BC TIMBER SALES
CHINOOK BUSINESS AREA

ROBERTS CREEK AND STEPHENS CREEK WATERSHED ASSESSMENT: PHASES 1 & 2 (VOLUME 1)

Polar File: 740301
FINAL REPORT
DECMBER 2023

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December 5, 2023
Polar File: 740301
BCTS File: 10005-40/PD21TBF001

Mr. Pierre Aubin, RPF
Practices Forester
BC Timber Sales, Chinook Business Area
7077 Duncan Street
Powell River, BC, V8A 1W1

Dear Mr. Aubin:

Re: **ROBERTS CREEK AND STEPHENS CREEK WATERSHED ASSESSMENT: PHASES 1 & 2, FINAL REPORT**

Polar Geoscience Ltd. (Polar) is pleased to provide this final report on the above-noted study. The report summarizes our key findings from our office and field reviews as well as information collected during the consultation process, and provides recommendations to mitigate potential adverse hydrologic effects from future forest development in the Roberts Creek and Stephens Creek watersheds. We trust this completes our assignment to your satisfaction.

Polar Geoscience Ltd.

2023-12-05

Lars Uunila, MSc, PGeo (BC), PGeol (AB), PH, CPESC, CAN-CISEC, BC-CESCL
Senior Hydrologist & Geoscientist

WATERSHED OR HYDROLOGIC ASSESSMENT ASSURANCE STATEMENT: REGISTERED PROFESSIONALS

This Statement is to be read and completed in conjunction with the Professional Practice Guidelines – Watershed Assessment and Management of Hydrologic and Geomorphic Risk in the Forest Sector (Joint Practices Board, 2020) and is to be provided for watershed assessments or hydrologic assessments when requested by a client.

Client: Mr. Pierre Aubin, RPF
Practices Forester
BC Timber Sales, Chinook Business Area
7077 Duncan Street
Powell River, BC V8A 1W1

Date: December 5, 2023

With reference to the following assessment area: Roberts Creek and Stephens Creek

The undersigned hereby gives assurance that he/she is a Registered Professional:

Name	**Professional designation/associations:**
Lars Uunila	• Professional Geoscientist (P.Geo.), *Engineers & Geoscientists British Columbia* • Professional Geologist (P.Geol.), *Association of Professional Engineers and Geoscientists of Alberta* • Professional Hydrologist (P.H.), *American Institute of Hydrology* • Certified Professional in Erosion & Sediment Control (CPESC), *Envirocert International, Inc.* • Canadian Certified Inspector of Sediment & Erosion Control (CAN-CISEC), *CISEC, Inc.* • BC Certified Erosion and Sediment Control Lead (BC-CESCL), *Erosion & Sediment Control Association of BC* • Member, Canadian Water Resources Association

I/we have signed, sealed and dated the attached ☒ **watershed assessment report**, or ☐ **hydrologic assessment report** in general accordance with the Joint Professional Practices Guidelines: Watershed Assessment and Management of Hydrologic and Geomorphic Risk in the Forest Sector (Engineers and Geoscientists British Columbia and Association of British Columbia Forest Professionals, 2020) and the scope of work in Section 3.0 of that document.

Signature & seal:

L. S. UUNILA #27700

Lars S. Uunila

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2023-12-05

EXECUTIVE SUMMARY

BC Timber Sales (BCTS), Chinook Business Area (TCH) is planning forest development within its Crown land tenure in the Roberts Creek and Stephens Creek watersheds near Roberts Creek, BC. Roberts Creek has two main tributary basins: Clack Creek and East Roberts Creek, the former of which is fed by the Gough Creek sub-basin. Although BCTS Forest Stewardship Plan (FSP #672) does not have watershed assessment requirements for this area, multiple downstream values have been identified and both local government and the public have expressed concern over these values. As such, a multi-phased watershed assessment was initiated by BCTS beginning in summer 2020. The principal objectives of the assessment are to review the current conditions within each of the assessment watersheds, identify the potential hydrogeomorphic hazards and risks from future forest development within BCTS chart area on downslope watershed values, and provide risk management options to reduce, mitigate or avoid such risks within the context of the projected effects of climate change. It is important to recognize that the scope of the assessment is intended to provide BCTS with watershed-level guidance on how to proceed with forest development planning in order to minimize hydrogeomorphic risks; it does not review site-specific forest development plans. Such plans are the focus of subsequent assessments.

Within the assessment watersheds, the following downslope/downstream potential elements-at-risk were identified: human safety, private property (including residences, structures, water intakes, wells, stream crossings), public infrastructure (e.g., roads and road crossings), drinking water supply (including quantity and quality), and fish and fish habitat. Flooding (including debris floods and debris flows), low flows, sediment yields, channel destabilization, and water contamination by pollutants are the principal hazards under review. Based on the characteristics of the assessment watersheds and the research literature, the likelihood of the above-noted hazards under current levels of forest development (or disturbance) are provided. In order to minimize incremental increases in the above-noted hazards with future forest development, a number of recommendations have been identified for BCTS consideration. These include recommendations on cutblock opening size, retention and overall extent of harvesting (i.e., equivalent clearcut area) to minimize risk within the context of climate change and the values present downstream. Recommendations are also identified to minimize sediment and riparian risks, which along with hydrologic risks, are intended to minimize risks on stream channels and the values present.

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1. INTRODUCTION

1.1. BACKGROUND AND OBJECTIVES

BC Timber Sales (BCTS), Chinook Business Area (TCH) is planning forest development within its Crown Land tenure in the Roberts Creek and Stephens Creek watersheds (hereafter referred to as the "assessment area", "assessment streams" or "assessment watersheds") near Roberts Creek, BC. This area lies within the traditional and unceded territory of the Sḵwx̱wú7mesh Úxwumixw (Squamish) and shíshálh (Sechelt) First Nations, and within the Sunshine Coast Regional District (SCRD) Electoral Areas D (Roberts Creek), and F (West Howe Sound). The Roberts Creek watershed includes two basins and one sub-basin: 1) Clack Creek basin and 2) East Roberts Creek basin which are both tributaries of Roberts Creek, and 3) Gough Creek sub-basin which is a tributary of Clack Creek (FIGURE 1.1, MAP 1). Prior to advancing forest development plans within the Roberts Creek and Stephens Creek watersheds, BCTS retained Polar Geoscience Ltd. (Polar) to conduct a watershed assessment of the two watersheds[1].

The principal objectives of the watershed assessment are to review the conditions within each of the stream catchments, identify the watershed values[2] present and their sensitivity to disturbance, and analyze the potential hydrogeomorphic hazards (Section 3) and risks that forest development in the assessment area may pose to watershed values. Although a review of specific harvest plans is beyond the scope of this report, the assessment is intended to provide guidance and management options to reduce, mitigate or avoid risks as forest development planning advances. As informed by BCTS, near-term development plans are expected to be generally located in the eastern portion of the assessment area. As such, the assessment was generally focused in this area and downstream.

This assessment consisted of Phase 1 in 2020-2021, and Phase 2 (2021-2023). This report summarizes both Phases 1 and 2 and provides findings and recommendations for consideration in BCTS forest development planning process. A third phase of assessment involves site-level reviews of specific block and road plans, once confirmed.

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[1] The area between the assessment watersheds evaluated in Polar (2023a) and the two watersheds evaluated herein were considered beyond the scope of the assessment, given no near-term BCTS development plans within this area.

[2] Watershed values include the specific or collective set of natural resources and human developments in a watershed that have measurable or intrinsic worth. Values can include human life and bodily harm, aquatic and terrestrial habitat, and public and private property (including buildings, structures, lands, resources, recreational sites, transportation systems and corridors, utilities and utility corridors, water supplies for domestic, commercial, industrial, or agricultural use). Refer to Section 5 for further details.

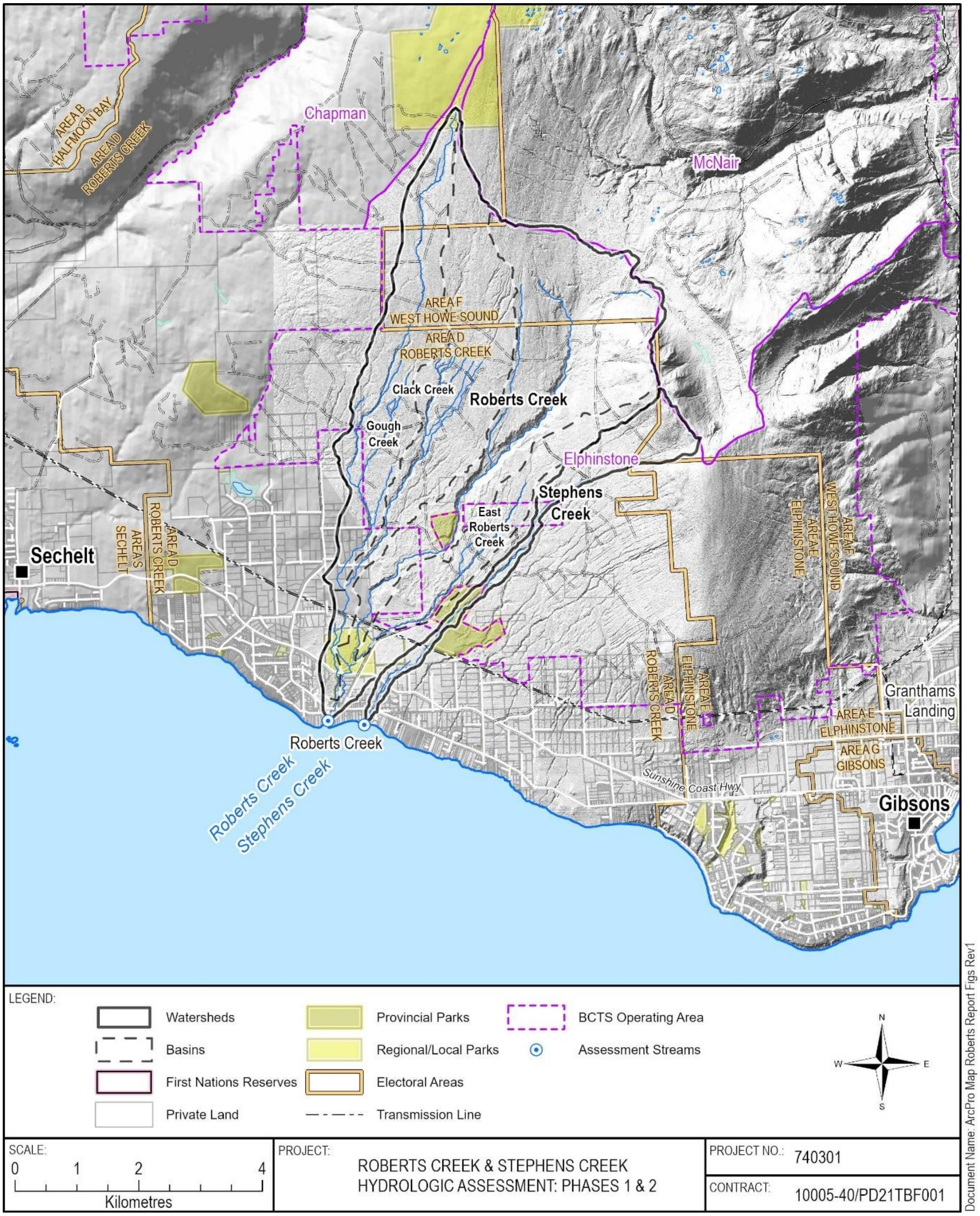

FIGURE 1.1 *Location of the assessment area comprised of the Roberts Creek and Stephens Creek watersheds near Roberts Creek, BC. Refer to MAP 1 for additional detail.*

The general approach and the specific tasks completed to achieve the study objectives are outlined in Section 2. The approach aligns with BCTS *Watershed Risk Management Framework (WRMF)* (Polar, 2022). The WRMF was developed to meet the current standards of professional practice as outlined in the *Joint Professional Practices Guidelines: Watershed Assessment and Management of Hydrologic and Geomorphic Risk in the Forest Sector* (Engineers and Geoscientists British Columbia and Association of British Columbia Forest Professionals, 2020). These guidelines govern watershed assessments and management in BC through the *Forest and Range Practices Act*, the *Private Managed Forest Land Act*, the *Lands Act*, *Professional Governance Act* as well as bylaws of the Engineers and Geoscientists British Columbia (EGBC) and the Association of BC Forestry Professionals (ABCFP).

Under the *Joint Professional Practice Guidelines*, this report consists of watershed assessments of Roberts Creek and Stephens Creek watersheds. These watersheds fall within an urban-interface area with known surface and groundwater users along the lower slopes (FIGURE 1.1, MAP 1). As a result, the assessment considered potential forest development effects on both surface water and groundwater resources in the assessment area. However, this overview assessment is not a detailed groundwater investigation.

1.2. PLANNED DEVELOPMENT

BCTS is currently drafting plans for forest development in the assessment watersheds. These plans have not been confirmed and are contingent in part on the findings of this assessment. As such, analysis of hazards and risks associated with specific blocks or roads is beyond the scope of this report.

1.3. ASSESSMENT TEAM

The contract for this assessment was managed by Pierre Aubin, RPF, Practices Forester of BCTS TCH (Powell River) and Tom Johnson, RPF, former Woodlands Manager of BCTS TCH (Chilliwack). Key members of the technical team included:

- Lars Uunila, MSc, PGeo, PGeol, PH, CPESC, CAN-CISEC, BC-CESCL (Senior Hydrologist & Geoscientist of Polar) served as Project Manager and Lead Author;
- Robbie Johnson, MASc, GIT (Hydrologist of Polar) served as Project Hydrologist and Contributing Author;
- Hunter Rigatti, BSc (Hydrologist of Polar) served as contributing author and provided analytical support;
- Derek Brzoza, AScT (Senior Hydrologic Technician) served as Field Technician;

- Russell Thorsteinsson, RPF of Forsite Consultants Ltd.[3] served as Field Technician;
- Jeremy Hachey, RPF (Forest Analyst of Forsite Consultants Ltd.) provided spatial data analysis and supported the operational-level hydrologic recovery modelling; and
- Dr. William Floyd, PhD, RPF, Research Hydrologist for the Coast Area Research Section, BC Ministry of Forestry and Adjunct Professor, Vancouver Island University served as an independent Advisor and External Reviewer of the assessment report.

All comments from reviews are greatly appreciated and were taken into consideration in preparation of this report. However, all analyses and conclusions remain the sole responsibility of the authors.

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[3] Currently with the Canadian Forest Service.

2. RISK ASSESSMENT METHODOLOGY

2.1. Risk Assessment Framework

This section highlights the key components of the assessment. Watershed assessments generally characterize a watershed, identify past impacts (both natural and development-related), current condition (i.e., sensitivity), and any drivers of its future state (e.g., climate or land use change). Within this context, the first two steps of a risk assessment are performed to understand the potential impacts of forest development. Risk assessment refers to the overall step-by-step process of: 1) risk identification, 2) risk analysis, and 3) risk evaluation.

In the first step, risk identification, potential sources of risk and their consequences are identified and characterized. During the second step, the level of risk associated with one or more watershed processes or events is described either qualitatively or quantitatively based on an evaluation of the likelihood of occurrence and the severity of the consequences. The third step of a risk assessment is the responsibility of forest managers (i.e., BCTS forest professionals) and involves risk evaluation. In this step, the results of the risk analysis are compared against the organization’s risk tolerance criteria. This step weighs the anticipated outcomes of forest development against the identified risks, and risk treatment measures available, to determine if they are acceptable, tolerable, or unacceptable.

2.2. Risk Analysis

Since 2020, a standardized approach has been mandated for assessing hydrologic and geomorphic risks in watersheds in BC (Engineers and Geoscientists BC and ABCFP, 2020). The methodology and terminology used in this report are consistent with Engineers and Geoscientists BC and ABCFP (2020). As outlined by Engineers and Geoscientists BC and ABCFP (2020), the term “risk” is defined as *the chance of injury or loss, expressed as a combination of the consequence of an event and the associated likelihood of occurrence*. In this case, an “event” may be a hydrologic or geomorphic (i.e., hydrogeomorphic) process such as a landslide, debris flow, debris flood or flood, that has a potential for causing harm in terms of human injury, damage to property, the environment, quality of life, or other value. A harmful event may also be associated with watershed processes that result in an insufficient water supply or degradation in quality of water relied upon by humans and/or aquatic organisms.

Consequence refers to the likelihood of damage or losses to some value in the event of a specific hazardous event. Consequences can be expressed qualitatively (i.e., using a defined rating scheme) or quantitatively (e.g., by estimating the cost of damage). Analysis of consequence includes evaluation of the spatial and temporal exposure (i.e., is the element at a location and at a time when it could be affected by the hazard?) as well as the vulnerability of the value deemed to be at risk (i.e., element-at-risk).

The general risk framework adopted from Wise et al. (2004) is summarized as:

R(S) = P(H) x [P(S:H) x P(T:S)] x V(L:T) [Equation 2.1]

Where:

R(S) = Specific risk to a specific element from a specific event.

P(H) = P(Hazardous Event) = probability of occurrence of a specific event and that event being a hazard to a specific element.

[P(S:H) x P(T:S)] = probability of the specific event reaching or otherwise affecting the specific element, where:

> **P(S:H)** = probability of a spatial effect of the specific event on the specific element if the event occurs (e.g., the probability of the specific landslide reaching or otherwise affecting the specific element at risk).
>
> **P(T:S)** = probability of temporal effect of the specific event on the specific element, given a spatial effect (e.g., the probability of the specific element occupying that location when the landslide occurs).
>
> **V(L:T)** = vulnerability of the element, given a temporal effect. This accounts for the probability of loss of life or the proportion of loss, or damage to, property, the environment or other things of value.

Based on the information requirements of BCTS, this hydrologic assessment utilizes a qualitative partial risk[4] analysis approach. Partial Risk Analysis considers the effects of a specific hazard on a specific element, but it does not explicitly evaluate the vulnerability of the element **[V(L:T)]**. Such an evaluation is beyond the scope of this assessment, and requires obtaining detailed information on the elements at risk. Therefore, we have conservatively assumed that **V(L:T)** = 1, meaning that if an element is affected by an event, total loss will occur. The Partial Risk Analysis is summarized by Equation 2.2.

P(HA) = P(H) x [P(S:H) x P(T:S)] [Equation 2.2]

Where:

P(HA) = P(Hazardous and Affecting Event) = probability of occurrence of a specific hazardous event and that event affecting a specific element.

For a stationary specific element at risk, **P(T:S)** = 1, therefore **[P(S:H) x P(T:S)] = P(S:H)**. If it is certain a specific event will reach or affect a stationary specific element at risk, then **[P(S:H) x P(T:S)]** = 1, and Equation 2.2 is reduced to **P(HA) = P(H)**. In this case, Equation 2.1 is also reduced to **R(S) = P(HA) = P(H)**.

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[4] Partial risk refers to the likelihood of occurrence of a hazardous event and the likelihood of it affecting the site occupied by a specific element. Partial risk analysis is often used when it is sufficient to know whether or not a hazardous event or change to watershed process will reach or affect a watershed value. The extent of harm to the value of interest (i.e., vulnerability) is not investigated. A partial risk analysis is often the first level of investigation by a Specialist since the vulnerability of specific values (e.g., water supply infrastructure, fish and fish habitat, etc.) often requires assessments by other Specialists (e.g., engineers, biologists, foresters, etc.) who tend to have greater knowledge of the elements-at-risk.

However, in the case where there is some uncertainty that a specific event will reach or affect a specific stationary element at risk, P(S:H) < 1. Therefore Equation 2.2 is reduced to:

$$\mathbf{R(S) = P(HA) = P(H) \times P(S{:}H)} \qquad \text{[Equation 2.3]}$$

Since all elements at risk in this study are associated with the stream network (which is stationary), we have assumed throughout the risk analysis that P(T:S) = 1. Therefore, P(HA) and R(S) were evaluated based Equation 2.3 and assigned relative ratings that vary depending on the element at risk. Furthermore, the following scenarios are normally considered: 1) the current state; 2) the projected future state due to climate change; 3) the projected future state following forest development; and 4) the projected future state due to climate change and future forest development[5]. In this case, without block-specific harvest plans the latter two scenarios are not explicitly assessed; nevertheless, an effort is made to provide context on the anticipated risks under these scenarios (i.e., describe under what circumstances risks may increase or decrease).

The likelihood of hazard occurrence under each scenario is assigned qualitative ratings from very low to very high (TABLE 2.1). These ratings are associated with expected annual probabilities of occurrence, Pa (i.e., likelihood of hazard in a single year), or probabilities over a given period, Px[6]. For this assessment, the range in probabilities assigned to each hazard rating is based on the BCTS Watershed Risk Management Framework (Polar, 2022). It is the responsibility of the forest manager (i.e., BCTS) to understand and accept the rating definitions used herein as they are not set by any regulatory or professional body.

The level of risk under each of the scenarios noted above takes into account the likelihood of hazard occurrence and the likelihood of it affecting the location occupied by a specific element-at-risk. The latter is ranked qualitatively as:

- **High**: it is probable that the hazard will adversely affect the element-at-risk;
- **Moderate**: it is possible that the hazard will adversely affect the element-at-risk; or
- **Low**: it is unlikely that the hazard will adversely affect the element-at-risk.

For each hazard, risks are assigned based on the qualitative partial risk matrix presented in TABLE 2.2.

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[5] In each case, the potential reduction in risk as a result of the implementation of control measures or other hazard mitigation is also considered.

[6] The probability of occurrence over a specified number of years (Px) is based on (Wise et al., 2004) as follows:

$Px = 1 – (1-Pa)^x$

where,

Px = Probability of at least one event over the specified number of years

Pa = Annual probability of occurrence

x = Number of years

TABLE 2.1 *Definitions used for likelihood of hazard occurrence (from Polar, 2022).*

Rating for likelihood of hazard occurrence	**Description**	**Range of annual probabilities of occurrence, Pa**		**Range of probabilities of occurrence over a 10-year period, P_{10}**		**Range of probabilities of occurrence over a 20-year period, P_{20}**	
		(decimal)	**(%)**	**(decimal)**	**(%)**	**(decimal)**	**(%)**
Very high	**Imminent**, the event or sustained change to the watershed process would almost certainly occur.	>0.10	>10%	>0.65	>65%	>0.88	>88%
High	**Likely**; the event or sustained change to watershed process will probably occur.	0.01-0.10	1.0%-10%	0.096-0.65	9.6%-65%	0.18-0.88	18%-88%
Moderate	**Possible**; the event or sustained change to watershed process could occur.	0.001-0.01	0.10%-1.0%	0.010-0.096	1.0%-9.6%	0.02-0.18	2.0%-18%
Low	**Unlikely**; the event or sustained change to watershed process might occur.	0.0002-0.001	0.02%-0.10%	0.002-0.01	0.20%-1.0%	0.004-0.02	0.40%-2.0%
Very low	**Remote**, the event or sustained change to watershed process is only a remote possibility.	<0.0002	<0.02%	<0.002	<0.20%	<0.004	<0.40%

TABLE 2.2 *Qualitative partial risk matrix.*

		Likelihood of hazard occurrence				
	Partial Risk ↘	**Very high**	**High**	**Moderate**	**Low**	**Very low**
Likelihood of hazard affecting the location occupied by a specific element-at-risk	**High**	Very high	Very high	High	Moderate	Low
	Moderate	Very high	High	Moderate	Low	Very low
	Low	High	Moderate	Low	Very Low	Very low

As a last step, the potential reduction in partial risk following implementation of risk control measures is evaluated and reported.

2.3. KEY TASKS

This watershed assessment combines an office-review with the findings of ground-based reviews. In Phase 1, the key objectives were to:

1. Identify the principal streams and their respective catchments (i.e., the assessment watersheds) where forest development is being considered;
2. Characterize the assessment watersheds;
3. Identify watershed values along each main stream in the assessment area (i.e., potential elements-at-risk);
4. Identify potential hydrogeomorphic risks[7] posed by future forest development in the assessment area;
5. Provide preliminary recommendations to BCTS to avoid, minimize or mitigate hazards and risks during the forest development planning process.

In order to meet the Phase 1 objectives, the following tasks were conducted:

1. Compilation and review of background reports and information. This included, but was not limited to, the following consulting reports: Madrone (2012), Statlu (2020), FPB (2006), and Hudson (2001);
2. Compilation and review of GIS/mapping information, including high-resolution LiDAR data[8], which was used to characterize the topography, identify streams, refine drainage areas[9] and estimate tree heights.
3. Operational-level (i.e., detailed) hydrologic recovery (i.e., ECA) modelling. Based on recommendations from Dr. William Floyd, PhD, Research Hydrologist for the Coast area Research Section within the BC Ministry of Forestry, ECAs were calculated using an adapted approach from Hudson and Horel (2007) (Floyd, pers comm., 2023). Rather than stratifying the assessment area into elevation bands based on the dominant runoff-generating process, as proposed in Hudson and Horel (2007), Dr. Floyd suggests applying a single rain-on-snow hydrologic recovery curve across all elevations. The rationale being that rain-on-snow can occur across all elevations, forest cover removal has the greatest impact on melt when

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[7] An evaluation of water quality parameters such as Nitrate, Phosphorous or pH levels was considered beyond the scope of this assessment.

[8] LiDAR data for the assessment area was sourced from the Province of BC and Sunshine Coast Regional District (SCRD).

[9] Stream alignments and drainage areas presented on legacy base mapping were inaccurate in several locations and are a potential source of confusion when referencing previous studies.

compared to rain only and radiations driven melt, and rain-on-snow is often responsible for producing some of the largest peak flows. As such, mitigating the potential effect of forest harvest on peak flows should be targeted towards mitigating effects on the dominant ***flood***-generating process rather than the dominant ***runoff***-generating process. ECAs were calculated for overall watershed area (i.e., at the mouth of both Roberts and Stephens Creeks), as well as above key points-of-interest (POIs) within the Roberts Creek Watershed[10]. The principal inputs to the ECA model are median forest canopy heights projected on an annual basis for 2021-2071 (i.e., 50 years) using provincial tree growth modelling (i.e., SiteTools). The data used in the analysis, and ECA assumptions and methodology are provided in APPENDIX B.

4. Review of available digital imagery including 2018 Sunshine Coast Regional District Orthophotos, 2019 Planet Labs (Blackbridge) imagery, GoogleEarth and satellite imagery of various years to 2022;
5. Review of available historical air photos obtained from the UBC Air Photo Library, including the years 1947, 1957, 1964, 1967, 1976, 1982, 1990, 1994, 1998, 2003 and 2005 (TABLE 2.3).
6. Ground-based review on August 25, 2020 was performed by Lars Uunila and Derek Brzoza of Polar. The Phase 1 review covered Crown land and publicly accessible areas in the assessment watersheds (FIGURE 2.1)[11] [12] [13]; and
7. Synthesis of information collected during Phase 1.

Phase 2 was initiated in Summer 2021. The goals of Phase 2 were to confirm stream channel conditions and evaluate the elements-at-risk. The key tasks in Phase 2 included:

1. Identification of property owners downstream of BCTS chart area in the assessment watersheds, including those who hold water rights on the assessment streams;
2. Field review was performed on July 16, 2021 and again on August 6, 2021 by Lars Uunila and Russell Thorsteinsson, RPF of Forsite Consultants Ltd., (FIGURE 2.1). A fourth field review was conducted on August 8, 2022 by Lars Uunila and Robbie Johnson of Polar, as well as Gino

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[10] These points of interest included the confluences of main tributaries (i.e., Clack/Roberts, Gough/Clack, East Roberts/Roberts) and where the main streams flow out of BCTS Chart Area (i.e., Roberts, Gough, and Clack). The exceptions to this include Stephens Creek, which is only reported at the mouth (given its size), and East Roberts Creek, which is only reported at its mouth, given it is very close to the BCTS Chart Area boundary.

[11] Although most roads were observed during the field reviews, a formal road risk evaluation, such as the FREP WQEE, was not conducted and sediment yield from roads was evaluated at an overview-level.

[12] For the purposes of this assessment, a high-level overview of riparian function was conducted to evaluate the current riparian condition and its effect on sediment yield and channel stability. This included reviews of historical air photos and other imagery, as well as ground-based reviews at selected locations along the streams.

[13] Similar to the assessment of riparian function, channel stability was also assessed at an overview level during the field review.

Amato, RFT and Pierre Aubin, RPF of BC Timber Sales – Chinook Business Area. The Phase 2 review focused on reviewing stream conditions and elements-at-risk along the lower portions of the assessment streams. APPENDIX D in Volume 2 provides a catalogue of photographs along the assessment streams.

3. Synthesis of information collected during Phase 2; and
4. Preparation of the Phase 1 and 2 report.

TABLE 2.3 *List of historical air photos reviewed by year (roughly organized north to south and west to east)*[14]*:*

Year	Flight Line	Photos
1947	BC349	112-110
	BC349	96-102
	BC349	11-7
1957	BC2392	21-19
	BC2392	98-103
	BC2393	21-14
	BC2099	59-50
	BC2099	21-29
1964	BC5102	74-76
	BC5102	37-32
	BC5102	26-29
1967	BC4426	247-249
	BC4427	42-47
	BC4427	63-57
	BC4427	73-79
	BC4427	265-260
	BC4427	88-86
1976	BC5758	270-268
	BC5758	256-259
	BC5758	237-233
	BC5758	222-227
	BC5758	219-217
1982	BC82003	86-88
	BC82003	93-91
	BC82003	55-59
	BC82003	14-10
	BC82002	242-248
	BC82002	237-231
	BC82002	216-218
1990	BCB90014	149-150
	BCB90014	173-170
	BCB90014	212-217
	BCB90014	236-230
	BCB90045	13-6
	BCB90045	42-35
	BCB90045	46-48
1994	BCC94151	47-50
	BCC94151	17-10
	BCC94145	130-138
	BCC94145	102-91
	BCC94145	67-79
	BCC94145	43-32
	BCC94145	11-22
1998	BCB98008	190-191
	BCB98008	209-205
	BCB98008	225-230
	BCB98007	223-229
	BCB98007	246-239
	BCB98008	245-240
	BCB98007	252-254
2003 & 2005	BCC03039	70-68
	BCC03039	20-25
	BCC05026	156-150
	BCC05026	178-185
	BCC05143	181-174
	BCC05143	182-185

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[14] Historical air photo review of the assessment area was conducted in conjunction with the review of the Mt. Elphinstone South assessment area (Polar, 2023a). As such, many of the photos listed above are beyond Roberts Creek.

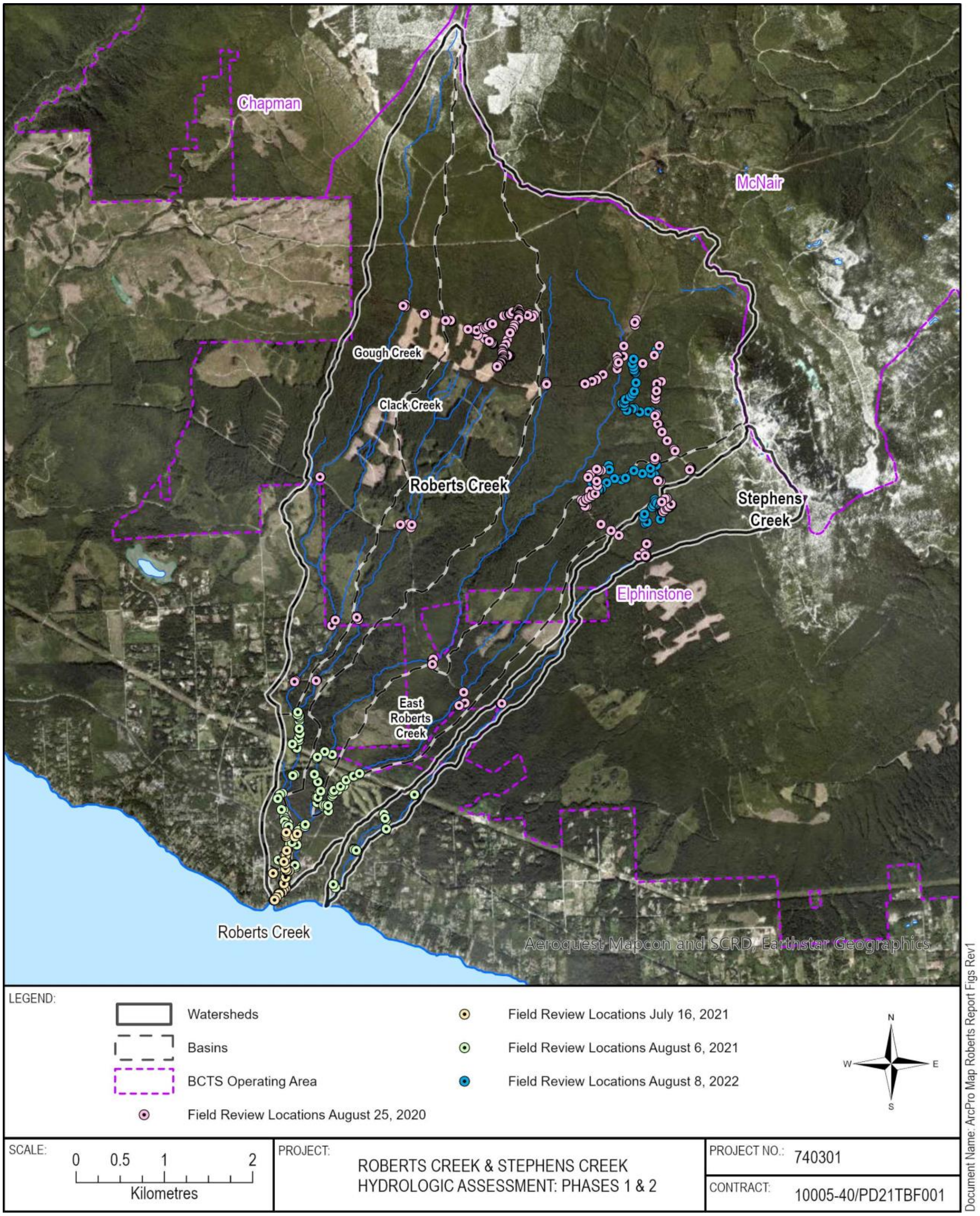

FIGURE 2.1 *Locations reviewed during the Phase 1 field review on August 25, 2020 and Phase 2 field review on July 16, 2021, August 6, 2021 and August 8, 2022.*

3. OVERVIEW OF HAZARDS

As noted above, hydrogeomorphic hazards may be associated with sustained changes to watershed processes or conditions (Green, 2005). However, these do not in themselves present risks until they are identified as having the potential to harm specific value(s). The watershed processes or characteristics typically of concern are outlined below. The following section is intended as background on the types of hydrogeomorphic hazards that are typically reviewed in watershed assessments. Details on the current state of the science on these topics are provided. This information was originally presented in Polar (2023a) and is in large part based on literature from the Pacific Northwest that is applicable to the assessment area.

3.1. STREAMFLOW REGIME

The collective timing and volume of water that flows in a stream is considered its flow regime. Changes to a stream's flow regime can affect downstream ecosystems, private land, and infrastructure that is vulnerable to damage from floods or high water (Poff et al., 1997; PCIC, 2017). Stream systems in British Columbia are often broadly classified into pluvial[15], nival[16], or hybrid[17] hydrological regimes (Trubilowicz and Moore, 2017; Winkler et al., 2010b).

In assessing the streamflow regime, the focus is on identifying the likelihood and/or degree to which the baseline (or, pre-disturbance) hydrologic regime[18] (e.g., peak flow and/or low flow magnitude and frequency) has changed in response to watershed disturbance (e.g., timber harvesting, road building and/or other land use) and climate change. Increases in peak flow magnitude and/or frequency, for example, can affect channel stability and channel destabilization can in turn result in increased sediment impacts, which may affect downstream elements-at-risk (depending on the sensitivity of those elements).

Runoff Generation Potential (RGP)

The potential for a change in the streamflow regime is derived through consideration of runoff generation potential (RGP). Runoff generation potential (RGP), also referred to as flood response

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[15] Pluvial refers to rainfall-dominated streamflow typical of lower elevation coastal watersheds.

[16] Nival refers to snowmelt-dominated streamflow typical of coastal high elevation or interior watersheds that are snow-covered for much of the winter.

[17] Hybrid refers to a mixed system where both rainstorm and snowmelt process regularly affect peak flows, which can occur throughout the winter or spring.

[18] The baseline (or pre-disturbance) hydrologic regime refers to conditions under mature/old growth forest. It may include projected effects of climate change if long-term risks are being analyzed.

potential (Green, 2005), describes the propensity by which precipitation and/or snowmelt are converted to surface runoff and ultimately streamflow within a given spatial area of interest (i.e., drainage area or catchment). A high runoff generation potential corresponds to a relatively rapid runoff generation, whereas a low runoff generation potential corresponds to relatively lower rates of runoff generation. Physical characteristics that affect runoff generation include, but are not limited to, vegetation (e.g., forest type), soil type, geology, stream density, presence of lakes and wetlands, surface water and groundwater interaction, and physiography.

Meteorological factors affecting RGP include the type of precipitation; rainfall/snowmelt intensity, amount and duration; distribution of rainfall over the stream catchment, antecedent precipitation (as rain and as snow stored on the ground), and melt factors such as wind, humidity, radiation and temperature, and other conditions that affect evapotranspiration such as temperature, wind, relative humidity and season.

In coastal watersheds, such as the assessment area, the mechanism of runoff generation varies by elevation. In general, rainfall is the dominant runoff mechanism at lower elevations; however, rainfall can occur across all elevations. A transient snow zone exists at mid-elevations (i.e., from approximately 300 to 1,200 m) where snow is limited in extent and may melt more than once each winter. In this zone, runoff is typically generated either from rain or from rain-on-snow. Above approximately 1,200 m the snowpack is seasonal, where snow accumulation and melt are the dominant hydrologic process, although rain-on-snow can still occur. However, there are effectively no areas above 1,200 m in the assessment area. In terms of peak flows, rain-on-snow is considered the dominant peak flow generation mechanism in the assessment area. This is in large part due to the possibility for rain to occur across all elevations, and for snow to be present, on occasion, down to sea level. Rain-on-snow events typically occur when rain falls on a snowpack that is at or near isothermal[19]. Rainfall, wind and turbulence bring energy to the snowpack, increasing the melt-rate which can result in large volumes of meltwater and consequently significant runoff (Harr, 1986). These events are often responsible for producing some of the largest peak flows. Assuming the presence of a snowpack, rain-on-snow runoff is often most severe when warm temperatures, strong winds, and intense rainfall, potentially associated with an atmospheric river (AR), coincide. As elevation increases, there is a greater probability there will be snow on the ground when it rains. Further, areas without trees will often have melt rates two to three times more intense than in forested areas, due largely to exposure to higher turbulent fluxes associated with wind (Marks et al., 1998).

The frequency and nature of meteorological factors affecting RGP have been and are expected to continue changing as anthropogenic greenhouse gas emissions change our climate (PCIC, 2013; Schnorbus et al., 2014; BC MOE, 2016). In general, the climate along the southern coast of British

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[19] Isothermal snowpack refers to a snowpack that is the same temperature, usually 0°C, throughout.

Columbia is predicted to become warmer, with wetter winters and drier summers (PCIC, 2013; Section 4.7.2). With warmer temperatures, less precipitation is expected to fall as snow whereby coastal hybrid hydrologic regimes are predicted to transition towards rain dominated regimes (Schnorbus et al., 2014). However, given the high variability in weather, rain-on-snow events are still expected to occur under future climate scenarios, potentially generating large peak flow events (Schnorbus et al., 2014; Floyd, pers comm., 2023).

Physiographic factors that influence RGP include slope aspect, slope gradient and elevation. While elevation is generally a factor in snow accumulation and the volume of water available for runoff, the energy balance at the stand level influences the rate of snowmelt contributions to runoff. Hillslope gradient and hillslope aspect, collectively known as topographic exposure, are important factors controlling insolation (i.e., solar radiation at the ground surface) and thus net radiation available for snowmelt. In general, for snowmelt-dominated regimes, south aspects are more likely to see earlier and more rapid snowmelt (and runoff) than north aspects. Differences in solar radiation across aspect plays a lesser role in snowmelt during rain-on-snow events; however, given the typically deeper and longer lasting snowpack on northern aspects[20], there is an increased probability for rain-on-snow on north-facing slopes. Topographic exposure does, however, play an important role during rain-on-snow events in controlling wind and wind-driven rain, whereby more rapid snowmelt rates can be expected on windward aspects (Guthrie et al., 2010).

There are many processes and events that can affect the water balance at the site-level and the flow regime at the watershed-level. The presence of forests controls several hydrological processes. The forest canopy intercepts a portion of rain or snow preventing it from reaching the ground. Some of this intercepted precipitation may evaporate or sublimate depending on weather and atmospheric conditions (e.g., temperature, solar radiation, humidity and wind speed). The canopy also can decrease or smooth the intensity of rainfall when compared to open areas (Keim and Skaugset, 2003; Keim et al, 2004).

Given the moist climate (i.e., high humidity) of the assessment area, intercepted snow losses via sublimation are expected to be minimal, whereas meltwater drip[21] from the canopy to the forest floor may be considerable (Storck et al., 2002; Bonner et al., 2022). This is particularly the case at low and mid-elevations when winter temperatures are often near freezing (0 ˚C +/-). If a snowpack is present beneath the canopy, meltwater drip is incorporated into the snowpack, transferring advective heat to the snowpack. In some instances, especially when a snowpack is isothermal, meltwater drip flows preferentially through the snowpack, and infiltrates into the soil (Bründl, et al., 1999). In addition to rain and snow, the forest canopy can intercept fog, which condenses on branches and foliage, and a

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[20] This issue is not widespread in the assessment area given the absence of north aspects.

[21] Meltwater drip refers to water that melts from snow intercepted by the tree canopy and drips down from the canopy or flows down the stem to the ground or snowpack below.

portion of which drips down to the snowpack or soil below. Fog interception and subsequent drip can be an additional moisture input to the soil or snowpack in forested stands relative to unforested stands (Harr, 1982; Jones and Grant, 1996).

If the precipitation is in the form of snow, once it reaches the ground, it may accumulate, sublimate to the atmosphere, or melt. Meltwater and precipitation in the form of rain that reaches the ground may evaporate near the soil surface or be drawn up through the soil by trees and vegetation to be subsequently released through transpiration. The collective process of evaporation and transpiration is termed evapotranspiration (ET). The remaining liquid water may infiltrate into the soil depending on antecedent soil moisture conditions, with any excess water moving downslope through surficial soils as shallow groundwater flow, eventually feeding streams or entering a deeper groundwater system. Runoff on the surface of forest floors due to infiltration excess (i.e., Hortonian flow) is rare due to high soil porosity[22], however overland flow can occur when soils become saturated and can be common in certain terrain features and areas with poorly drained soils. Surface runoff can also occur in areas where soils are compacted by heavy equipment (e.g., along roads and trails) (Wondzell and King, 2003); however, such effects generally make up a small proportion of the watershed area and are localized[23].

The effects of forestry on the key hydrological processes and the flow regime of streams have been studied extensively in watersheds in BC, the Pacific Northwest, and elsewhere in North America. While the research results vary, there is general consensus that the removal of forest cover typically increases water available for runoff at the site-level, often resulting in increased annual water yields at the watershed scale. The effect of harvesting on peak and low flows, however, is more nuanced. The following sections provide a brief review on how forest harvesting in areas similar to the assessment watersheds can affect hydrological processes and how these in turn affect peak flows, low flows and aquifer recharge.

When logging occurs in forested watersheds, the hydrological processes (i.e., water balance) at the site-level changes, primarily due to altered interception of rain and snow, changes to ET and altered energy sources for snowmelt. These changes in turn affect both peak flows and low flows downstream. An increased magnitude or frequency of peak flows can affect sediment mobilization, water quality and stream channel stability. Changes in frequency and magnitude of low flows

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[22] Dunnean, or saturation-excess overland flow, can occur when groundwater levels rise to the surface; however, Hortonian, or infiltration-excess overland flow is uncommon on undisturbed forest floors.

[23] It is important to recognize that avoidance of such impacts is a BCTS management objective as stated under Section 4.2.1 (Soils) of BCTS' Forest Stewardship Plan No, 672. https://www.for.gov.bc.ca/ftp/TCH/external/!publish/FSP/PowellR/FSP/FSP%20Extension/BCTS%20SCNRD%20FSP%20672%20-%20Consolidated%20-%2020221021_draft.pdf

(especially during drought) may affect water supplies for human use as well as instream flows and water quality (e.g., water temperature) for fish.

Forest cover disturbance such as logging, insect infestation and wildfire can affect RGP. One metric to assess the impact of disturbance is equivalent clearcut area (ECA)[24]. Land use, including forestry, may affect runoff generation potential by affecting site-level water balance following deforestation or reforestation, by changing drainage patterns and rates of flow through road construction, and by affecting soil permeability along roads or areas trafficked by heavy equipment (i.e., soil compaction). Forestry effects are a function of several factors, including area harvested and recovered (i.e., ECA); size, shape, orientation and spatial distribution of individual forest openings, silvicultural system (e.g., clearcut, selective harvest) and method of harvesting (e.g., ground, cable-based, or air).

When snowmelt is the dominant flood generating process, a greater emphasis is put on the level of disturbance above the snowline. In cases where rain or rain-on-snow is dominant, the overall level of disturbance or level of disturbance within the rain-on-snow or rain zone, respectively, may provide a better indication of RGP.

3.1.1. Effects of Forestry on Peak Flows

Peak flow refers to the maximum rate of discharge during a period of interest. It is of concern since its magnitude, frequency and duration can influence sediment mobilization, water quality (e.g., turbidity) and stream channel stability as well as pose hazards to property and infrastructure (e.g., water intakes and stream crossings). Typically, flows near or above “bankfull flow” are of interest as they are capable of mobilizing coarse-textured bedload (e.g., gravel, cobbles, boulders) along alluvial and semi-alluvial stream channels (Copeland et al., 2000). Bankfull flow usually occurs on average every 1.0 to 2.5 years (Grant et al., 2008), with 1.5 years being the representative average of many streams (Leopold, 1994).

Peak flow hazard refers to the likelihood and/or degree to which the baseline or pre-disturbance peak flow magnitude and frequency has or could change in response to watershed disturbance, specifically forest development (e.g., timber harvesting and road building); however, other land uses or natural disturbances that affect the forest land base are also considered. In simple terms, the peak flow hazard refers to the likelihood that flooding along a particular stream or stream reach will become measurably more severe or frequent under 1) current conditions, and then 2) following forest development or other disturbance, relative to baseline conditions. In the case of the assessment streams, baseline refers

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[24] Equivalent clearcut area (ECA) is a commonly used index of the extent of forest disturbance and regrowth in a watershed (Winkler et al., 2010b). The ECA of a clearcut is derived by reducing the total area cut by recovery, which is estimated from relationships between snow accumulation and melt or precipitation interception and crown closure (Winkler and Roach, 2005) or tree height (Hudson and Horel, 2007). The cumulative ECAs for all openings may be summed to provide an ECA for the entire catchment (Winkler et al., 2010b).

to mature/old growth conditions. Current conditions are not necessarily natural, but rather have been influenced by past forest disturbance in the upper portion of the watersheds and increased urbanization over many years in the lower elevations of the watersheds. Future conditions include the cumulative effects from historical disturbances and potential future development.

The peak flow regime is characterised by the magnitude (i.e., size of peak flows), frequency (i.e., how often peak flows occur), and timing of peak flows (i.e., when peak flows occur) in a given watershed. The relationship between peak flow magnitude and frequency is often expressed in the form of a peak flow frequency curve[25]. These curves are developed by looking at the history of peak flows in a specific area and determining the likelihood that a peak flow of a given size might occur. Peak flows are then ranked based on how they compare in size to other peak flows in the historical record.

Forest disturbances such as harvesting can change the peak flow regime, meaning that the distribution of peak flow magnitudes and frequencies experienced in the past may no longer represent conditions in the future. One approach to determine the effect of forest harvesting on peak flows is to compare peak flow frequency curves from before and after harvesting. Changes to these curves provides insight on how harvesting may affect the peak flow regime.

Green and Alila (2012)[26] proposed that, in snowmelt-dominated catchments, an increase in the average of a peak flow frequency curve represents an increase in the amount of moisture available for runoff. Following forest harvesting, an increase in moisture available for runoff can occur as a result of reduced evapotranspiration and from the conversion of longwave to shortwave-dominated snowmelt. The authors also proposed that the variability around the mean, represents the efficiency by which snowmelt is delivered to streams, with the largest increases in post-treatment peak flow variability occurring where increased snowmelt is most effectively and synchronously delivered to the stream channel (discussed in greater detail below). Alternatively, a decrease in the variability of the peak flow distribution, or in other words a reduction in the range of peak flows, could be caused by snowmelt de-synchronization following forest harvesting (Green and Alila, 2012).

In snow-dominated watersheds, peak flows are dominantly controlled by the amount of snow on the ground, the energy available for melt, rainfall, and antecedent soil moisture conditions (Yu and Alila, 2019). In hybrid regimes, rainfall plays a more important role than snow, however snow can be a significant component of peak flow during rain-on-snow events. In pluvial regimes, peak flows are primarily dependent on rainfall and antecedent soil moisture conditions, however snow can also play a significant role, especially when transient snow packs are present to low elevations. Forest cover

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[25] Flood frequency curves are a graphical representation showing the probability of different flood sizes occurring.

[26] Green and Alila's (2012) study was conducted in a snowmelt-dominated watershed; however, the concepts are considered to be applicable to hybrid streamflow regimes.

removal can influence all of these factors to varying degrees, consequently influencing the timing, magnitude and frequency of peak flow events.

Changes in the energy balance[27] and snowmelt associated with the loss of forest cover has been found to be a dominant process responsible for increased peak flows in watersheds where snowmelt is a principal driver of runoff (Green and Alila, 2012), and may also be a factor in the timing and magnitude of low flows in summer. The change in net radiation following forest cover loss is positively related to the solar radiation received at the stand level. As such, snow depth in forest openings is generally greater than under forests, especially in the late fall and early winter. The removal of trees not only eliminates interception losses through evaporation and sublimation, but also eliminates transpiration losses[28]. Both result in a net increase in the proportion of precipitation (both rain and snow) that reaches the ground surface. Increased precipitation at the ground surface increases the net water available for infiltration[29] and ultimately streamflow at the watershed-scale. Such increases in streamflow can cause an increase in the mean of the peak flow frequency distribution. While this may be undesirable with respect to peak flows, it may be beneficial in increasing streamflow during low flow periods, assuming any net increases in runoff are effectively captured in storage (e.g., groundwater / aquifer storage) and are later released as baseflow.

Given the physical limits of a forest canopy's interception capacity, a smaller proportion of rainfall during a given storm will be intercepted from higher magnitude, intensity, and duration storms relative to storms of smaller magnitude, shorter duration and lower intensity. In other words, during smaller rainfall events, a forest canopy may be able to intercept a majority of the precipitation; however, once a canopy's interception capacity is exceeded, any additional precipitation inputs will reach the ground surface. Similarly, a greater proportion of snowfall can be intercepted during smaller snowstorms, relative to larger storms which exceed a canopies interception capacity. Therefore, the difference in snowpack depth between forested and open sites is expected to be greatest in years that receive little snowfall, and smallest in years that receive higher snowfall amounts (Floyd and Weiler, 2008; Bonner et al., 2022). Although, interception from the forest canopy may have little or no influence on large and extreme precipitation events, this does not necessarily translate to no influence on large peak flow events (described below).

Where precipitation falls as snow, the elimination of the forest canopy may promote a deeper snowpack, which represents an increase in the bulk volume of water available for melt. Snow that

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[27] Loss of forest cover is associated with increases net radiation that is the result of the conversion from longwave-dominated snowmelt beneath the forest canopy to shortwave-dominated snowmelt in harvested areas (Green and Alila, 2012).

[28] These losses are reduced over time as forests are re-established and mature (i.e., hydrologically recover).

[29] Before precipitation can induce infiltration, any saturation deficit must be replenished. Usually, the soil saturation deficit is greatest in early fall and largely disappears after the first fall storms (Madrone, 2015).

accumulates in forest openings is at relatively greater exposure to winds, rainfall and solar radiation than in forested areas, the former factor being important in causing snowmelt during rain-on-snow events (Marks et al., 1998; Marks et al., 2001; Floyd, 2012). Therefore, in hybrid hydrologic regimes, snowpacks are expected to be deeper and snowmelt is expected to be greater in open areas relative to forested areas, particularly those areas subject to wind. In hybrid regimes, meltwater drip from the canopy can be one of the dominant processes responsible for creating large differences in snowpack between forested and open areas (Storck et al., 2002). Intercepted snow in the forest canopy can melt and either increase the energy input to the snowpack or flow into the soil (Bründl, et al., 1999). In a study conducted in southwestern Oregon, researchers found that during conditions conducive to snowmelt, roughly 70% of intercepted snow became meltwater drip, resulting in a reduction in snow accumulation beneath the canopy (Storck et al., 2002). The authors note, however, that the reduction in snowpack caused by meltwater drip does not represent a loss of water from the snow-soil system (Storck et al., 2002). Conversely, in areas that experience fog interception, soils beneath forested areas can receive additional moisture inputs as fog condenses on vegetation and drips down to the soils below (Harr, 1982; Jones and Grant, 1996). Moisture contributions from fog interception can influence the snowpack in a similar fashion as meltwater drip.

The runoff response during rain-on-snow events is highly dependent on antecedent soil and snowpack conditions. If a snowpack is isothermal, additional moisture and energy inputs will be rapidly conveyed as runoff. If a snowpack is not isothermal, additional energy inputs will go towards raising the snowpack's temperature before significant melt occurs. The deeper the snowpack, the more energy required to induce melting (Rong, 2017). In some cases, a deep non-isothermal snowpack can temporarily store additional moisture inputs and reduce runoff (Heggli et al., 2022). As such, the presence of a snowpack can either augment or reduce the runoff response during a precipitation event.

Synchronization of runoff within a catchment is directly related to peak flows, and is strongly associated to catchment-wide RGP and the natural or development-related factors that affect RGP. Synchronization occurs when forest disturbance (e.g., forest harvesting and road construction) alters the rate and timing of snowmelt or storm runoff at different locations within a watershed so that there is an increase in the amount of water that is conveyed to a stream over a given period. In a probabilistic framework, this translates to an increase in the variability of the peak flow frequency distribution. The synchronization of hydrological processes is commonly attributed to increases in the magnitude of peaks flows (Schnorbus and Alila, 2004; Moore and Wondzell, 2005). Synchronization of runoff during rain or rain-on-snow events is common in coastal BC when entire catchments are at or are approaching saturation, whereby, the entire catchment area is simultaneously producing runoff. Synchronization of snowmelt typically only occurs at higher elevations in coastal BC. In hybrid hydrologic regimes, differences in runoff between forested and unforested stands are primarily a result of differences in snowpack conditions (e.g., depth and density), energy available for melt (largely from wind), and rainfall interception (Harr, 1986; Rong, 2017). At the watershed-scale, differences in snowpack conditions between forested and unforested areas of the watershed have the potential to desynchronize runoff response (Rong, 2017).

Previous reviews have found that logging can increase the magnitude and frequency of peak flows in pluvial, nival, or hybrid hydrological regimes, albeit with a high amount of variability (Hudson, 2001; Whitaker et al., 2002, Schnorbus and Alila, 2004; Moore and Wondzell, 2005; Alila et al., 2009; Winkler et al., 2010b; Winkler et al., 2015; Stednick and Troendle, 2016; Winkler et al., 2017). Studies evaluating how forest cover removal affects peak flows on a single event basis (e.g., evaluating the effects for a single rain storm or snowmelt event) have generally concluded that forest cover removal can affect smaller peak flows, but has little to no effect on large or extreme peak flow events (Bathurst et al., 2020; Moore and Scott, 2005). Frequency-based studies[30] in snow-dominated watersheds, on the other hand, suggest by comparing pre- and post-harvest flood frequency curves, that removal of forest cover can affect floods of all magnitudes and frequencies (Alila et al., 2009; Green and Alila, 2012; Yu and Alila, 2019). Green and Alila (2012) found that harvesting 33-40% of catchments ranging in size from 3 to 37 km^2 caused 20-year return period peak flow events to double in frequency and larger 50-year events to become 2- to 4-times more frequent. Yu and Alila (2019) evaluated the effect of harvesting on peak flows in the Camp Creek watershed in interior BC. They found that at 24% ECA, peak flow magnitudes associated with the 2- to 100-year return period events increased by 31% to 10%, respectively. Such an increase in magnitude translates to an increase in frequency of three to four times. However, the frequency-based studies discussed above were conducted in purely snowmelt-driven hydrologic regimes. Since the hydrological regime of the assessment area is rain-dominated and hybrid, these findings are less certain apply, but nevertheless should be assumed particularly under rain-on-snow conditions.

The master's research of Rong (2017) evaluated the effect of forest harvesting on floods across three study sites in the Pacific Northwest (Coyote Creek, Fox Creek, and the H.J. Andrews Experimental Forest) using a frequency-based approach. Similar to nival hydrologic regimes, Rong (2017) found that harvesting in rain-on-snow (i.e., hybrid) hydrologic regimes can increase both small and large peak flows; however, there was considerable variability between watersheds and study sites. Increases in peak flow means and variability around the mean varied from 9% to 86% and 3% to 154%, respectively, for catchments subject to 100% clear-cut. Catchments subject to 25% to 30% harvest experienced smaller increases in the mean (5% to 35%) and the variability around the mean either increased or decreased (-9% to 52%). The range in responses was attributed to differences in watershed characteristics, where lower relief catchments with drier and warmer climates were considered more sensitive to forest harvesting.

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[30] Frequency-based studies evaluate how forest harvesting has affected the frequency of a flood event of a given magnitude, or conversely, how harvesting has affected the magnitude of a flood event of a given frequency. Rather than pairing events by equal storm input, as is done in conventional paired watershed studies, floods are paired by equal frequency.

Jones (2000) evaluated the effect of forest harvest on peak flows in the HJ Andrews Experimental Watershed in Oregon. The five Andrews study catchments ranged in size from 13 ha to 101 ha and were subject to either 100% clearcut[31], 50% selection cut, or 25% patch cut. The authors reported an increase for winter rain-on-snow peak flows of 31% for Andrews 1 (100% clearcut, no roads), 26% for Andrews 3 (25% patch-cut with roads), 26% for Andrews 6 (100% clearcut, roads), 30% for Andrews 7 (50% selection cut, no roads), and no change for Andrews 10 (100% clearcut, no roads). These results emphasize the high variability in response to rain-on-snow events.

Grant et al. (2008) conducted a state-of-the-science synthesis on the effects of forest harvesting on peak flows in the Pacific Northwest, by compiling and evaluating the results from a number of relevant studies in the area. They found the effect of harvesting in the rain-on-snow (i.e., transient snow) zone was detectable when forest harvest exceeded approximately 20% of the catchment area. Peak flow risks in purely snowmelt regimes are also generally considered low when less than 20% of the catchment area is subject to clearcut (Winkler et al., 2010). As such, 20% ECA is often considered a threshold beyond which increases in peak flows can generally be detected. In the synthesis of Grant et al. (2008), harvest effects could only be detected in rain-dominated zones when harvest on average exceeded 46% of the catchment area. Chapman's (2003) review of rainstorm-driven peak flows in seven watersheds on Vancouver Island suggests that logging effects in rain-dominated watersheds on the south coast of BC are small because rainstorm-driven floods in the region are often a combination of long-duration rainfall followed by intense storms that overwhelms any potential water reduction that might be due to canopy interception and evaporation[32].

It is important to recognize that the work of Jones (2000), Chapman (2003), and studies synthesized by Grant et al. (2008) did not evaluate how the frequency distribution of peak flows was affected by forest harvesting. Moreover, these studies, in large part, evaluated the effect of forest harvesting on peak flows by applying an analysis of variance or analysis of covariance, which are statistical approaches designed for analyzing means (i.e., averages) and not extremes (i.e., peak flows). There have since been calls to abandon this approach to evaluate the effect of forest harvesting on peak flows (Alila et al., 2009).

Alila and Green (2014) propose in their comment on Birkinshaw (2014) that larger and more frequent floods can be expected with logging even in rain-dominated watersheds. They propose that following the removal of forest cover, the likelihood of saturated antecedent soil conditions due to reduced evapotranspiration is increased. Under such conditions, even medium-sized rainstorms have the potential to trigger relatively large floods. This was demonstrated by Kim et al. (2019), who found that

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[31] This extreme level of harvest across an entire catchment is an exception and uncommon in practice in BC.

[32] This concept does not apply to rain-on-snow events. Chapman's (2003) analysis did not distinguish between rain-only and rain-on-snow events.

a 7-year precipitation event falling on saturated soils could generate a 100-year flood, whereas a 200-year precipitation event falling on unsaturated soils may only result in a 15-year flood event. This same concept can be extended to watersheds that experience rain-on-snow, whereby forest openings (i.e., logged areas) generally have more snow on the ground and melt faster than under forested conditions (Storck, et al., 2002), particularly when subject to high winds (Floyd, 2012). As such, there is an increased likelihood that medium sized rainstorms falling on deeper snowpacks in forest openings could result in an increased frequency of large flood events.

Beckers et al. (2002) developed normalised flood frequency curves for different climate regions and watershed sizes within British Columbia. They found that the drier, Thompson Plateau region was generally characterised by steep flood frequency curves, whereas the southern Rocky Mountains and coastal regions were characterised by shallower sloping curves. Moreover, smaller watersheds had steeper sloping curves relative to larger watersheds. As discussed above, the slope of the flood frequency curve is thought to represent the efficiency by which moisture is delivered to the outlet, whereby watersheds with steeper sloping flood frequency curves deliver water more efficiently (Green and Alila. 2012). Johnson and Alila (2023), evaluated the effect of forest harvesting on floods in two snow dominated watersheds in interior British Columbia. They found that the larger of the two watersheds was more sensitive to changes in frequency following forest development, given its shallower sloping flood frequency curve.

Of the study watersheds evaluated by Rong (2017), the two Fox Creek treatment watersheds, which experienced 25% harvest with roads, were found to be the most sensitive in terms of changes in frequency following forest development. The heightened sensitivity was attributed to the relative low variability of their respective peak flow frequency curves. Although the peak flow variability was not reported for both treatment watersheds, Rong (2017) reported a coefficient of variability of 0.38 for the Fox Creek control watershed. For comparison, the coefficient of variability of peak flows at Roberts Creek at Roberts Creek (Water Survey of Canada station 08GA047) from 1960 to 2021, is 0.62[33].

Given that the assessment area is located on the coast, the flood frequency curves of the assessment streams are expected to be shallow in slope relative to interior British Columbia, and slightly steeper in slope relative to the southern Rocky Mountains (Beckers et al., 2002). Relative to the Fox Creek treatment watersheds, the peak flow variability of the assessment streams is expected to be greater. As such, the assessment streams are expected to be more sensitive to changes in frequency following forest development relative to watersheds in the interior, although less sensitive than the Fox Creek treatment watersheds evaluated by Rong (2017). Nonetheless, relatively large changes in peak flow frequency can be expected with relatively small increases in peak flow magnitude (Johnson and Alila, 2023).

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[33] This represents the current conditions, which have been subject to past forest disturbances, including forest harvesting, wildfire, and residential and commercial development.

Despite considerable variability in results and disagreement amongst forest hydrologists on the effect of forest harvesting on peak flows, one commonality between studies is the harvested area required to detect a harvesting effect. As illustrated in the synthesis conducted by Grant et al. (2008), and more recent frequency-based studies, the forest hydrology literature has generally been consistent in identifying a harvested area of 20% as the detection limit, below which the effects of harvesting cannot generally be detected.

In addition to the effect of forest cover removal on peak flows, roads can alter how runoff is conveyed to streams by intercepting shallow groundwater along road cuts. Winkler et al. (2010) notes, however, that in most studies involving road-only treatments, roads did not appear to have a measurable effect on peak flows. Moreover, due to relatively rapid preferential flow[34] and high drainage density in many coastal watersheds, shallow groundwater and surface water flow rates are often similarly rapid, such that road-related effects (e.g., interception of shallow groundwater flow and conveyance as ditch flow) on drainage patterns and rates are also expected to be small (Hudson and Anderson, 2006).

3.1.2. Effects of Forestry on Low Flows

During the summer months, high human demand for water resources coincides with naturally occurring low flows (Bradford and Heinonen, 2008), which are being exacerbated by climate change. In addition to direct water withdrawals and climate change, the timing and magnitude of low flows can also be impacted by land use activities such as logging (Smakhtin, 2001). Despite the summer low flow period being a critical period for the management of water resources, it remains an understudied topic (Moore and Wondzell, 2005). Earlier research specific to BC reviewed the effects of forest harvesting on the low flow hydrology in snowmelt-dominant catchments (Pike and Scherer, 2003)[35]. Pike and Scherer's (2003) review identified eight studies in watersheds with predominantly coniferous forests in the Pacific Northwest. Of these eight studies, four identified an increase in low flow volumes and four identified no statistical change in low flow volumes following logging. The increase in low flow is associated with the elimination of interception and transpiration losses and a net increase in soil moisture, which may contribute to groundwater recharge. Measurable effects, however, were found to last only 5-8 years (Keppler and Ziemer, 1990; Pike and Scherer, 2003; Surfleet and Skaugset, 2013), after which time re-establishing vegetation appears to consume and transpire any net increases

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[34] Preferential flow refers to rapid shallow groundwater flow through preferential flow pathways. These pathways typically occur above low permeability soils/surficial materials (i.e., basal till), and through macropores (e.g., from decaying roots, cracks in the soil, and worm/insect holes).

[35] This work is applicable because in the Pacific Northwest, both rainfall-dominant and snowmelt dominant hydrological systems experience a period of low flows during the late summer and fall. In addition, previous reviews on the effects of forest harvesting on streamflow in both snowmelt systems (Pike and Scherer, 2003) and rainfall dominant systems (Austin, 1999) contained similar findings, suggesting similarity between these different systems for the low flow period (i.e., they are largely driven by groundwater processes).

in soil moisture. In some cases, where dense deciduous stands become established in forest openings, particularly near riparian areas, there is the possibility that transpiration rates exceed those of the original conifer stands.

We recognize that there are two primary components of the forest which can influence low flows - the riparian area and the upland forest. The research of Hicks et al. (1991) looked at the colonization of riparian areas by deciduous species following stream-side harvesting and suggested that evapotranspiration rates by such colonizing species could exceed those of the pre-harvest (mature) stand and result in reduced runoff during the low flow period. Moore (2004) compared transpiration rates between young (40-year-old) and old-growth (450-year-old) Douglas-fir stands and found that the riparian area[36] in the younger stands used 3.3 times more water than that of the old stands during the growing season. As a result, logging particularly in riparian areas has the potential to decrease summer low flows in the long-term (Hicks et al., 1991).

Austin (1999) examined the streamflow response to forest harvesting in both snowmelt- and rainfall-dominant hydrological systems. Austin (1999) evaluated streamflows of 28 different watersheds: 16 exhibited an increase in low flow volumes, 10 did not exhibit an increase in low flows, and two identified a decrease in low flows. The studies reviewed by Austin (1999) along with those of Keppler and Ziemer (1990), Pike and Scherer (2003), and Surfleet and Skaugset (2013) broadly demonstrated that low flows tend to be either unaffected or increased by forest harvesting. It is important to recognize that observed effects of forest harvesting were relatively short (i.e., a few years), and that there are few studies that consider the longer-term forest harvesting effects on low flows. Two such studies that examined longer-term forest harvesting effects on low flows are that of Perry and Jones (2017) and Segura et al. (2020), summarized below.

The work of Perry and Jones (2017) was conducted using a paired-watershed approach with long-term streamflow data for eight small (9-101 ha) headwater catchments in Oregon with rainfall and hybrid hydrologic regimes. Each catchment had been subject to forest harvesting in the 1960s-1980s, with four subject to 100% clearcut, one subject to 100% basal area removal in two passes 10 years apart, one subject to 50% removal by thinning, and two subject to 25-30% patch cut. In each catchment, Douglas-fir was the primary species planted post-harvest. It is important to note that these experimental watersheds are relatively small and harvest at such levels is remarkably high, with exception of the 25-30% patch cut. As a result, the research findings reflect an extremely high level of

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[36] Riparian forests contained approximately 36% and 7% deciduous species in the young and mature forest, respectively. Riparian areas were defined as the vegetation 50 m on each side of the stream. Stream size was not described in the study although the study watersheds are 96 ha and 60 ha, so the principal streams are expected to be relatively small.

harvest that is uncommon in current forest management in BC[37]. Perry and Jones (2017) concluded that conversion of mature and old-growth mixed conifer forests to Douglas-fir plantations produced summer streamflow surpluses for 10 to 15 years post-harvest, similar to that previously reported in the literature. However, after 15 years of plantation growth, relatively high rates of summer evapotranspiration by young (25-40 years old) Douglas-fir relative to mature and old-growth forests were associated with observed summer streamflow deficits up to approximately 50%. It is important to emphasize that these results were identified in relatively small watersheds subject to 100% basal area removal. Amongst the range of silvicultural treatments that Perry and Jones (2017) reviewed, summer streamflow deficits were not observed under two scenarios. The first scenario involved selective harvest of 50% of the overstory canopy across the entire study catchment. The second scenario involved 30% canopy removal with 2- to 3-ha patch cuts. The authors conclude based on their observations combined with soil moisture dynamics in canopy gaps from Gray et al. (2002), that persistent summer streamflow deficits are not anticipated in openings up to approximately 8 ha. These results suggest that for the conservation of summer streamflows in headwater catchments, that forest managers should consider alternative silvicultural systems such as limiting the size of forest openings and/or selective harvest.

More recently, Segura et al. (2020) evaluated long-term effects of forest harvesting on low flows in the Alsea Watershed Study in Oregon, USA. Relative to the assessment watersheds, the Alsea study watersheds share a similar forest type; however, are generally smaller in size (75 ha – 311 ha). Nonetheless, outcomes from this study are generally considered applicable to the assessment area.

Segura et al. (2020) compared differences in streamflow response for a reference watershed with mature/old (90- to 170-year-old) Douglas-fir forest relative to the Deer Creek and Needle Branch Creek treatment watersheds. The Needle Branch Creek watershed was subject to 100% clearcut over ten years (17% clearcut in 1956 and 82% clearcut in 1966) and the Deer Creek watershed was subject to 25% patch cut in 1966. The authors found that by 2006 (40 to 53 years post-treatment) daily summer[38] streamflow was 50% less in the Needle Branch watershed relative to the watershed containing mature/old forests. Roughly 40 to 51 years after the Deer Creek watershed was subject to 25% patch-cut, mean daily summer streamflow was 14% lower than in the reference watershed. The reduction in low flows following harvest is thought to be due to higher evapotranspiration rates associated with the younger plantation forests relative to the old/mature forest.

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[37] Although it is not uncommon for watersheds to be comprised nearly entirely of second growth stands (i.e., nearly the entire watershed area has been harvested at some point), harvest is typically staggered over many years rather than occurring all at one time.

[38] June 1 to September 15.

Additionally, Segura et al. (2020) examined how clearcut harvest with a 15 m riparian buffer[39] affects streamflow in subsequent plantation forests. Harvesting (with riparian buffers) nearly 100% of the 40- to 53-year-old forest in the Needle Branch Creek watershed caused marginal increases in streamflow, which only persisted for two years before dropping to below pre-harvest levels. Despite a marginal increase in streamflow immediately following harvesting, streamflow deficits were still greater (i.e., lower streamflow) relative to the old/mature forest. The authors theorize that the relatively short-lived increase in streamflow is a result of high evapotranspiration rates associated with the riparian buffer and rapidly regenerating plantation and higher stand density of young relative to older mature forests. As such, Segura et al. (2020) conclude that rotations of young (i.e., 40- to 50-year-old) Douglas-fir plantations can result in a persistent decrease in low flows. This research suggests that young regenerating forests can have potentially adverse effects on low flows for many years, and highlights the importance of having a mix of forest age distributions in a watershed.

A reduction in fog interception associated with forest harvesting can also have implications on low flows. Harr (1982) estimated the net annual precipitation to be 25% greater in a forested area relative to a nearby clearcut area, attributing the difference to fog interception by the forest canopy. It is suggested that this increase in precipitation input could offset the increased evapotranspiration of forests (Harr, 1982; Jones and Grant, 1996). The amount of precipitation input, and its effect on annual and seasonal water availability depends on the amount and timing of fog. While Harr (1982) found fog interception to play a significant role in the water yield of a coastal catchment, it is worth noting that Perry and Jones (2017) and Segura et al. (2020) did not.

3.1.3. Effects of Forestry on Groundwater/Aquifer Recharge

Water balance changes following logging at the site-level (i.e., cutblock) can potentially affect groundwater recharge; however, the linkages are complex and difficult to quantify, in part because the time-scales of the hydrologic processes above and below the ground surface are often orders of magnitude different (Smerdon et al., 2009). Moreover, quantifying changes in groundwater can be difficult, although inferences can be made based on changes to the water table, water yield, and/or base flow (Winkler et al., 2010). Research on the interaction between forest activities and groundwater is rather limited, particularly for deeper/confined aquifers. However, Smerdon et al., (2009) conducted a review on the topic with a focus on British Columbia. Their review suggests that the effect of forest harvesting on groundwater is highly dependant on the hydrogeologic landscape, which is defined by the bedrock and surficial geology, soil type, and topography.

In general, and similar to low flows noted above, forest harvesting results in a reduction of site-level interception and transpiration. Even though this may be offset by increased evaporation post-harvest at the soil surface (due to increased solar radiation and wind in the forest opening), an increase in net

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[39] The species composition of the riparian buffer is unknown.

soil moisture is expected following forest harvesting (Smerdon et al., 2009). Such an increase in soil moisture can in turn can lead to an increase in the water table. One study at Carnation Creek on the west coast of Vancouver Island, BC, reported increases in the water table of 30-50 cm after logging, which persisted for 10-years, despite recovery of vegetation (Heatherington, 1998). However, another study in the same watershed recorded increases between 9-28 cm and noted the response to be highly variable across the study site, particularly below new roads (Dhakal and Sidle, 2004). For example, peak pressure head (a proxy for the groundwater table) was recorded as being 50 cm lower below a newly constructed road as a result of shallow groundwater interception from the road cut above (Dhakal and Sidle, 2004). Groundwater tables can also be increased locally as a result of soil disturbance, whereby the disturbed soils cause water to infiltrate more slowly into the soil, leading to a build-up of the water table (Heatherington, 1982; 1998).

Increased site-level groundwater tables can translate to an increase in groundwater recharge downslope; however, whether such an increase occurs, or is measurable, is highly dependant on groundwater travel times (Smerdon, et al., 2009). Increases in groundwater recharge as a result of forest harvesting will only be realized if the persistence of forest disturbance effects is within the same order of magnitude as the time for groundwater flow to reach the area of recharge. Winkler et al. (2010) notes that potential increases in recharge as a result of forest harvesting may be detectable at local scales, where recharge occurs relatively quickly; however, may not be detectable in slower responding and larger-scale flow regimes. They further state that the effect of forest harvesting on recharge areas in the uplands could go undetected in adjacent valley-bottom aquifers for decades, and that these effects could be masked or magnified by climate variability and/or change.

Relative to rainfall, snowmelt releases water into the soil at a slower rate. As such, proportional groundwater contributions are greater for snowmelt relative to rainfall due to the lower likelihood for overland flow. Hyman-Rabeler and Loheide (2023) identified a positive correlation between the proportion of precipitation falling as snow and groundwater recharge, noting, however, that the relationship is expected to vary depending on the hydroclimate and site characteristics affecting snow accumulation, melt rate and infiltration. Wright and Novakowski (2020) found, in a rain-on-snow environment, that the amount of aquifer recharge was dependant on antecedent soil conditions and the intensity of the precipitation event. Once soils are saturated, aquifer recharge is more likely to occur. High intensity rain-on-snow or melt events may lead to ponding that can be lost as streamflow or contribute to basal ice and frozen soil, reducing infiltration for subsequent events (Hyman-Rabeler and Loheide, 2023); Wright and Novakowski, 2020). In a study conducted in a Pacific Northwest coastal catchment, McGill et al. (2021) found that snowmelt did not contribute to groundwater recharge. Thin soil and impermeable bedrock underlying seasonable snowpack at upper elevations meant that the melting snow was rapidly conveyed to the watershed outlet as a single pulse. Furthermore, McGill et al. (2021) noted that given high antecedent moisture conditions in the Pacific Northwest during the freshet, spring snowmelt regularly exceeds soil storage capacity.

As discussed above, the snowpack beneath a forest canopy can be affected by meltwater drip and/or fog interception. Melting snow in the forest canopy can drip onto the snowpack below, and depending on antecedent conditions, either induce further melt or be captured and stored in the snowpack (Garvelmann et al., 2015). Research on the relationship between meltwater drip and groundwater recharge is limited; however, inferences can be made based on how meltwater influences snowpack accumulation and melt. Meltwater drip is an important factor that causes the snowpack in forested sites to be shallower than in open areas (Storck et al., 2002; Bonner et al., 2022). Meltwater drip may either infiltrate through the snowpack and into the soil relatively quickly, or be retained temporarily in a cold snowpack as storage until the snow becomes isothermal and liquid water is released into the ground. Following forest cover removal, meltwater drip is suppressed, and solar and turbulent energy inputs to the snow are increased, causing snowpacks to be deeper and melt faster in open areas. This means that greater amounts of moisture are available for groundwater recharge; however, snowmelt may occur earlier. Given the large travel times associated with groundwater recharge, the effect of suppressing meltwater drip on groundwater recharge is expected to negligible or a slight increase.

3.1.4. Effects of Residential and Commercial Development on Streamflows

Residential and commercial development has long been known to result in increased runoff volume and peak flows as a result of the conversion of green spaces to impervious areas and the establishment of stormwater drainage systems intended to effectively convey water and reduce flooding (NRCC, 1989; Urbonas and Roesner, 1993). Impervious areas (e.g., paved roads, rooftops, etc.) increase the volume and rate of runoff transmitted to streams (BC MWLAP, 2002a). For example, Blum et al. (2020) looked at 280 catchments in the United States and found that annual floods increased by 3.3% on average for each percentage point increase in impervious land cover. Similarly, Prosdocimi et al. (2015) found a “significant” effect of increasing urbanization levels on high flows in an urbanized catchment in the UK, although they did not quantify the increase. Villarini et al., (2009) also found using nonstationary flood frequency analysis that rapid urbanization caused an increase in frequency of the 100-year flood event. May et al. (1998 and references therein) state that stream ecosystem impairment begins when roughly 10% of a watershed is covered by impervious area. Additionally, conventional storm water management infrastructure, which are often composed of ditches and pipes, are designed to rapidly transport runoff to nearby streams (BC MWLAP, 2002a). As such, the receiving waters are typically subject to increased flows which can alter channel morphology and negatively impact aquatic habitat.

3.2. SEDIMENT YIELD

As described by Jordan (2001), sediment can be divided into two broad categories: fine[40] and coarse[41]. Fine sediment is carried in suspension in water and is deposited only when streamflow velocity is low. Fine sediment in suspension within the water column increases stream turbidity[42], which is a measure of the sediment content in water, with increasing turbidity usually associated with increasing suspended sediment[43] concentrations. Stream turbidity is a concern since it can have physiological effects on fish (Newcombe, 2003). If utilized for potable water, turbid source water can also foul filters, interfere with disinfection of drinking water (i.e., shield pathogens from the effects of disinfection), is aesthetically unpleasing, and increases the total available surface area of solids in suspension upon which bacteria can grow (Cavanagh et al., 1998 and Pike et al., 2010). Coarse sediment is transported along the stream bed and is of interest due to its effect on stream channel stability, water supply infrastructure, and fish habitat. These are further discussed in Section 3.4.

Sediment yield refers to the rate of sediment flux through a watershed. It is a function of the collective processes of *erosion*[44] and *sedimentation*[45] throughout a watershed and depends on the erodibility or rate of erosion from each area or source and the degree of hillslope-stream coupling (i.e., connectivity between the source of erosion and the stream network). Furthermore, for sediment to cause harm it must be transported to the location of a value of interest; this depends on the effectiveness of the stream to transport displaced sediment (i.e., stream power) from the point of entry to the location of interest.

Erosion is associated with several processes, including:

- Surface erosion of soils through the processes of raindrop/splash erosion[46], sheet erosion[47] and/or rill and gully erosion[48].

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[40] Includes fine sand, silt and clay (i.e., particle sizes ≤0.25 mm)

[41] Includes medium sand and large particles (>0.25 mm)

[42] Turbidity is the amount to light scattered by a fluid (Stednick, 1991) and is measured in nephelometric turbidity units (NTUs).

[43] Suspended sediment normally consists of clay, silt and very fine sand particles less than 0.1 mm (100 micron) in diameter (MacDonald et al., 1991).

[44] Erosion refers to processes, by the action of water or wind, that displaces soil particles. Also known as sediment generation or sediment production.

[45] Sedimentation refers to the process of deposition of soil particles usually within a waterbody. Also known as sediment loading or sediment delivery.

[46] Raindrop/splash erosion refers to soil particles that are dislodged by raindrop impacts.

[47] Sheet erosion refers to the process by which saturated soil particles are uniformly removed by surface runoff.

[48] Rill and gully erosion are described as long, narrow depressions formed in soils by concentrated surface runoff.

- Streambank erosion, whereby streamflows cause toe cutting and bank sloughing along streambanks, and
- Landslides (e.g., rockfall, debris slide, debris flows, rockslide, slump, etc.).

Soil erosion can often be mitigated by the presence of an effective and protective soil cover, usually in the form of vegetation and organic matter (e.g., grass, shrubs, trees, etc.); however, it can include coarse rock, mulch, wood debris or manufactured erosion control products. Thus, where vegetation and organic matter are lost by forest development or other natural disturbances (e.g., wildfire), the likelihood and rate of erosion tends to increase unless control measures are implemented.

In terms of assessing sediment yield, focus is on identifying the likelihood that watershed disturbance, such as forest development, increases the rate of sediment supply to the stream network, relative to natural or background rates. It considers both sediment production (i.e., erosion) and sediment delivery to the stream network (i.e., sedimentation), where it may affect elements-at-risk. The potential change in sediment yield is derived through consideration of *sediment generation potential*[49] and *sediment delivery potential*[50].

The following highlights where sediment is typically generated in a forestry context – along roads and from landslides. Although cutblocks can be subject to erosion, in the event that heavy equipment trafficking occurs under adverse soil moisture conditions, there is usually ample organic material (i.e., woody debris and slash) that serves as a protective soil cover such that erosion rates are low if not negligible (Jordan, 2001). Streambank and bed erosion and channel instability is another source of erosion and sedimentation that may be associated with changes in peak flows following harvesting and/or riparian logging (Sections 3.3 and3.4).

3.2.1. Roads

The effects of resource roads on sediment yields are well documented in the literature (Luce, 2002; Wemple et al., 2001). Along roads, there are three main components to consider: 1) the cut slope and ditch, 2) the road surface, and 3) fill slope. Of these components, active road surfaces are often the primary producer of fine sediment to streams (Reid and Dunne, 1984), particularly in areas where landslides are infrequent (Bilby et al., 1989). For example, in a study in western Washington, Reid and Dunne (1984) found that a paved road (i.e., where sediment was only sourced from cut slopes and

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[49] Sediment generation potential is the likelihood that land use activity will increase the magnitude and/or frequency of sediment production (i.e., erosion) considering: terrain stability, soil erodibility, evidence of mass wasting, extent and location of resource roads, and other land-use related soil disturbance.

[50] Sediment delivery potential is the likelihood that sediment generated in upslope or instream sources will reach the stream network and be transported downstream to an element-at-risk. Factors considered include: hillslope-stream coupling, stream gradient, and location of lakes and wetlands.

ditches) generated only 1% of the sediment yield of a heavily used[51] gravel road. Moreover, they estimated sediment production from road cuts to be roughly 5% of the combined production rate from roads for the study watershed (Reid and Dunne, 1984). However, in areas prone to landslides, sediment production from road-related landslides triggered during extreme storm events can often outweigh chronic sediment inputs from road surfaces (Wemple et al., 2003).

A study conducted on a medium-sized road-affected stream, located in Haida Gwaii, BC found that 18 ± 6% of the suspended sediment in the study reach was derived from nearby road surfaces (Reid et al., 2016). The same study found that road-derived sediment inputs were significantly greater during the wetter winter months, and during higher intensity rainstorms. During fall and winter rainstorms, 5% to 70% of sediment inputs to the streams were derived from roads compared to 0.5% to 15% during the spring and summer (Reid et al., 2016). A similar study using simulated rainfall on a road surface in the same watershed found that the intensity of rainfall and number of loaded logging trucks were the primary and secondary controls on road surface sediment production, respectively (van Meerveld et al., 2014). Similarly, Reid and Dunne (1984) found that roads contributed 7.5 times more sediment when heavily used, compared to when they are not in use. Van Meerveld et al., (2014) also found that increases in sediment concentrations persisted for up to 30 minutes following the passage of a loaded logging truck.

In addition to precipitation intensity and traffic, road surface material also plays an important role in determining sediment yield from road surfaces. Silt-sized particles are most prone to erosion, as they can be easily transported in suspension via overland flow, whereas coarser aggregate is less easily eroded and transported. Erosion rates are also lower for road surfaces with a high clay content as a result of particle aggregation (Luce and Black, 1999).

If cut slopes are required during road construction, near-surface groundwater flow becomes intercepted, increasing runoff and hence erosion potential along ditches. Sediment yield from cut slope erosion and ditches is often the greatest immediately after road construction. Erosion rates tend to decrease as vegetation recovers along cut slopes and in ditch lines following construction. In western Oregon, one study found that cut slopes and ditches cleared of vegetation produced approximately seven times more sediment than those where vegetation was retained (Luce and Black, 1999).

Erosion of the fill slope is typically only significant at poorly designed culvert outlets (i.e., with no armour) or where uncontrolled drainage occurred across the road surface due to a fault in the drainage system (e.g., plugged culvert) (Jordan, 2000). In addition to drainage system failures, factors influencing observed erosion rates include climate (e.g., the wetter the location, the higher the rate of

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[51] Heavy use was considered to be more than four loaded trucks per day.

erosion) and the presence of groundwater (e.g., seeps). Secondary factors include soil coarse fragment content, soil depth and road gradient (Jordan, 2000).

Adverse effects can often be mitigated through proper road design, construction, and maintenance (Carson and Younie, 2003). Mitigation should be incorporated during all phases of operation (i.e., planning, construction, use and deactivation). Such options could include but are not limited to utilizing existing roads, minimizing road lengths/number of crossings, avoiding problematic soils, crossing at right angles to streams, and implementing effective erosion and sediment control plans, which may include wet-weather shutdown guidelines similar to those normally used to protect workers and the public from exposure to mass movement events.

As part of the Forest and Range Evaluation Program (FREP), a protocol has been developed for evaluating the potential impact of forestry and range use on water quality (Maloney et al., 2018). Known as the Water Quality Effectiveness Evaluation (WQEE), this protocol is intended for detailed site-level assessments to evaluate the effectiveness of the Forest Range and Practices Act (FRPA) and its regulations in achieving stewardship objectives. Specifically, the FREP WQEE is a tool used to estimate sediment contributions from forestry activities, with a particular emphasis on sediment contributions from roads. This protocol is intended to act as a monitoring tool and is considered beyond the scope of a watershed assessment.

3.2.2. Landslides

Landslide is a generic term that refers to a suite of mass movement (or mass wasting) processes, such as rockfall, debris slides, debris flows, and debris floods. In mountainous areas of coastal BC, landslides are a natural process that occurs throughout the landscape when the gravitational forces and hydrologic conditions exceed the strength of the soil (or rock). Where hillslopes are coupled to streams, landslides can impact instream values (e.g., fish habitat) and other values downstream (e.g., human health, property and infrastructure). The frequency of landslide occurrence has long been recognized as potentially increasing following forest harvesting and road and trail construction. Readers are encouraged to review Geertsema et al. (2010), Jordan et al. (2010) and the references therein for a comprehensive review of the topic within the context of British Columbia.

Both logging and road building have been associated with landslides in coastal British Columbia (Millard et al., 2007). After a block is logged, stumps often remain in the soil to die and rot, which reduces the strength of the soil. Soil strength can also be reduced with an increased rate of delivery of water to the soil, especially during rain-on-snow events because canopy interception is reduced with the removal of the canopy until trees regenerate. Logging and yarding activities may also physically damage soil structure and reduce the ability of the soil to drain water. These changes in slope stability factors have been observed to lead to landslides in harvested areas (Jordan et al., 2010). Forest roads can also affect the structure of the slope and drainage of water down the slope. Both can affect where and when a landslide is initiated. Depending on condition, some over-steepened fill slopes may be vulnerable to landslides. In addition, road cuts have the potential to intercept near-surface groundwater and concentrate such water below discharge locations, usually outlets culverts draining ditches. If the slope below the road is not conditioned to the rate of water delivered, the slope may be become unstable causing a landslide. Many coastal British Columbia examples have been noted where road construction does not adequately consider potentially unstable terrain and the influence of drainage diversions on natural surface and groundwater flow patterns (Jordan et al., 2010). Following high-profile landslides in coastal BC in the late 1970s and early 1980s, including one east of the assessment area (Section 6.2.2), forest management practices in landslide-prone terrain were critically reviewed by the provincial agencies. This was followed by implementation of the *Forest Practices Code of British Columbia Act (FPC)* in 1994[52], which required professional terrain assessment and improvements in road planning and construction. As a result, the added level of diligence has substantially reduced the frequency of post-logging landslides (FPB, 2005).

3.3. RIPARIAN FUNCTION

Riparian function is the interaction of various hydrologic, geomorphic, and biotic processes across a range of spatial and temporal scales within the riparian environment. As a result, riparian function includes a wide variety of processes that determine the character of the riparian area[53] and exerts an influence on the adjacent aquatic and terrestrial environment. Riparian areas provide several functional roles which include providing critical habitat for insects, amphibians and other wildlife; providing food sources for aquatic insects and shelter for fish; filtering nutrients from water; dissipating energy during flood events; filtering sediment from entering a stream; and offers wind protection. In the context of forest management, riparian function is often defined more narrowly, focussing on three specific processes:

1) the provision of bank stability mostly through root strength, particularly where alluvial materials are involved (e.g., along floodplains and fans)[54],
2) the recruitment of large woody debris (LWD) to aquatic systems, which helps to control the movement of coarse sediment in stream channels as well as providing fish habitat (e.g., cover), and
3) the provision of shade to aquatic systems that can help maintain stream temperatures.

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[52] The *Forest Practices Code (FPC)* was subsequently replaced by the *Forest and Range Practices Act (FRPA) in 2004.*

[53] Riparian area (or zone) is an area of land adjacent to a stream, river, lake or wetland that contains vegetation that, due to the presence of water, is distinctly different from the vegetation of adjacent upland areas.

[54] By promoting bank stability, riparian vegetation mitigates sediment generation (i.e., erosion).

Loss of riparian function can affect channel equilibrium and result in bank erosion, channel shifting, and sedimentation. This can have negative effects, such as fish and fish habitat degradation, water quality reduction, infrastructure (e.g., stream crossings) damage, and private land damage or loss. Moreover, blowdown in riparian areas can potentially contribute excessive amounts of wood, sediment and debris to the channel.

When assessing riparian function, focus is on identifying the degree to which natural riparian function (e.g., to provide shade, cover, stream habitat, stream bank stability, etc.) has or will be disturbed by watershed disturbance. Loss of riparian function can affect channel equilibrium (Section 3.4) and result in bank erosion, channel shifting, and sedimentation. The riparian function hazard incorporates both the level of past riparian forest cover disturbance and the degree to which it has recovered.

Similar to the WQEE protocol described in Section 3.2.1, a FREP protocol has been developed for evaluating riparian condition (Tripp et al., 2022). The purpose of the riparian FREP protocol is to assess the effectiveness of riparian management practices and evaluate the functioning condition of streams and riparian areas. These protocols are intended for detailed site-level assessments and were not applied as part of this review.

3.4. CHANNEL STABILITY

Channel stability, better described as *dynamic channel equilibrium*, refers to a state of balance resulting from the interplay of four basic factors (streamflow, sediment yield, sediment particle size, and channel gradient) that maintains alluvial or semi-alluvial stream channels in their most efficient and least erosive form (Buffington, 2012). The term “dynamic” is important, as the energy of a stream is always at work sustaining or re-establishing its equilibrium condition. Land-use impacts at site-specific or watershed scales have the potential to upset dynamic channel equilibrium thereby triggering a process of stream adjustments. If one of the four factors change, one or more of the other variables must increase or decrease proportionally if equilibrium is to be maintained. For example, if channel gradient is increased (e.g., by channel straightening) and streamflow remains the same, either the sediment load or the size of the particles must also increase. Likewise, if flow is increased and the channel gradient remains constant, sediment load or sediment particle size has to increase to maintain channel equilibrium. Under these conditions, a stream seeking a new equilibrium (i.e., in a state of disequilibrium) will tend to erode more of its banks and bed, transporting larger particle sizes and a greater sediment load. Such channel disequilibrium or destabilization may be undesirable as it can result in increases in fine and coarse sediment yield, which can affect downstream water quality, fish and fish habitat, and water supply and transportation infrastructure (e.g., bridges and culverts).

Salmon and trout egg-to-fry survival is dependent on the stability of redds and a well oxygenated flow of water. During the rising limb of a storm hydrograph, redds may be at risk of scour.

Furthermore, during the receding limb of the storm hydrograph, finer sediments may deposit and plug the interstices of redds, thus compromising oxygen flow. Both effects can result in reduced fry survival (Scrivener and Tripp, 1998). While fine sediment may be transported during a range of flows, coarse sediment is generally stored for long periods in channel banks and bars, and typically moves episodically, usually when flows approach or exceed bankfull.

Analysis of channel stability requires an understanding of current or baseline stream channel conditions both in terms of channel equilibrium (i.e., does the channel display evidence of disequilibrium from past impacts either streamflow and/or sediment-related?) and channel sensitivity to future disturbance. The analysis also requires estimation of potential future streamflow and sediment yields, including the influence of climate change and/or forestry.

The sensitivity of a channel is also referred to as its *channel response potential* (Montgomery and Buffington, 1997 and 1998). *Channel response potential* is the inherent susceptibility of a stream channel to changes in discharge and sediment supply. It is a factor controlling whether and to what extent forest disturbance effects, if any, will be realized. Channels can be broadly described as *alluvial*[55], *semi-alluvial*[56] or *non-alluvial*[57], and relative channel response potential tends to decrease in that respective order. Reach-specific response potential is further affected by influences such as channel confinement, riparian vegetation[58], and presence of in-channel large woody debris. Differences in reach morphology and physical processes result in different potential responses to similar changes in discharge or sediment supply (Montgomery and Buffington, 1997 and 1998).

The assessment streams were observed in several locations (FIGURE 2.1); however, no formal or systematic stream channel stability procedure was applied in this assessment. Such an approach is considered beyond the scope of this review.

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[55] Alluvial channels are those comprised of potentially mobile sediments deposited by the stream (e.g., sand and gravel). The nature of these channels makes them relatively more sensitive to disturbance than semi-alluvial or non-alluvial channels.

[56] Semi-alluvial channels are those comprised of a combination of potentially mobile alluvium and immobile material (e.g., bedrock, colluvium, glacial lag-deposits).

[57] Non-alluvial channels are those comprised largely of immobile material (e.g., bedrock, colluvium, glacial lag-deposits).

[58] Riparian vegetation serves many purposes (e.g., to provide shade, cover, stream habitat, stream bank stability, etc.) and can be a major factor contributing to the robustness of channels and observed channel response. Loss of riparian function can affect channel equilibrium and result in bank erosion, channel shifting, and sedimentation. The level of past riparian forest cover disturbance and the level of recovery of the riparian vegetation are both considered in characterizing channel response.

4. WATERSHED OVERVIEW

4.1. LOCATION & ACCESS

The assessment watersheds extend northeast from the community of Roberts Creek on the southwest slopes of Mt. Elphinstone. Access to the upper portions of assessment area is via Largo Road northbound from the Sunshine Coast Highway (101), then by the Sechelt Roberts Creek Forest Service Road (FSR) (7575) and several branch roads. Lower portions of the assessment area are accessed via several local roads around Roberts Creek. A BC Hydro Transmission Line right of way (ROW), which has a gated access road and trail for much of its length also crosses the assessment area between elevations of 100 and 200 m (FIGURE 4.1).

FIGURE 4.1 *View westward along the BC Hydro ROW. Bridge crosses Stephens Creek at an elevation of approximately 161 m. Photo DSC09916, August 6, 2021.*

4.2. PHYSIOGRAPHY

The assessment area is located in a transitional area between the Georgia Lowlands and Pacific Ranges of the Coast Mountains (Holland, 1976). The area is characterized by moderate relief and gently to moderately sloping terrain on the southwest side of Mt. Elphinstone. Two watersheds, two basins and one sub-basin have been identified with some potential for BCTS forest development. The two watershed, Roberts Creek and Stephens Creek, flow directly into the Strait of Georgia. The basins, Clack Creek and East Roberts Creek drain into Roberts Creek, whereas the sub-basin Gough Creek drains first into Clack Creek. The assessment area has a high density of subparallel gullies, which is especially evident on LiDAR bare-earth imagery (FIGURE 4.4, MAP 1). Many of these gullies do not necessarily contain stream channels[59] with perennial or intermittent flow; however, they may be paths for near-surface groundwater flow. It is important to emphasize that the streams presented on the maps herein are identified using GIS techniques (i.e., flow accumulation modelling) with LiDAR data and have not necessarily been field verified.

The overall drainage areas of Roberts Creek and Stephens Creek are 26.63 km^2 and 2.52 km^2, respectively. Drainage areas for the basins and sub-basin within Roberts Creek are presented in TABLE 4.1. Total watershed relief for Roberts Creek is 1,180 m whereas for Stephens Creek it is 1,160 m (TABLE 4.1). Each watershed has considerable areas below 800 m elevation where rain- or occasionally rain-on-snow drives runoff (FIGURE 4.5). Areas in each watershed above 800 m are considerably less (e.g., 20% for Roberts Creek and 36% for Stephens Creek), but may nevertheless play a role in snow-related runoff. According to Floyd pers. comm. (2023), based on LiDAR surveys, near Arrowsmith Lake on eastern Vancouver Island (i.e., across the Strait of Georgia from the assessment area) the snowpack on average tends to accumulate above 800 m elevation.

Median elevations in the Roberts Creek and Stephens Creek watersheds are 600 m and 660 m, respectively. With the exception of several incised gullies, hillslope gradients across the assessment area reflect gently to moderately sloping terrain. A total of 86% of the drainage area of the Roberts Creek watershed is gentler than 30%. In Stephens Creek, 63% of the drainage area is gentler than 30% slope (FIGURE 4.3). Slope aspects in the Roberts Creek watershed and its basins are biased to south and southwest slopes.

Field observations suggest that the streams are primarily semi-alluvial or alluvial with non-alluvial reaches along the middle and lower stream segments and alluvial near the mouth. Stream gradients are presented in FIGURE 4.6. Stephens Creek is unique amongst the basins in the assessment area as it is generally steeper, particularly between stream km 6.2 and 7.5. The lower 6.2 km of Stephens Creek has an average gradient of 10.6%, whereas above 6.2 km it has an average gradient of 30.4%. The remaining portions of Stephens Creek generally have lower gradients. Below about stream km 4.5, stream gradient averages 6.4%. Between about stream km 4.5 and 8.5 stream gradient averages 12.8%. Above that point, streams range in gradient from 4.6% to 9.0 %. Selected photos of the assessment streams are provided in Volume 2, APPENDIX D. Stream channel conditions as observed during our field reviews are summarized in Section 6.4.

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[59] According to Province of BC (2018), a “stream" means a watercourse, including a watercourse that is obscured by overhanging or bridging vegetation or soil mats, that contains water on a perennial or seasonal basis, is scoured by water or contains observable deposits of mineral alluvium, and that: (a) has a continuous channel bed that is 100 m or more in length, or (b) flows directly into (i) a fish stream or a fish-bearing lake or wetland, or(ii) a licensed waterworks.

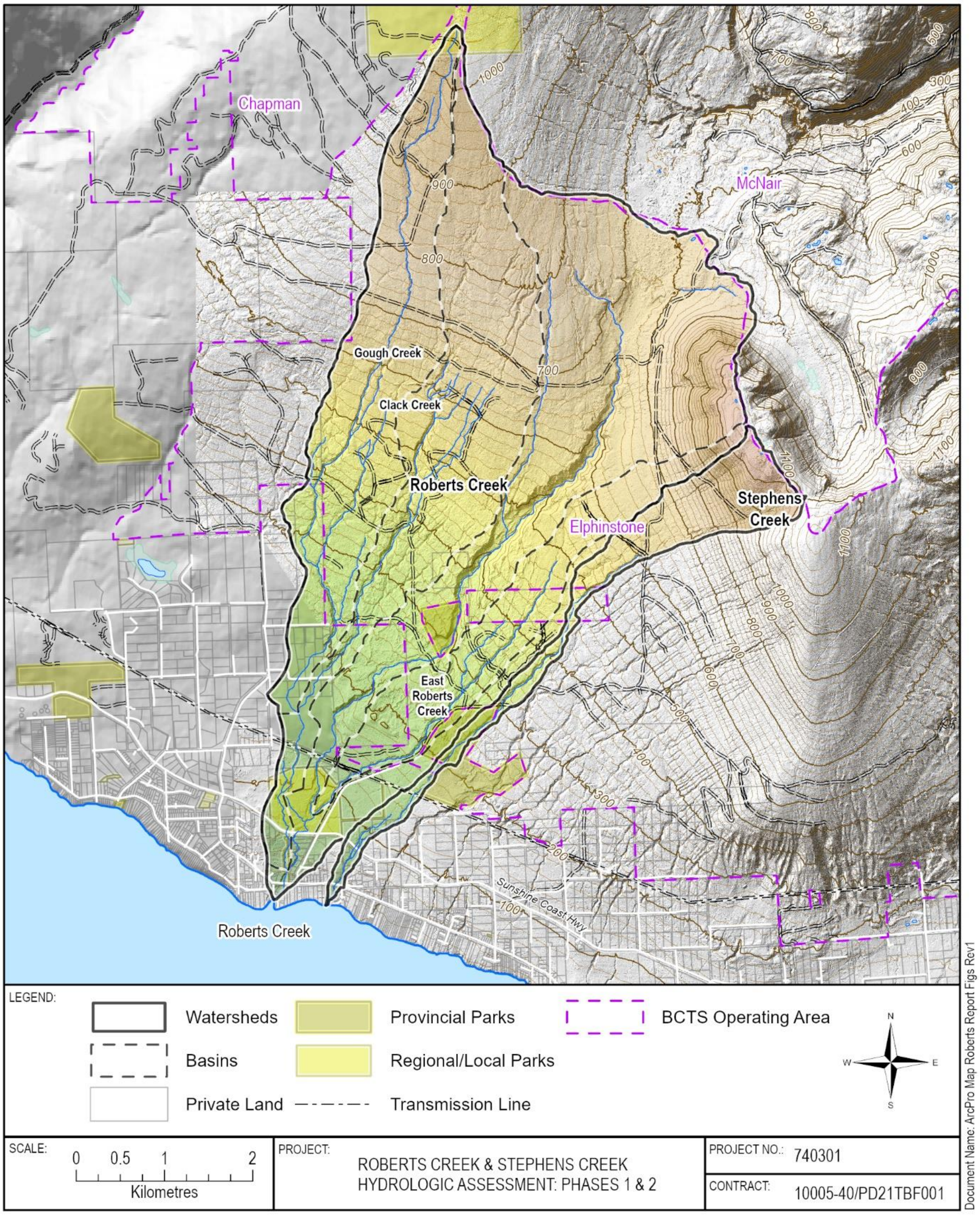

FIGURE 4.2 *Assessment area topography and elevations.*

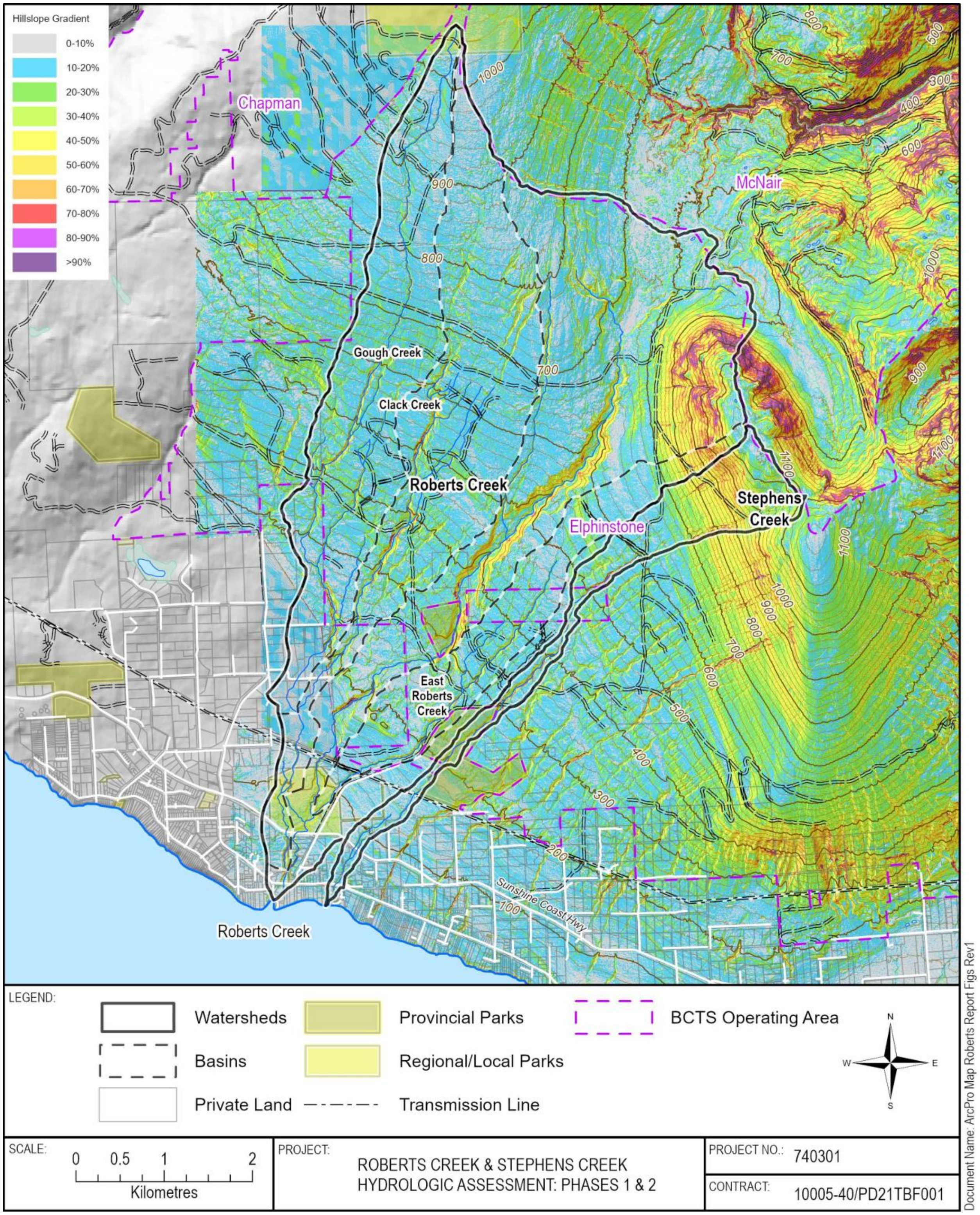

FIGURE 4.3 *Hillslope gradients in the assessment area.*

FIGURE 4.4 *3D perspective view of the Roberts Creek Watershed and Stephens Creek Watershed (outlined in white). Basins are outlined in black and white dashes. Vertical exaggeration 1.25x. DEM source: Province of BC and SCRD; Imagery source: ESRI (2021).*

TABLE 4.1 *Characteristics of the principal streams / watersheds in the assessment area.*

Watershed Units					
Stream / Watershed	**Roberts Creek Watershed**	**Gough Creek Sub-basin**	**Clack Creek Basin**	**East Roberts Creek Basin**	**Stephens Creek Watershed**
Drainage Area					
Total drainage area (ha)	2,662.51	589.08	1,259.49	310.53	251.70
Total drainage area (sq km)	26.63	5.89	12.59	3.11	2.52
Elevations (Hypsometric data)					
Minimum elevation (m)	0	160	7	80	0
Maximum elevation (m)	1,180	1,060	1,060	1,160	1,160
Total watershed relief (m)	1,180	900	1,053	1,080	1,160
H40 elevation (H40) (m)	680	460	780	460	740
H50 (median) elevation (m)	600	400	730	400	660
H60 elevation (H60) (m)	500	320	670	320	600
Slope Gradient (ha)					
0-10%	597.45	125.59	2.34	68.62	29.81
11-20%	1,321.85	345.04	7.50	157.54	83.27
21-30%	367.74	86.72	1.92	45.47	46.01
31-40%	143.52	18.16	0.47	18.00	33.18
41-50%	96.03	6.80	0.20	9.39	29.37
51-60%	62.66	3.10	0.08	6.24	16.76
61-70%	40.04	2.00	0.04	4.08	9.14
71-80%	16.79	0.91	0.02	1.07	2.93
81-90%	7.87	0.24	0.01	0.13	0.94
90% +	8.53	0.54	0.01	0.07	0.24
Slope Aspect (ha)					
North	171.14	15.41	0.10	11.59	7.92
East	336.40	39.25	1.07	13.89	7.72
South	1,418.65	443.82	8.65	148.83	108.63
West	736.27	90.60	2.77	136.28	127.38
BEC Sub-zones/Variants (ha)					
MH mm1	73.45	21.21	0.30	6.15	55.44
CWH vm2	800.71	170.35	3.92	18.11	56.14
CWH dm	1,623.82	397.5	7.88	269.16	109.35
CWH xm1	164.53	-	0.50	17.11	30.78
Land Base (ha)					
Crown Forest Land Base	2,225.97	492.36	11.06	237.18	219.61
Timber Harvest Land Base	1,962.78	426.80	10.81	204.84	192.19
Private Land	304.29	94.82	1.64	65.09	27.17
Parks or protected areas	65.84	5.78	22.60	10.81	15.23
Area of lakes	0.25	-	-	-	0.08
Area of wetlands	-	-	-	-	-

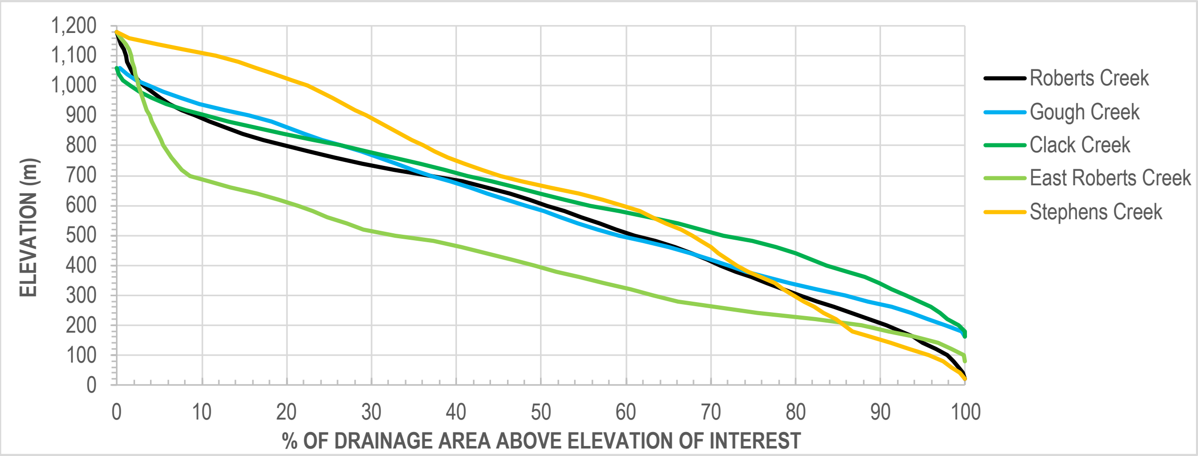

FIGURE 4.5 *Hypsometric (area-elevation) curves for the watersheds of interest in the assessment area.*

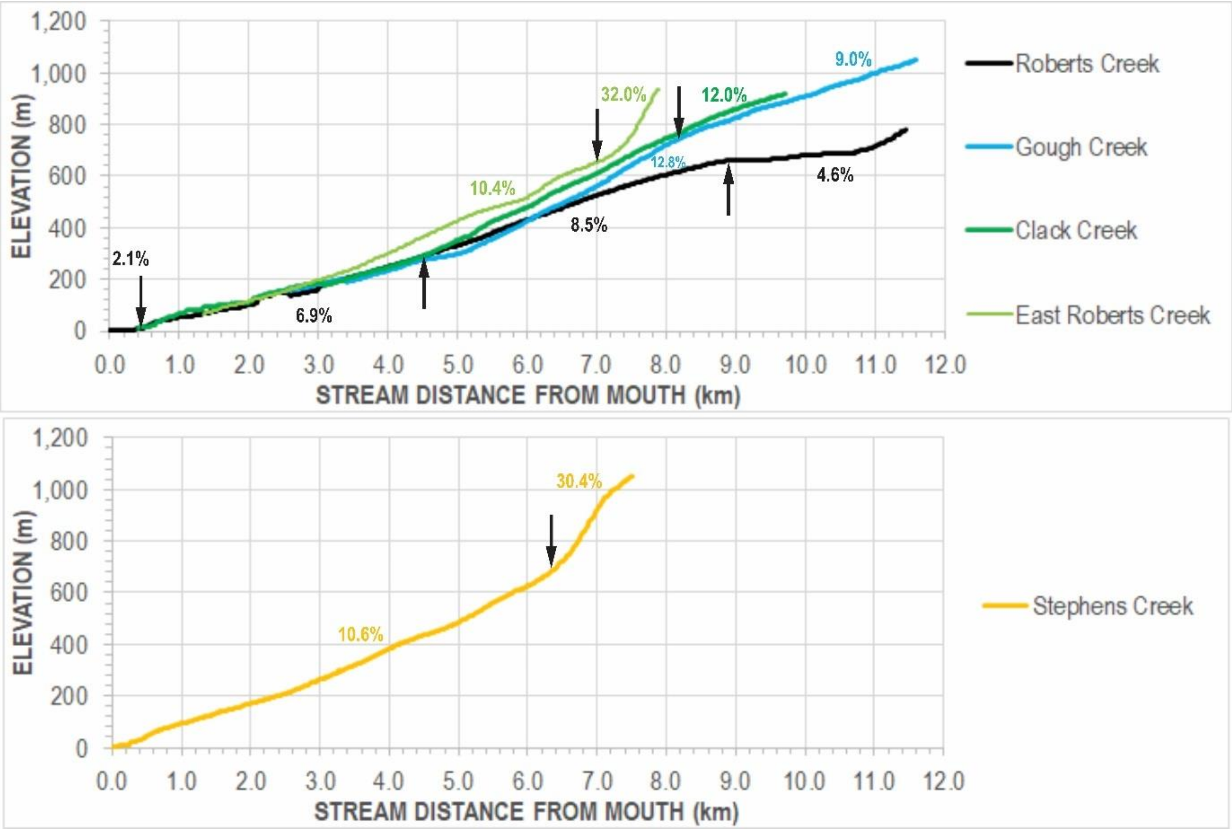

FIGURE 4.6 *Representative longitudinal profiles of the streams in the watersheds of interest in the assessment area. There are several other tributaries in each watershed, many of which are not shown. Stream gradients for main reaches are shown.*

4.3. BEDROCK GEOLOGY

The description of bedrock geology provided below is based on Cui et al. (2019) and Journeay and Monger (1994).

Three bedrock geology units are located within the assessment area (FIGURE 4.7). According to Cui et al. (2019), the southwest portion is underlain by variably foliated granodiorite of early Cretaceous-aged rocks of the Quatam, Sakinaw Lake, Malaspina and Quarry Bay plutons. The centre of the study area is underlain by Late Jurassic-aged, variably foliated granodiorite and quartz diorite of the Paradise River Pluton. The northeast side of the area is underlain by Jurassic-aged sedimentary and metamorphic rocks of the Bowen Island Group, including, sandstone, siltstone, argillite and greenschist (Journeay and Monger, 1994).

Characteristics of the bedrock, including mineral composition and structure, determine the shape and texture of its weathered material. These characteristics influence the shape and size of clasts (i.e., rock fragments) and the matrix texture of soils that are created. Sandstone weathers to sand and siltstone breaks down into silt. Sedimentary rocks, where bedded, tend to fracture along bedding planes to produce slab-shaped clasts. Foliated or schistose metamorphic rocks, such as greenschist, break down into silt and consequently result in silty matrix soil. Such rocks fracture along foliation planes to produce slab-shaped clasts. Where well jointed, igneous rocks, break into blocks and boulders and can produce bouldery tills. On weathering, the rock breaks down into silt and sand and consequently, areas of granitic bedrock tend to produce till with a silty sand matrix.

Waterline (2013) noted that joints and fractures in the rock types in the lower Sunshine Coast were roughly parallel and perpendicular to the boundaries of bedrock formations in a nearby area. Fractures in bedrock can contribute to mountain block recharge to downslope aquifers.

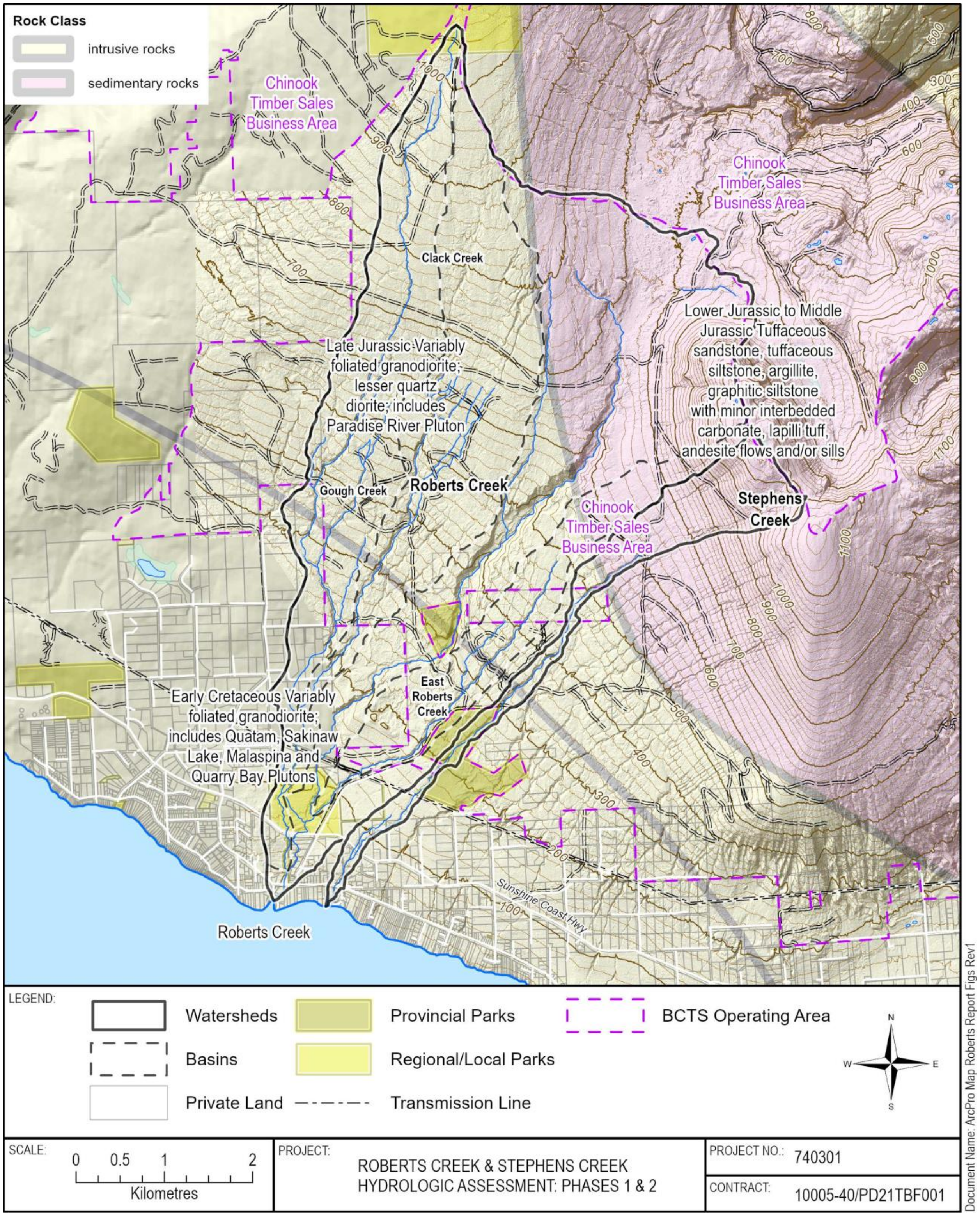

FIGURE 4.7 *Bedrock geology underlying the assessment area.*

4.4. SURFICIAL GEOLOGY

The description of surficial geology provided below is based on McCammon (1977), Ryder et al., (1980), Madrone (2012) and the LiDAR hillshade.

The Roberts Creek area was subject to several Quaternary glaciations (i.e., over the past 2.6 million years); however, the unconsolidated sediments present within the area were primarily deposited during Fraser Glaciation, which occurred between 29,000 and 11,000 years ago. Some of these sediments were subsequently subject to post-glacial erosional and depositional processes that occurred over the Holocene period (i.e., over the last 10,000 years). Surficial materials in the Roberts Creek area differ by location and elevation, and can be characterized by three general areas: 1) all areas above about 400 m elevation, 2) between 180 m and about 400 m elevation, and 3) all areas below 180 m elevation. Above an elevation of approximately 400 m, hillslopes are characterized by a blanket of till over bedrock. Generally, till thickness decreases with elevation with scattered bedrock outcrops noted on the upper slopes of Mt. Elphinstone. Locally the till has been described as loose to highly consolidated with a predominantly sandy matrix texture but also silty matrix texture has been observed. Colluvium may also be locally present where hillslope gradient is greater than about 70%. Between 180 m and about 400 m elevation, a discontinuous cover of glaciofluvial sediments (sands and gravels) may cover the till. Several eskers are visible in the LiDAR bare earth imagery near Clack Creek and Roberts Creek. Below 180 m elevation, up to 3 layers of sediments may be found overlying bedrock, including from top to bottom a discontinuous cover of glaciofluvial sediments, glaciomarine sediments and till. The glaciomarine sediment are locally described as stony, till-like clay but may also occur as sandy, cobbly former beach deposits. Scattered bedrock outcrops may be present below 180 elevation.

4.5. BIOGEOCLIMATIC ZONES

Forests within the assessment area primarily lie within the Coastal Western Hemlock biogeoclimatic zones, with only a small portion at highest elevations in the Mountain Hemlock zone (TABLE 4.1, FIGURE 4.8). The following summary is from Green and Klinka (1994).

The Mountain Hemlock Windward Moist Maritime (MH mm1) subzone is located at high elevations in maritime areas of the mainland coast. The lower elevational limit is between 800 m and 1,000 m and the upper limit is between 1,100 m and 1,350 m. It is characterized by long, wet cold winters and short, cool moist summers. Annual precipitation is typically on the order of 2,600-2,900 mm[60], with snowfall

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[60] These precipitation estimates are broad generalizations for the BEC subzone. Recorded precipitation presented in Section 4.6 is considered a more accurate representation of precipitation in the assessment area. Additionally, the BEC zone climate estimates are based on climate normal from the past, which may differ somewhat from current conditions.

accounting for about 30%. The substantial snowpack can persist into July. Forests are dominated by amabilis fir (Ba) and mountain hemlock (Hm) and to a lesser extent yellow cedar (Yc). In the assessment area MH mm1 occupies 73 ha or 2.8% of the Roberts Creek watershed and 55 ha or 22% of the Stephens Creek watershed.

The Coastal Western Hemlock Montane Very Wet Maritime Variant (CWH vm2) is generally located between 650 m and 1,000 m and grades into the Mountain Hemlock zone above. It is characterized by wet, humid climate with cool short summers and cool winters. Annual precipitation in the CWH vm2 is typically slightly lower than in the MH mm1 subzone, with a smaller proportion falling as snow. Forests tend to be dominated by western hemlock (Hw), amabilis fir (Ba) and to a lesser extent western red cedar (Cw), yellow cedar (Yc), and mountain hemlock (Hm).

The Coastal Western Hemlock Dry Maritime Subzone (CWH dm) tends to occur below 650 m elevation and has warm, relatively dry summers and moist, mild winters with little snowfall. Annual precipitation is on the order of 1,860 mm, with snowfall accounting for only 5%. Forests are dominated by Douglas-fir (Fd), western red cedar (Cw) and western hemlock (Hw).

The Coastal Western Hemlock Very Dry Eastern Variant (CWH xm1) is generally located from sea level to approximately 150 m elevation in the assessment area and has warm, dry summers and moist, mild winters with relatively little snowfall. Snowfall often accounts for less than 5% of annual precipitation. Forests are dominated by Douglas-fir (Fd), accompanied by western hemlock (Hw) and minor amounts of western red cedar (Cw).

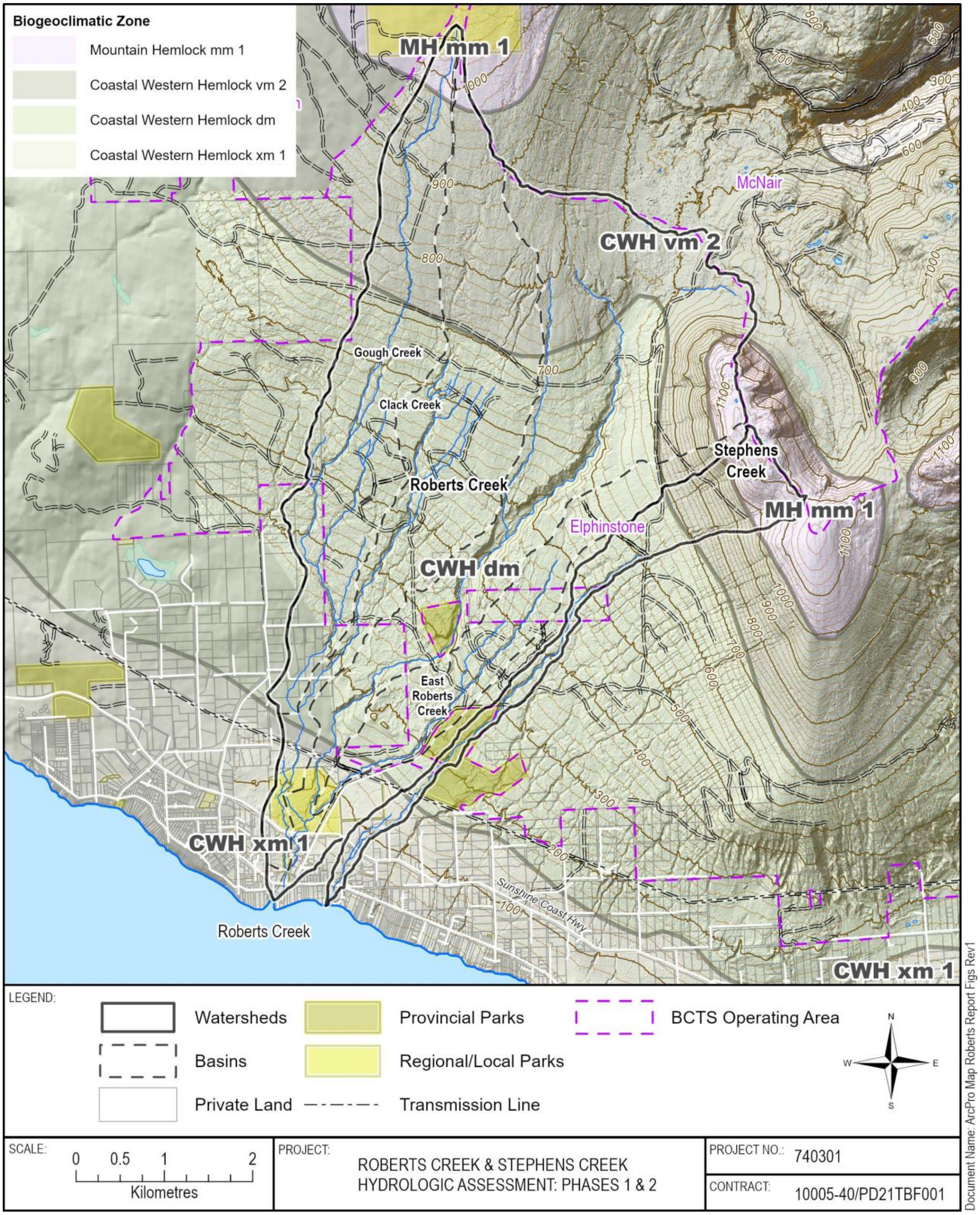

FIGURE 4.8 *Biogeoclimatic zones in the assessment area.*

The BEC subzone variants are a good proxy for identifying areas where the removal of forest cover may have a disproportional effect on runoff. In general, the wetter and colder the variant, the greater the potential for forest harvesting to increase streamflow.

4.6. CLIMATE

The assessment area lies within a coastal maritime climate that experiences relatively warm dry summers and mild wet winters. Snowfall occurs occasionally throughout the winter with transient snowpacks developing at middle- and upper-elevations. Seasonal snowpacks can develop at high elevations; however, this varies considerably from year to year. Similarly, snow on the ground at sea-level is not common, although does occur occasionally. To illustrate the inter-annual variability in snow cover across the assessment area, remotely sensed snow cover data from the National Operational Hydrologic Remote Sensing Center[61] is presented for two years in FIGURE 4.9.

According to the Pacific Climate Impacts Consortium (PCIC) data portal[62], 13 weather stations have operated along the Sunshine Coast between Langdale and Sechelt (TABLE 4.2). Of these stations, only two are currently operating: Gibsons Gower Point (Environment Canada Station 1043152, El. 34 m, 1961-present) and TS Elphinstone (BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development - Wildfire Management Branch Station 1002, El. 593 m, 2008-present) (MAP 1). The former is generally representative of lower elevations whereas the latter is representative of mid elevations in the assessment area.

The available weather data at Gibsons Gower Point and TS Elphinstone demonstrate that temperature patterns are relatively consistent in the area although elevation differences result in daily temperature difference by a few degrees on average (FIGURE 4.10). The available data also show that precipitation patterns are similar, both reflecting wet winters and dry summers (FIGURE 4.11). The higher elevation TS Elphinstone station, however, tends to receive about 40% greater precipitation annually than the Gower Point station. It is important to note that these stations are not equipped to measure snow, and therefore provide no indication of total snowfall or how often snow is on the ground.

Rainstorms can occur throughout the year; however, they are more prevalent in fall and winter as a result of frontal systems off the Pacific Ocean (FIGURE 4.12). At Gibsons Gower Point, the likelihood of a 24-hour storm in excess of 25 mm varies from 0.5% in June to 5.9% in November. At the higher elevation TS Elphinstone station, the same likelihood ranges from 1.1% in May to 9.7% in December. 24-hour storms in excess of 50 mm are rare at Gibsons Gower Point and have a 1-2% likelihood of

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[61] https://www.nohrsc.noaa.gov/interactive/html/map.html

[62] https://www.pacificclimate.org/data/bc-station-data

occurrence at TS Elphinstone between August and April. 24-hour storms in excess of 50 mm have not been observed at either weather station between May and July.

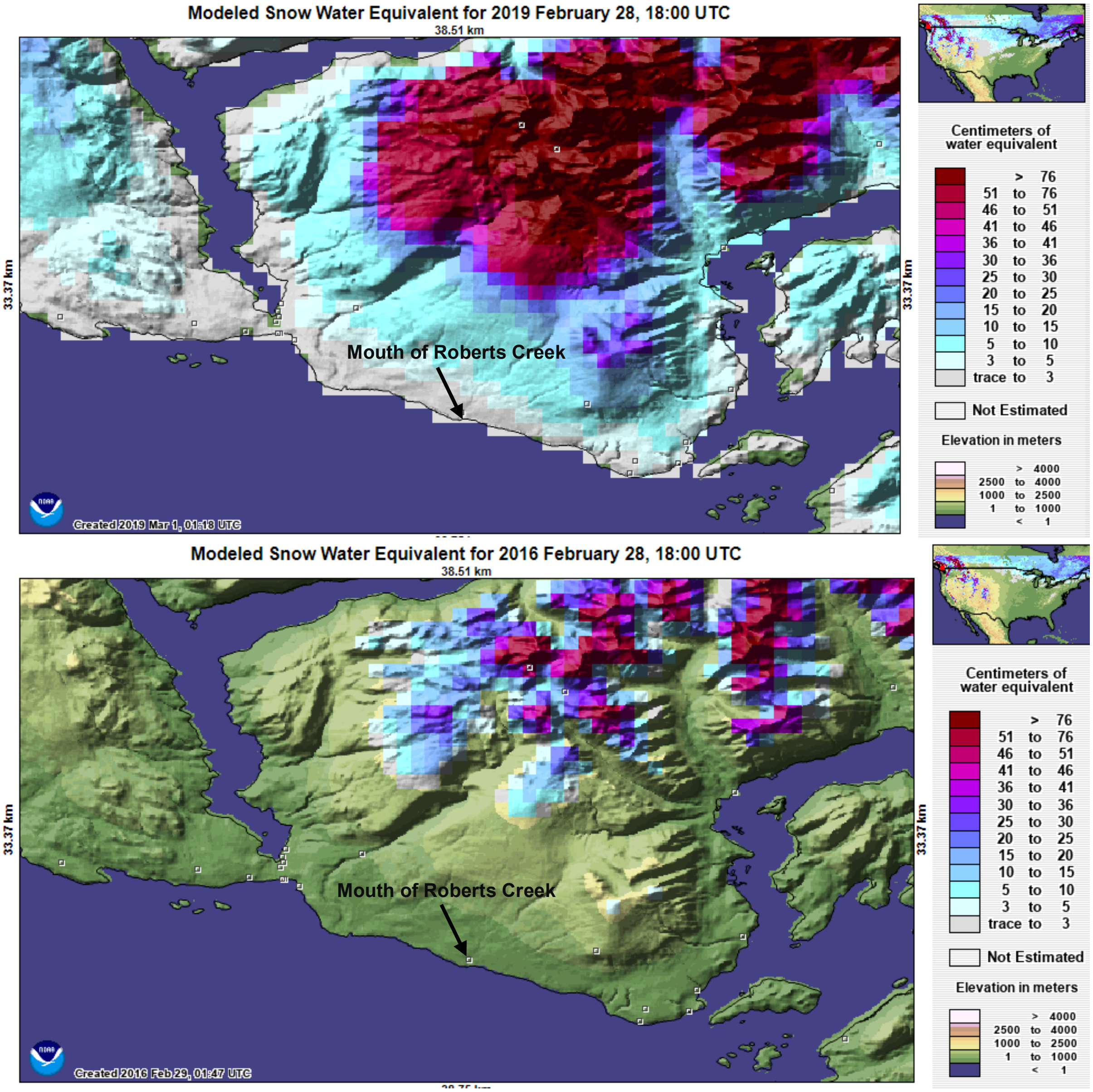

FIGURE 4.9 *Remotely sensed snow cover data for the assessment area. The upper plot shows snow cover for the end of February 2019. The lower plot shows snow cover for the same day in 2016. Maps sourced from National Operational Hydrologic Remote Sensing Center*[63].

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[63] https://www.nohrsc.noaa.gov/nsa/

TABLE 4.2 *Weather stations along the Sunshine Coast between Langdale and Sechelt (PCIC station data portal, 2021).*

Network Name	Native ID	Station Name	Lat.	Long.	Elev. (m)	Record Start	Record End
ARDA	104408	EXASPERATED	49.463	-123.714	110	1973-06-06	1975-11-20
ARDA	104327	HOOKED	49.438	-123.664	82	1973-09-28	1975-12-16
ARDA	104417	JOE SMITH CK	49.418	-123.570	290	1974-10-30	1975-12-16
ARDA	104307	ROBERTS PARK	49.433	-123.623	125	1973-05-30	1975-12-16
EC	1043150	GIBSONS	49.400	-123.517	62	1949-02-08	2006-07-31
EC	1043152	GIBSONS GOWER POINT	49.386	-123.541	34	1961-10-01	present
EC	1046791	ROBERTS CREEK	49.400	-123.683	4	1924-01-01	1942-11-30
EC	1046795	ROBERTS CREEK EAST	49.433	-123.617	143	1956-02-01	1960-12-31
EC	1047172	SECHELT	49.450	-123.700	86	2007-08-02	2017-12-31
ENV-AQN	M104273	LANGDALE FERRY TERMINAL	49.434	-123.472	15	1987-09-11	2016-08-09
FLNRORD-WMB	46	SECHELT ORCHARD	49.450	-123.719	75	1999-09-27	2009-11-04
FLNRORD-WMB	1002	TS ELPHINSTONE	49.428	-123.565	593	2008-03-08	present
MOTIm	12001	GIBSONS	49.407	-123.532	140	1988-10-31	1995-03-31

ARDA: Agricultural and Rural Development Act Network; EC: Environment Canada; ENV-AQN: BC Ministry of Environment; Air Quality Network; FLNRORD-WMB: BC Ministry of Forests, Lands, and Natural Resource Operations - Wildfire Management Branch; MOTIm: Ministry of Transportation and Infrastructure (manual).

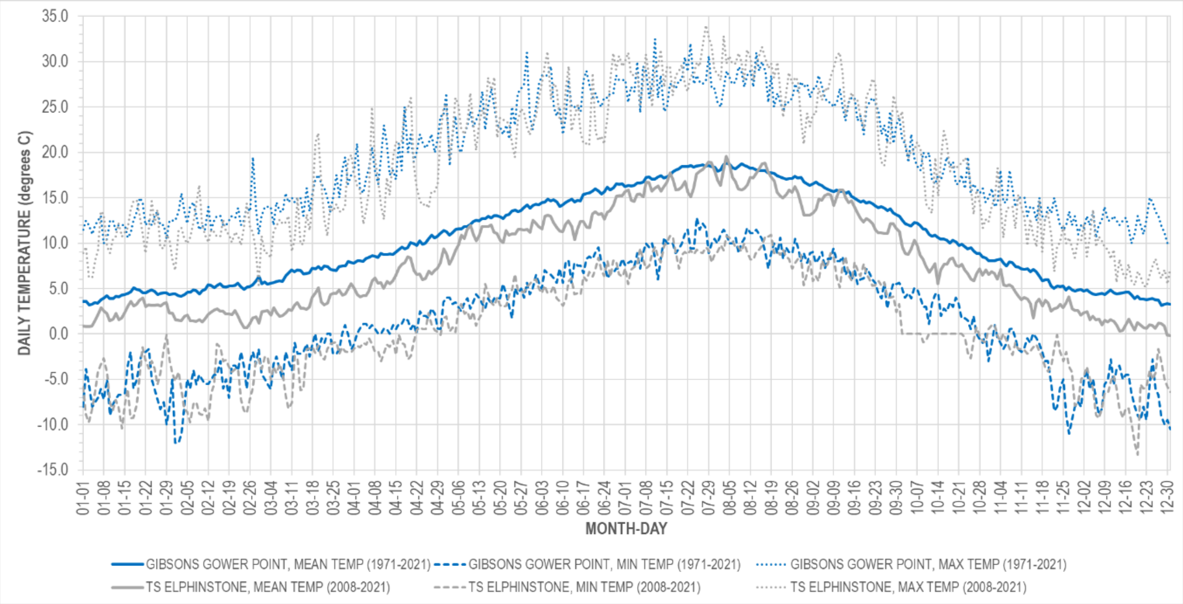

FIGURE 4.10 *Daily minimum, maximum and mean temperatures for Gibsons Gower Point (EC 1043152, El. 34 m, 1971-2021) and TS Elphinstone (FLNORD-WMB 1002, El. 593 m, 2008-2021).*

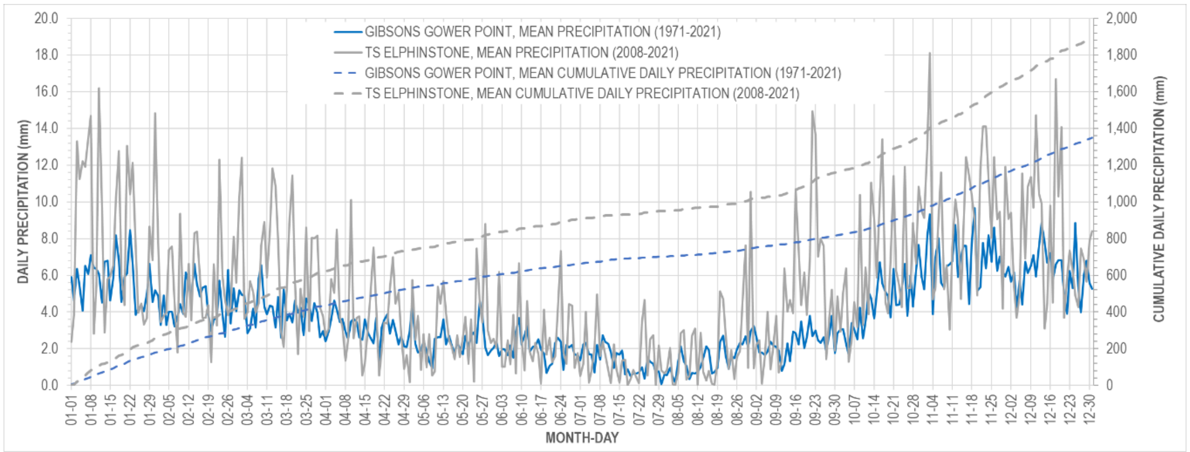

FIGURE 4.11 *Mean daily precipitation and cumulative daily precipitation for Gibsons Gower Point (EC 1043152, El. 34 m, 1971-2021) and TS Elphinstone (FLNORD-WMB 1002, El. 593 m, 2008-2021).*

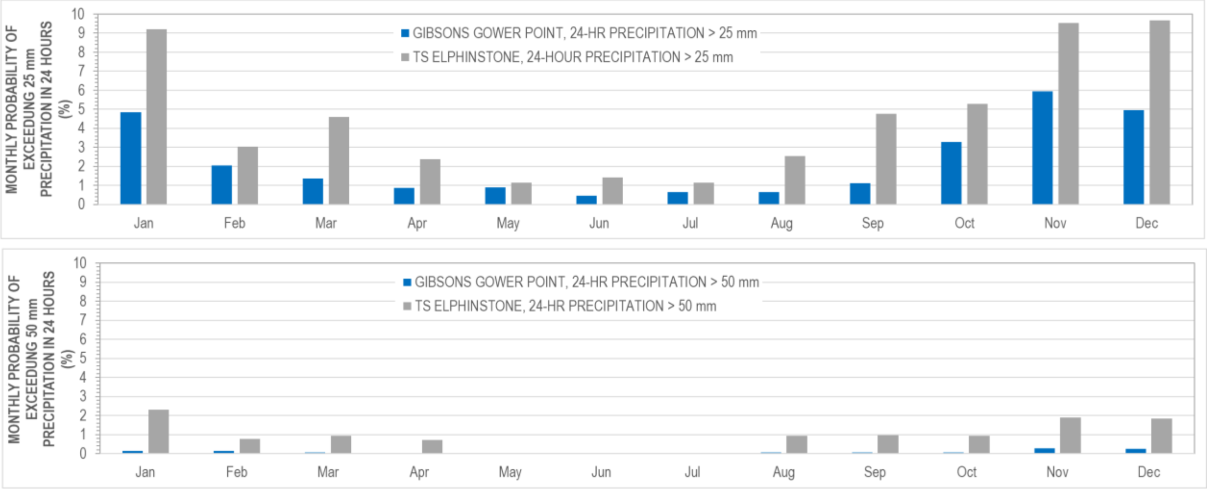

FIGURE 4.12 *Monthly probability of daily precipitation exceeding 25 mm (upper plot) and 50 mm (lower plot) on a monthly basis for Gibsons Gower Point (EC 1043152, El. 34 m, 1971-2021) and TS Elphinstone (FLNORD-WMB 1002, El. 593 m, 2008-2021).*

In order to characterize the climate throughout the assessment area, climate normals (for 1991-2020) were estimated using ClimateBC (version 7.40), an application that uses available weather station data and adjusts these to account for location, elevation and other factors (Wang et al., 2022). Historical climate normals were extracted at representative locations and elevations. This includes the following locations (TABLE 4.3, MAP 1):

- 150 m elevation: 49.435°, -123.627°;
- 600 m elevation: 49.465°, -123.596°; and
- 1,100 m elevation: 49.468°, -123.570°.

At lower elevations, as represented by “150 m elevation”, monthly mean temperatures are estimated to range from 3.9 °C in December to 17.7 °C in August. Annual precipitation is estimated to be 1,333 mm, of which about 3% falls as snow. At mid elevations, represented by “550 m elevation”, monthly mean temperatures range from 1.8 °C in December to 15.9 °C in August. Annual precipitation is estimated at 2,159 mm, with 7% of that falling as snow. At higher elevations, as represented by “1,100 m elevation”, mean monthly temperatures range from -0.3 °C in December to 14.0 °C in August. Annual precipitation is estimated to be 2,621 mm with 19% of that as snow. These data indicate that rainfall and to a lesser extent rain-on-snow are the dominant drivers of runoff in the assessment watersheds. However, it is important to recognize that the amount of precipitation as snow is represented as an average. As illustrated in FIGURE 4.9, there is tremendous variability in snow cover from year to year. Even though only a relatively small percentage of annual precipitation falls as snow, particularly at lower elevations, the snowfall typically occurs over a short period and has the potential to melt quickly, particularly during a warm rain-on-snow event (Floyd, pers. comm., 2023).

Under normal conditions, the assessment area is expected to have a climate moisture deficit (i.e., evapotranspiration exceeds precipitation) during summer. On average, lower elevations are expected to have a moisture deficit typically between May and August, whereas mid and upper elevations are typically in deficit in July and August (Wang et al., 2022). However, exceptions can occur (e.g., fall of 2022), where deficits persist well into the fall. This can have a direct influence on streamflows in late summer and fall.

When considering the effects of storms on peak flows and other hydrogeomorphic hazards, it is also important to consider shorter storm durations that occur over hours and days. Modelled precipitation for storms of different durations and intensities are summarized in TABLE 4.5. These data, which represent current conditions and future projections (discussed below) are derived from climate modelling by Western University (2021).

TABLE 4.3 *1991-2020 climate normals for representative elevation bands in the assessment area. Source: Wang et al. (2022).*

Month	**ID**	**150 m elevation**			**600 m elevation**			**1,100 m elevation**		
	lat.	49.435°			49.465°			49.468°		
	long.	-123.627°			-123.596°			-123.570°		
	elev.	150 m			600 m			1,100 m		
		Mean Temp (°C)	**Min Temp (°C)**	**Max. Temp (°C)**	**Mean Temp (°C)**	**Min Temp (°C)**	**Max. Temp (°C)**	**Mean Temp (°C)**	**Min Temp (°C)**	**Max. Temp (°C)**
Jan		4.1	2	6.1	1.8	-0.4	4	-0.5	-2.8	1.7
Feb		4.9	2.1	7.7	3.1	-0.6	6.9	0.1	-3.3	3.4
Mar		6.5	3.1	9.9	3.7	0.5	7	1	-2.2	4.1
Apr		9	5.2	12.9	6.4	2.6	10.2	3.3	-0.2	6.8
May		12.7	8.5	16.9	10.2	5.9	14.4	7.1	3	11.2
Jun		15	10.9	19	12.4	8.3	16.5	9.4	5.4	13.4
Jul		17.5	13.2	21.8	15.3	11	19.7	13.1	8.6	17.6
Aug		17.8	13.4	22.1	15.7	11.4	20	13.5	9.2	17.8
Sep		14.8	10.8	18.8	12.9	9	16.8	11	7.1	15
Oct		10.1	7.1	13.1	7.9	5	10.9	5.6	2.9	8.4
Nov		6.3	3.9	8.8	3.8	1.3	6.2	1.2	-1.3	3.7
Dec		4.1	1.9	6.2	1.6	-0.7	3.8	-0.8	-3.1	1.4
Annual		**10.2**	**-**	**-**	**7.9**	**-**	**-**	**5.3**	**-**	**-**

	Mean Precip. (mm)	**Precip. as snow (mm water equiv.)**	**Climatic moisture deficit (mm)**	**Mean Precip. (mm)**	**Precip. as snow (mm water equiv.)**	**Climatic moisture deficit (mm)**	**Mean Precip. (mm)**	**Precip. as snow (mm water equiv.)**	**Climatic moisture deficit (mm)**
Jan	207	12	0	359	46	0	393	107	0
Feb	135	6	0	226	21	0	248	81	0
Mar	141	3	0	253	30	0	281	121	0
Apr	94	1	0	196	14	0	233	75	0
May	68	0	18	126	3	0	148	18	0
Jun	55	0	40	112	1	0	131	5	0
Jul	34	0	70	61	0	37	79	1	14
Aug	40	0	50	49	0	35	59	1	21
Sep	79	1	0	143	3	0	155	6	0
Oct	153	1	0	200	3	0	247	13	0
Nov	224	9	0	342	36	0	371	91	0
Dec	204	10	0	262	34	0	307	95	0
Annual	**1,434**	**42**	**178**	**2,331**	**191**	**72**	**2,649**	**614**	**35**

4.7. CLIMATE VARIABILITY & CHANGE

4.7.1. El Niño/Southern Oscillation & Pacific Decadal Oscillation

In addition to climate variations associated with elevation (i.e., location) and seasons, the climate on the Sunshine Coast is influenced by large-scale atmospheric circulation patterns that occur over inter-annual time scales. The two most important are the Pacific Decadal Oscillation (PDO) and the El Niño/Southern Oscillation (ENSO) (BC MWLAP, 2002b). The PDO pattern is known to fluctuate between warm and cold phases roughly every 20-30 years. The ENSO relates to changing ocean currents and atmospheric pattern in the Indian and Pacific Oceans and predominantly impacts winter conditions every few years (Nelson et al., 2012). The cold, wet phase of the ENSO is known as a *La Niña* and the warm, dry phase of the ENSO is known as the *El Niño.*

There are six combinations of the PDO (cool and warm) and ENSO (cool, neutral, warm) phases that have been historically observed that affects regional climate. The potential for precipitation and temperature extremes tends to be greater when PDO and ENSO are in-phase. For example, when both PDO and ENSO are experiencing a cool phase more snow tends to accumulate, and conversely, when both PDO and ENSO are in the warm phase there tends to be a thinner snowpack. There is relatively poor predictive ability when PDO and ENSO are in opposite phases (e.g., cool-warm or warm-cool) (Wang et al., 2014). Patterns of ENSO and PDO between 1979 and 2020 are shown in FIGURE 4.13.

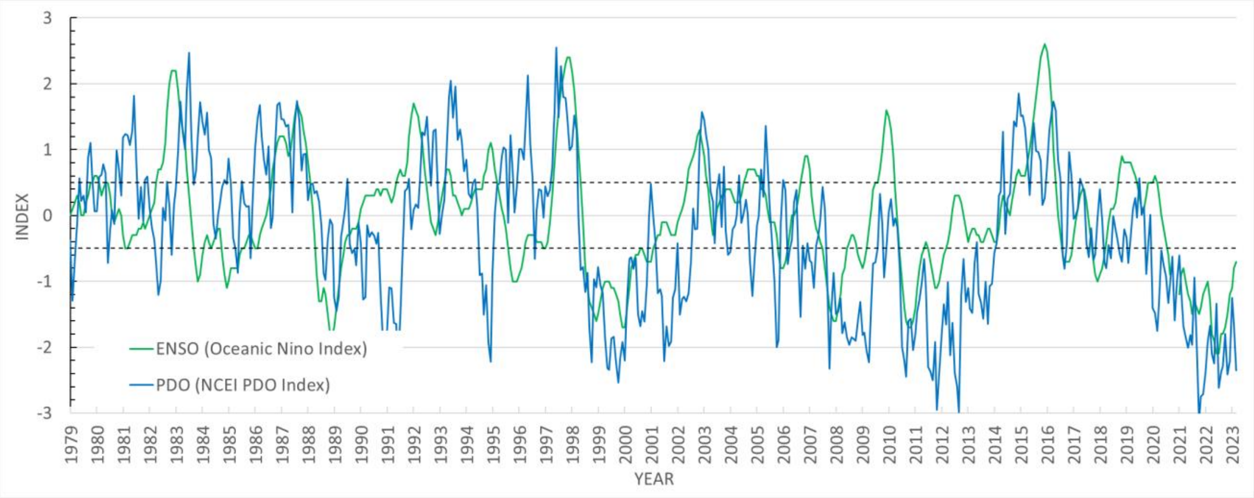

FIGURE 4.13 *ENSO and PDO Index patterns from 1979 – 2023. Horizontal lines roughly indicate boundaries between warm (> 0.5), neutral (0.5 to – 0.5), and cool (< -0.5) phases. ENSO data from NOAA (2020a) and PDO data from NOAA (2020b).*

4.7.2. Climate Change

There is scientific consensus that the Earth's climate is changing, primarily due to anthropogenic greenhouse gas emissions. This change has and will continue to affect the climate of the South Coast. According to the Pacific Climate Impacts Consortium (PCIC, 2013), warming has already occurred over the last century in all seasons in the region. A report by the British Columbia Ministry of Environment (BC MOE, 2016) indicates that the assessment area has experienced an increase average precipitation by 14% per century from 1900 to 2013. However, climate trend analyses in the Pacific Northwest suggest that summertime precipitation has been decreasing over the last several decades, resulting in increased drought (Abatzoglou et al., 2014; Kormos et al., 2016). Such effects have been realised locally as the Sunshine Coast has experienced Stage 4 "Severe" drought in five of the past nine years. This included the fall of 2022, forcing the Sunshine Coast Regional District to declare a state of local emergency that banned non-essential commercial water-use (MacDonald, 2022). As of August 28, 2023, the Sunshine Coast is currently experiencing Stage 3 "Acute" drought. ENSO conditions over the past eight years have been largely neutral suggesting the drought conditions may be driven by climate change.

Understanding future climate scenarios is generally conducted by analyzing the output of a number of global climate models. The Plan2Adapt tool[64] uses an ensemble of 12 different global climate models (GCMs)[65], each using one run of the RCP 8.5 (high emissions) greenhouse gas emissions scenario[66]; this set of projections is referred to as the "ensemble" (PCIC, 2021). These projections are statistically downscaled using empirical climate data to produce predictions at a 4 km resolution. Projections for the Sunshine Coast are summarized in TABLE 4.4. The mean value derived from the ensemble of climate model projections suggests the mean annual temperature is currently (i.e., 2020's) 1.6 °C higher than the 1961-1990 mean annual temperature and will be 3.0 °C higher by the 2050s and 4.7 °C higher by the 2080s.

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[64] Accessible at: Plan2Adapt.ca. All projections are referenced to the 1961-1990 period.

[65] Each GCM comes from a different modelling centre (e.g., the Hadley Centre (UK), National Centre for Atmospheric Research (USA), Geophysical Fluid Dynamics Laboratory (USA), and Commonwealth Scientific and Industrial Research Organisation (Australia).

[66] By the end of the 21st century, the RCP 8.5 scenario from the fifth phase of the Coupled Model Intercomparison Project (CMIP5) includes an atmospheric concentration of greenhouse gases, expressed as carbon dioxide (CO2) equivalent, of approximately 950 ppm.

TABLE 4.4 *Summary of climate change projections for the Sunshine Coast. Refer to PCIC (2021) for details on climate modelling and down-scaling method.*

Climate Variable	Season	Projected change from 1961-1990 period			
		by 2050s[67]		by 2080s[68]	
		Median	Range	Median	Range
Mean Temperature (°C)	Annual	+3.0°C	+2.0°C to +4.1°C	+4.7°C	+3.5°C to +6.4°C
Precipitation (%)	Annual	-1.0%	-5.0% to +3.4%	+4.8%	-4.5% to +10%
	Summer	-13%	-40% to +1.4%	-22.0%	-55% to -5.7%
	Winter	+0.97%	-4.0% to +5.4%	+9.7%	-3.5% to +17%
Snowfall (%)[69]	Annual	-54%	-61% to -45%	-75%	-83% to -57%
	Winter	-56%	-59% to -45%	-69%	-81% to -54%
	Spring	-58%	-68% to -38%	-83%	-91% to -55%

Projected precipitation changes have relatively higher uncertainty than temperature changes, partly due to the challenges of modelling complex terrain in BC. Nevertheless, general trends from these modelling results indicate that on an annual basis precipitation may increase slightly by the 2080s. However, the models suggest a shift towards drier summers and wetter winters, with a greater proportion of rain falling instead of snow at higher elevations. These projections are based on relatively coarse spatial data and present one average response for the Sunshine Coast. One study projected similar precipitation trends for Campbell River on Vancouver Island, BC, with increased precipitation in the winter and a decrease in the summer (Zwiers et al., 2011). However, the authors noted greater uncertainty in the projected magnitude of change for winter versus summer precipitation. Due to differences in elevations throughout the Sunshine Coast, there will likely be considerable variation in terms of how a specific watershed responds to climate change. The highest elevations in the assessment watersheds, which already receive limited annual snowfall, are projected to receive even less in the future as precipitation falls increasingly in the form of rain as opposed to snow. As a result, the hydrologic regime of the assessment streams will be increasingly dominated by rainfall (Schnorbus et al., 2014; Islam et al., 2017; 2019; Jeong and Sushama, 2017). However, there is still a possibility for more frequent anomalous snowfall with the shift in weather patterns, resulting in snow still occurring to sea level on occasion (Floyd, pers. comm., 2023).

Given the relatively limited storage available in the assessment watersheds (i.e., in soils and as groundwater), streamflow changes are expected to reflect precipitation changes with increases expected during winter (up to 9.7% more by the 2080s, largely in the form of rain) and reductions

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[67] Refers to period 2040-2069.

[68] Refers to period 2070-2099.

[69] This variable may have a low baseline value. Percent changes from a low baseline value can result in deceptively large percent change values. A small baseline can occur when the season and/or region together naturally make for zero or near-zero values. In other words, given the low proportion of precipitation as snow on ***average***, a small change in magnitude can translate into a large relative change (i.e., change in %).

during summer (as much as 22.0% less by the 2080s). The recent drought conditions experienced on the Sunshine Coast in late summer of 2023, and drought conditions and state of local emergency in late summer and fall 2022 provide some indication of the possible adverse effects of such reductions in precipitation[70].

Climate warming is also projected to increase high-intensity precipitation (Burn et al., 2011), which has potential to result in a greater frequency and magnitude of flooding (Sobie, 2020). For example, in their evaluation of the human influence on the November 14, 2021 British Columbia floods, Gillett et al. (2022) concluded that human-induced climate change has increased the probability of such extreme streamflow events by roughly 120-330%. Sharma and Déry (2020) found a statistically significant increase in the frequency of landfalling atmospheric rivers between 1979 and 2016. Moreover, they found a higher likelihood of occurrence of such events during neutral ENSO phases and positive phases of the PDO (Sharma and Déry, 2020). Murdock et al. (2016) found that for Metro Vancouver, three-hour extreme precipitation events that would normally be exceeded every ten years (i.e., ten-year return period), are projected to occur almost every three years by the 2050s.

The intensity of precipitation events is commonly evaluated using intensity-duration-frequency (IDF) curves, that show the relationship between storm intensity and magnitude of precipitation that is expected for a given return period. The IDF_CC tool (Western University, 2021) provides estimates for how IDF curves will change into the future, given a number of different greenhouse gas emissions scenarios. It bases these estimates on gauge data (i.e., Gibsons, Environment Canada Station 1043150) along with downscaled global climate models (Schardong et al., 2020).

TABLE 4.5 presents the estimated total precipitation for a range of storm durations and return periods (i.e., magnitude) under "current" conditions at Gibsons. In addition, the table presents projected storm-related precipitation totals for the 2050s and 2080s based on an ensemble of 23 global climate models (GCMs) and RCP 8.5[71]. By the 2050s, storms with 2-year, 10-year, and 50-year return periods, are expected to deliver increased rainfall by 6-11%, 11-14%, and 12-24%, respectively. By the 2080s, storms with 2-year, 10-year, and 50-year return periods, are expected to deliver increased rainfall by 14-20%, 22-24%, and 30-38%, respectively. These results indicate that the intensity of rainstorms is projected to increase into the future, and that the greatest increases are projected to be associated with high intensity, low frequency storms. This means that relatively infrequent storm events, for example, an event magnitude associated with a 50-year return period, can be expected to occur more frequently under future climate scenarios. This is an important consideration when designing new bridges,

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[70] https://vancouversun.com/news/local-news/sunshine-coast-drinking-water-supply-issues-culminate-in-state-of-emergency

[71] RCP 8.5 is the representative concentration pathway resulting in radiative forcing of 8.5 W/m^2 by 2100 and where radiative forcing continues to rise beyond 2100. This RCP represents a scenario that leads to the greatest climate change impacts when compared to other RCPs.

culverts or drainage infrastructure, or when assessing the capacity of existing infrastructure to future floods. It is also an important consideration in designing and planning erosion and sediment control measures during construction activities.

TABLE 4.5 *Modeled total precipitation (mm) for storms of different intensities and durations at Gibsons (Environment Canada Station 1043150)*[72] *(Western University, 2021).*

Storm Duration (hours)	Total Precipitation (mm)								
	Return Period								
	2-Year			10-Year			50-Year		
	Current	2050s	2080s	Current	2050s	2080s	Current	2050s	2080s
1	10.7	11.2	12.0	15.0	17.0	18.5	19.1	23.7	25.7
2	15.0	15.9	17.1	22.0	24.5	26.8	28.1	35.9	38.8
6	26.2	29.1	31.3	33.4	37.6	40.9	39.8	44.5	49.1
12	37.4	40.9	44.1	47.6	54.4	58.7	56.7	68.6	73.7
24	54.9	59.9	64.6	70.4	79.7	87.0	84.0	100.8	110.4

4.8. HYDROLOGY

The assessment area is located within the Western South Coast Mountains hydrologic zone (Ahmed, 2017). As noted above, lower relief coastal watersheds, such as the assessment watersheds have a pluvial (rain-dominated) hydrologic regime[73] in which streamflows are normally generated by fall and winter rainstorms. According to Eaton and Moore (2010), the temporal pattern of streamflow closely follows that of rainfall. Highest monthly stream discharge typically occurs in November and December when the most intense frontal systems move over the coast of BC. The lowest monthly flows occur in July and August, when high-pressure systems typically direct precipitation-generating weather systems away from southern BC. Since the assessment area does receive a modest amount of snowfall at higher elevations, snowmelt can supplement streamflows during rain-on-snow events, especially during warm rain-on-snow events associated with atmospheric rivers. Such rain-on-snow events are generally recognized as having the potential to produce relatively high magnitude peak flow events (Pomeroy et al., 2016; Trubilowicz and Moore, 2017; van Heeswijk et al., 1996). Moreover, given the occasional occurrence of snowfall at or near sea-level, rain-on-snow can occur across all elevations.

There are relatively few Water Survey of Canada (WSC) hydrometric stations on the Sunshine Coast (TABLE 4.6); however, one is located within the assessment area. The station Roberts Creek at Roberts Creek (WSC No. 08GA047) is currently active and has a lengthy record. This record is potentially influenced by water extractions upstream (i.e., it has a "regulated" flow regime according to the WSC).

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[72] Latitude: 49.40° N, Longitude: -123.51° E

[73] Occasionally, a melting snowpack within a limited area at the highest elevations of the assessment watersheds may augment storm-related runoff.

The only nearby station with a lengthy record of natural flows is Chapman Creek above Sechelt Diversion (WSC No. 08GA060); however, it was discontinued in 1988. Chapman Creek also drains considerably higher relief terrain with a greater snowpack. As a result, Chapman Creek has a hybrid flow regime in which snowmelt is a major contributor to runoff along with rainfall, unlike the rainfall-dominated runoff in the assessment area.

TABLE 4.6 *Water Survey of Canada hydrometric stations along the Sunshine Coast between Langdale and Sechelt (Province of BC, 2021f).*

Station No.	Station Name	Natural / Regulated	Record Start	Record End
08GA051	Langdale Creek at Highway No. 101 near Gibsons	Natural	1965-05-11	1968-09-30
08GA050	Chaster Creek above Highway No. 101	Natural	1965-05-11	1965-09-30
08GA047	Roberts Creek at Roberts Creek	Regulated	1959-04-28	present
08GA046	Chapman Creek near Wilson Creek	Regulated	1959-04-27	1970-12-14
08GA060	Chapman Creek above Sechelt Diversion	Natural	1970-07-02	1988-10-25
08GA078	Chapman Creek below Sechelt Diversion	Regulated	1993-01-01	2003-12-31

In spite of the streamflow record for Roberts Creek at Roberts Creek potentially reflecting some human influence, it provides a good representation of the magnitude and pattern of streamflows in the assessment area. This record also demonstrates the relatively rapid runoff generation in response to storms, which is a function of several watershed characteristics, including shallow soils, gullied terrain and limited lake and wetland storage. FIGURE 4.14 presents the annual hydrograph of daily unit discharge for Roberts Creek at Roberts Creek in units L/s/km^2. Unit discharge allows the comparison of streamflows between streams with differing drainage areas[74] [75].

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[74] To calculate discharge in m^3/s, multiply the unit discharge in L/s/km^2 by [0.001 x drainage area in km^2].

[75] Runoff can also be presented in unit-based terms of mm. However, the period over which the runoff occurs should be specified (e.g., annual, monthly, daily).

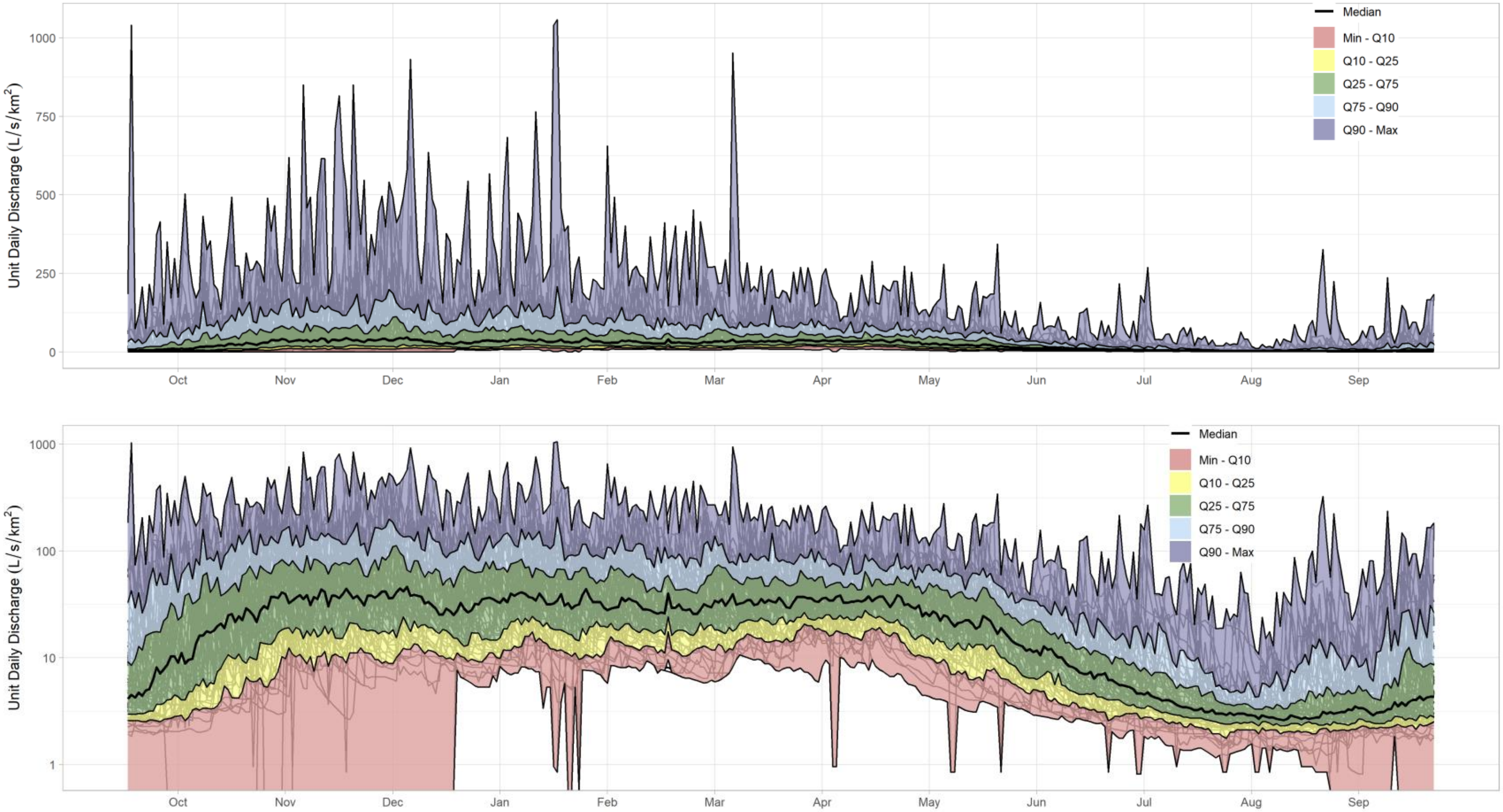

FIGURE 4.14 *Daily streamflow from the Water Survey of Canada (WSC) hydrometric station Roberts Creek at Roberts Creek (WSC No. 08GA047) from 1959-present. The lower plot has a logarithmic vertical scale to better visualise low flows. The black line represents the median daily discharge over the period of record. Selected percentile flows (10th, 25th, 75th and 90th), whereby the Q10, for example, represents the 10% lowest flows, are also shown to demonstrate the range in historical flows. Note the different vertical scales on the upper and lower plots. The Min-Q10 records show zero or near zero values from September to December (note the y-axis does not go to zero).*

TABLE 4.7 summarizes the recorded streamflow statistics for Roberts Creek hydrometric station as well as the estimated streamflow statistics Stephens Creek. These estimates are based on data presented by Ahmed (2017). Due to the close proximity and similar physiography, the same unit discharge of Roberts Creek was used for Stephens Creek.

TABLE 4.7 *Estimated streamflows for the two watersheds of interest based on the regional hydrometric data presented by Ahmed (2017).*

Stream/Location:	**Roberts Creek at Roberts Creek (WSC 08GA047)**		**Stephens Creek at the mouth**	
Drainage area (km^2):	29.4		2.52	
Median elevation	606		660	
Normal annual runoff (mm)	1089		1089	
Normal annual unit discharge (L/s/km^2):	3.45		3.45	
Normal annual discharge (m^3/s):	1.01		0.087	
Normal monthly discharge:	**Proportion of normal annual discharge**	**m^3/s**	**Proportion of normal annual discharge**	**m^3/s**
Jan	0.15	0.152	0.15	0.013
Feb	0.11	0.111	0.11	0.010
Mar	0.11	0.111	0.11	0.010
Apr	0.10	0.101	0.10	0.009
May	0.08	0.081	0.08	0.007
Jun	0.04	0.040	0.04	0.003
Jul	0.02	0.020	0.02	0.002
Aug	0.01	0.010	0.01	0.001
Sep	0.02	0.020	0.02	0.002
Oct	0.07	0.071	0.07	0.006
Nov	0.15	0.152	0.15	0.013
Dec	0.15	0.152	0.15	0.013
Peak flow & Low flow estimates:	**Peak daily flow (m^3/s):**	**7-day low flow (m_3/s)**	**Peak daily flow (m^3/s):**	**7-day low flow (m_3/s)**
2-year	22.5	0.061	1.9	0.0052
5-year	36.0	0.052	3.1	0.0044
10-year	45.0	0.047	3.9	0.0040
20-year	54.0	0.038	4.6	0.0032
50-year	67.5	0.033	5.8	0.0028
100-year	76.5	0.028	6.6	0.0024

4.9. HYDROLOGIC EFFECTS OF CLIMATE CHANGE

As described in Section 4.7.2, climate change will affect both temperature and precipitation in British Columbia and the Sunshine Coast for years to come. According to the Pacific Climate Impacts Consortium (PCIC, 2013), warming has already occurred over the last century in all seasons in the South Coast region. The South Coast is likely to see continued warming for several decades to come (PCIC, 2013, 2021). Despite an increase in average annual precipitation over the last century (BC MOE, 2016), summer precipitation has been decreasing (Abatzoglou et al., 2014; Kormos et al., 2016). Although projected precipitation changes are less certain, annual precipitation is projected to decrease by 1.0% by the 2050s and increase by 4.8% by the 2080s. More importantly, decreased precipitation is projected in summer by 13% and 22% by the 2050s and the 2080s, respectively. In winter, precipitation projections vary, with the median projection increasing by 0.97% by the 2050s and 9.7% by the 2080s (TABLE 4.4).

Changes to air temperature and precipitation are projected to decrease snow accumulation, increase winter rainfall, and promote earlier snowmelt (Winkler et al., 2010b; Hatcher and Jones, 2013; Schnorbus et al. 2014; Islam et al., 2017, 2019). A recent study evaluated 46 long-term streamflow gauges in the United States and Canada to determine changes to the flow regime and found an increased influence of rainfall on flood regimes (Burn and Whitfield, 2023). In the assessment watersheds, this is expected to result in thinning of an already limited and/or transient snowpack. As a result, snow is expected in the long-term to play a decreasing role in the annual hydrograph. Nonetheless, snowfall is still expected to occur in the future, and across all elevations (Floyd, pers. comm., 2023), as demonstrated several times in recent years. Snow is therefore expected to continue to contribute to flooding during fall and winter rain-on-snow events.

Additionally, the severity of individual rainstorms is expected to increase in the region, particularly for high intensity, low frequency winter storms and atmospheric rivers (Section 4.7.2). Given rainfall is the dominant driver of runoff in the assessment streams, there is an increased potential for high winter streamflows in the future (Musselman et al., 2017).

Climate change will also affect the timing, duration, and magnitude of low flows in the assessment streams. In addition to the reduction of an already limited or transient snowpack, projected reductions in summertime precipitation will directly reduce late summer and early fall streamflows and may increase the duration of zero or near-zero flow conditions already noted along some of the assessment streams, especially those that have been subject to sedimentation or aggradation from past fluvial activity.

4.10. LAND USE & FOREST COVER DISTURBANCE

An understanding of historical context within the assessment area is important to understand the current condition and natural processes as well as for projecting risks associated with future forest development. The primary disturbance agents identified in the assessment area includes land clearing and residential and commercial development (including a golf course) on the lower slopes and forestry on Crown Land along the mid and upper slopes. In addition, major linear infrastructure, including as the Sunshine Coast Highway (Highway 101) and BC Hydro transmission line rights-of-way (ROWs), as well as many public roads are present in the area. The highway and transmission line ROWs runs roughly parallel to the coast at elevations of about 100 m, and 200 m, respectively. Recreational use on Crown land is widespread, with several hiking, mountain biking, equestrian and ATV trails located throughout the assessment area.

4.10.1. Forestry

The assessment area has a long history of development-related forest cover disturbance with a majority of the area logged or affected by wildfire at some time since the late 19th century. Forests currently consist of maturing second growth or regenerating stands following second-pass harvesting; this is clearly evident by the mosaic of forest ages and canopy heights in the area (FIGURE 4.15 - FIGURE 4.17). Approximately 9% of the assessment area stands are estimated to be in excess of 150 years old.

A review of historical air photos indicates that as urban and rural development progressed along the lower slopes between Gibsons and Roberts Creek, logging occurred within the second growth stands on the upper slopes. By 1947, logging by clearcutting was noted between 400 m to 700 m elevation along most of the assessment area. Access was primarily from the Sechelt Roberts FSR. Between 1967 and 1976, logging expanded further upslope of the original openings towards the height of land. Meanwhile the original openings were regenerating, albeit deciduous species tended to colonize moist area along gullies and minor streams. This may have affected the water balance along riparian areas, with increased vegetative demands during the growing season. Logging after 1976 appears to have occurred at a slower rate, with several relatively small openings established through the 1980s and 1990s. During this period some private land logging was noted as was some research trials in the Roberts Creek Research Watershed (Section 4.11).

According to the Sunshine Coast Museum & Archives[76], coastal logging outposts were established in the area before any towns were developed. In the Gibsons area in the late 19th century, timber harvesting provided an opportunity for agricultural development. Between 1900 and 1930 logging in the area supported several mills. Early on, logs were transported by horses, oxen and manual labour;

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[76] https://www.sunshinecoastmuseum.ca/early-logging.html

however, after 1914 logging began to mechanize, and by the 1930s the use of chainsaws, steam donkeys which winched logs from the bush, flumes, and later, truck logging for transport became commonplace. In 1906, a major wildfire near Leek Road to the east of Stephens Creek (in the vicinity of lower Higgs Brook) spread over 5 km towards Gibsons, burning a mill, log flume and considerable timber throughout the area. Although the fire paused logging activity for a time, it became a catalyst for expanded settlement on the Sunshine Coast. Harvesting in Roberts Creek began between 1907 and 1910, with logs being transported to the ocean via a flume in neighboring Flume Creek (Madrone, 2012; Statlu, 2020).

The distribution of forest ages within the assessment area (FIGURE 4.15) provides some indication on levels of past forest disturbance. There are a mix of seral stages (early seral, mid-seral and mature-seral) with less than 10% of the forest stands older than about 150 years (i.e., old-seral). Mature stands are generally located in the lower two thirds of the assessment area. Forest age distributions for each assessment watershed are provided in Section 6.1.2. The level of forest disturbance typically peaked around 71-80 years ago (i.e., between 1941-1950) for the entire assessment area. In Stephens Creek, the peak level of forest disturbance occurred between 61-70 years ago (i.e., between 1951-1960).

The age of a stand is also indicative of relative water consumption. This is a result of differences in site-level evapotranspiration rates for different seral stages (discussed further in Section 6.1.2). As such, the pie charts presented in FIGURE 4.15 and FIGURE 6.6 are broken into four classes, meant to represent relative water consumption. On these plots, blue, red, yellow and green represents stands with ages 0-10 years, 11-40 years, 41-80 years, and over 80 years, respectively. The potential implications of stand age distributions on low flows is discussed further in Section 6.1.2.

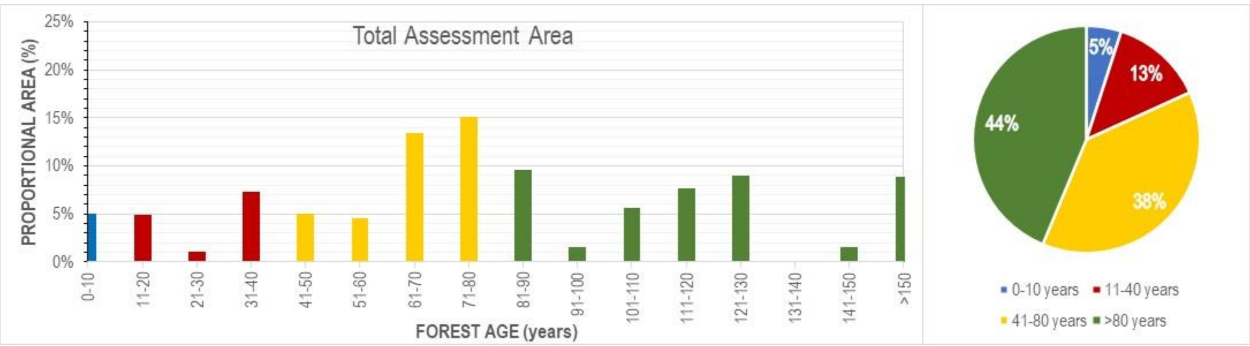

FIGURE 4.15 *Distribution of forest ages in the assessment area. The histogram presents age classes by decade. The pie chart shows stand age distribution for four age classes.*

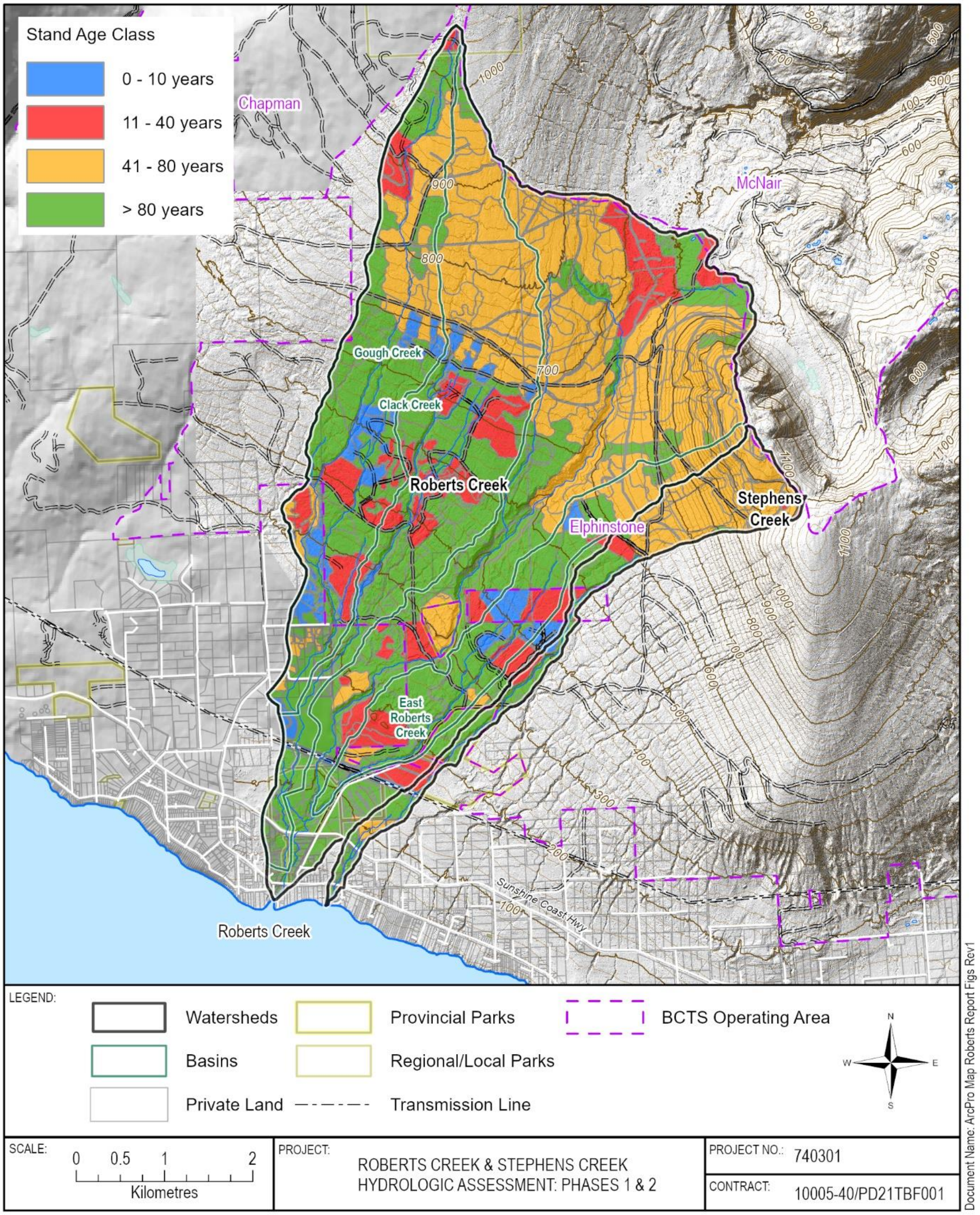

FIGURE 4.16 *Spatial distribution of forest stand ages within the assessment area.*

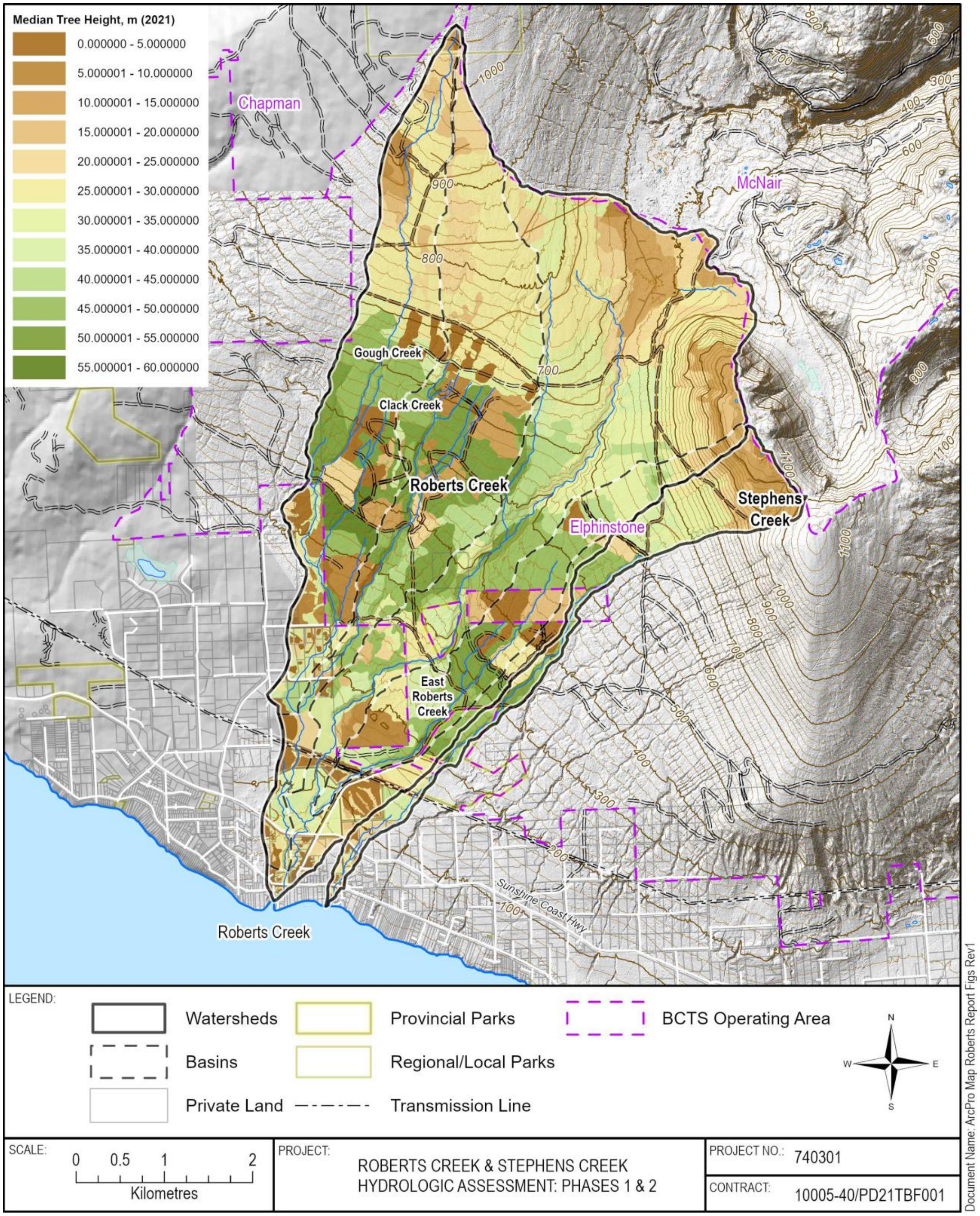

FIGURE 4.17 *Spatial distribution of projected (2021) forest canopy heights in the assessment area.*

4.10.2. Residential and Commercial Areas

Private property within the assessment area is primarily concentrated downstream of Highway 101, although there are some residences along the lower reaches of Gough and Clack Creek. These properties support varied land uses, including residential, commercial, agricultural and recreational. Private land accounts for 11.4% of the Roberts Creek watershed and 10.8% of the Stephens Creek watershed. (TABLE 4.1). Land clearing is evident over much of this area (FIGURE 2.1, FIGURE 4.17, FIGURE 4.19). For the purposes of hydrologic recovery modelling (Section 6.1.1), we have assumed that cleared areas on private land will be devoid of mature forest canopy indefinitely.

The hydrology of the lower portion of the assessment area has been influenced by various levels of urban development. Permanent land clearing, paving, and implementation of storm management infrastructure has likely changed the runoff response in the lower portions of the assessment watersheds, although to varying degrees. Observations such as these may be cause for concern, depending on downstream values and their sensitivities, and are a major reason that has driven efforts over the last couple decades to improve stormwater planning by local governments (Stephens et al., 2002). We are aware the SCRD, in cooperation with the BC Ministry of Transportation and Infrastructure, has had urban stormwater assessments done, intended to help guide infrastructure planning and design (Delcan, 2009). With the anticipated increase in higher density residential communities as population increases, and a transition from open crop farming to greenhouse farming, Delcan (2009) provided estimates on projected changes to streamflow in the East Roberts Creek basin. Projected increases for the 2- year to 200-year return period peak flow events ranged from roughly 3% to 14% depending on the stream. Delcan (2009) recommended that one mitigation strategy would be to require on-site vegetation and tree canopy retention with new development. They further recommended that the SCRD evaluate the results from the Tree Canopy Research Project[77] at the University of British Columbia and potentially update their existing Tree Cutting Bylaw (No. 350, 1991)[78].

There is also an abundance of public and private roads distributed across the lower portions of the assessment area. These roads can alter drainage patterns as runoff is conveyed off of road surfaces and into adjacent ditch lines. Water is then transported along ditches until the ditch discharges into a stream. Of note is the Sunshine Coast Highway which runs perpendicular to most of the assessment streams (MAP 1).

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[77] https://ece-treecanopy.sites.olt.ubc.ca/

[78] It is unknown whether these recommendations have since been applied by the SCRD.

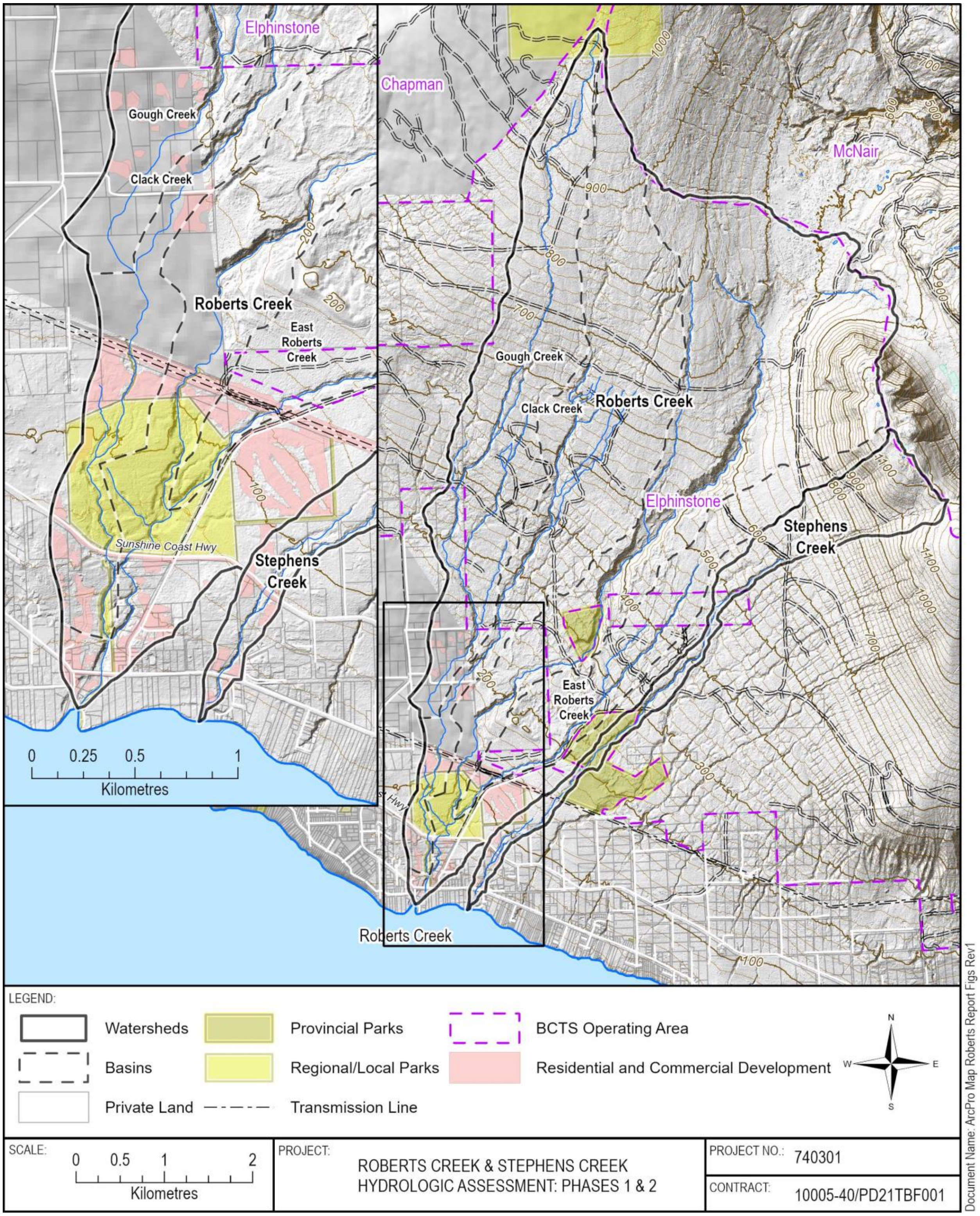

FIGURE 4.18 *Residential and commercial development within the assessment area.*

4.10.3. Biotic Disturbances

According to provincial surveys, natural disturbance agents have had moderate effects within the assessment area (Province of British Columbia, 2021e). Approximately 250 ha of the upper elevation portion of the Roberts Creek watershed has experienced light to moderate Western Hemlock Looper disturbance in 2019 and 2020. In addition, there is 6.6 ha of Armillaria root disease identified in the eastern portion of the Roberts Creek watershed between 140 and 200 m elevation in 2014 and 13.4 ha of White Pine Blister Rust and Douglas-fir Beetle overlapping the eastern portion of the Roberts Creek and Stephens Creek watersheds between an elevation of 140 and 200 m in 2021.

4.10.4. Wildfire

According to the provincial wildfire database (Province of British Columbia, 2021d), a 1 ha wildfire occurred in 1946 along the western boundary of the Roberts Creek watershed near the 120 m elevation. No data is available regarding the major 1906 wildfire noted in Section 4.10.1.

While thinning stands (i.e., selective harvest), in conjunction with prescribed burning, can be an effective management option for mitigating wildfire risk in some wildfire regimes (Prichard et al., 2021), it may not be a suitable option for the assessment area. Halofsky et al., 2020 states that in wet forests of the Pacific Northwest, lowering stand density, reduces competition between trees, which can increase water availability. However, given that wetter, coastal forests of the Pacific Northwest generally experience infrequent, stand-replacing wildfire during periods of extreme drought, thinning of these forests may not significantly alter wildfire risk (Halofsky et al., 2018), although the fire regime may change with climate change.

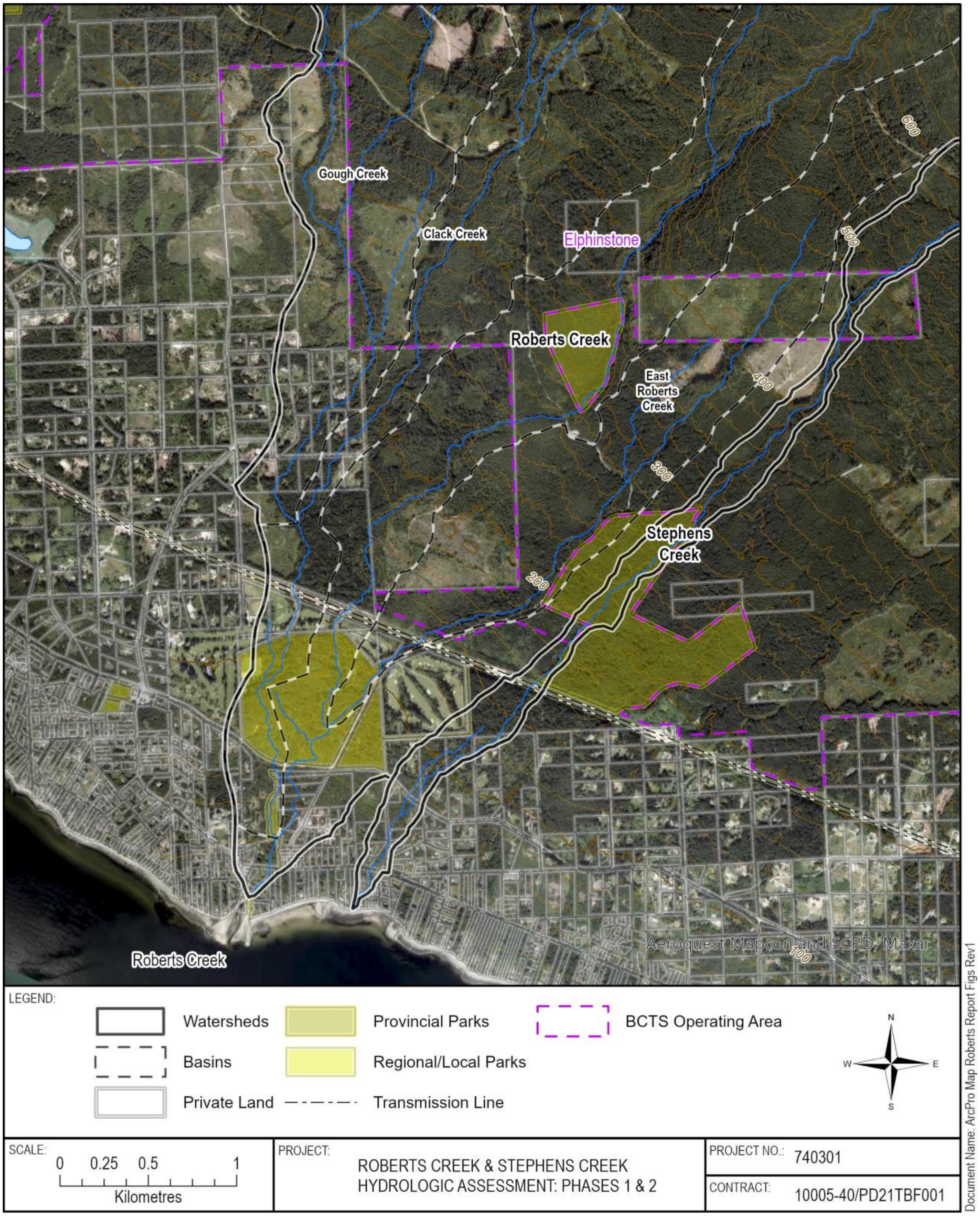

FIGURE 4.19 *Satellite image (2021) of the lower elevations of the assessment area showing the extent of land clearing and urban development.*

4.11. ROBERTS CREEK STUDY FOREST

The Roberts Creek Study Forest (RCSF) is located within the western portion of the assessment area and was established to demonstrate, describe and compare a wide range of approaches for harvesting and managing lower elevation (i.e., 350-590 m elevation) Douglas-fir dominated ecosystems in the CWH dm biogeoclimatic zones. Specific objectives of the RCSF included: 1) evaluation of harvesting economics and refinement of skills related to development and layout of alternatives; 2) monitoring planted and natural regeneration growth and development; 3) monitoring windthrow, and 4) measuring the effects of alternative harvesting systems on local hydrology including water quality and quantity (BC Ministry of Forests, 2001). The Study Forest included a demonstration block established in 1993 with a second pass in 1999, the Phase 1 blocks established in 1996/1997, and Phase 2 blocks established primarily for hydrology research in 1998/1999.

Of the several studies conducted in the RCSF[79], two studies with some relevance to this assessment included an examination of the influence of alternative silviculture systems on streamflows in small S6[80] stream catchments (Hudson, 2001) and sediment production from blowdown (Hudson and D'Anjou, 2001).

Hudson (2001) applied the paired watershed approach[81], which involved comparing peak flows generated from a control catchment to those generated from the treatment catchments (i.e., different silvicultural systems). The preliminary results of the study, however, were variable and generally inconclusive, albeit some differences in snow accumulation and melt dynamics were observed between the treatments (i.e., the edges of the strip shelterwood treatment generally had less snow than variable retention treatment).

Hudson and D'Anjou (2001) evaluated blowdown potential on a small S6 streams[82] subject to a shelterwood cut silviculture system. Following the treatment, blowdown of susceptible leave trees occurred, which included three trees rooted in the stream channel. The authors concluded that the

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[79] https://www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/silviculture/silviculture-research/silvicultural-systems-research/robert-s-creek-study-forest

[80] S6 streams are identified as non-fish bearing streams not within a community watershed that are less than 3 m wide. https://www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/silviculture/silvicultural-systems/silviculture-guidebooks/riparian-management-area-guidebook

[81] It is important to note that the chronological pairing approach was applied in this study, which has since been deemed an "uncontrolled" experiment (Alila et al., 2009; Yu and Alila, 2019). As such, the results should be interpreted cautiously.

[82] In this study, a zero-order stream is considered an S6 stream that does not convey flow year-round (i.e., ephemeral) whereas a first-order stream is considered an S6 stream that conveys flow year-round (i.e., perennial).

proper streamside management for zero-order streams subject to partial harvesting systems is to remove trees adjacent to the channel with a high windthrow potential, while retaining understory vegetation to maintain stream channel stability. They also found that a buffer strip width of 20 m with edge feathering and/or canopy pruning was effective at mitigating blowdown potential along first-order S6 streams. It is important to note, however, that the authors highlight that this was a pilot study and was not a completely controlled experiment. The results should therefore be interpreted cautiously.

4.12. WATER USE

4.12.1. Surface Water Use

Although there are no registered community watersheds in the assessment area, according to the BC Water Rights Database (Province of British Columbia, 2022a), downstream or downslope of BCTS chart area there are 27 currently registered water licences in the assessment area (FIGURE 4.20, TABLE 4.8, MAP 1)[83]. This includes licences to support domestic use, golf course irrigation, livestock & animal stockwatering and residential power.

Along Clack Creek there are six licences downstream of BCTS chart area, all but one was reviewed in the field. This includes five licences for domestic use and one for golf course irrigation. Along Clack Creek, no intake structure was noted at the mapped location of licence F015563 near stream km 0.75. Water pipes, presumably associated with water licences C123183, C123184 and C123185, located near the Sunshine Coast Highway crossing, were noted as being in a state of disrepair. Similarly, several PVC pipes were noted roughly near stream km 2.1, although were in disarray and no intake structures were noted. The licences along Clack Creek upstream of stream km 2.1 and those along Gough Creek were not observed during the field review so their conditions are unknown.

Along lower Roberts Creek there are five licences for domestic use, all with intakes downstream of the Sunshine Coast Highway; however, none appeared in use. One intake structure was noted near stream km 0.77 although was filled with sediment (FIGURE 019, Volume 2, APPENDIX D) and a PVC pipe was noted along the bank near stream km 0.8.

A total of 16 licences are active on Stephens Creek. Domestic use is assigned to all but two of these licences, while, livestock and animal stockwatering and residential power is assigned to the remaining two. With exception of a hose noted at a crossing near stream km 1.75, no other intake structures were noted; however, not all mapped surface water licence locations were observed during the field review

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[83] Two licences not tallied in this total have a catchment area that excludes BCTS chart area (C113611 and C072735).

given private property access challenges.

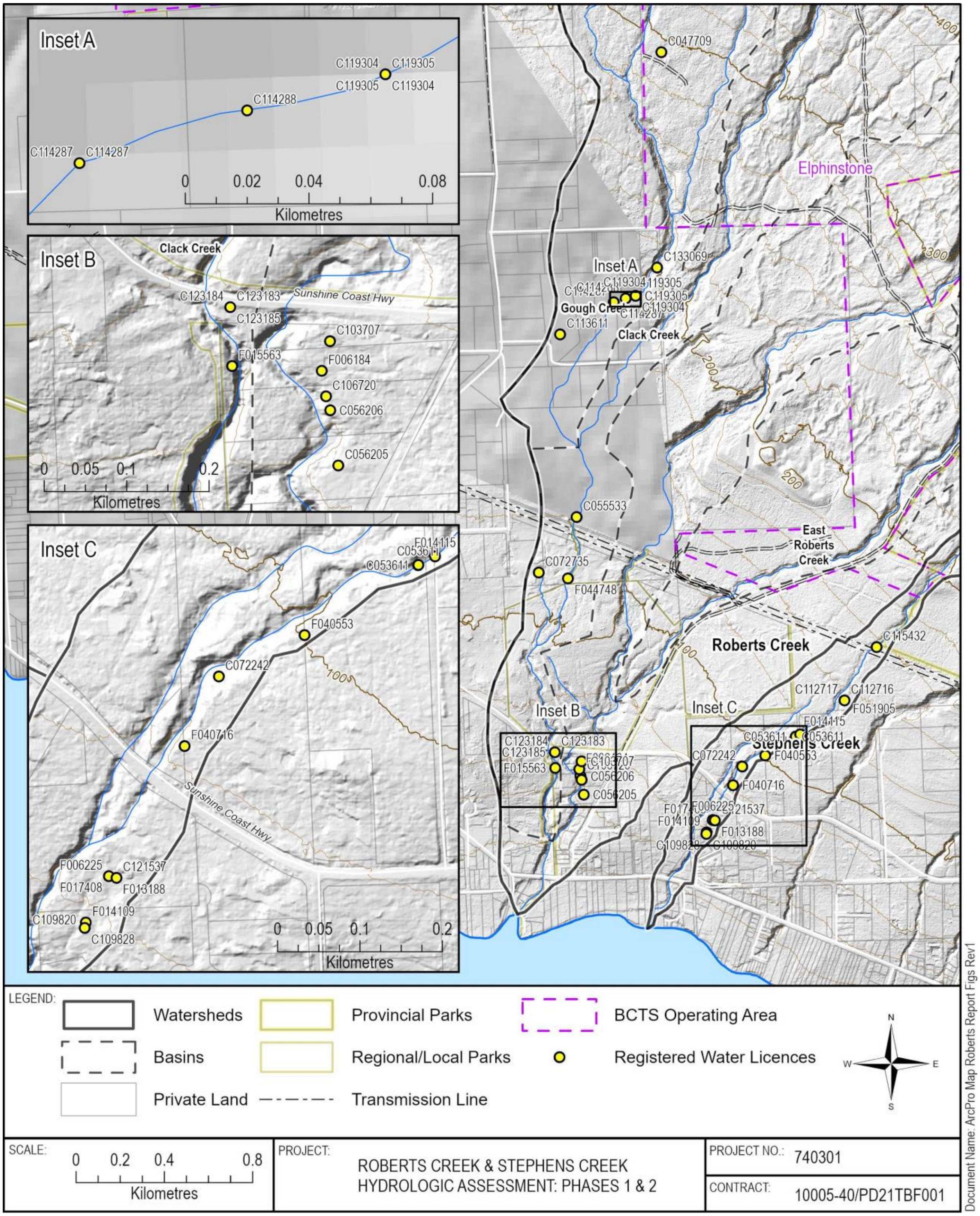

FIGURE 4.20 *Current water licences in the assessment area.*

4.12.2. Aquifers & Groundwater Use

Aquifers

The description of aquifers in the assessment area, provided below, is based on Advisian (2019), Waterline (2013), and McCammon (1977).

There is one principal aquifer located along the lower slopes of the assessment area: Roberts Creek bedrock aquifer No. 555 (FIGURE 4.21). It is possible a shallower aquifer (Capilano Aquifer) is located above the principal aquifers; however, it is generally less productive, and less utilized.

The Roberts Creek Aquifer is located in bedrock and spans the length of lower south and southwest-facing slopes. Bedrock is covered by about 20 m +/- of surficial materials. Recharge of this bedrock aquifer likely occurs by the following processes:

- mountain block recharge where precipitation infiltrates the upland bedrock joints and fractures or moves as groundwater along the contact between surficial materials and underlying bedrock; or as
- direct precipitation over the aquifer, which infiltrates through the surficial materials and into joints and fractures in the bedrock.

Advisian (2019) reports that a majority of the water-bearing fracture zones in the bedrock aquifer are deep, with median well depths of approximately 60 m (197 feet). They report the permeability within the aquifer to be low, although higher permeability can occur along bedrock fractures. As such, the vulnerability to surface contamination was considered moderate.

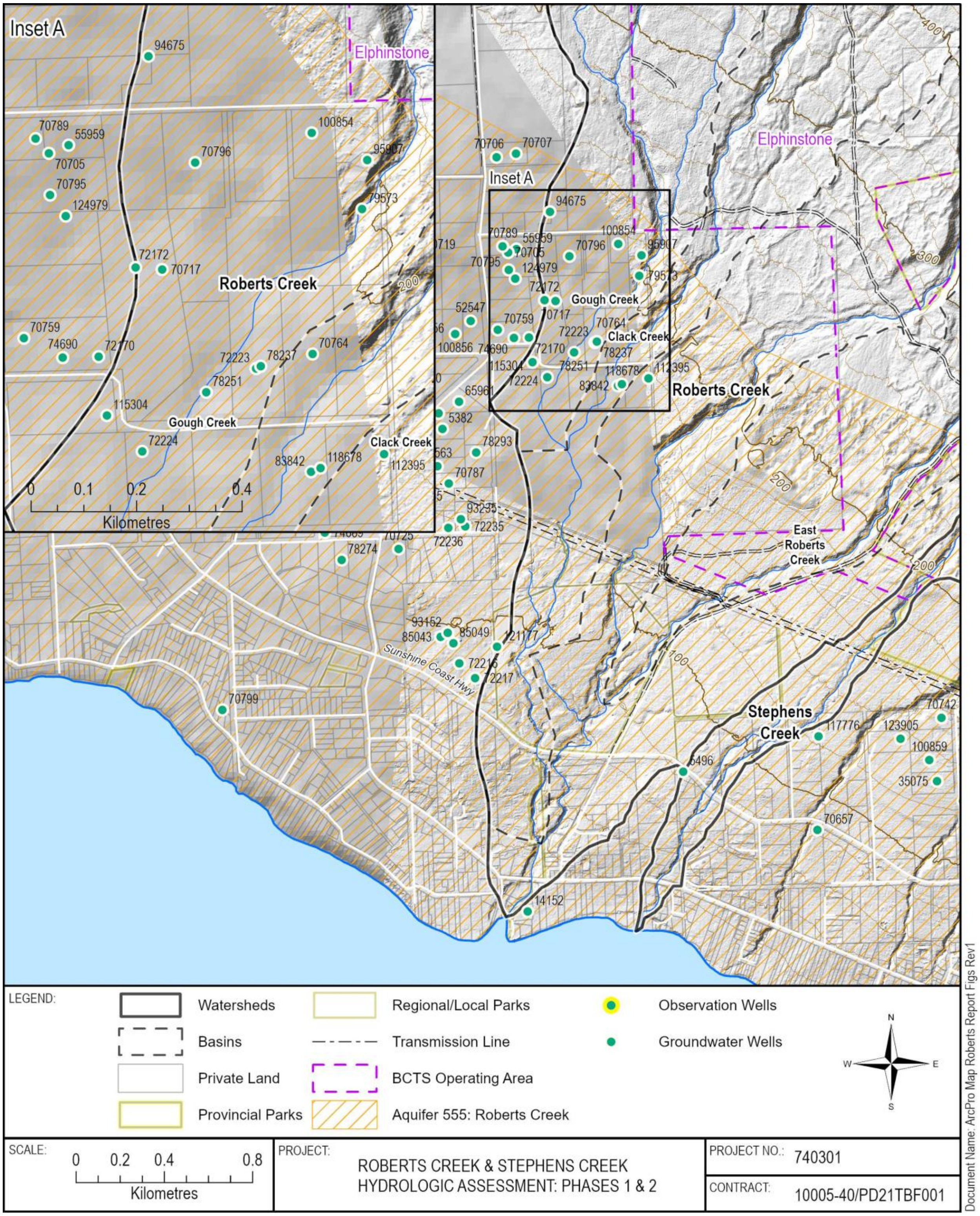

FIGURE 4.21 *Provincially recorded aquifers and groundwater wells in the assessment area. Well tag numbers are indicated.*

Groundwater Wells

According to the BC Groundwater Wells and Aquifers database (Province of British Columbia, 2022b), there are 54 recorded wells located over the Roberts Creek aquifer within 0.5 km of the Roberts Creek and Stephens Creek watersheds (FIGURE 4.21, MAP 1). This includes wells within Gough Creek sub-basin, Clack Creek basin, East Roberts Creek basin, Stephens Creek watershed, and as residual areas between or beyond these watersheds[84]. Of the 54 recorded wells, 40 are located within the Roberts Creek and Stephens Creek watersheds and are listed in TABLE 4.9. The majority of the wells are assumed to source water from the Roberts Creek bedrock aquifer, based on their depths. An undetermined number of wells may source water from the relatively shallow unconfined Capilano Aquifer.

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[84] It is important to recognize that groundwater flow patterns may not necessarily reflect surface flow patterns.

TABLE 4.8 *List of current surface water licences within Roberts Creek Watershed and Stephens Creek Watershed. Refer to MAP 1 for location.*

Watershed Unit	Source Name	Licence No.	Point of Diversion	Priority Date (YYMMDD)	Purpose	Quantity	Units	Quantity Flag[85]	Licensee
Roberts Creek watershed	Clack Creek	C055533	PD44975	19800925	01A - Domestic	2.27305	m^3/day	T	PRIVATE INDIVIDUAL NAME
	Clack Creek	C123183	PD44971	19300616	01A - Domestic	1.81844	m^3/day	T	PRIVATE INDIVIDUAL NAME
	Clack Creek	C123184	PD44971	19300616	01A - Domestic	1.81844	m^3/day	T	PRIVATE INDIVIDUAL NAME
	Clack Creek	C123185	PD44971	19300616	01A - Domestic	1.81844	m^3/day	T	PRIVATE INDIVIDUAL NAME
	Clack Creek	F015563	PD44970	19510122	01A - Domestic	2.27305	m^3/day	T	PRIVATE INDIVIDUAL NAME
	Clack Creek	F044748	PD44974	19660615	02F - Lwn, Fairway & Grdn: Watering	4933.92	m^3/year	T	Sunshine Coast Golf and Country Club (25455)
	Gough Creek	C119305	PD44977	19860721	03B - Irrigation: Private	1233.48	m^3/year	T	PRIVATE INDIVIDUAL NAME
	Gough Creek	C133069	PD66316	19920728	WSA11 - Lawn, Fairway & Garden	548	m^3/year	T	PRIVATE INDIVIDUAL NAME
	Gough Creek	C114287	PD44976	19860721	03B - Irrigation: Private	1850.22	m^3/year	T	PRIVATE INDIVIDUAL NAME
	Gough Creek	C114288	PD74492	19860721	02E - Pond & Aquaculture	0.00006	m^3/sec	T	PRIVATE INDIVIDUAL NAME
	Gough Creek	C119304	PD44977	19860721	01A - Domestic	2.27305	m^3/day	T	PRIVATE INDIVIDUAL NAME
	Roberts Creek	C056205	PD60272	19800925	01A - Domestic	3.18226	m^3/day	T	PRIVATE INDIVIDUAL NAME
	Roberts Creek	C056206	PD44964	19800722	01A - Domestic	2.27305	m^3/day	T	PRIVATE INDIVIDUAL NAME
	Roberts Creek	C103707	PD44967	19910823	01A - Domestic	2.27305	m^3/day	T	PRIVATE INDIVIDUAL NAME
	Roberts Creek	C106720	PD67871	19930614	01A - Domestic	2.27305	m^3/day	T	PRIVATE INDIVIDUAL NAME
	Roberts Creek	F006184	PD44966	19130807	01A - Domestic	2.72765	m^3/day	T	PRIVATE INDIVIDUAL NAME
Stephens Creek watershed	Stephen Creek	C053611	PD44959	19680826	01A - Domestic	2.72765	m3/day	T	PRIVATE INDIVIDUAL NAME
	Stephen Creek	C072242	PD44954	19460917	01A - Domestic	2.27305	m3/day	T	PRIVATE INDIVIDUAL NAME
	Stephen Creek	C109820	PD60268	19870403	01A - Domestic	2.27305	m3/day	T	PRIVATE INDIVIDUAL NAME
	Stephen Creek	C109828	PD60268	19870403	07A - Power: Residential	0.01416	m3/sec	T	PRIVATE INDIVIDUAL NAME
	Stephen Creek	C112716	PD44963	19740327	01A - Domestic	2.27305	m3/day	T	PRIVATE INDIVIDUAL NAME
	Stephen Creek	C112717	PD44963	19850619	01A - Domestic	4.54609	m3/day	T	PRIVATE INDIVIDUAL NAME
	Stephen Creek	C115432	PD75494	20000612	02I31 - Livestock & Animal: Stockwatering	0.90922	m3/day	T	Sunshine Coast Equestrian Club (61673)
	Stephen Creek	C121537	PD60267	19271109	01A - Domestic	2.27305	m3/day	T	PRIVATE INDIVIDUAL NAME
	Stephen Creek	F006225	PD60271	19270216	01A - Domestic	9.09218	m3/day	T	PRIVATE INDIVIDUAL NAME
	Stephen Creek	F013188	PD60267	19420527	01A - Domestic	4.54609	m3/day	T	PRIVATE INDIVIDUAL NAME
	Stephen Creek	F014109	PD60269	19410909	01A - Domestic	2.27305	m3/day	T	PRIVATE INDIVIDUAL NAME
	Stephen Creek	F014115	PD44960	19470818	01A - Domestic	2.27305	m3/day	T	PRIVATE INDIVIDUAL NAME
	Stephen Creek	F017408	PD60271	19270216	01A - Domestic	0.90922	m3/day	T	PRIVATE INDIVIDUAL NAME
	Stephen Creek	F040553	PD44958	19671128	01A - Domestic	2.27305	m3/day	T	PRIVATE INDIVIDUAL NAME
	Stephen Creek	F040716	PD60263	19611205	01A - Domestic	4.54609	m3/day	T	PRIVATE INDIVIDUAL NAME
	Stephen Creek	F051905	PD44963	19700526	01A - Domestic	2.27305	m3/day	T	PRIVATE INDIVIDUAL NAME

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[85] Quantity flag: T = total licensed quantity is sourced from a single point of diversion; M = total licensed quantity may be sourced from multiple points of diversion.

TABLE 4.9 *List of registered groundwater wells within the Roberts Creek and Stephens Creek watersheds. Online information may be available at: https://apps.nrs.gov.bc.ca/gwells/well/<insert Well Tag No.>.*

Watershed Unit	Well Tag No.	Plate No.	Well Status	Well Classification	Intended Water Use	Licence Status	Artesian Well	Artesian Well Flow Rate (USgpm)	Finished Well Depth (ft below ground surface)	Bedrock Depth (ft below ground surface)	Yield (USgpm)	Static Water Level (ft below ground surface)	Well Diameter (inches)	Aquifer ID (see footnote)[86]	Aquifer Material
Roberts Creek	83842	-	New	Water Supply	Private Domestic	Unlicensed	N	-	225	-	4	-	-	1143	Unknown
Roberts Creek	118678	-	New	Water Supply	Private Domestic	Unlicensed	N	-	-	-	-	-	-	-	-
Roberts Creek	112395	-	New	Water Supply	Irrigation	Unlicensed	N	-	25	-	9	-	-	1143	Unknown
Roberts Creek	72224	-	New	Unknown	Not Applicable	Unlicensed	N	-	165	45	6	38	-	555	Bedrock
Roberts Creek	115304	51206	New	Water Supply	Private Domestic	Unlicensed	N	-	190	29	60	15	6	-	Unknown
Roberts Creek	78251	-	New	Unknown	Not Applicable	Unlicensed	N	-	125	-	8	26	-	555	Unknown
Roberts Creek	72223	-	New	Unknown	Not Applicable	Unlicensed	N	-	200	-	2	37	-	555	Unknown
Roberts Creek	78237	-	New	Water Supply	Unknown Well Use	Unlicensed	N	-	200	-	2	37	-	555	Unknown
Roberts Creek	70764	-	New	Water Supply	Private Domestic	Unlicensed	N	-	200	-	2	-	-	555	Unknown
Roberts Creek	70717	-	New	Unknown	Not Applicable	Unlicensed	N	-	140	55	30	35	-	555	Bedrock
Roberts Creek	79573	-	New	Water Supply	Private Domestic	Unlicensed	N	-	200	44	2	-	-	555	Unknown
Roberts Creek	70796	-	New	Unknown	Not Applicable	Unlicensed	N	-	160	-	5	40	-	555	Unknown
Roberts Creek	95907	3100	New	Water Supply	Unknown Well Use	Unlicensed	N	-	260	43	4	60	6	555	Unknown
Roberts Creek	100854	-	New	Water Supply	Private Domestic	Unlicensed	N	-	210	-	3	48	6	555	Unknown
Roberts Creek	94675	27265	New	Water Supply	Unknown Well Use	Unlicensed	N	-	182	54	4	51	6	555	Bedrock
Clack Creek	83842	-	New	Water Supply	Private Domestic	Unlicensed	N	-	225	-	4	-	-	1143	Unknown
Clack Creek	118678	-	New	Water Supply	Private Domestic	Unlicensed	N	-	-	-	-	-	-	-	-
Clack Creek	72224	-	New	Unknown	Not Applicable	Unlicensed	N	-	165	45	6	38	-	555	Bedrock
Clack Creek	115304	51206	New	Water Supply	Private Domestic	Unlicensed	N	-	190	29	60	15	6	-	Unknown
Clack Creek	78251	-	New	Unknown	Not Applicable	Unlicensed	N	-	125	-	8	26	-	555	Unknown
Clack Creek	72223	-	New	Unknown	Not Applicable	Unlicensed	N	-	200	-	2	37	-	555	Unknown
Clack Creek	78237	-	New	Water Supply	Unknown Well Use	Unlicensed	N	-	200	-	2	37	-	555	Unknown
Clack Creek	70764	-	New	Water Supply	Private Domestic	Unlicensed	N	-	200	-	2	-	-	555	Unknown
Clack Creek	70717	-	New	Unknown	Not Applicable	Unlicensed	N	-	140	55	30	35	-	555	Bedrock
Clack Creek	79573	-	New	Water Supply	Private Domestic	Unlicensed	N	-	200	44	2	-	-	555	Unknown
Clack Creek	70796	-	New	Unknown	Not Applicable	Unlicensed	N	-	160	-	5	40	-	555	Unknown
Clack Creek	95907	3100	New	Water Supply	Unknown Well Use	Unlicensed	N	-	260	43	4	60	6	555	Unknown
Clack Creek	100854	-	New	Water Supply	Private Domestic	Unlicensed	N	-	210	-	3	48	6	555	Unknown
Clack Creek	94675	27265	New	Water Supply	Unknown Well Use	Unlicensed	N	-	182	54	4	51	6	555	Bedrock
Gough Creek	72224	-	New	Unknown	Not Applicable	Unlicensed	N	-	165	45	6	38	-	555	Bedrock
Gough Creek	115304	51206	New	Water Supply	Private Domestic	Unlicensed	N	-	190	29	60	15	6	-	Unknown
Gough Creek	78251	-	New	Unknown	Not Applicable	Unlicensed	N	-	125	-	8	26	-	555	Unknown
Gough Creek	72223	-	New	Unknown	Not Applicable	Unlicensed	N	-	200	-	2	37	-	555	Unknown
Gough Creek	78237	-	New	Water Supply	Unknown Well Use	Unlicensed	N	-	200	-	2	37	-	555	Unknown
Gough Creek	70717	-	New	Unknown	Not Applicable	Unlicensed	N	-	140	55	30	35	-	555	Bedrock
Gough Creek	79573	-	New	Water Supply	Private Domestic	Unlicensed	N	-	200	44	2	-	-	555	Unknown
Gough Creek	70796	-	New	Unknown	Not Applicable	Unlicensed	N	-	160	-	5	40	-	555	Unknown
Gough Creek	95907	3100	New	Water Supply	Unknown Well Use	Unlicensed	N	-	260	43	4	60	6	555	Unknown
Gough Creek	100854	-	New	Water Supply	Private Domestic	Unlicensed	N	-	210	-	3	48	6	555	Unknown
Gough Creek	94675	27265	New	Water Supply	Unknown Well Use	Unlicensed	N	-	182	54	4	51	6	555	Bedrock

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[86] https://apps.nrs.gov.bc.ca/gwells/aquifers

4.13. FISHERIES RESOURCES

Although none of the assessment streams are provincially recognized as Fisheries Sensitive Watersheds (FSWs), some support known fisheries values (FIGURE 4.22). According to provincial fish inventories (Province of British Columbia, 2022c) and SCRD and DFO (2021), fish have been recorded or suspected in the following streams:

- Roberts Creek, including its tributaries
    - Clack Creek, and
    - East Roberts Creek; and
- Stephens Creek.

Within the assessment area, Roberts Creek supports the greatest number of fish species. Along the lowermost 400 m below the Sunshine Coast Highway the following species have been identified:

- Anadromous Cutthroat Trout,
- Chinook Salmon,
- Chum Salmon,
- Coho Salmon,
- Cutthroat Trout,
- Dolly Varden,
- Pink Salmon,
- Rainbow Trout,
- Steelhead, and
- Unidentified species

There are a series of falls in the lower reaches of Roberts Creek below the highway and above Roberts Creek Road, which prevent upstream fish migration, the largest being 7 m near stream km 0.5. A 3.4 m falls on Clack Creek, near its confluence with Roberts Creek, prevents upstream fish migration within Clack Creek. Despite these barriers, Cutthroat and Dolly Varden are present within 1 km upstream of the highway in Clack Creek and East Roberts Creek. Cutthroat have been reported up to an elevation of 370 m in Clack Creek and both Cutthroat and Dolly Varden have been found in the headwaters of Roberts Creek at an elevation of 700 m. According to Province of British Columbia (2021a) the only species present in Stephens Creek are Cutthroat Trout, located within 200 m upstream and 500 m downstream of the highway. There have also been unidentified species found 50 m below the highway on Roberts Creek, and 650 m upstream of the highway on Clack Creek (Province of British Columbia, 2021a).

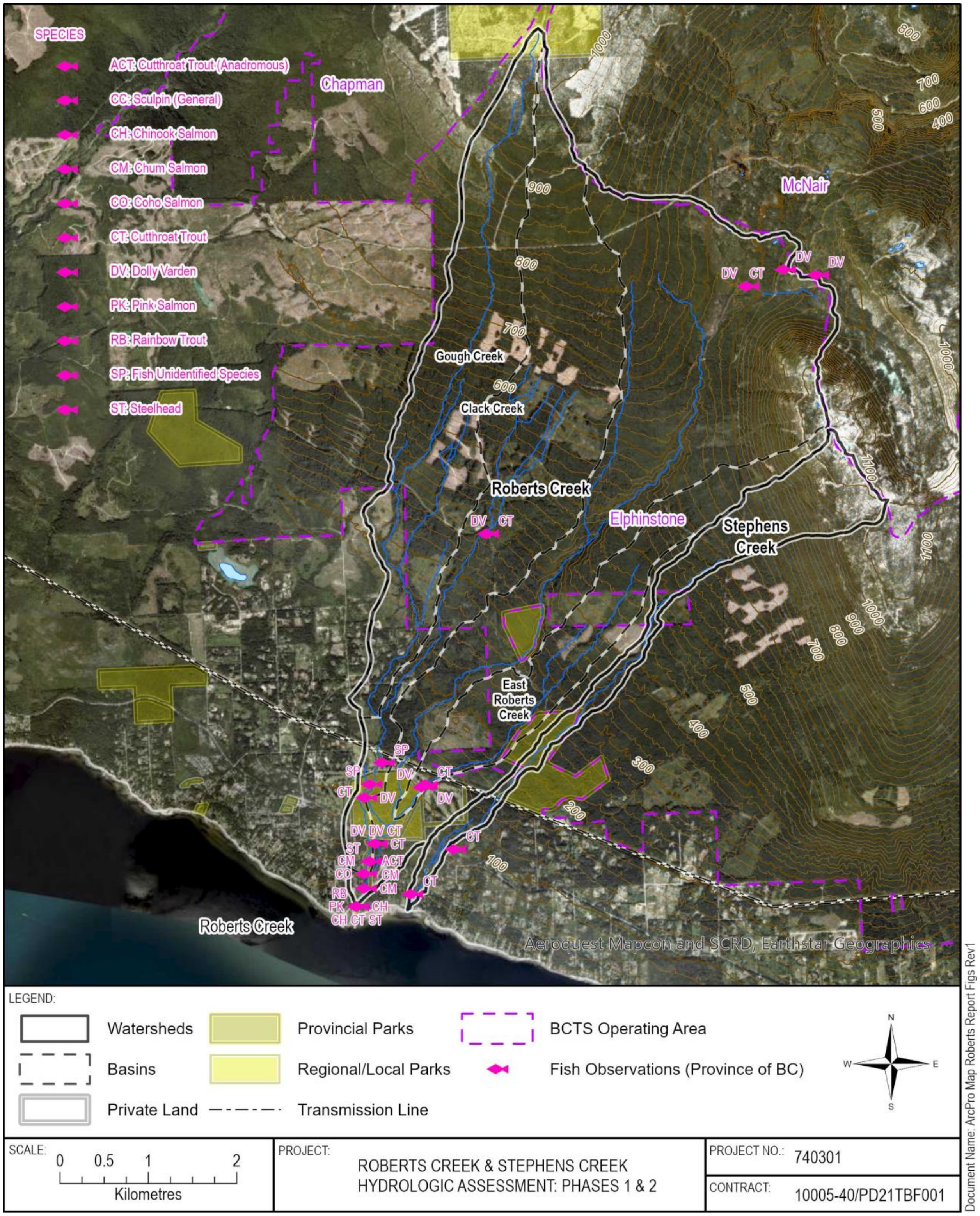

FIGURE 4.22 *Recorded fish presence in the assessment area. Note that some points may be offset due to inaccurate legacy base maps upon which the fisheries data is based.*

5. WATERSHED VALUES

As noted in Section 2.1, risk identification is the first step in a risk analysis. It involves identifying the watershed values present in the watershed that could potentially be affected by one or more hydrogeomorphic hazards or processes[87]. TABLE 5.1 identifies the primary values identified during the course of this assessment. This list is not intended to be exhaustive[88], but rather guide the assessment in considering what hydrogeomorphic processes should be evaluated. Based on our review of available background information, and with reference to BCTS Watershed Risk Management Framework checklists, TABLE 5.1 identifies the following principal values for consideration: human safety, private property, transportation, utilities, water rights & use, and fish and fish habitat. Furthermore, TABLE 5.2 identifies the potential hazard types specific to the assessment streams.

TABLE 5.1 *Summary of identified values within the assessment area.*

Value	Notes on potential type of risk
Human Safety	Residents, workers and the travelling public may be present at various locations downstream of BCTS chart area. Recreational users and workers may also be present within BCTS chart area. Some may also be vulnerable to hydrogeomorphic hazards (e.g., floods, debris flows, debris floods, etc.) if they are present near streams subject to such hazards at the time they occur. Flood conditions may develop in response to noticeable storm events, usually over an extended period (hours to days). In such cases, there is typically some warning (e.g., rising stream levels) so that risks to human safety can be effectively mitigated (e.g., by evacuating flood-prone areas). Although less common, relatively destructive debris floods or debris flows can potentially be initiated along some of the incised gullies in the assessment area. Such events may occur as a result of natural or development-related sediment and debris delivery from landslides or sediment mobilization along stream channels (e.g., if log jams breach).
Private Property	Several private residences, properties, roads, including stream crossings, water intakes and wells are identified in the assessment area. Some of these values may potentially be vulnerable to flooding-related damage along the streams of interest and/or their tributaries.
Transportation Infrastructure	Several public roads (e.g., Sunshine Coast Highway #101, Roberts Creek Road, Lower Road) are located downstream of BCTS chart area and cross streams in the assessment area that may be subject to damage from flooding or other hydrogeomorphic events. In addition, there are several resource roads and trails that cross streams that are subject to flooding in the assessment area.

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[87] These values are referred to as potential elements-at-risk.

[88] First Nation cultural or archeological sites, aesthetic, or effects on corporate social licence are not considered.

Value	Notes on potential type of risk
Utilities	Electrical and telecommunication lines run principally along public highways and public roads or along transmission line rights-of-way. Although these may be subject to service interruption as a result of windstorms and blowdown, they are generally not subject to the hydrogeomorphic hazards considered in the assessment (Section 2.3). Underground natural gas pipelines may, however, be susceptible to flood-related scour where they cross streams (e.g., along Lower Road).
Water Rights & Use	As noted in Section 4.12, domestic water is sourced from several locations within or downslope of BCTS chart area. This includes Roberts Creek and its tributary Clack Creek, as well as Stephens Creek. It should be recognized, however, that of the total number of surface water licences registered in the assessment area, a relatively small percentage are currently in use (Section 4.12.1). Many licences are associated with private water systems that have been damaged by natural fluvial activity (e.g., aggradation), abandoned or otherwise not utilized for a number of reasons (e.g., alternative source available from SCRD or from groundwater). Domestic water supply can potentially be affected if there is a reduction of supply (i.e., drought), specifically in late summer and early fall. In addition, water quality (e.g., turbidity) can potentially be affected by land use activities upslope, especially where soils are disturbed. Lastly, water intakes, particularly those that are poorly engineered or constructed, may be susceptible to floods. While water quality requirements are not as stringent, irrigation, watering, and stockwatering use can similarly be impaired if supplies decrease or if water intakes are subject to damage. As noted in Section 4.12.2, a total of 54 groundwater wells are located over the Roberts Creek aquifer within 0.5 km of the assessment watersheds. Some wells may also source water from the unconfined alluvial Capilano Aquifer (Section 4.12.2).
Fish and fish habitat	Several fish species are present downstream of BCTS chart area, principally within the lower reaches of Roberts Creek. Potential changes to peak and low flows (magnitude, frequency and/or duration) may affect habitat values (e.g., via channel degradation/aggradation, loss of functioning wood, stream cover, food sources). Instream flows for fish survival may also be adversely affected during drought usually in late summer and early fall. Sedimentation associated with land uses can also be detrimental to fish habitat, impacting both water quality and stream channel conditions.

TABLE 5.2 *Summary of type of hazard by stream catchment.*

Hazard	Elements-at-risk	Roberts Creek	Clack Creek	Gough Creek	East Roberts Creek	Stephens Creek
1) **Peak flows** (flooding, debris flood, and/or debris flow) - increased magnitude, frequency and/or duration	a) Human safety	✓	✓	✓	✓	✓
	b) Private property (e.g., flooding of property, damage or loss of land, damage to stream crossings, damage to water intakes and wells)	✓	✓	✓	✓	✓
	c) Transportation & Utilities	✓	✓	✓	✓	✓
2) **Low flows & aquifer recharge** – reduced baseflows and/or groundwater recharge	a) Water rights & use	✓	✓	**X**	**X**	✓
	b) Instream flow requirements for fish	✓	✓	✓	✓	✓
3) **Sediment yield** - increased erosion and subsequent deposition of sediment in streams	a) Water quality, for domestic use and fish	✓	✓	✓	✓	✓
4) **Channel instability** (i.e., channel disequilibrium) associated with increased flooding, sediment yield and/or loss of riparian function.	a) Private property (e.g., loss of land, damage to stream crossings and water intakes)	✓	✓	✓	✓	✓
	b) Fish habitat	✓	✓	✓	✓	✓
5) **Water contamination by pollutants**	a) Water quality, for domestic use and fish	✓	✓	✓	✓	✓

"**X**" denotes not applicable (value not identified)

6. SUMMARY OF HAZARDS IN THE ASSESSMENT AREA

This section reviews the types of hydrogeomorphic processes or hazards that have potential to affect identified values in the assessment watersheds (Section 5). This includes an overview of the hazard, a description of current watershed conditions and processes that influence that hazard, and the potential effects of forest development in the context of projected climate change. As indicated in Section 1.2, this assessment does not review specific forest development plans but rather forest development in general.

6.1. STREAMFLOW REGIME

Two primary goals of this assessment were to: 1) identify the likelihood and/or degree to which past disturbance in the assessment area influences the hydrologic regime; and 2) identify the likelihood and/or degree to which the hydrologic regime will change in response to potential future forest development. The potential for a change in the streamflow regime is assessed by considering the history of disturbance in the watershed as well as physical characteristics that influence runoff generation potential [e.g., climate, forest characteristics, elevation, slope, aspect, gradient, soils and method and extent of harvesting (i.e., ECA)], and the potential for runoff synchronization. Discussion of potential changes to the streamflow regime are discussed below for peak flows, low flows and aquifer recharge as effects on each may have the potential to adversely affect identified watershed values.

6.1.1. Peak Flows

As noted in Section 3.1, evaluation of peak flow hazard considers runoff generation potential and runoff synchronization. The former consideration is potentially influenced by ECA, a factor that differs from most other intrinsic characteristics of a stream catchment in that it can be influenced by forest management. In coastal watersheds, an evaluation of ECA typically includes identifying overall ECAs and ECAs within the elevation bands where rain, rain-on-snow zone or snow runoff generation typically occur (Hudson and Horel, 2007). Runoff generation during rain-on-snow events is often responsible for generating the most severe floods. Moreover, rain-on-snow tends to be more sensitive to forest disturbance than rain-only events. As such, and following recommendations from Dr. William Floyd, the evaluation of ECA was conducted assuming that rain-on-snow occurs at all elevations and a single rain-on-snow recovery curve was applied across all elevations of the assessment area.

Madrone (2012) conducted a hydrologic assessment of the Roberts Creek Watershed and suggested that a ECA below 20% would equate to a '*very low*' peak flow hazard. In addition, Madrone (2015) conducted a hydrologic assessment in six watersheds along the hillslopes of Mt. Elphinstone, which included the Gough Creek and Clack Creek watersheds, located within the assessment area. Madrone (2015) recommended that ECA within Gough Creek and Clack Creek be capped at 25%; however, they noted that an ECA cap of 15% may be desirable, depending on BCTS' level of caution, in order to reduce the likelihood of increased turbidity associated with a potential increase in intra-annual peak flows following harvesting. The 25% ECA threshold was identified as a measure to reduce the likelihood of adversely increasing peak flow along lower, more sensitive alluvial reaches. For non-alluvial and semi-alluvial streams, no ECA recommendation was provided, believing those streams are sufficiently robust not to be adversely affected by any potential harvesting-related peak flow increases. The streams in the Roberts Creek and Stephens Creek watersheds are primarily semi-alluvial or alluvial with non-alluvial reaches along the middle and lower stream segments and alluvial near the mouth (refer to Section 6.4 for a description of channel morphology).

Based on the characteristics of the assessment watersheds, the runoff generation potential (RGP) is considered high in both watersheds. With consideration of RGP and the research literature (Section 3.1.1), a majority of the assessment watersheds are expected to have a low peak flow hazard if overall ECA is below 20%[89]. Given the increased potential for a snowpack to develop above 800 m elevation in the assessment area, the potential effects of harvesting on snow accumulation and melt are increasing important in these areas (Floyd, pers. comm., 2023). As such, to maintain a low peak flow hazard, ECA should also not exceed 15% in areas above 800 m elevation. It is also recommended, that any future harvest above 800 m elevation in the assessment area consider selective harvest or small openings[90] to minimize melt rates associated with exposure to solar radiation and winds.

Current ECAs and how they relate to peak flow hazards for each assessment watershed is described below.

Current stand-level ECAs are spatially presented in FIGURE 6.1. To evaluate how the level of disturbance varies throughout the assessment area, eight POIs[91] were identified (FIGURE 6.2, FIGURE 6.3). These include:

- The mouths of each watershed;
- The confluence of major tributaries (to evaluate conditions within major basins); and

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[89] Between 20% and 30%, peak flow hazard is moderate, and above 30% such hazard is high.

[90] Similar to those recommended to conserve low flows.

[91] To facilitate communication of ECAs through the assessment area, a finite number of POIs is required (i.e., eight). While the number of watershed values present may exceed the number POIs identified, the POIs still effectively represent streamflow conditions at each of the values present.

- The boundary of BCTS chart area (to approximate the level of disturbance within the timber harvest land base).

Current overall ECAs above each POI and for the portion of BCTS chart area above each POI are identified in TABLE 6.2. Current ECAs within areas above 800 m elevation are presented in TABLE 6.3. Projected future overall ECAs that account for hydrologic recovery (assuming no additional forest development) are identified in APPENDIX C. The intent of the long-term projections is not to predict what actual conditions will be like in future (as specific forest development plans or other natural disturbances are unknown), but rather to demonstrate the pattern and rate of hydrologic recovery that is expected under current conditions in each of the assessment watersheds.

Peak flow hazard for each POI is presented in TABLE 6.2 and FIGURE 6.3 and is described below. If a selective harvest silviculture system (i.e., thinning) is used, ECAs are scaled based on the values in TABLE 6.1.

TABLE 6.1 *Assumptions for ECA calculations based on silviculture system [from BC MOF (1999)].*

Basal Area Removed	ECA Assumption
<20%	100% recovery (i.e., 0% ECA)
20% to 40%	0.2 of area harvested[92]
40% to 60%	0.4 of area harvested
60% to 80%	0.6 of area harvested
>80% (i.e., clearcut)	0% recovery (i.e., (100% ECA)

ECA recommendations for each POI in TABLE 6.2 are based on the objective to limit the increase in peak flow hazard at POIs downstream of BCTS chart area, while maintaining ECAs below 20% for the portion of the watershed within BCTS chart area. It is important to recognize that in a nested system, the ECA recommendations for all watershed units must be met simultaneously. For example, if the ECA recommendation for a nested basin is greater than for the larger watershed in which it is located, ECAs within the nested basin can increase as long as the larger watershed ECA recommendations are not exceeded. Given that Roberts Creek has nested catchments, the maximum additional ECA to maintain current peak flow hazard levels are presented in FIGURE 6.4. In addition to the overall ECA constraints, to maintain low peak flow hazard, ECAs above 800 m elevation in each watershed unit should also be maintained below 15%.

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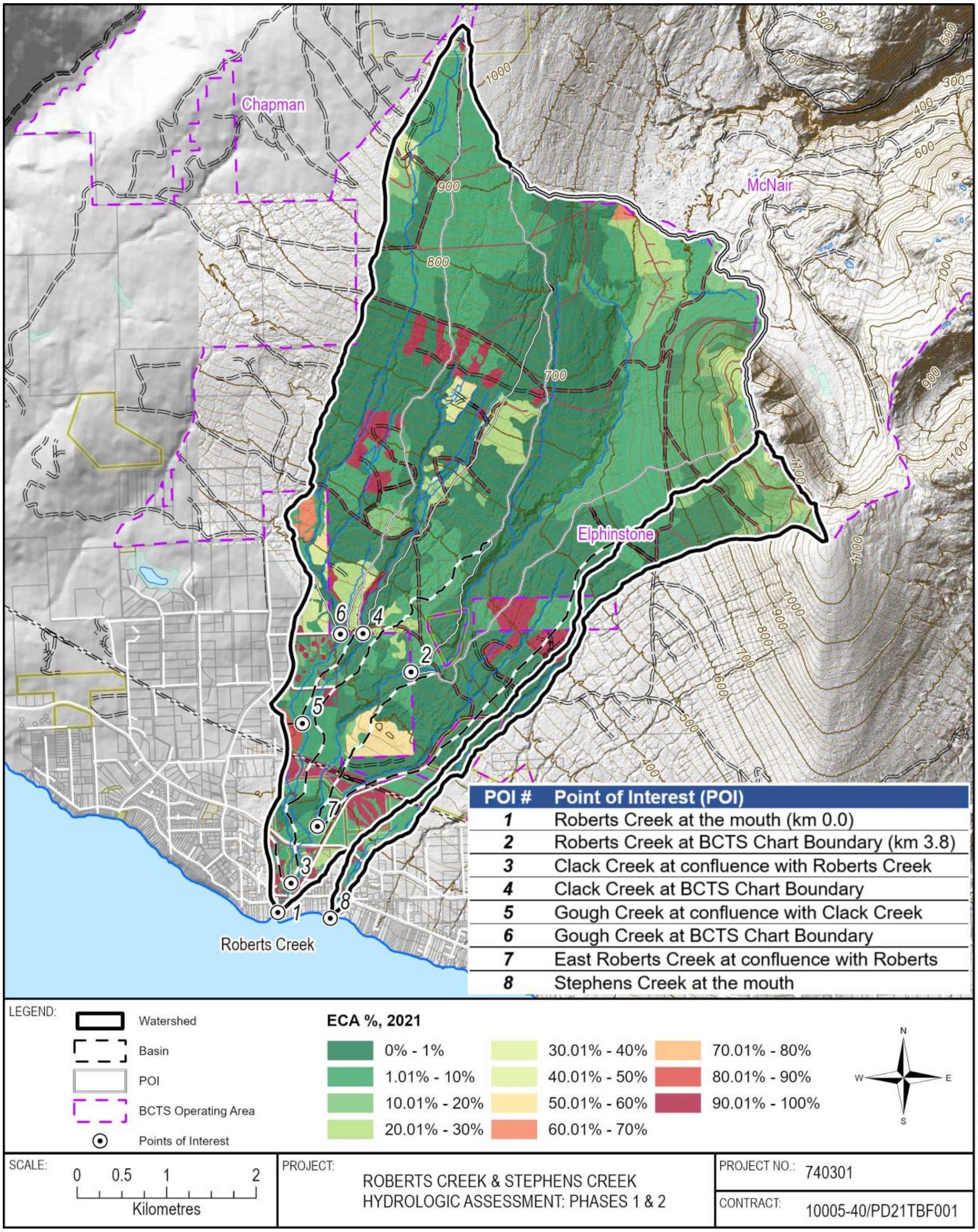
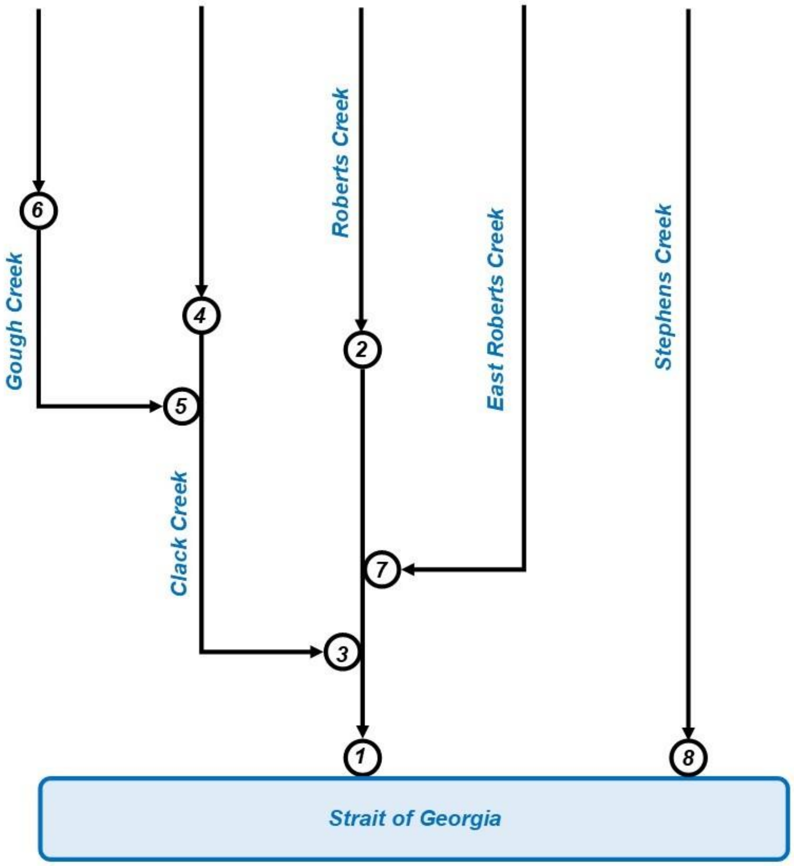
[92] For example, 1 ha subject to 35% removal would have an ECA of 0.2 ha.



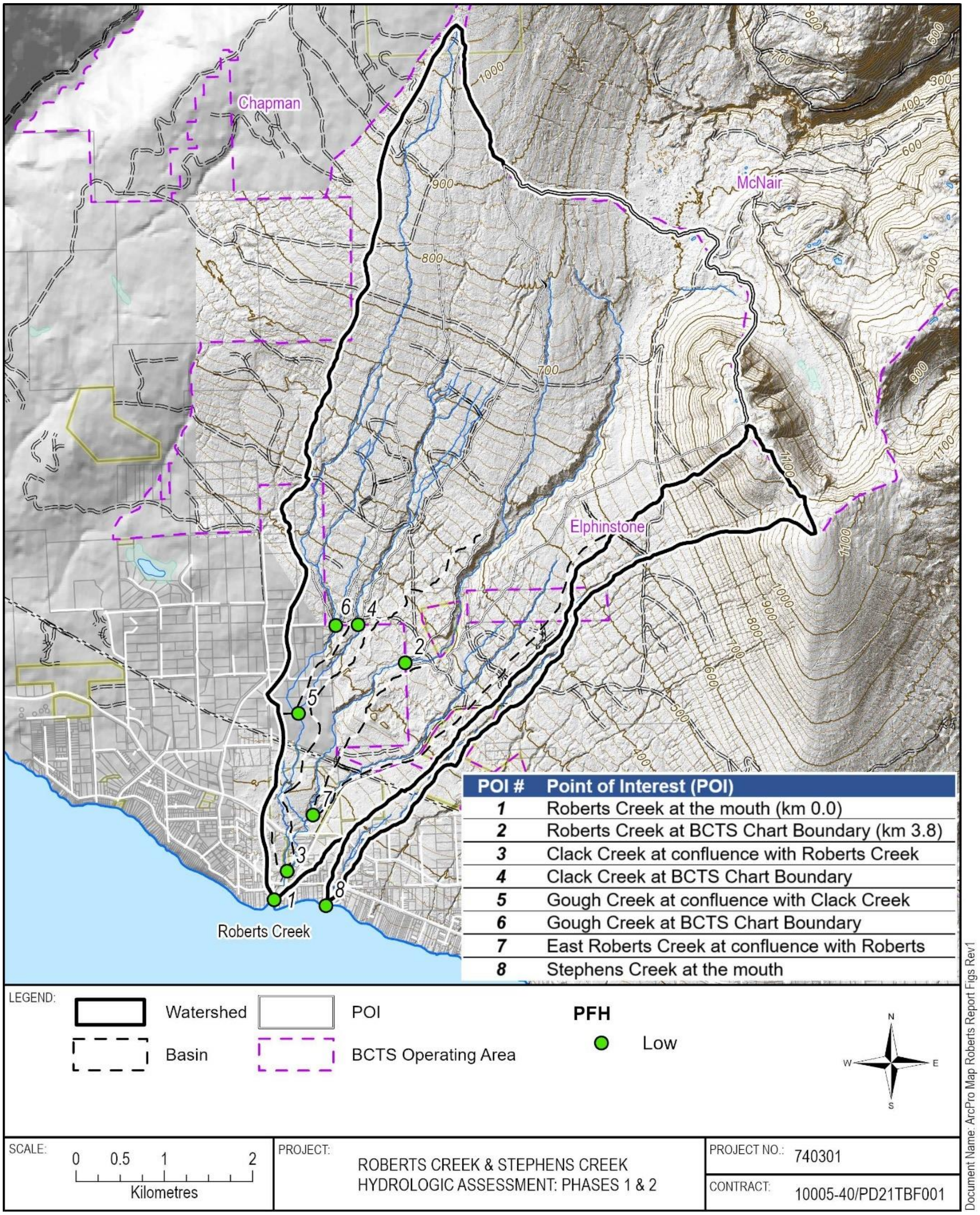
POI #	Point of Interest (POI)
1	Roberts Creek at the mouth (km 0.0)
2	Roberts Creek at BCTS Chart Boundary (km 3.8)
3	Clack Creek at confluence with Roberts Creek
4	Clack Creek at BCTS Chart Boundary
5	Gough Creek at confluence with Clack Creek
6	Gough Creek at BCTS Chart Boundary
7	East Roberts Creek at confluence with Roberts
8	Stephens Creek at the mouth

FIGURE 6.1 *Stand-level equivalent clearcut area (ECA) (2021) throughout the assessment area.*



POI #	Point of Interest (POI)
1	Roberts Creek at the mouth (km 0.0)
2	Roberts Creek at BCTS Chart Boundary (km 3.8)
3	Clack Creek at confluence with Roberts Creek (km 0.4)
4	Clack Creek at BCTS Chart boundary (km 3.5)
5	Gough Creek at confluence with Clack Creek (km 2.4)
6	Gough Creek at BCTS Chart boundary (km 5.5)
7	East Roberts Creek at confluence with Roberts Creek (km 1.4)
8	Stephens Creek at the mouth

FIGURE 6.2 *Schematic of the assessment watersheds including points-of-interest (POIs)*



POI #	Point of Interest (POI)
1	Roberts Creek at the mouth (km 0.0)
2	Roberts Creek at BCTS Chart Boundary (km 3.8)
3	Clack Creek at confluence with Roberts Creek
4	Clack Creek at BCTS Chart Boundary
5	Gough Creek at confluence with Clack Creek
6	Gough Creek at BCTS Chart Boundary
7	East Roberts Creek at confluence with Roberts
8	Stephens Creek at the mouth

FIGURE 6.3 *Points-of-interest (POIs) used to evaluate ECAs. Current peak flow hazard (PFH) at each POI is also presented.*

TABLE 6.2 *Current overall ECAs and peak flow hazard (PFH) levels above points-of-interest (POIs) in the assessment area. ECAs are presented in both hectares and % of overall drainage area. Due to nested stream catchments, recommended ECA constraints to maintain low peak flow hazard are based on the most limiting constraint amongst the nested catchments. Note that in addition to these constraints, ECAs should be maintained below 15% in areas above 800 m elevation.*

Assessment Watershed	POI #	POI	Area above Points-of-Interest						Area within BCTS Chart					Maximum Additional ECA to Maintain Current PFH (ha)	ECA Assuming Maximum Harvest Occurs (ha)	ECA Assuming Maximum Harvest Occurs (%)	ECA Recommendations
			Drainage Area (ha)	Current ECA Above POI (ha)	Current ECA Above POI (%)	Current Peak Flow Hazard (PFH)	Maximum ECA to Maintain Current Peak Flow Hazard		Chart Area (ha)	Current Chart Area ECA (ha)	Current Chart Area ECA (%)	Default Maximum					
							ECA Above POI (ha)	ECA Above POI (%)				Chart Area ECA (ha)	Chart Area ECA (%)				
Roberts Creek	1	Roberts Creek at the mouth	2,662.5	346.9	13.0%	**Low**	532.5	20%	2,176.4	216.2	9.9%	435.3	20%	~~185.6~~	481.2	18.1%	At present, no more than 185.6 ha should be harvested within BCTS chart area within the Roberts Creek Watershed, while at the same time no more than 102.8 ha should be harvested above POI 2, no more than 35.8 ha should be harvested above POI 4, no more than 19.0 ha should be harvested above POI 6, and no more than 15.3 ha should be harvested above POI 7.
	2	Roberts Creek at BCTS Boundary	808.2	58.9	7.3%	**Low**	161.6	20%	789.9	54.9	7.0%	158.0	20%	102.8	161.7	20.0%	
Clack Creek	3	Clack Creek at the confluence with Roberts Creek	1,251.4	178.6	14.3%	**Low**	250.3	20%	1,081.2	130.8	12.1%	216.2	20%	71.7	233.4	18.6%	
	4	Clack Creek at BCTS Boundary	402.5	44.7	11.1%	**Low**	80.5	20%	402.5	44.7	11.1%	80.5	20%	35.8	80.5	20.0%	
Gough Creek	5	Gough Creek at the confluence with Clack Creek	589.8	98.9	16.8%	**Low**	118.0	20%	491.6	71.1	14.5%	98.3	20%	19.0	117.9	20.0%	
	6	Gough Creek at BCTS Chart Boundary	523.6	80.2	15.3%	**Low**	104.7	20%	484.9	69.0	14.2%	97.0	20%	24.5	99.2	18.9%	
East Roberts Creek	7	East Roberts Creek at confluence of Roberts Creek	310.5	46.8	15.1%	**Low**	62.1	20%	229.6	17.9	7.8%	45.9	20%	15.3	54.6	17.6%	
Stephens Creek	8	Stephens Creek at the mouth	255.4	32.0	12.5%	**Low**	51.1	20%	198.6	21.0	10.6%	39.7	20%	18.7	50.7	19.8%	No more than 18.7 ha be harvested within BCTS chart area within the Stephens Creek Watershed

Note:

1) Yellow highlighted cells show limiting factor for maximum ECA identified for each POI.
2) When identifying the maximum additional ECA to maintain current PFH, consideration is given to the overall watershed constraint as well as the constraints for catchments nested within. Values struck out would maintain current PFH for the respective POI/catchment; however, PFH would increase for another POI/catchment in the same watershed – thus values struck out are not recommended.
3) The maximum harvest assumption is based on constraints for all POIs within the watershed and not just for a single POI. For example, although 178.1 ha is available above POI 1, only 134.3 ha is available given the constraints of POIs upstream.

TABLE 6.3 *Current (2021) ECAs in the portion of the watershed unit above 800 m elevation.*

Assessment Watershed Unit	Drainage area above 800 m (ha)	ECA above 800 m (ha)	
		ha	%
Roberts Creek Watershed	458.90	38.54	8.40
Clack Creek Basin[93]	142.75	6.10	4.27
Gough Creek Sub-basin	285.01	32.62	11.45
East Roberts Creek Basin	16.04	1.93	12.06
Stephens Creek Watershed	87.46	14.12	16.14

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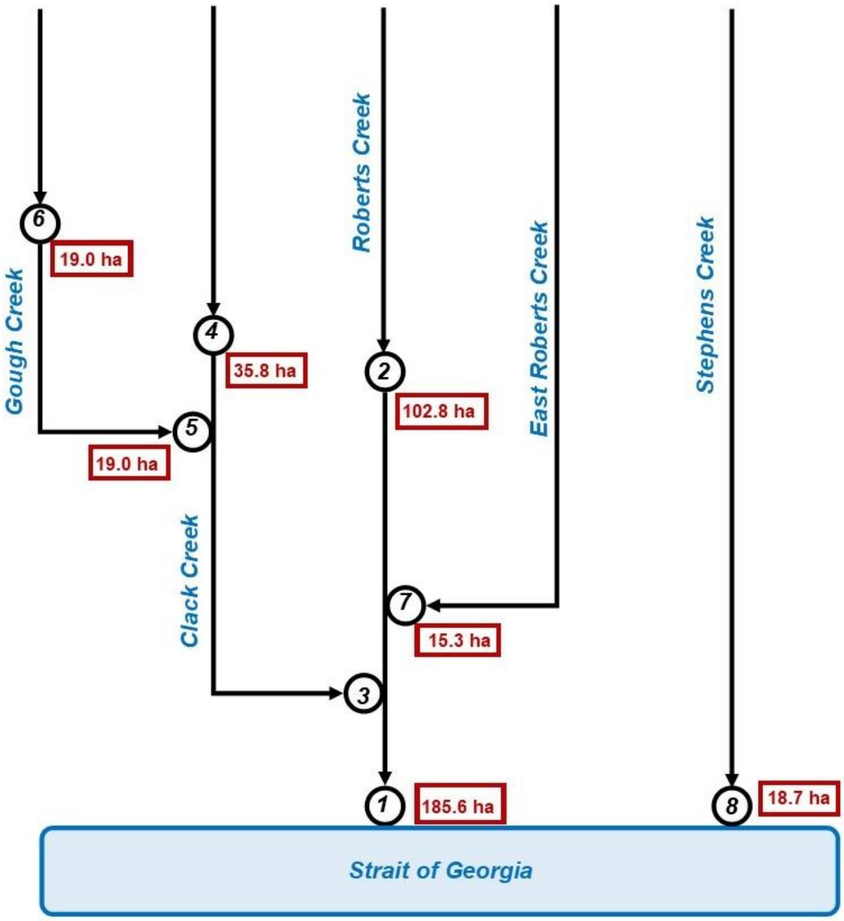
[93] Excluding Gough Creek Sub-basin



POI #	Point of Interest (POI)
1	Roberts Creek at the mouth (km 0.0)
2	Roberts Creek at BCTS Chart Boundary (km 3.8)
3	Clack Creek at confluence with Roberts Creek (km 0.4)
4	Clack Creek at BCTS Chart boundary (km 3.5)
5	Gough Creek at confluence with Clack Creek (km 2.4)
6	Gough Creek at BCTS Chart boundary (km 5.5)
7	East Roberts Creek at confluence with Roberts Creek (km 1.4)
8	Stephens Creek at the mouth

FIGURE 6.4 *Schematic of the maximum additional ECA (values in red) to maintain current low peak flow hazard in the assessment area.*

ECAs in the assessment area range from 7.3 % for Roberts Creek at BCTS chart boundary (POI 2) to 16.8% for Gough Creek at the confluence with Clack Creek (POI 5). FIGURE 6.1 and FIGURE 4.18 demonstrate that forests within the assessment watersheds have been subject to some residential and commercial development in the lower portions and to past forest development in the upper portions.

The following descriptions by assessment stream identify the expected forest development effects on the current hydrologic condition. It should be recognized that even though BCTS maintains a low peak flow hazard within BCTS chart area, peak flow hazards downslope of the chart are also affected by residential and commercial development. As such, meaningful reductions for some downstream POIs may never be realized because there is little to no hydrologic recovery associated with downstream residential and commercial development areas (e.g., the golf course). Fortunately, current overall ECAs above all POIs are below 20%. Further, with the exception of Stephens Creek, ECAs above 800 m elevation are below 15% (TABLE 6.3). Consequently, peak flow hazard for all POIs is currently low with exception of Stephens Creek where it is marginally higher, but still considered low given the overall ECA.

Roberts Creek

In the Roberts Creek watershed, seven POIs have been identified above which overall ECAs have been calculated (TABLE 6.2). Current ECA for the watershed (i.e., Roberts Creek at the mouth) is 13.0% (346.9 ha). ECA above Roberts Creek at BCTS chart boundary (POI 2) is currently 7.3% (58.9 ha). Current ECA for the POIs within the watershed are greatest within Gough Creek at the confluence with Clack Creek, which has a current ECA 16.8% (98.9 ha). In the Clack Creek basin, ECAs range from 14.3% (178.6 ha) at the confluence with Roberts Creek to 11.1% (44.7 ha) at BCTS chart boundary. In Gough Creek, ECAs range from 16.8% (98.9 ha) at the confluence with Clack Creek to 15.3% (80.2 ha) at BCTS chart boundary. In East Roberts Creek at confluence with Roberts Creek, ECA is 15.1% (46.8 ha). Above 800 m elevation, ECAs in the Roberts Creek watershed range from 4.3% to 12.1% (TABLE 6.3).

As such, the current peak flow hazard (PFH) is considered low for all stream reaches within the Roberts Creek watershed. If BCTS is seeking development opportunities and wishes to maintain current low PFH levels, ECAs within BCTS chart area should be limited to an increase of no more than 185.6 ha overall, while at the same time no more than 102.8 ha is harvested above POI 2, no more than 35.8 ha is harvested above POI 4, no more than 19.0 ha is harvested above POI 6, and no more than 15.3 ha is harvested above POI 7. Furthermore, ECAs within areas above 800 m elevation should be maintained below 15%.

These recommendations reflect current (2021) conditions. More availability for harvest may be available in the future as stands recover. Assuming no additional development, recovery of 44.8 ha is projected by 2026 and 93.4 ha of recovery is projected by 2031 for the watershed overall (TABLE E.1, APPENDIX C).

Stephens Creek

Current overall ECA in Stephens Creek is 12.5% (32.0 ha) at the mouth, with 16.1% (14.1 ha) above 800 m elevation. As such, the current PFH the watershed is deemed low. A low PFH is expected as long as no more than 18.7 ha be harvested within BCTS chart below 800 m elevation under current (2021) conditions. By 2026 and 2031, ECAs are projected to decrease by 3.0 ha and 5.5 ha, respectively.

Effects of roads on peak flows

Although the removal of forest cover along road rights-of way are accounted for in ECA calculations, roads can also affect natural drainage patterns and increase runoff generation potential, thereby increasing the rate at which runoff water is delivered to streams. This is particularly important where roads intercept near-surface groundwater (Wemple and Jones, 2003).

Current (2021) road densities and lengths were calculated for the watershed units and are presented in TABLE 6.4. The road layer was compiled using the FTA, Digital Road Atlas, DEM bare earth hillshade, and streaming imagery. It is important to note, however, that these road densities were calculated solely from a GIS-based exercise and were not field verified. Moreover, no information was available to differentiate between existing and deactivated roads.

Urbanization is generally concentrated below approximately 300 m, and the area above 300 m is largely Crown Land. As such, road lengths and densities above 300 m can be considered to generally represent the influence of forestry.

Recommended road density management thresholds are not provided as they can be somewhat misleading. For example, a high density of well built (i.e., well-spaced and working drainages, robust road surface, etc.) may have a lesser effect on hydrology than a low density of poorly built roads. As such, only qualitative ratings are provided. Road densities above 300 m are generally low or moderate ranging from 0.46 km/km^2 in the East Roberts Creek basin to 2.76 km/km^2 in the Stephens Creek watershed. Despite moderately elevated road densities in some watershed units, road conditions within the assessment area were observed to be in good condition. The current road alignments in the assessment area are generally on relatively low gradient terrain (FIGURE 4.3). Exceptions include a section of road along relatively steep ground (roughly 40-60% gradient) in the upper portion of the Stephens Creek watershed; however, this road section appears inactive (FIGURE 6.5). As a result, most road cuts are relatively shallow. Furthermore, due to relatively rapid preferential flow and high drainage density, shallow groundwater and surface water flow rates are similar, such that road-related effects (e.g., interception of shallow groundwater flow and conveyance as ditch flow) on drainage patterns and flow rates are expected to be small. Based on this, the net effect of forest resource roads on near-surface groundwater interception and ultimately peak flow hazard is low.

TABLE 6.4 *Road lengths and road densities for the assessment watersheds. An elevation of 300 m serves as a rough approximation for the boundary between urban roads (below) and forest resource roads (above).*

Watershed Units					
Stream / Watershed	**Roberts Creek Watershed**	**Gough Creek Sub-basin**	**Clack Creek basin**	**East Roberts Creek basin**	**Stephens Creek Watershed**
Roads					
Total road length (km)	55.41	15.11	10.54	2.10	10.31
Total road density (km/km²)	2.08	2.57	1.72	0.67	4.01
Total road area (ha)	73.67	14.89	15.47	5.67	10.45
Road length below 300 m el. (km)	18.78	3.35	1.43	1.23	1.01
Road density below 300 m el. (km/km²)	3.29	3.25	2.69	1.01	1.88
Road area below 300 m (ha)	20.83	3.18	1.47	2.86	1.98
Road length above 300 m el. (km)	36.63	11.76	9.12	0.87	5.46
Road density above 300 m el. (km/km²)	1.75	2.42	1.63	0.46	2.76
Road area above 300 m (ha)	52.85	11.72	14.00	2.80	8.47

FIGURE 6.5 *View eastward along inactive road alignment leading towards the western boundary of the Stephens Creek watershed. Photo DSC09520, August 25, 2020.*

6.1.2. Low Flows

The current distribution of seral stages (FIGURE 4.15) across the assessment area indicates that most of the forested land base has been either naturally disturbed (e.g., by wildfire) or harvested within the last 150 years. In other words, forests in the assessment area are predominantly, second growth stands. As such, the history of disturbance has potentially influenced low flows of the assessment streams. The distribution of forest age classes within BCTS chart area offers some indication of relative water consumption overall (FIGURE 4.15) and for each of the assessment watersheds (FIGURE 6.6). This type of analysis as part of a watershed assessment is novel and based on limited data, so, the analysis is restricted to a qualitative exercise. Four age classes were identified based on structural stages outlined in the Standard for Terrestrial Ecosystem Mapping in British Columbia (Ecosystems Working Group, 1998) and research literature on forest structure (Spies and Franklin, 1991) and on the effects of forest cover removal on low flows in the Pacific Northwest (e.g., Perry and Jones, 2017; Segura et al., 2020).

As discussed in Section 3.1.2, increases in late summer (i.e., July to September) flow volumes can occur in the first several years following forest cover removal[94]. The increase in late summer flow is associated with the elimination of interception and transpiration losses and a net increase in soil moisture, which may contribute to groundwater recharge. However, such increases typically persist from a few years (Segura et al., 2020) to upwards of fifteen years (Perry and Jones, 2017). Once sufficiently dense regenerating forest becomes established, the potential for water demands from the forest increases, often resulting in less water available for infiltration and runoff than prior to harvesting. This is a phenomenon referred to as *over-recovery*, whereby the density and forest cover provided by vigorously growing tree plantations exceeds the original stand. Perry and Jones (2017) found that persistent low flow deficits (i.e., over-recovery) were less likely to occur when openings were smaller than approximately 8 ha and were unlikely to occur when catchments were subject to a 50% thinning (i.e., shelterwood) silviculture system. If the area experiences fog, retaining canopy cover will also facilitate fog interception. As forest stands age, evapotranspiration rates decrease and low flows will trend towards baseline conditions; however, a return to baseline can be a lengthy process. Segura (2020) found that summer streamflow generated from 40- to 53-year-old Douglas-fir stands was still 50% less than runoff generated from the mature/old (90- to 170-year-old) Douglas-fir stands.

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[94] It is important to recognize that the majority of studies evaluating the effect of forest cover removal on low flows are based on 100% basal area removal.

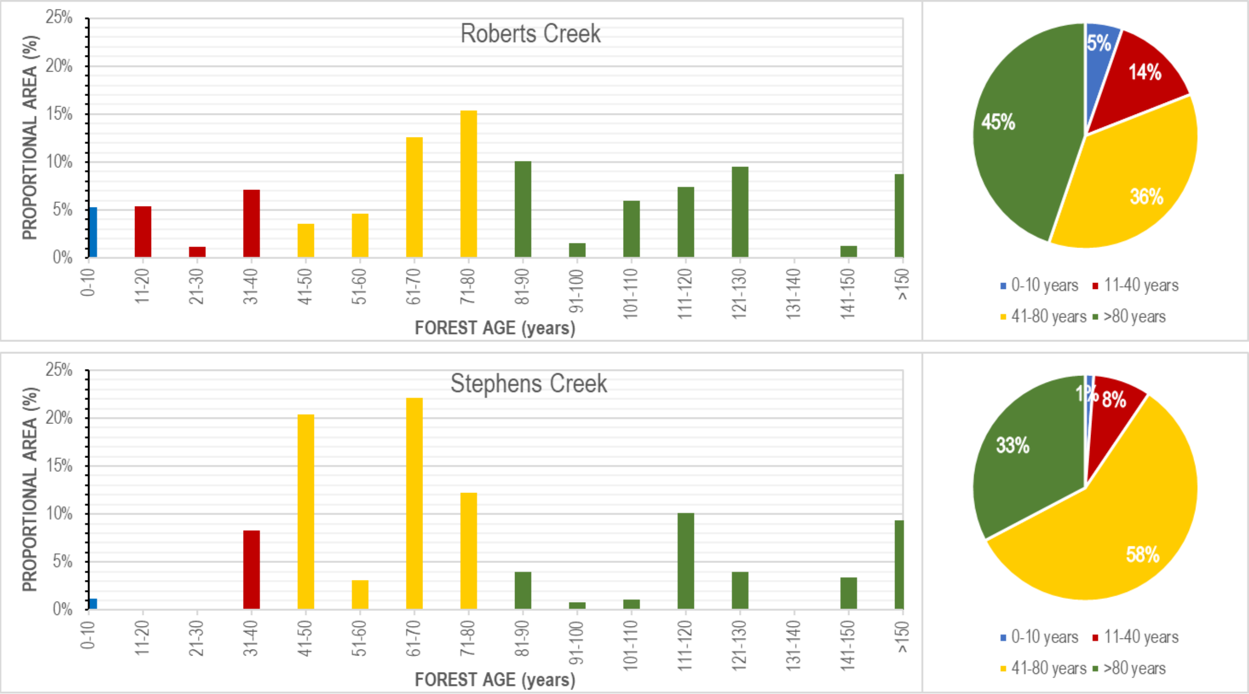

FIGURE 6.6 *Distribution of forest ages within by watershed. The histogram presents age classes by decade. The pie chart shows stand age distribution for four age classes based on water consumption (i.e., evapotranspiration rates) relative to mature (i.e., >80-year-old) stands. Stands 0-10 years old are expected to have relatively low water consumption, stands 11-40 years are expected to have relatively high water consumption, stands 41-80 years are expected to have relatively moderate water consumption and stands >80-years are expected to have normal water consumption (i.e., baseline).*

As indicated above, forest stand ages throughout BCTS chart area have been classified into four age classes to illustrate summer water use relative to baseline conditions. In this case, baseline conditions are represented by mature (>80-year-old) stands. Forest stands aged 0-10 years are considered to have relatively low water consumption, potentially resulting in water surpluses; young forest stands aged 11-40 years are considered to have relatively high water consumption; young/mature forest stands aged 41-80 years are considered to have relatively moderate water consumption; and mature forest stands greater than 80-years old are considered to have normal (baseline) water consumption. The likelihood that low flow conditions are currently being adversely affected in each of the assessment streams is assessed based on the distribution of forest ages in FIGURE 6.6. It is important to recognize, however, that as the age distributions change over time, so will the potential effect on low flows.

Upland Forest Cover

The likelihood that low flow conditions are adversely affected by the current distribution of seral stages is presented in TABLE 6.5.

Forest stands in Roberts Creek are for the most part old/mature stands (> 80-years old) followed by young/mature stands (41-80-years). Only 5% of the forest stands are newer openings (0- to 10-year-old stands) with the remaining 14% occupied by young stands (11- to 40-year-old). Despite the relatively large portion of old/mature stands and potential water surpluses from the newer openings, there is a moderate likelihood that flows during the late summer period (i.e., July to September) are currently reduced by the distribution of forest stand ages. This is in large part due to the fact that half of the forest stands are likely over-consuming water relative to baseline conditions. Assuming no further development, the influence of maturing forest stands on late summer flows is expected to improve[95] (i.e., reduced potential for flow reduction) in the short-term as young/mature stands continue to mature and evapotranspiration rates decrease.

A majority of forest stands in Stephens Creek are between 41- and 80-years old with 33% and 8% made up of old/mature and young stands, respectively. A relatively negligible portion of stands consist of newer openings. As such, there is a moderate likelihood that flows during the late summer period are currently reduced by the distribution of forest stand ages. Assuming no further development, the influence of maturing forest stands on late summer flows is expected to gradually improve. Recovery, however, is expected to be relatively slow given the high proportion of young/mature stands aged between 41- and 50-years. Once the younger stands mature and evapotranspiration rates decrease, we would expect flows during the late summer period to be increased.

TABLE 6.5 *Effects of current stand age distributions on low flows in the assessment watersheds.*

Assessment Watershed	Likelihood that current forest structure is adversely affecting low flows
Roberts Creek	Moderate
Stephens Creek	Moderate

Riparian Areas

The research of Hicks et al. (1991) looked at the colonization of riparian areas by deciduous species following stream-side harvesting and suggested that evapotranspiration rates by such colonizing species could exceed those of the pre-harvest (mature) stand and result in reduced runoff during the low flow period. Moreover, Moore (2004) found evapotranspiration rates within the riparian areas of young Douglas-fir forests exceeded those of mature forests by nearly 3.3 times.

Historical logging practices in the assessment area often included harvesting of riparian areas, which led in some cases to colonization of deciduous species. The earliest available air photos from 1947 indicate that riparian areas were logged along several small streams and portions of Roberts Creek.

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[95] The increase in late summer flow conditions only accounts for the influence of forest cover and does not include potential reductions in flows associated with climate change.

Most riparian corridors were occupied by deciduous species by that time. Harvest of riparian areas continued to varying degrees until at least 1994 (a detailed description of riparian disturbance is provided in Section 6.3).

In addition to the influence of the upland forest cover (i.e., everywhere excluding the riparian area) described above, the colonization of deciduous species within riparian corridors has likely resulted in increased water demands and consequently a reduction in low flows in most assessment streams. Fortunately, a majority of the deciduous vegetation is mature and therefore expected to utilize less water than it would have when it originally established (Moore, 2004). Harvesting deciduous riparian corridors as a means of potentially improving low flow conditions is not recommended. Any short-term amelioration of low flows would likely be superseded relatively quickly by rapidly regenerating and more vigorous young deciduous species.

The likelihood that low flows have been adversely affected by the current distribution of seral stages is moderate for both Roberts and Stephens Creek. With regards to future development, recommendations to mitigate potential adverse effects on low flows are provided in Section 9.

6.1.3. Groundwater/Aquifer recharge

Although relatively little research has been conducted on potential interactions between forest management activities and groundwater systems (Smerdon et al., 2009), several factors suggest that if BCTS maintains a low peak flow hazard and low likelihood of adversely affecting low flows (as described above), the risks associated with BCTS development in the assessment area on the groundwater supply are low. Similar to low flows, forest harvesting results in a reduction of site-level interception and transpiration. As such, an increase in net soil moisture can be expected following forest harvesting (Smerdon et al., 2009). As noted above, such an increase may be observed for up to 10-15 years (Perry and Jones, 2017). Beyond that time, there is a potential for decrease, but only if opening size exceeds approximately 8 ha or where thinning occurs, if >50% of the overstory canopy is removed.

Most groundwater wells appear to be established sufficiently deep within regional-scale bedrock groundwater systems. As a result, travel times for groundwater flow from BCTS chart area to the principal aquifers and wells are expected to be on the order of decades or greater. One exception includes an 8.3 m deep well located between Clack Creek and Roberts Creek; however, given its location >150 m from principal channels, it is not expected to be influenced by forestry activities upstream. Several deep wells are located near BCTS chart along Gough Creek. Despite being relatively deep (i.e., > 60 m deep), these should be reviewed in greater detail if forestry activities are planned within roughly 500 m upstream.

In the assessment area, an increase in the site-level water balance and hence increase in the site-level groundwater table is possible following harvest, although with a high level of variability. Depending on the proximity of the harvested area to the zone of groundwater recharge, an increase in recharge may be realized; however, it is likely to occur over timescales too large for the increase to be measurable. Moreover, a majority of aquifer recharge occurs during the wetter fall and winter months. During these times, evapotranspiration rates are low and therefore the likelihood that the removal of forest cover would measurably influence groundwater recharge is low. Combined with the measures noted above to maintain low peak flow and low flow hazard, such long time-scales for groundwater movement relative to future forest harvest and silvicultural activities are likely to make harvest-related effects undetectable.

6.1.4. Summary

In summary, the hydrology of the assessment watersheds is driven predominantly by rainfall; however, rain-on-snow is considered the principal driver of peak flows. The lower portions of the assessment area have been subject to varying degrees of residential and commercial development. Moreover, most, if not all, forest stands in the upper portion of the assessment area have been subject to historical disturbance, either by wildfire or logging. As such, regenerating forest stands within BCTS chart area are at various levels of recovery and contain various proportions of deciduous species, which are considered less hydrologically recovered relative to coniferous stands.

Peak Flows

Based on the characteristics of the assessment streams, RGP is considered high for both watersheds. To identify peak flow hazard at various locations throughout the assessment area, eight points-of-interest have been identified (FIGURE 6.2, FIGURE 6.3). With consideration of RGP and the research literature, recommended ECA maxima are provided with the objective of limiting increases in peak flow hazard at points of interest (POIs) downstream of BCTS chart area, while maintaining ECAs below 20% for the portion of the watershed within BCTS chart area.

ECAs in the assessment area range from 7.3 % for Roberts Creek at BCTS chart boundary (POI 2) to 16.8% for Gough Creek at the confluence with Clack Creek (POI 5). Considering that ECAs are below 20% for all identified POIs, the current peak flow hazard is low for all watershed units.

If BCTS wishes to pursue development opportunities in the assessment watersheds, the maximum additional ECA available to maintain current peak flow hazard levels are identified (TABLE 6.2). Moreover, projected hydrologic recovery in terms of expected increases in ECA are provided in APPENDIX C.

Low Flows

With regards to summer low flows, the distribution of seral stages (i.e., forest ages) suggest that low flows have been influenced to varying degrees by historical disturbance. The likelihood that low flows have been adversely affected by the current distribution of seral stages is moderate for both Roberts Creek and Stephens Creek. With respect to future development and based on the literature, alternative silviculture approaches in upland and riparian areas are recommended to minimize the likelihood of causing an incremental adverse effect on summer low flows. Furthermore, we also encourage the planting of a mix of conifer species similar to the pre-harvest (mature) stands to achieve similar long-term evapotranspiration rates.

Groundwater/Aquifer Recharge

If BCTS maintains current low peak flow hazards and a low likelihood of adversely affecting low flows as described above, the risks associated with BCTS development in the assessment area on the groundwater supply are low. Site-level increases in the water balance can be expected following the removal of forest cover. This may result in localised increases in the groundwater table; however, such increases are only expected to persist for up to 10-15 years. Beyond that time, there is a potential for decrease, but only if opening size exceeds approximately 8 ha. Given the long time periods associated with groundwater movement and recharge, harvest-related effects are expected to be undetectable if the above constraints are met.

6.2. SEDIMENT YIELD

6.2.1. Roads

Based on our office and field review, few development-related sediment risks were identified in the assessment area[96]. Sechelt Roberts FSR (7575) and its branch roads have stable road surfaces and functional drainage infrastructures were noted along all reviewed active roads (FIGURE 6.7). Consequently, the erosion potential from active roads is low. Erosion potential does marginally increase in the vicinity of crossings of incised gullies, due to the increased height of road cuts that are typically required; however, these site-level risks appear to have been effectively mitigated where necessary, and sediment risks are low. Sediment from new roads and trails is a primary concern with future forest development. As such, effective drainage, erosion and sediment control is paramount to minimizing sediment yields.

Road Crossings

Given the relatively small size of the streams in the assessment area, downstream dilution of sediment inputs is minimal. As such, sediment contributions from roads, particularly at stream crossings, can

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[96] As discussed in Section 3.2.1, no formal site-level assessment of sediment yield (i.e., FREP WQEE protocol) was conducted at stream crossings.

result in increased sediment concentrations downstream. A total of 122 road crossings in the assessment area were identified[97] during the field reviews and a review of satellite imagery (FIGURE 6.8). Of these, roughly 52 were identified along the principal assessment streams and are summarized in TABLE 6.6. Although this does not necessarily represent an exhaustive inventory, it does represent a large sample of the stream crossings. For the most part the crossings consisted of culverts or pipes, although at least seven bridges were identified. A ford crossing was also identified along the BC Hydro right-of-way (ROW). Additionally, 17 pedestrian bridges, generally along hiking and biking trails, were identified during the field review. The spatial distribution of crossings is summarized in FIGURE 6.8.

The distribution of crossings within BCTS chart area (i.e., on resource roads) or outside of BCTS chart area (i.e., public roads and highways) varies by watershed (TABLE 6.7). In Roberts Creek, a majority of the stream crossings are within BCTS chart area. Exceptions include in East Roberts Creek where the road crossings are generally evenly distributed between chart and non-chart area. The specific type of crossing and size (if known) are presented in TABLE 6.6.

Although the number of stream crossings, or density of stream crossings per km^2 (reported in TABLE 6.7), may be useful as a high-level screening tool of the potential for sediment-related hazards (particularly on resource roads), we have placed little emphasis on this indicator for this assessment, instead relying on field-specific observations to evaluate the overall hazard in each watershed. Our field observations within BCTS chart area generally indicate that sediment hazards associated with stream crossings is low[98], largely as a result of gentle road grades, deactivation of unused roads, and effective control measures such as coarse gravel road surfacing and/or rock armour at culvert inlets and outlets or along bridge abutments. There are very few examples where sediment hazards are elevated in the assessment area within BCTS chart area. Exceptions include the path of a debris flood, which appeared to be initiated from a road crossing along Clack Creek tributary 5 that is now deactivated (MAP 1) (discussed in Section 6.2.2). Such examples, however, are uncommon in the assessment area.

Potential Effects of BCTS Planned Development

BCTS chart area within the assessment watersheds is largely characterized as gentle to moderate terrain (FIGURE 4.3). Sediment risks associated with forest development are primarily associated with

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[97] It is important to recognize that a complete inventory of road crossings was beyond the scope of this assessment. Stream crossings were identified during the field review; however, as mentioned previously the review was generally focused in the eastern portion of the assessment area. Crossings not observed in the field were identified using satellite imagery. As such, it is likely that the crossings reported herein do not capture all of the crossings in the assessment area.

[98] The sediment hazard refers to the likelihood of measurable erosion and sedimentation to occur in the vicinity of stream crossings. It does not consider the potential for crossing damage or washout in the event of an extreme flood. Evaluation of design flows and flood conveyance at crossings is beyond the scope of the assessment.

the construction (including reactivation), maintenance, and use of new and existing roads and trails. Fine-textured soils may be susceptible to rutting, compaction and erosion if subject to mechanical disturbance or excessive traffic during wet weather or wet ground conditions. Sediment risks can, however, be mitigated with a number of well-planned, implemented and monitored[99] control measures, depending on site-conditions. Several of these measures are outlined in Section 9. Assuming that these (or equally effective) control measures are documented implemented during harvest planning and construction, sediment yields and the risks associated with future forest development should be maintained at low levels.

FIGURE 6.7 *View of the Sechelt Dakota (Br01) within the East Roberts Creek basin at an elevation of 675 m. This example shows a stable road surface. Photo DSC09550, August 25, 2020.*

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[99] In order to minimize sediment risks during future forest development, works involving potential soil disturbance or large cuts and fills within 50 m of a classified stream channel and installation of bridges or major culverts should be monitored by a Qualified Professional (QP) at a frequency and intensity commensurate with amount of soil disturbance and stream values at risk.

TABLE 6.6 *List of active stream crossings along the* ***principal*** *streams identified during the course of the assessment.*

No.	Type	Road	Diameter (mm)	Stream	Stream km
1	Bridge	Lower Road	-	Roberts Creek	0.2
2	Foot Bridge	-	-	Roberts Creek	0.8
3	Foot Bridge	-	-	Roberts Creek	0.8
4	Culvert	Sunshine Coast Highway	3,000	Roberts Creek	0.9
5	Foot Bridge	-	-	Roberts Creek	1.2
6	Foot Bridge	-	-	Roberts Creek	1.8
7	-	Golf Course	-	Roberts Creek	1.9
8	Foot Bridge	-	-	Roberts Creek	2.2
9	Bridge	Flume Road	-	Roberts Creek	4.2
10	Bridge	Sechelt Dakota	-	Roberts Creek	8.7
11	-	-	-	Roberts Creek	9.8
12	-	-	-	Roberts Creek	10.7
13	-	-	-	Roberts Creek	11.4
14	Foot Bridge	-	-	East Roberts Creek	1.5
15	Foot Bridge	-	-	East Roberts Creek	1.75
16	Bridge	Golf course	-	East Roberts Creek	1.8
17	Bridge	Hydro right-of-way	-	East Roberts Creek	2.1
18	-	Flume Road	-	East Roberts Creek	3.75
19	-	Sechelt Guys Gulch	-	East Roberts Creek	6.4
20	-	Sechelt Roberts	-	East Roberts Creek	7.2
21	-	Pit Road	-	East Roberts Creek	7.6
22	Foot Bridge	-	-	Clack Creek	0.8
23	Culvert (2x)	Sunshine Coast Highway	1,700/1,500	Clack Creek	0.8
24	Foot Bridge	-	-	Clack Creek	0.9
25	Foot Bridge	-	-	Clack Creek	1.2
26	Foot Bridge	-	-	Clack Creek	1.3
27	Foot Bridge	-	-	Clack Creek	1.7
28	-	Golf Course	-	Clack Creek	1.8
29	Foot Bridge	-	-	Clack Creek	2.1
30	Foot Bridge	-	-	Clack Creek	2.4
31	-	Day Road	-	Clack Creek	2.8
32	Bridge	Flume Road	-	Clack Creek	3.8
33	-	Flume Road	-	Clack Creek	5.2
34	-	-	-	Clack Creek	5.8
35	-	-	-	Clack Creek	6.2
36	-	-	-	Clack Creek	6.8
37	-	Sechelt Dakota	-	Clack Creek	7.6
38	-	-	-	Clack Creek	8.2
39	-	Flume Road	-	Gough Creek	5.6
40	-	Sechelt Dakota	-	Gough Creek	8.0
41	-	Sechelt Chapman	-	Gough Creek	8.7
42	-	D-1000	-	Gough Creek	9.9
43	-	D-3000	-	Gough Creek	11.5
44	Foot Bridge	-		Stephens Creek	0.0
45	Foot Bridge	-		Stephens Creek	0.0
46	Culvert	Lower Road	1,400	Stephens Creek	0.3
47	Culvert	Sunshine Coast Highway	1,200	Stephens Creek	0.7
48	Foot Bridge	-	-	Stephens Creek	1.3
49	Bridge	Hydro right-of-way	-	Stephens Creek	1.8
50	-	Largo Road	-	Stephens Creek	3.3
51	-	-	-	Stephens Creek	4.7
52	-	Sechelt Guys Gulch	-	Stephens Creek	5.8
53	-	Pit Road	-	Stephens Creek	7.2

Notes:

1) The list of active stream crossings is based on field observations made during the course of the assessment and should not be considered an exhaustive list (i.e., this is not a detailed stream crossing inventory). E.g., we are aware of several foot bridges that were on private property not accessed during the review.
2) Locations of stream crossings are presented on FIGURE 6.8.
3) Diameter of stream crossing is identified where known.

TABLE 6.7 *Number of stream crossings in the assessment area.*

Watershed	Drainage Area (km²)	Number of pedestrian bridges	Number of road crossings	Number of Stream Crossings (all types)	Density of pedestrian bridges (#/km²)	Density of road crossings (#/km²)	Density of stream crossings (#/km²)
Roberts Creek (BCTS chart area)	21.8	-	78	**78**	-	0.8	**0.8**
Roberts Creek (Non BCTS chart area)	4.9	14	29	**43**	2.9	18.3	**21.2**
Roberts Creek (Overall)	26.6	14	107	**121**	0.5	4.0	**4.5**
East Roberts Creek (BCTS chart area)	2.3	-	9	**9**	-	3.9	**3.9**
East Roberts Creek (Non BCTS chart area)	0.8	2	6	**8**	2.5	7.4	**9.8**
East Roberts Creek (Overall)	3.1	2	15	**17**	0.6	4.8	**5.5**
Clack Creek (BCTS chart area)	10.8	-	51	**51**	-	4.7	**4.7**
Clack Creek (Non BCTS chart area)	1.7	7	8	**15**	4.1	4.7	**8.8**
Clack Creek (Overall)	12.5	7	59	**66**	0.6	4.7	**5.3**
Gough Creek (BCTS chart area)	4.9	-	18	**18**	-	3.7	**3.7**
Gough Creek (Non BCTS chart area)	1.0	-	2	**2**	-	2.0	**2.0**
Gough Creek (Overall)	5.9	-	20	**20**	-	3.4	**3.4**
Stephens Creek (BCTS chart area)	1.9	-	-	**0**	-	0.0	**0.0**
Stephens Creek (Non BCTS chart area)	0.6	1	15	**16**	1.7	26.2	**27.9**
Stephens Creek (Overall)	2.5	1	15	**16**	0.4	6.0	**6.3**

Total Assessment Area (BCTS chart area)	101.3	-	78	**78**	-	0.2	**0.2**
Total Assessment Area (Non BCTS chart area)	79.6	15	44	**59**	0.2	1.3	**1.5**
Total Assessment Area (Overall)	176.0	15	122	**137**	0.1	0.7	**0.8**

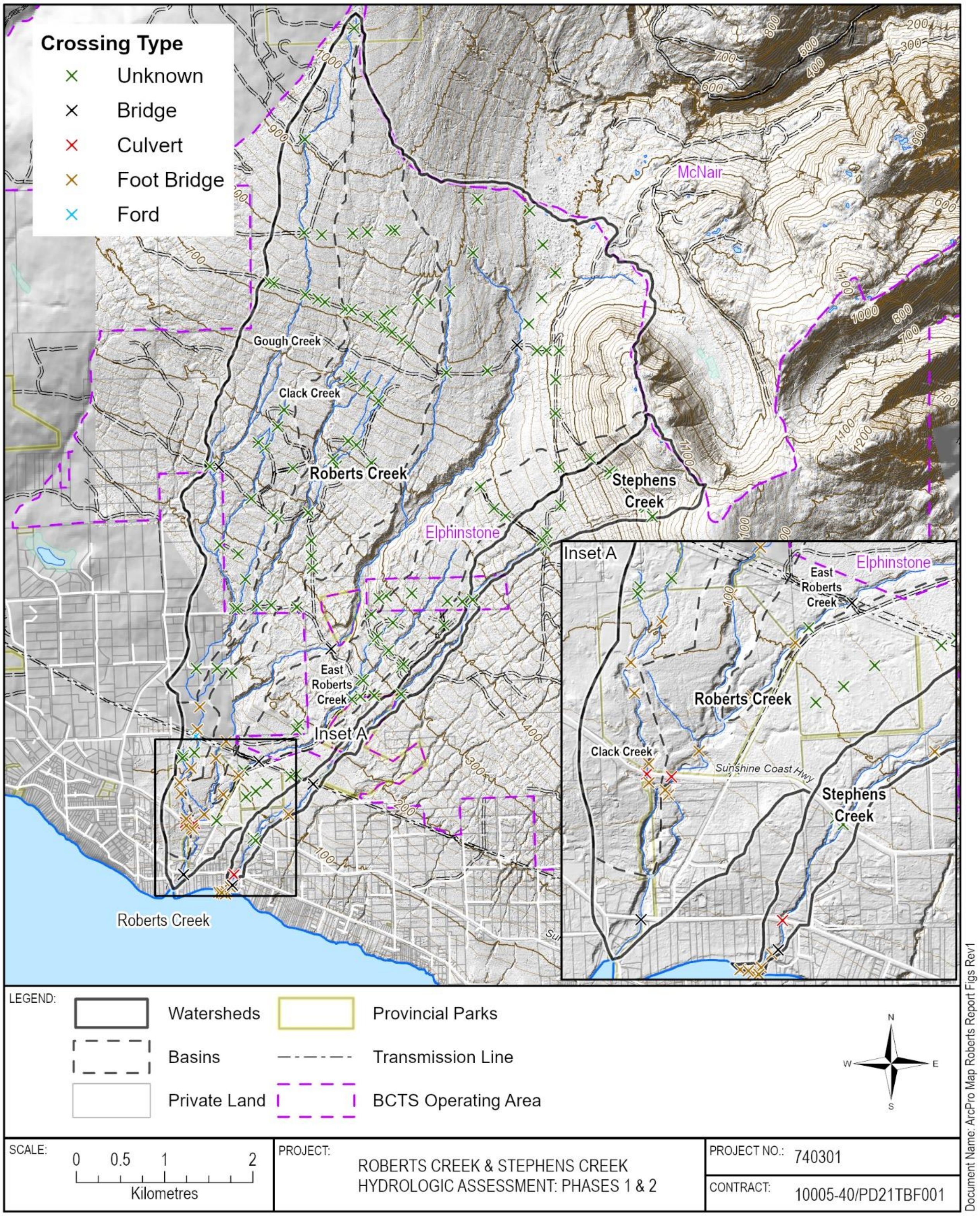

FIGURE 6.8 *Locations of stream crossings in the assessment area.*

6.2.2. Landslides

There is a history of landslides in or near the assessment area (see below). This includes debris flows in Clack Creek (Madrone, 2012), and in Clough Creek (just east of Stephens Creek) in November 1983 [prior to the *Forest Practices Code (FPC)* and *Forest and Range Practices Act (FPRA*)]. Each of these events, discussed below, appear to have been triggered by extreme rainstorms, and in the case of Clough Creek inadvertent drainage diversion along an old road appears to have been a contributing factor. During the field review, we noted evidence of a debris flood that occurred between stream km 8.0 and km 7.5 of Clack Creek tributary 5 (MAP 1). This relatively recent event (date unknown) appears to have triggered by a road crossing washout (which has since been deactivated) (FIGURE 6.9) and run for about 750 m between elevations of 775 m and 685 m (FIGURE 6.9, FIGURE 6.10). With the exception of road washouts at stream crossings and some loss of productive forest soil, this event had limited downstream effects that were likely isolated temporary water quality impacts.

A historical air photo review revealed a number of development-related landslides in the assessment area. Air photos from 1947 to 1982 indicate little to no slope instability in the assessment area; however, air photos from 1990 indicate the presence of a few small debris slides and three debris flow paths on the upper slopes of the assessment area, likely associated with the November 1983 storm responsible for the Clack and Clough Creeks debris flows (FIGURE *6.12*). Two are noted within or adjacent to Roberts Creek Tributary 11, and one was noted in Stephens Creek Tributary 4.2 and 4.3 (MAP 1). In each case, the bulk of the debris flows terminated less than 750 m below the initiation points.

By 2003, the smaller debris slide paths had greened up; however, portions of the debris flow paths were still unvegetated and may have been a source of sediment. No other development-related or natural landslides were noted in the assessment area based on historical air photo and field reviews.

Limited relief and gentle to moderate hillslope gradients generally reduce the likelihood of landslides in the area (Madrone, 2015) and thus current sediment yields from landslides are low. However, as evidenced by the Clough Creek and the Clack Creek tributary 5 washout, debris flows and debris floods along incised gullies, while rare, can be triggered by land use activities, especially where natural drainage patterns are modified on or above potentially unstable slopes. Initiation of such events can occur by landslides along unstable gully sidewalls (usually triggered by excess soil moisture or disturbance by windthrow) or by entrainment of accumulated in-channel debris and sediment during high flows (usually after log jams decay, lose integrity and release stored sediment and debris). In order to avoid or mitigate the potential for landslides, BCTS regularly engages with qualified terrain professionals during the development planning process and has an active road inspection and maintenance program.

FIGURE 6.9 *View upstream of a deactivated road crossing where a recent debris flood appears to have initiated from. Photo DSC09603, August 25, 2020.*

FIGURE 6.10 *View upstream along Clack Creek tributary 5 that was subject to a recent debris flood. This location is approximately 400 m downstream of the initiation point. Note the aggradation along the stream bed. Photo DSC09625, August 25, 2020.*

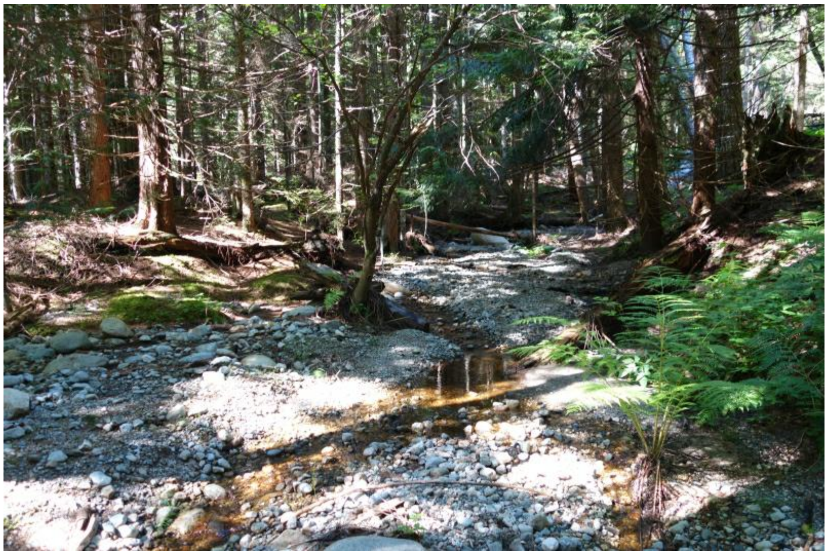

FIGURE 6.11 *View upstream along Clack Creek tributary 5 that was subject to a recent debris flood. This location is approximately 620 m downstream of the initiation point. Note the aggraded conditions along the channel. Photo DSC09635, August 25, 2020.*

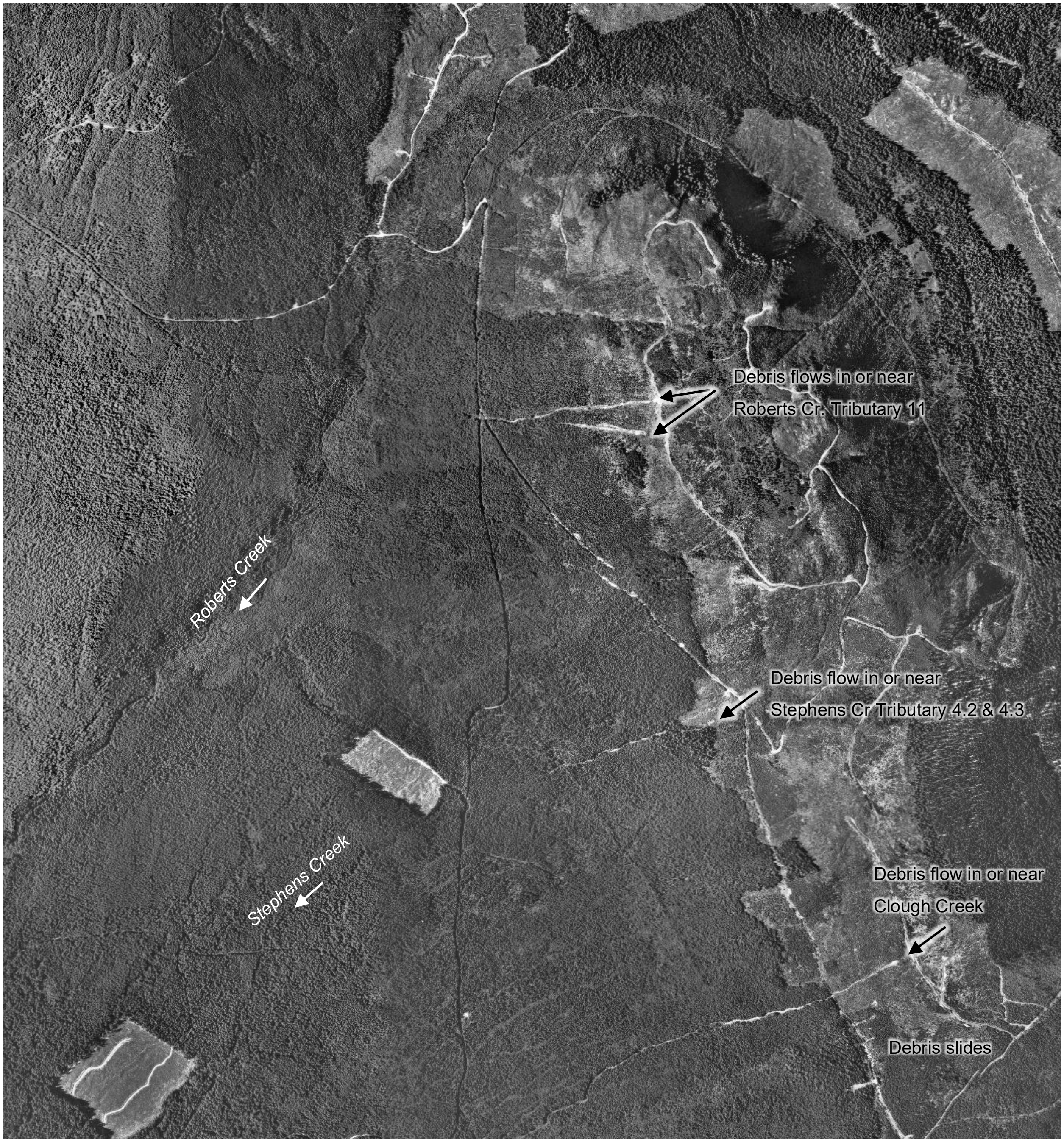

FIGURE 6.12 *1990 Aerial photo showing evidence of debris flows in and near the assessment area, likely associated with a November 1983 storm.*

Local Examples of Landslides

Clack Creek Debris Flow

Clack Creek is a tributary of Roberts Creek. In 1983 a debris flow occurred in Clack Creek. No indicators of an associated landslide were found. No other debris flows or landslides were reported in the Roberts Creek watershed at the time (Madrone, 2012). During Polar's field review, a relatively recent debris flow event (date unknown) appears to have occurred below a now deactivated road crossing along Clack Creek tributary 5 (MAP 1).

Clough Creek Debris Flow

An example of a pre-FPC landslide occurred along Clough Creek in November 1983. Clough Creek is located to the east of the Stephens Creek watershed, outside of the current assessment area. In this case, a debris flow initiated near the 1,000 m elevation (stream km 6) at a location where logging occurred 15 years earlier (FPB, 2006). According to the Forest Practices Board (FPB) (2006) and Emergex (2005), the event was triggered by rainfall-saturated soils that slumped into the creek where it entrained old logging debris and flowed approximately 6 km downslope, where it forced evacuation of homes and caused considerable property damage. Based on an examination of historical air photos, drainage diversion along an old road upslope is suspected to have been a contributing factor. Historical air photos also suggest that although riparian vegetation has effectively recolonized disturbed riparian areas, and is dense, the channel has only modestly recovered and has a lack of large diameter functional wood in the channel. Although this is not critical for the bedrock- and colluvial-dominated channel morphology, it could mean that sediment transport is not well regulated along the creek.

Whittaker Creek Washout at Lower Road

A recent washout of Lower Road at Whittaker Creek, a relatively small drainage between Smales Creek and Higgs Brook, located to the east of the current assessment area, demonstrates the risks associated with poorly managed (urban) stormwater drainage above a steep ravine. According to Carson (2020), the washout that occurred on February 1, 2020 was one of several mass movement events associated with stormwater drainage upslope of the ravine since the 1960s. In addition to damage to the crossing, a debris flow was triggered for 400 m to the ocean, where it damaged several properties and caused considerable aggradation (APPENDIX D, FIGURES 117-119 in Polar, 2023a). The 2020 washout occurred in response to an extreme runoff generated by a two-day rainstorm, which appears to have been exacerbated by interception and conveyance of runoff along the highway and road ditches. Diversion of flows from Smales Creek to Whittaker Creek along the highway ditch is also suspected as a contributor to the flows observed at the Lower Road crossing of Whittaker Creek. Carson (2020) noted that Smales Creek has since been rerouted to flow east along the road ditch towards End/Walker Creek (rather than west towards Whittaker Creek) and estimated this may reduce storm flows by up to 25% in Whittaker Creek. Carson (2020) considers the primary contributing factors to the washout to be the Smales Creek diversion and lack of maintenance of the extensive culvert system along the steep ravine floor below Lower Road.

Potential Effects of BCTS Planned Development

In order to maintain low sediment-related hazard, planning of road alignments and cutblocks should consider and take precautions to avoid alteration of natural drainage patterns upslope of sensitive gullied terrain, minimize windthrow in riparian zones (e.g., by having windthrow assessments performed) and avoid wherever possible physical soil disturbance in riparian zones by heavy equipment (e.g., by establishing machine-free zones along riparian corridors). Such control measures should be tailored to the risk posed by increased sediment yield on downstream values. In such cases, effective cutblock and road layout upslope, combined with control measures are of paramount importance given the close proximity of the elements-at-risk.

6.3. RIPARIAN FUNCTION

When assessing riparian function, the focus is on identifying the degree to which natural riparian function (e.g., to provide shade, cover, stream habitat, stream bank stability, etc.) has or will be influenced by watershed disturbance. For the purposes of this assessment, a high-level overview of riparian function was conducted to evaluate the current riparian condition and its effect on sediment yield and channel stability. This included reviews of historical air photos and other imagery, as well as ground-based reviews at selected locations along the streams (FIGURE 2.1). As discussed in Section 3.3, applying the riparian FREP Protocol is considered beyond the scope of this assessment.

Historical conditions

As discussed in Section 6.1.2, a review of historical air photos dating from as early as 1947 serve to illustrate how historical logging practices and natural disturbances (e.g., wildfire) may have influenced riparian areas along the assessment streams. Most riparian corridors that had not been recently logged were dominated by deciduous species by 1947, which is suggestive that riparian areas were either subject to historic logging and/or naturally disturbed.

In areas where logging had occurred close to 1947, the air photos reveal that riparian areas are logged along the upper reaches of all small streams and portions of Roberts Creek. By 1957, extended logging with little to no riparian protection was noted along Roberts Creek near the Wilson Creek FSR crossing. Air photos from 1967 show the areas logged in 1947 to be densely colonized by deciduous trees. Between 1982 and 1990, riparian areas along Gough Creek were harvested roughly near stream km 9.5 to 10.0. The uppermost portion of Roberts Creek was harvested by 1994 with a sparse riparian buffer. Similarly, riparian harvest was noted on the north side of Flume Road along Gough Creek and Clack Creek with minimal riparian protection, and no buffer noted along East Roberts Creek near stream km 5.5, and in Stephens Creek south of Sechelt Guys Gulch FSR. From 1998, harvesting near streams generally included riparian buffers.

Current Conditions

With the exception of road crossings and the BC Hydro right-of-way, riparian conditions within BCTS chart area on Crown land within the assessment watersheds are characterized by mixed deciduous and second growth conifers with varying amounts of understory vegetation. Along classified streams, riparian vegetation is largely functional in providing bank stability and shade but is occasionally lacking in future recruitment of large woody debris. Many stream reaches have scarce volumes of instream wood; however, several log-jams were noted in lower reaches. Of the in-stream wood present, many of the stable larger-diameter pieces are disintegrating and are likely being replaced by smaller-diameter, less stable wood recruited from the riparian zone. A reduction in stable in-stream wood could increase sediment transport rates over time (Montgomery et al., 2003), which could adversely affect stream crossings, water supply infrastructure and fish habitat. Although development in urbanized areas has resulted in localized riparian impacts due to the increased number of stream crossings and private properties with various land uses, riparian conditions were reasonably healthy and functional. This is partly due to the incised nature of many of the lower stream reaches (i.e., streams flow along deep ravines) that tend to prevent land use impacts. Where riparian disturbance was noted on private land, it tended to be localized and posed relatively low risk, since channels along the lower slopes with some exceptions are non-alluvial or semi-alluvial.

Potential effects of BCTS Planned Development

Conservation of water quality, fish habitat, wildlife habitat and biodiversity in riparian areas is an objective under Section 4.2.4 of BCTS Forest Stewardship Plan #672 (BCTS Chinook Business Area, 2022). In order to achieve this objective, BCTS is tasked with identifying stream, lake and wetland riparian classes according to Sections 47, 48, and 49 of the *Forest Planning and Practices Regulation (FPPR);* adhering to restrictions in Riparian Management Areas, Riparian Reserve Zones and Riparian Management Zones as per Sections 50, 51, and 52(2) of *FPPR*; and where forest activities are planned for a Riparian Management Zone, meeting retention levels determined by a qualified professional through riparian assessment.

Normally, BCTS forest professionals plan harvesting opportunities to minimize disturbance of riparian zones along classified streams by establishing riparian reserves, wildlife tree retention areas (WTRAs), and/or machine-free zones. Road alignments are also planned, where possible, to minimize the number of stream crossings and localized riparian impacts. These general precautions are intended to minimize adverse effects on riparian function. Since a review of specific blocks was beyond the scope of this assessment, the riparian-related hazards associated with specific harvest plans cannot be determined at this time. However, such assessments are expected for the subsequent assessment phase.

6.4. STREAM CHANNEL STABILITY

Each of the assessment streams were field reviewed during Phase 1 and 2. Streams were observed above and below accessible locations, often near road crossings, and on or near private land with permission from property owners. Several stream reaches were fully reviewed if accessible. A selection of photos documenting current conditions observed along each stream is provided in Volume 2, APPENDIX D[100].

Overall, the assessment streams include a mix of channel morphologies and are generally semi-alluvial on BCTS chart area, and semi-alluvial or non-alluvial along the lower slopes, and alluvial near the mouths. As noted above, despite historical disturbance to riparian areas, current riparian conditions are generally functional. In-stream wood is common in the form of log-jams along the lower stream reaches; however, is generally scarce in the middle and upper portions of the channels. Furthermore, evidence of active bedload transport was common in most streams. A summary of channel response potential for each stream is presented in TABLE 6.8, and additional characteristics of each stream, which influences channel response potential, are provided below.

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[100] For referencing purposes, photo locations are identified by stream name and distance upstream from the mouth (MAP 1). Tributaries that feed directly to the assessment streams are assigned numbers, e.g., Tributary 1, 2, 3. Streams that feed those tributaries would be identified by adding a decimal point, e.g., Tributary 1.1, 1.2, 1.3. And, streams feeding those (e.g., 1.1) would be assigned another decimal point, e.g., Tributary 1.1.1, 1.1.2, 1.1.3. If known, local stream names are also identified.

TABLE 6.8 *Channel response potential for the assessment streams.*

Assessment Streams	Channel Response Potential
Roberts Creek	**Low/Moderate**
Clack Creek	**Low/Moderate**
Gough Creek	**Moderate**
East Roberts Creek	**Low/Moderate**
Stephens Creek	**Low/Moderate**

Roberts Creek

Photos of Roberts Creek are shown on Figure 1 through Figure 50 (Volume 2, APPENDIX D). Roberts Creek is the largest of the assessment streams and is fed by several tributaries on the southwest side of Mt. Elphinstone. Many of these tributaries originate as non-classified drainages or minor intermittently flowing streams on the upper slopes of the watershed (MAP 1). As these streams converge, flows and the degree of channel incision increases. Stream gradients along the upper portion of Roberts Creek are generally mild (4.6% on average) and steepen to 8.5% roughly between stream km 9.0 and km 4.5 (FIGURE 4.6). Roberts Creek is joined by East Roberts Creek above the Sunshine Coast Highway near stream km 1.4. Immediately below the highway are 3-4 m high falls. Between Lower Road and the highway, the mainstem remains incised and passes through a bedrock canyon. The level of incision decreases and channel widens near the confluence of Clack Creek above Lower Road near stream km 0.35 (APPENDIX D, Figure 14). Stream gradient decreases and the channel widens from the confluence of Clack Creek to the mouth of Roberts Creek.

Channel morphology varies along Roberts Creek from boulder-dominated step-pool and plane-bed channels on upper and mid-slopes to bedrock-dominated channels on the mid- to lower slopes, and cobble/gravel dominated near the mouth. Roberts Creek is generally semi-alluvial, with alluvial sections found in the upper and middle reaches, and an alluvial reach near the mouth. Several non-alluvial (i.e., bedrock-controlled) reaches are found throughout the stream, including a bedrock canyon between the Sunshine Coast Highway and Lower Road. Many of these bedrock-controlled reaches contain pockets of gravel and cobble which appear to be actively transported during high flows. Near Lower Road, the channel is alluvial with a streambed dominated by boulders and cobbles. Evidence of aggradation and bank erosion was noted along this reach. The bed material becomes finer as the stream approaches the mouth with greater proportions of gravel and smaller cobbles.

Functional instream wood has formed several jams along the lower reaches and regulates to some extent sediment transport along the creek. The abundance of in-stream wood decreases upstream and much of the larger functional wood currently present is old and decaying. New recruitment of wood generally consists of smaller diameter, younger trees as a result of riparian harvest during early 20th-century forestry activities. Sediment transport rates appear high along Roberts Creek, which may be an artifact of reduced in-stream wood, and are responsible for abundant deposits of boulder, cobble, and gravel noted throughout the stream. Much of this sediment is supplied naturally from the abundance of glacially-derived sediments present along the length of the creek. Wood present along the channels tends to be mature and is deteriorating. As this occurs, debris jams should become increasingly unstable and with each storm, the likelihood of log jam collapse and sediment transport increases.

Despite active sediment transport and deposition throughout the channel, Roberts Creek appears relatively robust with some channel reaches controlled by bedrock. As such, the channel response potential (i.e., channel sensitivity) is considered low for much of Roberts Creek although is considered moderate where the channel is semi-alluvial or alluvial. As the channel is incised for much of its length and contains coarse bed material, changes in channel morphology are unlikely. However, floods are capable of locally eroding banks, entraining in-channel sediment (i.e., stored behind debris jams) and transporting such sediment downstream. As a result, local channel conditions in terms of streambed texture and gradients have potential to change with changes to the flood regime, especially upstream of stream crossings where aggradation is often promoted.

Clack Creek

Selected photos of Clack Creek are shown on Figure 91 through Figure 99 (APPENDIX D). Clack Creek is fed by a high density of sub-parallel tributaries draining off a gentle slope near the Dakota Ridge Winter Recreation Area in the western portion of the assessment area. Stream gradients are relatively consistent for much of its length, averaging 12.0% (FIGURE 4.6), with exception of shallower gradients near the mouth. Clack Creek is joined by Gough Creek near stream km 2.43, which is similar in width and conveys similar flows as Clack Creek (APPENDIX D, Figure 86).

Channel morphology ranges from semi-alluvial and alluvial in the upper and middle reaches, to bedrock controlled in the lower reach. The streambed in the upper portion of Clack Creek is dominated by boulders with evidence of gravel transport. The channel contains moderate amounts of in-stream wood in the upper and middle reaches with some log jams noted in the lower reach near stream km 2.0. Bedrock controlled sections are noted beginning near stream km 2.5, interspersed with aggrading cobble and gravel bars. An 8 m long bedrock cascade is noted near stream km 1.32. Below the cascade the channel becomes increasingly incised into a ravine and enters a bedrock canyon near stream km 1.2. The channel remains dominantly bedrock controlled until the confluence with Roberts Creek and passes over a series of falls, one of which is 7 m high. Within the bedrock canyon are several log jams retaining gravel and cobble.

Evidence of sediment deposition and aggradation is noted along reaches where channel gradient decreases locally, particularly where log-jams are present. However, much of the creek is bedrock-controlled and appears relatively stable. As such, the channel response potential along Clack Creek is generally low for most of its length and moderate along alluvial and semi-alluvial reaches. Like Roberts Creek, sediment transport rates may be a result of decreased in-stream wood from early 20th century riparian harvest.

Similar to many streams on the southwest coast of BC and the Sunshine Coast, Clack Creek was subject to major flooding as a result of the atmospheric river event in mid November 2021. We are aware that that this resulted in the washout of a 2 m diameter culvert crossing of Day Road (near stream km 2.8).

Gough Creek

Selected photos of Gough Creek are shown on Figure 91 through Figure 98 (APPENDIX D).
Gough Creek drains from the Dakota Ridge Winter Recreation Area west of Clack Creek and roughly parallels Clack Creek until their confluence near stream km 2.43. Gough Creek is joined by several smaller tributaries draining off the same slope.

Where the creek was observed on the ground, channel morphology was generally semi-alluvial or alluvial. No bedrock-controlled reaches were noted. In the middle reaches, Gough Creek appears incised in a ravine with bed material dominated by boulders and cobbles and moss present on larger clasts. Abundant in-stream wood and some small log jams were present near stream km 8.0, although in-stream wood may be less abundant in other reaches. Finer bed material becomes more abundant near the confluence with Clack Creek, although boulders are still present. Gravel bars are noted along some stream segments near the mouth of the creek.

Given the absence of bedrock-controlled stream reaches along Gough Creek, the channel may be subject to geomorphological changes provided a change in sediment input or a change in the flow regime. However, the channel appears relatively stable despite an active bedload. As such, the channel response potential is considered moderate.

East Roberts Creek

Selected photos of East Roberts Creek are shown on Figure 100 through Figure 116 (APPENDIX D). East Roberts Creek drains off of relatively steep hillslopes in the northeastern portion of the assessment area, generally running sub-parallel to Roberts Creek. Average stream gradient along the uppermost kilometre of East Roberts Creek is 32.0% (FIGURE 4.6). Downstream, gradients decrease and remain relatively constant for the remainder of the stream. The channel is joined by several smaller tributaries.

Channel morphology varies along East Roberts Creek and is generally semi-alluvial or alluvial along the upper reaches, and semi-alluvial or non-alluvial along the lower reaches. The upper portion of the creek has a step-pool morphology with moss-covered boulders and mobile cobble and gravel. In-stream wood is scarce along this reach although a functional riparian zone has maintained channel stability. The lower reaches of the creek are incised in a ravine and the bed material is dominantly bedrock-controlled, interspersed with some boulders and gravel.

Although in-stream wood was scarce in some locations, an intact and functional second-growth riparian area has helped maintain a stable channel. Given minimal evidence of channel instability along the creek and the stable bed material (i.e., bedrock or moss-covered boulders), the channel response potential in East Roberts Creek is considered low, although is considered moderate along alluvial or semi-alluvial stream reaches.

Stephens Creek

Selected photos of Stephens Creek during our field review are shown on Figure 118 through Figure 135 (APPENDIX D). Stephens Creek has a relatively long and narrow catchment that drains the southwestern slopes of Mt. Elphinstone, immediately east of Roberts Creek. Stream gradients are typically around 10% although increase to 30.4% in the uppermost portion of the watershed (FIGURE 4.6). Bed material along the upper portion of the creek is composed of cobble and gravel, which coarsen to small boulders downstream. Near stream km 1.25 the channel is bedrock-controlled and channel gradient decreases to approximately 3-4%. Downstream of the Sunshine Coast Highway, the channel is incised in a ravine and is either semi-alluvial with a cobble and boulder-dominated streambed, or is bedrock-controlled. Approximately 80 m from the oceanfront, the creek emerges from the ravine onto a low gradient and unconfined alluvial fan with several residential properties. Only a few metres from the oceanfront, the creek abruptly turns west and meanders along the front of several properties for 120 m before discharging into the ocean (Figures 118-122 in APPENDIX D). It is unclear whether the alignment of the lower 120 m of stream has its origins following natural processes (i.e., the result of shoreline processes) or human-caused (i.e., when development first occurred), but nevertheless appears to have been in place in that approximately location for many decades according to the historical aerial photo imagery reviewed. According to a local property owner, this lowermost reach of the creek was subject to unsanctioned realignment by a previous property owner adjacent to the creek, in an effort to extend their property (Birch, pers. comm., 2023). In addition, the left bank of the creek (on the oceanside) was armoured with riprap (FIGURE 6.13). These stream modifications are believed to have contributed to flooding of the properties near the mouth of Stephens Creek (Birch, pers. comm., 2023).

FIGURE 6.13 *View westward and down Stephens Creek along the oceanfront. White arrow shows flow direction. Note the left bank of the creek is armoured with riprap. Placemark 114, August 6, 2021.*

A notable build-up of sediment and woody debris was noted in summer 2021 above the inlet of the Sunshine Coast Highway and Lower Road crossings[101]. In-stream wood is generally abundant and functional along most stream reaches observed during the field review. It is our understanding that the Lower Road crossing was washed out during the major atmospheric river event in November 2021. We also understand that this crossing has since been replaced with a metal culvert of similar size to the original concrete culvert, however the elevation of the culvert inlet and outlet is now considerable higher (FIGURE 6.14). As a result of the active bedload transport in Stephens Creek, especially following the introduction of additional sediment when Lower Road washed out, aggradation and channel in-filling has been noted by local property owners along the lowermost reach near the oceanfront. This is not unexpected given the low gradients that promote deposition of sediment. Unfortunately, a distinct lack of channel capacity has resulted in flooding as recently as November 2023 causing damage to properties near the creek (Birch, pers. comm., 2023).

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[101] Polar promptly informed BCTS of these conditions, and it is our understanding that BCTS communicated this to the local authorities responsible for the crossings.

FIGURE 6.14 *View downstream of the culvert inlet at the Lower Road crossing of Stephens Creek. The left image shows conditions at the culvert inlet on August 6, 2021. The white arrow shows the location of the culvert invert obscured by wood debris. The right image shows conditions at the same location in November 9, 2023 approximately two years after the crossing was washed out and replaced (photo courtesy of Pierre Aubin of BCTS). Note the higher elevation of the culvert and streambed on the right image.*

Notwithstanding the active bedload and notable issues at properties on the floodplain of the creek near the mouth, Stephens Creek is dominantly bedrock-controlled and generally appeared stable. As such, the channel response potential along much of its length is considered low, and is considered high along the relatively limited alluvial and semi-alluvial stream reaches.

Potential Effects of BCTS Planned Development

As noted above, the likelihood of channel disequilibrium (i.e., instability) following forest development is based on channel response potential and whether there are measurable increases in flood magnitude/frequency and coarse sediment yield, as well as measurable reductions in riparian function and future woody debris recruitment.

Based on the most sensitive portions of each stream, channel response potential can effectively be considered moderate for all assessment streams. Provided that peak flow hazard is not incrementally increased, sediment yields are not measurably increased, and riparian function is not impaired, there is a low likelihood of decreased channel stability following forest development[102].

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[102] This is contingent upon effective control measures being implemented as outlined in Section 9.

6.5. POLLUTANTS

Accidental oil and fuel spills and leaks associated with heavy equipment operation are of concern at any location, and especially in riparian areas along fish streams or streams that are relied upon for water supply. Pollutants have the potential to cause significant contamination of streams and/or aquifers upon which the public rely for their water supply. BCTS Environmental Management System (EMS) environmental field procedure (EFP) 06 Fuel Handling outlines appropriate fuel storage & securing, dispensing, transportation, spill prevention and response measures, with restrictions specifically identified for riparian management areas. With strict adherence to and monitoring of these control measures during all forest development activities, risks of contamination should be minimized. As noted in Section 9, we recommend that a Qualified Professional (QP) act as environmental monitor during forest development activities at a frequency and intensity commensurate with the level of activity on-site. The QP should ensure that all control measures are in place and functioning and that all EFPs are adhered to.

7. RISK SUMMARY

A main goal of this watershed assessment is to identify the potential hydrogeomorphic risks associated with future BCTS forest development in the assessment watersheds, although no specific plans have been confirmed. Key elements-at-risk, identified in Section 5, include: human safety, private property[103], transportation infrastructure, utilities, water rights & use, and fish and fish habitat. Peak flows (including floods, debris floods and debris flows), low flows & aquifer recharge, sediment yield, channel destabilization, and water contamination by pollutants are the principal hazards under review. If the likelihood or severity of one or more of these hazards is increased, there are elements at risk downstream that could be affected. Partial risk for each of the principal hazards are described in the following sections.

7.1. PEAK FLOWS

TABLE 7.1 provides a summary of the qualitative partial peak flow risk analysis for the assessment streams. Based on elements-at-risk identified along all assessment streams, peak flow risk in the assessment area is equivalent to peak flow hazard (Section 2.2). As such, the current peak flow risk is low at and above the eight identified points-of-interest.

Peak flow risk is not expected to incrementally increase if future BCTS development remains consistent with the recommendations outlined in Section 6.1.1 and Section 9. It should be recognized that incremental flood risks due to forest development are within a context of assessment watersheds currently with a low peak flow hazard, which are naturally subject to frequent rainstorm-driven and less frequent rain-on-snow-driven floods. Further, gradually increasing rainfall and storm intensity is projected with climate change (Section 7.7).

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[103] Includes, but is not limited to, residences, structures, water intakes, wells, stream crossings.

TABLE 7.1 *Summary of stream segments, potential elements-at-risk and current partial peak flow risk. Organized roughly in upstream order along each stream segment.*

Watershed	Stream segment	Stream distance (km)	Partial Peak Flow Risk $P(HA_{pf})$[104]	Potential elements-at-risk	Notes	Refer to figures in APPENDIX D (Volume 2)
Roberts Creek	Roberts Creek	0.00-0.35	Low	Fish & fish habitat	Several fish species have been recorded along this reach, including many species of salmon. The channel is fluvially active with considerable bedload transport. Aggradation noted throughout. Habitat conditions are highly variable.	000-014
				Lower Road bridge (stream km 0.2)	Concrete bridge deck. Bridge abutments armoured with riprap.	010
				Water Survey of Canada hydrometric station (stream km 0.2)	Roberts Creek at Roberts Creek (08GA047) hydrometric station is encased in a vertical culvert mounted on bridge supports.	010
		0.35-1.40	Low	Fish & fish habitat	Several fish species have been recorded along this reach, including salmon up to falls located near km 0.5. Resident cutthroat and Dolly Varden have been recorded above the falls (refer to Section 4.13). Aggradation noted in some locations.	015-037
				Domestic water licences	Domestic water licences C056205, C056206, C103707, C106720, and F006184 are mapped along this reach. Water supply infrastructure could only be identified for one licence; although the intake appeared filled with sediment and appeared non-functional.	019
				Foot bridges	Three wooden pedestrian bridges are located near stream km 0.8 and km 1.1. Erosion noted at bridge abutments near stream km 1.1.	019, 020, 036
				Highway 101 crossing	3,000 mm diameter multi-plate metal culvert near stream km 0.9. Riprap bank protection noted adjacent to culvert inlet.	033, 034
		1.40-11.00	Low	Fish & fish habitat	Resident cutthroat and Dolly Varden have been recorded along this reach.	038-050

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[104] Equivalent to the peak flow hazard, $P(H_{pf})$

Watershed	Stream segment	Stream distance (km)	Partial Peak Flow Risk $P(HA_{pf})$[104]	Potential elements-at-risk	Notes	Refer to figures in APPENDIX D (Volume 2)
				Foot bridge	Wooden pedestrian bridge near stream km 1.78. Aggradation and bank erosion noted near bridge.	040
				Bridge	Golf course bridge near stream km 1.9.	
				Foot bridge	Wooden pedestrian bridge near stream km 2.20	044
				Bridge	Bridge on Roberts Flume FSR 8546 Br01 near stream km 4.2.	045, 046
				Bridge	Bridge on Sechelt Dakota FSR near stream km 8.7	049
				Stream crossings	Three crossings (unknown crossing type) are located near stream kms 9.8, 10.7, and 11.4.	-
	Clack Creek	0.38-2.43	Low	Fish & fish habitat	A 3.4 m high falls near the confluence with Roberts Creek prevents upstream fish migration; however, cutthroat and Dolly Varden are present above the falls.	051-090
				Domestic water licences	Domestic water licences C055533, C123183, C123184, C123185, F015563 are mapped along this reach. Water supply infrastructure was noted near stream km 0.85 and km 2.08, although in both cases appeared in disrepair and inactive.	-
				Foot bridge	Wooden pedestrian bridge near stream km 0.82.	065
				Highway 101 crossing	Sunshine Coast Highway stream crossing consists of one 1,700 mm corrugated metal pipe (cmp) and one 1,500 mm concrete pipe near stream km 0.85.	066, 068
				Foot bridge	Wooden pedestrian bridge near stream km 0.9.	-
				Foot bridge	Wooden pedestrian bridge near stream km 1.17.	073, 074
				Foot bridge	Wooden pedestrian bridge with instream bridge supports near stream km 1.32.	077, 078
				Foot bridge	Wooden pedestrian bridge near stream km 1.68. Aggrading gravel bar below bridge provides limited clearance for flood flows. Bank erosion appears to be an issue. Ad hoc placement of gabion baskets for bank protection was noted.	079
				Golf Course crossing	Located near stream km 1.8.	-
				Foot bridge	Wooden mountain bike bridge near stream km 2.08.	082
		2.43-8.50	Low	Fish & fish habitat	Cutthroat and Dolly Varden have been recorded in this reach.	087-090

Watershed	Stream segment	Stream distance (km)	Partial Peak Flow Risk P(HA_{pf})[104]	Potential elements-at-risk	Notes	Refer to figures in APPENDIX D (Volume 2)
				Day Road crossing	2,000 mm diameter cmp located near stream km 2.45.	088
				Roberts Flume FSR 8546 Br04 crossing	Bridge near stream km 3.84.	089
				Roberts Flume FSR 8546 Br01 crossing	Bridge near stream km 5.15.	090
				Stream crossings	There are five stream crossings of unknown type and condition, located near stream kms 5.8, 6.2, 6.8, 7.6, and 8.2.	-
	Gough Creek	2.43-11.5	Low	Domestic water licences	Domestic water licences C119305, C133069, C114287, C114288, C119304 are located along this reach although were not observed during the field review.	-
				Foot bridge	Wooden pedestrian bridge near stream km 3.8	095
				Roberts Flume FSR crossing	Crossing of unknown type and condition near stream km 5.6.	-
				Sechelt Dakota crossing	Crossing of unknown type and condition near stream km 8.0.	-
				Sechelt Chapman crossing	Crossing of unknown type and condition near stream km 8.7.	-
				D-1000 crossing	Crossing of unknown type and condition near stream km 9.9.	-
				D-3000 crossing	Crossing of unknown type and condition type near stream km 11.5.	-
	East Roberts Creek	1.35-7.5	Low	Domestic water licences	Domestic water licences C056205, C056206, C103707, C106720, F006184 are located along this reach although were not observed during the field review.	-
				Foot bridge	Wooden pedestrian bridge near stream km 1.5.	102
				Foot bridge	Wooden pedestrian bridge near stream km 1.75.	
				Golf course bridge	Located near stream km 1.89.	107
				Bridge	Bridge at hydro right-of-way near stream km 2.10.	111
				Roberts Flume FSR 8546 Br01 crossing	Bridge near stream km 3.76.	114
				Stream crossings	There are five stream crossings of unknown type and condition located near stream kms 1.8, 3.8, 6.4, 7.2 and 7.6.	-

Watershed	Stream segment	Stream distance (km)	Partial Peak Flow Risk P(HA_{pf})[104]	Potential elements-at-risk	Notes	Refer to figures in APPENDIX D (Volume 2)
Stephens Creek	Stephens Creek	0-7.5	Low	Fish & fish habitat	Cutthroat have been recorded within 200 m upstream and 500 m downstream of the Sunshine Coast Highway.	-
				Private Bridges	Six pedestrian bridges and one vehicle bridge on private land were noted near the mouth of Stephens Creek.	121, 122
				Private property	There are several properties located on the alluvial fan of Stephens Creek along the lowermost 200 m of the creek. These properties have been subject to flooding, erosion, and property damage, partly as a result of aggradation following storms, road washout (e.g., November 2021 washout of Lower Road), and realignment of the channel by local property owners.	
				Culvert	1,400 mm diameter concrete culvert at Lower Road crossing near stream km 0.25. Woody debris was blocking the culvert inlet during the time of the August 2021 field review.	123
				Culvert	1,200 mm diameter concrete culvert at Sunshine Coast Highway crossing near stream km 0.77. Woody debris was accumulated at the culvert inlet during the time of the August 2021 field review.	125
				Foot bridge	Wooden pedestrian bridge near stream km 1.25.	127
				Bridge	11 m long bridge on the hydro right-of-way near stream km 1.75.	129
				Stream crossings	There are four stream crossings of unknown type and condition located near stream kms 3.3, 4.7, 5.8, and 7.2.	-
				Domestic water licences	Domestic water licences C072242, C109820, C109828, C112716, C112717, C115432, C121537, F006225, F013188, F014109, F017408, F040553, F040716, F051905 are located along this reach. Only one intake structure was noted along this reach, although not all mapped licence locations were observed during the field review.	-

7.2. LOW STREAMFLOWS

Water supply during late summer and fall is of great concern on the Sunshine Coast, especially following severe drought conditions experienced in 2022[105]. Inadequate water supplies directly affect water users as well as fish and aquatic organisms. It should be noted that low streamflows at a specific location can be affected not only by the volumetric rate of water conveyed along a stream, but also stream conditions, specifically where a stream is aggraded and some or all of the available streamflow moves sub-surface. In this section, reference is made to the volumetric rate of flow and not the effect of aggradation on surface flow.

With consideration of the physical watershed characteristics, meteorological drivers, and current distribution of seral stages (i.e., stand ages) across the assessment area, the research literature suggests that the likelihood that low flows have been adversely affected by forest cover disturbance to date is moderate across the assessment area. Increased low flow risk[106] is primarily a result of higher water use associated with younger regenerating stands relative to older mature stands.

Based on the identified elements-at-risk, low flow risk in the assessment area is currently moderate in Roberts Creek and Stephens Creek.

It should be recognized that these risk ratings are within a context of assessment watersheds that are subject to decreasing summer precipitation and increasing temperatures, which not only reduce natural water supply but also result in increasing water demand (Section 7.7).

As a result, there is potential that low flow risk may be amplified with the projected effects of climate change (Section 6.6) even though the incremental risk from forest harvesting remains low.

7.3. GROUNDWATER/AQUIFER RECHARGE

Assuming BCTS maintains current peak flow and low flow risks, the risks associated with BCTS development in the assessment area on the groundwater supply and aquifer recharge are low. Site-level increases in the water balance can be expected following the removal of forest cover, which may result in localised increases in the groundwater table. However, such increases are only expected to persist for up to 10-15 years. Beyond that time, there is a potential for decrease, but only if opening

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[105] https://www.scrd.ca/files/File/Community/EmergencyOps/2022-Nov-15%20Drought%20Order%202%20amended%20non-critical%20use%20SCRD%20signed%20copy.pdf

[106] A higher low flow risk is considered as an increased likelihood that forest disturbances have negatively influenced the magnitude, timing, and frequency of low flows.

size exceeds approximately 8 ha or where thinning occurs, if approximately >50% of the overstory canopy is removed. Given the long time periods associated with groundwater movement and recharge to the confined Roberts Creek Aquifer (No. 555), harvest-related effects are expected to be undetectable if the above constraints are met.

7.4. SEDIMENT YIELD

Sediment yields from BCTS chart area, associated both with sediment generation on roads and by landslides, are currently low. In part this is due to well planned, constructed and maintained resource roads, consideration of riparian management zones, and referral to qualified professionals to identify terrain-related risks or blowdown risks and provide options for risk mitigation. Reliance on such professionals has been standard practice since the implementation of the Forest Practice Code[107], which was implemented to reduce the likelihood of events such as the debris flow that occurred in Clough Creek in 1983 and the more recent debris flow event in Clack Creek tributary 5.

Potential sediment risks associated with future forest development are primarily associated with the construction (including reactivation), maintenance, and use of new and existing roads, trails and crossings, and with potentially sensitive (gullied) terrain adjacent to streams. An example is the debris flood which appeared to be initiated from a road washout along Clack Creek tributary 5. Assuming that best management practices around streams and riparian zones as identified in BCTS Environmental Management System (EMS) and environmental field procedures (EFPs) are followed and control measures identified in Section 9 are considered, sediment yields and the hazards associated with planned forest development can be maintained at low levels.

7.5. STREAM CHANNEL STABILITY

Based on our office and field analyses, channel response potential (i.e., channel sensitivity) is considered low along non-alluvial reaches and moderate or high along semi-alluvial and alluvial reaches. This means that while some localized reaches have potential to adjust morphologically, they are generally insensitive to changing hydrologic or sediment inputs. This robustness is driven by the incised or confined nature of most channels, the presence of bedrock-controlled or coarse-textured (cobble and boulder) streambed, lateral and vertical control provided by bedrock or erosion-resistant glacial deposits (e.g., till), and functional riparian conditions. Evidence of bank erosion, aggradation and a lack of in-stream wood along several reaches has resulted in increased channel instability locally. Despite localized instability along some reaches, increased channel stability risks associated with forest development on BCTS chart area are presently low and are expected to remain so assuming that the peak flow hazard and sediment hazard are not incrementally increased.

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[107] Subsequently replaced with the *Forest and Range Practice Act (FRPA)* in 2004.

It is important to recognize that low risks posed by the forested land base do not imply that the assessment streams are or will be static or fluvially inactive. To the contrary, the assessment streams are very much fluvially active and do naturally respond to rainstorm- and rain-on-snow-driven events with episodes of sediment transport. Evidence of such activity is widespread. In most cases, this is regulated by functional wood debris. However, this debris is mature and deteriorating at various rates. As debris jams collapse over a number of years to decades, there will be natural increases in sediment pulses, even without any measurable change to the flood regime. Unfortunately, in some cases, the pulses of sediment and wood may impair the conveyance of water both through culverts and along channels. This can result in road washouts, as was witnessed at the Lower Road crossing of Stephens Creek in November 2021. It will also mean that properties situated along the floodplain (i.e., lower 200 m of Stephens Creek) will be at risk of flooding and damage regardless of upslope land use.

7.6. POLLUTANTS

As noted in Section 7.6, pollutants such as fuel, can pose a risk to water quality in the event of spills and leaks. Such risk is omnipresent across the assessment watersheds, particularly along highways, roads and urban areas. On BCTS chart area on Crown land, such hazards are low and can be mitigated with planned future forest development by strict adherence to BCTS EMS and EFPs. As a result, the risks posed by planned forest development is expected to be low.

7.7. CLIMATE CHANGE CONTEXT

Each of the hydrogeomorphic risks described above should be understood within the context of on-going and future climate variability and change. As discussed in Section 4.7, the hydrology of the assessment watersheds is driven principally by fall and winter rain, with snow and subsequently rain-on-snow occasionally influencing the watersheds. With limited surface storage (e.g., lakes, reservoirs, wetlands), streamflows in the assessment watersheds generally have a high runoff generation potential that closely reflect the magnitude, frequency and duration of rainstorms in the region.

The climate of the assessment area is influenced not only by large-scale atmospheric circulation patterns that occur over inter-annual time scales (PDO and ENSO), but also long-term climate change associated with anthropogenic greenhouse gas emissions (PCIC, 2013, 2021). Temperatures have steadily increased over many decades, and are projected to further increase in future under a number of assumed CO_2 emission scenarios; RCP 8.5 is utilized here for discussion. On the Sunshine Coast, annual temperature is projected to increase by 4.7 °C by the 2080s (PCIC, 2021). This poses several risks, including, but not limited to, elevated stream temperatures and reductions in water quality for fish, increased water demands for irrigation, increased potential for drought, and increased severity and extent of wildfires.

In addition, evaporation could intensify as temperatures rise as will the transfer of heat from oceans to the air. This could mean stronger winds and increased risk of blowdown of susceptible trees. It also could mean more frequent and intense rainstorms. By the 2080s, storm-related rainfall is projected to increase by up to 20% for relatively frequent 2-year return period events and up to 40% for relatively rarer 50-year return period events (Western University, 2021). High intensity precipitation, often associated with land-falling atmospheric rivers, are expected to be of higher magnitude and occur more frequently as a result of climate change (Murdock et al., 2016; Gillett et al., 2022).

On an annual basis, precipitation is expected to modestly increase (+4.8%) by 2080. However, seasonal changes pose more direct risks in the assessment watersheds. By the 2080s, winter precipitation is projected to increase by 9.7%. This may increase the potential for flooding, but it may also be beneficial for water supply if some of this water recharges local aquifers. Summer precipitation, however, is projected to decrease by 22% by the 2080s, which could mean an increased severity and frequency of drought conditions, which could reduce late summer and fall low flows.

Given these ongoing and increasing pressures, minimizing incremental increases to current hazard levels within BCTS chart area with regards to peak flows, low flows, sediment yield and channel instability is paramount to the conservation of water resources and protection of watershed values. As such, risk management options should be implemented as part of future forest development planning. These recommendations are summarized in Section 9.

Although outside the scope of this assessment, overall watershed management, particularly in light of the projected changes from climate change (e.g., increased frequency and magnitude of storm) will also require effective coordination by local and provincial government, First Nations, and other stakeholders in order to identify and implement active control measures outside of BCTS chart area to reduce near- and long-term hazards. This could include promoting retention of forests and engineering approaches to mitigate the effects of urbanization in the lower portions of the watersheds.

8. CONCLUSIONS

This report summarizes the results of a watershed assessment of two urban interface watersheds (i.e., assessment streams/watersheds) on the southwestern slopes of Mt. Elphinstone, BC (MAP 1). These streams include: Roberts Creek, and Stephens Creek, the former of which includes the Clack Creek, Gough Creek, and East Roberts Creek tributaries. The principal objectives of the assessment are to review the current conditions within each of the assessment watersheds, identify the potential hydrogeomorphic hazards and risks from future forest development within BCTS chart area on downslope watershed values, and provide risk management options to reduce, mitigate or avoid such risks. It is important to recognize that the scope of the assessment is intended to provide BCTS with direction on how to proceed with forest development planning in order to minimize hydrogeomorphic risks; it does not review specific forest development plans.

The assessment is guided by BCTS *Watershed Risk Management Framework* (Polar, 2022) and is consistent with *Joint Professional Practices Guidelines: Watershed Assessment and Management of Hydrologic and Geomorphic Risk in the Forest Sector* (Engineers and Geoscientists British Columbia and Association of British Columbia Forest Professionals, 2020). The approach includes office-based analyses and field-based reviews performed in two phases. The first phase examined watershed and underlying aquifer characteristics, levels of past land use disturbance, identification of potential watershed values downslope of BCTS chart area, and identification of potential hazards and risks. The second phase refined the risk analysis by conducting further field review of streams and potential elements-at-risk. A third phase of assessment work separate from this report will be focussed on site-level review of specific forest development plans.

Within the assessment watersheds, the following downslope/downstream potential elements-at-risk were identified: human safety, private property, transportation infrastructure, utilities, water rights & use, and fish and fish habitat. Peak flows, low flows, sediment yields, channel destabilization, and water contamination by pollutants are the principal hazards under review.

Based on an understanding of history of the area, current conditions, and the context of ongoing and future climate change, an analysis of current and projected future hazards and risks from forest development within BCTS chart area in the assessment watersheds was conducted. Based on this assessment, the following conclusions were drawn:

Streamflows (Peak and Low Flows) and Aquifer Recharge

1. The assessment streams have a rain-dominated flow regime, with highest flows generally driven by frontal systems in November and December. Rain-on-snow is considered to be the dominant process responsible for major, potentially damaging floods at all elevations.

Assuming the presence of a snowpack, rain-on-snow runoff is often most severe when warm temperatures, strong winds, and intense rainfall, potentially associated with an atmospheric river (AR), coincide. Given the moderate relief of the assessment watersheds, snow is transient in many years, and often plays a minor role in the annual hydrograph of the assessment streams. It can, however, contribute to runoff particularly above 800 m elevation.

2. Based on the physical watershed characteristics that affect runoff generation, meteorological conditions typical of the area, and land uses, the runoff generation potential (RGP) for the assessment watersheds is high in all watersheds. This means that streamflows generally respond relatively rapidly to precipitation inputs in most of the assessment watersheds. As such, the flood regime closely reflects the magnitude, frequency and duration of rainstorms in the assessment area.

3. Low (base) flows in the assessment streams, which are controlled by rainfall inputs and groundwater contributions, are generally at their lowest in July and August, under the influence of high-pressure weather systems but can extend well into the fall (e.g., fall 2022).

4. The climate of the assessment area is influenced not only by large-scale atmospheric circulation patterns that occur over inter-annual time scales (PDO and ENSO), but also long-term climate change associated with anthropogenic greenhouse gas emissions. PCIC (2021) project that average annual temperatures and precipitation will increase by 4.7 °C and 4.8% by the 2080s, respectively (assuming RCP 8.5).

5. Increased temperatures with climate change are projected to pose a number of risks, including, but not limited to elevated stream temperatures and reductions in water quality for fish, increased potential for drought, increased water demands for irrigation, and increased severity and extent of wildfires. In addition, evaporation will intensify as temperatures rise as will the transfer of heat from the ocean to the air. This could mean more intense windstorms and rainstorms along the Sunshine Coast.

6. Although the range of uncertainty in future precipitation projections is considerable, on an annual basis precipitation is projected to decrease by 1.0% by the 2050s and increase by 4.8% by the 2080s (PCIC, 2021). Summer precipitation, which is relevant to the maintenance of water supplies and instream flows for fish, is projected to decrease by 13% by the 2050s, and 22% by the 2080s. This suggests an increasing potential for drought conditions on the Sunshine Coast. Conversely, seasonal precipitation in winter is projected to only slightly increase by 0.9% by the 2050s; however, by the 2080s, the increase rises to 9.7% (PCIC, 2021). These increases could be beneficial in replenishing aquifers; however, they also could increase antecedent soil moisture conditions leading up to potential storm-driven flood events. According to Western University (2021), storm-related rainfall intensity is also projected to

increase. Relatively frequent rainstorms with a 2-year return period are projected to increase in magnitude by 6-11% by the 2050s and 14-20% by the 2080s. Rarer 50-year return period storms are projected to increase by 12-24% by the 2050s and 30-38% by the 2080s (Western University, 2021). These changes would suggest an increased likelihood of floods over time. Moreover, occasional snowfall can still be expected to occur in the future across all elevations (Floyd, pers. comm., 2023). Rain-on-snow generated peak flows are therefore expected to persist in the future.

7. Peak flow hazard is a function of runoff generation potential and runoff synchronization (Section 2.3.1). The former is potentially influenced by equivalent clearcut area (ECA), an index of forest disturbance and regrowth in a watershed, which can be influenced by forest management. Following recommendations from Dr. William Floyd[108], the evaluation of ECA was conducted assuming that rain-on-snow is the primary peak flow generating mechanism and can occur at all elevations. Therefore, ECA was evaluated using a single rain-on-snow recovery curve from Hudson and Horel (2007) and was applied across all elevations. In addition, based on ongoing research, areas above 800 m elevation are more likely to support a snowpack over winter and are therefore more sensitive to forest harvesting effects on snow accumulation and melt (Floyd, pers. comm., 2023).

8. ECAs in the assessment area demonstrate that that forests within the lower portion of the assessment watersheds have been subject to varying degrees of residential and commercial development. Moreover, most, if not all, forest stands in the upper portion of the assessment area have been subject to historical disturbance, either by wildfire or logging. As such, regenerating forest stands within BCTS chart area are at various levels of recovery and contain various proportions of deciduous species, which are considered less hydrologically recovered relative to coniferous stands.

9. ECAs were evaluated for drainage areas upstream of eight points-of-interest (POIs) in the assessment area. Currently, overall ECAs in the assessment area range from 7.3% for Roberts Creek at BCTS chart boundary (POI 2) to 16.8% for Gough Creek at the confluence with Clack Creek (POI 5). ECAs above 800 m elevation range from 4.3% to 12.1% in Roberts Creek, while ECA above 800 m in Stephens Creek is 16.1% (i.e., marginally above the low threshold). As such, the current peak flow hazard is low along all assessment streams, including Stephens Creek, despite its ECA above 800 m being marginally above a low threshold.

10. Although the removal of forest cover along road rights-of-way are accounted for in ECA calculations, roads can affect natural drainage patterns and effectively increase runoff

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[108] Research Hydrologist for the Coast area Research Section, BC Ministry of Forestry.

generation potential through the interception of shallow groundwater flow and conveyance as ditch flow to the stream network. In the assessment watersheds, the likelihood of such effects, both associated with current and future roads is low. This stems from a combination of relatively rapid preferential shallow subsurface flow along effectively impermeable surficial materials or bedrock and relatively high drainage density. As a result, shallow groundwater and surface water flow rates are similarly rapid, such that road-related effects on drainage patterns and rates are expected to be small.

11. With regards to summer low flows, the distribution of seral stages (i.e., forest ages) suggest that low flows have been influenced to varying degrees by historical disturbance. The likelihood that low flows have been adversely affected by the current distribution of seral stages is moderate for both the Roberts Creek and Stephens Creek watersheds. With respect to future development, recommendations are provided in Section 9 to minimize the likelihood of causing an incremental adverse effect on summer low flows.

12. If BCTS maintains current low peak flow hazards and a low likelihood of adversely affecting low flows (as described in Section 9), the risks associated with BCTS development in the assessment area on the groundwater supply are low. Site-level increases in the water balance can be expected following the removal of forest cover. This may result in localised increases in the groundwater table; however, such increases are only expected to persist for up to 10-15 years. Beyond that time, there is a potential for decrease, but only if opening size exceeds approximately 8 ha or where thinning occurs, if >50% of the overstory canopy is removed. Furthermore, most wells downslope of BCTS chart area appear to be established sufficiently deep within regional-scale bedrock groundwater systems. Given the long time periods associated with groundwater movement and recharge, to the confined Roberts Creek Aquifer No. 555, harvest-related effects are expected to be undetectable if the above constraints are met.

Sediment Yield

13. Few forest development-related sediment risks were identified in the assessment area. Overall, the current erosion potential from active roads is low. Erosion potential does marginally increase in the vicinity of crossings of incised gullies, due to the increased height of road cuts that are typically required; however, these site-level risks appear to have been effectively mitigated where necessary, and sediment risks remain low.

    A total of 122 stream crossings in the assessment area were identified during the field reviews and a review of satellite imagery. Of these, roughly 52 were identified along the principal assessment streams. Although this does not necessarily represent an exhaustive inventory, it does represent a large sample of stream crossings. Our field observations within BCTS chart area generally indicate that sediment hazards associated with stream crossings is low[109], largely as a result of gentle road grades, deactivation of unused roads, and effective control measures such as coarse gravel road surfacing and/or rock armour at culvert inlets and outlets or along bridge abutments. There are very few examples where sediment hazards are elevated in the assessment area within BCTS chart area.

14. In addition to the debris flow documented along Clough Creek (to the east of the assessment area) in 1983 [prior to the *Forest Practices Code (FPC)* and *Forest and Range Practices Act (FPRA)*], a historical air photo review revealed several smaller development-related landslides initiated in the assessment area. These included several debris slides and three debris flows in the upper portion of the assessment area, all suspected to have been initiated during the same 1983 storm. No other development or natural landslides were noted in the assessment area, with exception of a relatively recent debris flood following a road washout from stream km 8.0 and km 7.5 of Clack Creek tributary 5. Limited relief and gentle to moderate hillslope gradients combined with BCTS standard operating procedures that require engagement with qualified terrain professionals where necessary during the development planning process, reduces the likelihood of landslides in the assessment area, such that current sediment yields from landslides are low.

15. Potential sediment risks with future forest development are likely to be associated with the construction (including reactivation), maintenance, and use of new and existing roads trails and crossings. Fine-textured soils, where present, may be susceptible to rutting, compaction and erosion if subject to mechanical disturbance or excessive traffic during wet weather or wet ground conditions. These risks can, however, be effectively mitigated with a number of control measures, depending on site-conditions. Several of these measures are outlined in Section 9. Assuming that these (or equivalent) control measures are effectively implemented, sediment yields and the risks associated with future forest development can be maintained at low levels.

Riparian Function

16. With the exception of road crossings and the BC Hydro right-of-way (ROW), riparian conditions within BCTS chart area on Crown land within the assessment watersheds are characterized by mixed deciduous and second growth conifers with varying amounts of understory vegetation. Along classified streams, riparian vegetation is largely functional in providing bank stability and shade but is occasionally lacking in future recruitment of large woody debris. While most streams have ample volumes of instream wood, many of the stable larger-diameter pieces are disintegrating and are likely being replaced by smaller-diameter

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[109] The sediment hazard refers to the likelihood of measurable erosion and sedimentation to occur in the vicinity of stream crossings. It does not consider the potential for crossing damage or washout in the event of an extreme flood. Evaluation of design flows and flood conveyance at crossings is beyond the scope of the assessment.

less stable wood recruited from the riparian zone. A reduction in stable in-stream wood could increase sediment transport rates over time, which could adversely affect stream crossings, water supply infrastructure and fish habitat. Urbanization in the lower portion of the assessment area increases the potential for localized reductions in riparian function (e.g., near stream crossings and private properties); however, given the incised nature of most stream reaches, riparian areas remain largely intact and functional.

17. BCTS forest professionals plan harvesting opportunities to minimize disturbance of riparian zones along classified streams by establishing riparian reserves, wildlife tree retention areas (WTRAs), and/or machine-free zones. Road alignments are also planned, where possible, to minimize stream crossings and localized riparian impacts. These general precautions are intended to minimize adverse effects on riparian function. Since a review of specific blocks will be completed during Phase 3, the riparian related hazards associated with specific harvest plans cannot be determined at this time.

Stream Channel Stability

18. A selection of photos documenting current conditions observed during the field review along each stream is provided in Volume 2, APPENDIX D. Overall, the assessment streams include a mix of channel morphologies and are generally semi-alluvial on BCTS chart area, semi-alluvial or non-alluvial along the lower slopes, and alluvial near the mouths. Additional description of each of the assessment streams is provided in Section 6.4.

19. The likelihood of channel disequilibrium (i.e., instability) following forest development is a function of channel response potential and whether there are measurable increases in flood magnitude/frequency and coarse sediment yield, as well as measurable reductions in riparian function and future woody debris recruitment. Based on the most sensitive portions of each assessment stream, channel response potential is effectively moderate for all assessment streams. The robustness of the assessment streams is a function of the incised or confined nature of most channels, the presence of bedrock-controlled or coarse-textured (cobble and boulder) gravel streambeds, lateral and vertical control provided by bedrock or erosion-resistant glacial deposits (e.g., till), and functional riparian conditions. However, a lack of in-stream wood was noted along upper stream reaches and bank erosion and aggradation was noted locally along some stream reaches, typically along the lower alluvial portions of the assessment streams. Given these factors, the hazard associated with channel instability is presently moderate in all assessment streams. Provided that peak flow hazard remains low, sediment yields are not measurably increased, and riparian function is not impaired, there is a low likelihood of increased channel instability associated with future forest development in the assessment watersheds.

Pollutants

20. BCTS Environmental Management System (EMS), environmental field procedure (EFP) 06 Fuel Handling outlines appropriate fuel storage & securing, dispensing, transportation, spill prevention and response measures, with restrictions specifically identified for riparian management areas. With strict adherence to these control measures during all future forest development activities, risks of contamination can be minimized.

Risk Analysis

21. A main goal of this watershed assessment is to determine the potential hydrogeomorphic risks associated with future BCTS forest development in the assessment watersheds and provide risk management options to avoid or mitigate such risks. Key elements-at-risk include: human safety, private property, transportation infrastructure, utilities, water rights & use, and fish and fish habitat. Peak flows (including floods, debris floods and debris flows), low flows & aquifer recharge, sediment yield, channel destabilization, and water contamination by pollutants are the principal hazards under review herein.

22. Based on the identified elements-at-risk within the assessment area and assuming that the recommendations presented in Section 9 are met:
    a. Peak flow risk is currently **low** along all assessment streams;
    b. Low flow risk is currently **moderate** in Roberts Creek and Stephens Creek;
    c. Risks to the groundwater supply and aquifer recharge are **low**;
    d. Sediment risks associated with roads and landslides are currently **low**;
    e. Channel response potential (i.e., channel sensitivity) is considered **low** along non-alluvial reaches and **moderate** along semi-alluvial reaches. Alluvial reaches are also **moderate**, with the exception of the lowermost reach on Stephens Creek, which is **high**; and
    f. The current risk from pollutants is considered **low**.

23. TABLE 7.1 provides a summary of the identified elements-at-risk along each of the assessment streams with selected notes from our field observations where available. The partial peak flow risk for each stream segment is identified. Currently these risks are low in all stream reaches. Assuming management recommendations outlined in Section 9 are addressed, future peak flow risks are also projected to be low.

Each of the hydrogeomorphic risks described above should be understood within the context of on-going and future climate variability and change (Sections 4.7 and 7.7). Given these ongoing and increasing pressures, minimizing incremental increases in hazard ratings within BCTS chart area with regards to peak flows, low flows, sediment yield and channel instability is paramount to the conservation of water resources and protection of watershed values. As such, risk management options should be implemented as part of future forest development planning. These are summarized in Section 9.

9. RISK MANAGEMENT OPTIONS

This section outlines management recommendations available to avoid or mitigate the hydrogeomorphic risks identified above.

Streamflow Regime (Peak and Low Flows) & Aquifer Recharge

1. Based on the characteristics of the assessment watersheds and the research literature, ECA recommendations for each POI are presented with the objective of limiting incremental increases in peak flow hazard at POIs downstream of BCTS chart area. Moreover, it is recommended that the ECA be maintained below 20% for the portion of the watershed within BCTS chart area, while at the same time maintaining ECA above 800 m elevation below 15%. The ECA recommendations made include a level of conservatism beyond what previous assessments (i.e., Madrone, 2012) have identified in the assessment area, and furthermore these recommendations are considered prudent within the context of climate change (Section 7.7), the inherent uncertainty in ECA estimates (APPENDIX B), and the values identified along each stream (Section 5). The maximum additional ECA to avoid increasing current peak flow hazards while also maintaining ECAs below 20% within BCTS chart area are listed in TABLE 9.1. These values represent current (2021) conditions and are expected to change with hydrologic recovery.

TABLE 9.1 *Maximum additional ECA to avoid incremental increase in peak flow hazard. Note that ECAs must also remain below 15% within the area of each watershed unit above 800 m elevation.*

Assessment Watershed	Recommended additional ECA within BCTS chart area to avoid incremental increase in peak flow hazard
Roberts Creek	**≤ 185.6[110] ha overall AND** ≤ 102.8 ha above POI 2 ≤ 35.8 ha above POI 4 ≤ 19.0 ha above POI 6 ≤ 15.3 ha above POI 7
Stephens Creek	**≤ 18.7 ha overall**

2. Alternative silvicultural[111] approaches may be considered to minimize hydrologic effects, especially where ECAs are approaching recommended thresholds to avoid incremental

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[110] Although there is currently 185.6 ha available in the Roberts Creek watershed to maintain a low peak flow hazard, the ECA availability in the sub-catchments within the watershed restrict this amount of harvest from being realized.

[111] The ECA recommendations assume a clearcut silviculture system. If a selective harvest silviculture system is used, ECAs are scaled based on the values in TABLE 6.1.

increases in peak flow hazard. This may include small openings[112], strip cuts or individual tree selection, which are aimed at preserve natural levels of wind exposure and shade.

3. In order to manage runoff generation at the site-level, it is important to maintain natural drainage patterns throughout all watersheds. This includes continued alignment of new roads to avoid or minimize interception of surface or near-surface groundwater. If groundwater interception cannot be avoided, minimize the heights of road cuts and/or use alternative road construction methods (e.g., overlanding and using coarse, porous rock ballast) with limited disturbance to natural drainage. Restore natural drainage patterns by deactivating unnecessary roads and trails, and lastly, avoid excessive soil compaction to prevent creation of preferential pathways for runoff during and following forest harvesting.

4. With respect to future development, the literature suggests that to minimize incremental adverse effects on summer low flows, alternative silviculture approaches should be considered. These approaches include small openings or individual tree selection (i.e., thinning). The principal objective of applying such silvicultural approaches is to limit changes to site-level energy balance by promoting shade to reduce the potential for increased solar radiation, and limiting the potential for increased energy from wind (i.e., turbulent heat fluxes) following harvest.

   In the late summer low flow period, riparian zones serve as primary conduits for water movement. Riparian area retention should be a management objective to limit the potential for increased water demands from recolonizing deciduous and coniferous species, which tend to be higher than mature conifer species. For S4 and larger streams, current riparian management and free-growing standards should serve to minimize not only disturbance of sensitive riparian areas, but also the likelihood of deciduous colonization in such areas. For the smaller S5 and S6 streams, a management zone is recommended within defined gullies or draws[113]. Unless riparian reserves are sufficiently windfirm, thinning or retention of nonmerchantable species may be preferred for S5 and S6 streams to limit the risk of blowdown associated with reserves (Hudson and D'Anjou, 2001). Moreover, thinning with relatively high retention levels would serve to maintain some level of shade and reduce the potential for deciduous colonization. Based on the above, the following management options should be considered[114]:

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[112] If more than one opening is associated with a single cutblock, the space between openings should be large enough such that the adjacent opening us sufficiently buffered from wind and solar radiation.

[113] These areas should be determined through site-level field review.

[114] These management objectives should be met while maintaining the ECA thresholds identified previously.

In riparian areas:

- For S4, S5, and S6 streams, a management zone is recommended within gullies or draws, and these areas should be prioritized for relatively high retention levels in order to minimize changes in riparian water demands via evapotranspiration.

In upland areas:

- Maintaining net opening size to less than approximately 8 ha[115],
- Implementing partial harvest silviculture systems (i.e., thinning), or
- A combination thereof.

5. Several wells are located near BCTS chart along Gough Creek. Despite being relatively deep (i.e., > 60 m deep), these should be assessed in greater detail by a qualified professional (i.e., hydrogeologist) if forestry activities are planned within roughly 500 m upstream.

6. Climate change is projected to increase stress on water supply and water quality in the assessment area. In light of such projections, forest management could play a role in mitigating climate change and supporting long-term sustainable water supply through establishment of a broad range of seral stages across each watershed. This has the potential to reduce overall water demands from the forest land base, to promote biodiversity, and could reduce the potential for interface wildfires, which are expected to become increasingly common and severe with climate change. While difficult to quantify, we also encourage the planting of a mix of species[116] similar to the pre-harvest (mature) stands to achieve similar evapotranspiration rates in the long-term.

7. Many crossings in BCTS chart area, residential and commercial areas, and on MOTI roads were installed several decades ago and may be undersized in light of climate change projections. They may also become more prone to debris plugging as mature instream wood deteriorates and is transported downstream. A good example of this was the November 2021 washout of the Lower Road crossing of Stephens Creek. We note that the 1,400 mm concrete culvert that was washed out appears to have been replaced by the same diameter metal culvert. We recommend that BCTS share this information with MOTI and the Sunshine Coast Regional District. We recommend the appropriate party consider a stream crossing review to pre-emptively identify and replace undersized or potentially non-functional crossings, especially those which pose higher downstream environmental risks with failure. BCTS should consider examining the design and capacity of existing and future crossings within

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[115] If more than one opening is associated with a single cutblock, the space between openings should be large enough such that the adjacent opening is sufficiently buffered from wind and solar radiation.

[116] Stocking standards require a mix of species, particularly along riparian areas (Johnson, pers. comm., 2023).

BCTS chart area. This could serve to reduce the likelihood of future washouts such as the one identified in Section 6.2.2 along Clack Creek Tributary 5 (MAP 1).

8. The lowermost 200 m of Stephens Creek, which flows across a low-gradient alluvial fan, is subject to aggradation, flooding and unfortunately damage to properties located on the fan. Such conditions appear to have become worse since the washout of Lower Road in November 2021, likely as a result of the volume of sediment contributed to the creek. It is recommended that BCTS share this information with the Sunshine Coast Regional District and request the district to consider a detailed flood review that area with the objective of identifying options to mitigate flooding, erosion and damage to several properties near the mouth of the creek. This may include diversion of the creek more efficiently into the ocean, dredging portions of the creek, constructing flood control dykes, or some combination thereof.

Sediment Yield

9. In order to minimize the risk of increasing sediment yields associated with landslides, BCTS should continue to retain qualified professionals to identify terrain-related and blowdown risks and provide options for risk mitigation. With the benefit of high-resolution LiDAR-based bare-earth imagery, we recommend that terrain stability assessments guide forest development planning in both assessment watersheds where harvesting or road construction is planned on slope gradients exceeding 50%. This largely occurs along deeply-incised gullies identified in FIGURE 9.1.

10. While the potential for generation and delivery of sediment to the stream network from current roads is low, BCTS should continue to employ best management practices around streams and riparian zones as identified in BCTS Environmental Management System (EMS) and environmental field procedures (EFPs). This includes adherence to wet weather shutdown procedures (Statlu, 2018) during all forestry activities involving heavy equipment not only for safety reasons (i.e., to reduce the risk of workers from exposure to mass movement events) but also to minimize soil erosion and sediment delivery to the stream network.

    Moreover, to help minimize sediment risks during future forest development, we recommend that works involving potential soil disturbance or large cuts and fills within 50 m of a stream channel and installation of bridges or major culverts be monitored by a Qualified Professional (QP) at a frequency and intensity commensurate with amount of soil disturbance and stream values at risk.

    The QP should be experienced in erosion and sediment control and should be in direct communication with BCTS in the event a stop work order is necessary should the weather or other factors pose unacceptable risks (e.g., damaged or ineffective control measures).

Furthermore, we recommend that prior to harvesting, a monitoring program be established, preferably by the same QP, to gauge the specific sediment contributions from those specific roads and road crossings that will be utilized. Monitoring and record keeping should adhere to FREP WQEE protocols and sample locations before, during and after road construction and harvest, especially where fish and/or water intakes are a concern.

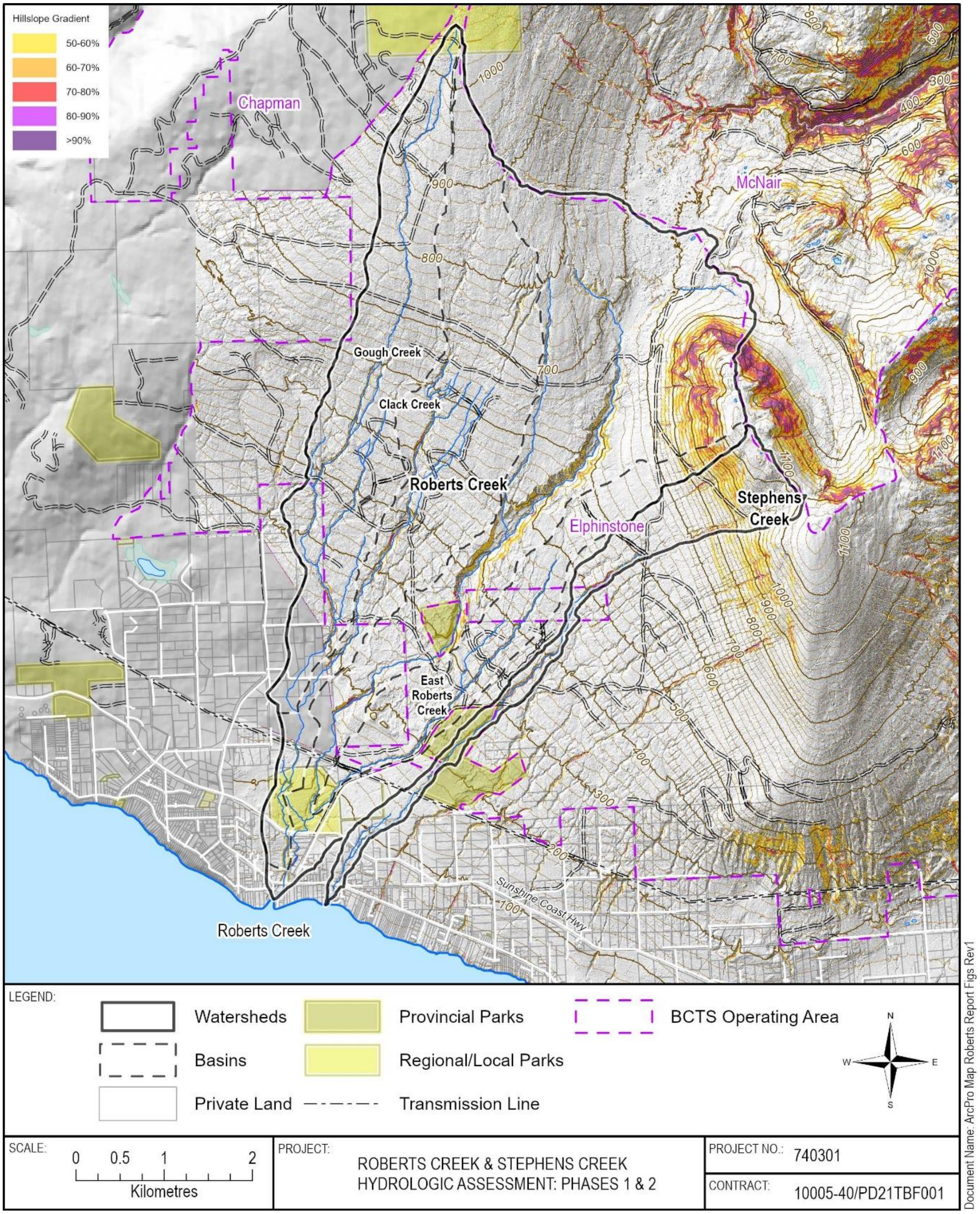

FIGURE 9.1 *Hillslope gradients in excess of 50% in the assessment area.*

11. It is recommended that road building and surface materials be sourced from the lower portion of the assessment area (or other area offsite) where the geology is primarily intrusive rocks (FIGURE 4.7). The sedimentary rocks in the upper portion of the assessment area are expected to be more erosive, with a greater potential to increase suspended sediment if transported to streams.

12. In order to maintain low sediment-related hazard, planning of road alignments and cutblocks should consider and take precautions to avoid alteration of natural drainage patterns upslope of sensitive gullied terrain, minimize windthrow in riparian zones (e.g., by having windthrow assessments performed) and avoid wherever possible physical soil disturbance in riparian zones by heavy equipment (e.g., by establishing machine-free zones along riparian corridors). Such control measures should be tailored to the risk posed by increased sediment yield on downstream values. In areas where planned development is in close proximity to elements-at-risk, effective cutblock and road layout upslope of elements-at-risk, combined with control measures, are of paramount importance.

13. Future sediment risks can further be mitigated using control measures, currently employed by BCTS. These include the following:
    - Avoiding, where possible, road alignments near riparian areas and areas with high hillslope-stream connectivity;
    - Reducing surface erosion on cut and fill slopes by planning road alignments that: i) minimize the height of road cuts; ii) avoid fine-textured soils, especially in groundwater seepage areas; and iii) utilize appropriate erosion control measures[117], with the guidance of a qualified erosion control professional;
    - Reducing the erosion of ditches by: i) minimizing ditch flow with establishment of water-bars and cross-ditches spaced according to field conditions; and ii) applying appropriate erosion control measures along ditches with the guidance of a qualified erosion control professional[118];
    - Reducing erosion of the road surface and improving drainage off the road surface by: i) establishing an appropriate density of water bars and/or cross ditches, ii) crowning, out-sloping or in-sloping road surfaces, and iii) regular grading to minimize rutting while being careful not to leave grader berms that may prevent drainage of the road surface; iv) limiting the lengths of climbing grade where possible; v) elevating the road surface with coarse road ballast if areas of high groundwater/soil moisture are encountered; and vi) where necessary, adding a cap of aggregate over the native soil, underlain by geotextile (to avoid downward migration of the aggregate);

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[117] For example, hydro- or pneumatically-applied mulch/seed, or installation of erosion control blankets.

[118] For example, riprap, turf-reinforcement mat, seeding.

- Reducing erosion at stream crossings by: i) ensuring the crossing is appropriately sized to permit the design flow, and the design flow accounts for the projected increases in storm intensity in the future (Section 4.7.2); and ii) armoring culvert inlets and outlets, typically with riprap; and
- Reducing surface runoff to streams by: i) minimizing the length of ditches that directly flow into streams; and ii) directing ditch flow via cross-ditches into stable forested areas where there is no classified stream within a short distance downslope.
- Reducing sediment risks at bridge crossings by regularly cleaning bridge decks.

14. The alignment of new road crossings should be perpendicular to the orientation of the channel and only in areas with lateral stability to minimize interference with natural hydrogeomorphic processes (e.g., alluvial fans, debris flow gullies). Climbing roads on fans should be avoided and fail-safe designs should be considered where roads are aligned across active gullies or alluvial fans.

15. Risk ratings and detailed mitigation options should be included in all phases of access from construction to deactivation. This includes culvert sizing or location, stabilization of road cuts, fills and road surface, erosion and sediment controls, and any special site- and weather-specific shut-down guidelines [over and above those outlined by Statlu (2018)] to avoid heavy equipment trafficking and sediment production.

Riparian function

16. In accordance with the Riparian Management Area Guidebook[119], riparian reserves should be established on S1-S3 streams to avoid reduction of riparian function and to mitigate erosion and sediment delivery. For S4, S5, and S6 streams, retention of mature overstory and nonmerchantable timber is recommended within their respective riparian management zones.

17. Based on recommendations from Hudson and D'Anjou (2001), in areas subject to a partial harvest silviculture system, trees adjacent to S6 streams with a high windthrow potential should be removed to mitigate the potential for increased sedimentation as a result of blowdown. Moreover, windthrow assessments will be increasingly important if projections for more intense windstorms materialize.

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[119] https://www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/silviculture/silvicultural-systems/silviculture-guidebooks/riparian-management-area-guidebook

Pollutants

18. To avoid water contamination, we recommend that all forest development activities follow strict adherence to BCTS EMS and EFPs for the appropriate fuel storage & securing, dispensing, transportation, spill prevention and response measures, including specific restrictions within riparian management (or reserve) zones.

Site Level Recommendations

19. The following are site-level recommendations noted during the field reviews. Should these recommendations not fall within BCTS chart area or are beyond BCTS authority, we recommend that BCTS inform the appropriate party of the issues identified below.

Roberts Creek:

- Recommend clearing the boulder blocking the culvert entrance along Roberts Creek tributary 12.2 in the upper eastern portion of Roberts Creek (FIGURE 9.2).
- Recommend monitoring erosion of pedestrian bridge abutments noted at stream km 1.10 (APPENDIX D, FIGURE 036).
- Recommend monitoring level of aggradation near pedestrian bridge at stream km 1.78 (APPENDIX D, FIGURE 036).

Clack Creek:

- Recommend monitoring in-stream pedestrian bridge supports at stream km 1.32 (APPENDIX D, FIGURE 077).
- Recommend monitoring level of aggradation beneath pedestrian bridge at stream km 1.68 (APPENDIX D, FIGURE 079).

Stephens Creek

- Recommend clearing woody debris blocking the 1,400 mm diameter concrete culvert at Lower Road crossing near stream km 0.25 (APPENDIX D, FIGURE 123).
- Recommend clearing woody debris immediately upstream of the 1,200 mm diameter concrete culvert at the Sunshine Coast Highway crossing near stream km 0.77 (APPENDIX D, FIGURE 125).

FIGURE 9.2 *View of boulder blocking 800 mm diameter culvert along Roberts Creek tributary 12.2 in the upper easter portion of Roberts Creek (latitude: 49.470°, longitude: -123.579°). Photo DSC09534, August 25, 2020.*

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APPENDIX A: DEFINITIONS

ABCFP	Association of British Columbia Forest Professionals
Active Fluvial Units (AFUs)	The portion of a floodplain which water can be expected to flow during a runoff event of magnitude 1 in 100 years or more and that portion of an alluvial fan on which there is evidence of active hydrogeomorphic processes such as naturally occurring fluvial erosion or evidence of mass wasting. AFUs should be expected to occur on portions of all streams > 1.0 m stream channel width.
Adaptive Management Plan (AMP)	A monitoring or research initiative that is developed and implemented during operational planning, timber harvesting, silvicultural treatment, or road construction, including maintenance and deactivation phases, to examine the outcomes of management strategies and practices that vary from default legislative requirements, the results of which will inform the development of future management strategies and practices.
Agreement Holder	The holder of an agreement under British Columbia's Forest Act or Range Act.
Alluvial fan	A conical deposit of stream-derived sediment that is formed where stream gradient decreases and stream channels become laterally unconfined. These can exist either mid-slope or near the mouth of a stream.
Assurance Statement	A declaration by a Specialist assuring that the Specialist's work meets the intent and direction as provided by Joint Professional Practices Guidelines and a forest licensee's Watershed Risk Management Framework.
Bare Ground	All land surface not covered by vegetation, rock, or litter.
BC Timber Sales Program	An independent organization within the BC Ministry of Forests, Lands and Natural Resource Operations, created to develop Crown timber for auction. BCTS was founded in 2003 with a mandate to provide the cost and price benchmarks for timber harvested from public land in British Columbia. Through 12 Business Areas and an operational presence in 33 locations, BCTS manages some 20 percent of the provincial Crown allowable annual cut.
Bedload	Bedload is a term used to describe particles in a stream that are being carried or transported along the streambed.
Biogeoclimatic Classification System	A hierarchical classification system of ecosystems that integrates regional, local and chronological factors and combines climatic, vegetation and site factors.
Biogeoclimatic Unit	Part of the biogeoclimatic ecosystem classification system. Recognized biogeoclimatic units are a synthesis of climate, vegetation and soil data and are defined as "classes of geographically related ecosystems that are distributed within a vegetationally inferred climatic space."
Biogeoclimatic (BEC) Zone (and Subzone)	A BEC zone is a geographic area having similar patterns of energy flow, vegetation and soils, as a result of a broadly homogenous macroclimate. A BEC subzone is a unit with less climatic variability and a narrower geographic distribution than the zone. Subzones are distinguished by a unique composition of plant species. They are climatically based and represent precipitation and temperature regimes.
Blowdown (Windthrow)	Uprooting by the wind. Also refers to a tree or trees so uprooted.
Blue List Species	Species of special concern (formerly called "vulnerable") in British Columbia. These species are not immediately threatened, but are of concern because of characteristics that make them particularly sensitive to human activities or natural events.
Bog	A class of wetland characterized by a thick layer of sphagnum-based peat. It receives its water primarily from direct precipitation. Bog waters tend to be acidic and nutrient-poor.
Canopy Cover	The percentage of ground covered by a vertical projection of the outermost perimeter of the natural spread of foliage of plants. Small openings within the canopy are included, and coverage may exceed 100 percent.
Channel	The stream banks and stream bed formed by fluvial processes.
Channel Bed	The bottom of the stream below the usual water surface. Beds contain sediments deposited by moving water, such as rocks, sand, gravel and sediment.

Channel Sensitivity (Channel Response Potential)	The inherent susceptibility of a stream channel to changes in discharge and sediment supply. The response of a channel may include changes in bed texture (e.g., grain size), geometry (i.e., width, depth, slope), planform (e.g., sinuosity), and/or bedforms (e.g., pools). Such potential responses have potential direct impacts on water quality, water supply infrastructure, and fish and fish habitat.
Clearcut	An area of forestland from which all merchantable trees have recently been harvested.
Climate	The average weather conditions of a place over many years.
Climate Change	An alteration within the climate system that departs significantly from previous average conditions and is seen to endure, bringing about corresponding changes in ecosystems and socio-economic activity.
Consequence	The effect on human well-being, property, the environment, or other things of Value, or a combination of these. Consequence can be certain or uncertain and have positive or negative effects. Most commonly, consequence is considered to be the change, loss, or damage to risk elements caused by a harmful event such as a flood or landslide.
Colluvium	Unconsolidated sediments deposited at the base of hillslopes. Colluvium is transported by hillslope processes and may range in size from silt to boulders.
Community Watershed	The drainage area above the most downstream point of diversion on a stream for which the water is for human consumption, and which is licensed under the *Water Act* for (i) a waterworks purpose, or (ii) a domestic purpose if the licence is held by, or is subject to, the control of a water users' community as incorporated under the *Water Act*. Community watersheds are designated under the Government Actions Regulation. To protect the water that is diverted for human consumption, such areas require special management to: conserve the quality, quantity and timing of water flow and prevent cumulative hydrological effects having a material adverse effect on water. There are currently 466 designated community watersheds in B.C. with most established in the 1980s and 1990s.
Control Measure	Actions and/or activities that are taken to prevent, eliminate or reduce the occurrence of an identified hazard.
Coupled Hillslope (Hillslope-stream coupling)	A channel is considered coupled to a hillslope when sediment mobilized on the hillslope by landslide activity directly enters the stream channel. Sediment delivery to coupled reaches is dominated by landslides, while sediment movement through the reach is by debris flow and fluvial processes. Channel gradient is typically >5 per cent. Coupled reaches are identified by the following indicators: • There is no valley flat; sediment or debris mobilized by landslides directly enters the stream channel; • The surrounding slopes are steep and likely to initiate landslides that can transfer sediment directly to the stream channel; • The channel is small relative to the volume of sediment and debris that may be transferred from the surrounding hillslopes; and • Debris flows may be initiated from within the reach.
Cross Ditch	A ditch excavated across the road at an angle and at a sufficient depth, with armouring as appropriate, to divert both road surface water and ditch water off or across the road.
Crown forested land base (CFLB)	The CFLB is the area of productive forested Crown land in a defined area. It does not include private land, non-forested areas like alpine, lakes, roads, or non-productive forest like brush. A proportion of old-growth targets can be located within the forested portion of parks, ecological reserves and other areas managed by the Crown. Within the CFLB, the area or amount of old-growth can be identified or located in constrained or inaccessible areas within the unit area to which the order applies, up to the target stated for each biogeoclimatic variant.
Crown Land	Land that is owned by the government of Canada or the province of British Columbia.
Crown Range	Crown land included within the boundaries of a range district, but does not include Crown land that is subject to a lease issued under the *Land Act*.
Culvert	A culvert is one or more pipes, pipe arches, or structures below the road surface, used to let water flow from one side of the road to the other.

Cumulative Effects	Cumulative effects are changes to environmental, social and economic values caused by the combined effect of past, present and potential future human activities and natural processes.
Cutblock	A specific area of land with defined boundaries, authorized for harvest.
Cutslope	The face of an excavated bank required to lower the natural ground line to the desired road profile.
Deactivation	Measures taken to stabilize roads and logging trails during periods of inactivity, which include control of drainage, removal of sidecast where necessary, and re-establishment of vegetation in preparation for permanent deactivation.
Debris	Wood and other organic materials typically mixed with mineral soils resulting from mass-wasting events which can be delivered to stream channels and the aquatic environment
Deleterious substance (as defined by Fisheries Act)	"A substance or water containing substance in such quantity or concentration, or that has been so treated, processed or changed, by heat or other means, from a natural state that it degrades or alters water quality to the detriment of fish, fish habitat or use by man of fish found in the receiving water"
Domestic Water Intake	A domestic water intake is the point at which water is diverted from a stream for domestic purposes (e.g., human consumption, food preparation or sanitation and household purposes).
Dynamic Channel Equilibrium	A state of balance resulting from the interplay of four basic factors (sediment discharge, sediment particle size, streamflow, and channel gradient) that maintains alluvial stream channels in their most efficient and least erosive form. The term "dynamic" is important, as the energy of a stream is always at work sustaining or re-establishing its equilibrium condition. Land-use effects at site-specific or watershed scales can upset the dynamic equilibrium thereby triggering a process of stream adjustments. If one of the four factors change, one or more of the other variables must increase or decrease proportionally if equilibrium is to be maintained. For example, if channel gradient is increased (e.g., by channel straightening) and streamflow remains the same, either the sediment load or the size of the particles must also increase. Likewise, if flow is increased (e.g., by upslope forest cover removal) and the channel gradient stays the same, sediment load or sediment particle size has to increase to maintain channel equilibrium. Under these examples' conditions, a stream seeking a new equilibrium will tend to erode more of its banks and bed, transporting larger particle sizes and a greater sediment load. Such stream adjustments may be undesirable, particularly where they affect downstream elements-at-risk.
EGBC	The Association of Professional Engineers and Geoscientists of the Province of British Columbia, also operating as Engineers and Geoscientists BC.
Engineering/Geoscience Professional	Professional engineers, professional geoscientists, and licensees[120], who are registered or licensed by Engineers and Geoscientists BC and entitled under the Engineers and Geoscientist Act to engage in the practice of professional engineering or professional geoscience in British Columbia.
Element at Risk (Risk Element)	Values that are put at Risk by an identified source of harm or potential harm.
Ephemeral Drainage	An area of land where water drains away for brief, transient periods following an influx of moisture such as from localized snowmelt or heavy precipitation.
Equivalent Clearcut Area (ECA)	Equivalent clearcut area (ECA) is a commonly used index of the extent of forest disturbance and regrowth in a watershed (Winkler et al., 2010b). The ECA of a clearcut is derived by reducing the total area cut by recovery, which is estimated from relationships between snow accumulation and melt or interception of precipitation and crown closure (Winkler and Roach, 2005) or tree height (Hudson and Horel, 2007). The

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[120] The use of the term "licensees" here means as defined in the Act.

	cumulative ECAs for all openings are summed to provide an ECA for the entire catchment (Winkler et al., 2010b).
Even-aged	A forest stand or forest type in which relatively small (10-20 years) age differences exist between individual trees. Even-aged stands are often the result of fire or a harvesting method, such as clearcutting or the shelterwood method.
Fish (as defined by Fisheries Act)	“Parts of fish; shellfish, crustaceans, marine animals and any parts of shellfish, crustaceans or marine animals; and the eggs, sperm, spawn, larvae, spat and juvenile stages of fish, shellfish, crustaceans and marine animals”
Fish-bearing	Lakes, streams, and ponds that have resident fish populations.
Fish Habitat (as defined by Fisheries Act)	“Spawning grounds and nursery, rearing, food supply and migration areas on which fish depend directly or indirectly in order to carry out their life processes”
Forest Management Activities	Activities carried out by Forest Professionals and others affecting forest ecosystems including, but not limited to, forest harvesting and roads; silviculture; forest wildfire prevention, suppression, and post-wildfire Risk Management; forest pathogen suppression and post-attack rehabilitation; and right-of-way clearing.
Forest Professional	Registered professional foresters, registered forest technologists, or special permit holders who are registered with or licensed by the Association of British Columbia Forest Professionals (ABCFP) and entitled under the Professional Governance Act to engage in the practice of professional forestry in British Columbia.
Framework	A written document that provides the context, scope, and standards for managing risks from forest management activities in a licensee’s Chart. A framework is intended to optimize the use of organizational resources by focusing the greatest efforts on the areas of greatest concern. In managing risks to watershed values, the following principle should apply: as the severity of consequence increases, the degree of caution applied to risk management also increases.
Floodplain	An area of low-lying ground adjacent to streams that are primarily formed by stream-derived sediments and are subject to being flooded.
Fluvial	Pertaining to, or produced by, the action of a stream or river.
Forest and Ranges Practices Act (FRPA)	The Forest and Range Practices Act and its regulations govern the activities of forest and range licensees in BC. Replaced the Forest Practices Code of British Columbia Act.
Forest Licence (Forest Licensee)	A forest licence allows orderly timber harvest over a portion of a sustained yield management unit, and the timely reforestation of harvested areas according to a strategic resource management plan for each timber supply area. The licence has a term of 15 to 20 years, generally replaceable every five years (some are non-replaceable) and Charts that shift over time. A forest licence specifies an annual allowable cut, requires a management and working plan, and specified management activities.
Forest Resources	Resources and values associated with forests and range including, without limitation, soil, visual quality, timber, water, wildlife, fisheries, recreation, botanical forest products, forage, and biological diversity.
Forest Stewardship Plan (FSP)	A key planning element in the *Forest and Range Practices Act* framework and the only plan subject to public review and comment and government approval. In FSPs licensees are required to identify results and/or strategies consistent with government objectives for values such as water, wildlife and soils. These results and strategies must be measurable and once approved are subject to government enforcement. FSPs identify areas within which road construction and harvesting will occur but are not required to show the specific locations of future roads and cutblocks. FSPs can have a term of up to five years.
Free Growing	An established seedling of an acceptable commercial species that is free from growth-inhibiting brush, weed, and excessive tree competition; or young trees that are as high as or higher than competing brush, with one metre of free-growing space around their tops.
Geomorphology	The science of landforms with emphasis on their origin, evolution, form, and distribution across the physical landscape.
Geotextile Filter Fabric	A synthetic material placed on the flat, under road fill, with the primary functions of layer separation, aggregate confinement, and distribution of load.

GIS	Geographic Information System
Gully	A channel or small valley cut by concentrated, non-continuous runoff such as during snowmelt or following heavy rains.
Habitat	The place where an organism lives including the characteristics of that environment that make it especially well suited to meet the life cycle needs of that species.
Harvesting	The practice of felling and removing trees or the removal of dead or damaged trees from an area.
Hazard	A source of potential harm, or a situation with a potential for causing harm, in terms of human injury; damage to property, the environment, and other things of value; or some combination of these (Wise et al., 2004). Hydrologic and geomorphic processes in themselves are not hazards until they are identified as having the potential to harm a specific Value. When a hydrologic or geomorphic process has the potential to harm a Value, the process is a hazard in relation to that Value, and the Value becomes an element at risk in relation to that hazard. Note: The term hazard is sometimes used synonymously with the terms probability and likelihood of occurrence. Hazard, however, describes a harmful or potentially harmful event or situation, while probability and likelihood of occurrence describe the potential for the event or situation to occur. The interchangeable use of these terms is confusing and is discouraged.
Higher Level Plan	A resource management plan that establishes the broader, strategic context for operational plans. The objectives determine the mix of forest resources to be managed in a given area.
Hydraulicking (Hydraulic Mining)	Hydraulic mining, or hydraulicking, is a form of mining that uses high-pressure jets of water to dislodge rock material or move sediment. In the placer mining of gold, the resulting water-sediment slurry is directed through sluice boxes to remove the gold.
Hydrogeomorphic Hazards	A collective term use to describe hazards associated with hydrologic and geomorphic processes that often interact and affect the nature and characteristics of stream channels and watersheds. Examples include landslides, debris flows, debris floods, and floods.
Hydrologic Assessment	An investigation of a particular area, site, process, or event within a Watershed Unit. This type of assessment can involve a study of both hydrologic and geomorphic processes but may not include either the full scope of a Watershed Assessment or the entire area of a Watershed Unit. The objectives and scope of these assessments can vary widely, depending on the reason for the assessment.
Hydrologic Recovery	Refers to stand-scale interactions between forests and hydrologic processes, and means the extent to which a regenerating forest stand compares to a reference stand (typically a pre- disturbance stand) with respect to characteristics affecting streamflow response (rainfall interception, snowpack development, and ablation behaviour).
Hydrology	The science that deals with the waters above and below the land surfaces of the Earth; their occurrence, circulation and distribution, both in time and space; their biological, chemical, and physical properties; and their interaction with their environment.
Hydrometric	Pertaining to the measurement of components of the hydrological cycle including rainfall, flow characteristics of surface water, groundwater, and water quality.
Insolation	The amount of solar radiation that reaches the ground surface.
Interface Watershed	Watersheds that support land uses other than forestry and other resource-based industries (e.g., mining). Interface watershed may include one of more of the following: communities, settlements, private land, residences, commercial development, industrial operations, agriculture, public infrastructure, recreational areas.
Isothermal snowpack	A snowpack that is the same temperature, usually 0°C, throughout.
Key watershed reporting unit	Defined as basins, sub-basins and residual areas within the Key Watersheds.
Landform	A distinct topographic feature, is three-dimensional in form, and is generally defined by ridges, valleys, shorelines, and skylines. Landform examples include hills and mountains.

Landslide	A movement of rock, debris or earth down a slope. Landslides can be a result of a natural events and/or human activities.
Latent heat	Energy released or absorbed as a substance changes state.
Licensee	An individual, company, or Provincial Crown agency that has the legal right to carry out Forest Management Activities on public or private land.
Likelihood	The chance of something happening. Likelihood is often expressed as the chance of occurrence over a given time period (ISO, 2015) using relative terms such as very low to very high or very unlikely to almost certain. Probability is a mathematical expression of likelihood. Note: If Specialists choose to use terms such as "hazard", they should define the term as it is used in their reports. The use of the term "hazard" to mean "Likelihood" is discouraged.
Local Resource Use Plan (LRUP)	A plan approved by the district manager for a portion of the provincial forest that provides area-specific resource management objectives for integrating resource use in the area.
Major culvert	As per the *Forest and Range Practices Act (FPRA), Forest Planning and Practices Regulation (FPPR), a* "major culvert" means a stream culvert that (a) is one of the following: (i) a pipe having a diameter of 2 000 mm or greater; (ii) a pipe arch having a span greater than 2 130 mm; (iii) an open bottom arch having a span greater than 2 130 mm, or (b) has a maximum design discharge of 6 m3 per second or greater.
Managing Professional	An individual, typically a Member of ABCFP or EGBC, responsible for establishing and implementing the steps outlined in the Watershed Risk Management Framework, that addresses management of Hydrologic and Geomorphic Risks in relationship with Forest Development.
Meltwater drip	Water that melts from snow intercepted by the tree canopy and drips down from the canopy or flows down the stem to the ground or snowpack below.
Mitigate	To take measures in advance to offset or reduce the Likelihood of negative effects; for example, distributing harvest areas with regard to aspect, elevation zone, or other factors to reduce the Likelihood that peak flow increases will occur, or to reduce the possible magnitude of peak flow increases, or to establish standard operating procedures for road construction to reduce the potential for instability or drainage problems.
Natural Resource District	A natural resource district is an administrative area established by the BC Ministry of Forest, Lands, Resource Operations and Rural development (FLNRORD) with resources and values associated with forest and range including, and without limitation to, soil, visual quality, timber, water, wildlife, fisheries, recreation, botanical forest products, forage, and biological diversity.
Objective	A concise, time-specific statement of measurable planned results that correspond to pre-established goals in achieving the desired outcome. Commonly includes information on resources to be used, forms the basis for further planning to define the precise steps to be taken, and the resources to be used and assigned responsibility in achieving the identified goals."
Old Growth	A forest that contains live and dead trees of various sizes, species, composition, and age class structure. Old-growth forests, as part of a slowly changing but dynamic ecosystem, include climax forests but not sub-climax or mid-seral forests. The age and structure of old growth varies significantly by forest type and from one biogeoclimatic zone to another.
Old Growth Management Ara (OGMA)	Defined areas that contain, or are managed to attain, specific structural old-growth attributes and that are delineated and mapped as fixed areas.
Outslope	To shape the road surface to direct water away from the cut slope side of the road.
Overlanding	Placing road construction fill over organic soil, stumps and other plant materials, corduroy or geotextiles, any of which is required to support the fill.
Overstorey	That portion of the trees in a forest of more than one storey forming the upper or uppermost canopy layer.

Partial Cutting	A general term referring to silvicultural systems other than clearcutting, in which only selected trees are harvested. Partial cutting systems include seed tree, shelterwood, selection, and clearcutting with reserves.
Partial Risk	The likelihood of occurrence of a hazardous event and the likelihood of it affecting the site occupied by a specific element. Partial risk analysis is often used when it is sufficient to know whether or not a hazardous event or change to watershed process will reach or affect a watershed value. The extent of harm to the value of interest (i.e., vulnerability) is not investigated. A partial risk analysis is often the first level of investigation by a Specialist since the vulnerability of specific values (e.g., water supply infrastructure, fish and fish habitat, etc.) often requires assessments by other Specialists (e.g., engineers, biologists, foresters, etc.) who have greater knowledge of the elements-at-risk.
Point(s) of Interest	A point identified to establish the lower limit of a drainage area that is the subject of a Watershed Assessment or Hydrologic Assessment. Typically, it is at the location of a Value of interest (e.g., a water intake); or at a stream confluence or shoreline; or at the downstream limit of a fish-bearing reach of interest.
Peak flow	The maximum rate of discharge during a period of runoff. Peak flow may be associated with melting of a snowpack, rain storm, or combination of the two.
Peak flow hazard	Peak flow hazard refers to the likelihood and/or degree to which the baseline or pre-disturbance peak flow magnitude and frequency has or could change in response to watershed disturbance, specifically forest development (e.g., timber harvesting and road building); however, other land uses or natural disturbances that affect the forest land base are also considered. In simple terms, the peak flow hazard refers to the likelihood that flooding along a particular stream or stream reach will become measurably more severe or frequent under 1) current conditions, and then 2) following forest development or other disturbance, relative to baseline conditions.
Primary Forestry Activity	One or more of: timber harvesting, silviculture treatments, wildlife habitat enhancement, and road construction, maintenance, and deactivation.
Probability	A mathematical expression of Likelihood over a given time frame, using a number between 0 (an event will not occur) and 1 (an event will certainly occur).
Professional Biologist (RPBio)	A person admitted to and registered with the College of Applied Biology as a Professional Biologist.
Professional Engineer (PEng)	An Engineer who is a registered or licensed member in good standing with EGBC and typically is registered in the disciplines of geological engineering, mining engineering or civil engineering, which are designated disciplines of professional engineering.
Professional Geoscientist (PGeo)	A Geoscientist who is a registered or licensed member in good standing with EGBC and typically is registered in the disciplines of geology or environmental geoscience, which are designated disciplines of professional geoscience. Until 2000, EGBC referred to the discipline of environmental geoscience as 'geotechnics.'
Quantitative vs Qualitative	Quantitative estimates use numerical values or ranges of values, while qualitative estimates use relative terms such as high, moderate and low. Both quantitative and qualitative estimates can be based on either objective (statistical or mathematical) estimates or subjective (professional judgmental or assumptive) estimates, or some combination of both. No standard definitions exist for relative qualitative terms. Therefore, to avoid ambiguity, such terms must be defined with reference to quantitative values or ranges of values. Quantitative estimates may be no more accurate than qualitative estimates. The accuracy of an estimate does not depend on the use of numbers. Rather, it depends on whether the components of risk analyses have been appropriately considered; and on the availability, quality and reliability of required data.
Range	Any land supporting vegetation that is suitable for grazing.
Range Land	Crown range and land subject to an agreement under section 18 of the *Range Act*.
Reach	A relatively homogeneous portion of a stream that has a sequence of repeating structural characteristics.

Red Listed Species	Indigenous species that are extirpated, endangered or threatened in British Columbia.
Referral	The process by which applications for permits, licences, etc., made to one government agency by an individual or industry, are given to another agency for review and comment.
Reforestation	The re-establishment of trees on denuded forest land by natural or artificial means, such as planting and seeding.
Relief	The difference between highest and lowest elevations in a watershed unit.
Remediate	To take measures to fix effects after they have occurred; for example, deactivating old unstable roads or implementing sediment control measures on active roads.
Reserve	An area of forestland that, by law or policy, is not available for harvesting. Areas of land and water set aside for ecosystem protection, outdoor and tourism values, preservation of rare species, gene pool, wildlife protection, etc.
Reserve Zone	An area in which no timber harvesting is allowed to occur.
Residual Area (Face Unit)	An area located outside of defined stream catchments. A residual area is typically found between stream catchments and may have small streams (i.e., smaller than the scale of the stream catchments on either side) or no identified streams present. Nevertheless, the residual area may contribute dispersed surface runoff or groundwater to a stream below.
Rill	A small channel created on steep slopes by water erosion.
Riparian Area	The banks and adjacent areas of a stream, river, lake or wetland. It contains vegetation that, due to the presence of water, is distinctly different from the vegetation of adjacent upland areas.
Riparian Feature	River, stream, lake or wetland.
Riparian Function	Riparian vegetation serves many purposes (e.g., to provide shade, cover, stream habitat, stream bank stability, etc.) and can be a major factor contributing to the robustness of channels and observed channel response. Loss of riparian function can affect channel equilibrium and result in bank erosion, channel shifting, and sedimentation. The level of past riparian forest cover disturbance and the level of recovery of the riparian vegetation are both considered in characterizing channel response.
Riparian Leave Strip	An unharvested border of forest around a riparian feature.
Riparian Management Area (RMA)	An area that consists of a riparian management zone and a riparian reserve zone.
Riparian Management Zone (RMZ)	A portion of the riparian management area established to conserve the fish, wildlife habitat, biodiversity and the water values of the riparian management zone, and to protect the riparian reserve zone, if any, within the riparian management area.
Risk	The chance of injury or loss, expressed as a combination of the Consequence of an event and the associated likelihood of occurrence. Note: If Specialists choose to use terms such as "hazard", they should define the term as it is used in their reports. The use of the term "hazard" to mean "Likelihood" is discouraged.
Risk Analysis	The systematic use of information to comprehend the nature of Risk and to estimate the level of Risk (ISO, 2015; Wise et al., 2004).
Risk Assessment	The overall process of Risk Identification, Risk Analysis, and Risk Evaluation (ISO, 2015.
Risk Evaluation	The process of comparing the results of Risk Analysis with Risk Tolerance Criteria to determine if the Risk is acceptable, tolerable, or unacceptable; weighs the estimated level of Risk against the expected benefits (ISO, 2015; Wise et al., 2004)
Risk Identification	The process of finding, recognizing, and describing Risks; involves identifying the Values, the sources of Risk (sources of potential harm), their causes, and the potential Consequences.
Risk Management	Coordinated activities to control risks.
Risk Tolerance Criteria	References against which the significance of a risk is evaluated. Generally, these are associated with defined qualitative or quantitative risk levels.

Road Deactivation	Consists of measures to stabilize roads and logging trails during periods of commercial harvesting inactivity. It includes controlling drainage, removing side-cast where necessary and re-establishing vegetation for permanent deactivation.
Road Prism	A road prism is the area consisting of the road surface, any cut slopes, ditches or road fill.
Road Rehabilitation	A rehabilitated road has all structures removed (including water bars and cross ditches), the road surface is loosened, surface re-contoured, and natural drainage patterns restored and trees planted (on forest land) to get roads back into forest production.
RPBio	Registered Professional Biologist
Runoff Generation Potential	Runoff generation potential or flood response potential (Green, 2015) describes the propensity at which precipitation and/or snowmelt are converted to surface runoff and ultimately streamflow. Watersheds with high runoff generation potential tend to have relatively rapid runoff generation, whereas those with low runoff generation potential tend to have slower runoff generation. Physical watershed characteristics that affect runoff generation include vegetation (e.g., forest type), soil type, geology, elevation, hillslope aspect, and hillslope gradient. Meteorological factors affecting runoff generation include the type of precipitation; rainfall intensity, amount and duration; distribution of rainfall over the drainage basin, antecedent precipitation, and other conditions that affect evapotranspiration such as temperature, wind, relative humidity and season. Land use, including forestry, may affect runoff generation potential by affecting site-level water balance following deforestation or reforestation and by affecting soil permeability along roads or areas trafficked by heavy equipment. Forestry effects are a function of several factors, including area harvested (i.e., ECA); size, shape and orientation of individual forest openings, and method of harvesting (e.g., ground, cable-based, or air).
Salvage Harvesting	Logging operations specifically designed to remove damaged timber (dead or in poor condition) and yield a wood product. Often carried out following fire, insect attack or windthrow.
Sediment Delivery Potential	The likelihood that sediment generated in upslope or instream sources will reach the stream network and be transported downstream to an element-at-risk (i.e., sedimentation). Factors considered include: hillslope-stream coupling, stream gradient, and location of lakes and wetlands.
Sediment Generation Potential	The likelihood that land use activity will increase the magnitude and/or frequency of sediment production (i.e., erosion) considering: terrain stability, soil erodibility, evidence of mass wasting, extent and location of resource roads, and other land-use related soil disturbance.
Sediment Yield	The rate of sediment flux through a stream system.
Seep	Wet areas, normally not flowing, arising from an underground water source.
Soil Disturbance	Disturbance to the soil in the net area to be reforested resulting from the construction of temporary access structures or gouges, ruts, scalps or compacted areas resulting from forestry activities. Without rehabilitation, disturbed sites often have reduced soil productivity and may not provide optimum growing conditions for new trees. For that reason, maximum allowable amounts of soil disturbance are set in regulation.
Specialist	An individual with specialized training, certification, and experience in a particular occupation, practice, or branch of learning. Such individuals include but are not limited to registered professionals with specialized expertise such as fisheries, Hydrology, Geomorphology or fluvial Geomorphology, slope stability, terrain mapping, erosion control and sediment management, aquatic or riparian terrestrial habitats, water quality, windthrow, forest health, or human health; and non-professionals who may be individuals with certification in specific occupational skills. Typically, the lead Specialist for a Watershed Assessment or Hydrologic Assessment would be a Specialist in Hydrology and/or Geomorphology.
Specific Risk	The risk of loss or damage to a specific element, resulting from a specific hazardous event or sustained change to watershed process occurring and of it affecting the location

	occupied by a specific element of value. Consideration of the vulnerability of the element-at-risk is required to estimate specific risk. For example, a common question may be: what is the extent of flood damage that could occur? How vulnerable is a water system to flooding (i.e., is there a backup source)?
Specific Value of Risk	The worth of loss or damage to a specific element, excluding human life, resulting from a specific hazardous event or sustained change to watershed process occurring and of it affecting the location occupied by a specific element of value.
Stakeholder	Any individual, group, or organization able to affect, be affected by, or believe they might be affected by, a decision or activity. Note that a decision-maker can be a Stakeholder.
Stream Bed	The bottom of the stream below the usual water surface.
Stream Channel	The stream bed and banks formed by fluvial processes, including deposited organic debris.
Streamflow Regime	The streamflow regime is described by the magnitude, frequency, and timing of streamflow.
Subordinate	Any person directly supervised by an Engineering/Geoscience Professional or Forest Professional who assists in the practice of the relevant profession; for example, a member-in-training, another person not registered or licensed to practice the profession(s), or another Engineering/Geoscience Professional or Forest Professional.
Sustainability	A state or process that can be maintained indefinitely. The principles of sustainability integrate three closely interlined elements-the environment, the economy and the social system-into a system that can be maintained in a healthy state indefinitely.
Sustainable Development	Preservation and protection of diverse ecosystems—the soil, plants, animals, insects and fungi—while maintaining the forest's productivity.
Sustainable Forest Management	Management regimes applied to forest land which maintain the productive and renewal capacities as well as the genetic, species and ecological diversity of forest ecosystems.
Swamp	A tree or tall-shrub dominated wetland with mineral or occasionally peat soils that experiences periodic flooding and nearly permanent subsurface water flow. The waters are nutrient rich.
Synchronization	Refers to the how forest cover removal alters the rate and timing of snowmelt at different locations within a watershed so that there is an increase in the amount of water that is released from the snowpack over a given period (often the period of interest is around the peak streamflow in spring). The synchronization of hydrological processes is commonly attributed to increases in the magnitude of peaks flows (Moore and Wondzell, 2005).
Tenure Holder	An individual, group or company that holds a licence agreement under the Forest Act or Range Act.
Timber Harvesting Land Base	Crown forest land within the timber supply area where timber harvesting is considered both acceptable and economically feasible, given objectives for all relevant forest values, existing timber quality, market values, and applicable technology.
Tree Farm Licence (TFL)	An area-based tenure agreement that issues the rights to harvest an allowable annual cut in a specified area. These licences commit the licensee to manage the entire area under the general supervision of the Forest Service. Cutting from all lands requires Forest Service approval through the issuance of cutting permits. A TFL has a term of 25 years.
Understorey	Any plants growing under the canopy formed by other plants, particularly herbaceous and shrub vegetation under a tree canopy.
Upland	Land elevated above a riparian area.
Value	The specific or collective set of natural resources and human developments in a watershed that have measurable or intrinsic worth. Values can include human life and bodily harm, public and private property (including buildings, structures, lands, resources, recreational sites, and cultural heritage features), transportation systems and corridors, utilities and utility corridors, water supplies (for

	domestic, commercial, industrial, or agricultural use), aquatic and terrestrial habitats, visual resources, and timber.
Vegetative Cover	The plants or plant parts, living or dead, which protect the ground surface. Cover may also refer to the area of ground cover by plants of one or more species.
Vulnerability	A measure of the robustness (or alternatively the fragility) of a thing of Value, and its exposure to a source of Risk.
Watershed	An area of land drained by a stream or river, above a given point on a waterway that contributes runoff water to the flow at that point.
Watershed Assessment	Identification and analysis of hydrologic and geomorphic processes in a Watershed Unit that is consistent with Section 3.0 of EGBC and ABCFP (2020).
Watershed Routing Efficiency	The relative rate of water transmission through the drainage unit, considering the area and location of lakes and wetlands (i.e., storage), surficial geology and soils, drainage density, road density, and slope gradient.
Watershed Unit or Watershed Reporting Unit	The surface drainage area upstream of a defined Point of Interest. A Watershed Assessment may be for a single Watershed Unit, or may subdivide a large drainage area into smaller Watershed Units for the purpose of the assessment. The hierarchy of watershed units from large to small include: large watershed, watershed, basin, and sub-basin. Units smaller than sub-basins may be referred to as local drainages.
Wet Meadow	A class of wetland having mineral soils which are periodically saturated. Dominant vegetation consists of water-tolerant grasses, sedges, rushes and forbs.
Wetlands	Areas characterized by soils that are usually saturated and support mostly water-loving plants.
Windfirm	A single or stand of trees that retains the ability to withstand strong winds and thus resist overturning (i.e., to resist windthrow, windrocking, and major breakage).

APPENDIX B: EQUIVALENT CLEARCUT AREA MODELLING

Background

Equivalent Clearcut Area (ECA) is a commonly used metric to characterize hydrologic recovery following forest cover disturbance (e.g., harvesting) in forest hydrology. ECA reflects the extent of forest disturbance and regrowth (or recovery toward pre-disturbance conditions) in a watershed (Winkler et al., 2010b)[121]. The ECA of a clearcut is derived by reducing the total area cut by recovery, which is estimated from relationships between rainfall interception or snow accumulation/melt and crown closure or tree height (Hudson and Horel, 2007). The cumulative ECAs for all openings are summed to provide an ECA for entire watershed or portion thereof (Winkler et al., 2010b)[122].

ECA was originally used in provincial watershed assessment procedures as one of many indicators of peak flow hazard due to forest harvesting (BC MOF, 1999). It is important to recognize, however, the complexities and uncertainties in applying stand-scale recovery estimates (i.e., ECA indices) to the evaluation of hydrologic change at the watershed scale (Winkler et al., 2010b). Fortunately, the studies from which these stand-scale recovery estimates are based, are often conducted in small watersheds, similar in size and characteristics as the assessment watersheds. As such, there is greater confidence that outcomes from these studies are more directly relatable to the assessment area.

There are potential limitations and challenges in calculating and interpreting ECA. This includes the following:

- ECAs are calculated on the basis of defined drainage areas. Such areas must be defined for selected points-of-interest – usually the mouths of major streams (watersheds), tributaries (basins), or above elements-at-risk. If there are numerous points-of-interest within a watershed, ECAs can vary considerably depending on the location and distribution of disturbed areas (e.g., a concentration of cutblocks in the lower portion of a watershed);
- ECA modelling was developed for forested watersheds, and is not necessarily representative of urbanized areas. While the loss of forest cover can be accounted for (as done herein), ECAs do not account for the hydrologic effects of extensive impervious areas (e.g., buildings, roads), nor the widespread modification of natural drainage patterns vis a vis ditches, drains, and stormwater systems; and
- It should be noted that ECAs were developed based on changes to interception and snowmelt as a result of forest cover loss, and hence focused on peak flows. No formal work has been done in British Columbia to assess how forest cover loss affects transpiration rates and consequently low flows.

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[121] The higher the ECA the lower the level of hydrologic recovery in a watershed. E.g., an ECA of 30%, implies 70% recovery, whereas 10% ECA implied 90% recovery.

[122] Some workers refer to the cumulative watershed-level ECA as equivalent clearcut index (ECI) (Madone, 2015) or hydrologically equivalent disturbed area (HEDA) (Beaudry, 2013). In order to reduce technical jargon, we refer to ECA as representing the hydrologic recovery of a defined area, e.g., watershed (unless otherwise specified).

In spite of some caveats, ECA remains a useful approximation of the state of forest cover disturbance and hydrologic recovery (relative to pre-disturbance levels) in a watershed. It should be recognized, that although ECAs may be reported with some precision, in our opinion, there is always some uncertainty with the ECA assumptions and recovery estimates.

Methodology & Assumptions

Current ECAs were calculated for the assessment watersheds following a methodology adapted from Hudson and Horel (2007), which is based on research data on stand-level hydrologic recovery collected on Vancouver Island and Gray Creek near Sechelt (Hudson, 2000a, 2000b, 2001, 2002 and 2003). Stand-level hydrologic recovery is an index of the degree to which a regenerating forest stand is similar to old growth in its rainfall interception characteristics and its influence over snowmelt. The hydroclimatic conditions, tree growth and hydrological recovery at the research sites reported in Hudson and Horel (2007) are considered comparable to those in the watershed units of interest. Hudson and Horel (2007) propose evaluating mean recovery for three elevation bands as well as for the watershed overall. The elevation bands include 0-300 m, where rainfall is considered dominant; 300-1,200[123] m where rain and rain-on-snow is common; and >1,200 m where peak flows are considered to be primarily generated from snowmelt. Given that rain-on-snow can occur across all elevations, and that these events are often responsible for producing some of the largest peak flows, Dr. William Floyd (Research Hydrologist for the Coast Area Research Section, BC Ministry of Forestry) suggested applying a single rain-on-snow curve across all elevations. Furthermore, he suggested the Hudson and Horel (2007) cold rain-on-snow recovery curve was most applicable to the assessment area. As such, hydrologic recovery, and hence ECA, was evaluated using the cold rain-on-snow curve across all elevations.

Provincial sources were initially used to identify disturbed areas (e.g., harvested areas). The analysis referenced the Vegetation Resource Inventory (VRI) (with a harvest flag), RESULTS and Forest Tenure Authority (FTA), as well harvesting data supplied by BCTS. Issued blocks from the FTA layer and sold blocks from BCTS were treated as current depletions. Disturbed areas not captured by the provincial block sources, were manually flagged and/or digitized based on a detailed imagery review using available 2019 and 2020 satellite imagery[124] and LiDAR-derived canopy height model.

Current road alignments were compiled from FTA, Digital Road Atlas, DEM bare earth hillshade, and streaming imagery. A single merged layer was created and reviewed against the 2019 satellite imagery. All roads were given a total clearing width of 15m.

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[123] This elevation band is further subdivided into two zones, the warm and cold rain-on-snow zone, each with their own recovery curve.

[124] PlanetLabs (Blackbridge) 2019 and Sentinel-2 (ArcGIS online) 2020.

Anthropogenic non-productive (NP) areas (e.g., gravel pits) on public and private land were flagged using BC Land Survey Codes in VRI and included in the tally of disturbed areas[125]. A manual satellite imagery review was necessary for many areas due to data gaps. As a result, additional NP area was added. Natural NP land (e.g., alpine, low SI stands, wetlands, etc.) were identified using BC Land Survey Codes from VRI, although these areas do not contribute to ECA as they are not disturbed. In other words, only areas presumed to be previously forested contribute to ECA.

Stand heights were estimated using 2019 LiDAR-derived 1 m x 1 m canopy height model (CHM) provided by BCTS. The LiDAR CHM was resampled to 5 m x 5 m and stands were assigned a median (50th percentile) CHM height. To model hydrologic recovery (i.e., ECA) over time, it was required that heights in 2019 be updated to the current year and then projected 50 years into the future. Based on site index, species composition, and stand age, a provincial tree growth modelling tool (i.e., SiteTools) was used to grow tree heights into the future (assuming no additional forest cover disturbance). For natural stands, the natural site index from VRI was utilized, whereas for managed stands a managed site index was generated using the BC Site Productivity data and the leading species. Roads and non-productive areas were not modelled for recovery. For stands containing deciduous species, ECAs for the deciduous portion were scaled by 25% to account for reduced interception of rain and snow by deciduous species relative to conifers. In other words, if a 20 ha stand was 20% deciduous, maximum hydrologic recovery for that stand could only be 19 ha (95% hydrologically recovered).

ECAs were compiled on a watershed-basis, using LiDAR-derived stream catchments. Streams derived from the LiDAR data were cross-referenced and refined with stream data from the Freshwater Atlas and Sunshine Coast Regional District. The drainage areas for the assessment streams were generated using GIS tools and were visually reviewed and edited to eliminate errors that often occur near roads and stream crossings. The streams and drainage areas were selectively field verified. In addition, checks were made against available stream survey information collected previously for BCTS.

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[125] These areas are considered to be disturbed indefinitely with no assumed forest recovery.

APPENDIX C: ECA PROJECTIONS

TABLE C.1 *ECA projections over the next 50-years for points-of-interest in the assessment area. ECAs are expressed as a % of drainage area and in hectares.*

Watershed Unit	POI #	POI	Drainage Area (ha)	ECA (ha)							ECA (%)						
				Projection Year							Projection Year						
				0 (2021)	5 (2026)	10 (2031)	20 (2041)	30 (2051)	40 (2061)	50 (2071)	0 (2021)	5 (2026)	10 (2031)	20 (2041)	30 (2051)	40 (2061)	50 (2071)
Roberts Creek	1	Roberts Creek at the mouth	**2,662.5**	346.9	302.2	253.6	182.5	162.4	155.8	152.8	13.0%	11.3%	9.5%	6.9%	6.1%	5.8%	5.7%
	2	Roberts Creek at BCTS Boundary	**808.2**	58.9	50.8	44.8	36.5	32.9	31.2	30.1	7.3%	6.3%	5.5%	4.5%	4.1%	3.9%	3.7%
Clack Creek	3	Clack Creek at the confluence with Roberts Creek	**1,251.4**	178.6	151.9	123.5	78.7	66.3	62.6	61.1	14.3%	12.1%	9.9%	6.3%	5.3%	5.0%	4.9%
	4	Clack Creek at BCTS Boundary	**402.5**	44.7	38.2	30.4	17.7	13.8	12.5	12.0	11.1%	9.5%	7.6%	4.4%	3.4%	3.1%	3.0%
Gough Creek	5	Gough Creek at the confluence with Clack Creek	**589.8**	98.9	84.4	66.9	37.8	30.1	27.9	27.1	16.8%	14.3%	11.3%	6.4%	5.1%	4.7%	4.6%
	6	Gough Creek at BCTS Chart Boundary	**523.6**	80.2	68.9	53.4	26.0	18.8	16.7	15.9	15.3%	13.2%	10.2%	5.0%	3.6%	3.2%	3.0%
East Roberts Creek	7	East Roberts Creek at confluence of Roberts Creek	**310.5**	46.8	40.0	30.1	15.7	12.3	11.4	11.1	15.1%	12.9%	9.7%	5.0%	4.0%	3.7%	3.6%
Stephens Creek	8	Stephens Creek at the mouth	**255.4**	32.0	29.0	26.5	23.7	22.4	21.7	21.3	12.5%	11.4%	10.4%	9.3%	8.8%	8.5%	8.3%

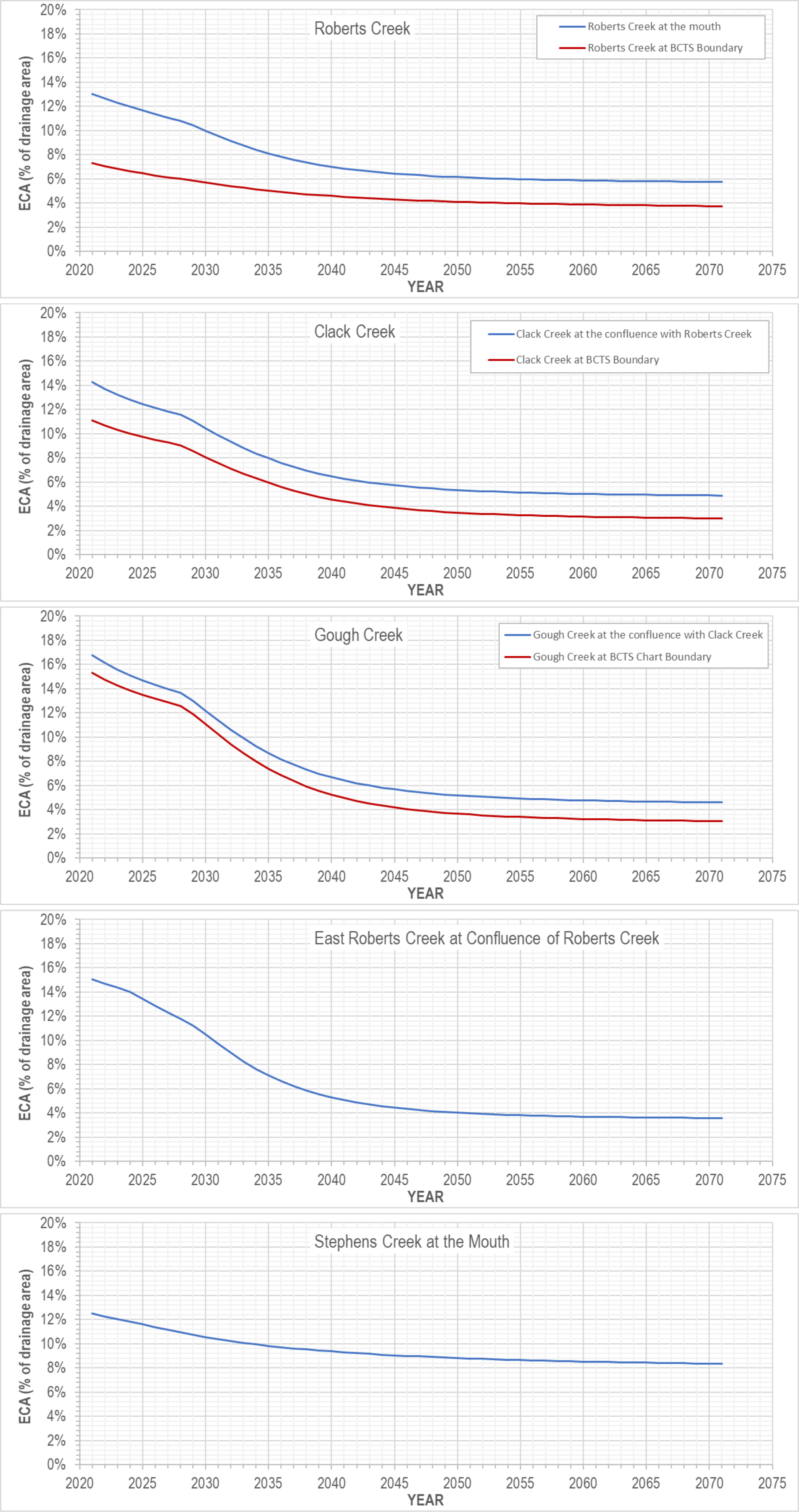

FIGURE C.1 *ECA projections over the next 50-years for points-of-interest in the assessment area. Relatively slow hydrologic recovery is noted for most of the assessment watersheds given the portion of residential and commercial area, where recovery does not occur.*