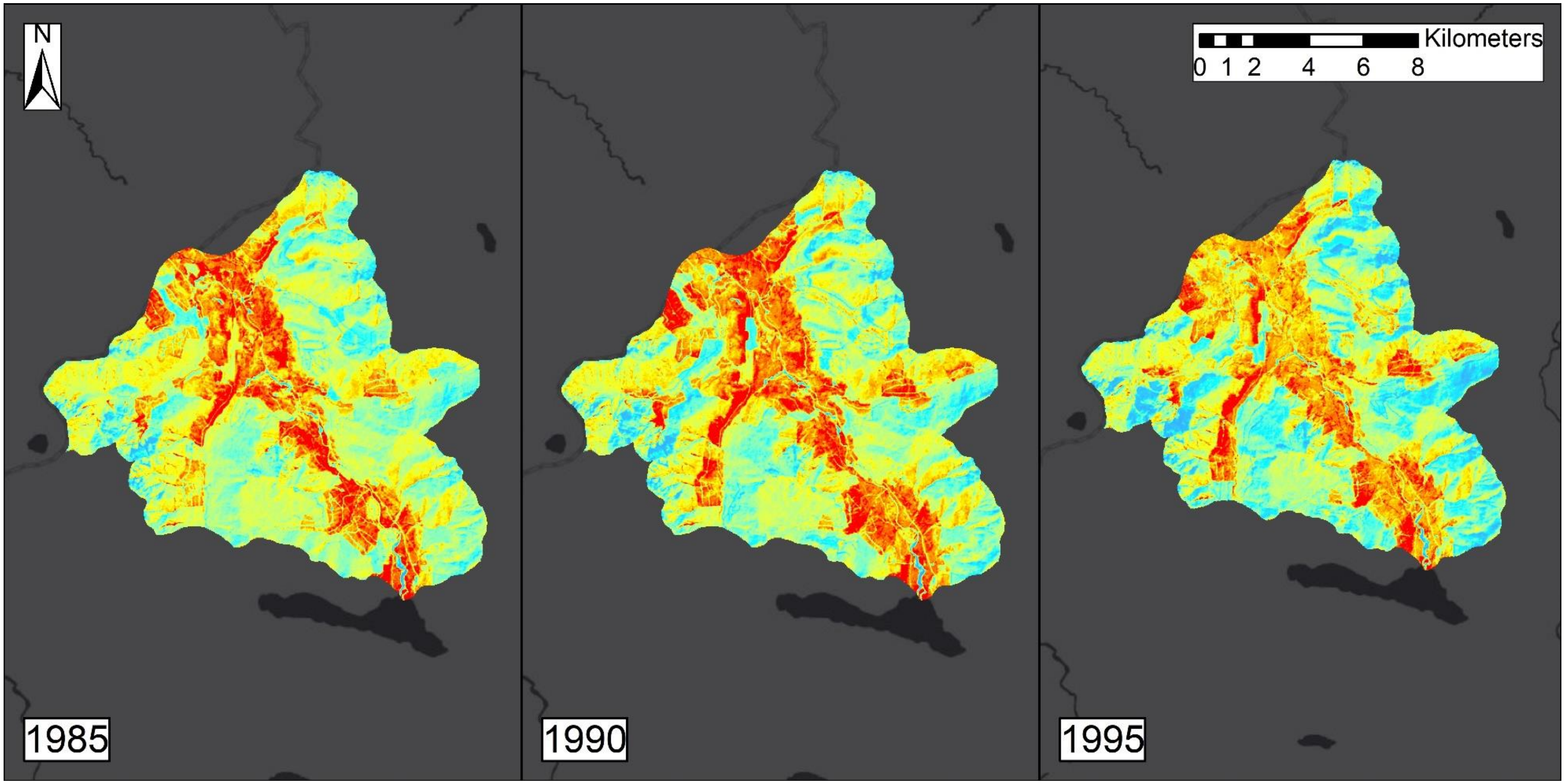

Figure 14. **Multispectral images showing the coverage of vegetation in the Oktwanch watershed in 1985, 1990, and 1995. Red represents areas that have no vegetation and are associated with impervious surfaces and clear-cuts. Yellow represents areas that have higher abundance of shrubs or deciduous vegetation associated with areas that have recently been disturbed and are in the early stages of succession towards a forest community. Green represents forest vegetation with higher concentrations of chlorophyll. Blue represents areas that have the highest coverage of mature forest or water.**

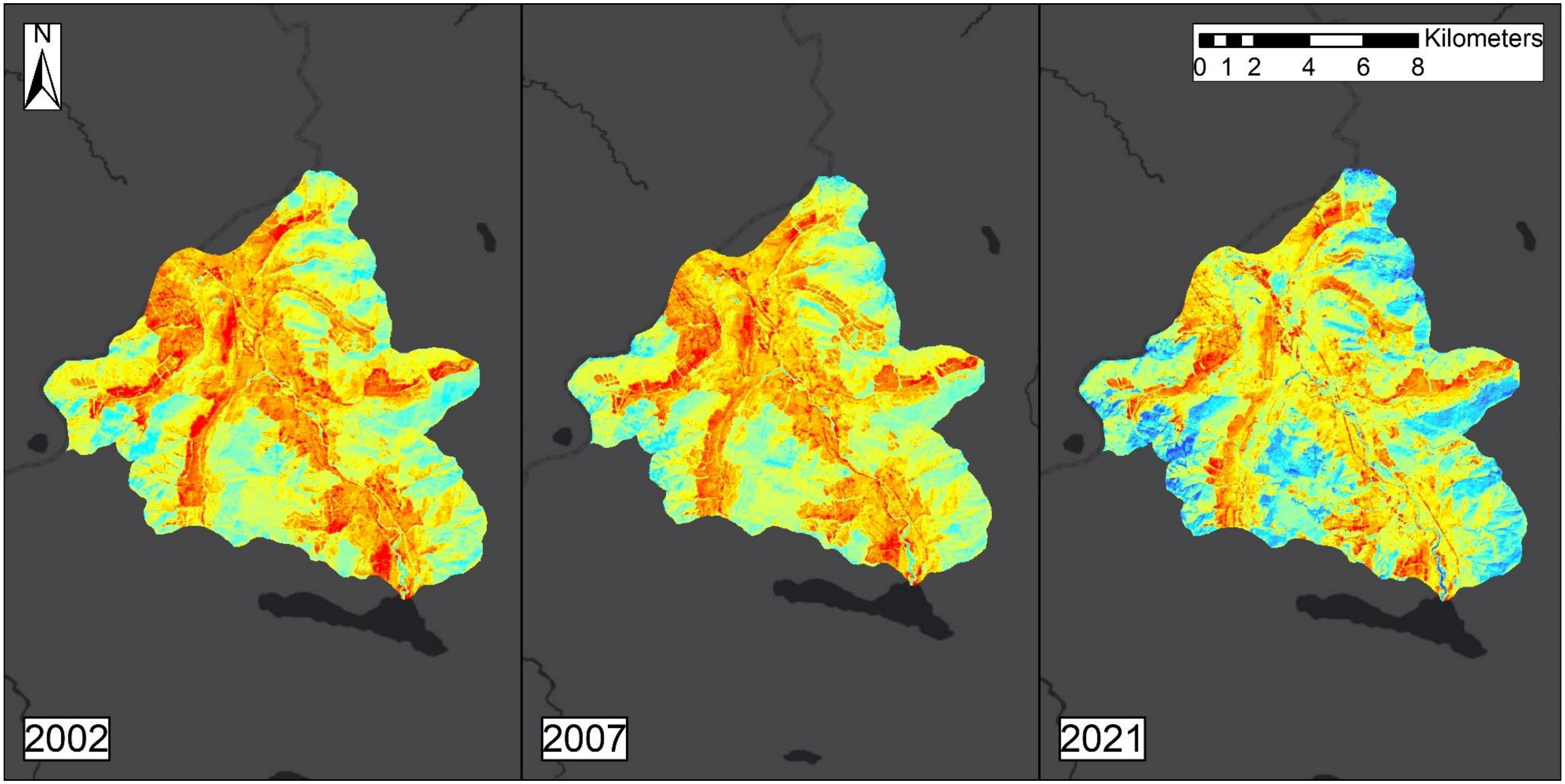

Figure 15. **Multispectral images showing the coverage of vegetation in the Oktwanch watershed in 2002, 2007, and 2021. Red represents areas that have no vegetation and are associated with impervious surfaces and clear-cuts. Yellow represents areas that have higher abundance of shrubs or deciduous vegetation associated with areas that have recently been disturbed and are in the early stages of succession towards a forest community. Green represents forest vegetation with higher concentrations of chlorophyll. Blue represents areas that have the highest coverage of mature forest or water.**

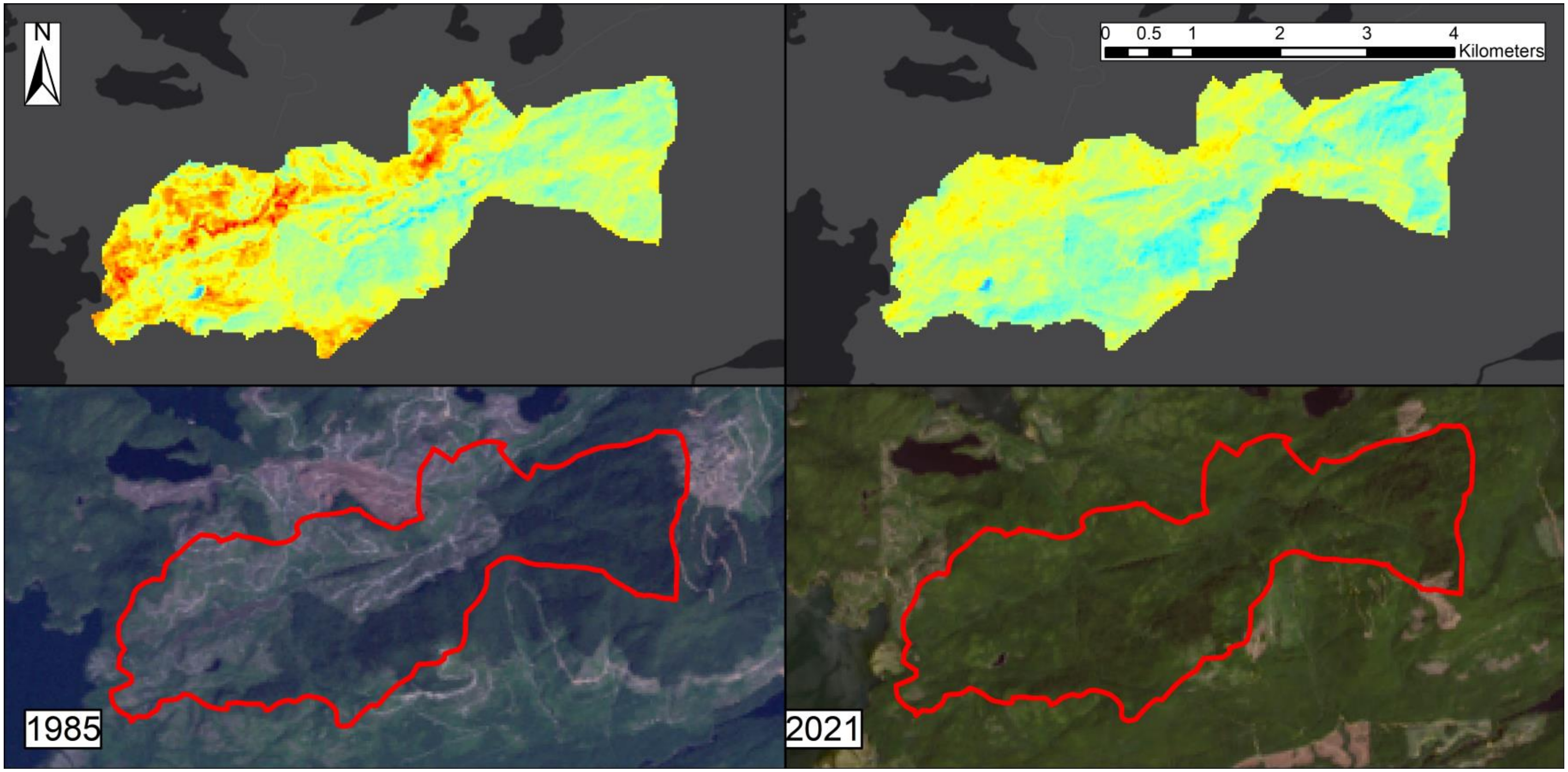

Figure 16. **Multispectral images showing the coverage of vegetation in the Carnation Creek watershed in 1985 and 2021. The images from 1985 shows logging occurred in the northwest region of the watershed. By 2021, the disturbed area had revegetated but had not reached the chlorophyll levels of undisturbed forest. Red represents areas that have no vegetation and are associated with impervious surfaces and clear-cuts. Yellow represents areas that have higher abundance of shrubs or deciduous vegetation associated with areas that have recently been disturbed and are in the early stages of succession towards a forest community. Green represents forest vegetation with higher concentrations of chlorophyll. Blue represents areas that have the highest coverage of mature forest or water.**

3.2.2. Vegetation Analysis

In 2017, most areas of the Oktwanch watershed that were logged had revegetated with Douglas fir (*Pseudotsuga menziesii*). Trees in the riparian zone adjacent to the mainstem of the Oktwanch River and its direct tributaries are younger than 50 years old. Western hemlock, amabilis fir, and Western redcedar were the primary tree species in undisturbed areas of the watershed. Remaining old-growth forest was restricted to headwaters and steeper regions of the watershed (Figure 17; Figure 18).

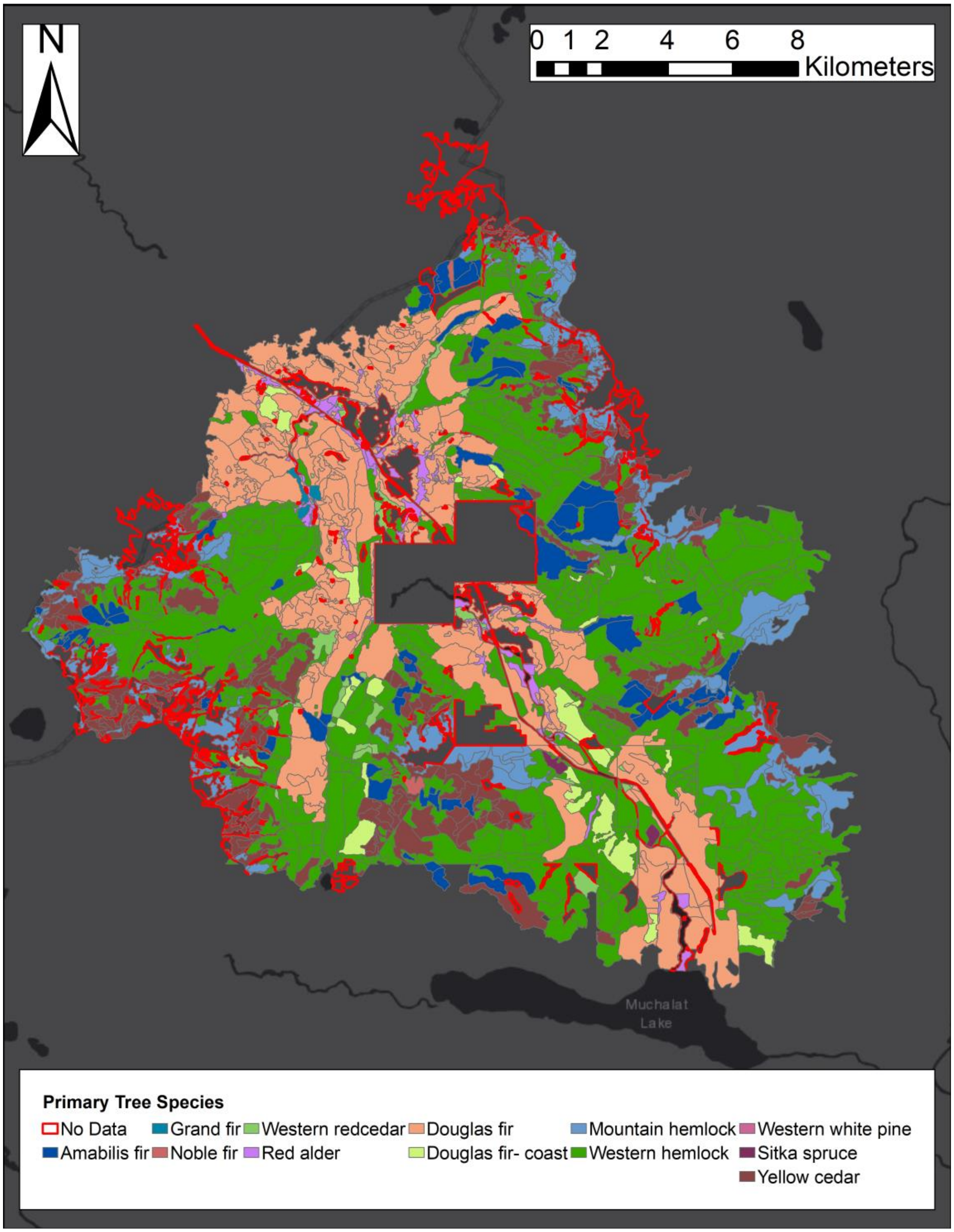

Figure 17. **Primary tree species in the Oktwanch watershed in 2017. Douglas fir was dominant in areas of the watershed that were disturbed by logging. The Oktwanch watershed is within the very wet maritime Coastal Western Hemlock biogeoclimatic zone (CWHvm). Dominant tree species within undisturbed watersheds in the CWHvm were restricted to steeper areas of the watershed.**

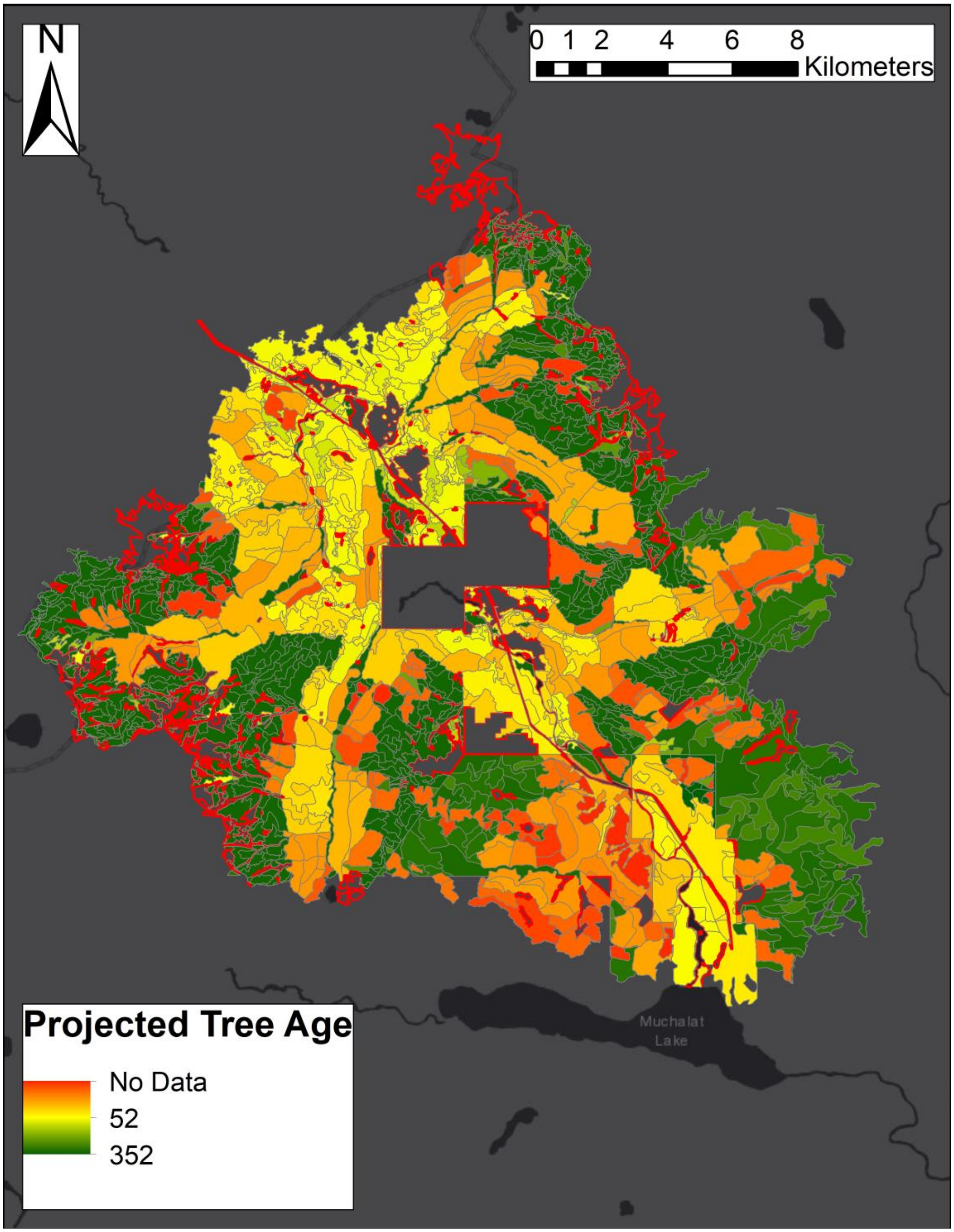

Figure 18. **Projected tree age in the Oktwanch watershed in 2017. Most trees were below 52 years of age, which correlates with historical logging in the watershed. Remaining areas of old-growth forest were restricted to steeper areas of the watershed.**

3.2.3. i-Tree Canopy Analysis

Tree coverage in the Oktwanch watershed subset increased by 35.6 % between 1985 and 2021 (Table 3). Most other cover classes decreased. During this time, precipitation runoff decreased by 87.0% and evapotranspiration increased by 87.0%.

Table 3. Percentage cover and area of land cover classes in a subset of the Oktwanch watershed in 1985 and 2021.

Cover Class	1985		2021		Change in % Cover
	% Cover	Area (km^2)	% Cover	Area (km^2)	
Clear-Cut	10.70	3.04	6.50	1.85	- 4.20
Non-tree Vegetation	26.30	7.47	4.00	1.14	- 22.3
Road	7.30	2.07	1.50	0.43	- 5.80
Soil/Bare Ground	14.80	4.21	11.20	3.18	- 3.60
Tree	40.90	11.62	76.50	21.74	+ 35.6
Water	0.00	0.00	0.30	0.09	+ 0.30

Tree coverage in the 100 m RMA subset increased by 15.3% between 1985 and 2021 (Table 4). This was the largest change in cover class followed by clear cut area and non-tree vegetation, which decreased by 8.80% and 7.70% respectively. Coverage of road, soil/bare ground, and water changed by less than 1%. Precipitation runoff decreased by 26.1% and evapotranspiration increased by 26.1%.

Table 4. Percentage cover and area of land cover classes in a 100 m buffer zone surrounding streams in a subset of the Oktwanch watershed subset in 1985 and 2021.

Cover Class	1985		2021		Change in % Cover
	% Cover	Area (km^2)	% Cover	Area (km^2)	
Clear-Cut	10.90	1.27	2.10	0.24	- 8.80
Non-tree Vegetation	13.90	1.62	6.20	0.72	- 7.70
Road	0.50	0.06	1.00	0.12	+ 0.50
Soil/Bare Ground	15.90	1.85	16.6	1.93	+ 0.70
Tree	58.70	6.83	74.0	8.61	+ 15.3
Water	0.10	0.01	0.10	0.01	0.00

Between 1985 and 2021, tree cover in the Carnation Creek watershed increased from 52.7 % to 96.7% (Table 5). Precipitation runoff decreased by 83.5% and evapotranspiration increased by 83.5%.

Table 5. Percentage cover and area of land cover classes in the Carnation Creek watershed in 1985 and 2021.

Cover Class	1985		2021		Change in % Cover
	% Cover	Area (km^2)	% Cover	Area (km^2)	
Clear Cut	2.3	0.26	0.4	0.05	- 1.90
Non-tree Vegetation	40.2	4.52	0.8	0.09	- 39.40
Road	4.8	0.54	0.7	0.08	- 4.10
Soil/Bare Ground	0.0	0.00	0.6	0.07	+ 0.60
Tree	52.7	5.93	96.7	10.88	+ 44.00
Water	0	0.00	0.0	0.00	0.00

4.0. Discussion

4.1. Fish Habitat Assessment

The overall quality of spawning and rearing habitat for steelhead in Reach 1 and adjacent side channels was poor. Fine substrate percent coverage in both the east and west side channels was above thresholds of 20-25%, above which survival rates of steelhead eggs sharply decline (Jensen et al. 2009). Fine substrate percent coverage may have been below this threshold in the mainstem as the result of variability in sample data, but substrate quality in the mainstem was still considered poor, as fines were a sub-dominant substrate. Steelhead are predominantly mainstem spawners (Scrivener et al. 1998) that will utilize gravel-dominant, cobble-subdominant substrate to construct their redds, but they have also been observed spawning in side channel habitat (Hunter 1973; Roberge et al. 2002). Overall, salmonid eggs deposited in Reach 1 of the Oktwanch River and associated side channels would have a reduced probability of survival as fine sediment filling interstitial space restricts exchange of oxygen and nutrients. Channel instability in the mainstem may also lead to eggs being crushed if the channel restructures during high flow events.

Steelhead young of the year (YOY) and juveniles are most commonly associated with large substrate particles (>256 mm) that are used as cover (Bustard & Narver 1975; Bradford & Higgins 2001). The lack of boulder cover and high proportion of fines in the Reach 1 side channels resulted in a lack of rearing habitat for steelhead YOY. This may be partly compensated for by woody debris coverage that both YOY and juveniles are frequently associated with (Roberge et al. 2002). Availability of overhead coverage within Reach 1 should not affect rearing habitat quality for steelhead as they are not commonly associated with this cover type, instead using instream cover during the day and feeding in the water column at night (Bradford & Higgins 2001). Instream vegetation (11%) in the main channel was concentrated 1600 m upstream of the start of Reach 1 and was not representative of the entire reach, where instream vegetation was either present in trace amounts or absent.

DO levels in pools was of particular concern for the development of juvenile salmon. DO in 39.29% of pools was below the 5 mg/L threshold for instantaneous minimum DO content in the water column necessary for all stages of aquatic life other than alevins and buried eggs according to the provincial water quality guidelines (British Columbia Ministry of Environment and Climate Change Strategy 2021). Only one pool had a DO content greater than 8 mg/L, below which juvenile salmonid survival is impaired (Carter 2008). Seventy one percent of pools had DO levels below which the average juvenile steelhead has been observed displaying symptoms of hypoxia (6 mg/L) (Davis 1975). Thirty two percent of pools contained less than 4.16 mg/L of dissolved oxygen, at which point juvenile steelhead survival is severely impaired and acute mortality can occur (Davis 1975).

Water temperatures recorded in Reach 1 were below the provincial guideline optimum range of 16-18˚C for steelhead (British Columbia Ministry of Environment and Climate Change Strategy 2021). Generally, water temperatures in Reach 1 and adjacent side channels should not cause thermal stress in steelhead juveniles (Oliver and Fidler 2001; Richter and Kolmes 2005). As average temperatures rise in the PNW as the result of climate change (Mote & Salathé 2010), water temperatures may rise in pools and become a limiting factor for juvenile steelhead survival in the future.

Pool frequency was generally poor for salmonids, with only one channel in the west side channel network rated as fair. According to FHAP diagnostics (Johnston & Slaney 1996) the main channel had good pool frequency, however this is not representative of summer/winter rearing habitat requirements for salmonids in Reach 1. FHAP diagnostics were designed for streams with bankfull widths <15 m and caution is advised when applying these standards to wider streams. As Reach 1 of the Oktwanch River has an average bankfull width of 93.71 m caused by bank instability and lateral erosion, the applicability of some FHAP standards to this stream is limited.

Functional LWD content was severely lacking in the mainstem of Reach 1, with 0.02 pieces of LWD per bankfull width. Pieces of LWD recruited to the mainstem were mostly non-functioning as the result of increased bankfull width, as channel instability limits the influence of LWD on stream morphology and hydrology (Bilby & Ward 1991). Lack of functional LWD has been shown to last for decades in coastal watersheds in the PNW following the cessation of logging (Scrivener & Brown 1992). A functional LWD deficit in the mainstem is likely to persist while the Oktwanch watershed is actively logged. Functional LWD occurrence was better in the east and west side channels but was not sufficient to deem salmonid habitat quality as good when considered holistically with other determinants of spawning and rearing habitat quality.

4.1.1. Limitations of Fish Habitat Assessment

A lack of baseline data and the degree of disturbance occurring within the watershed limit conclusions that can be drawn from the data. The extent of dewatering in Reach 1 resulted in few fish habitat units to survey. Although fish habitat that was surveyed was almost unanimously poor for all variables considered in Reach 1, ideally data collection would be repeated over multiple years. This would improve understanding of the main drivers of salmonid habitat degradation in the Oktwanch watershed and strengthen conclusions. Multi-year data collection would also assist with disassociating fish habitat degradation from being a consequence of single year anomalous climatic events.

In June 2021, an extreme heatwave occurred in the PNW and the national temperature record in Canada increased by 4.5°C (Henderson et al. 2022). Average climate projections for the PNW predict a temperature increase of 3°C before the end of the 21st century, with a one to two percent increase in annual precipitation compared with 1970 to 1999 averages (Mote & Salathé 2010). In a climate 2°C hotter than pre-industrial temperatures, extreme heat events equivalent to those in June 2021 are predicted to occur every 5-10 years (Philip et al. 2021). This will strengthen the long-term trend of annual dewatering and degraded fish habitat characteristics that have been observed in the Oktwanch watershed and in streams across the PNW (Tripp 1997). Although data to assess fish habitat quality in this study was only collected in 2021, it is unlikely that the extent of the dewatering observed was an isolated consequence of this one in 1000 year climate event (Philip et al. 2021).

4.2. Spatial Analysis

Forest vegetation indices showed that new logging disturbance moved away from the valley bottom along the mainstem of the Oktwanch River into the headwaters between 1985 and 2021. Headwaters typically account for between 60 to 80% of the length of a stream network and act as sediment reservoirs (Benda et al. 2005). Delivery of fine sediment from undisturbed headwater channels is typically limited by resistance to flow caused by LWD and stepped pool morphology (Benda et al. 2005). Logged streams have a deficit of LWD that results in a simplified channel morphology that lacks hydraulic complexity (Bilby & Ward 1991; Livers & Wohl 2016), allowing sediment to be transported more easily (MacDonald & Coe 2007). In the Caspar Creek experimental watersheds in Northern California, the length of stream channel lacking a riparian buffer was found to significantly affect suspended sediment loads instream (Lewis et al. 2001). The riparian zone around headwater streams in B.C. can be logged to the banks as they are commonly non-fish bearing. The lack of riparian buffers surrounding headwater streams in the Oktwanch may be significantly increasing the volume of fine sediment entering the Oktwanch River.

New logging disturbance as of 2021 was concentrated in steeper headwaters and as such, the frequency of landslides and the volume of fine sediment deposited in the stream network is likely to have increased. Logging road networks are the primary cause of increased hillslope failures in logged watersheds. Aerial imagery from 2021 showed a logging road density of 1.71 km/km^2 in the Oktwanch watershed. Both the Artlish River and Nahwitti River watersheds on Vancouver Island have a lower density of logging road networks compared to the Oktwanch watershed and saw a 200 and 1500% increase in landslide frequency, respectively (Guthrie 2002). As logging disturbance and associated logging road density are now concentrated in the headwaters in the Oktwanch watershed, increased mass-wasting events are likely depositing proportionately larger volumes of sediment into the stream network compared with sediment inputs related to disturbance in valley bottoms. In Carnation Creek, fine sediment that was deposited in headwater channels following logging and the associated increase in landslides was transported by higher peak flows and deposited in anadromous salmonid habitat in streams in the valley bottom (Tschaplinski & Pike 2017). This is likely the primary mechanism of fine sediment delivery into the mainstem of the Oktwanch River and the volume of fine sediment transported to the mainstem will continue to increase as logging disturbance increases in the headwaters.

FI highlighted that vegetation surrounding the mainstem of the Oktwanch River had lower concentrations of chlorophyll, indicating a higher abundance of non-mature forest, shrub, and herbaceous vegetation. This is problematic as the root network of this vegetation has weaker cohesion than mature coniferous forest and is more prone to erosion (Young 2000; Schmidt et al. 2001). The consequences of this change are exhibited by the widening of the Oktwanch River mainstem. Areas disturbed by logging highlighted by FIs correlated with VRI data that showed the dominant vegetation in these areas was not old-growth forest.

The abundance of young Douglas fir may also be exacerbating the severity of dewatering in the Oktwanch watershed. Stream flow deficits in logged watersheds with densely replanted Douglas fir stands have been shown to be 50% greater during the low flow period in summer (Segura et al. 2020). Compared to mature coniferous trees, young Douglas fir have higher rates of evapotranspiration, a higher concentration of leaf area in the canopy, and a higher sapflow per unit of sapwood area (Perry & Jones 2017). Consequently, young Douglas fir may reduce soil moisture, limiting groundwater input into streams and therefore reducing the wetted area of streams and juvenile salmon habitat in the Oktwanch watershed during low flow periods. If the growth of Douglas fir stands limit groundwater input to streams in the Oktwanch watershed, pool temperatures could increase above thresholds at which growth inhibition has been observed in steelhead (McCullough et al. 2001; Richter and Kolmes 2005). Additionally, channels in the east and west side channel network would have an increased risk of dewatering during the low flow period as they are disconnected from the mainstem and reliant on groundwater input (Walsh 2006). The reduction of soil moisture caused by Douglas fir will also become more problematic in the context of climate change, as groundwater input is vital for water temperature moderation as summers become hotter in the PNW (Mote & Salathé 2010; Kaandorp et al. 2019).

4.2.1. i-Tree Canopy Analysis

i-Tree Canopy analysis showed that tree coverage increased in the Oktwanch watershed subset, 100 m RMA subset stream buffer, and the Carnation Creek watershed between 1985 and 2021. The percentage change in tree coverage and avoided runoff was greater when considered at a watershed scale rather than at the RMA buffer scale. The area of the tributary watershed is 2.42 times larger than the buffer surrounding the stream network but the percentage decrease in runoff was 3.33 times greater when considered at the watershed scale. A similar pattern was observed when comparing the 100 m stream buffer to the Carnation Creek watershed. The area of the Carnation Creek watershed is 0.957 times the size of the stream buffer, but the percentage change in avoided runoff was 3.20 times greater in Carnation Creek. This indicates that peak flows are more influenced by disturbance outside of the riparian management area.

Greater peak flows result in higher volumes of suspended sediment and sediment transport that can degrade fish habitat at downstream (Beschta 1978; Troendle & Olsen 1993). The Deer Creek watershed in Oregon was 25% clear cut with the retention of a 15-30 m riparian buffer zone around streams and experienced a statistically significant 40.2% increase in sediment yield (Beschta 1978), mostly attributed to landslides associated with the logging road network. This same study also demonstrated that 36% of suspended sediment in the Flynn Creek watershed, also in Oregon, could be attributed to two storm events that caused extreme peak flows. An analysis of sediment accumulation in streams within watersheds in the Fraser Experimental Forest in Colorado demonstrated that peak flows were the strongest explanatory variable rather than forest disturbance (Troendle & Olsen 1993). This suggests that if the magnitude of peak flows in the headwaters of the Oktwanch watershed were to increase following logging disturbance, more fine sediment would be deposited into the stream network.

4.2.2. Limitations of Spatial Analysis

As the spatial analysis techniques applied in this study are novel and the Oktwanch watershed is an understudied area, findings from this analysis are limited to inferences as they are not supported by long term quantitative data collected within the watershed. This study alone should not be used to inform land management decisions, but rather as a basis for expanded research of watersheds within the CWHvm. There are also limitations with the FI and i-Tree Canopy analysis that must be considered before expanding the application of this research.

An error with FI analysis causes the reflectance of water to increase to levels similar to mature forest vegetation and be visualized in the FI as dark blue, falsely indicating that the concentration of chlorophyll is very high. The underlying cause of this error is currently unknown. While this does not affect terrestrial analysis of vegetation disturbance, in future research waterbodies should be delineated and removed from analysis prior to calculation of the FI. Additionally, as the Oktwanch watershed is rugged and topographically varied, terrain shadow effects may be introducing some error to FIs

(Jiang et al. 2019). Terrain shadowing occurs when direct light is blocked, causing the loss of spectral information of the objects in shade and altering their reflectance (Zhou et al. 2014). To address the terrain shadowing effect, FI of the Oktwanch watershed were validated through comparison with VRI data detailing tree age. Alternatively, FIs could be combined with indices that account for shadow effects in future analysis (Jiang et al. 2019)

The i-Tree Canopy analysis indicates that tree coverage has increased within the watershed, and consequently precipitation runoff into streams has decreased. This does not correlate with FIs showing vegetation disturbance or real-world observation of fish habitat degradation. There are two main limitations associated with assessing tree coverage with i-Tree Canopy analysis to model changes in avoided runoff in the Oktwanch watershed that may be the cause of this disconnect. Firstly, the 30 m resolution of historical aerial imagery made distinguishing between tree, shrub, and herbaceous vegetation difficult. The use of higher resolution imagery when categorizing land cover class in future studies would be more accurate. Additionally, i-Tree Canopy does not distinguish between coniferous and deciduous tree species and this distinction would be useful for inference of avoided runoff and evapotranspiration rates. For many areas of the province this could be achieved with the use of archived VRI data. This was not an option for the Oktwanch watershed as collection of VRI data within TFLs was not conducted prior to 1996.

There are also inherent limitations with the hydrological model used by i-Tree Canopy to calculate avoided runoff and evapotranspiration. The model does not consider tree species, tree age, or topography, all of which can influence precipitation runoff and evapotranspiration rates. The inclusion of this data would improve the applicability of the model to new environments. Data for precipitation and climate is also currently limited to Sweden, the United Kingdom, and the United States of America. For this study, the regional settings for Grays Harbor County in Washington were used, as the average annual precipitation is most similar to the Oktwanch watershed, it is within the Coastal Western Hemlock zone, and it has a similar pluvial hydrologic regime. Were the software to develop and incorporate climate data from British Columbia, i-Tree Canopy would be improved as a tool to inform land management within the province.

5.0. Conclusions

The findings of this study suggest that restoration of a steelhead population in the Oktwanch River will not be achievable if the current pattern of logging disturbance continues. Any short-term benefits to fish habitat from reach-scale restoration efforts such as LWD placement or channel modification are likely to be rendered ineffective as time progresses. The deleterious effects of logging on fish populations can persist for decades. Logging in the Carnation Creek watershed was halted three decades ago and salmonid populations remain below pre-harvest levels (Tschaplinski & Pike 2017). Successful restoration will become increasingly difficult as climate change accelerates and further contributes to anadromous salmonid habitat degradation through increasing water temperatures and more severe low flow periods. Spatial analysis suggests that a review of current forestry practices including, but not limited to, the effectiveness of riparian buffers adjacent to streams, the protection given to non-fish bearing streams in the upper reaches of watersheds, and replanting practices following logging are necessary to successfully restore steelhead habitat in the Oktwanch watershed.

There is hope for restoration of a steelhead population in the Oktwanch watershed with adjustments to forestry practices in the area. Populations of rainbow trout have been shown to act as reservoirs for the anadromous phenotype and may improve the capacity to restore steelhead in watersheds that have extensive anthropogenic disturbance (Courter et al. 2013). Additionally, steelhead and rainbow trout are capable of interbreeding and their offspring may express either the anadromous or resident phenotype (Kendall et al. 2017). If steelhead habitat quality is improved by measures such as reducing fine sediment input and bank stabilization, rainbow trout from within the Nootka Sound watershed could be used to re-establish a viable steelhead population.

FIs present a novel and accessible tool to assess watershed-scale disturbance to vegetation. They effectively highlight areas of the watershed that may be contributing the most to fish habitat degradation and inform where monitoring and research should be directed prior to ecological restoration. While i-Tree canopy can quickly assess changes in land cover classes over time and the associated hydrological change, without high resolution historical aerial imagery and an expansion of model parameters, its application to inform forestry management practices on Vancouver Island is limited.

This research has identified opportunities for further study in the Oktwanch watershed. Quantitative data on fine sediment contributions from tributaries into the Oktwanch River would help to further validate FIs as a method to identify areas actively contributing to increased sediment input and salmonid habitat degradation. This data could also inform the placement of sediment traps to limit aggradation in the lower reaches of the Oktwanch watershed. A reduction in the dominance of young Douglas fir should also be prioritized to reduce the severity of dewatering during the low flow period. Replanting vegetation that is more representative of a climax forest community in the CWHvm could improve the success of long-term steelhead habitat restoration in the Oktwanch watershed by lowering transpiration rates compared to young Douglas fir stands. Accelerating vegetation succession to mature coniferous forest in clear-cuts may help re-establish a stabilizing root network around streams and lower fine sediment transport by improving canopy interception.

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Appendix A

UTM coordinates of assessment of fish habitat channels/sites.

Location	Channel/Site Number	UTM (09U)
East Side Channels	1 lower	702568 5529273
East Side Channels	1 upper	702686 5529699
East Side Channels	2	702681 5529618
East Side Channels	3	702698 5529562
East Side Channels	4	702654 5529914
East Side Channels	5	702606 5529271
East Side Channels	6	702545 5529315
East Side Channels	7	702566 5529433
East Side Channels	8	702571 5529565
East Side Channels	9	702566 5529529
East Side Channels	10	702595 5529668
East Side Channels	11	702569 5529647
East Side Channels	12	702567 5529703
Mainstem	1	702867 5529361
Mainstem	2	702903 5529412
Mainstem	3	702972 5529588
Mainstem	4	702866 5529789
Mainstem	5	702895 5529996
Mainstem	6	702768 5530233
Mainstem	7	702682 5530385
Mainstem	8	702550 5530575
Mainstem	9	702581 5530775
West side channels	1	703135 5529349
West side channels	2	703144 5529489
West side channels	3	703145 5529970
West side channels	4	703045 5530022
West side channels	5	703162 5530046
West side channels	6	703011 5530299
West side channels	7	703235 5530016
West side channels	8	703238 5530075
West side channels	9	703269 5530097
West side channels	10	703235 5530152
West side channels	11	703206 5530220
West side channels	12	703168 5530124

Appendix B

Fish Habitat Assessment Procedures in British Columbia diagnostic table.

Habitat Parameter	Gradient or W_b Class	Use	Quality Poor	Fair	Good
Pool Frequency (mean pool spacing)	<2%, <15 m wide	Summer/winter rearing habitat	>4 channel widths per pool	2-4 channel widths per pool	<2 channel widths per pool
LWD pieces per bankfull channel width	All	Summer/winter rearing habitat	<1	1-2	>2
Boulder cover in gravel-cobble riffles	All	Summer/winter rearing habitat	<10%	10-30%	>30%
Substrate	All	Winter rearing habitat	Interstices filled: sand or gravel subdominant in cobble or boulder dominant	Interstices reduced: sand subdominant in some units with cobble or boulder dominant	Interstices clear: sand or small gravel rarely subdominant in any habitat