BGC

RDCK FLOODPLAIN AND STEEP CREEK STUDY

Goat River

Final
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TABLE OF REVISIONS

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EXECUTIVE SUMMARY

This report and its appendices provide a detailed flood hazard assessment of the Goat River near the Town of Creston, British Columbia. This river was chosen as a high priority clearwater hazard amongst hundreds in the Regional District of Central Kootenay (RDCK) from a risk perspective because of its comparatively high hazards and consequences from flooding. This report describes hydrological conditions and details the methods applied to create scenario and hazard maps for the Goat River. This work is the foundation for possible future quantitative risk assessments or conceptualization of mitigation measures such as potential upgrades to existing dikes.

Flood mapping is used for estimating the extent and depth of different magnitude floods for application in community planning, policy development, and emergency response planning in areas subject to flood hazards. Results from a two-dimensional (2D) hydraulic model developed for about a 11 km length of the Goat River provides potential flood inundation extents and establishes flood construction levels (FCLs) based on the 200-year return period event or annual exceedance probability (AEP) of 0.5% and includes a freeboard allowance for planning purposes.

The following types of maps were produced for the Goat River:

- Flood depth, velocity and intensity maps for the 20-, 50-, 100-, 200- and 500-year return period events
- Designated floodplain maps depicting the 200-year flood levels including a freeboard allowance 0.6 m (200-year)
- Air photo interpretation and channel change mapping.

Flood mapping developed by BGC provides an update to historical floodplain mapping previously conducted for the Goat River. Flood extents are similar to the 1984 designated floodplain maps created by the BC Ministry of Forests, Lands and Natural Resource Operations (BC MFLNRO), however, FCLs are higher due to the increased 200-year return period flood event that accounts for climate change, and the application of more advanced modelling methods. Implementation of the Goat River FCLs and community planning for development outside of high hazard areas and will lead to greater flood resiliency within the Town of Creston. Flood mapping results are also provided digitally through a BGC web application called Cambio™.

Channel change mapping conducted by BGC indicates that the Goat River channel is highly dynamic, indicating that the flood hazard assessment and modelling should be updated over time. Furthermore, the assumptions made on changes in runoff due to climate change will likely need to be updated periodically as scientific understanding evolves.

Table E-1 provides key observations derived from the hazard assessment.

Table E-1. Summary of key hazard assessment results.

Process	Key Observations
Bank erosion and channel changes	• Aerial photo interpretation and channel change mapping results indicate that the identified channel reaches have experienced bank erosion resulting in lateral migration over the reviewed period (1958-2019). The channel protection work installed in the studied area has controlled the magnitude of these changes. However, high flows have the potential to exacerbate existing erosion processes. The sections where bank erosion has the potential to continue are: 1) where shear stresses concentrate (e.g., outside of meander bends); and, 2) where the banks are unprotected and erodible.
Clearwater inundation	• In general, modelling results and predicated floodplain extents are similar to results presented in historical floodplain mapping (MFLNRO, 2016). However, flooding may still occur outside the defined floodplain boundary. • Hydraulic modelling results for Goat River indicate that the dike crest is typically greater than 0.4 m above the 200-year flood level for most of the diked reach. An exception is between Dike B and C near the location of the gravel berm where the crest is below the 200-year flood level for several hundred meters.
Hydraulic Structures (Bridges)	• The flood elevations for all scenarios modeled did not reach the low chord of the Highway 21 bridges over the North and South Channel (Drawing 01). This was verified through one-dimensional (1D) modelling. • There is approximately 1 m of clearance between the lower chord of the northern Highway 21 bridge and the 200-year return period flood. • There is greater than 1.5 m of clearance between the lower chord of the southern Highway 21 bridge and the 200-year return period flood.
Flood Protection Structures (Dikes)	• The dike crest is typically greater than 0.4 m above the 200-year flood depth for the first kilometer of the diked reach upstream (east) of Highway 21 in the North Channel. • The dikes located approximately 2 km upstream (east) of the Highway 21 bridge overtop in the 200-year return period event indicating that potential overtopping of the dikes and berm occurs under a 200-year flood on Goat River with accounting for climate change. • Some flooding occurs due to flow around dikes from flow upstream (east) of the dikes.

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1. INTRODUCTION

The Regional District of Central Kootenay (RDCK, the District) is located in a mountainous region in southeastern British Columbia (BC) that is subject to damaging floods, which have resulted in impacts to communities and infrastructure. In 2018, RDCK retained BGC Engineering Inc. (BGC) to carry out a regional geohazard risk prioritization study for the District (BGC March 31, 2019). Supported by National Disaster Mitigation Program (NDMP) Stream 1 funding, the objective of the study was to characterize and prioritize flood and steep creek (debris-flood and debris-flow) geohazards. Through the regional study, BGC identified and prioritized 427 flood and steep creek hazard areas within the RDCK, of which, six floodplains and ten steep creeks in the District were selected for further detailed assessment (Table 1-1, Figure 1-1).

Table 1-1. List of study areas.

Site Classification	Geohazard Process	Hazard Code	Jurisdiction	Name
Floodplain	Clear-water Flood	340	Village of Salmo	Salmo River
		372	Village of Slocan	Slocan River
		393	Town of Creston	Goat River
		408	RDCK Electoral Area A	Crawford Creek
		375	Electoral Area K	Burton Creek
		423	Village of Kaslo	Kaslo River
Steep Creek	Debris Flood	212	RDCK Electoral Area F	Duhamel Creek
		252	RDCK Electoral Area F	Kokanee Creek
		248	RDCK Electoral Area D	Cooper Creek
		137	RDCK Electoral Area H	Wilson Creek
		242	RDCK Electoral Area E	Harrop Creek
		95	RDCK Electoral Area K	Eagle Creek
		238	RDCK Electoral Area F	Sitkum Creek
	Hybrid Debris Flood / Debris Flow	116	RDCK Electoral Area E	Procter Creek
		251	RDCK Electoral Area E	Redfish Creek
	Debris Flow	36	RDCK Electoral Area A	Kuskonook Creek

The six clearwater hazard areas were prioritized either for development of new flood maps or modernization of existing historical flood maps. Flood maps provide information on the hazards associated with defined flood events, such as water depth, flow velocity, and the probability of occurrence. These maps are critical decision-making tools for local and regional governments to inform flood mitigation, land use planning, emergency management, and public awareness. Generally, the historical flood maps in the District are 20 years out-of-date and lack consideration of more robust hydraulic models, additional hydrological data, changes in land use such as urban development or the impacts of climate change. In response, updated floodplain mapping was conducted by BGC for each of the six prioritized clearwater hazard areas and provided under separate cover along with digital deliverables through a BGC web application called Cambio™[1].

This report details the approach used by BGC to conduct detailed floodplain mapping for the Goat River located near the Town of Creston, BC (Drawing 01). The Goat River is a major tributary to the Kootenay River and has an approximate watershed area of 1,259 km^2 that includes the Goat River Dam in the upper reaches as described in Section 2. The Goat River poses a flood hazard to properties and infrastructure constructed on the adjacent floodplain and low-gradient alluvial fan of the river. The Goat River has a long history of past damaging flood events and is extensively diked as described in Section 3.

Flood mapping developed by BGC provides an update to historical floodplain mapping conducted previously for the Goat River in 1984 (BC Ministry of Forests, Lands and Natural Resource Operations [BC MFLNRO], 2016). The historical mapping lacks a design report to document the methods and assumptions used to create the maps. A two-dimensional (2D) hydraulic modelling was developed for about a 11 km length of the river using methods described in Section 4. Modelling results described in Section 5 provide potential flood inundation extents and establishes flood construction levels (FCLs) based on the 200-year return period event or annual exceedance probability (AEP) of 0.5% and includes a freeboard allowance for planning purposes.

An outcome of the study is an improved basis for community planning, bylaw development, and emergency response planning in developed areas subject to flood hazards, with consideration of climate change. Recommendations are provided in Section 6 and include considerations for next steps from the study such as possible future quantitative risk assessments (QRAs) or conceptualization of mitigation measures such as potential upgrades to existing dikes.

BGC is providing a summary report for the entire assessment, *RDCK Floodplain and Steep Creek Study Summary Report* (referred to herein as the “Summary Report”). Readers are encouraged to read the Summary Report to obtain context about the objectives, scope of work, deliverables, and recommendations of the larger study.

[1] *www.cambiocommunities.ca.*

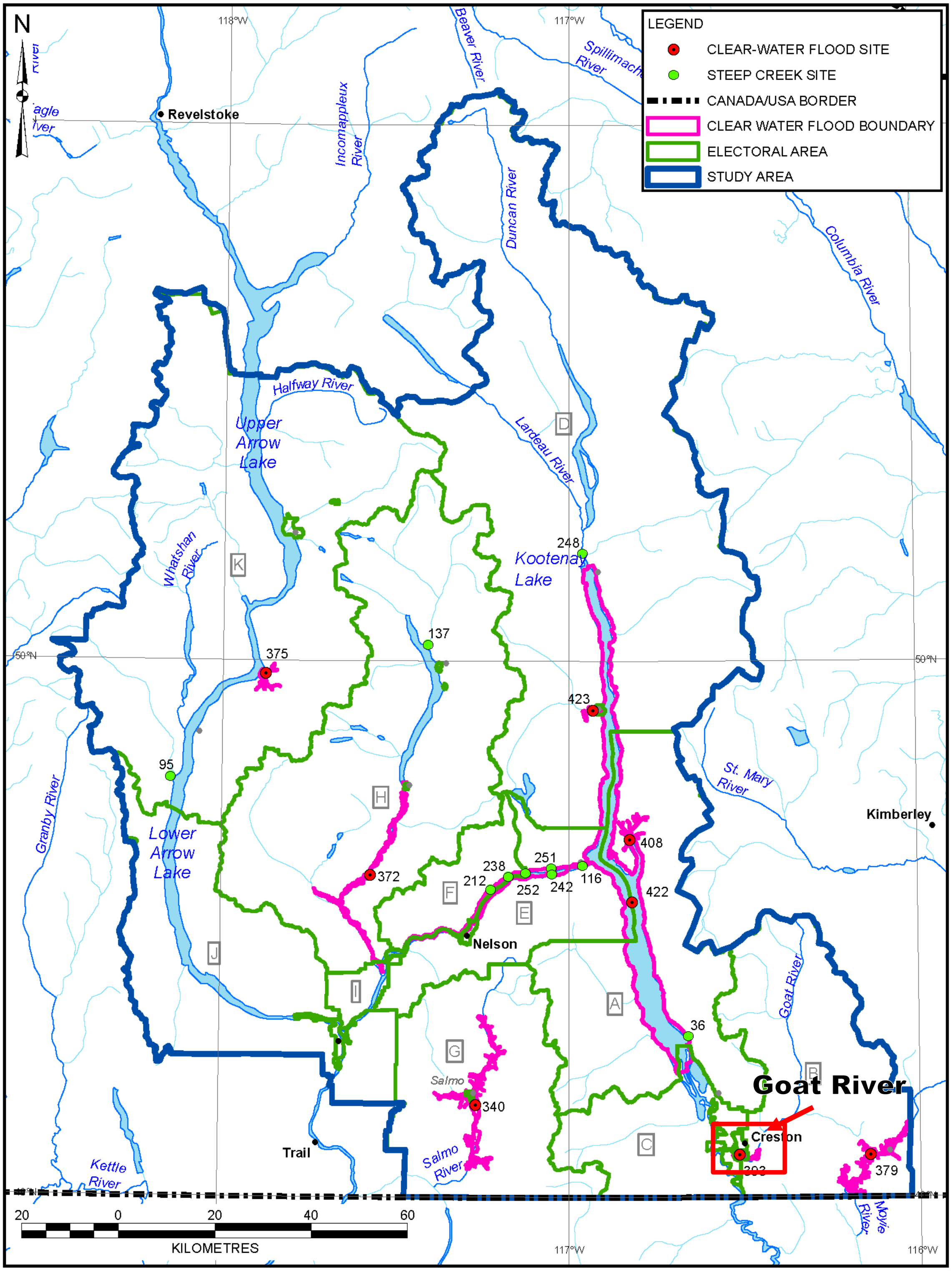

Figure 1-1. Hazard areas prioritized for detailed flood and steep creek mapping. Site labels correspond to hazard identification numbers in Cambio. Goat River (No. 393) is labelled on the figure.

1.1. Scope of Work

BGC's scope of work is outlined in the proposed work plan (BGC, May 24, 2019), which was refined to best meet RDCK's needs as the project developed (BGC, November 15, 2019). It was carried out under the terms of contract between RDCK and BGC dated June 20, 2019. The work scope was funded by Emergency Management BC (EMBC) and Public Safety Canada under Stream 2 of the NDMP.

For the Goat River, the scope of work included:

- Characterization of the study area including regional physiography and hydroclimate, and local watershed characteristics, geology and site characteristics.
- Development of a comprehensive site history of floods and mitigation activity.
- Compilation of data and baseline analyses required as inputs for flood geohazards assessment. This includes topographic and river bathymetry data collection including terrain, hydrologic, hydraulic, fluvial geomorphologic analyses and consideration of climate change impacts.
- Complete hazard mapping and assessment according to provincial and national standards including mapping of inundation areas, flow velocity, and flow depth for a spectrum of return periods. Dike and dam breach scenarios were not included.
- Integrate flood mapping results with the regional study and disseminate flood hazard mapping and data in web-accessible formats amenable to incorporation into policy and risk-informed decision making.

The study scope was informed by Engineers and Geoscientists of British Columbia (EGBC, 2018) professional practice guidelines, *Legislated Flood Assessments in a Changing Climate in BC,* and EGBC (2017) guidelines for flood map preparation. The assessment is consistent with the *Federal Floodplain Mapping Framework* (Natural Resources Canada [NRCan], 2017). Within the NRCan framework, this study provides the foundation to risk assessment and mitigation (Figure 1-2).

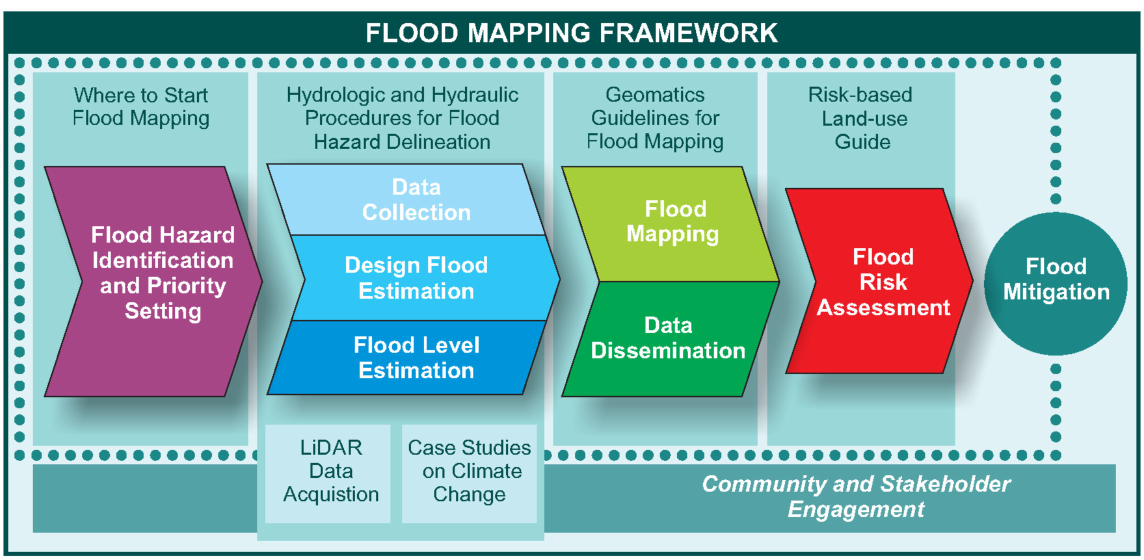

Figure 1-2. Federal flood mapping framework (NRCan, 2017).

1.2. Terminology

This assessment uses specific hazard terminology provided in Appendix A.

1.3. Deliverables

The deliverables of this study include this assessment report and digital deliverables (hazard maps) provided via the Cambio web application and as geospatial data provided to the RDCK.

This report is best read with access to a web application. Cambio displays the results of both the NDMP Stream 1 and Stream 2 studies. The application can be accessed at www.cambiocommunities.ca, using either Chrome or Firefox web browsers. The Summary Report provides a Cambio user guide.

1.4. Study Team

This study was multidisciplinary. Contributors are listed below, and primary authors and reviewers are listed in Table 1-2.

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2. STUDY AREA CHARACTERIZATION

The following section provides a characterization of the study area including physiography, hydroclimatic conditions and projected impacts of climate change, glacial history and surficial geology, as well as a description of the Goat River channel and floodplain.

2.1. Physiography

The Goat River floodplain runs east to west approximately 10 km north of the Canada / United States (US) border near the Town of Creston in the Kootenay Region of southeastern BC. The Goat River has a watershed area of 1,259 km^2 and discharges directly to the Kootenay River approximately 3 km downstream (west) of the Town of Creston (Drawing 01).

A portion of the Town of Creston is located within the floodplain of the lower reaches of the Goat River. Originating in the Moyie Range of the Purcell Mountains of the Columbia Mountain Ranges at an elevation of 2,622 m, the headwaters of the Goat River flow in a southward direction before turning west and joining the Kootenay River at an elevation of 532 m. The Kootenay River flows north from its confluence with the Goat River and discharges into the south end of Kootenay Lake, near the town of Kuskonook, BC. The lower 3.5 km of the Goat River is located in the historical floodplain of the Kootenay River (BC MFLNRO, 2016). The Goat River Dam, a 25 m concrete arch dam built in 1933 for electricity generation, is located about 6 km upstream (east) of the Town of Creston at Erickson, BC.

The Goat River watershed lies in the Columbia Mountains physiographic region. Vegetation on the lower valley slopes is characteristic of the Interior Cedar Hemlock (ICH) forests, while the upper valley slopes are dominated by Engelmann Spruce Subalpine Fir (ESSF) forests and sparse alpine vegetation (Demarchi, 2011). The Goat River watershed area has a southwest orientation with a watershed length of 60 km. The Goat River watershed boundary is presented in Drawing 02 and the physiographic parameters of the watershed are listed in Table 2-1.

Table 2-1. Watershed characteristics of Goat River.

Characteristic	Value
Watershed area (km^2)	1,259
Maximum watershed elevation (m)	2,622
Minimum watershed elevation (m)	532
Watershed relief (m)	2,090
Watershed centroid elevation (m)	1,049
Average channel gradient above the Creston Valley (%)	1.5
Average channel gradient through the Creston Valley (%)	0.3

2.2. Alluvial Fan and Floodplain Morphology

Downstream of the Goat River Dam, the Goat River is confined in a narrow canyon for 1.5 km before reaching the apex of an alluvial fan, a low-gradient cone-shaped depositional feature formed where the river becomes unconfined within a wide valley. Upstream of the fan apex, the watershed is characterized by steep bedrock-controlled slopes of the incised river valley. From the fan apex, the Goat River channel widens and flows west until the river splits into the North and South Channel, approximately 1.4 km upstream of the Creston-Rykerts Highway (Highway 21) bridges (Figure 2-1, Drawing 01). The North Channel is the larger of the two channels and at high flows it takes about two-thirds of the total flow (Klohn Crippen, 2002). In addition, the South Channel has gradually filled with sediments and receives seasonal flow (AMEC 2005). Gravel and cobble-sized sediment is transported to the alluvial fan of the Goat River, which is deposited before the river reaches the mainstem channel of the Kootenay River. Alluvial fans are laterally unstable due to the accumulation of sediments that can cause the channel to shift course quickly and deposit sediments that fill the current channel bed (channel aggradation). Deposited sediments create an obstruction to conveyance of water downstream and raise the bed above the adjacent fan surface and cause the water to find a new course.

Figure 2-1. Panoramic photograph of the Goat River upstream of the Highway 21 bridge on the North Channel looking north (July 2019).

The average bankfull width of Goat River is approximately 20 to 50 m. The active floodplain of Goat River is approximately 70 to 150 m wide with the active channel width ranging from 15 to 60 m. The creek has a sinuous, meandering channel morphology. The average channel gradient decreases from approximately 4.5% (~2.5°) at the fan apex to approximately 1.5% (~1°) near the channel outlet at Kootenay River. Historically, the channel migrated and avulsed into new locations within this reach. The active channel appears to be actively aggrading and depositing large gravel bars. Sediment sizes within the active channel range from 22 mm to 180 mm in diameter (Table 2-2). Additional site photographs are provided in Appendix B.

Table 2-2. Goat River sediment distribution from Wolman count data.

Grain Size	Goat River
Location	200 m downstream (west) of north Highway 21 bridge
Number of stones measured	109
D_{95} (mm)	127
D_{90} (mm)	116
D_{84} (mm)	105
D_{75} (mm)	90
D_{50} (mm)	64
D_{15} (mm)	40
D_{5} (mm)	33

2.3. Hydroclimatic Conditions

Large-scale airflows moving in from the Pacific bring moist, marine air to the BC Interior. The Columbia Mountains, lying perpendicular to the prevailing winds, influences the distribution of precipitation and temperatures within the Columbia River watershed. The upper watershed of the Goat River at an elevation over 2,600 m receives an annual precipitation of approximately 1,200 mm whereas the Town of Creston at an elevation of approximately 600 m receives an annual precipitation of approximately 660 mm due to the location of the town within the rain shadow of the Columbia Mountains.

Distributed across the watershed, the mean annual precipitation (MAP) is 857 mm, of which approximately 433 mm is snowfall (Table 2-3). The annual temperature in the watershed is approximately 3.2 ºC. The spatial distribution of historical average precipitation, temperature and snowfall is depicted in Figure 2-2 based on climate data from Wang et al. (2016). Generally, the climate of the Goat River is characteristic of the Columbia Mountains with warm, dry summers and rainy winters.

Table 2-3. Historical annual climate statistics for the Goat River watershed (1961 to 1990).

Variable	Mean Annual Total	Percent of total annual precipitation (%)
Temperature	3.2 ºC	-
Precipitation	857 mm	100
Precipitation as Snow	433 mm	51
Precipitation as Rainfall	424 mm	49

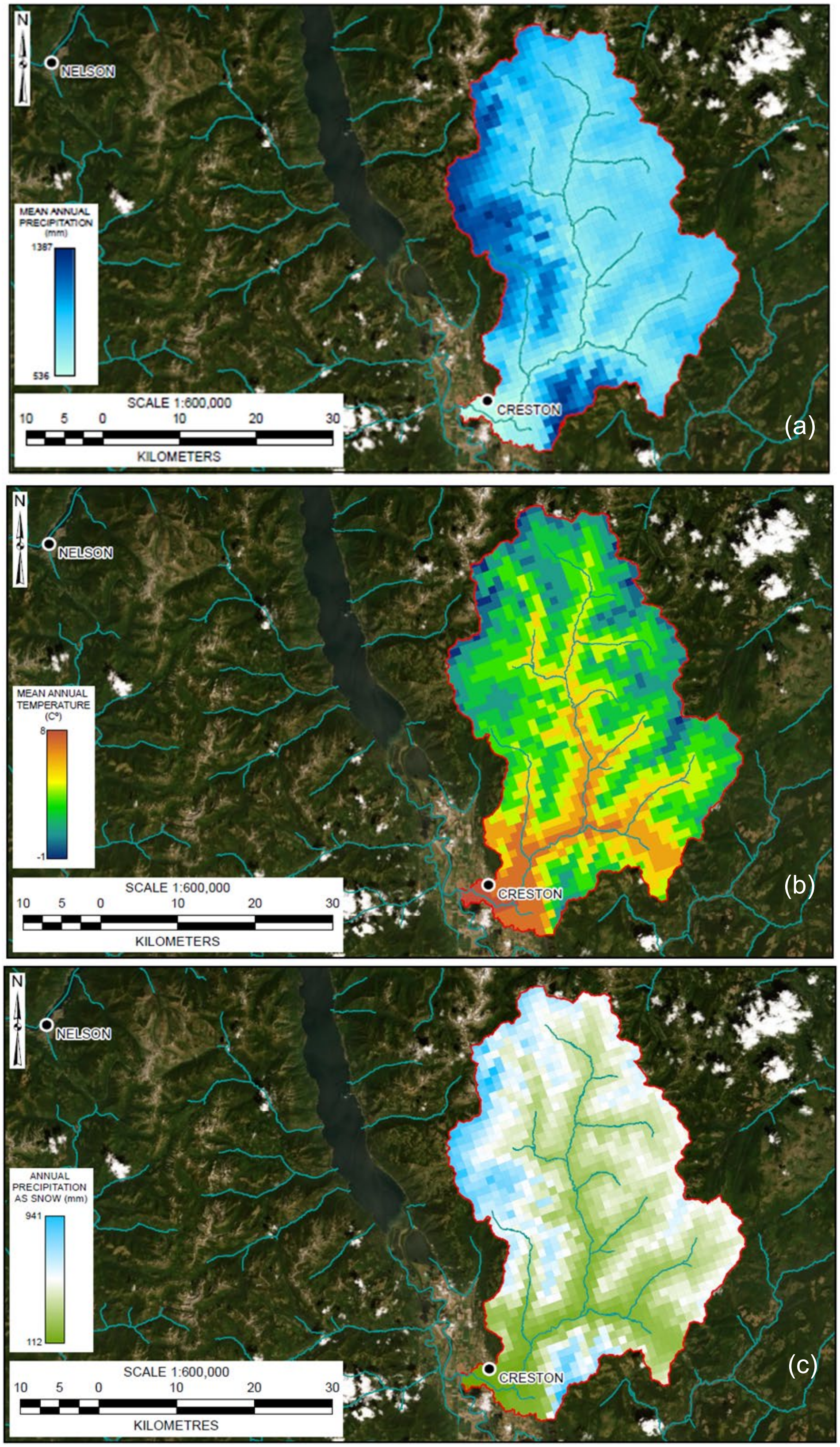


Figure 2-2. Historical (1961 to 1990) mean annual precipitation (MAP) (a), mean annual temperature (MAT) (b), and precipitation as snow (PAS) (c) averaged over the Goat River watershed.

The Goat River was gauged at a hydrometric station from 1915 to 1995. The hydrometric station *Goat River near Erickson* (08NH004) was located 10 km upstream from the confluence with the Kootenay River near Erickson, BC. The Goat River Dam is located approximately 1 km upstream from the hydrometric station. The annual maximum peak instantaneous streamflow measured at the 08NH004 gauge is shown in Figure 2-3. The timing of peak discharge generally occurs in late May to early June corresponding with snowmelt.

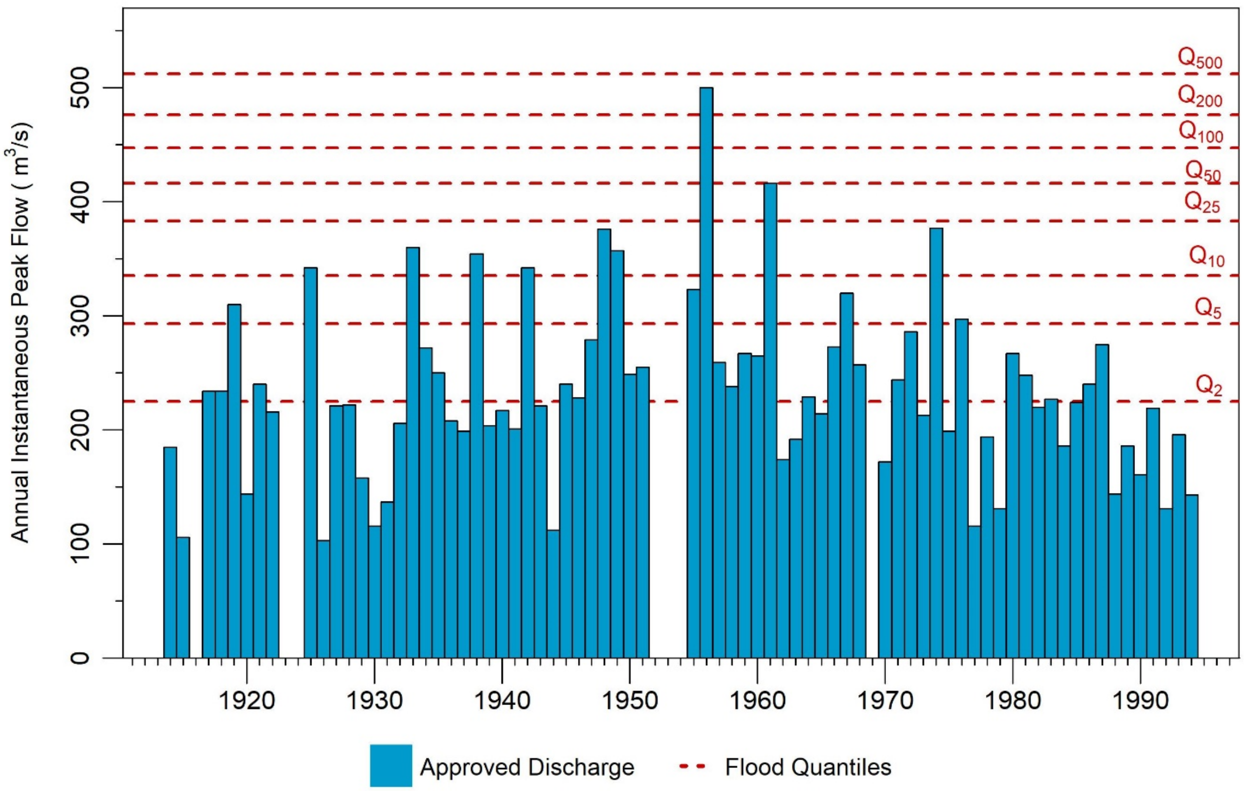


Figure 2-3. Annual maximum peak instantaneous discharge at Goat River near Erickson (08NH004).

Water levels in the Kootenay River, downstream of the Goat River, are regulated by the Libby Dam in Montana, US. Operational since 1972, the Libby Dam has resulted in decreased peak discharge and water levels on the downstream reaches of the Kootenay River. The Duncan Dam, which was completed in 1967, affects Kootenay Lake levels, which in turn affect the lower Kootenay River levels. Kootenay River water levels have an impact on the water surface elevation within the Goat River through a backwater effect.

2.4. Climate Change Impacts

The mean annual temperature in the Goat River watershed is projected to increase from 3.5°C (based on historical period 1961 to 1990) to 6.7ºC by 2050 (based on period 2041 to 2070) assuming the representative carbon pathway 8.5 (RCP 8.5). Annual precipitation is projected to increase to 879 mm while the component as snow is projected to decrease to 282 mm by 2050 in the Goat River watershed. Projected change in climate variables from historical conditions for the Goat River watershed are presented in Table 2-4.

Extreme flood events in the Montane Cordillera are often associated with rain-on-snow events in the spring (Harder et al., 2015). Although the effects of climate change on precipitation are not clear, projected increases in temperature are expected to have the largest impact on annual minimum temperatures occurring in the winter months (Harder et al., 2015). The effects of temperature change differ throughout the region. High elevation regions throughout parts of the Montane Cordillera (e.g., Upper Columbia watershed) are projected to experience increases in snowpack, limiting the response in high elevation watersheds while lower elevations are projected to experience a decrease in snow water equivalent (Loukas & Quick, 1999; Schnorbus et al., 2014).

Changes in streamflow vary spatially and seasonally based on snow and precipitation changes and topography-based temperature gradients. Researchers anticipate that streamflow will increase in the winter and spring in this region due to earlier snowmelt and more frequent rain-on-snow events, while earlier onset of peak discharge is expected in many rivers (Schnorbus et al., 2014; Farjad et al., 2016).

Table 2-4. Projected change (RCP 8.5, 2050) from historical conditions (1961 to 1990) for the Goat River watershed.

Climate Variable	Projected Change
Mean Annual Temperature	+3.5 ºC
Mean Annual Precipitation	+40 mm
Precipitation as Snow	-151 mm

2.5. Glacial History and Surficial Geology

The Creston Valley has been significantly altered in the recent geologic past by repeated advances and retreats of continental glaciers. As the glaciers retreated during the last glacial period, an ice dam blocked the outlet at the West Arm of Kootenay Lake. The dam formed glacial Kootenay Lake, the waters of which backed all the way to Libby, Montana, US. Formation of this glacial lake resulted in the deposition of lacustrine sediments (predominantly clays, silts and sands) throughout the valley bottom. The Kootenay River and tributaries such as the Goat River have extensively reworked these sediments to the extent that there is little surficial evidence of this ancestral valley floor. An exception is a terrace of lacustrine sediments on the east side of the valley that is approximately 50 m above the current Kootenay River floodplain. This benchland forms an important component of the agricultural base for the Town of Creston.

3. SITE HISTORY

3.1. Area Development

Prior to European arrival, the Creston Valley was part of the traditional territory of the Kutenai, a hunting and fishing people who formed the Ktunaxa First Nation. A portion of the floodplain of the lower Goat River has been progressively developed for agriculture, residential and commercial development over the last century. The first subdivision of the Creston Valley was made in 1909 and reclamation of the Creston Diking District started in 1934. The reclamation program included cutting a channel through the east bank of the Kootenay River in order to redirect the Goat River west directly into the Kootenay River (Figure 3-1). Prior to development, the lower Goat River channel flowed parallel to the Kootenay River before discharging into Duck Lake creating an inter-connected wetland ecosystem (Figure 3-2). The entrance to the old Goat River channel was blocked off with a dike however the historical channel still conveys some flow. Wetland management also occurs on the lands of the Lower Kootenay Band (LKB) to the south of the lower Goat River through the maintenance of dikes (Drawing 01).

Figure 3-1. 1935 dredging activities at mouth of Goat River.

In 1933, the West Kootenay Power and Light Company built the Goat River Dam. The power plant operated as a run-of-the-river facility until 1951 when it was shut down for economic reasons. The dam has been reported as being completely filled by sediment within 15 years after construction. It was restarted in 1991 by the Cascade Pacific Power Corporation (Klohn Crippen, 2002).

Today the Town of Creston is a business center for the Creston Valley and has a population of over 5,200 people according to the 2016 census (Statistics Canada, 2016). The estimated total improvement value of parcels intersecting the Goat River hazard area based on the 2018 BC Assessment Data is $17,838,600 (BGC, March 31, 2019). The economy is largely resource-based with agriculture and forestry the primary industries.

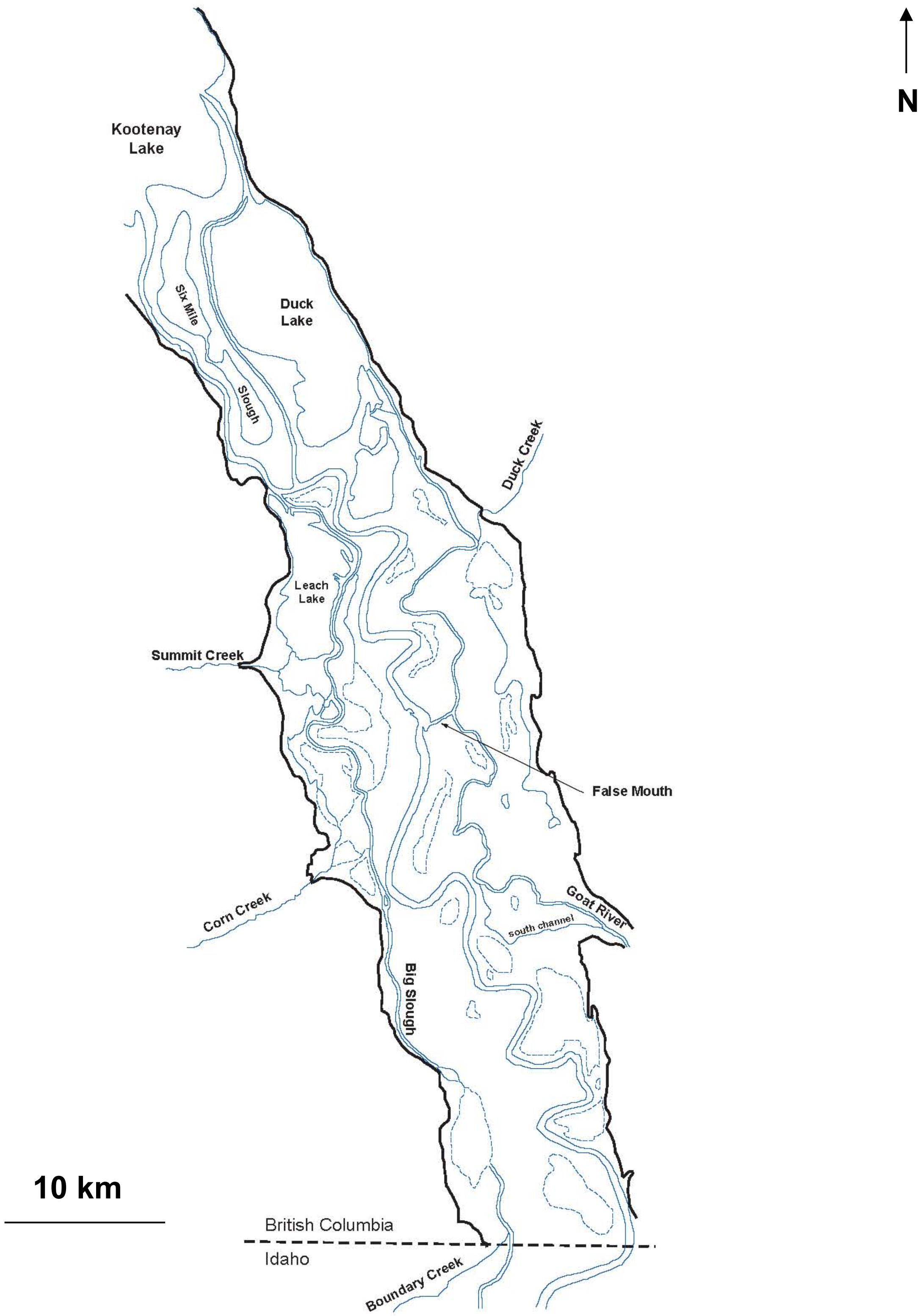


Figure 3-2. Kootenay River and lower Goat River 1890's (from BGC, April 8, 2014).

3.2. Historical Flood Events

The Goat River has overtopped its banks on numerous occasions since the founding of the Town of Creston in the 1930s, prompting the construction of an extensive diking system through the Creston Valley as described in Section 3.3. Construction of the main dikes commenced in the early 1930's, with significant damage incurred in both 1933 and 1948 during major freshet floods. Significant reconstruction of the diking system occurred after 1948 and ongoing annual maintenance has been required since extension of the dikes in 2006 and 2007. Figure 3-3 shows overtopping of the Goat River Dam during the 1933 flood event.

The years with the largest floods on the Goat River occurred in 1894, 1933, 1948 and 2012 as documented in BGC (March 31, 2019). The flood of 1894 is considered to be the largest flood on record in the Fraser and Columbia basins. The 1894 flood is estimated to have a return period inflow of approximately 500 years at the Fraser River at Hope, BC and is the design event for the lower Fraser River (NHC, October 2008a). The same event is estimated at an approximately 200-year event in the Kootenay Region. The 1933, 1948, 1956 are estimated as 50 to 100-year events and the recent event of 2012 is estimated as a 20-year flood event based on historical flow data.

The provincial floodplain mapping program began in BC in 1974 aimed at identifying flood risk areas. This was in part due to the large Fraser River flood of 1972, which resulted in damage in the BC Interior. From 1975 to 2003, the province managed development in designated floodplain areas under the Floodplain Development Control Program. In 2003, the Program ended resulting in a significant change in how MFLNRO participated in land use regulation in flood-prone areas. The responsibility for developing and applying floodplain mapping tools was transferred to local governments, with the requirement that provincial guidelines be taken into consideration (EGBC, 2017). Figure 3-4 provides a timeline summary of floods and mitigation history for Goat River. The historical event inventory is based upon a variety of sources including newspaper articles, government records and consulting reports. Some sources may not be completely accurate or only provide partial records of flood events but are provided to present an overview of events.

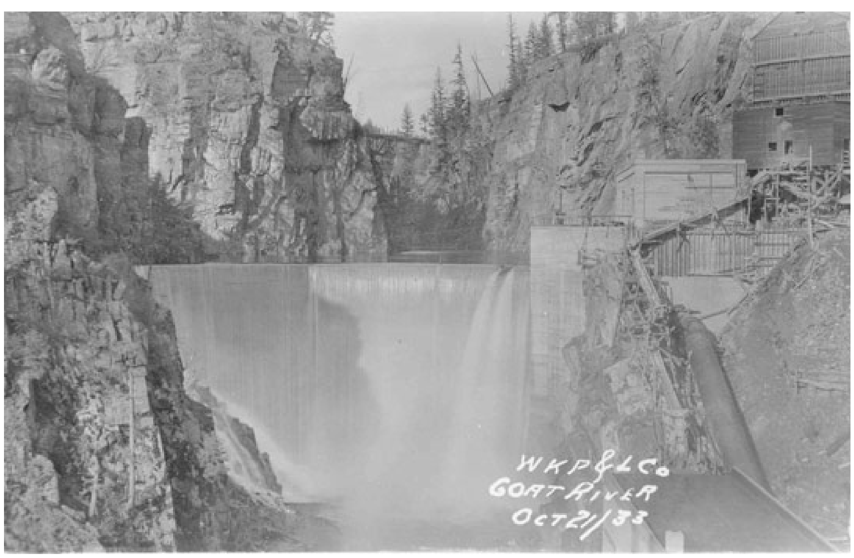
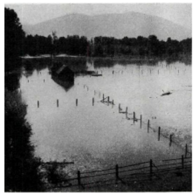


Figure 3-3. Water overflowing the top of the concrete arc dam of the Goat River Dam near Erickson BC in October 1933 (source: Fortis BC Archives).

Flood History



Damage to property caused by spring flood of Goat River, May 21, 1956 (BC Lands and Forests)

Water flooded the old Goat River Channel from the north side of the diversion, 1948 (Creston Museum)

Goat River flooding, 1938 (Creston Museum)

Goat River diversion project, 1935 (Creston Museum)

Flood (major flood)
Landslide
Mitigation
Development event

January 2017 - Ice jam led to localized flooding in Creston

June 2012 - Heavy rain and snowmelt led to flooding of the Goat River and damage to the Highway 21 bridge; local state of emergency declared

March - May 1999 - Snowmelt saturated fills and triggered shoulder failure 3 km east of the intersection of North Goat Road and Highway 3, Creston; failure was approximately 25 m long and 2 m from edge of shoulder, threatening properties below the slide

June 17, 1974 - Rising temperatures melted high-elevation snowpack causing Goat River to over-top its banks

May 1961 - Flooding washed out bridge; water levels were up to 7.6 m

June 1960 - Flooding of the Goat River near Creston

May 20, 1956 - Goat River flooded; peak flow measured 365 m^3/s; bridge washed out, 80 ha of land inundated and evacuations enforced; water levels indicated as higher than the 1948 flood with a peak of 7.65 m measured on the Creston Ferry gauge; military aid requested to reinforce sand-bagging on the dikes

1955 - Spring flooding damaged bridge over Goat River

June 12, 1948 - Flooding along the Goat River; gauge at Creston Ferry read 7.19 m (3.65 m higher than average land elevation behind the dikes)

June 1938 - Floodwaters broke through dikes and flooded 5,870 ha of land

June 1933 - Sudden rise of Goat River flooded Creston Flats

September 28, 1927 - Heavy autumn rains caused flooding in an overflow of Goat River putting the south end underwater

May 1925 - Flood over-topped the Goat River Canyon dam causing damage to the Continental Lumber Company sawmill, downstream bridges and roads

May 16, 1921 - Goat River flooded road near Creston

June 1913 - Flooding on Goat River caused property damage due to rapid snowmelt; flood levels reached close to high water mark

June 1894 - High snowfall levels and rapid melting coupled with heavy rainfall led to flooding in the Creston Valley; newly constructed dikes destroyed

Mitigation

January 2017 - Ice jam removed by excavators

March - May 1999 - Slope failure restoration work included water diversion, slope reconstruction, and slope monitor installation

May 1961 - Dike construction undertaken along Goat River

1956 - Temporary pile trestle constructed over White Channel of Goat River replacing structure damaged during spring flooding

1955 - Goat River No. 2 bridge repaired following flooding

1934-1935 - Goat River dredged with a drag line to dig a 45 x 9 m channel to provide a diversion of Goat River into the Kootenay River

September 1934 - Kootenay Flats lands diking project undertaken by the Creston Dyking Company Ltd.; Goat River diverted into the Kootenay River through channel construction

October 1933 - West Kootenay Power & Light Co. hydro dam completed at Goat River canyon, 6 km from Creston, providing electric light and power to Creston Valley residents

August 1921 - Public Works surveyors took steps to locate permanent channel for the Goat River above and below abandoned railway bed, attempting to control river at the site of new bridge construction

1892-1893 - The Alberta-British Columbia Exploration Company constructed dikes at the southern end of the Creston Valley

Development

1968 - The Creston Valley Wildlife Management Area established, covering 7,000 ha of land

1966 - Creston incorporated as a town

1963 - Salmo-Creston highway opened

1947 - BC Southern Transprovincial Highway established, passing through Creston Valley

August 1935 - Bridge constructed over Goat River just south of Creston on the north and south highway

March 1927 - Bridge constructed across the Goat River 16 km east of Creston

August 1926 - Bridge constructed over the Goat River 19 km east of Creston

May 1924 - Community of Creston incorporated as a village

March 1922 - Goat River Mission Road Bridge built on abandoned railway right of way

1919-1920 - Construction started on 46 m No. 3 wooden truss bridge on concrete piers across the Goat River at Erickson

1908 - Thousands of hectares of farmland in the Creston Valley offered for sale by the provincial government

1905 - Sawmill established in Erickson

1899 - First plan of Creston townsite recorded and name "Creston" is adopted

1898 - Sawmill established just east of CPR station in Creston

1898 - CPR built railway line into the Creston Valley alongside Goat River

Figure 3-4. Summary of recorded flood history, mitigation, and development history at the Goat River.

3.3. Flood Protection and Hydraulic Structures

3.3.1. Bridges

Two Highway 21 bridges cross the Goat River at both the North and South Channels approximately 1 km upstream (east) from the confluence with the Kootenay River (Drawing 02). The dimensions of the north and south Highway 21 bridges (Figure 3-5 and Figure 3-6), as measured by Explore are presented in Table 3-1.

Figure 3-5. View from downstream of the Highway 21 bridge over the main (north) channel of the Goat River looking upstream (east). Photo: BGC, July 3, 2019.

Figure 3-6. View from upstream of the Highway 21 bridge looking downstream (west) at the dry secondary (south) channel of the Goat River. Photo: BGC, July 3, 2019.

Table 3-1. Bridge dimensions surveyed by Explore Survey Inc., July 2019.

Bridge	Top Deck Elevation (m)	Bottom Deck Elevation (m)	Pier Thickness (m)	Number of Piers	Shape of Piers	Deck Span (m)	Deck Width (m)
Highway 21 north	542.8	540.5	0.8	3	Rectangular Concrete	73.6	12.2
Highway 21 south	544.0	542.7	0.7	2	Rectangular Concrete	34.9	13.3[1]

Note:
1. Value measured from Google Earth by BGC, February 12, 2020.

3.3.2. Dikes

Approximately 3.8 km of dikes have been constructed on both banks of the Goat River, which are managed and maintained by the Goat River Residents Association (GRRA). Material used to construct the dikes consisted of fine-grained sands and silts either dredged from the river with a drag-line or scraped from the adjacent floodplain. The original dikes are typically 5 to 6 m high with a 4 m crest width and 2H:1V sideslopes (BGC April 8, 2014). Erosion repairs to the Goat River dikes were made in 2006 (Klohn Crippen, January 12, 2006).

Two additional dikes, referred to as the Long Dike (3.1 km) and Short Dike (1.3 km), are located adjacent to the South Channel of the lower Goat River (Drawing 03), but are not listed in the provincial flood protection structure database (BC MFLNRO, 2017). These two dikes protect a further 900 ha of reserve land and are primary used for wetland management and also provide flood protection from the Kootenay and Goat Rivers.

Originally three discontinuous dikes with a total length of 2.5 km were constructed on the north side of the Goat River including Dike A (1540 m), Dike B (55 m) and Dike C (370 m). Previous AMEC Earth & Environmental (AMEC) reports indicate that Dikes B and C are not a continuous section of dike and there is an approximately 370 m gap between the two dikes that is an existing gravel berm (AMEC 2005; 2007). The GRRA contracted AMEC to design the following dike improvements because the original dike sections were not continuous and also repairs were need to existing dikes that had sustained bank erosion:

- General repairs of Dikes A and C (including replacement of riprap)
- Extension of Dike B to Dike A
- Extension of Dike C to tie into high ground.

Approximately 1.3 km of new dikes were constructed in 2006 and 2007. The top-of-dike elevation for the new dikes were designed to the 200-year event plus freeboard based on the 1984 floodplain mapping (BC MFLNRO 2016). If the new dikes occurred adjacent to an existing dike with a crest height greater than the 200-year flood level, the new dike was built to that height. Dike were designed using granular fill and 800 mm Class II riprap placed over bedding gravel. The dike extensions were typically 4 m wide at the crest with 2.5H:1V side-slopes. Drawing 03 and Figure 3-7 provides a summary of existing flood protection structures on the lower Goat River.

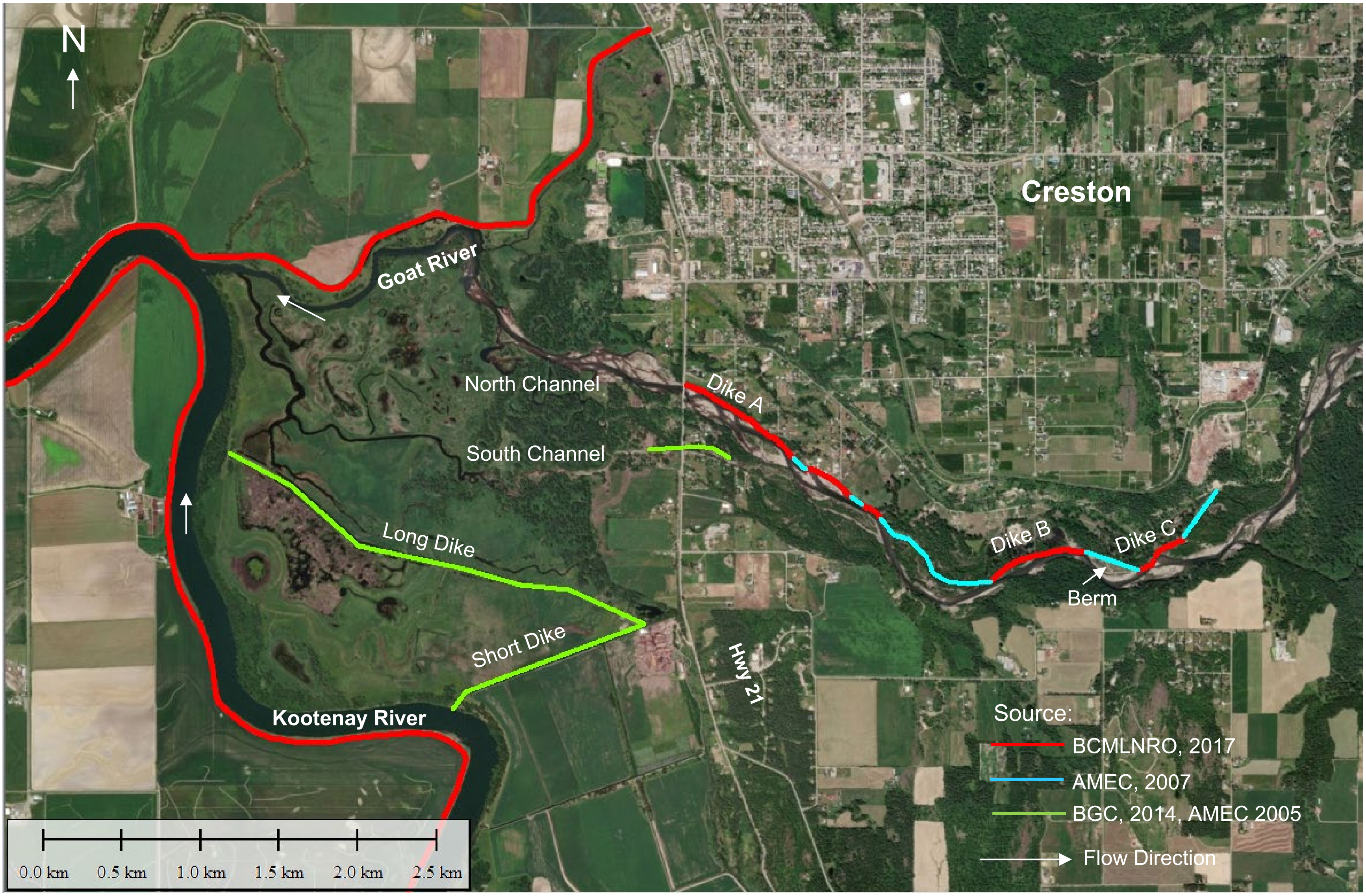


Figure 3-7. Summary of dike and flood protection structures on the Goat River. Line sections in red are in the provincial flood protection structure database (BC MFLNRO, 2017). Line sections in green are existing flood protection structures that are indicated in AMEC (2005) and BGC (April 8, 2014). Line sections in blue are dike extensions designed by AMEC in 2007.

3.4. Previous Mitigations

Gravel removals were routinely conducted on the Goat River in an attempt to reduce the amount of erosion to the channel banks, eliminate sediment accumulated upstream of the highway bridge piers, and reduce flood risks, as described in BC Department of Lands, Forests and Water Resources (June 6, 1975):

> *"The Regional Engineer has initiated a channel clearing scheme in the Goat River to ensure that the river channel is cleared of the previous years deposit of gravel in time for the freshet flows."*

In 1975, 1.8 m (6 ft) of gravel had deposited in the channel during the flood of 1974, which was removed prior to the 1975 freshet. Brown (1987) indicated that approximately 40,000 m^3 was excavated from the bars of the river and from lands behind some of the dikes during the removal program. Gravel removal was carried out from 1948 until 1985, after which licences were no longer granted due to concerns centered on the adverse impacts to fish habitat.

In 1999, the BC Ministry of Transportation and Highways (MoTH) initiated the design of instream works to prevent channel scour from undercutting the highway embankment on the north bridge (referred to as the Creston-Porthill Bridge No. 0944; MoTH 1999). Klohn Crippen (2002) indicated that bank protection works were permitted on the condition that fish habitat structures and large woody debris (LWD) was incorporated into the design. Conducted between 1999 to 2000, approximately 40 m of riprap was placed, and root wads were incorporated into the design to provide fish habitat and lessen flow velocities against the riprap. In addition, five log deflectors and 25 m of whole tree revetments were constructed. These structures have failed since installation (D. Boyer, pers.comm).

3.5. Bank Erosion and Avulsion History

Channel migration controlled by bank erosion is a typical process in rivers. This process may occur either as gradual erosion at the outside of river bends, or as sudden widening of the river during floods. Gradual bank erosion occurs as material is eroded of the outer bank of a meander bend and is deposited (as a point bar) inside of the meander bend (Charlton, 2007). On its alluvial fan, the Goat River has migrated as a result of both natural processes, and as a response to changes in land use. AMEC (2005) analyzed historic air photos of the Lower Goat River, and discussed changes in the channel morphology that occurred over four time periods:

<u>1900s to early 1930s</u>

Throughout this period, the Lower Goat River remained in a relatively natural condition. On 1929 air photos, the North Channel has a meandering planform upstream of the bridge crossings, which were in place by this time. Further downstream on the Kootenay River floodplain, several distributary channels are evident. Some of these channels are groundwater-fed, as there is no direct connection to the main channels. The North Channel was the dominant channel during this period, as it is today.

Mid 1930s to Late 1950s

It was during this period that the Goat River incurred the most significant changes. Human impacts included:

- Diversion of the Goat River into its present-day course into the Kootenay River and closure of the Old Goat River by diking.
- Agricultural development of the Goat River floodplain, which included the clearing of riparian vegetation and instream LWD.
- Construction of the Goat River Dam near Erickson, BC.
- Excessive gravel removals from the North Channel occurred upstream of the highway bridge that resulted in excessive widening and straightening of the Goat River. A comparison of air photos from 1929 and 1946 clearly show the impacts of these instream channel works. It is possible that due to these works, the South Channel experienced a reduction in discharge relative to historic levels.

Early 1960s to Late 1980s

According to Brown (1987), the majority of dikes and river engineering works were conducted during this period. These works have changed the river from a more braided morphology (a number of wide and shallow channels) into a channel that is straighter, more incised, and with a narrower meander width. That is, the channel is less prone to lateral instability. Gravel removals would also have contributed to this change in morphology.

During this period, the flow distribution between the North Channel and South Channel was managed through gravel removals and movement of gravel in the vicinity of the channel bifurcation. The intent of these works was to increase the portion of flow conveyed by the South Channel. Flow management was so extreme that AMEC (2005) noted that most of the flow appeared to be in the South Channel on 1988 air photos. During this period, discharge in the South Channel was likely higher than historic levels.

Finally, AMEC noted that three main tributaries of the South Channel are evident on the 1956, 1972, and 1981 air photos. However, the 1988 air photo shows that the tributaries were blocked off by diking.

1990 to Present

Due to fisheries concerns, gravel removals and management of the flow distribution have not occurred since the late 1980s. Since that time, the South Channel has progressively infilled with sediment and typically only receives flow during periods of high runoff such as the spring freshet. A structure to control flows in the South Channel is in consideration to improve fish habitat downstream. According to AMEC (2005), the impacts of diking and river engineering works are evident in the 1990 and 2000 air photos: the channel is straighter, more incised and with a narrower meander width.

4. METHODS

This section summarizes the assessment methodology applied to at the Goat River. Additional details on the methodology applied are summarized in Appendices C, D, and E.

4.1. Field Data, Topographic Data and River Bathymetric Surveys

4.1.1. Fieldwork and Site Investigations

Fieldwork on Goat River was conducted from July 2 to 5, 2019 and on July 31, 2019 by BGC personnel (Elisa Scordo, P.Geo., Marc Oliver Trottier, P.Eng., and Rob Millar, P.Geo., P.Eng.). Field work included measurement of grain size diameters (Wolman sampling) to characterize the grain size distribution of in-channel materials, and observations at bridge and other infrastructure crossing locations and flood protection structures (e.g., dikes, riprap armouring). Field work was conducted to coordinate the survey extent and data collection with the survey crews.

4.1.2. Topographic Mapping

Detailed topographic data of the floodplain were available from a classified high-resolution lidar dataset obtained from RDCK and flown in August 2018. BGC was provided with tiles containing the classified point cloud and a 1 m bare-earth Digital Elevation Model (DEM). Lidar coverage provided by RDCK for the entire study area is shown in Figure 4-1.

The lidar data were provided with the following coordinate system:

- Horizontal Datum: NAD83 CSRS
- Projection: UTM Zone 11 North
- Vertical Datum: CGVD 2013
- Geoid Model: CGG2013.

As part of the lidar acquisition, orthophotos were not collected. As a result, the classification of the raw lidar point cloud contained inaccuracies particularly around gravel bars and the location of the river shoreline. In order to account for this, BGC collected additional ground and bathymetric survey data to capture in-channel features that were not classified in the lidar survey.

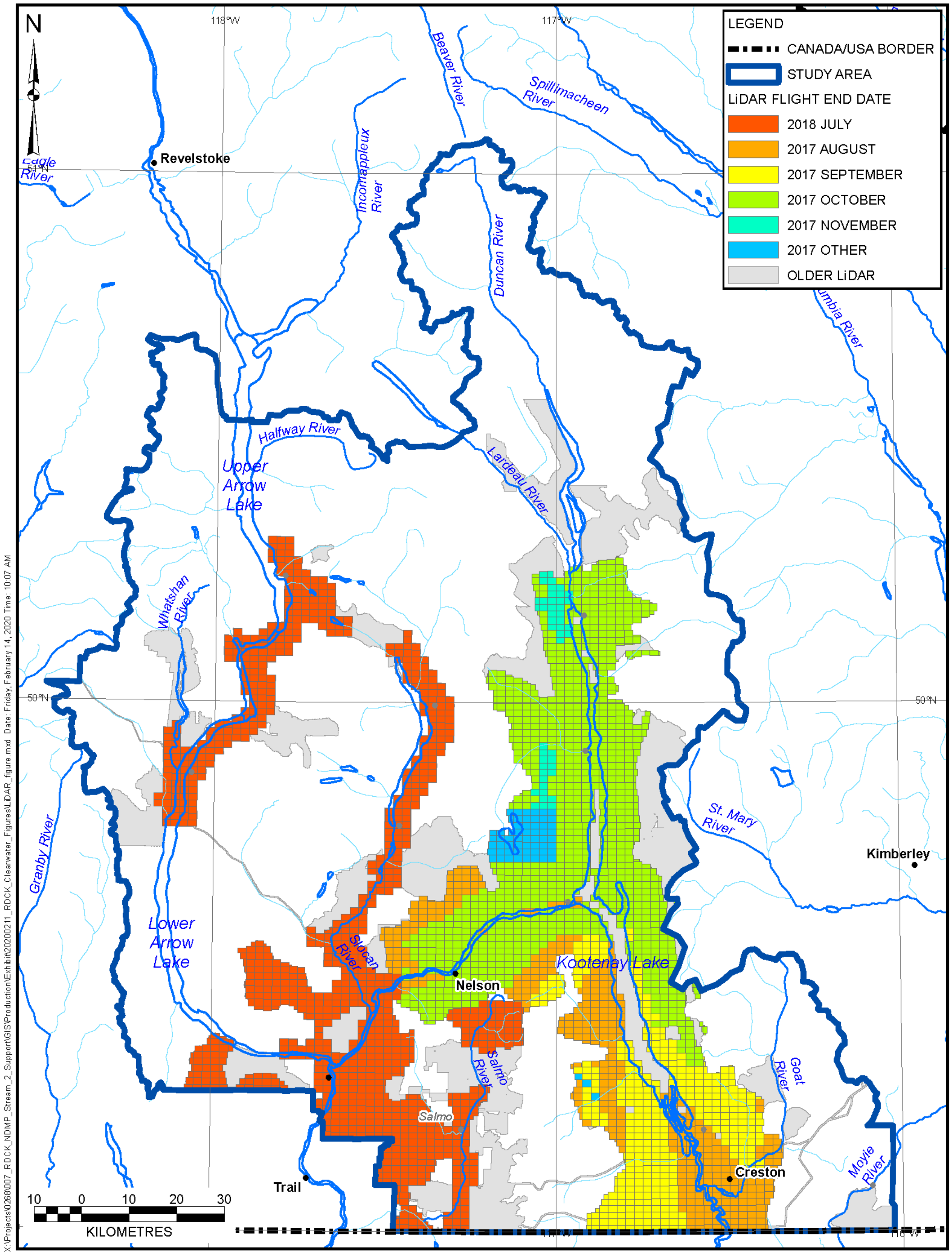


Figure 4-1. Lidar coverage for clearwater flood study sites.

4.1.3. Ground and Bathymetric Surveying

BGC contracted Explore Surveys Inc. (Explore) to conduct a detailed survey of the Goat River and the confluence of the Kootenay River (Drawing 03). The scope of work included surveying of the channel bed, bridges, and dikes. A combination of Static Global Navigation Satellite System (GNSS) techniques, real-time kinematic (RTK) and real-time network (RTN) techniques were used to establish a precise, reliable Survey Control Network (SCN) for the length of the project. The SCN was integrated with existing BC Survey Control and/or the Canadian Base Network. The survey data were provided in the 3TM NAD 83 (CSRS) UTM 11 North coordinate system with elevation in the CGVD2013 Vertical Datum.

The survey was conducted from July 4 to 31, 2019. The survey covered approximately 11 km of the Goat River and 2.7 km of the Kootenay River. Surveying of the channels was completed using GNSS RTK GPS. Bathymetric survey in the Kootenay River was completed using a Single Beam echosounder (sonar) from a boat. Drawing 03 provides a summary of locations collected using survey and sonar techniques. Bathymetric data were collected at an average spacing of 2 to 5 m along cross-section profiles extending from bank to bank. Cross-sections were spaced every 10 to 20 m and perpendicular to the shoreline. Sonar data were collected along continuous transects collected at a density of 5 to 10 m.

The south and north bridges along Highway 21 were surveyed to collect details such as the length of the span, width of the bridge, top of curb elevation, bottom of deck (lower chord) elevation and width of piers as shown on Figure 4-2. A total of 2 km of dikes along the north bank were also surveyed including the crest elevation and length, type and general condition of the dike.

Figure 4-2. Example of bridge structure features collected during the Goat River survey.

During the ground and bathymetric survey, a significant shift in the channel geometry between the collection of the lidar (2018) and the collection of the bathymetric survey (2019) was identified (Figure 4-3). The change was most significant downstream of the Highway 21 north bridge where the channel had migrated by over 50 m north in one location. From a review of near-by hydrometric gauges, it appears that the region may have experienced a 2-year to 5-year return period event between the lidar and survey data collection time periods. Ground and bathymetric surveying was used to update topography within these areas.

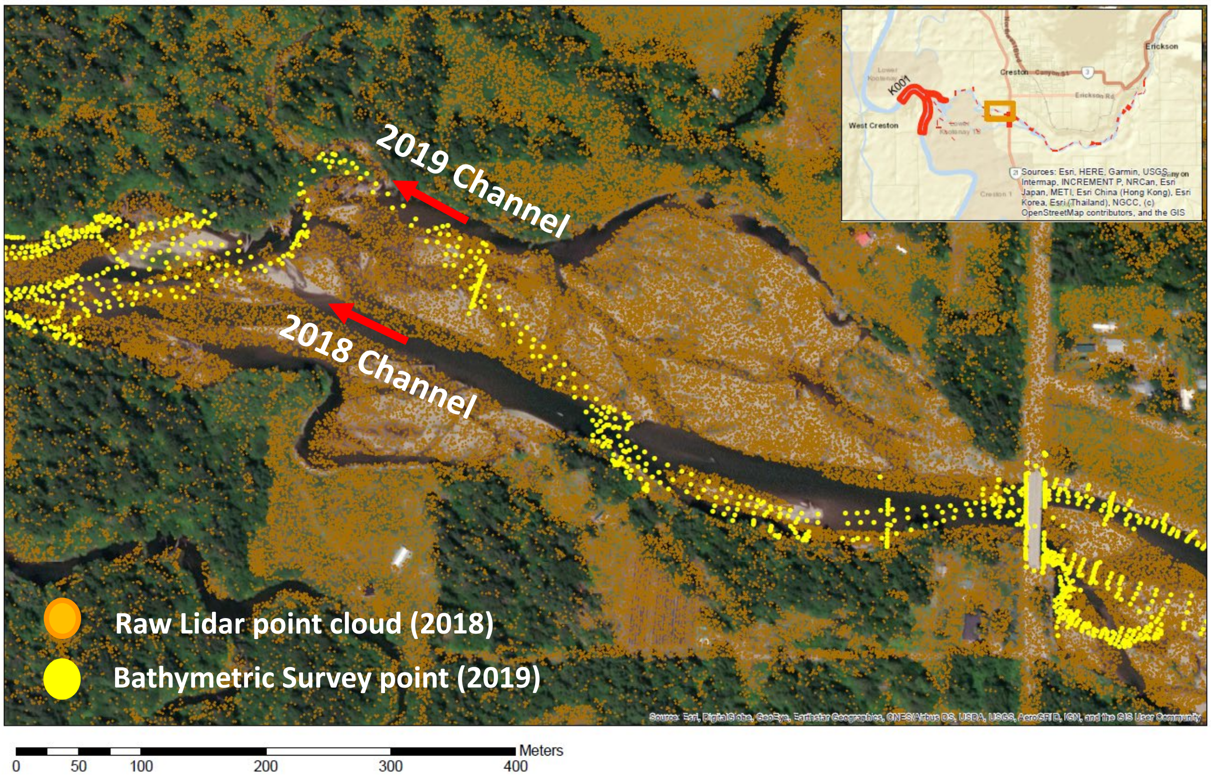


Figure 4-3. Comparison of 2018 raw lidar point cloud (orange) to 2019 ground and bathymetric survey data (yellow) collected during the Goat River survey in 2019 due to an approximately 50 m shift in the main channel since lidar acquisition.

4.1.4. Survey Equipment, Accuracy and Processing Software

Table 4-1 provides a list of survey equipment and the reported accuracy. Hypack 2018 Hydrographic Software was used to correlate global position system (GPS) and hydrographic data together.

Table 4-1. Summary of survey equipment.

Equipment Type	Reported Accuracy
GPS	
Trimble R10 GNSS Trimble R8 GNSS Trimble R6 GNSS	• Single Baseline: <30 km • Horizontal: 8 mm + 1 ppm RMS • Vertical: 15 mm + 1 ppm RMS • Horizontal: 3 mm + 0.1 ppm RMS • Vertical: 3.5 mm + 0.4 ppm RMS
Total Station	
Trimble SX10 Robotic Scanning Total Station	• Angular Accuracy: +/- 1" (0.3 mgon) • EDM Range: 1 m – 5,500 m to single prism • Scanning EDM Range: 1 m – 800 m • Distance Accuracy: 1 mm + 1.5 ppm • Distance Accuracy Scanning: 2 mm + 1.5 ppm
Hydrographic Equipment	
CEESCOPE Hydrographic System	• Depth Range: 0.20 m to 200 m • Accuracy (Corrected for Sound Velocity): 0.01 m +/-0.1 % depth

4.1.5. Terrain Creation

Following completion of the survey, BGC integrated the bathymetry data with the lidar bare-earth DEM to generate a continuous terrain model for use in hydraulic modelling. The process to generate the terrain model from the topographic modelling and the bathymetric survey was as follows:

1. Elevation contours were generated along the banks of the surveyed channels from the ground classified lidar point cloud. The contours were clipped to the banks of the channels.
2. The survey data points and the clipped elevation contours along the channels were interpolated into a DEM representing the channel bathymetry where the surveying was performed. The interpolation was performed using the Topo to Raster tool within ArcGIS. This DEM was masked so that it only contained elevations within the channels and a portion of the banks.
3. The masked channel bathymetry DEM was merged back into the bare-earth DEM to form the complete terrain model.

The results of this process were reviewed, and adjustments made to remove artifacts from the process. Many of the artifacts encountered were due to changes in the channel alignment between the period of the lidar collection and the survey.

The bathymetry was integrated with the lidar to generate a 1.0 m resolution DEM to represent the model terrain for the HEC-RAS model. A DEM for the channel was generated by creating a boundary around the survey points with a 1 m buffer zone on either side using lidar data. The lidar and survey data were then meshed together using an iterative finite difference interpolation method similar to the discretized thin plate spline technique (Wahba, 1990).

Hydraulic structures were not included in the terrain. Bridge decks for both the north and south Highway 21 bridges were removed from the DEM as they were sufficiently high above the water surface elevation of a 200-year flood and do not have an impact on flow. The flow hydraulics at bridge crossings are detailed in Appendix E.

4.2. Channel Change and Bank Erosion Analysis

Floods induce high shear stresses on channel banks, which can promote bank erosion. Non-cohesive materials such as sands and gravels are more susceptible to this process than cohesive banks. Standard hydraulic models to simulate floods do not consider bank erosion. BGC conducted a separate analysis to assess changes in the floodplain and channel and their potential influence on flooding.

Channel change mapping and bank erosion approaches using remote sensing have been widely used to detect variations in the position of channel geomorphic features (e.g., channels, banks, and bars) (Trimble & Cooke, 1991; Marcus, 2012). These methods have been reviewed and considered useful to quantify the rate of change over a study period (Lawler, 2006).

This section briefly describes the data and methods used to document planform channel changes within the study area and analyze the bank erosion processes observed between 1958 and 2019. It also outlines the limitations and uncertainties of the methodology. The investigated area for this assessment comprises the reach immediately after the canyon (Reach 1), at the alluvial fan apex, up to the distal section of the alluvial fan (Reach 4), (located approximately 3.9 km upstream of the Goat River confluence with the Kootenay River) (Drawing 04).

4.2.1. Data Sources

Aerial photographs and satellite imagery supported with lidar were used to assess historical changes in channel planform geomorphology and bank erosion within the Goat River floodplain. The characteristics of these data is described in Table 4-2. The channel mapping was also informed by the river bathymetric survey described in Section 4.1.

Table 4-2. Aerial photographs and satellite imagery used in the analysis.

Imagery / Aerial Photo	Year	Roll / Frame	Photo Number	Nominal Scale	Source
Aerial photographs	1958	BC2454	4 - 12	-	BC Government
Aerial photographs	1958	BC2504	114-122	-	BC Government
Aerial photographs	1978	BC78107	230 - 231	1:40,000	BC Government
High resolution imagery	2004	N/A	N/A	1:10,000	Google Earth Pro (v 7.3.2.5776)
Orthophoto	2017	BC17507	N/A	1:6,250	BC Government

4.2.2. Methods

In this analysis, the following tasks were completed:

Data preparation:

This task involved the acquisition of historic aerial photographs and imagery for georeferencing and mosaics creation. All the imagery and photographs were georeferenced to the same coordinate systems (NAD 1983 CSRS UTM, Zone 11N).

Geomorphic analysis:

The geomorphic analysis involved three steps. First, the identification of the channel reaches (i.e., length of the channel with similar physical characteristics). These reaches were then used to quantify the average bank retreat in meters recorded in the analyzed period.

Second, the delineation of the channel thalweg and planform. The channel planform refers to the form of a river as viewed from above (Charlton, 2007). The 2019 thalweg was generated from the river bathymetric survey data. The historical channel thalwegs were interpreted from the photographs and manually digitized on-screen. Third, the mapping of geomorphic features. The criteria for geomorphic mapping are provided in Table 4-3 and Table 4-5.

Table 4-3. Geomorphic features used for geomorphic floodplain and channel mapping.

Feature	Type	Map Symbol	Description
Channel	Main-channel	Fmc	Flowing channel with distinct banks that carries most of the river discharge. This feature is always active.
	Side-channel	Fsc	Flowing channel with distinct banks that carries a portion of the river discharge less than the main-channel. This feature is active.
	Back-channel	Fbc	Abandoned-channel with distinct banks whose downstream end is connected to the river but whose upstream end is plugged. This feature is always active.
	Flood-channel	Ffc	Channel with distinct banks connected to a main- or side-channel only in overbank flood conditions.
	Abandoned-channel	Fac	Inactive channel remnant(s). No longer directly connected to active flow (e.g., oxbow lake).
Bars	Lateral and point-bars	Flb	Deposition and accumulation of sediments against the bank (lateral or side bars) and on the inside of a meander bend (point-bars).
	Mid-channel bar	Fmb	Feature characterized by the accumulation of sediments within the main channel. When the position of the bar become stable and vegetated during decades, they are commonly called islands.
Plain	Floodplain	Fp	Includes the level-ground area susceptible to overbank flow or flooding during high-flow events.
Fan	Alluvial fan/delta	Ff	A fan is a relatively smooth sector of a cone with a slope gradient from apex to toe up to and including 15°, and a longitudinal profile that is either straight, or slightly concave or convex (Howes and Kenk, 1997).
Terrace	Terrace	Ft, FGt LGt	Flat or gently sloping areas bounded by an adjacent scarp. Fluvial terrace (Ft) deposits consist of channel deposits that may include some overbank materials.

Table 4-4. Levels of activity assigned to the geomorphic features.

Activity Class	Map Symbol	Description
Active	A	This indicates that the fluvial processes were active on the identified feature during the year when the remote sensing data were collected. The floodplain and lateral, point or mid-channel bars are considered active until vegetation cover is established. Less than 75% of vegetation coverage or isolated patches of vegetation were classified as active.
Dormant/ Inactive	D	This indicates that there is no observable evidence of fluvial processes being active on the identified feature during the year when the remote sensing data were collected. The floodplain and lateral, point or mid-channel bars are considered dormant when at least 75% of the mapped feature is covered by vegetation.

Channel Change and Bank Erosion Analysis

The channel banks and geomorphic features delineated in the previous stage were used to quantify net bank erosion between the analyzed periods. A spatial analysis using ArcGIS software by ESRI (Version 10.6.1) was applied to estimate the net change in riverbank positions (bank retreat) between each set of imagery. The following steps were completed:

- A numerical value of 1 (active) or 2 (dormant/inactive) was assigned to each mapped feature in the map attribute table. The values were determined based on the activity criteria described in Table 4-4. The general assumption was that unvegetated bars are active and would be submerged during bankfull conditions and, therefore, part of the active channel. A raster layer consisting of 1 and 2 values was created for each year of analysis.
- Then, the map algebra tool was used to subtract any two raster layers and estimate net change within the period. Negative values indicate bank erosion. Zero values indicate no change within the period and positive values indicate either bar stabilization, lateral accretion or deposition Table 4-5.

Table 4-5. Channel change classes.

Map Algebra Results	Class	Definition
-1	Bank Erosion, Channel Migration	Lateral migration of the channel due to the removal of bank material has occurred at raster cell.
0	No Change	The channel features remained the same at the raster cell between the reviewed periods.
1	Stabilization, Bank Accretion	Two conditions are possible for this result. First, pre-existing channel bars have remained stable during the period, allowing for vegetation to grow (stabilization). Second, the fluvial processes acting during the reviewed timeframe have promoted the sideway deposition along channel meanders (lateral accretion).

4.2.3. Limitations and Uncertainties

Some limitations of the interpretation of remote sensing data to the quantification of channel change include:

- The scale and resolution of available aerial photographs, which affects the level of detail that can be identified for a given year.
- The geometric distortion that results from terrain and imagery acquisition method (e.g., camera tilt in aerial photographs). These factors may result in a displacement of the geomorphic features from its true position.
- The degree to which the historical photographs represent relevant channel changes within the investigated timeframe to within tolerable levels of accuracy.
- Challenges related to the quantification of the error during the process. Possible sources of error in this analysis include scanning, georeferencing error and on-screen digitizing errors.

These errors were reduced in this study by applying common procedures including:

- Focusing on the central part of each aerial photograph
- Scanning the paper photographs at a high resolution
- Conducting geometric corrections on ArcGIS 10.6.1 software using the spline transformation tool which is commonly used when local accuracy is wanted.

4.3. Hydrological Analysis

4.3.1. Flood Frequency Analysis

Peak discharge estimates were calculated using a pro-rated flood frequency analysis (FFA) based historical streamflow data recorded at the Goat River near Erickson (08NH004) hydrometric station. Hydrometric station information is listed in Table 4-6. The estimates for the Goat River were compared to results using a regional FFA based on the index-flood method and compared with historical estimates published by previous studies (e.g., Klohn Crippen, 2002).

Table 4-6. Hydrometric station formation for the Goat River near Erickson (08NH004).

Station Name	Goat River near Erickson
Station ID	08NH004
Real-time recording	No
Latitude	49.089170
Longitude	-116.455560
Drainage Area (km^2)	1180
Record Period	1914 to 1995
Record Length (Complete years of data)	74
# Years of published peak instantaneous flows	22
Approximate Elevation (masl)	568
Hydrologic Regime	Regulated
Location with Respect to the Town of Creston	4 km east

As part of the regional FFA, the Goat River watershed was assigned to the Cluster 7 hydrologic region for watersheds greater than 500 km^2 based on its characteristics. Hydrologic regions are made up of hydrometric stations that share similar watershed characteristics. The hydrologic regions that cover the RDCK include Cluster 1 West, Cluster 4 East, and Cluster 7. The methodology for the regional FFA as well as the estimation of peak discharge at the hydrometric station are described in Appendix C. The methodology for the single-station FFA is described herein.

Peak discharge estimates based on the Annual Maximum Series using recorded peak instantaneous discharges were calculated at the hydrometric station (08NH004) assuming a Generalized Extreme Value (GEV) probability distribution. The parameters of the distribution were calculated using the L-moments. The peak discharge estimates at the hydrometric station were transferred to the ungauged location by relating the annual maximum peak instantaneous discharges at the hydrometric station to the ungauged site using watershed area. The equation used for this relation is as follows (Eq. 4- 1):

$$\frac{Q_U}{Q_G} = \left(\frac{A_U}{A_G}\right)^n \qquad \text{[Eq. 4-1]}$$

where Q_U and Q_G are the annual maximum peak instantaneous discharges (m^3/s) at the ungauged site and the hydrometric station respectively, A_U and A_G are the watershed areas (km^2) for the ungauged and gauged sites respectively, and n is a site-specific exponent related to peak discharges data at both sites (Watt 1989). Typically, a value for n is chosen based on the watershed area size (Watt 1989). In the case of the Goat River, an exponent of 0.55 was used in the calculation. This approach is consistent with previous studies (e.g., Klohn Crippen, 2002).

4.3.2. Climate Change Considerations

Engineers and Geoscientists British Columbia (EGBC) offer guidelines that include procedures to account for climate change when flood magnitudes for protective works or mitigation procedures are required (EGBC, 2018). The impacts of climate change on peak discharge estimates in the Goat River were assessed using statistical and processed-based methods (Appendix D). The statistical methods included a trend assessment on historical flood events using the Mann-Kendall test as well as the application of climate-adjusted variables (mean annual precipitation, mean annual temperature, and precipitation as snow) to the Regional FFA model. The process-based methods included the trend analysis for climate-adjusted flood data offered by the Pacific Climate Impacts Consortium (PCIC).

4.4. Hydraulic Modelling

4.4.1. General Approach

The preparation of flood hazard maps requires the development of a hydraulic model. The two-dimensional (2D) hydraulic model HEC-RAS 2D (Version 5.0.7) was used to simulate the flood scenarios summarized in Table 4-7. HEC-RAS is a public domain hydraulic modelling program developed and supported by the United States Army Corps of Engineers (Brunner & CEIWR-HEC, 2016). Each scenario was modelled with climate-change adjusted discharges to represent projected future conditions as described below.

Table 4-7. Return period classes.

Return Period (years)	Annual Exceedance Probability
20	0.05
50	0.02
200	0.005
500	0.002

Within the Goat River modelling extents there are two bridges. These bridges were modelled using a one dimensional (1D) hydraulic model (also in HEC-RAS 2D Version 5.0.7). The 1D model results indicated that the bridges provide 1 m of clearance for a 500-year flow event. Furthermore, the WSE from the 1D model with the bridges was also found to be very similar to the WSE from the 2D model without the bridges. Bridge decks must be removed for HEC-RAS to perform 2D flow modelling. A 1D HEC-RAS model of the bridges was therefore created to assess the validity of the 2D flow modelling. Results from the 1D bridge model indicated that results from the 2D model were satisfactory. Further details on modelling methods are presented in Appendix E and summarized in the sections below.

4.4.2. Model Inputs

Key model inputs include: (1) the topographic model to represent the floodplain and in-channel bathymetry, (2) the boundary conditions at the upstream and downstream end of the study extent and (3) the flood hydrology to represent peak discharges for various return period as shown in adjusted to the upstream boundary of the hydraulic model. Table 4-8 summarizes the key numerical modelling inputs selected for the HEC-RAS 2D model. Additional description of the topographic model and boundary conditions are provided in the sections below.

Table 4-8. Summary of numerical modelling inputs.

Variable	HEC-RAS
Topographic Input	Lidar (2018); Bathymetry (2019)
Grid cells	Variable (2- 20 m)
Manning's n	0.032 (channel), varied based on landcover data (NALCMS, 2010), (out of channel) Manning's n values from Chow (1959).
Upstream boundary condition	Steady Flow (Q_{20}, Q_{50}, Q_{200} and Q_{500})
Downstream boundary condition	Q_{20} of Kootenay River (3,230 m^3/s)

4.4.2.1. Terrain Model

Following completion of the survey, BGC integrated the bathymetry data and surveyed cross sections with the lidar to generate a DEM for use in hydraulic modelling using the process, as described in Section 4.1.5.

4.4.2.2. Model Domain and Boundary Conditions

Discharge through the Kootenay River at the outlet of Goat River is used as the downstream boundary for the hydraulic model. It is essential to consider the flow of Kootenay River during a design flood on the Goat River, as it has a direct impact on the water surface elevation within the river through a backwater effect. The 20-year peak discharge in the Kootenay River was assumed for all modelling scenarios. This discharge was prorated from the *Kootenai River at Porthill* (08NH021) hydrometric gauge located 17 km upstream of the confluence. The upstream boundary conditions for the modelling effort are the estimated peak flows for the Goat River and for 20, 50, 200 and 500-year return periods. The modelling extents, and the location of the upstream and downstream boundary conditions are shown in Figure 4-4.

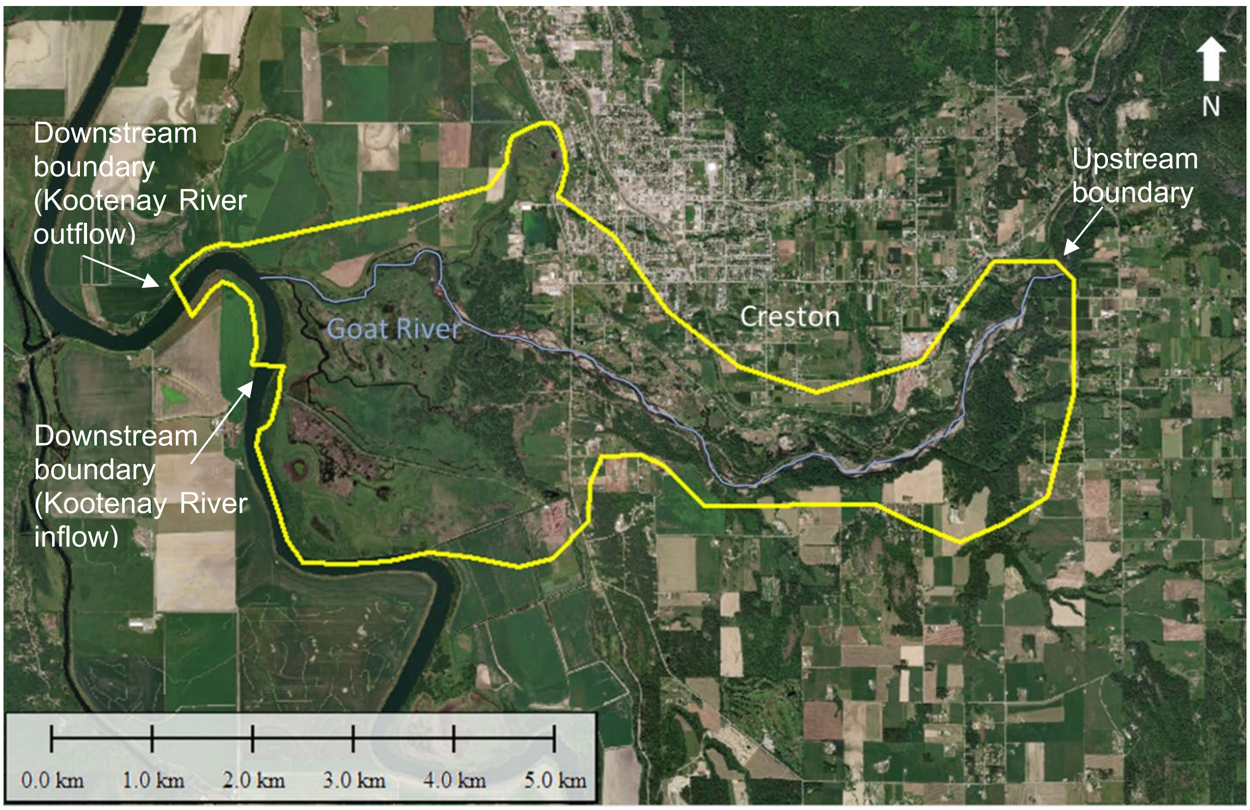


Figure 4-4. Goat River study area modelling domain.

4.5. Hazard Mapping

BGC prepared hazard maps based on the results from the numerical flood modelling. Specifically, BGC prepared two types of maps for Goat River: hazard scenario maps and a flood construction level (FCL) map. The scenario maps support emergency planning and risk analyses, and the FCL map supports communication and policy implementation, as described further below.

4.5.1. Hazard Scenario Maps

Hazard scenario maps display the hazard intensity (destructive potential) and extent of inundated areas for each scenario assessed. Two versions of the hazard scenario maps for each return period are provided: i) maps showing flood depth, and ii) maps showing flow impact force (IF) defined as the combination of fluid bulk density (ρ), area of impact (A) and velocity (v) shown in Equation 4-2:

$$IF \propto \rho A v^2 \quad \text{[Eq. 4-2]}$$

For clearwater flooding, 1000 kg/m^3 was assumed for ρ as shown Equation 4-2. The area of impact represents the area of the object that is impacted or the portion thereof. For this level of study, depth of flow from modelling results is used as a proxy for the height of the area and the impact force is then represented as an impact force per unit width, in this case 1 m.

Maps displaying flow depth support assessments where inundation is the primary mechanism of damage. Flow impact force maps highlight locations where a combination of higher flow velocity and depth may warrant additional assessment (i.e., analyses of bank stability, erosion, or life safety). Table 4-9 provides a description of the flow impact force ranges and their impacts on life safety and impacts on the built environment. A flow depth map for the 200-year peak discharge is provided in this report in Drawing 06. Flow depth and flow impact force maps for all return periods are displayed on Cambio.

Table 4-9. Flow impact force values shown on the flood hazard scenario maps (Cambio)

Impact Force (kN/m)	Description
≤ 1	Slow flowing shallow and deep water with little or no debris. High likelihood of water damage. Potentially dangerous to people in buildings, in areas with higher water depths.
1 to 10	Mostly slow but potentially fast flowing shallow or deep flow with some debris. High likelihood of sedimentation and water damage. Potentially dangerous to people in the basement or first floor of buildings without elevated concrete foundations.
10-100	Fast flowing water and debris. High likelihood of structural building damage and severe sediment and water damage. Dangerous to people on the first floor or in the basement of buildings. Replacement of unreinforced buildings likely required.
>100[1]	Fast flowing debris. High likelihood of building destruction. Very dangerous to people in buildings irrespective of floor.

Note:
1. Flow intensities greater than 100 kN/m in clear water creeks are generally confined to the main channel.

4.5.2. Flood Construction Level Mapping

FCLs are required for areas adjacent to river floodplains for consideration during planning. An FCL can be incorporated into regulation by authorities to provide guidance for new constructions on the extent and elevation of possible flooding in the area. In BC, FCLs have historically been calculated as the higher of the followings:

- Water surface profile for the design peak instantaneous flow plus 0.3 m of freeboard
- Water surface profile for the design daily flow plus 0.6 m of freeboard.

The freeboard is applied to the estimated water surface profile to account for uncertainties in the calculation of the water surface. As noted in EGBC (2017; 2018), for many BC rivers freeboard has been set higher than these minimum values to account for sediment deposition, debris jams, and other factors. Recently, several studies have recommended using 0.6 m of freeboard above the design peak instantaneous flow (KWL, 2014; 2017; NHC, 2008b; 2014; 2016; 2018). As such, we have selected to use this approach as well for the Goat River study area.

The presence of dikes needs to be considered when defining the FCLs. Depending on the situation, the presence of a dike may lead to a local rise in the flood levels as the dike constrains the flow within the channel. Should a dike fail through overtopping or geotechnical failure, the resulting flooding depth and extent of flooding may be greater than if the dike was not present due to the elevated flood level (e.g., Figure 4-5). Dike breach scenarios were not conducted as part of the flood hazard assessment. As a result, FCLs developed from the modelling results are assumed to be higher than they would be if dike breaching was considered. In large floodplains or areas with complex diking systems, a more detailed approach to estimating FCLs may be warranted.

For the Goat River study area, the FCLs were generated by creating isolines from the predicted 200-year water surface plus a 0.6 m freeboard and extending the isolines across the limits of the floodplain generally perpendicular to the flow direction. The FCL maps are presented in Drawing 07.

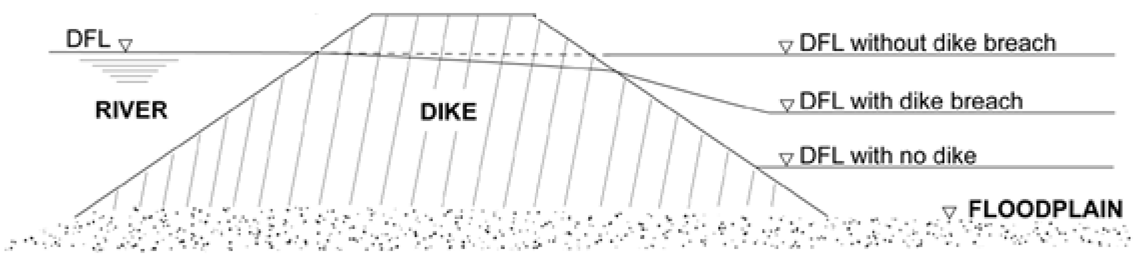


Figure 4-5. Definition of design flood levels (DFL) in the presence of a dike. DFL refers to the estimated water levels from a design flood event such as the 200-year return period flood (Modified from Water Management Consultants, March 19, 2004).

5. RESULTS

5.1. Channel Change Mapping and Bank Erosion

The geomorphic and bank erosion analysis documented historical changes in channel width and related geomorphic processes using remote sensing data, as described in Section 4.2.1. The mapped geomorphic units are illustrated in Drawing 04. The investigated area was divided into four reaches to facilitate the analysis of the observed changes (Figure 5-1). The relevant features of these reaches including average bank retreat based on the planimetric analysis are provided in Table 5-1. A summary of the key changes observed within the area is included in Table 5-2 and a description of the interpreted channel changes follows.

The first reach (Reach-1) comprises the section immediately after the bedrock canyon. It extends for 500 m downstream to where the channel bifurcates into the main branch and a side-channel (Figure 5-1). This is a transitional channel as described by AMEC (2005) between the canyon and the alluvial fan reaches. In this section, the Goat River is characterized by a straight steep channel. The channel width varies approximately from 15 to 47 m. A sequence of riffles and pools is evident in the recent imagery. The main changes at this reach involve a progressive increase in channel sinuosity towards the right bank and formation of a meander bend, with the resulting deposition of a bar along the left bank. As shear stress concentrates at the meander bend, erosion of the right bank is expected to continue. An old landslide feature (about 9500 m^2) was identified at this location (Drawing 04). This landslide can be reactivated during high flows triggered by erosion at the slope toe. A reactivation of this feature may result in:

- Channel infilling and reduction of the cross-sectional area (restricting the channel capacity to contain high flows)
- Channel displacement towards the right bank promoting bank instability.

The second reach (Reach-2) is a wandering channel and extends 1.5 km downstream of the channel bifurcation (Figure 5-1). The river widens, and the channel flattens at this location, promoting the deposition of lateral bars. The planimetric analysis and the lidar data display evidence of channel migration at this section resulting in the reworking of channel bars. This is the reach that has experienced the most change within the analyzed period. The third reach (Reach-3) is about 5.1 km long. Most of the changes in this reach were recorded before the channel protection work. Following the diking deposition appears to be dominant process.

The fourth reach (Reach-4) extends for 1.3 km. It is transitional between the floodplain processes that dominate in the alluvial fan and the wetland processes on the Kootenay River floodplain. In this section, the changes appear to be controlled by channel diking and reactivation of flood channels during high flows.

Table 5-1. Channel reaches characterization and average bank retreat.

Reach	Length[1] (km)	Channel Width Variation (m)	Average Bank Retreat (m) 1958-1978	Average Bank Retreat (m) 1978-2004	Average Bank Retreat (m) 2004-2017	Channel Pattern
Reach-1	0.5	40-95	10.8	3.5	0.8	Straight
Reach-2	1.5	55-110	83.9	68.2	44.9	Wandering
Reach-3	5.1	35-80	49.4	16.9	9.2	Wandering
Reach-4	1.3	60-114	27.4	43.8	18.3	Wetland

Note:
1. Based on 2019 lidar data.

Table 5-2. Summary of key changes observed within the analyzed periods.

Period	Maximum Channel Bank Retreat (m)	Highlighted observations
1958 - 1978	140 +/- 5 m	The maximum channel retreat was estimated within Reach 03 (right bank). Deposition or stabilization appears to be dominant over this period.
1978 - 2004	102 +/- 5 m	The maximum channel retreat was estimated at a meander bend on the right bank (Reach 04). Channel shift toward the left bank in Reaches 01 and 02, promoting deposition and stabilization of lateral bars on the right side of the river. Narrowing of the active floodplain within Reach 03 (section controlled by dikes).
2004 - 2019	80 +/-2 m	Reactivation of flood channels and lateral and mid-channel bars was evident within the entire fan. Stabilization of some lateral bars within the mid- fan reaches (Reaches 02 and 03). Bank erosion was noted on both banks. This erosion resulted in channel widening in Reaches 02 and 04. The highest bank retreat was recorded in the distal section of the fans (Reach 04). Extreme bank retreat experienced at some locations is likely related to the June 2012 flood event.

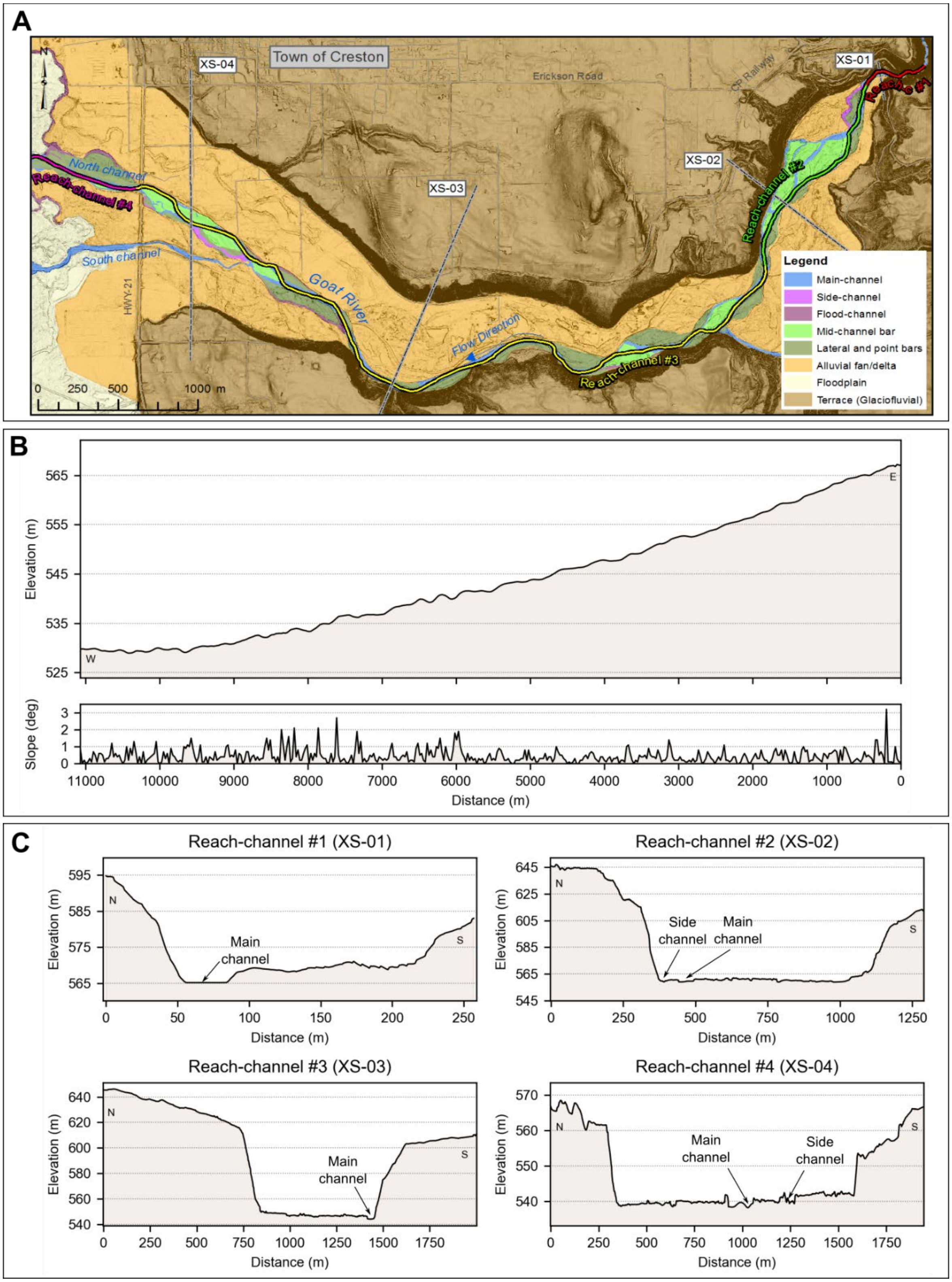


Figure 5-1. Identified channel reaches within the Goat River floodplain at Creston. (A) Plan view of the river and floodplain. (B) Channel long-profile and slope gradient. Section lines are from left (north) to right (south) bank. (C) Typical cross-sections within the characterized channel reaches. N= North bank. S= South bank.

5.2. Hydrological Modelling

5.2.1. Historical Peak Discharge Estimates

The historical peak discharge estimates for the Goat River were based on the historical streamflow data recorded at the Goat River near Erickson (08NH004) hydrometric station which were pro-rated to the downstream end of the model as discussed in Section 4.3.1. The peak discharges based on the historical data are presented in Table 5-3. A comparison of the estimates to results from previous reports and the regional FFA also presented in Figure 5-2.

5.2.2. Accounting for Climate Change

The climate change impact assessment results based on the methods presented in Section 4.3.2 were difficult to synthesise in order to select climate-adjusted peak discharges on a site-specific basis. The assessment of the trends in the discharge records was inconclusive. The results of the statistical flood frequency modelling generally show a small decrease in the flood magnitude, while the results of the process-based discharge modelling generally show an increase with a wide range in magnitude. As a result, peak discharge estimates were adjusted upwards by 20% to account for the uncertainty in the impacts of climate change in the RDCK as per Appendix D. The climate-adjusted peak discharge estimates for various return periods are also listed in .

Table 5-3. Historical and climate-adjusted peak discharge estimates for the Goat River.

Return Period (years)	AEP	Historical Peak Discharge (m^3/s)	Climate-adjusted Peak Discharge (m^3/s)
2	0.5	235	280
5	0.2	305	365
10	0.1	350	420
20	0.05	385	465
25	0.04	400	480
50	0.02	435	520
100	0.01	465	560
200	0.005	495	595
500	0.002	530	640

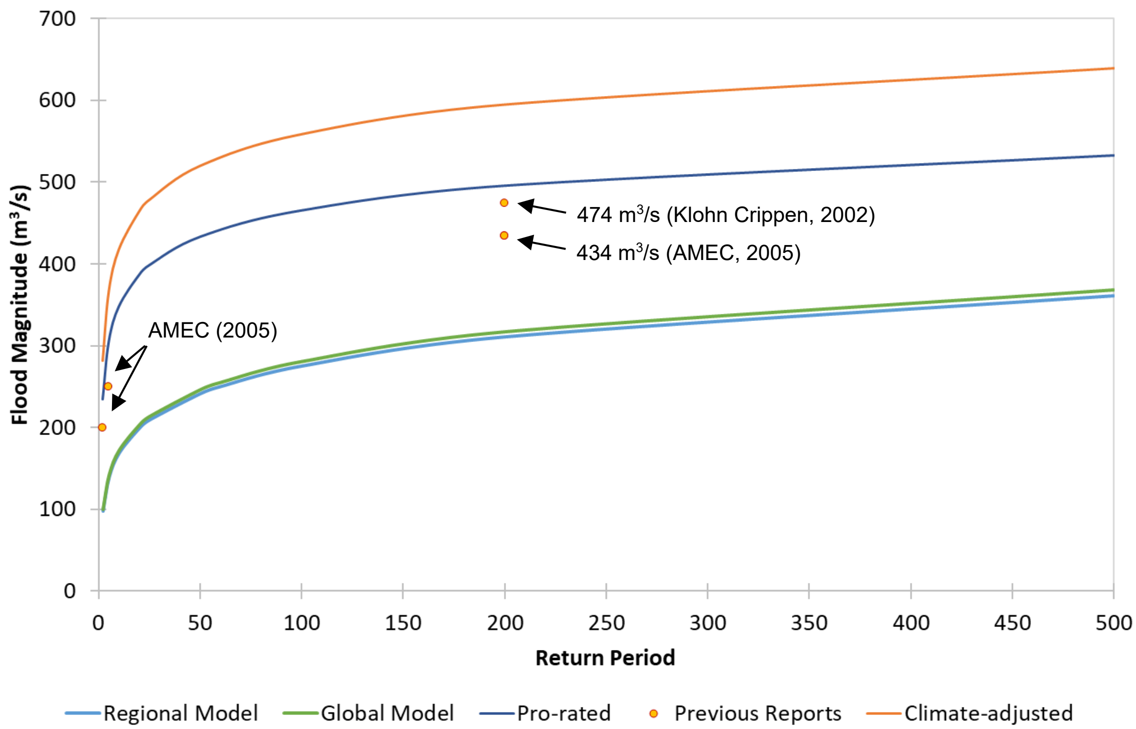


Figure 5-2. Historical peak discharge estimates based on regional FFA, single-station FFA, and previous reports. Climate-adjusted flows are based on the single-station FFA plus 20%. Note: AMEC (2005) applied 200-year flood estimates from the 1984 floodplain map (MFLNRO 2016).

5.3. Hydraulic Modelling

A summary of the key observations from the hydraulic modelling is included in Table 5-4. A channel profile showing the 200-year water surface and dike elevations are shown on Figure 5-3.

Table 5-4. Summary of modelling results.

Process	Key Observations
Clearwater inundation	• In general, modelling results and predicated floodplain extents are similar to results presented in historical floodplain mapping (MFLNRO, 2016). Flooding may still occur outside the defined floodplain boundary. • Hydraulic modelling results for Goat River indicate that the dike crest is typically greater than 0.4 m above the 200-year flood level for most of the diked reach. An exception is between Dike B and C near the location of the gravel berm where the crest is below the 200-year flood level for several hundred meters. The crest of Dike A is also below the 200-year flood level for approximately 50 m, 1.5 km upstream of the Highway 21 bridge.
Hydraulic Structures (Bridges)	• The flood elevations for all scenarios modeled did not reach the low cord of the Highway 21 bridges over the North and South Channel. This was verified through 1D modelling. • There is approximately 1 m of clearance between the lower chord of the northern Highway 21 bridge and the 200-year return period flood. • There is greater than 1.5 m of clearance between the lower chord of the southern Highway 21 bridge and the 200-year return period flood.

Process	Key Observations
Flood Protection Structures (Dikes)	• The dike crest is typically greater than 0.4 m above the 200-year flood depth for the first kilometer of the diked reach upstream (east) of Highway 21 in the North Channel. • The dikes located approximately 2 km upstream (east) of the Highway 21 bridge overtop in the 200-year return period event indicating that potential overtopping of the dikes and berm occurs under a 200-year flood on Goat River with accounting for climate change. • Some flooding occurs due to flow around dikes from flow upstream (east) of the dikes.

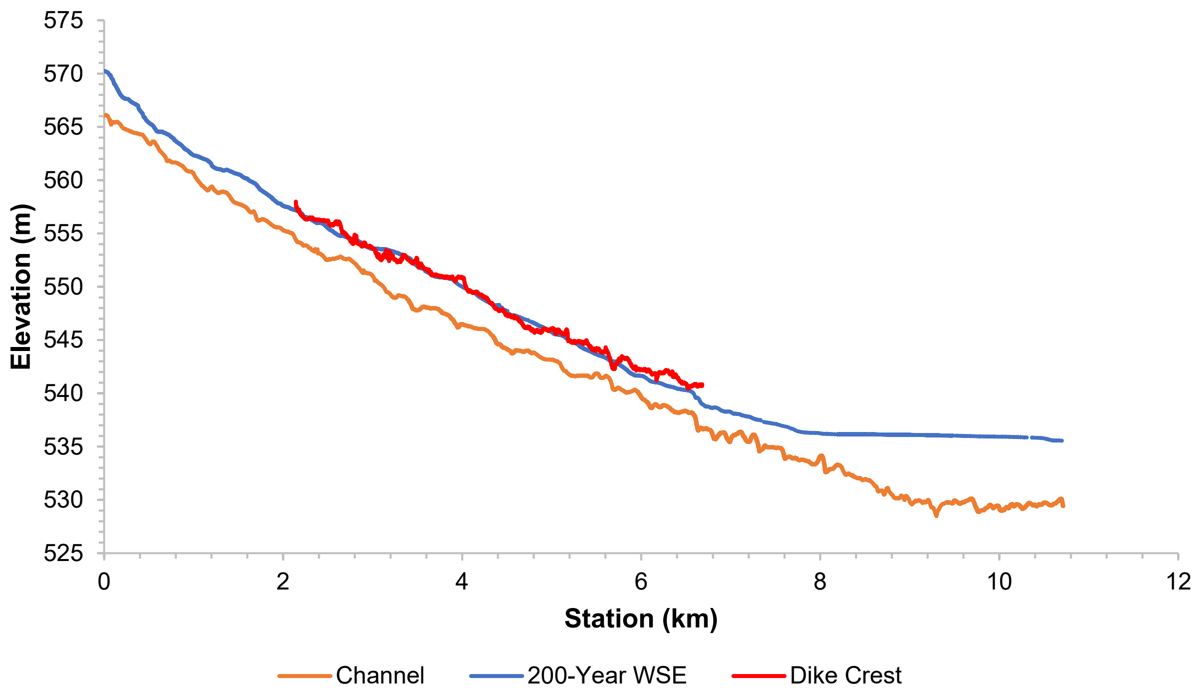


Figure 5-3. Model profile showing channel bed, 200-year water surface elevation (WSE), and dike crest elevation.

5.4. Flood Hazard Mapping

Hazard scenario results from the range of return periods modelled are presented in Cambio. Drawing 06 provides estimated water surface depths estimated for the 200-year return period event.

5.5. Flood Construction Level Mapping

FCL results for the 200-year water surface elevation plus 0.6 m freeboard are presented on Drawing 07. Note that elevations from the FCLs have not been surveyed in the field and should not be relied upon for accuracy of ground levels at the building lot scale.

6. SUMMARY AND RECOMMENDATIONS

This report and appendices provide a detailed flood hazard assessment of the Goat River floodplain. This river was chosen as a high priority site amongst hundreds in the RDCK due to its comparatively high risk. This study has resulted in digital hazard maps that provide the backbone of any eventual quantitative risk assessment It also provides the basis to inform the conceptualization and potential design and construction of mitigation measures should those be found to be required for the Goat River. A variety of analytical desktop and field-based tools and techniques were combined to understand the Goat River geomorphological and hazard history, its hydrology and hydraulics.

6.1. Flood Hazard Assessment

6.1.1. Channel Change Mapping and Bank Erosion

These analyses were completed to gain an understanding of historical geomorphic changes on the fan and how these changes relate to channel migration and flooding. Channel change and bank erosion results illustrate:

- The observable geomorphic features identified from the different sets of aerial photographs and imagery (Table 5-1). These maps are useful to understand the geomorphic evolution of the channel, and how the fluvial processes may influence or being accelerated by flooding (Drawing 04).
- The channel change rate identified between the analyzed set of imagery as summarized in Table 5-2 (Drawing 05).

Both maps guide the analysis of channel dynamics within the analyzed area and their possible influence on flood hazards.

6.1.2. Peak Discharge Estimates

In recognition of the impacts of climate change, the clearwater flows estimated from a pro-rated FFA were adjusted. Key findings from estimating peak discharges suitable for modelling are:

- The climate change impact assessment results were difficult to synthesize to select climate-adjusted peak discharges on a site-specific basis. Consequently, a 20% increase in peak discharge was adopted (Appendix D).
- The climate-change adjusted peak discharges for Goat River range from 282 m^3/s (2-year flood) to 640 m^3/s (500-year flood). These values are higher than historical peak discharge presented in .

6.1.3. Hydraulic Modelling

A 2D numerical model developed using HEC-RAS was employed to simulate the chosen hazard scenarios on the Goat River. Table 5-4 provides key observations derived from the numerical modelling. The numerical modelling demonstrates that the key hazards and associated risks at Goat River stem from potential dike breaches and avulsions.

6.1.4. Flood Hazard Mapping

Model results are cartographically expressed in two ways:

- The individual hazard scenarios are captured through hazard maps that display estimated flow velocity, flow depth and flood intensity. These maps are useful for assessments of development proposals and emergency planning.
- A flood construction level map that combines the estimated water surface elevation for the 200-year return period event plus a 0.6 m freeboard. This map is useful to designated hazard zones.

Both the individual scenario hazard and FCL maps serve as decision-making tools to guide subdivision and other development permit approvals.

6.2. Limitations and Uncertainties

While systematic scientific methods were applied in this study, some uncertainties prevail. As with all hazard assessment and concordant maps, the hazard maps prepared at Goat River represent a snapshot in time. Future changes to the Goat River watershed or fan including the following may warrant re-assessment and/or re-modelling:

- Future land use (urbanization) or landcover (deforestation, forest fire) changes in the floodplain or fan
- Substantial flood events
- Major changes in the channel planform or aggradation
- Bridge re-design
- Alteration to the existing dikes or construction of new dikes or flood control structures
- Substantial changes to Kootenay River flood levels.

The assumptions made on changes in runoff due to climate change, while well-reasoned, are not infallible and will likely need to be updated occasionally as scientific understanding of such processes evolves. Despite these limitations and uncertainties, BGC believes that a credible hazard assessment has been achieved on which land use decisions can be made.

6.3. Considerations for Hazard Management

Recommendations are provided in the Summary Report (BGC, March 31, 2020) as they pertain to all studied RDCK areas. This section notes Goat River-specific issues that could be considered in the short term given the findings of this report. They are purposely not named “recommendations” as those would come out of a more in-depth discussion with the District.

Key considerations are:

- Predicated floodplain extents are generally similar to results presented in historical floodplain mapping for the Goat River (MFLNRO, 2016). Flooding may occur outside the defined floodplain boundary and floodplain limits were not established on the ground by legal survey.
- Numerical modelling indicates that the surveyed dike crest elevation is typically greater than 0.4 m above the 200-year return period flood depth for the first kilometer of the diked reach upstream (east) of Highway 21 bridge crossing of the North Channel.
- The dikes located approximately 2 km upstream (east) of the Highway 21 bridge could overtop during high (200-year and 500-year) peak discharges. This section of dike and berm could be improved to avoid breach.
- An assessment of the geotechnical stability of the dikes was not conducted. Dike stability assessments could be completed in future as part of a separate scope of work for the clearwater assessment areas. This work would inform if failure may occur due to reasons other than flood overtopping.
- Discharge through the Kootenay River at the outlet of Goat River is used as the downstream boundary for the model to consider the direct impact on the water surface elevation within the river through a backwater effect. Additional modelling work could consider the impacts of high peak discharges (greater than the 20-year return period) on the Kootenay River resulting in water backing up on the Goat River and contributing to overtopping of the dikes upstream of the Highway 21 bridges.
- Hydraulic modelling (1D and 2D) results indicate that the north and south Highway 21 bridges are not predicted to overtop during a 200-year return period. This assessment does not consider the potential for the bridge to be blocked with large woody debris or due to accumulation of gravel.
- The hazard mapping conducted for a range of return periods provides an improved hazard basis to apply for funding for additional risk assessment, emergency response planning and mitigation projects. Results of the hazard mapping are provided on Drawing 06 for the 200-year return period water depth and Cambio for the range of scenarios modelled (e.g., 20-year, 50-year, 500-year).
- The FCLs presented in Drawing 07 for the 200-year return period flood event plus 0.6 m freeboard provides an improved basis for community planning, bylaw development, and emergency response planning in areas subject to flood hazards, with consideration of climate change. The application of the FCL map requires discussions and regulatory decisions for both existing and proposed development. Building and floodproofing elevations should be established from legal survey and benchmarks. Setback distances from the natural boundaries of watercourses are not shown on maps. FCLs provide a standards-based approach which are simple to apply and interpret. In some cases, the FCL may be impossible or impractical to implement for several reasons. Allowances should be permitted for stakeholders to apply for a site-specific reduction in the FCLs contingent on a report by a suitably qualified Professional Engineer, preferably using a risk-based approach.

- Dike breach assessments could be completed in future as part of a separate scope of work for the clearwater assessment areas (i.e., related to dike stability assessment, mitigation planning and risk control design). The addition of a dike breach scenario could result in lower FCLs for the floodplain.

6.4. Recommendations

Recommendations are provided in the Summary Report (BGC, 2020) as they pertain to all studied RDCK creeks.

7. CLOSURE

We trust the above satisfies your requirements at this time. Should you have any questions or comments, please do not hesitate to contact us.

Yours sincerely,

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Final stamp and signature version to follow once COVID-19 restrictions are lifted

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APPENDIX A
TERMINOLOGY

Table A-1 provides defines terms that are commonly used in geohazard assessments. BGC notes that the definitions provided are commonly used, but international consensus on geohazard terminology does not fully exist. **Bolded terms** within a definition are defined in other rows of Table A-1.

Table A-1. Geohazard terminology.

Term	Definition	Source
Active Alluvial Fan	The portion of the fan surface which may be exposed to contemporary hydrogeomorphic or avulsion hazards.	BGC
Aggradation	Deposition of sediment by a (river or stream).	BGC
Alluvial fan	A low, outspread, relatively flat to gently sloping mass of loose rock material, shaped like an open fan or a segment of a cone, deposited by a stream at the place where it issues from a narrow mountain valley upon a plain or broad valley, or where a tributary stream is near or at its junction with the main stream, or wherever a constriction in a valley abruptly ceases or the gradient of stream suddenly decreases	Bates and Jackson (1995)
Annual Exceedance Probability (P_H) (AEP)	The Annual Exceedance Probability (AEP) is the estimated **probability** that an event will occur exceeding a specified magnitude in any year. For example, a flood with a 0.5% AEP has a one in two hundred chance of being reached or exceeded in any year. AEP is increasingly replacing the use of the term **'return period'** to describe flood recurrence intervals.	Fell et al. (2005)
Avulsion	Lateral displacement of a stream from its main channel into a new course across its fan or floodplain. An "avulsion channel" is a channel that is being activated during channel avulsions. An avulsion channel is not the same as a paleochannel.	Oxford University Press (2008)
Bank Erosion	Erosion and removal of material along the banks of a river resulting in either a shift in the river position, or an increase in the river width.	BGC
Clear–water flood	Riverine and lake flooding resulting from inundation due to an excess of clear-water discharge in a watercourse or body of water such that land outside the natural or artificial banks which is not normally under water is submerged.	BGC
Climate normal	Long term (typically 30 years) averages used to summarize average climate conditions at a particular location.	BGC
Consequence (C)	In relation to risk analysis, the outcome or result of a **geohazard** being realised. Consequence is a product of **vulnerability** (V) and a measure of the **elements at risk** (E)	Fell et al. (2005); Fell et al. (2007), BGC

Term	Definition	Source
Consultation Zone	The Consultation Zone (CZ) includes all proposed and existing development in a geographic zone defined by the approving authority that contains the largest credible area affected by specified **geohazards**, and where damage or loss arising from one or more simultaneously occurring specific **geohazards** would be viewed as a single catastrophic loss.	Adapted from Porter et al. (2009)
Debris Flow	Very rapid to extremely rapid surging flow of saturated, non-plastic debris in a steep channel (Hungr, Leroueil & Picarelli, 2014). Debris generally consists of a mixture of poorly sorted sediments, organic material and water (see Appendix B of this report for detailed definition).	BGC
Debris Flood	A very rapid flow of water with a sediment concentration of 3-10% in a steep channel. It can be pictured as a flood that also transports a large volume of sediment that rapidly fills in the channel during an event (see Appendix B of this report for detailed definition).	BGC
Elements at Risk (E)	This term is used in two ways: a) To describe things of value (e.g., people, infrastructure, environment) that could potentially suffer damage or loss due to a **geohazard**. b) For risk analysis, as a measure of the value of the elements that could potentially suffer damage or loss (e.g., number of persons, value of infrastructure, value of loss of function, or level of environmental loss).	BGC
Encounter Probability	This term is used in two ways: a) **Probability** that an event will occur and impact an element at risk when the element at risk is present in the **geohazard** zone. It is sometimes termed **"partial risk"** b) For quantitative analyses, the **probability** of facilities or vehicles being hit at least once when exposed for a finite time period L, with events having a **return period** T at a location. In this usage, it is assumed that the events are rare, independent, and discrete, with arrival according to a statistical distribution (e.g., binomial or Bernoulli distribution or a Poisson process).	BGC
Erosion	The part of the overall process of denudation that includes the physical breaking down, chemical solution and transportation of material.	Oxford University Press (2008)

Term	Definition	Source
Flood	A rising body of water that overtops its confines and covers land not normally under water.	American Geosciences Institute (2011)
Flood Construction Level (FCL)	A designated flood level plus freeboard, or where a designated flood level cannot be determined, a specified height above a natural boundary, natural ground elevation, or any obstruction that could cause flooding.	BGC
Flood mapping	Delineation of flood lines and elevations on a base map, typically taking the form of flood lines on a map that show the area that will be covered by water, or the elevation that water would reach during a flood event. The data shown on the maps, for more complex scenarios, may also include flow velocities, depth, or other hazard parameters.	BGC
Floodplain	The part of the river valley that is made of unconsolidated river-borne sediment, and periodically flooded.	Oxford University Press (2008)
Flood setback	The required minimum distance from the natural boundary of a watercourse or waterbody to maintain a floodway and allow for potential bank erosion.	BGC
Freeboard	Freeboard is a depth allowance that is commonly applied on top of modelled flood depths. There is no consistent definition, either within Canada or around the world, for freeboard. Overall, freeboard is used to account for uncertainties in the calculation of a base flood elevation, and to compensate for quantifiable physical effects (e.g., local wave conditions or dike settlement). Freeboard in BC is commonly applied as defined in the BC Dike Design and Construction manual (BC Ministry of Water, Land and Air Protection [BC MWLAP], 2004): a fixed amount of 0.6 m (2 feet) where mean daily flow records are used to develop the design discharge or 0.3 m (1 foot) for instantaneous flow records.	BC Ministry of Water, Land and Air Protection [BC MWLAP] (2004)

Term	Definition	Source
Frequency (f)	Estimate of the number of events per time interval (e.g., a year) or in a given number of trials. Inverse of the **recurrence interval** (**return period**) of the **geohazard** per unit time. Recurring **geohazards** typically follow a **frequency**-magnitude (F-M) relationship, which describes a spectrum of possible **geohazard magnitudes** where larger (more severe) events are less likely. For example, annual **frequency** is an estimate of the number of events per year, for a given **geohazard event magnitude**. In contrast, annual **probability** of exceedance is an estimate of the **likelihood** of one or more events in a specified time interval (e.g., a year). When the expected **frequency** of an event is much lower than the interval used to measure **probability** (e.g., **frequency** much less than annual), **frequency** and **probability** take on similar numerical values and can be used interchangeably. When **frequency** approaches or exceeds 1, defining a relationship between **probability** and **frequency** is needed to convert between the two. The main document provides a longer discussion on **frequency** versus **probability**.	Adapted from Fell et al. (2005)
Hazard	Process with the potential to result in some type of undesirable outcome. Hazards are described in terms of scenarios, which are specific events of a particular frequency and magnitude.	BGC
Hazardous flood	A flood that is a source of potential harm.	BGC
Geohazard	Geophysical process that is the source of potential harm, or that represents a situation with a potential for causing harm. Note that this definition is equivalent to Fell et al. (2005)'s definition of Danger (threat), defined as an existing or potential natural phenomenon that could lead to damage, described in terms of its geometry, mechanical and other characteristics. Fell et al. (2005)'s definition of danger or threat does not include forecasting, and they differentiate Danger from Hazard. The latter is defined as the **probability** that a particular danger (threat) occurs within a given period of time.	Adapted from CSA (1997), Fell et al. (2005).

Term	Definition	Source
Geohazard Assessment	Combination of **geohazard analysis** and evaluation of results against a **hazard tolerance standard** (if existing). Geohazard assessment includes the following steps: a. **Geohazard analysis**: identify the **geohazard** process, characterize the geohazard in terms of factors such as mechanism, causal factors, and trigger factors; estimate **frequency** and magnitude; develop **geohazard scenarios**; and estimate extent and intensity of **geohazard scenarios**. b. Comparison of estimated hazards with a hazard tolerance standard (if existing)	Adapted from Fell et al. (2007)
Geohazard Event	Occurrence of a **geohazard**. May also be defined in reverse as a non- occurrence of a **geohazard** (when something doesn't happen that could have happened).	Adapted from ISO (2018)
Geohazard Intensity	A set of parameters related to the destructive power of a **geohazard** (e.g. depth, velocity, discharge, impact pressure, etc.)	BGC
Geohazard Inventory	Recognition of existing **geohazards.** These may be identified in geospatial (GIS) format, in a list or table of attributes, and/or listed in a **risk register**.	Adapted from CSA (1997)
Geohazard Magnitude	Size-related characteristics of a **geohazard**. May be described quantitatively or qualitatively. Parameters may include volume, discharge, distance (e.g., displacement, encroachment, scour depth), or acceleration. In general, it is recommended to use specific terms describing various size-related characteristics rather than the general term magnitude. Snow avalanche magnitude is defined differently, in classes that define destructive potential.	Adapted from CAA (2016)
Geohazard Risk	Measure of the **probability** and severity of an adverse effect to health, property the environment, or other things of value, resulting from a geophysical process. Estimated by the product of **geohazard probability** and **consequence**.	Adapted from CSA (1997)
Geohazard Scenario	Defined sequences of events describing a **geohazard** occurrence. Geohazard scenarios characterize parameters required to estimate risk such **geohazard extent** or **runout exceedance probability,** and **intensity.** Geohazard scenarios (as opposed to **geohazard risk scenarios**) typically consider the chain of events up to the point of impact with an element at risk, but do not include the chain of events following impact (the **consequences**).	Adapted from Fell et al. (2005)

Term	Definition	Source
Hazard	Process with the potential to result in some type of undesirable outcome. Hazards are described in terms of scenarios, which are specific events of a particular frequency and magnitude.	BGC
Inactive Alluvial Fan	Portions of the fan that are removed from active hydrogeomorphic or avulsion processes by severe fan erosion, also termed fan entrenchment.	BGC
LiDAR	Stands for Light Detection and Ranging, is a remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth. These light pulses - combined with other data recorded by the airborne system - generate precise, three-dimensional information about the shape of the Earth and its surface characteristics.	National Oceanic and Atmospheric Administration, (n.d.).
Likelihood	Conditional **probability** of an outcome given a set of data, assumptions and information. Also used as a qualitative description of **probability** and **frequency**.	Fell et al. (2005)
Melton Ratio	Watershed relief divided by square root of watershed area. A parameter to assist in the determination of whether a creek is susceptible to flood, debris flood, or debris flow processes.	BGC
Nival	Hydrologic regime driven by melting snow.	Whitfield, Cannon and Reynolds (2002)
Orphaned	Without a party that is legally responsible for the maintenance and integrity of the structure.	BGC
Paleofan	Portion of a fan that developed during a different climate, base level or sediment transport regime and which will not be affected by contemporary geomorphic processes (debris flows, debris floods, floods) affecting the active fan surface	BGC
Paleochannel	An inactive channel that has partially been infilled with sediment. It was presumably formed at a time with different climate, base level or sediment transport regime.	BGC
Pluvial – hybrid	Hydrologic regime driven by rain in combination with something else.	BGC

Term	Definition	Source
Probability	A measure of the degree of certainty. This measure has a value between zero (impossibility) and 1.0 (certainty) and must refer to a set like occurrence of an event in a certain period of time, or the outcome of a specific event. It is an estimate of the **likelihood** of the magnitude of the uncertain quantity, or the **likelihood** of the occurrence of the uncertain future event. There are two main interpretations: i) Statistical – **frequency** or fraction – The outcome of a repetitive experiment of some kind like flipping coins. It includes also the idea of population variability. Such a number is called an “objective” or relative frequentist probability because it exists in the real world and is in principle measurable by doing the experiment. ii) Subjective (or Bayesian) probability (degree of belief) – Quantified measure of belief, judgement, or confidence in the **likelihood** of an outcome, obtained by considering all available information honestly, fairly, and with a minimum of bias. Subjective probability is affected by the state of understanding of a process, judgement regarding an evaluation, or the quality and quantity of information. It may change over time as the state of knowledge changes.	Fell et al. (2005)
Return Period (Recurrence Interval)	Estimated time interval between events of a similar size or **intensity**. Return period and **recurrence interval** are equivalent terms. Inverse of **frequency**.	BGC
Risk	Likelihood of a geohazard scenario occurring and resulting in a particular severity of consequence. In this report, risk is defined in terms of safety or damage level.	BGC
Rock (and debris) Slides	Sliding of a mass of rock (and debris).	BGC
Rock Fall	Detachment, fall, rolling, and bouncing of rock fragments.	BGC
Scour	The powerful and concentrated clearing and digging action of flowing air or water, especially the downward erosion by stream water in sweeping away mud and silt on the outside curve of a bend, or during a time of flood.	American Geological Institute (1972)
Steep-creek flood	Rapid flow of water and debris in a steep channel, often associated with avulsions and bank erosion and referred to as debris floods and debris flows.	BGC

Term	Definition	Source
Steep Creek Hazard	Earth-surface process involving water and varying concentrations of sediment or large woody debris. (see Appendix B of this report for detailed definition).	BGC
Uncertainty	Indeterminacy of possible outcomes. Two types of uncertainty are commonly defined: a) Aleatory uncertainty includes natural variability and is the result of the variability observed in known populations. It can be measured by statistical methods, and reflects uncertainties in the data resulting from factors such as random nature in space and time, small sample size, inconsistency, low representativeness (in samples), or poor data management. b) Epistemic uncertainty is model or parameter uncertainty reflecting a lack of knowledge or a subjective or internal uncertainty. It includes uncertainty regarding the veracity of a used scientific theory, or a belief about the occurrence of an event. It is subjective and may vary from one person to another.	BGC
Waterbody	Ponds, lakes and reservoirs	BGC
Watercourse	Creeks, streams and rivers	BGC

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APPENDIX B
SITE PHOTOGRAPHS

Photo 1.

Goat River Dam, approximately 11 km upstream of the outlet to Kootenay River, looking upstream (northwest). Photo: BGC, July 16, 2019.

Photo 2.

Standing on left bank of Goat River looking upstream (west) at large woody debris in the main channel, approximately 500 m downstream of the north Highway 21 Bridge. Photo: BGC, July 16, 2019.

Photo 3.

Standing on right bank of Goat River looking upstream (west) at the north Highway 21 Bridge crossing the main channel. Photo: BGC, July 16, 2019.

Photo 4.

Standing under south Highway 21 bridge in dry Goat River channel. Photo: BGC, July 16, 2019.

Photo 5.

Looking across the Goat River at large woody debris in the channel, approximately 500 m downstream of the north Highway 21 Bridge. Photo: BGC, July 16, 2019.

Photo 6.

Signs of recently ponded water along the Goat River floodplain, approximately 500 m downstream of the north Highway 21 Bridge. Photo: BGC, July 16, 2019.

Photo 7.

Standing on gravel bar looking at right bank and a second channel of Goat River, approximately 500 m downstream of the north Highway 21 Bridge. Photo: BGC, July 16, 2019.

Photo 8.

Wolman sample location, on left bank looking downstream (east), approximately 100 m upstream of north Highway 21 Bridge. Photo: BGC, July 16, 2019.

Photo 9.

Standing on crest of Kootenay River Dike, approximately 1.5 km downstream of the Goat River's confluence with the Kootenay River. Photo: BGC, July 16, 2019.

Photo 10.

Standing on crest of Kootenay River Dike, approximately 1.5 km downstream of the Goat River's confluence with the Kootenay River, looking across the Kootenay river at the left (southeast) bank. Photo: BGC, July 16, 2019.

APPENDIX C
HYDROLOGICAL ANALYSIS METHODS

C.1. INTRODUCTION

Estimating flood magnitude is of fundamental importance to reliable floodplain mapping. As most watercourses are not gauged, flood magnitude is commonly estimated for an ungauged watershed using a Regional Flood Frequency Analysis (Regional FFA). There are several methods to complete a Regional FFA. This appendix documents the methodology followed by BGC Engineering Inc. (BGC) for the regionalization of floods in British Columbia using the index-flood method (Dalrymple 1960).

This appendix begins with a description of Regional FFA and the index-flood method (Section C1.0). The study area over which the index-flood is developed is discussed in Section C2.0. The data acquisition and compilation to support the analysis is described in Section C3.0. A description of the methods and assumptions for the regionalization of floods is included in Section C4.0. Results for the different hydrologic regions that cover the Regional District of Central Kootenay (RDCK) are presented in Section C5.0, while the application of the index-flood method to ungauged watersheds in the RDCK is presented in Section C6.0. Finally, the limitations of the study are discussed in Section C7.0.

C.1.1. Regional FFA

Extreme events are rare by definition and record lengths at hydrometric stations are often short. Regional FFA accounts for short record lengths by trading space for time where flood events at several hydrometric stations are pooled to estimate flood magnitude in a homogeneous region. Homogeneous regions can be defined as geographically contiguous regions, geographically non-contiguous regions, or as hydrological neighbourhoods. Grouping watershed areas of similar watershed characteristics into homogeneous regions is a critical part of Regional FFA because hydrologic information can be transferred accurately only within a region that is homogeneous. The more homogeneous a region is, the more reliable the flood quantile estimates. Some heterogeneity may be deemed acceptable in some cases. Studies show that even moderately heterogeneous regions can yield more accurate flood quantile estimates than a single-station FFA (Hosking & Wallis, 1997).

C.1.2. Index-flood Method

Several methods have been developed to conduct a Regional FFA in homogeneous regions. Among the quantile estimation methods, the index-flood is considered superior to other models (Ouarda et al., 2008). The index-flood is a method of regionalization with a long history in FFA (Dalrymple, 1960). The index-flood method involves the development of a dimensionless regional growth curve assumed to be constant within a homogenous region. The index-flood method also requires the selection of an index-flood which can be the mean annual flood, the median annual flood, or another quantile of choice calculated at each hydrometric station in the region.

The probability distribution of flood events at hydrometric stations in a homogeneous region are identical apart from a site-specific scaling factor, the index-flood. The parameters of the probability distribution are estimated at each hydrometric station. These at-site estimates are combined using a weighted average to generate a regional estimate. The regional growth curve is thus a dimensionless quantile function common to every hydrometric station in the region and takes on the following form (Eq. C-1):

$$X_T = Q_T \,/\, Q_m \qquad \text{[Eq. C-1]}$$

where X_T is the growth factor for return period $_T$, Q_T is the flood magnitude at return period $_T$, and Q_m is the index-flood magnitude. The flood magnitude at any return period is calculated using this relationship given the index-flood estimate.

C.1.3. Application to Ungauged Watersheds

The index-flood method can be applied to an ungauged watershed by developing a regional relationship between the index-flood and watershed characteristics at hydrometric stations in the region. The relationship can be expressed in many forms including a multivariate linear regression. Flood events can be assumed to depend on the characteristics of individual watersheds such as area, elevation, percent lake, forest coverage, mean annual precipitation, mean annual temperature, etc. Once the watershed characteristics are extracted at the ungauged site, the index-flood can be estimated. The flood magnitude of any annual exceedance probability (AEP) can be estimated for an ungauged watershed using the index-flood estimate and the regional growth curve by re-organizing equation Eq. C1-1.

C.2. STUDY AREA

A Regional FFA for British Columbia represents a considerable challenge given its regional variations in precipitation caused by sharp changes in topography as well as diverse geology. The proportion of annual precipitation that falls as snow as opposed to rain increases with latitude, elevation, and distance from the Pacific Ocean. Significant regional variations in precipitation are observed in British Columbia, influenced by the various mountain ranges. Storms approaching the West Coast are lifted rapidly along the windward mountain slopes, resulting in widespread precipitation. A rain shadow is created on the lee side of the mountains. For example, Tofino receives an average of 3,160 mm of annual precipitation while Nanaimo, on the east coast of Vancouver Island, receives 1,060 mm.

This climate pattern is repeated several times from east to west. As the weather systems approach the Coast Mountains, orographic effects result in twice as much precipitation in North Vancouver compared to Vancouver proper. Moving to the east, the Okanagan Valley is located on the lee side of the Coast Mountains resulting in an arid to semi-arid climate with annual precipitation on the order of 350 mm. The cycle is repeated over the Monashees, the Columbia Trench, and the Rocky Mountains. These orographic effects impact flood events and complicate regionalization efforts due to significant areal variations in precipitation, even for small watersheds. These significant variations in precipitation suggest that a multivariate approach to regionalization is practical for British Columbia.

Similar to precipitation, surficial geology in the province demonstrates significant spatial variability. This variability is important in that while two watersheds may be located in a similar precipitation zone, the hydrologic response can be significantly different. Watersheds dominated by colluvial veneers and bedrock will tend to have larger unit peak discharges, than those mantled by coarse morainal sediment, with the latter tending to attenuate peak discharges through available soil moisture storage. To avoid introducing boundary effects at the border with the Unites States and Alberta, the study area was extended to include the northern portion of Washington, Idaho, and Montana as well as the eastern Slopes of the Rocky Mountains. A map of the study area is presented in Figure C-1.

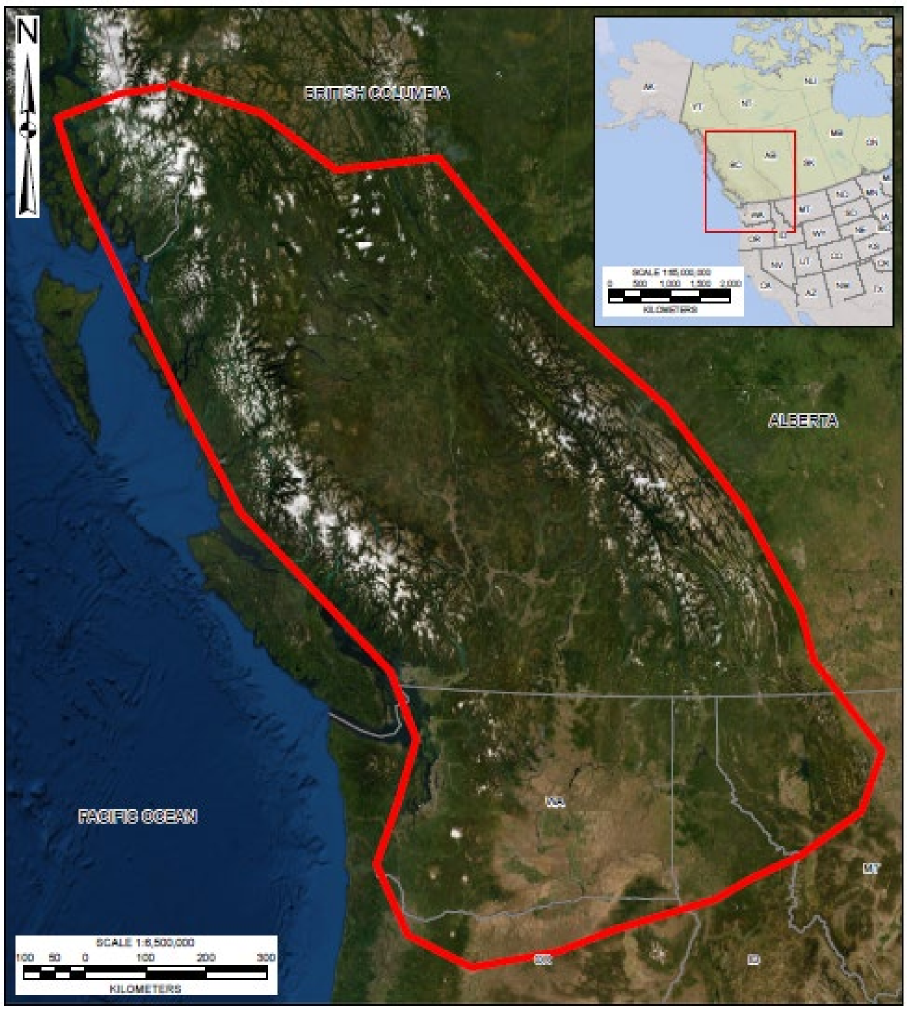

Figure C-1. Study area where the red outline defines the boundary.

C.3. DATA ACQUISITION AND COMPILATION

A large component of this study consisted of acquiring the data and compiling it in a format that was usable for analysis. Suitable hydrometric stations in the study area were identified and the flood records were acquired from the appropriate monitoring agency. The watershed polygons upstream from the hydrometric stations were then delineated and the area calculated using methods specific to the scale of the watershed. Lastly, a suite of watershed characteristics was selected based on potential to influence flood events. These watershed characteristics were extracted for each polygon. The acquisition and the compilation of this rich dataset was the most time-consuming portion of the procedure. The following sections include a detailed description of how the data were acquired and how the dataset was compiled for analysis.

C.3.1. Hydrometric Stations

A total of 3,309 hydrometric stations are located within the study area. Of these, 2115 are managed by the Water Survey of Canada (WSC) and the remaining 1194 are managed by the United States Geological Survey (USGS).

C.3.2. Flood Records

As an initial step, all flood events recorded at the hydrometric stations were extracted. This extraction was challenging as records are stored differently by the WSC and USGS. In Canada, flood events are stored in the HYDAT database, which includes the annual maximum peak instantaneous discharge, the maximum average daily discharge, as well as the date and time of each event. The watershed area and the number of years on record are also available in the HYDAT database. The flood records were acquired directly from the HYDAT database for hydrometric stations in Canada. In the US, flood events are stored online on websites specific to each hydrometric station. The annual maximum peak instantaneous discharge, the watershed area, and the number of years on record are also stored in this way. This information was extracted from the online storage space using a programming script for each USGS hydrometric station.

C.3.3. Maximum Peak Instantaneous Discharge

The preferred metric for analysis is the annual maximum peak instantaneous discharge. However, it is not uncommon for flood records to have more annual maximum average daily discharge records than peak instantaneous values, which are greater in magnitude. The ratio (I/D) between maximum peak instantaneous and maximum average daily discharge is typically greater for small watersheds than for very large watersheds. Therefore, where only a maximum daily discharge is reported for some years, maximum peak instantaneous discharge values can be estimated from available maximum average daily discharge records using regression analysis.

The reliability of the regression analysis was judged based on the coefficient of determination (R^2) in combination with the Cook distance (D). The R^2 is the proportion of the variance in the peak instantaneous discharge that is predictable from the average daily discharge. The D value is computed for every record within a sample and is used to assess the influence of each record on the regression (e.g., outliers). The regression analysis was deemed acceptable by BGC if the R^2 is above 0.95 and the maximum D value was less than 25. In this case, the maximum peak instantaneous discharge record was extended using the regression analysis for a longer record length. Alternatively, maximum peak instantaneous discharge record remained as-is where the regression analysis was deemed unacceptable.

C.3.4. Watershed Polygons

The watershed polygons at hydrometric stations within the study area were estimated using two different approaches.

1. River Networks Tools™[1] (RNT)
2. Using an Environmental Systems Research Institute (ESRI) process (i.e., GIS-based).

The RNT-based approach is dependent on the delineation of a stream network, while the ESRI-based process is dependent on topographic data. Watershed polygons were defined for all hydrometric stations located within the study area. Watershed delineation based on a stream network was observed to be more reliable for small watersheds, especially where topographic relief is low. The watershed polygons defined by the ESRI process were selected for larger watersheds (>1,000 km^2), while the RNT-based approaches were selected for smaller watershed areas (<1,000 km^2). The selection of the best watershed polygon for analysis could not be checked directly as the monitoring agencies (WSC and USGS) do not publish polygon shape information.

C.3.5. Watershed Areas

The watershed area was estimated for each watershed polygon (RNT, modification based on RNT, and ESRI) at each hydrometric station. The watershed area for each polygon was then compared with the value published by the respective monitoring agency. The watershed area published by monitoring agencies is generally considered most reliable (although recognizing many of the watershed areas for the WSC stations were calculated with 1:50,000 scale mapping and may not reflect more recent topographic mapping) and was used to quality check the calculated areas.

The estimated value of the watershed area was deemed acceptable if it was within ±15% of the published value. If more than 1 watershed area estimate (of the 3) was within ±15% of the published value, the watershed area with the smallest difference relative to the published value was selected as the best estimate for analysis. Approximately 90% of watershed polygons were within ±15% of the published value.

Published values are not available for all hydrometric stations. In those cases, the watershed area was deemed acceptable if the 3 estimates were within ±15% of each other. Watershed areas that did not meet the ± 15% criteria were not included in the analysis. A total of 2269 hydrometric stations were removed from the analysis because either the watershed area was deemed unreliable or water level data only was recorded at the station. Manual quality checks were not completed for these watersheds due to the time-consuming nature of this effort. The number of hydrometric stations lost that could have been considered useful is considered negligible. The

[1] The RNT is a proprietary software developed by BGC. RNT is based on publicly available 1:24,000-scale or better topographic and hydrographic datasets throughout North America that BGC has compiled and systematically developed to support a wide range of hydrotechnical calculations (e.g., watershed area) and site-specific precipitation and flood monitoring.

number of hydrometric stations in the study area is summarized in Table C-1. The ESRI watershed polygons were used for the hydrometric stations at the border between Canada and the United States because the polygons based on the two RNT approaches are observed to be poorly delineated due to differences in data resolution available between both countries.

Table C-1. Number of hydrometric stations in the study area.

Criteria	Number
Hydrometric Stations in Study Area	3284
Station with Unacceptable Watershed Area Estimates	2269
Stations with Acceptable Watershed Area Estimates	1015

C.3.6. Watershed Characteristics

Watershed characteristics were selected based on potential to influence flood events. A suite of 18 watershed characteristics was ultimately selected and estimated for each hydrometric station, as summarized in Table C-2. Several data sources were used to compile the watershed characteristics which are described in the following sections.

C.3.6.1. Watershed Statistics

The Shuttle Radar Topography Mission (STRM) dataset (Farr et al. 2007) was used to extract the watershed elevation statistics. The watershed elevation statistics were averaged over the watershed area. This dataset was used to calculate the watershed area (just for watersheds over 1000 km^2), relief, length, and slope. The centroid statistics were also extracted from this dataset.

C.3.6.2. Climate Variables

The Climate North America (ClimateNA) dataset was used to estimate the climate variables for each watershed polygon (Wang et al., 2016). The climate variables were averaged over the watershed area and were based on the average for the period 1961 to 1990.

Table C-2. List of selected watershed characteristics.

Type	No.	Acronym	Characteristic	Units	Dataset
Watershed	1	Centroid_Lat	Latitude at the centroid location in the watershed polygon	degrees	STRM
	2	Centroid_Long	Longitude at the centroid location in the watershed polygon	degrees	
	3	Centroid_Elev	Elevation at the centroid location in the watershed polygon	m	
	4	Area	Area of the watershed polygon	km^2	
	5	Relief	Maximum minus minimum watershed elevation	m	
	6	Length	Area divided by perimeter	km	
	7	Slope	Watershed length divided by relief times 100	%	
Climate	8	MAP	Mean annual precipitation	mm	Climate NA
	9	MAT	Mean annual temperature	ºC	
	10	PAS	Precipitation as snow	mm	
	11	PPT_wt	Winter precipitation (Dec, Jan, Feb)	mm	
	12	PPT_sp	Spring precipitation (Mar, Apr, May)	mm	
	13	PPT_sm	Summer precipitation (Jun, Jul, Aug)	mm	
	14	PPT_fl	Fall precipitation (Sep, Oct, Nov)	mm	
Physiographic	15	Forest	Forest cover in the watershed	%	NALCMS
	16	Water_Wetland	Wetland and open water cover in the watershed	%	
	17	Urban	Urban cover in the watershed	%	
	18	CN	Inferred based on integrating land cover and soils cover	unitless	NALCMS and HYSOGs250m

C.3.6.3. Land cover

The North American Land Change Monitoring System (NALCMS) land cover products include the 2005 land cover map of North America. This dataset includes 19 land cover classes derived from 250 m Moderate Resolution Spectroradiometer (MODIS) image composites (Latifovic et al., 2012). This dataset was used to calculate the percent forest, percent wetland and lake, and the urban portion of the watershed.

C.3.6.4. Curve Number

The curve number (CN) is an empirical parameter used for predicting runoff from rainfall. BGC integrated the land cover (NALCMS) and the hydrologic soils group (HYSOGs250m) datasets to infer the average CN over each watershed. The NALCMS dataset is described in Section C.3.6.3. The HYSOGs250m dataset represents typical soil runoff potential at a 250 m spatial resolution (Ross et al., 2018). Hydrologic soils groups are defined based on soil texture, depth to bedrock or depth to groundwater. There are four basic groups: A, B, C, D. Four additional groups are included where the depth to bedrock is considered to be less than 60 cm: AD, BD, CD, and DD. The area covered by each hydrologic soils group is summed for a total area over the watershed for each hydrologic soils group.

The CN was assigned following guidance from the USGS (1986). The CN values for soils where the depth to bedrock or depth to groundwater.is expected to be less than 0.6 m from the surface (i.e., D soils) were assumed to be the same as the case where it is not expected to be close to the ground surface. The CN value assignment for the combinations of land cover and hydrologic soils groups identified in the watersheds is presented in Table C-3. The CN values were averaged over the watershed area using a weighted mean. The weight reflects the percentage of the area covered by a given CN value.

Table C-3. CN values based on the integration between the land cover and soils datasets.

Land Cover (NALCMS 2005)	Cover Type (USGS 1986)	Soils			
		HSG-A	HSG-B	HSG-C	HSG-D
Temperate or sub-polar needleleaf forest	Woods - Good	30	55	70	77
Temperate or sub-polar broadleaf deciduous forest	Woods - Good	30	55	70	77
Mixed forest	Woods - Good	30	55	70	77
Temperate or sub-polar shrubland	Brush - brush-weed-grass mixture with brush the major element - Fair	35	56	70	77
Temperate or sub-polar grassland	Pasture, grassland, or range—continuous for grazing - Good	39	61	74	80
Sub-polar or polar grassland-lichen-moss	Pasture, grassland, or range—continuous for grazing - Good	39	61	74	80
Sub-polar or polar barren-lichen-moss	Desert shrub - major plants include saltbrush. Greasewood, creosotebush, blackbrish, bursage, palo verde, mesquite, and cactus - good	49	68	79	84
Sub-polar taiga needleleaf forest	Woods - Good	30	55	70	77
Cropland	Row crops - straight row (SR)	63	74	81	85
Barren land	Desert shrub - major plants include saltbrush. Greasewood, creosotebush, blackbrish, bursage, palo verde, mesquite, and cactus - good	49	68	79	84
Urban and built-up	Urban districts - commercial and business	89	92	94	95
Snow and ice	NA	0	0	0	0
Wetland	NA	0	0	0	0
Water	NA	0	0	0	0

C.4. METHODS AND ASSUMPTIONS

Once the dataset is compiled for analysis, the regionalization of floods procedure can begin. A description of the methods and assumptions for the index-flood method is included in this section.

C.4.1. Flood Statistics Calculations

Flood statistics were calculated using the flood record at each of the selected hydrometric stations (2101) in the study area. Flood statistics include L-moments and flood quantile estimates.

C.4.1.1. L-moments

The L-moment approach in the index-flood procedure was used by BGC for the regionalization of floods in British Columbia. The shape of a probability distribution has traditionally been described by the moments of the distribution including the mean, standard deviation, skewness, and kurtosis. However, moment estimators have some undesirable properties where the skewness and kurtosis can be severely biased. Both have algebraic bounds that depend on the sample size (Hosking & Wallis 1997).

L-moments are an alternative system for describing the shape of probability distributions. Studies have shown that L-moments are unbiased, less sensitive to outliers, and are better estimators of distribution parameters especially for short to moderate record length (Hosking, 1990). Furthermore, L-moments allow for the efficient computation of parameter estimates and flood quantile estimates.

L-moments evolved as modifications to the probability weighted moments (Greenwood et al., 1979). In terms of probability weighted moments, L-moments are defined as λ_1, λ_2, λ_3, and λ_4 with their mathematical expressions published for a range of probability distributions in Hosking and Wallis (1997, Appendix).

Dimensionless versions of L-moments are defined as L-moment ratios by dividing the higher order L-moments by λ_2. L-moment ratios are defined by Eq. C-2:

$$\tau_r = \lambda_r / \lambda_2 \qquad \text{[Eq. C-2]}$$

L-moment ratios depict the shape of a distribution independently of its scale measurement. Refer to Table C-4 for L-moment terminology.

Table C-4. L-moment terminology.

Symbol (population)	Symbol (sample)	Definition
λ_1	ι_1	L-location or the mean of the distribution
λ_2	ι_2	L-scale
τ	t	L-CV
τ_3	t_3	L-skewness
τ_4	t_4	L-kurtosis

C.4.1.2. At-site Peak Discharge Estimates

The flood quantile estimates at hydrometric stations are referred to as 'at-site' estimates and are used to compare with the modeled quantile estimates to assess the validity of the model. Flood quantile estimates were calculated using the flood data by means of a single-station FFA. A popular approach in FFA is the Annual Maximum Series (AMS) where the maximum peak instantaneous discharge for each year on record is used for analysis. The basic assumption is that the flood events are independent and identically distributed from a single population of flood events.

A probability distribution is selected to describe the flood events in the record. The true form of the underlying probability distribution is not known and there is no standard distribution appropriate in all cases. The goal is to select a probability distribution that fits the observed data well but also generates robust quantile estimates that are not sensitive to physical deviations of the true probability distribution (Hosking & Wallis, 1997). In extreme value statistics, data follow one of three extremal types of distributions: Gumbel, Fréchet, or Weibull (Coles, 2001). These three distributions can be expressed as a single formula and are considered a family of distributions known as the Generalized Extreme Value (GEV) distribution. The GEV distribution is shown to arise as an asymptotic model for maximum values in a sample and hence can be viewed as a natural model for observed flood events. In addition, the GEV distribution has been identified as a preferred probability distribution for at-site flood quantile estimates in Canada (Zhang et al., 2019). For these reasons, the GEV distribution was used to describe the recorded flood events. No statistical tests were used to assess this choice because the GEV distribution is considered flexible to account for the variability captured at a single hydrometric station.

The parameters of the GEV distribution were estimated using the L-moments. The flood quantiles were calculated for a range of return periods (Table C-5). The reliability of the quantile estimates depends on a range of factors including the record length and the range of flood event magnitudes captured in the record. The longer the record length, the more reliable the quantile estimates.

Table C-5. Return period and associated AEP.

Return Period (Years)	AEP
2	0.5
5	0.2
10	0.1
20	0.05
50	0.02
100	0.001
200	0.005
500	0.002

C.4.2. Formation of Hydrological Regions

The watershed characteristics extracted over the watershed polygons were used to group the hydrometric stations into hydrological regions using a cluster analysis. Cluster analysis is an objective method for creating regions (Tasker, 1982) which historically were based subjectively using geographical, political, administrative or physiographic boundaries. The essence of cluster analysis is to identify clusters (groups) of hydrometric stations such that the stations within a cluster are similar while there is dissimilarity between the clusters. Hosking and Wallis (1997) suggest that cluster analysis is the most practical method of forming regions for large datasets and provides several opportunities for subjective adjustments to the regions. The algorithm used by BGC to group hydrometric stations is Agglomerative Hierarchal Clustering.

C.4.2.1. Data Preparation

The watershed characteristics at each hydrometric station were normalized so that the average is zero and the standard deviation is approximately 1. The distance metric used is the Euclidian distance between the watershed characteristics. The suite of watershed characteristics at all hydrometric stations were compared to one another and organised using Ward's Distance measure (d) (Ward, 1963).

C.4.2.2. Number of Hydrological Regions

Several statistical measures were used to guide the number of clusters to partition the hydrometric stations. The statistical measures include the Elbow Method, the Silhouette Score, and review of the dendrogram. The selection of the number of clusters was also subjectively assessed by reviewing the physical basis of the cluster distribution (e.g., is there a physical meaning behind the number and distribution of the clusters?).

The Elbow Method accounts for the percentage of variance explained as a function of the number of clusters. The percentage of the variance explained decreases with increasing number of clusters. The minimum number of clusters that provides the most gain in the variance explained was selected for analysis.

The Silhouette Score is a measure of how similar the watershed of a hydrometric station is to its own cluster compared to other clusters. The Silhouette Score was calculated for each hydrometric gauge station and averaged over each cluster. The Silhouette Score ranges from -1 to +1 where a high value indicates that the hydrometric stations are well matched to their own clusters and poorly matched to neighboring clusters.

The dendrogram represents how the clustering algorithm (i.e., agglomerative hierarchal clustering) groups the watersheds and depicts a road map of the merging procedure showing which watersheds were merged and when in order of increasing cluster distance.

The spatial distribution of the clusters was then reviewed to verify that they are physically plausible. This review was done by superimposing the clusters on a map of British Columbia to see whether there is a physical meaning supporting the cluster distributions.

C.4.2.3. Manual Adjustments of Hydrologic Regions

The clusters identified using the clustering algorithm were adjusted manually to increase homogeneity. The manual adjustments were completed by considering the topography, spatial patterns in hydrological processes, and ecozones in Canada. The clusters were further separated based on the scale of watershed area to respect the statistical requirement for constancy in the coefficient of variation (CV) for homogeneous regions.

C.4.2.4. Refinement of the Hydrometric Station Selection

The hydrometric station selection was refined to increase the homogeneity of the clusters by reducing the variability introduced by many hydrometric stations. The refinement process was guided by the following 5 criteria.

1. Watersheds upstream of hydrometric stations with a regulation level greater than 25% were not included for analysis. The level of regulation is inferred by proportion of the watershed area upstream of the dams to the total watershed area upstream of the hydrometric station.
2. The watershed area range considered in the regionalization extends up to 5,000 km^2. Watersheds with a greater watershed area size are most likely well gauged and studied that a regionalization of flood is not required.
3. Nested hydrometric stations along the same watercourse were also removed from the region to reduce cross-correlation.
4. A minimum of 6 years of maximum peak instantaneous discharge data was set as a minimum for analysis. While this threshold is low, it is considered adequate since the influence of each hydrometric stations on the model reflects the record length.
5. Hydrometric stations recording water level only were excluded from the analysis at the onset. Hydrometric stations recording water level and discharge measurements but located within or immediately at the outlet of lakes were also removed from the analysis.

The flow regime at these locations is considered heavily regulated precluding the use of frequency analysis to estimate peak discharge.

In addition to these criteria, discordancy (*Di*) was considered to refine the selection. The discordancy is measured in term of the L-moments of the data at the hydrometric stations within a cluster. The formal definition for *Di* is found in Hosking and Wallis (1997, equation 3.3, page 46). A hydrometric station is considered discordant if *Di* is "large". The definition of "large" depends on the number of hydrometric stations in the cluster. If the cluster includes more than 15 hydrometric stations, the critical value for the discordancy statistic is 3. Discordancy was calculated for each hydrometric station within each hydrologic region. Hydrometric stations with *Di* values greater than 3 were removed from the cluster. This process was re-iterated until no more hydrometric stations showed *Di* values greater than 3.

C.4.2.5. Testing for Homogeneity

The hypothesis for homogeneity is that the probability distribution of the flood events at the hydrometric stations within a cluster is the same except for a site-specific scale factor. The goal is to have clusters that are sufficiently homogenous that the regionalization of floods is advantageous to a single station FFA. Testing for homogeneity is done using the H-Test. The H-Test result helps assess whether the hydrometric stations in a cluster may reasonably be considered homogeneous. The formal definition for the H-Test is found in Hosking and Wallis (1997, equation 4.5, page 63). Of note, some level of heterogeneity is expected in these clusters due to the natural variability of hydrological processes that control flood events. The H-Test is not intended to be used as a significance test but rather as a guideline to inform whether the re-definition of a region could lead to a meaningful increase in the accuracy of the flood quantile estimates (Hosking and Wallis, 1993).

C.4.3. Regionalization

Once the clusters were considered sufficiently homogeneous, they were considered "hydrologic regions". The regionalization of floods was then completed for each region. The L-moment approach in the index-flood procedure was used by BGC for the regionalization exercise. The procedure for each hydrologic region included: averaging the L-moments, selecting a distribution, estimating the parameters, developing the growth curve, and estimating the index-flood. The mean annual flood (MAF) was selected as the index-flood for this study. The following sections describe the methods and assumptions for the regionalization of floods for a given hydrologic region.

C.4.3.1. Regional L-moments

The L-moment ratios were averaged over each hydrologic region. A weighted average was used where the weight reflected the number of observations at each hydrometric station. The weighted average was used to put more weight on hydrometric stations with a longer record length. The weighted average helps take advantage of all available data as it is often limited in many areas of the province. The regional average L-moment ratios are defined in Table C-6. The L-moment ratios are used rather than the L-moments because they yield slightly more accurate quantile estimates.

Table C-6. Definition for regional average L-moment ratios.

Symbol (sample)	Definition
ι_1^R	L-location or the mean of the distribution
ι_2^R	L-scale
t^R	L-CV
t_3^R	L-skewness
t_4^R	L-kurtosis

C.4.3.2. Distribution Selection for Growth Curves

The selection of an appropriate probability distribution for the growth curves was done using a goodness-of-fit test and review of L-moment ratio diagrams. These tests were completed to assess the variability imposed compiling the results of many hydrometric stations into a single growth curve. The goodness-of-fit test was based on 1,000 simulations and looked at a suite of candidate distributions. The candidate probability distributions included Generalised Logistic (GLO), Generalised Extreme Value (GEV), Generalised Pareto (GPA), Generalised Normal (GNO), and Pearson Type III (PE3). Probability distributions with Z statistics $\leq$1.64 were deemed acceptable (Hosking & Wallis, 1997). The regional L-moments were also plotted with the L-skewness and L-kurtosis relationships for two (Exponential (E), Gumbel (G), Logistic (L), Normal (N), and Uniform (U)) and three-parameter (GLO, GEV, GPA, GNP, PE3) candidate distributions in L-moment ratio diagrams. The plotting position of the regional L-moments was reviewed for the distribution selection that provided an acceptably close visual fit.

C.4.3.3. Parameter Estimation

The regional L-moments were used to estimate the parameters of the selected probability distribution. The equations used to estimate the parameters for the GEV distribution are found in Hosking and Wallis (1997, A.52, A.55, and A.56, page 196) in addition to other select probability distributions.

C.4.3.4. Growth Curves and Error Bounds

The index-flood was selected to be the MAF. As a result, the regional mean was set to 1 ($\iota_1^R = 1$). The probability distribution was fit by equating the L-moment ratios of the population (λ_1, τ, τ_3, τ_4) to the regional average L-moment ratios (ι_1^R, t^R, t_3^R, t_4^R).

One of the strengths of the Regional FFA completed using the regional L-moments is that the procedure is useful even when the assumptions are not all satisfied (e.g., possibility of heterogeneity, misspecification of the probability distribution, and statistical dependence between observations at different sites). An approach to estimate the accuracy of the estimated flood quantiles is by Monte Carlo simulation. A Monte Carlo simulation was therefore run to estimate the variability in the quantile estimates from the regional GEV distribution. This variability was used to set the error bounds on the regional growth curve.

C.4.3.5. Index-flood Estimation

The index-flood was estimated using a multiple linear regression. Regression is a classic statistical method to describe the relationship between a dependent variable (index-flood) and independent variables (watershed characteristics). The multiple linear regression model is expressed as follows:

$$Q_T = aA^b B^c \ldots N^n \quad \text{[Eq. C-3]}$$

where Q_T is the flood magnitude at return period $_T$, A, B, …, N are the watershed characteristics, a is the regression constant, and b, c, …, n are the regression coefficients. Base 10 logarithms are used to convert this equation to a linear form by transforming the variables to the following:

$$\log Q_T = \log a + b(\log A) + c(\log B) + \cdots + n(\log N) \quad \text{[Eq. C-4]}$$

These coefficients were estimated using the Weighted Least Squares method introduced by Tasker (1980), which accounts for the sampling error introduced by unequal record lengths. Unequal record lengths mean that the sampling errors of the observations (flood quantiles) are not equal (heteroscedastic) and the assumption of constant variance in Ordinary Least Squares method is not valid.

The top 5 models were selected using consideration for the adjusted R^2 and the Bayesian information criterion (BIC). The 5 models with the lowest BIC were selected and the index-flood estimate was averaged. Select diagnostic plots were reviewed to control the quality of the regressions. The diagnostic plots are listed in Table C-7. The index-flood model was developed over two scales: regional and provincial. These two scales were compared to assess the influence of the distribution of hydrometric stations on the reliability of the MAF estimate.

Table C-7. Diagnostic plots.

Plot	Diagnostic
At-site vs. Modeled	Inspect for a one to one relationship as close to as possible
At-site Quantile vs. Modeled Quantile	Inspect whether the distribution of the fitted values match the distribution of the observed values
At-site Quantiles vs. Modeled Residuals	Inspect for constancy in residuals. Residuals are the differences between the at-site and the modeled estimates

C.4.3.6. Regional Model

The first scale considered is the regional scale where the MAF was modeled over an area consistent with the hydrologic regions defined across the province. This scale is consistent with the scale used to do develop the regional growth curves.

C.4.3.7. Provincial Model

The second scale considered is the provincial scale where all hydrometric stations across the province, that meet the selection criteria, were used to model the MAF. The provincial model was developed to capture the range of hydrological processes that control flood events in British Columbia.

C.4.3.8. Flood Quantile Estimates

Flood quantile were than estimated using the regional growth curve and index-flood estimates (both scales) for all hydrometric stations in a given region. Quantile plots were generated to compare the at-site and modeled results over the range of AEPs.

C.4.3.9. Watershed Characteristic Transformations

The relationship between flood events and watershed characteristics need not be linear. Experience and judgement were used to guide the selection of independent variables and inform the relationship between flood events and watershed characteristics. An exhaustive comparison of correlations between flood magnitude and watershed characteristics showed that watershed area and watershed length are proportional to flood magnitude. For this analysis, the remaining watershed characteristics needed to be log transformed.

C.4.4. Error Statistics

The quality of the flood quantile estimates was assessed using select error statistics including the Root Mean Square Error (SRMSE), the Percent Error (SPE), and the Bias (SBIAS) for the following AEPs: 0.5, 0.1, 0.02, 0.005. The standardized version of the error statistics is used to account for the different scales (Table C-8).

Table C-8. Error statistics, definitions, and diagnostic.

Error Statistic (acronym)	Definition	Diagnostic
SRMSE	Standard deviation of the residuals.	Inspect how concentrated the modeled estimates are around the line of best fit.
SPE	The difference between the modeled and at-site estimate, divided by the at-site estimate, multiplied by 100%.	Inspect how close the modeled estimate is to the at-site estimate/
SBIAS	The tendency to overestimate or underestimate the modeled variable.	Inspect for a consistent over or underestimate of the modeled variable

The mathematical expressions for the SRMSE, SPE, and SBIAS are included below in Eq. C-5, Eq. C-6, and Eq. C-7.

$$SRMSE = \sqrt{\frac{\sum_{i=1}^{Np}\left(\frac{Qm_{mod}^{i} - Qm_{at-site}^{i}}{Qm_{at-site}^{i}}\right)}{Np}} \quad \text{[Eq. C-5]}$$

$$SPE = \frac{\sum_{i=1}^{Np} abs\left(\frac{Qm_{mod}^{i} - Qm_{at-site}^{i}}{Qm_{at-site}^{i}}\right)}{Np} * 100 \quad \text{[Eq. C-6]}$$

$$SBIAS = \frac{\sum_{i=1}^{Np} \left(\frac{Qm_{mod}^{i} - Qm_{at-site}^{i}}{Qm_{at-site}^{i}}\right)}{Np} \quad \text{[Eq. C-7]}$$

C.4.5. Decision Tree

A decision tree model was used to assign hydrologic regions to ungauged watersheds. A decision tree was built using the Random Forest classification algorithm. The decision tree model was based on the watershed characteristics at the hydrometric stations in the study area. A total of 500 random samples were pulled from the dataset (with replacement). From each random sample, a decision tree was generated by using 3 variables at each decision point. The hydrologic region assignment was based on majority votes. The out-of-bag (OBB) error rate was 7.2%. The OBB is a method of measuring the prediction error specific to random forest algorithms.

C.4.6. Statistical Software

The statistical software used by BGC for the analysis was R (R Core Team, 2019). R is a free software environment for statistical computing. The analysis is completed with support from several packages. These packages are listed in Table C-9 for reference.

Table C-9. Analysis and associated R package.

Analysis	R Packages	Authors
Flood Statistics	Lmom	J. R. M. Hosking
Clustering	stats	R Core Team
Discordancy, H-Test, Distribution Selection, Parameter Estimation, and Growth Curve Development	lmomRFA	J. R. M. Hosking
Index-flood Estimation	stats and leaps	R Core Team and Alan Miller
Random Forest decision tree	Rpart, randomForest	Andy Liaw and Matthew Wiener

C.5. RESULTS

C.5.1. Hydrometric Station Selection

A total of 1015 hydrometric stations were included in the analysis. The hydrometric stations were distributed across the study area with a greater concentration in the south compared to the north, largely reflecting population density. There is also a greater concentration of hydrometric stations in the United States than Canada (Figure C-2).

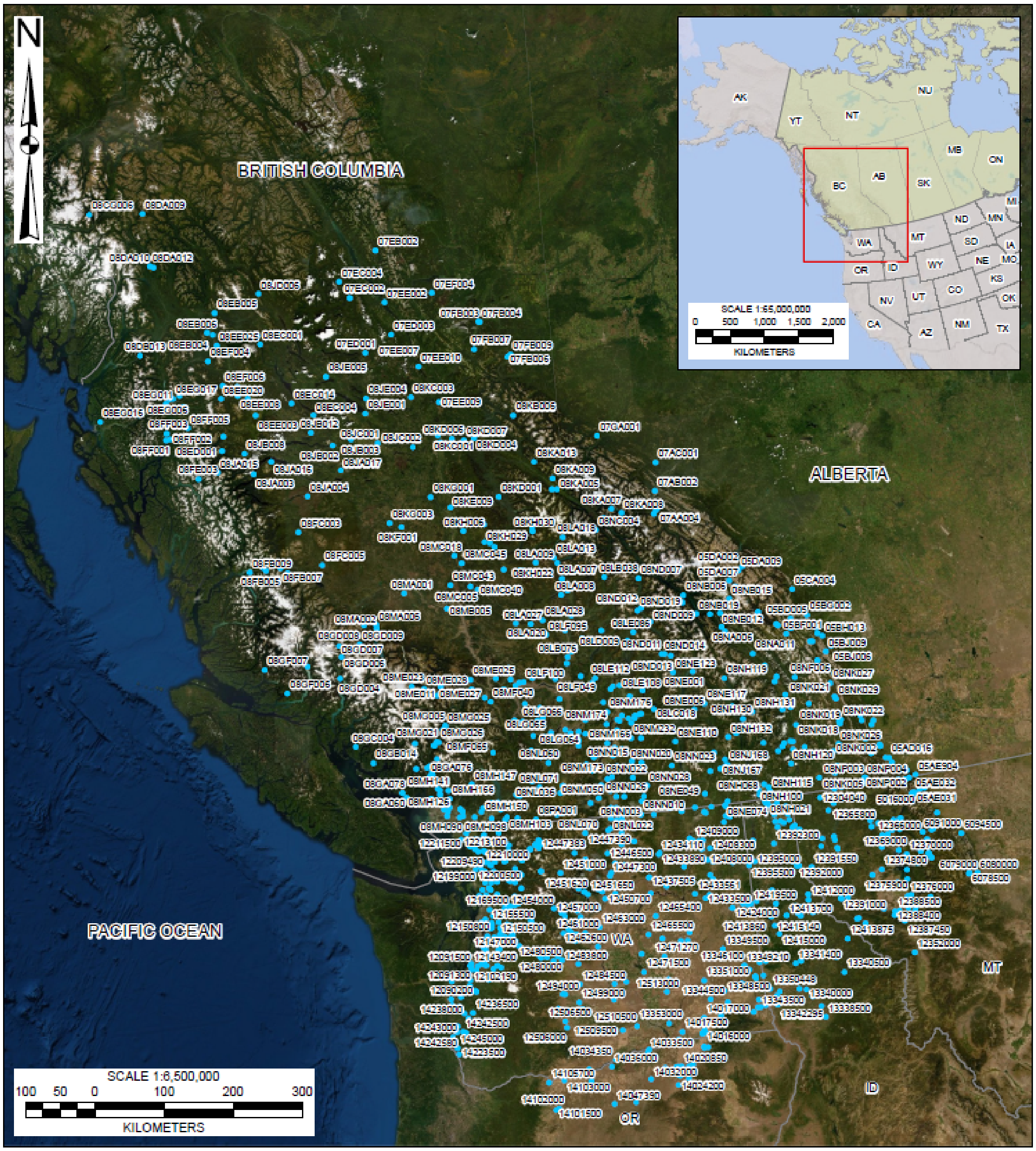

Figure C-2. Distribution of hydrometric stations within the study area.

The 18 watershed characteristics and their range in magnitude are summarized over the 1015 hydrometric stations in Table C-10. The climate watershed characteristics show a wide range in magnitude which is not surprising considering the sharp regional contrast imposed by the topography. The urban watersheds are concentrated in coastal Washington.

Table C-10. Summary of watershed characteristics, including the mean, maximum, and minimum values over all hydrometric stations considered for analysis (1,015).

Type	No.	Acronym	Mean	Min	Max	Standard Deviation
Watershed	1	Centroid_Lat	49.3092758	43.75066	57.094597	2.3
	2	Centroid_Long	-119.5562752	-130.965466	-112.917172	3.5
	3	Centroid_Elev	1,133	18	3,046	534
	4	Area	7,572	1.3	601,746	38,417
	5	Relief	1,639	19	4,355	791
	6	Length	5	0.2	71	7
	7	Slope	62	4	350	49
Climate	8	MAP	1,299	218	4,173	787
	9	MAT	4.1	-3.0	10.9	3.0
	10	PAS	499	25	2191	323
	11	PPT_wt	476	71	1,683	328
	12	PPT_sp	283	56	955	173
	13	PPT_sm	185	31	522	77
	14	PPT_fl	355	58	1,329	249
Physiographic	15	Forest	61	0	100	25
	16	Water_Wetland	1	0	18	2
	17	Urban	2	0	100	12
	18	CN	68	55	94	6

C.5.2. Formation of Hydrological Regions

Based on an interative selection process, the 1,015 hydrometric stations were ultimately organized into 10 clusters. The results of the Elbow Method showed that a selection of approximately 10 hydrological regions explained the most variance in the watershed characteristics (Figure C-3).

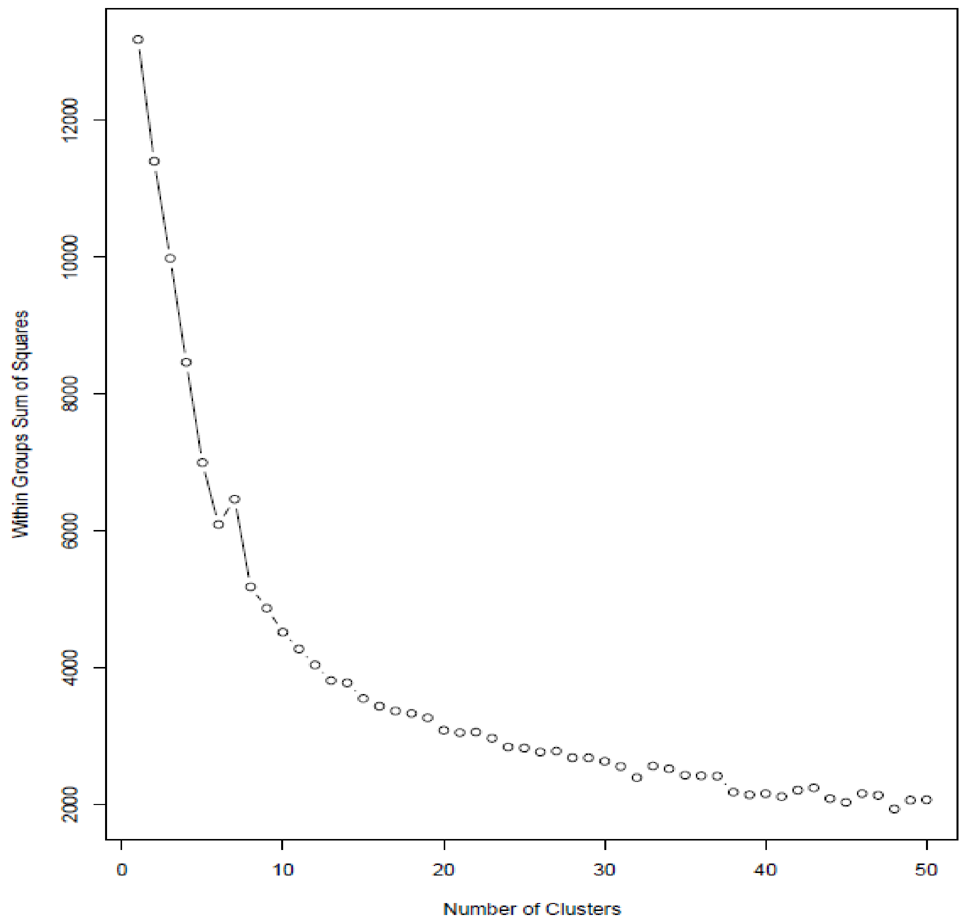

Figure C-3. The Elbow Plot.

The Silhouette Scores for the 10 clusters suggested some difficulty in organising the hydrometric stations based on watershed characteristics (Figure C-4). The average Silhouette Score is 0.2, suggesting that the hydrometric stations are poorly assigned to their hydrological regions. A low Silhouette Score is expected however, as it reflects the physical variability across the study area.

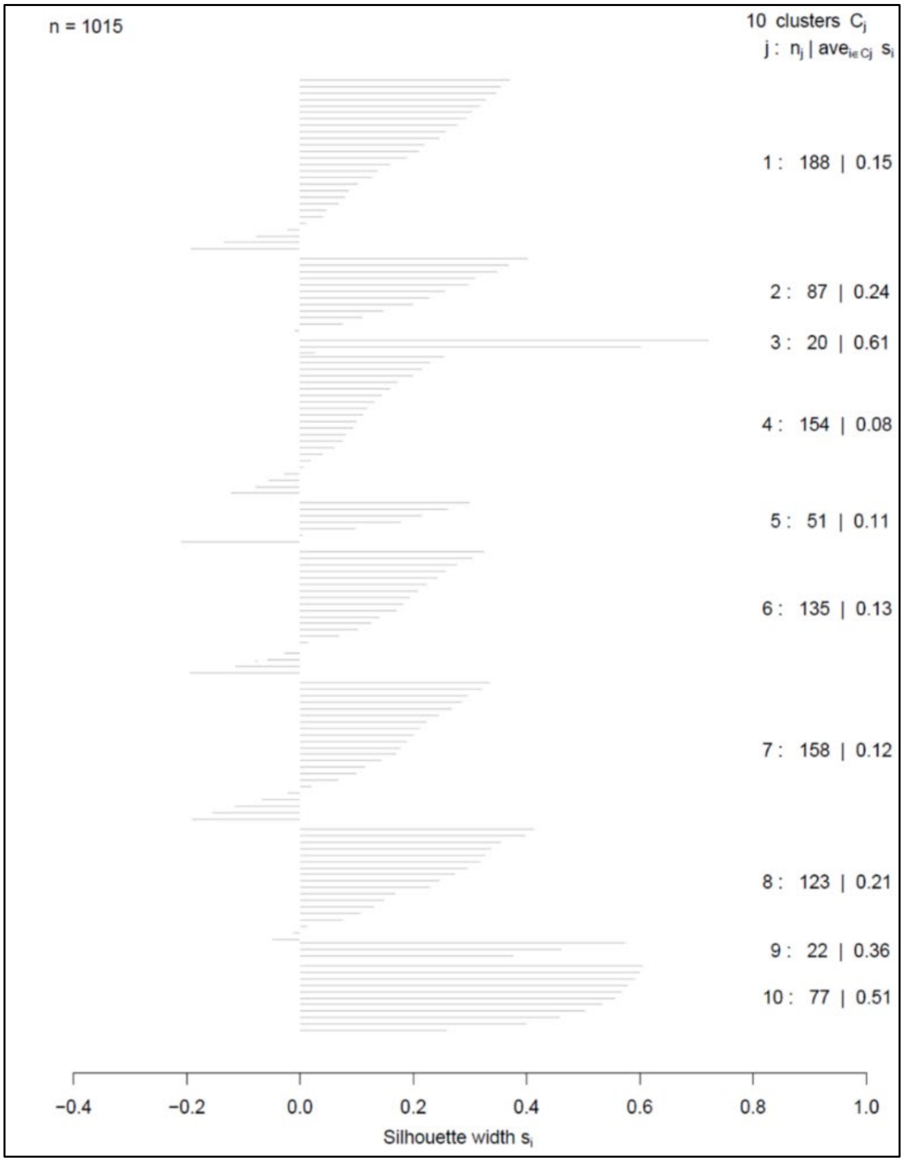

Figure C-4. Silhouette score.

The organization of the hydrometric stations into clusters is compiled in a dendrogram (Figure C-5). The y-axis is the dissimilarity index based on the distance metric. The horizontal axis represents the Ward's Distance (d). The green boxes separate the clusters. The 10 clusters are shown along the bottom of the dendrogram. Because we do not know how many clusters there should be in the landscape, the merging process was stopped once the clusters were more dissimilar than a threshold of approximately 90. The threshold was selected to generate a number of clusters consistent with the Elbow Plot.

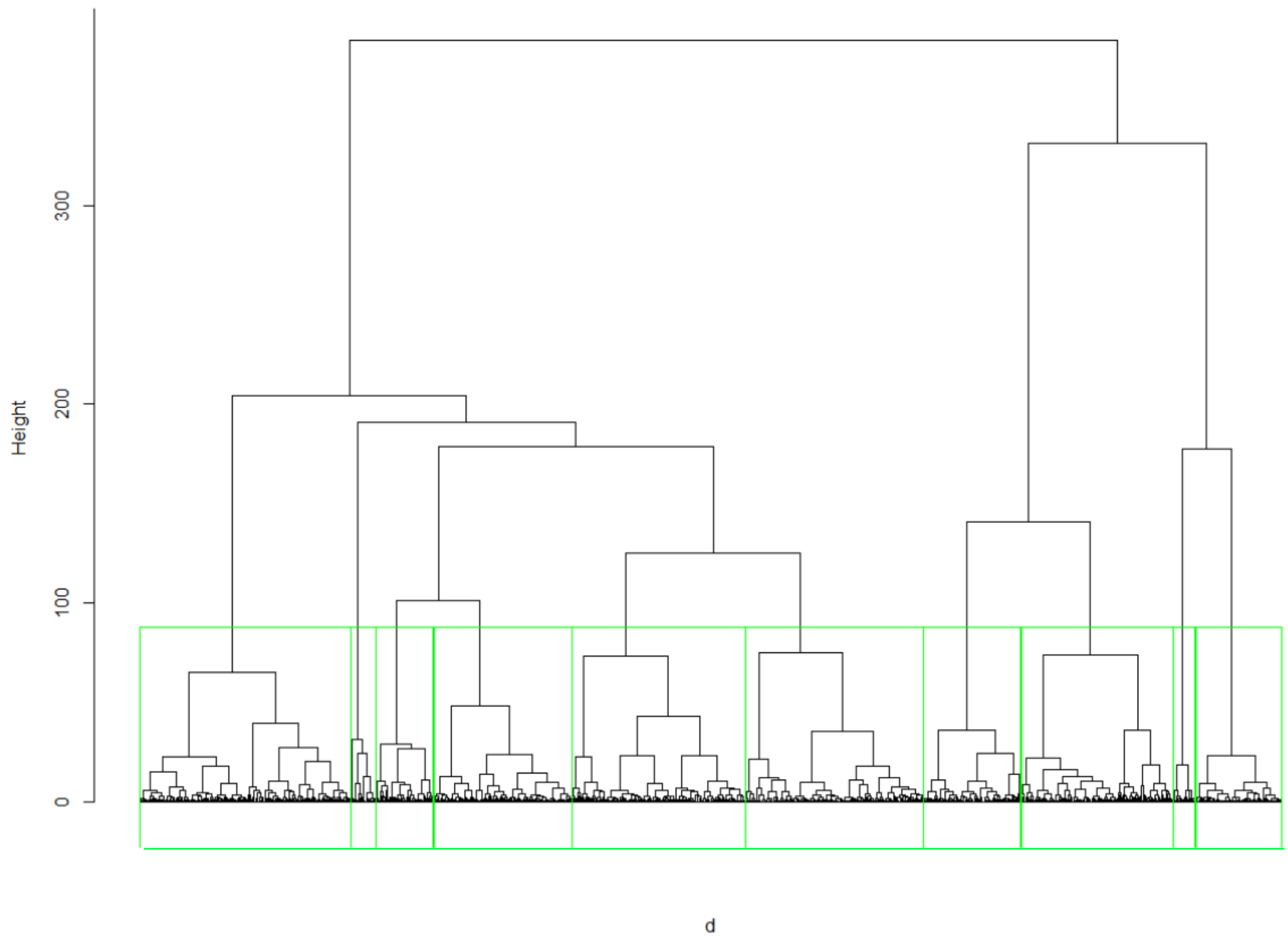

Figure C-5. Dendrogram.

C.5.2.1. Physical Basis of Regions and Flood Characteristics

The spatial distribution of the clusters is considered physically plausible, considering the range in the climate watershed characteristics. Significant regional variations are expected due to the influence of the mountain ranges across the study area (e.g., Coast Mountains, Monashees, the Columbia Trench, and the Rocky Mountains). These orographic effects are expected to control, at least in part, the distribution clusters (Figure C-6).

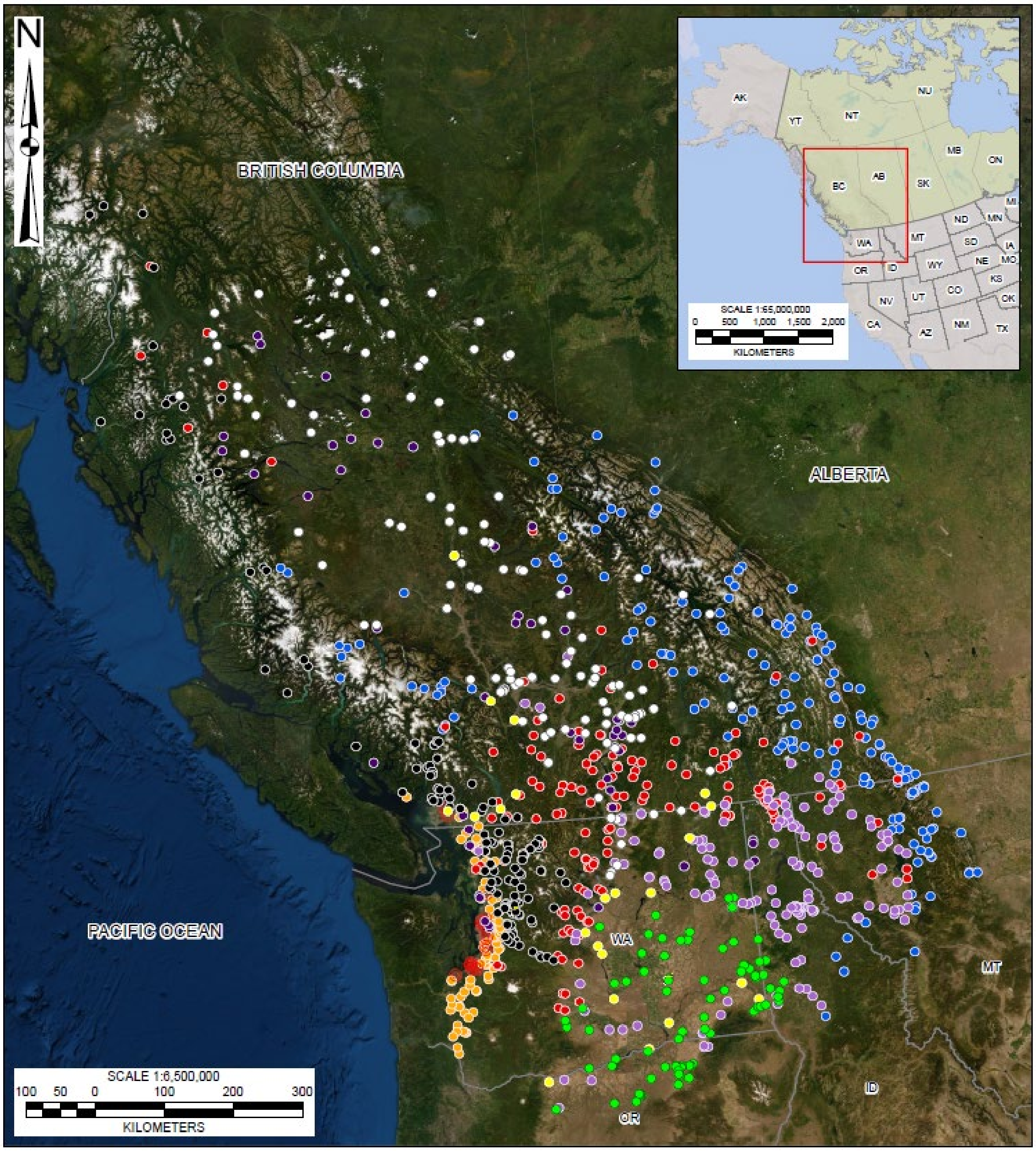

Figure C-6. Spatial distribution of 10 clusters.

The clusters that cover the RDCK region include 1 (blue), 4 (red), and 7 (lilac) with 188, 154, and 158 hydrometric stations, respectively. Cluster 1 is defined by the influence of the Rocky Mountains to the east forming the physiographic boundary with Alberta. Most flood events in this cluster are caused by snowmelt or rain-on-snow events in the spring. The eastern range of the Coastal mountains to the west also includes a small group of hydrometric station assigned to Cluster 1. Cluster 4 is defined generally by a climate characteristic of the semi-arid plateau between major mountain ranges. Most flood events are snowmelt dominated in the spring. In this drier climate, evaporation from water surfaces and from the land as well as transpiration from vegetation make up a large component of the regional water balance. Additional hydrometric stations assigned to Cluster 4 are in the montane cordillera to the east where flood events are often associated with rain-on-snow events during the spring freshet. Cluster 7 is defined by the southern edge of the Rocky Mountains in northwestern Montana. Significant floods in this region are caused by runoff from rain associated with moist air masses from the Gulf of Mexico, although most annual peak discharge events are from snowmelt or rain-on-snow events in the spring.

C.5.2.2. Manual Adjustments

The clusters were further separated manually due to the large number of hydrometric stations in each cluster. Cluster 1 was separated into the eastern and western ranges of the Rocky Mountains. The small group of hydrometric stations located along the eastern range of the Coastal Mountains were also separated from Cluster 1. Cluster 4 was separated into the eastern portion in the montane cordillera and the western portion in the semi-arid plateau. Cluster 7 was not separated due to the limited geographic spread of the hydrometric stations. Based on these manual adjustments, Cluster 1 West, 4 East, and 7 cover the RDCK region (Figure C-7).

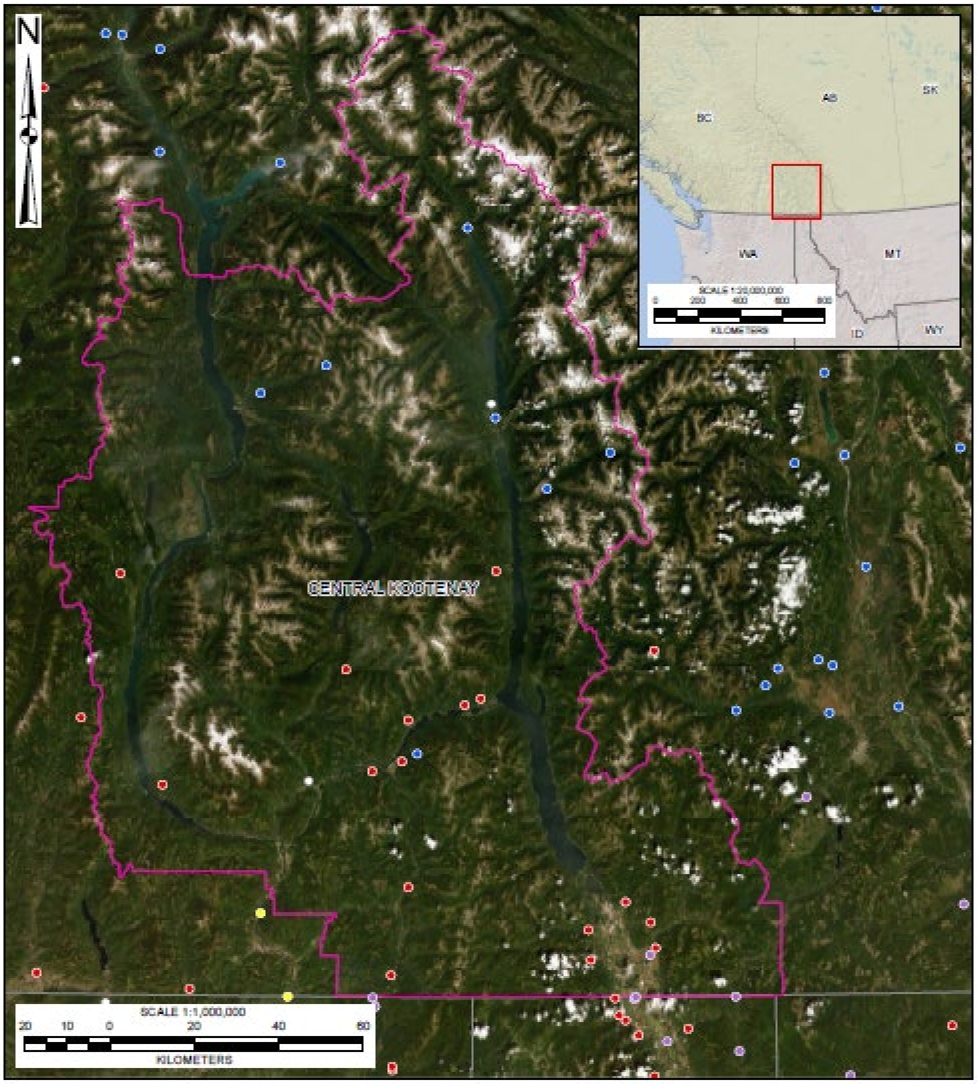

Figure C-7. Clusters that cover the RDCK region.

The clusters were further separated based on the scale of watershed area. The coefficient of variation (CV) is required to be constant for a given homogeneous region. A relationship between the watershed area and L-CV is observed in the clusters that cover the RDCK. However, the strength of the relationship varies considerably (Table C-11). In a flood regionalization study in British Columbia, Wang (2000) observed that in L-moment space, the L-CV varied with watershed area for the defined clusters making them heterogeneous. Wang (2000) demonstrated that the small watersheds show an increase and the large watersheds show a decrease in the L-CV.

Table C-11. R^2 for regression between watershed area and L-CV

Cluster	Number of Hydrometric Stations	R2 for regression between watershed area and L-CV
1 West	88	0.01
4 East	45	0.12
7	158	0.15

To account for the lack of constancy in the L-CV reported by Wang (2000) and observed in the clusters, the range in the watershed area considered in the study was modified to include two groups: 1) less than 500 km^2 and 2) more than 500 km^2 up to 5,000 km^2. The clusters that cover the RDCK region thus include the following which will be the focus of the results herein.

- Cluster 1 West < 500 km^2
- Cluster 1 West > 500 km^2
- Cluster 4 West < 500 km^2
- Cluster 4 West > 500 km^2
- Cluster 7 < 500 km^2
- Cluster 7 > 500 km^2.

C.5.2.3. Refinement of the Hydrometric Station Selection

The final number of hydrometric stations, including the range of discordancy (*Di*) values, for each hydrologic region is presented in Table C-12. The number of hydrometric stations removed is based on the criteria presented in Section C.4.2.4.

Table C-12. Final number of hydrometric stations and range in discordancy measure for each hydrologic region.

Cluster	Watershed Area Range	Initial Number of Hydrometric Stations	Number of Hydrometric Stations Removed	Final Number of Hydrometric Stations	Di (Min)	Di (Max)	Di (Mean)
1 West	< 500 km^2	36	10	26	0.13	3.0	1
	> 500 km^2	52	28	24	0.09	3.0	1
4 East	< 500 km^2	43	9	34	0.04	2.8	1
	> 500 km^2	2	Not enough data for regionalisation				
7	< 500 km^2	75	35	40	0.09	2.6	1
	> 500 km^2	83	65	18	0.11	2.9	1

C.5.2.4. Homogeneity

The H-Test results are summarized in Table C-13. A cluster is declared heterogeneous if H is sufficiently “large”. Hosking and Wallis (1997) recommend a cluster be considered “definitely heterogeneous” if H $\geq$ 2. Increasing the threshold implies that more heterogeneous regions are included in the analysis. Guse, Thieken, Castellarin, & Merz (2010) assessed the effect of the H-Test threshold on the performance of probabilistic regional envelope curves in Germany. Increasing the H-Test threshold from 2 to 4 resulted in a larger number of regions considered for analysis. This increase is important as it can include hydrometric stations that would have been excluded otherwise.

The reality is that while removing hydrometric stations may improve the homogeneity of a region, there may be some important reasons why the H-Test score is high. For example, the site may include a hydrometric station where a very large flood occurred. A representative heterogeneous region is better than a region that has been forced to be homogeneous (Robson and Reed 1999).

The physical variability of British Columbia was recognized by Wang (2000) where the average value for the H-Test was 6.85 based on 19 clusters. The physiographic regions in BC may be less distinct than other regions. As a result, the threshold for the H-Test was relaxed to what is practical for British Columbia.

Table C-13. Number of hydrometric stations, Discordancy values, and H-Test results.

Hydrologic Region	Watershed Area Range	Number of Hydrometric Stations	H-Test
1 West	< 500 km^2	26	6.8
	> 500 km^2	24	9.0
4 East	< 500 km^2	34	13.1
	> 500 km^2	2	Not enough data
7	< 500 km^2	40	4.5
	> 500 km^2	18	7.7

C.5.3. Regionalization

C.5.3.1. Regional Probability Distributions

The regionally averaged L-moments are presented in Table C-14 for hydrologic region 1 West, 4 East, and 7. For the index-flood procedure, ι_1 is set to 1.

Table C-14. Regionally averaged L-moments.

Hydrologic Region	Watershed Area Range	Number of Hydrometric Stations	ι_1	ι_2	t_3	t_4
1 West	< 500 km^2	26	1	0.1796	0.2519	0.1879
	> 500 km^2	24	1	0.1756	0.2411	0.2012
4 East	< 500 km^2	34	1	0.2364	0.2245	0.1624
7	< 500 km^2	40	1	0.3014	0.2539	0.1904
	> 500 km^2	18	1	0.2601	0.2138	0.1924

The Z-statistics for a range of candidate probability distributions is presented in Table C-15. The candidate probability distributions include GLO, GEV, GPA, GNO, and PE3. Probability distributions with Z statistics $\leq$1.64 are deemed acceptable (Hosking & Wallis 1997). All candidate distributions are deemed acceptable for the hydrologic regions that cover the RDCK based on the Z-statistic.

Table C-15. Goodness of fit Z statistic for probability distribution selection.

Hydrological Region	Watershed Area Range	GLO	GEV	GNO	PE3	GPA
1 West	< 500 km^2	1.30	-0.34	-1.14	-2.57	-4.47
	> 500 km^2	0.53	-1.59	-2.50	-4.16	-6.85
4 East	< 500 km^2	3.30	0.69	-0.21	-1.92	-5.60
7	< 500 km^2	1.41	-0.59	-1.59	-3.38	-5.66
	> 500 km^2	0.62	-1.79	-2.55	-4.01	-7.54

To help make the decision on the most representative probability distribution, L-moment diagrams were plotted for each hydrologic region. The t_3 and t_4 position of the regional average relative to the relationships for five three-parameter (GLO, GEV, GPA, GNP, PE3) and five two-parameter (E, G, L, N, and U) candidate probability distributions are depicted in Figure C-8. The three-parameter probability distributions are depicted by the coloured lines while the two-parameter distributions are depicted by the black squares. The L-skewness and L-kurtosis ratio for each hydrologic region is depicted by the cross symbol on Figure C-8. The GEV probability distribution gives an acceptably close fit to the regional L-moments for the different hydrologic regions. As a result, the GEV probability distribution was deemed representative for all hydrologic regions.

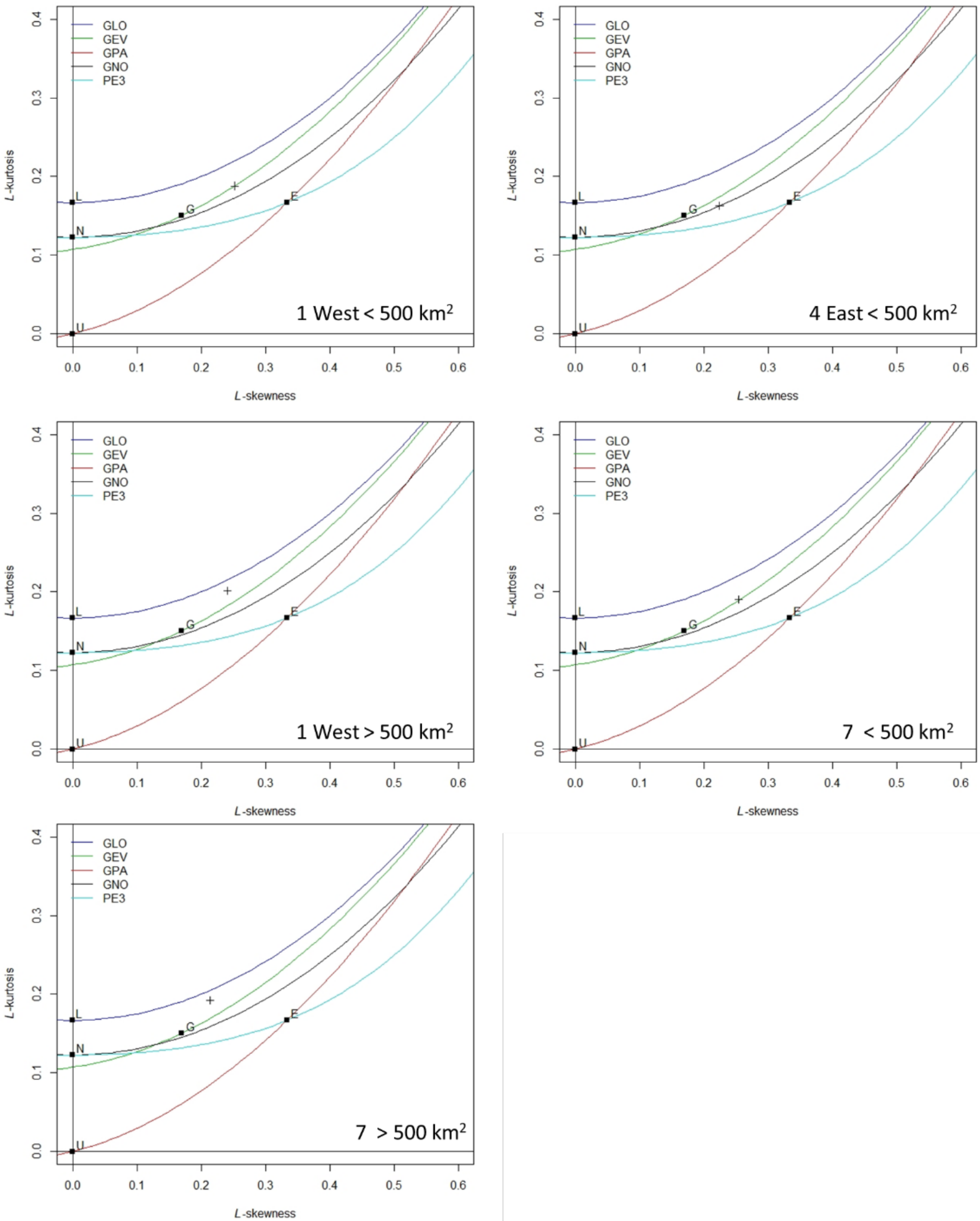

Figure C-8. L-moment ratio diagram for each hydrologic region.

C.5.3.2. Parameter Estimation

The regionally weighted L-moments are used to estimate the parameters of the GEV probability distribution. The parameters for each hydrologic region are presented in Table C-16.

Table C-16. Parameter estimates for the GEV distribution.

Hydrological Region	Watershed Area limit	ξ	α	κ
1 West	< 500 km^2	0.8369	0.2280	-0.1236
	> 500 km^2	0.8421	0.2269	-0.1078
4 East	< 500 km^2	0.7908	0.3139	-0.0832
7	< 500 km^2	0.7257	0.3814	-0.1266
	> 500 km^2	0.7724	0.3513	-0.0671

C.5.3.3. Growth Curves and Error Bounds

The regional growth curves and error bounds are presented for each region in Figure C-9.

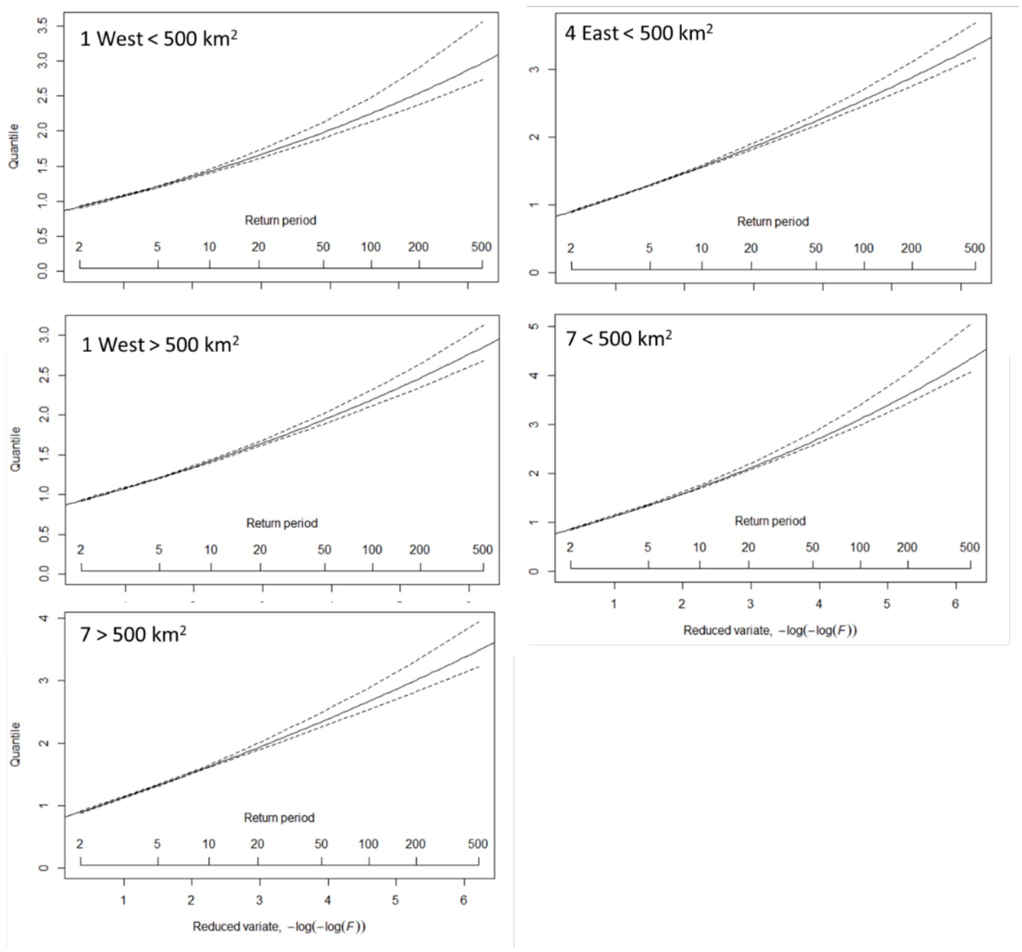

Figure C-9. Growth curves for each hydrologic region.

C.5.3.4. Index Flood

The regional equations for the index-flood for each hydrologic region are presented in Table C-17. The provincial equations are also included at the end of Table C-17. The results are reported to 5 significant figures. However, a total of 5 equations are developed for each hydrologic region and across the province with the intention to average the index-flood estimates. Consequently, the results should be rounded to the nearest unit for flood magnitudes greater than 10 m^3/s. The adjusted R^2 is included for comparison of the models. Models with more watershed characteristics tend to have a lower adjusted R^2 as these models are penalized for increased number of independent variables.

Table C-17. Regional and provincial equations for the index-flood including the adjusted R^2.

Hydrologic Region	Watershed Area Range		Index-flood Equations	Adj. R^2
1 West < 500 km^2	42 to 454 km^2	1	$\log Q_m = 10.169 + 1.8553(\log Area) - 0.012434(Slope) + 0.098984\,(Cen\_Long) + 0.0055555(PPT_{fl}) + 0.34911(Water\_Wetland)$	0.91
		2	$\log Q_m = 12.127 + 1.9358(\log Area) - 0.013271(Slope) + 0.11264\,(Cen\_Long) - 0.00022260(Cen\_Elev) + 0.0053230(PPT_{fl}) + 0.40695(Water\_Wetland)$	0.92
		3	$\log Q_m = 6.951 + 1.8564(\log Area) - 0.011048(Slope) + 0.071361\,(Cen\_Long) + 0.0053236(PPT_{fl})$	0.90
		4	$\log Q_m = -0.96349 + 1.7509(\log Area) - 0.0095976(Slope) + 0.0043293(PPT_{fl})$	0.89
		5	$\log Q_m = -3.2303 + 2.1932(\log Area) + 0.0015075(MAP)$	0.88
1 West > 500 km^2	586 to 4312 km^2	1	$\log Q_m = -2.5781 + 2.0480(\log Area) + 0.0012740\,(MAP)$	0.83
		2	$\log Q_m = -2.3716 + 1.8939(\log Area) + 0.41806(\log Catch\_Length) + 0.0012775(MAP)$	0.82
		3	$\log Q_m = 1.3411 + 1.9306(\log Area) + 0.18827(\log Catch\_Length) + 0.0011046\,(MAP) - 0.04866(CN)$	0.82
		4	$\log Q_m = -0.70946 + 1.6015(\log Area) - 0.0081664(Slope) + 0.0013574\,(MAP) + 0.057906\,(MAT) - 0.0036032(Forest)$	0.83
		5	$\log Q_m = 0.40059 + 1.6514(\log Area) - 0.0082135(Slope) + 0.0010135\,(MAP) + 0.15045\,(MAT) - 0.016425(Forest) - 0.19361(Water\_Wetland)$	0.88

Hydrologic Region	Watershed Area Range		Index-flood Equations	Adj. R^2
4 East < 500 km²	6 to 441 km²	1	$\log Q_m = -3.5763 + 2.7620(\log Area) - 0.15167(MAT) + 0.0035040(PPT_{wt}) - 0.26513(Water\_Wetland)$	0.96
		2	$\log Q_m = -4.1636 + 2.7871(\log Area) + 0.0037150(PPT_{wt}) - 0.30562(Water\_Wetland)$	0.96
		3	$\log Q_m = -1.8437 + 2.6974(\log Area) + 0.0038(PPT_{wt}) - 0.18063(MAT) + 0.0030438(PPT_{wt}) - 0.28288(Water_{Wetland}) - 0.020392(CN)$	0.96
		4	$\log Q_m = -4.0189 + 2.7063(\log Area) + 0.0047397(PPT_{fl}) - 0.3056(Water\_Wetland)$	0.95
		5	$\log Q_m = -1.3176 + 2.6880(\log Area) - 0.00069570(MAP) - 0.19022(MAT) + 0.0044279(PPT_{wt})$	0.96
7 < 500 km²	8 to 471 km²	1	$\log Q_m = -3.8856 + 1.8844(\log Area) + 0.010435(PPT_{fl})$	0.74
		2	$\log Q_m = -3.9002 + 1.9484(\log Area) + 0.10058(PPT_{fl}) - 0.17007(Water\_Wetland)$	0.74
		3	$\log Q_m = -4.4499 + 2.0486(\log Area) + 0.0051660(PPT_{wt}) + 0.0062765(PPT_{sm}) - 0.21014(Water\_Wetland)$	0.74
		4	$\log Q_m = -20.730 + 1.7210(\log Area) + 0.36720(Cen\_Lat) - 0.00093400(Cen_{Elev}) + 0.13920(PPT_{sp}) - 0.30900(Water\_Wetland)$	0.75
		5	$\log Q_m = -1.9967 + 2.9199(\log Area) - 0.44581(\log Catch\ Length) + 0.22219(Cen\_Lat) + 0.11838(Cen\_Long) + 0.007305(PPT_{wt}) - 0.32687(Water\_Wetland)$	0.75

Hydrologic Region	Watershed Area Range		Index-flood Equations	Adj. R^2
7 >500 km²	529 to 4138 km²	1	$\log Q_m = -2.8251 + 2.0765(\log Area) - 0.65058(MAT) - 0.01087(PAS) + 0.15245(PPT_{wt}) + 0.014215(PPT_{sm}) + 0.14232(Forest)$	0.93
		2	$\log Q_m = 0.51542 + 1.4852(\log Area) - 0.024121(Slope) - 0.0078710(MAP) - 0.69867(MAT) - 0.010055(PAS)$	0.93
		3	$\log Q_m = -0.28887 + 2.1311(\log Area) - 0.00048080(Cen_{Elev}) - 0.59076(MAT) - 0.10256(PAS) + 0.14034(PPT_{wt}) + 0.14291(PPT_{sm}) + 0.018084(Forest)$	0.94
		4	$\log Q_m = -12.290 + 4.2860(\log Area) - 4.4640(\log Catch\_Length) + 0.54240(Cen\_Lat) + 0.19690(Cen\_Long) - 0.0066490(PAS) + 0.013790(PPT_{wt}) + 0.38640(Forest)$	0.94
		5	$\log Q_m = -6.0632 + 2.1265(\log Area) + 0.0053923(PPT_{wt}) + 0.030556(Forest)$	0.90
Provincial Model	1 to 4,888 km²	1	$\log Q_m = -10.280 + 2.0840(\log Area) - 0.052950(Cen\_Long) + 0.00078170(PAS) + 0.0045490(PPT_{sp}) - 0.077680(Water\_Wetland) + 0.015770(CN)$	0.88
		2	$\log Q_m = -10.990 + 2.0900(\log Area) - 0.054870(Cen\_Long) + 0.00079820(PAS) + 0.0045680(PPT_{sp}) + 0.0022550(Forest) - 0.079050(Water\_Wetland) + 0.020340(CN)$	0.88
		3	$\log Q_m = -9.7160 + 2.0890(\log Area) - 0.044870(Cen_{Long}) - 0.00015400(Cen\_Elev) + 0.00095000(PAS) + 0.0043910(PPT_{sp}) + 0.0027010(Forest) - 0.081050(Water\_Wetland) + 0.021030(CN)$	0.89
		4	$\log Q_m = -8.3390 + 2.0610(\log Area) - 0.047040(Cen_{Long}) + 0.00070070(PAS) + 0.0043090(PPT_{sp}) + 0.0027010(Forest)$	0.88
		5	$\log Q_m = -2.7860 + 2.0520(\log Area) - 0.0023640(PPT_{wt}) + 0.0028430(PPT_{sm}) - 0.063700(Water\_Wetland)$	0.88

C.5.4. Error Statistics

The weighted standardized error statistics for the regional and provincial model over a range of flood quantiles for the different hydrologic regions are presented in Table C-18. The error statistics are not consistent across all hydrologic regions. The regional model may be selected for the 4 East < 500 km^2 hydrologic region. In the case of the 1 West region, either the regional or provincial model would be considered adequate. Lastly, the regional model is probably the model of choice for the 7 hydrologic region. As expected, the error statistics for the lower flood quantiles are lower than those for higher flood quantiles reflecting the increased uncertainty in higher quantile estimates.

Table C-18. Weighted standardized error statistics for the regional and provincial models over a range of flood quantiles. Green highlighted cells depict a positive bias while the red highlighted cells depict a negative bias.

Error Stats	AEP	1 West < 500 km^2		1 West > 500 km^2		4 East < 500 km^2		7 < 500 km^2		7 > 500 km^2	
		Regional Qm	Provincial Qm	Regional Qm	Provincial Qm	Regional Qm	Provincial Qm	Regional Qm	Provincial Qm	Regional Qm	Provincial Qm
SRMSE	0.5	0.24	0.31	0.27	0.26	0.39	0.92	2.71	3.80	0.19	0.99
	0.1	0.28	0.31	0.26	0.28	0.33	0.69	3.08	4.10	0.21	0.96
	0.02	0.40	0.41	0.31	0.33	0.38	0.64	3.70	4.80	0.27	1.01
	0.005	0.54	0.53	0.38	0.39	0.45	0.66	4.37	5.59	0.36	1.09
SPercent Error	0.5	18	21	20	21	27	59	70	122	15	65
	0.1	22	24	20	24	22	45	74	128	14	65
	0.02	31	32	25	29	27	39	84	144	20	68
	0.005	42	40	30	33	34	38	97	165	29	74
SBIAS	0.5	0.03	-0.08	0.04	-0.09	0.07	0.30	0.39	1.03	0.03	0.39
	0.1	0.06	-0.06	0.04	-0.07	0.07	0.23	0.44	1.08	0.03	0.39
	0.02	0.09	-0.03	0.06	-0.06	0.08	0.20	0.52	1.21	0.04	0.42
	0.005	0.13	0.02	0.08	-0.03	0.10	0.20	0.62	1.37	0.06	0.45

C.6. APPLICATION TO UNGAUGED WATERSHEDS

The goal of the regionalization of floods is to estimate quantiles for ungauged watersheds in the RDCK. A total of 12 watersheds are modeled for clearwater floods. To begin, a watershed polygon was defined for each ungauged watershed, as shown in Figure C-10. The suite of 18 watershed characteristics were then extracted and averaged over the area for each ungauged watershed. The resulting watershed characteristics are presented in Table C-19.

The ungauged watersheds were subsequently assigned to one of the hydrologic regions identified across the study area. The hydrologic region assignment was completed using the Random Forest classification algorithm. Once a hydrologic region was assigned to the ungauged watershed; the index-flood was estimated based on the appropriate model (regional and / or provincial). The flood quantiles were then estimated for a range of AEPs using the index-flood estimate and the appropriate regional growth curve. The hydrologic region assignment, index-flood estimate, and flood quantiles for each ungauged watershed are presented in Table C-20.

The magnitude of the flood quantiles is influenced by the watershed characteristics. This is because the index-flood is calculated using a multiple linear regression that depends on the watershed characteristics that define the best 5 models for a given region. Two watersheds of similar area may have significantly different flood quantile estimates because of major differences in watershed characteristics. For example, Lost Creek and Porcupine Creek share comparable watershed areas of 62 km^2 and 68 km^2, respectively. However, flood quantiles for Porcupine Creek are 35% greater than Lost Creek, with the difference in magnitude attributed to difference in climate characteristics.

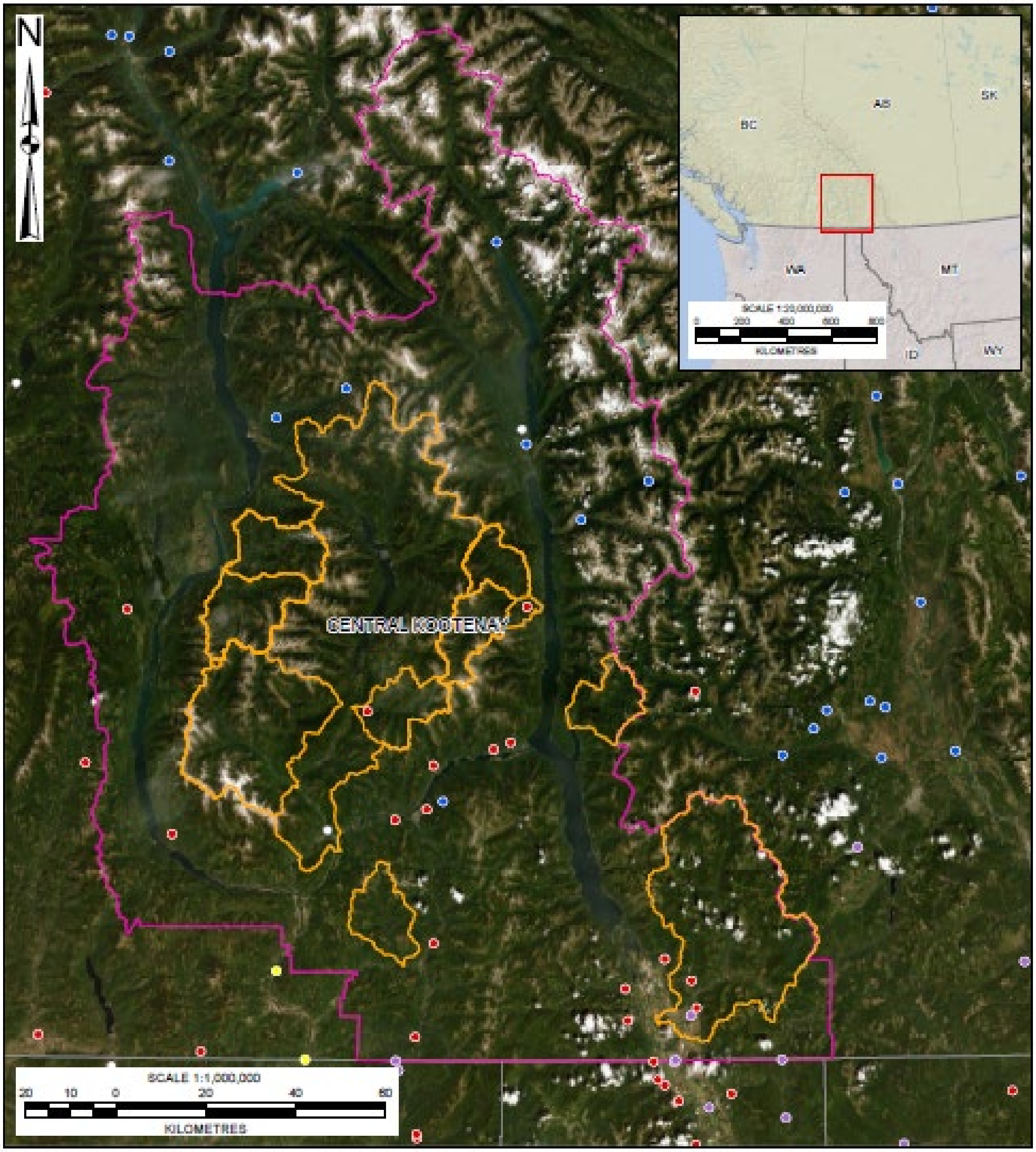

Figure C-10. Watershed polygons for the ungauged watersheds.

Table C-19. Watershed characteristics for the clearwater sites located in the RDCK region.

Watershed Name	Area (km^2)	Relief (m)	Watershed Length (km)	Slope (%)	Centroid Latitude (degrees)	Centroid Longitude (degrees)	Centroid Elevation (m)	MAP (mm)	MAT (ºC)	PAS (mm)	PPT_wt (mm)	PPT_sp (mm)	PPT_sm (mm)	PPT_fl (mm)	Forest (%)	Water and Wetland (%)	Urban (%)	CN
Crawford Creek	186	2092	2.53	83	49.693818	-116.700089	1181	1116	3.0	590	383	233	198	302	88	0.0	0.2	70
Keen Creek	202	2066	2.37	87	49.861962	-117.119617	1584	1390	1.3	857	460	307	240	384	66	0.2	7.7	67
Upper Kaslo Creek	150	1927	2.35	82	49.990505	-117.046683	1182	1244	2.7	668	416	265	223	340	90	0.0	0.8	70
Kalso Creek at Kootenay Lake	386	2228	3.09	72	49.914818	-117.077853	1280	1312	2.1	756	438	284	230	360	78	0.2	4.3	68
Lemon Creek	206	2046	2.58	79	49.717145	-117.338618	1956	1322	2.7	754	461	284	206	370	90	0.1	0.7	65
Burton at Arrow Lake	530	2323	4.13	56	49.952644	-117.773748	1300	1242	2.4	704	4280	258	220	336	85	0.3	1.2	64
Caribou Creek	238	2235	2.97	75	50.019565	-117.726695	1213	1260	2.4	709	432	261	226	341	92	0.1	0.3	67
Snow Creek	291	2314	3.05	76	49.897831	-117.811685	1742	1227	2.3	700	425	255	216	331	80	0.3	1.8	63
Little Slocan River	818	2281	5.40	42	49.664986	-117.79715	1612	1161	2.8	643	416	245	188	313	82	0.5	1.7	63
Slocan River	3475	2544	8.13	31	49.85497	-117.525816	1196	1224	3.0	666	431	256	206	332	81	2.9	2.1	66
Goat River	1259	2111	6.01	35	49.28428	-116.347233	1050	857	3.2	433	284	194	163	217	88	0.1	0.2	69
Erie Creek Upstream End	201	1575	2.71	58	49.288665	-117.392234	1010	1265	3.8	617	435	286	210	333	95	0.0	0.0	62

Table C-20. Hydrologic region assignment for the ungauged watersheds.

Watershed Name	Hydrometric Station	Watershed Area (km^2)	Hydrologic Region[1]	Qm (m^3/s)	Flood Quantiles		
					0.05 AEP (m^3/s)	0.02 AEP (m^3/s)	0.005 AEP (m^3/s)
Crawford Creek	-	186	7	27	50	61	80
Keen Creek	08NH132	202	pro-rated	-	78	94	125
Upper Kaslo Creek	08NH005	150	pro-rated	-	99	120	160
Kaslo Creek at Kootenay Lake	08NH005	386	pro-rated	-	160	200	260
Lemon Creek	08NJ160	206	pro-rated	-	72	84	105
Burton at Arrow Lake	-	530	4	80	150	180	230
Caribou Creek	-	238	4	42	78	94	120
Snow Creek	-	291	4	45	83	100	130
Little Slocan River		818	4	103	190	230	290
Slocan River	08NJ013	3475	pro-rated	-	685	770	880
Goat River	8NH004	1259	7	-	387	430	500
Erie Upstream End	-	201	4	35	65	79	102

Note:

1. A pro-rated calculation is completed when a representative hydrometric station is located upstream or downstream from the ungauged site and has a record length considered long enough for reliable frequency analysis. Flood quantile estimates calculated at the hydrometric station are transferred to the ungauged site by relating the annual maximum peak instantaneous discharge at the hydrometric station to the ungauged site using watershed area size.

C.7. UNCERTAINTY

The process of flood regionalization is inherently uncertain because of the several limitations. The probability distribution of flood events is unknown. While there are statistical tools to help reach a ‘best estimate’, it is not possible to know what the probability distribution is in practice. As a result, the flood quantile estimates are supported by a mathematical model that is considered reliable based on the available flood data.

The regionalisation of floods tends to underestimate peak discharges for small watersheds and overestimate peak discharges for larger watersheds. This is in part due to differences in hydrological processes that control peak discharges. For example, maximum annual peak instantaneous discharges in small watersheds within the study area are more likely controlled by rainfall compared to larger watershed that tend to be more snowmelt-dominated in the spring. The rainfall control in small watersheds reflects the greater likelihood that a rainfall event, like a convective storm, covers the entire watershed area. In the case for larger watersheds, it is more likely for snowmelt to occur across the entire area in the spring.

While hydrometric stations with watershed areas starting from approximately 6 km^2 up to 5,000 km^2 are included in the analysis, it is not likely that the equations apply to watersheds if they are either too small or too large. The regional models are only reliable if applied within the range of watershed areas used to build the models in the first place. Extrapolation beyond the limit of the model may yield poor or unreliable results.

The regional models are as reliable as the data that is used to support them. There is inherent measurement error in flood events, especially for larger flood events. Furthermore, the data record may simply be incorrect due to a transcription error. In addition, the measuring device may have been moved to a new location or trends over time may come about from changes in the monitoring device. It is not possible to inspect every record at every hydrometric station to control for these sources of error because so much data are pooled across such a large area.

The same applies to the watershed polygon delineation. Much of the watershed delineation was automated using tools that were developed to speed up this process (RNT and ESRI tools). Manual spot checks were completed in conjunction with quality control of the area by means of comparison with published values. Nevertheless, it was not possible to inspect every watershed polygon to control for delineation errors due to the high number of polygons that were generated for this study. It is expected that these sources of error are negligible next to the quantity of data that is processed across the study area.

Trends in the flood record imposed by climate change, land use change, wildfires, insect infestations, or urban development generally precludes the use of frequency analysis. Trend analyses were completed on the flood record to account for some level of trend. However, the flood record often captures a small window of the flood history at a given location. The limited record makes it difficult to identify a real trend from an artifact of the data record. Therefore, no hydrometric stations were discarded from the analysis due to the presence of a trend in the flood record.

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APPENDIX D
CLIMATE CHANGE CONSIDERATIONS

D.1. INTRODUCTION

The hydroclimate of British Columbia (BC) is complex because of proximity to the Pacific Ocean, mountainous terrain, and extent in latitude. The hydrologic regime is either freshet-dominated (nival regime) or snow-influenced (hybrid nival-pluvial or nival-glacial regimes) throughout most of BC (Eaton & Moore, 2010). Hydrologic trends over recent decades generally include a warming and decreasing snowpack (Kang, Shi, Gao, & Déry, 2014) and earlier onset of spring melt (Déry et al., 2009). The hydrologic response to climate change in BC is expected to be influenced by the regional variability in projected temperature and precipitation changes and by regional variations in physical geography. For example, snow dynamics are strongly influenced by elevation-based temperature gradients resulting in large spatial variations in regions of diverse topography (Schnorbus, Werner, & Bennett, 2014). Also, warmer hybrid nival-pluvial regimes may be more sensitive to changes in regional temperature, precipitation, and rainfall trends (Whitfield, Cannon, & Reynolds, 2002).

Climate change impacts were assessed by BGC for the clearwater watersheds using statistically- and process-based methods. This appendix presents a description of these methodologies and their results. This appendix begins with a description of the anticipated climate change impacts on the hydroclimate within the RDCK (Section D.2). The climate change sensitivity of clearwater watersheds within the region is examined in Section D.3. Finally, an evaluation of the climate change impacts using statistically- and process-based methods for the clearwater watersheds is presented in Section D.4. This appendix ends with a summary of the method that was used to account for the climate change impacts on the hydrology of clearwater watersheds in the RDCK region.

D.2. CLIMATE CHANGE IMPACTS

D.2.1. Hydroclimate

Historical changes to climate have been documented in BC (Barnett et al., 2008). While there is a natural variability component to the changes in climate, such as El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), historical trends in western North America have been attributed to climate change in the form of increased regional warming (Barnett et al., 2008).

Climate change is projected to impact the overall mean as well as the extremes for a range of climate variables including temperature, precipitation, snow, and rainfall intensities. Projected change in mean annual precipitation (MAP), temperature (MAT), and precipitation as snow (PAS) from historical conditions (1961 to 1990) for clearwater watersheds across the RDCK region for 2050 (average of years 2041 to 2070) are presented in Table D-1.

The climate-adjusted variables are calculated using projections based on the Representative Carbon Pathway (RCP) 8.5 which are averaged across 15 fifth phase Coupled Model Intercomparison project (CMIP5) models (CanESM2, ACCESS1.0, IPSL-CM5A-MR,MIROC5, MPI-ESM-LR, CCSM4, HadGEM2-ES, CNRM-CM5, CSIRO Mk 3.6, GFDL-CM3, INM-CM4, MRI-CGCM3, MIROC-ESM, CESM1-CAM5, GISS-E2R) that were chosen to represent all major clusters of similar atmosphere-ocean general circulation models (AOGCMs) (Knutti, Massin, & Gettleman, 2013), and that had high validation statistics in their CMIP3 equivalents.

Table D-1. Projected change (RCP 8.5, 2050) from 1961 to 1990 historical conditions (Wang et al., 2016).

Watershed	Change in MAP (mm)	Change in MAT (ºC)	Change in PAS (Snow Water Equivalent, mm)
Crawford Creek	59	3.5	-206
Keen Creek	82	3.6	-239
Upper Kaslo Creek	72	3.6	-231
Kalso Creek at Kootenay Lake	76	3.6	-233
Lemon Creek	82	3.5	-252
Burton at Arrow Lake	73	3.5	-221
Caribou Creek	75	3.5	-225
Snow Creek	72	3.6	-217
Little Slocan River	69	3.5	-215
Slocan River	74	3.5	-220
Goat River	40	3.5	-151
Erie Creek Upstream End	69	3.6	-247

Projected changes in average climate variables across the RDCK by 2050 show that there is likely to be:

- A net increase in MAP ranging from 40 mm to 82 mm
- A net increase in MAT ranging from 3.5 ºC to 3.6 ºC
- A net decrease in PAS ranging from 151 mm to 252 mm.

In addition, short-term precipitation extremes (sub-daily) are expected to increase in most of North America with a warming atmosphere. The frequency of extremes increases 5-fold in large parts of Canada in December, January, and February (Figure D-1a). The frequency of extremes decreases to approximately a 2-fold increase in southeast BC in June, July, and August (Figure D-1b). This shift in frequency covers the period January 2001 to September 2013. The increase is due to a shift towards moister and warmer climatic conditions (Prein et al., 2017). Extremes in short-term precipitation contributes to the frequency and magnitude of flood events, especially for small watersheds where soil storage is either low or full (i.e., < 250 km^2).

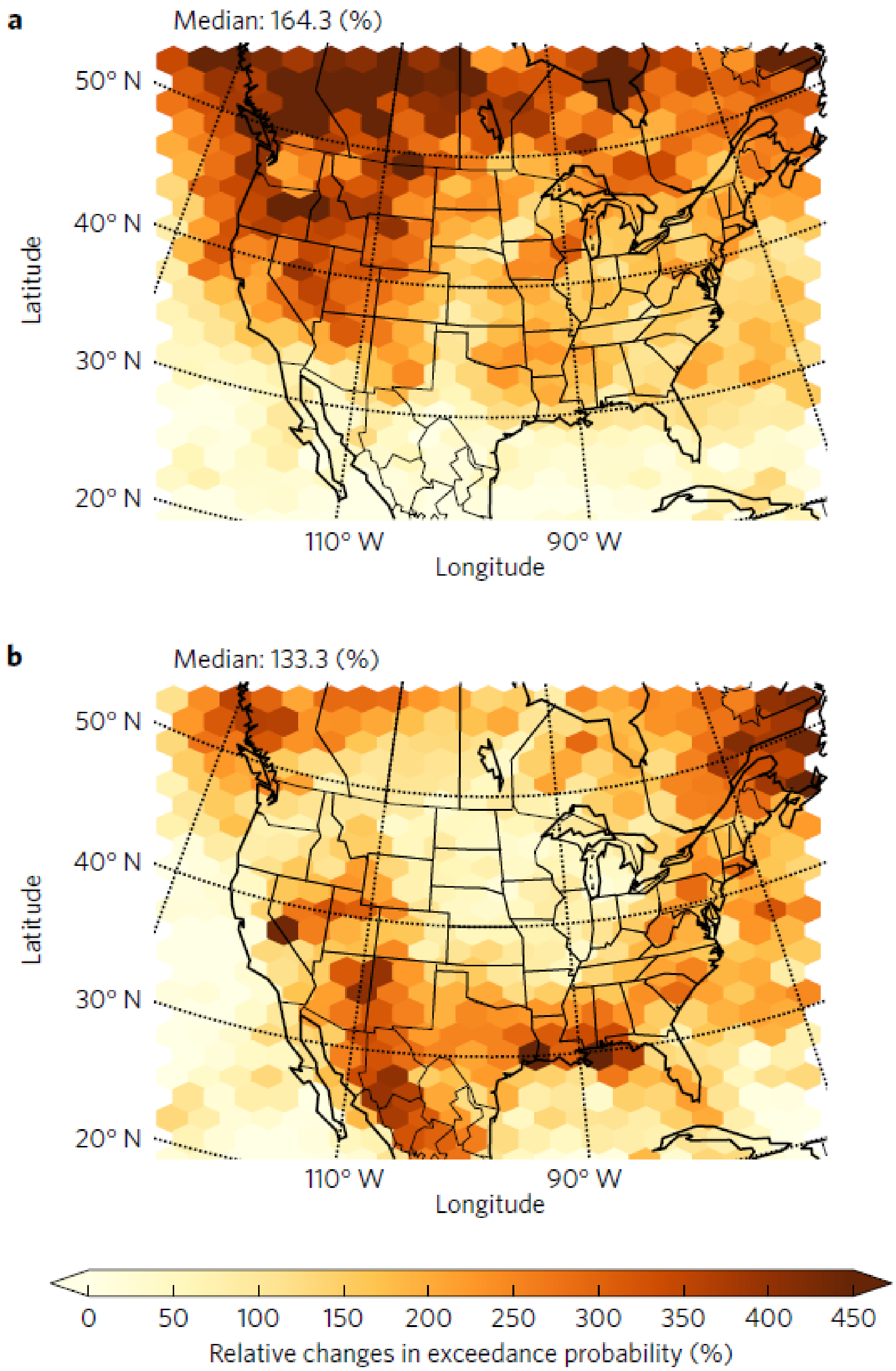

Figure D-1. Change in the exceedance probability of hourly precipitation intensities for (a) December, January, and February, and (b) June, July, and August (Prein et al., 2017).

D.2.2. Peak Discharges

The RDCK is situated within the Montane Cordillera ecozone which covers most of southern BC. Extreme flood events in this area are often associated with rain-on-snow events in the spring (Harder et al., 2015). A hydrograph example where the regime is freshet-dominated is shown in Figure D-2. Although the effects of climate change on precipitation are not clear, projected increases in temperature are expected to have the largest impact on annual minimum temperatures occurring in the winter months (Harder et al., 2015).

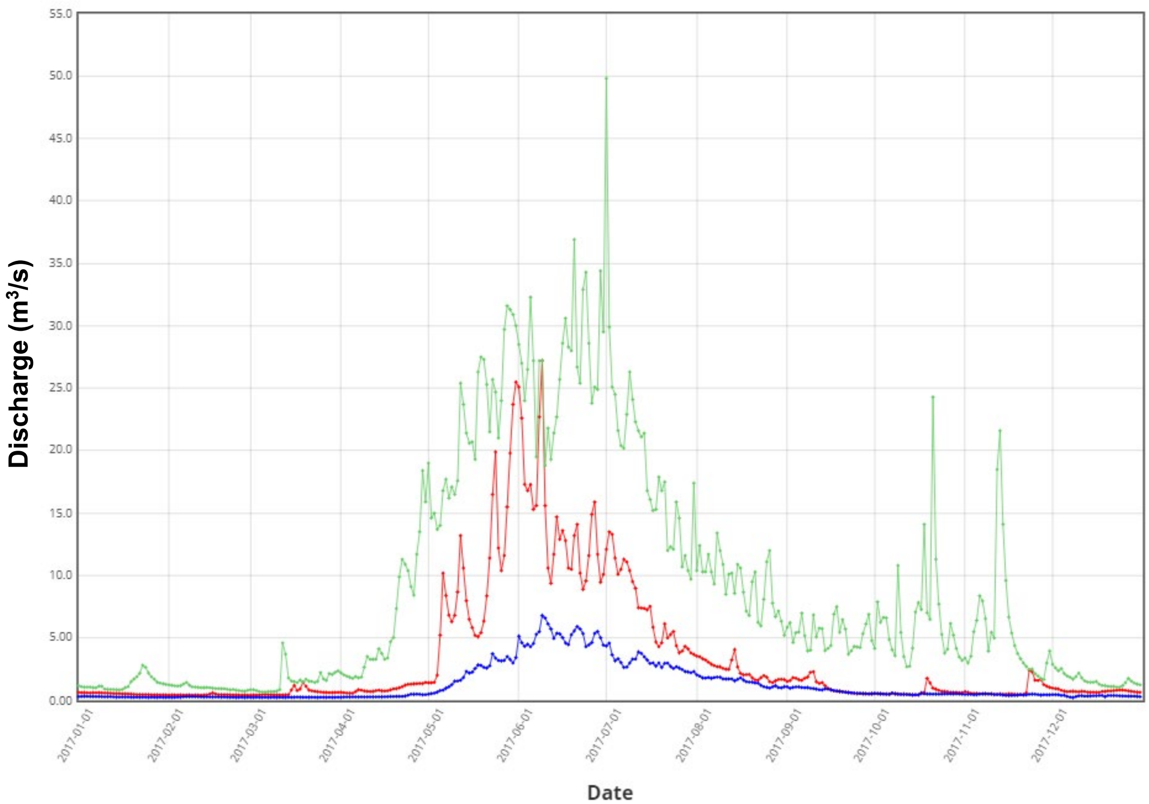

Figure D-2. Example freshet-driven hydrologic regime for Keen Creek below Kyawats Creek (08NH132). Green line is the maximum discharge, the blue line is the minimum discharge, and the red line is the 2017 discharge.

The effects of temperature change differ throughout the region. High elevation regions throughout parts of the Montane Cordillera (e.g., Upper Columbia watershed) are projected to experience increases in snowpack, limiting the response in high elevation watersheds while lower elevations are projected to experience a decrease in snow water equivalent (Loukas & Quick, 1999; Schnorbus et al., 2014).

Projected changes in discharge vary spatially and seasonally based on snow and precipitation changes and topography-based temperature gradients. Researchers anticipate that discharge will increase in the winter and spring in the RDCK due to earlier snowmelt and more frequent rain-on-snow events, while earlier peak discharge timing is expected in many rivers (Schnorbus et al., 2014; Farjad, Gupta, & Marceau, 2016).

D.3. WATERSHED SENSITIVITY

The RDCK includes 6 detailed clearwater study areas (Crawford Creek, Kaslo Creek, Slocan River, Burton Creek, Goat River, and Salmo River). Each study area includes one or more clearwater watersheds that were assessed to inform the floodplain delineation. All clearwater watersheds in the RDCK are characterized by a freshet-dominated regime. Freshet-dominant regimes are characterized by a maximum annual discharge in the spring

In a warmer climate, hydrologic regime shifts are likely to intensify although regional responses are expected due to each watershed's unique characteristics like elevation range and proximity to the 0^{o}C air temperature threshold during the cold season. The largest changes in the timing of peak floods would be expected for those areas with a hydrologic regime that shifts from a freshet-dominated to rainfall dominated regime. Therefore, those watersheds with the thinnest snowpacks would be the most sensitive.

The RDCK can be sub-divided into five regions, each with a relatively different, typical snowpack depth (Figure D-3). Two of those five regions cover the clearwater watersheds. The typical snow depths for the clearwater watersheds ranges from moderate snowpack at high elevations for Goat River and Crawford Creek to moderate to deep snowpack for the remaining sites (Table D-2). The elevation range for each clearwater watershed is included in Table D-2 for reference. The clearwater watershed with largest projected change in precipitation as snow by 2050 is Lemon Creek (decrease of 252 mm) followed by Erie Creek Upstream End (decrease of 247 mm) and Keen Creek (decrease of 239 mm) as listed in Table D-1. Hydrographs based on representative hydrometric stations for each study area are presented at the end of the appendix for reference (Figure D-8 to Figure D-11).

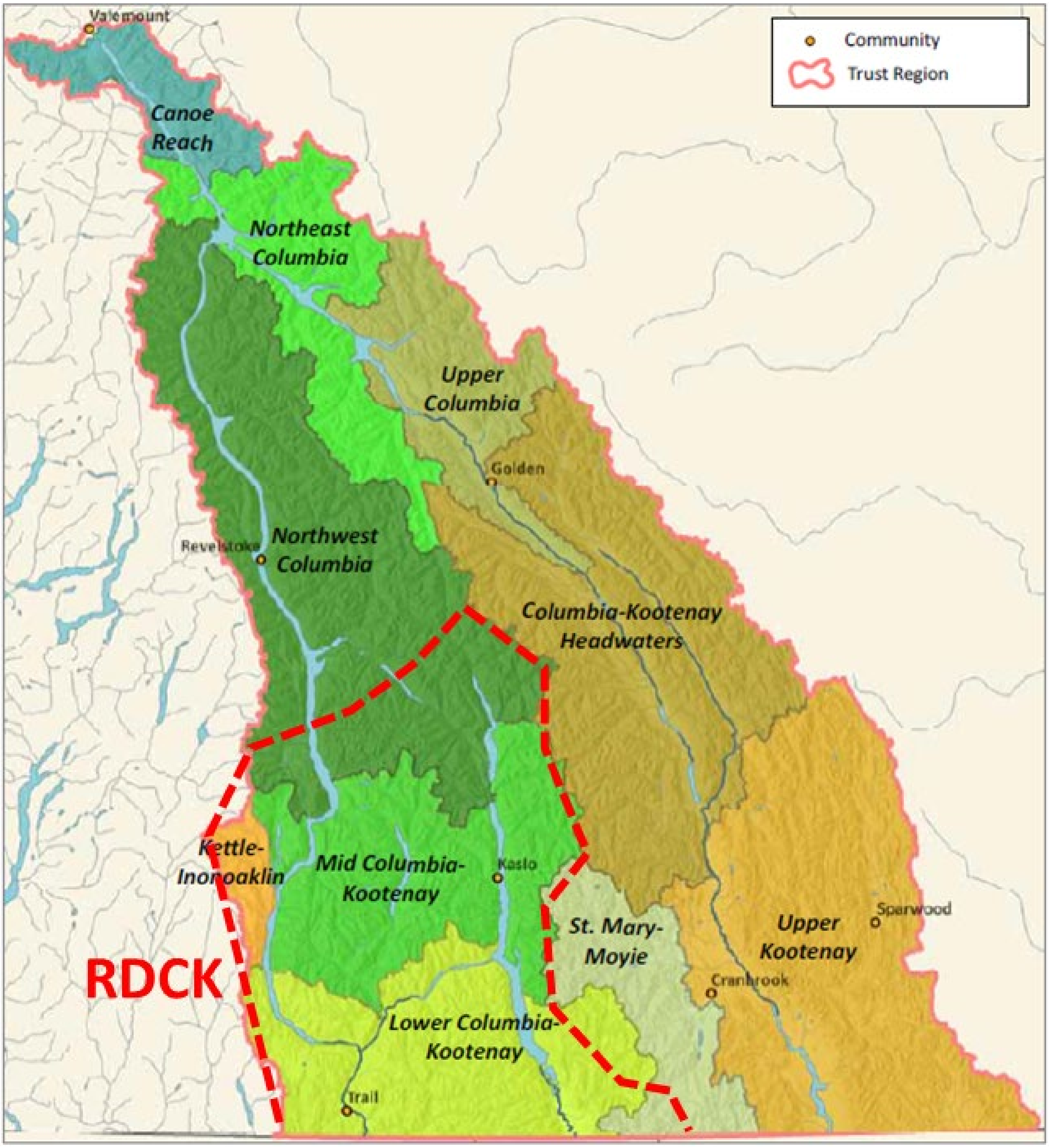

Figure D-3. **Regions of the Columbia Basin as defined by patterns of climate and surface runoff. The RDCK contains 5 of these regions, 2 of which cover the clearwater watersheds (CBT, 2017)**

Table D-2. Regions of the Columbia Basin covering the RDCK and their current relative snowpack depth (CBT, 2017).

Region	Existing Relative Snowpack Depth	Study Area	Representative Hydrometric Station	Clearwater Watersheds	Elevation Range (m)
Lower Columbia-Kootenay	Moderate snowpack at higher elevations	Goat River	08NH004	Goat River	532 to 2622
		Salmo River	08NE074	Erie Creek Upstream End	712 to 2287
Mid Columbia-Kootenay	Moderate to deep snowpack	Crawford Creek	ungauged watershed	Crawford Creek	530 to 2627
		Kaslo Creek	08NH005	Keen Creek	704 to 2797
				Upper Kaslo Creek	699 to 2670
				Kalso Creek at Kootenay Lake	549 to 2785
		Burton Creek	Ungauged watershed	Snow Creek	465 to 2731
				Burton at Arrow Lake	439 to 2785
				Caribou Creek	1117 to 2630
		Slocan River	08NJ013	Lemon Creek	538 to 2604
				Little Slocan River	498 to 2803
				Slocan River	450 to 2973

D.4. CLIMATE CHANGE IMPACT ASSESSMENT

Assessments of climate change impacts for all clearwater watersheds were performed to quantify the anticipated changes in the annual maximum discharge by 2050 (average between 2041 to 2070) under the RCP 8.5 emission scenario. The Engineers and Geoscientists British Columbia (EGBC) offer guidelines that include procedures to account for climate change when flood magnitudes for protective works or mitigation procedures are required (EGBC, 2018). BGC used four different approaches which can be classified into two statistically-based assessments and two process-based assessments to account for climate change in peak discharge, in consideration of the EGBC guidelines. The legislated guidelines as well as the two statistically-based and the two process-based assessment results are presented in the following sections.

D.4.1. Legislated Guidelines

The EBGC guidelines recommend that at-site time-series data (precipitation and/or discharge) be analyzed for statistically significant trends in magnitude or frequency. If no at-site data is available, nearby recorded precipitation or discharge records from watersheds of similar characteristics are to be used for assessment.

If a statistically significant trend is not detectable, the guidelines recommend that when regional discharge magnitude frequency relations are used, a 10% upward adjustment in design discharge is to be applied to account for likely future change in water input from precipitation.

If a statistically significant trend is detectable the guidelines recommend three different procedures.

1. For large basins in which the flows are seasonably driven, the flood magnitude and frequency are to be adjusted based on the best available regionally downscaled projections of annual precipitation and snowpack magnitude, assuming that the precipitation increment will all be added to peak runoff. For snowpack, compare projections with historical records of runoff from snowpacks of similar magnitude. Consider potential effects of plausible land use change and combine the effects if considered necessary.
2. For small basins adjust IDF curves for expected future precipitation and apply the results of stormwater runoff modelling appropriate for expected future land surface conditions.
3. Adjust expected flood magnitude and frequency according to the projected change in runoff during the life of the project, or by 20% in small drainage basins for which information of future local conditions is inadequate to provide reliable guidance. Consider potential effects of land use change in the drainage basin.

D.4.2. Statistically-based Assessment

Two statistically-based methods were developed to assess the effect of climate change on flood quantiles. The first method was based on an examination of the historical annual maximum flood series data to identify statistically significant trends (positive or negative). The second method was based on the index-flood model developed as part of the Regional Flood Frequency Analysis (Regional FFA) (see Appendix C) to estimate the climate-adjusted index flood using climate-adjusted variables derived from downscaled global circulation model (GCM) predictions (Wang et al., 2016). The two methods are described in more detail and results are presented in the following sections.

D.4.2.1. Discharge Trend Analysis

Statistical discharge trend analysis on the annual maximum series (AMS)[1] was performed on suitable hydrometric stations (e.g., sufficient period of record, not regulated) located within the watersheds of clearwater study areas and within the hydrological regions formed as part of the Regional FFA.

The presence of a trend (positive or negative) in the AMS was inferred to be caused, at least in part, by climate change. The Mann-Kendall (M-K) statistical test was used to conduct the trend analyses. The M-K test was preferred over alternative statistical tests because it is non-parametric, and therefore does not assume a functional relationship between time and discharge

[1] The Annual Maximum Series (AMS) is a time series of the largest peak discharge for each year.

magnitude. The M-K test detects consistently increasing or decreasing trends in time series. The M-K test examines for an absence of trend in the time series (the null hypothesis) and returns the probability that the null hypothesis (that there is no monotonic trend in the series) is true. Failing the null hypothesis would in turn suggest that there is a statistically significant temporal trend in the time series. The M-K test was applied only to hydrometric stations with periods of records which spanned the year 2000 to ensure the time series included the most current climate.

Although it was assumed that statistically significant trends were at least in part caused by climate change, changes to the watershed's land cover (e.g., wildfire, insect infestations, changes in land use) were considered as possible causes to trends in peak discharges. Furthermore, the peak discharge records often capture a small window of the flood history at a given location. The limited record lengths make it difficult to differentiate between a long-term trend cause by climate change and the intrinsic climate variability captured in the time series. Consequently, the presence of a statistically significant trend in the peak flow time series could not be solely attributed to climate change.

D.4.2.2. Assessment of Discharge at Hydrometric Stations within Study Areas

One or more suitable hydrometric stations were identified on the Slocan, Kaslo and Salmo Rivers for trend analysis. A hydrometric station with historical discharge data is available on the Goat River (*Goat River Near Erickson* (08NH004)); however, the data at the hydrometric station cannot be used for assessment of trends as the hydrologic regime of the Goat River is regulated by a dam. Of the six hydrometric stations assessed for the three rivers, none were found to show strong or even weak evidence of a trend in the AMS.

Table D-3. Trend results for hydrometric stations within the clearwater study areas (where suitable hydrometric station exist).

Hydrometric Station	Name	Start Year	End Year	p-value	Trend Direction	Sen's Slope[1]
Slocan River						
08NJ013	Slocan River Near Crescent Valley	1914	2018	0.18	-	0.48
08NJ160	Lemon Creek Above South Lemon Creek	1973	2017	0.23	-	0.17
Kaslo River						
08NH005	Kaslo River Below Kemp Creek	1972	2017	0.32	-	-0.21
08NH132	Keen Creek Below Kyawats Creek	1974	2016	0.79	-	0.04
Salmo River						
08NE074	Salmo River Near Salmo	1949	2018	0.47	-	-0.29
08NE114	Hidden Creek Near the Mouth	1973	2016	0.73	-	0.02

D.4.2.2.1 Assessment of Discharge Trends within Homogenous Regions

Each clearwater watershed was assigned to a homogeneous region as part of the Regional FFA formed using cluster analysis. (see Section 4.5 in Appendix C). A trend analysis was performed on the annual peak discharge time series recorded at the hydrometric stations located within the homogeneous region assigned to the clearwater watersheds

D.4.2.2.1.1 1 West – for Watersheds < 500 km²

Within the "1 West – for watersheds less than 500 km²" hydrological region, one hydrometric station out of 15 reported a statistically significant trend ($p < 0.05$ - less than a 5% chance of rejecting the null hypothesis) in the flood series: *Kuskanax near Nakusp* (08NE006). The trend in the magnitude of the flood series for that station was in the decreasing direction (Table D-4).

Table D-4. Trend results for the hydrometric stations in the 1 West – for watersheds < 500 km² hydrologic region.

Hydrometric Station Code	Start Year	End Year	p-value	Trend Direction	Sen's Slope[1]
08LB038	1985	2016	0.246	-	0.33
08NP004	1995	2017	0.239	-	0.13
08NH131	1973	2004	0.444	-	0.19
08KA001	1969	2013	0.738	-	0.06
08NJ168	1983	2014	0.475	-	0.04
08NB014	1973	2017	0.431	-	-0.25
08NH132	1974	2016	0.795	-	0.04
08ND019	1973	2005	0.650	-	0.13
08NE006	1968	2011	0.006	Decreasing*	-1.33
08NK022	1977	2015	0.143	-	-0.19
08NG076	1973	2017	0.314	-	0.07
08KA009	1967	2018	0.881	-	-0.04
08KB006	1978	2015	0.386	-	0.20
08LE086	1997	2016	1.000	-	0.00
08KA010	1908	2015	0.118	-	-0.25

Notes:

1. The Sen's slope is a robust estimate of the magnitude of a trend and commonly used to identify the slope of a trend line in hydrological time series (Yue et al. 2002). It is considered robust because it is sensitive to outliers.

* Strong evidence of trend ($p < 5\%$) – less than 5% chance that the null hypothesis – that there is no trend – is true.

** Weak evidence of trend ($p < 10\%$)– less than 10% chance that the null hypothesis – that there is no trend – is true.

D.4.2.2.1.2 1 West – for Watersheds > 500 km²

Within the "1 West – for watersheds greater than 500 km²" hydrological region, one out of 15 hydrometric stations reporting a statistically significant trend in the flood series (*Fraser River at Red Pass*, 08KA007) with a trend in the decreasing direction (Table D-5).

Table D-5. Trend results for the hydrometric stations in the 1 West – for watersheds > 500 km^2 hydrologic region.

Hydrometric Station Code	Start Year	End Year	p-value	Trend Direction	Sen's Slope[1]
08NB019	1985	2018	0.836	-	0.20
08NB012	1970	2017	0.818	-	0.11
08LE024	1973	2017	0.143	-	-1.07
08NP001	1929	2017	0.845	-	-0.06
08NK018	1973	2015	0.530	-	-0.23
08KA007	1955	2016	0.016	Decreasing*	-0.81
08NH130	1973	2012	0.990	-	0.00
08ND012	1964	2018	0.670	-	-0.11
08ND013	1964	2017	0.228	-	0.72
08NA006	1912	2017	0.317	-	-0.61
12358500	1940	2017	0.623	-	-0.45
08KA013	1998	2017	0.576	-	3.25
12355500	1911	2017	0.857	-	-0.11
08LE027	1915	2017	0.598	-	0.15
08NA011	1949	2018	0.319	-	-0.36

Notes:

1. The Sen’s slope is a robust estimate of the magnitude of a trend and commonly used to identify the slope of a trend line in hydrological time series (Yue et al. 2002). It is considered robust because it is sensitive to outliers.

* Strong evidence of trend ($p < 5\%$) – less than 5% chance that the null hypothesis – that there is no trend – is true.

** Weak evidence of trend ($p < 10\%$)– less than 10% chance that the null hypothesis – that there is no trend – is true.

D.4.2.2.1.3 4 East – for Watersheds < 500 km^2

Within the “4 East – for watersheds less than 500 km^2” hydrological region, 19 hydrometric stations were analysed for presence of a trend (Table D-6). The M-K test identified two stations as having statistically significant trends in their time series with the first showing an increasing trend (*Boundary Creek near Porthill Idaho,* 12321500) and the second showing a decreasing trend (*Arrow Creek near Erickson*, 08NH084). Two other stations, *Redfish Creek near Harrop* (08NJ061) and *Outlet Creek near Metaline Falls* (12397100), were found to have marginally statistically significant decreasing trends ($p < 0.1$ - less than a 10% chance of rejecting the null hypothesis), while *St-Mary River below Morris Creek* (08NG077) was found to have a marginally statistically significant increasing trend ($p < 0.1$).

Table D-6. Trend results for the hydrometric stations in the 4 East – for Watersheds > 500 km^2 hydrologic region.

Hydrometric Station Code	Start Year	End Year	p-value	Trend Direction	Sen's Slope[1]
08NK026	1986	2018	0.332	-	-0.01
08NJ130	1945	2017	0.177	-	0.01
12321500	1929	2017	0.002	Increasing**	0.23
08NH084	1980	2015	0.009	Decreasing**	-0.30
08NH005	1972	2017	0.322	-	-0.21
08NE110	1971	2015	0.567	-	0.14
08NJ061	1968	2017	0.052	Decreasing**	-0.06
08NG077	1973	2017	0.083	Increasing*	0.50
08NN023	1974	2015	0.555	-	-0.12
08NE087	2001	2017	0.964	-	-0.01
08NH016	1947	2017	0.504	-	-0.02
08NJ160	1973	2017	0.229	-	0.17
12313000	1928	2002	0.386	-	1.58
08NJ026	1995	2017	0.239	-	0.13
12397100	1959	2015	0.065	Decreasing*	-0.07
08NE114	1973	2016	0.727	-	0.02
08NE039	1930	2017	0.507	-	-0.06
12304040	1990	2000	0.533	-	0.43
08NH115	1964	2017	0.303	-	0.00

Notes:

1 The Sen's slope is a robust estimate of the magnitude of a trend and commonly used to identify the slope of a trend line in hydrological time series (Yue et al. 2002). It is considered robust because it is sensitive to outliers.

* Strong evidence of trend ($p < 5\%$) – less than 5% chance that the null hypothesis – that there is no trend – is true.

** Weak evidence of trend ($p < 10\%$)– less than 10% chance that the null hypothesis – that there is no trend – is true.

D.4.2.2.1.4 7 – for Watersheds > 500 km^2

Within the "7 – for watersheds greater than 500 km^2" hydrological region, 17 hydrometric stations were analysed for presence of a trend (Table D-7). The M-K test identified three USGS stations as having statistically significant decreasing trends in their time series: *Thompson River near Thompson Falls MT* (12389500), *Yaak River near Troy MT* (12304500), and *Yakima River at Umtanum, WA* (12484500). One other station, *Colville River at Kettle Falls, WA* (12409000), was found to have a marginally statistically significant increasing trend ($p < 0.1$).

Table D-7. Trend results for the hydrometric stations in the 7 – for Watersheds > 500 km^2 hydrologic region.

Hydrometric Station Code	Start Year	End Year	p-value	Trend Direction	Sen's Slope[1]
13339500	1980	2017	0.237	-	0.61
12414900	1966	2017	0.185	-	0.67
12433890	1972	2012	0.553	-	0.43
12354000	1911	2017	0.129	-	-0.98
12388200	1990	2010	0.124	-	0.77
12301300	1948	2016	0.189	-	-0.15
12365000	1931	2006	0.528	-	-0.08
12306500	1930	2017	0.983	-	0.00
12389500	1948	2017	0.044	Decreasing*	-0.55
12370000	1922	2017	0.290	-	-0.15
12304500	1948	2017	0.006	Decreasing*	-1.37
12302055	1948	2017	0.408	-	-0.35
12413000	1912	2017	0.542	-	0.75
12409000	1923	2017	0.076	Increasing**	0.13
12414500	1911	2017	0.935	-	0.00
12413500	1911	2017	0.125	-	1.67
12484500	1906	2017	0.021	Decreasing*	-0.70

Notes:

1 The Sen’s slope is a robust estimate of the magnitude of a trend and commonly used to identify the slope of a trend line in hydrological time series (Yue et al. 2002). It is considered robust because it is sensitive to outliers.

* Strong evidence of trend ($p < 5\%$) – less than 5% chance that the null hypothesis – that there is no trend – is true.

** Weak evidence of trend ($p < 10\%$)– less than 10% chance that the null hypothesis – that there is no trend – is true.

D.4.2.3. Statistical Flood Frequency Modelling

A statistical approach to estimating flood quantiles for the clearwater watersheds was performed using the Regional FFA model. The multivariate regression model to estimate the index-flood (mean annual peak discharge) included three climatic variables as predictors: MAP, MAT, and PAS. This regression model was calibrated using historical values of climatic variables, thus representing current conditions.

To estimate the climate-adjusted index flood for 2050, projected values of the climatic variables were input to the regression model. These projected values were estimated from model ensemble results for the RCP 8.5 emissions scenario using the ClimateNA v5.10 software package, available at http://tinyurl.com/ClimateNA, and based on the methodology described by Wang et al. (2016). The historical and climate-adjusted MAP, MAT, and PAS for the clearwater watersheds in the RDCK region are presented in Table D-8.

Table D-8. Climate variables used in the index flood quantile regression model with historical and climate-adjusted values for the clearwater watersheds in the RDCK.

Study Area	Watershed	MAP		MAT		PAS	
		Historical Value	Climate-adjusted	Historical Value	Climate-adjusted	Historical Value	Climate-adjusted
Crawford Creek	Crawford Creek	1116	1175	3.0	6.4	590	384
Kaslo Creek	Keen Creek	1390	1472	1.3	4.9	857	618
	Upper Kaslo Creek	1244	1316	2.7	6.3	668	437
	Kalso Creek at Kootenay Lake	1312	1389	2.1	5.7	756	523
Burton Creek	Burton at Arrow Lake	1242	1315	2.4	5.9	704	483
	Caribou Creek	1259	1334	2.4	6.0	709	484
	Snow Creek	1227	1299	2.3	5.8	700	483
Slocan River	Little Slocan River	1161	1230	2.8	6.3	643	428
	Lemon Creek	1322	1404	2.7	6.3	754	503
	Slocan River	1224	1297	3.0	6.6	666	446
Goat River	Goat River	857	897	3.2	6.7	433	282
Salmo River	Erie Creek Upstream End	1265	1334	3.8	7.4	617	371

Note:

1. The ensemble model projections are averages across 15 CMIP5 models (CanESM2, ACCESS1.0, IPSL-CM5A-MR, MIROC5, MPI-ESM-LR, CCSM4, HadGEM2-ES, CNRM-CM5, CSIRO Mk 3.6, GFDL-CM3, INM-CM4, MRI-CGCM3, MIROC-ESM, CESM1-CAM5, GISS-E2R).

Climate-adjusted flood quantiles were calculated using the climate-adjusted index flood and the regional growth curves. The regional growth curves are assumed to be stationary. The ratio between the magnitude of the index-flood and the other flood quantiles was assumed to be the same in a climate-adjusted context. The regional growth curves are presented in the Regional FFA (Appendix C). Historical and climate-adjusted flood quantiles are summarized in Table D-9. Results show a small decrease in magnitude between the historical and climate-adjusted flood quantiles. Examination of the regression model for the index flood revealed that both the MAP and PAS were dominant predictors. The increase in the MAP was found to offset the decrease in the PAS resulting in little change in the estimate of the climate-adjusted index flood.

Table D-9. Historical and climate-adjusted flood quantiles for clearwater watersheds in the RDCK.

Study Area	Clearwater Watershed	Index-flood		2-year return period (0.5 AEP)		20-year return period (0.05 AEP)		200-year return period (0.005 AEP)	
		Historical (m^3/s)	Climate-adjusted (m^3/s)	Historical (m^3/s)	Climate-adjusted (m^3/s)	Historical (m^3/s)	Climate-adjusted (m^3/s)	Historical (m^3/s)	Climate-adjusted (m^3/s)
Crawford Creek	Crawford Creek	27	27	25	24	50	49	78	76
Kaslo Creek	Keen Creek	45	45	42	41	75	74	115	114
	Upper Kaslo Creek	38	37	34	34	70	68	109	106
	Kalso Creek at Kootenay Lake	81	80	74	73	150	148	234	230
Burton Creek	Burton at Arrow Lake	81	79	73	71	149	145	232	227
	Caribou Creek	42	41	38	37	78	76	121	119
	Snow Creek	45	44	41	40	83	81	129	126
Slocan River	Little Slocan River	103	100	94	91	191	186	297	289
	Lemon Creek	39	38	35	34	72	69	111	108
	Slocan River	347	339	315	308	642	627	1000	977
Goat River	Goat River	110	109	100	98	172	170	317	312
Salmo River	Erie Creek Upstream End	35	34	32	31	65	63	102	97

Note:
1. Final flood quantiles for Upper Kaslo Creek, Kaslo Creek at Kootenay Lake, Lemon Creek, Little Slocan River, Slocan River, and Goat River were estimated using a pro-rated calculation because they are gauged by a hydrometric station. The flood quantiles reported in Table D-9 were not used for subsequent analysis.

D.4.3. Process-based Assessment

To complement the statistical assessment, results from process-based modelling were examined. Process-based models involve the direct application of the downscaled GCM model forecasts into hydrological models. Process-based assessments are better suited for situations where a threshold change in process is likely e.g., a transition from nival (snowmelt dominated) runoff regime to a pluvial-hybrid (snow influenced) runoff regime.

D.4.3.1. Climate-adjusted Discharge

PCIC provides simulated daily discharge time series for over 120 sites located in the Peace, upper Columbia, Fraser, and Campbell River watersheds. The time series are simulated at Water Survey of Canada (WSC) hydrometric stations and BC Hydro project sites. The simulated time series represent naturalized flow conditions (i.e., with effects of upstream regulation removed) for those sites affected by storage regulation. The hydrologic projections were forced with GCM data downscaled to a 1/16-degree resolution using Bias-Correction Spatial Disaggregation (BCSD) (Wood et al., 2004) following Werner (2011). Application of the Variable Infiltration Capacity (VIC) model and the generation of hydrologic projections for the Peace, Fraser, upper Columbia, and Campbell River watersheds are described in Shrestha et al. (2012) and Schnorbus et al. (2011, 2014).

An ensemble of 8 models forecasting daily discharge time series for locations near the study area was accessed from PCIC's website. This included forecasted time series on the Slocan and Salmo Rivers, specifically:

- Slocan River Near Crescent Valley (08NJ013)
- Salmo River Near Salmo (08NE074).

The RCP 8.5 emissions scenario was not available for this dataset so the IPCC A2 Emission Scenario (business as usual) was selected as the most similar. The 200-year flood quantile was assessed for three periods between 2009-2038, 2039-2068 and 2069-2098 and compared to the 200-year flood quantile based on the historical modelling (1955-2009). Maps showing the trend in the 200-year flood for the PCIC assessed sites and the location of the clearwater watersheds in the study for the three periods are shown in Figures D-4 to D-6 for the three periods assessed.

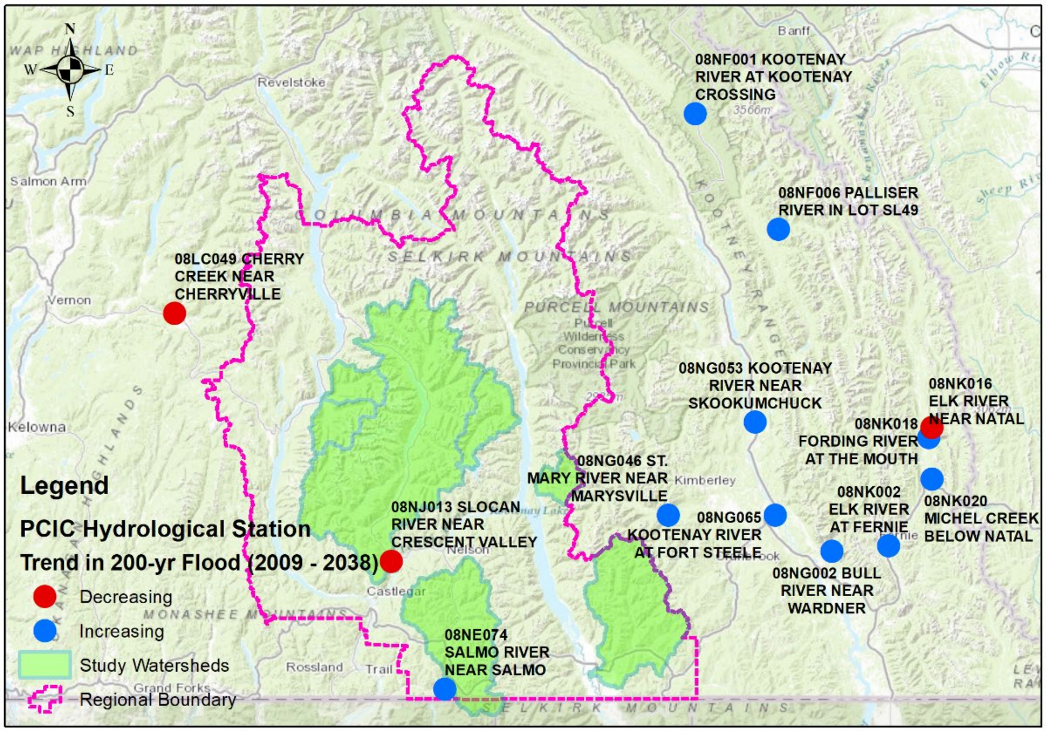

Figure D-4. **Map showing nearby the PCIC hydrometric stations examined and their trend in the 200-year flood (period between 2009-2038).**

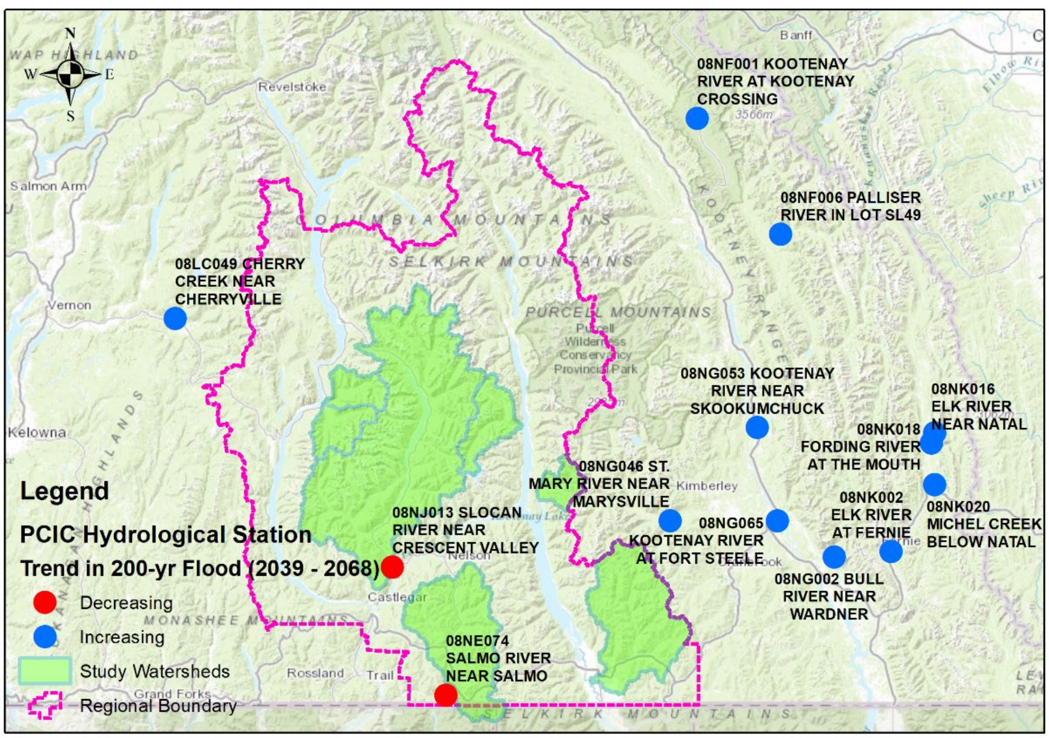

Figure D-5. **Map showing nearby the PCIC hydrometric stations examined and their trend in the 200-year flood (period between 2039-2068).**

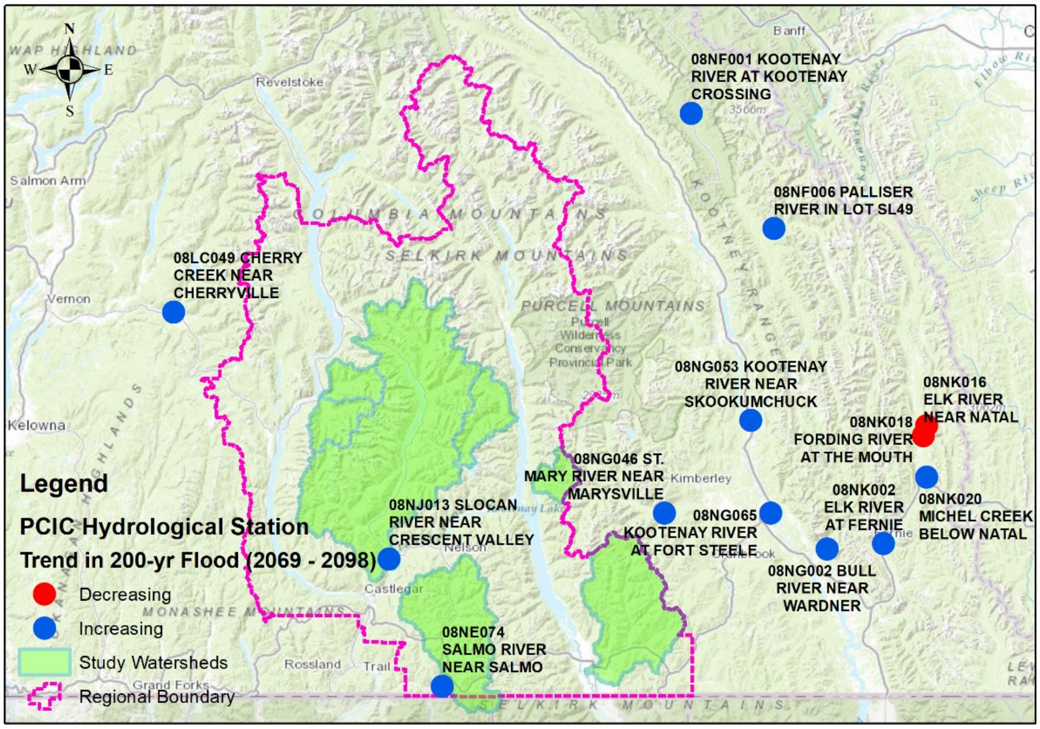

Figure D-6. Map showing nearby the PCIC hydrometric stations examined and their trend in the 200-year flood (period between 2069-2098).

The maps show that, in general, most of the thirteen stations examined show an increase in the magnitude of the 200-year flood over time with some exceptions based on an assessment of the mean of the eight models. A bar chart of the results for the individual hydrometric stations is shown in Figure D-7. The expected change in 200-year flood for the 2039-2068 period varies between – 9% and +28% from the 1955-2009 period. For the 2069-2098 period, the range in the change of the 200-year flood magnitude increases from -7% and +60% from the 1955-2009 period. The mean of the predicted changes in the 200-year flood for Slocan River Near Crescent Valley (08NJ013) show virtually no change for the 2009-2038 period (-0.1%) followed by a small decrease and small increase for the 2039-2068 (-5%) and 2069-2098 (+16%) periods respectively. The mean of the predicted changes in the 200-year flood for Salmo River Near Salmo (08NE074) show a small increase for the 2009-2038 period (+8%) followed by small decrease for the 2039-2068 period (-97%) followed by a large increase for the 2069-2098 period (+60%).

Boxplots of the results for the three periods for the eight model runs are provided in Figure D-12a and Figure D-12b. The boxplots provide a sense of the uncertainty in the analysis by the considerable range in the estimated 200-year flood quantile. Of note, the PCIC hydrologic model output was found by BGC to poorly predict historical flood quantiles.

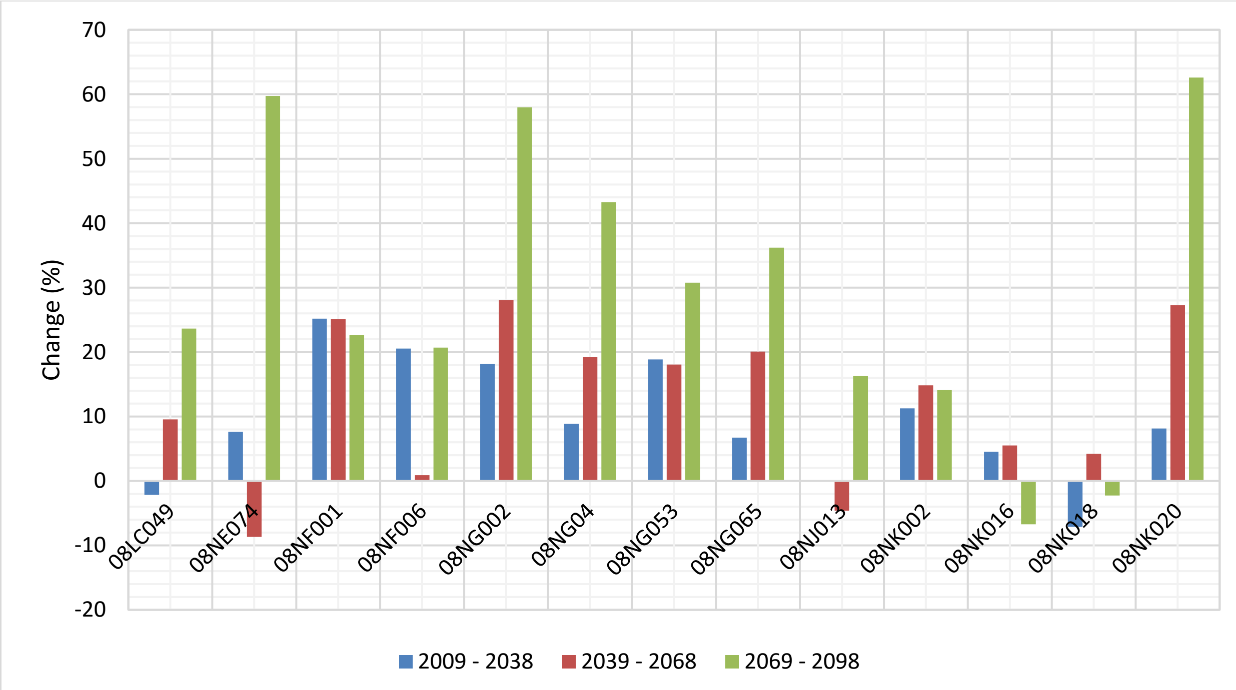

Figure D-7. Bar-graph of the PCIC hydrometric stations and their change in the magnitude of the 200-year flood for the three periods examined compared to the 1955-2009 historical period. *Note that Station 08NJ013 and 08NE074 are stations located on the Slocan and Salmo Rivers respectively.*

D.5. SUMMARY

The EGBC guidelines, summarized in Section D.4.1, offer procedures to account for climate change when flood magnitudes for protective works or mitigation procedures are required (EGBC, 2018). The guidelines recommend that at-site (or nearby) time-series data be analyzed for statistically significant trends. If a statistically significant trend is not detectable, the guidelines recommend that a 10% upward adjustment in design discharge is to be applied to account for likely future change in water input from precipitation. If a statistically significant trend is detectable the guidelines recommend three different procedures including consideration of 1) regionally downscaled projections of annual precipitation and snowpack magnitude, 2) adjustment of IDF curves for expected future precipitation, and or 3) adjustment of the expected flood magnitude and frequency according to the projected change in runoff during the life of the project, or by 20% in small drainage basins for which information of future local conditions is inadequate to provide reliable guidance.

For this study, the impacts of climate change on peak discharge estimates by 2050 (2041 to 2070) were assessed by BGC using statistical and processed-based methods. The statistical methods included a trend assessment on historical flood events using the Mann-Kendall test as well as the application of climate-adjusted variables (mean annual precipitation, mean annual temperature, and precipitation as snow) to the Regional FFA model. The process-based methods included a trend analysis for climate-adjusted flood and precipitation data offered by the PCIC.

The results of the statistical and process-based methods were found to be inconsistent across the RDCK by 2050 (2041 to 2070). Most of the discharge assessed from hydrological regions did not indicate statistically significant trends. The trends that were found were also not consistent with some showing an increasing trend while others a decreasing trend. The results of the statistical flood frequency modelling generally predict a small decrease in the flood magnitude, while the results of the process-based modelling of discharge generally show an increase with a wide range in magnitude. The results of the process-based assessment of the IDF quantiles show an increase during the 1961-1990 and 1971-2000 historical period and then are projected to remain generally constant until 2050. The wide range in magnitude can be a function of many variables including catchment characteristics (e.g., proportion of catchment elevation above a given threshold) which were not explicitly addressed in this assessment.

D.6. CONCLUSION

The climate change impact assessment results were difficult to synthesise in order to select climate-adjusted peak discharges on a site-specific basis. The assessment of the trends in the discharge records was inconclusive. The results of the statistical flood frequency modelling generally show a small decrease in the flood magnitude, while the results of the process-based discharge modelling generally show an increase with a wide range in magnitude. As a result, peak discharge estimates were adjusted upwards by 20% to account for the uncertainty in the impacts of climate change in the RDCK.

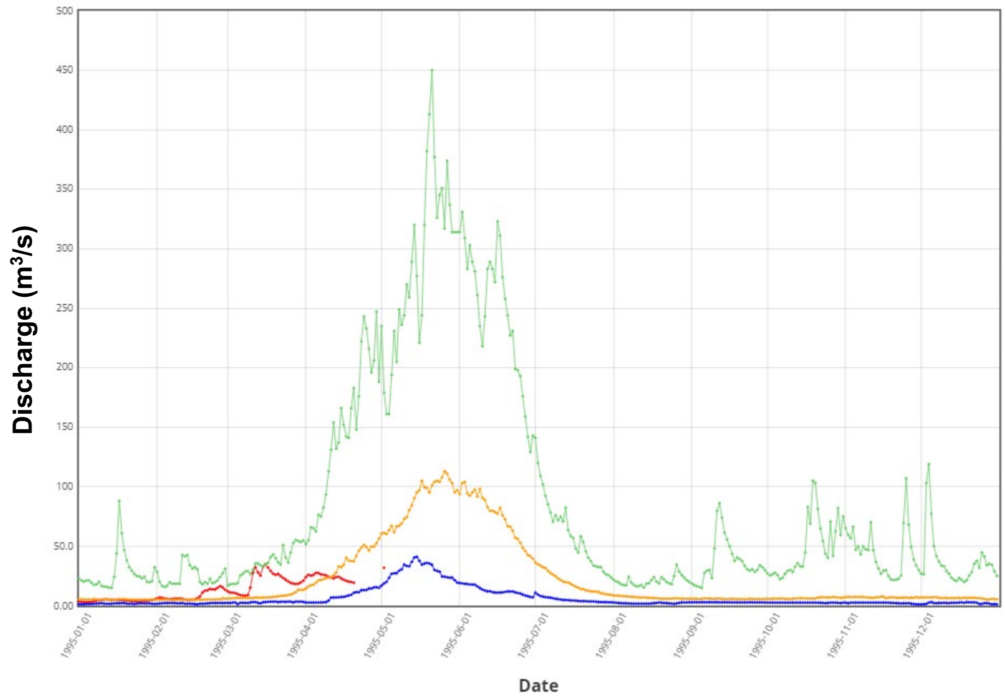

Figure D-8. Example freshet-driven hydrologic regime for Goat River near Erickson (08NH004). Green line is the maximum discharge, the blue line is the minimum discharge, the orange line is the median discharge, and the red line is the 1995 discharge.

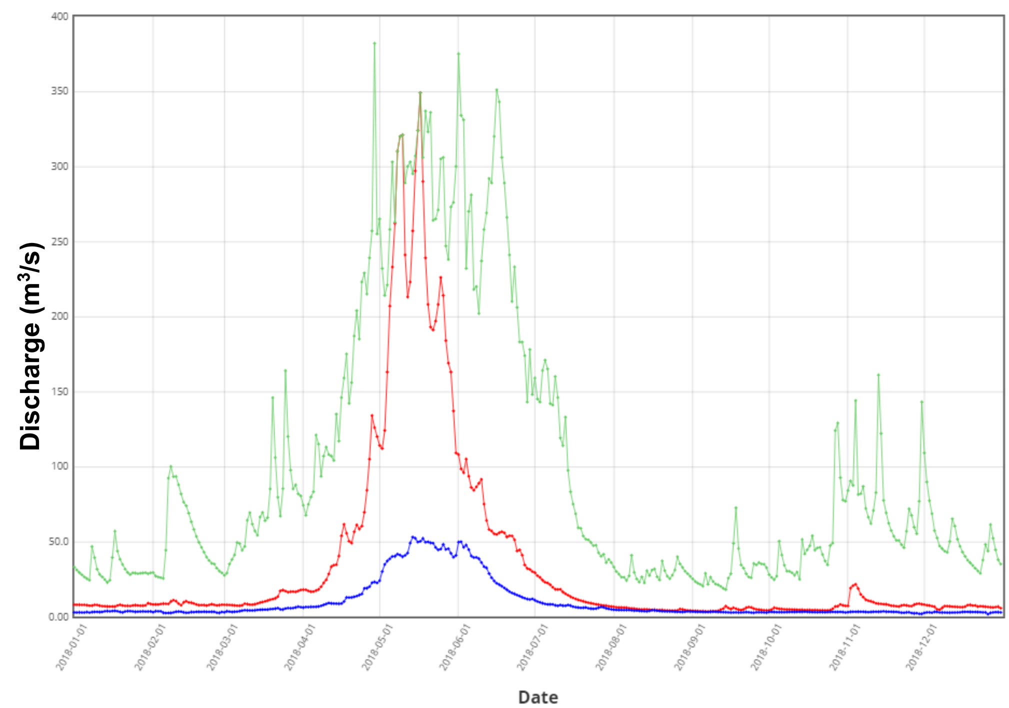

Figure D-9. Example freshet-driven hydrologic regime for Salmo River near Salmo (08NE074). Green line is the maximum discharge, the blue line is the minimum discharge, and the red line is the 2018 discharge.

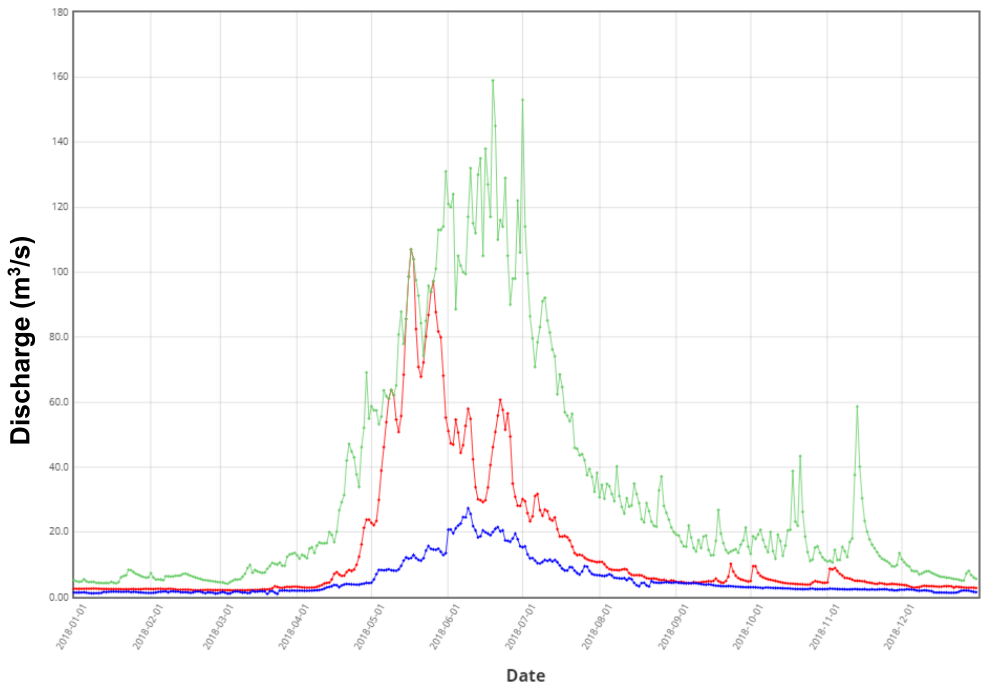

Figure D-10. Example freshet-driven hydrologic regime for Kaslo below Kemp Creek (08NH005). Green line is the maximum discharge, the blue line is the minimum discharge, and the red line is the 2018 discharge.

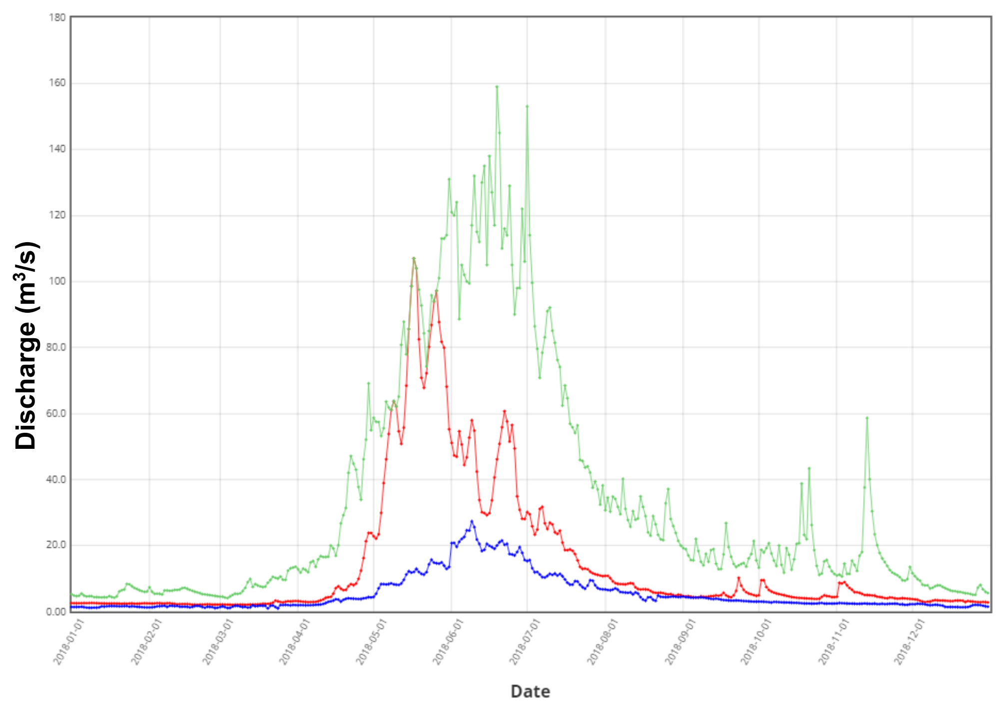

Figure D-11. Example freshet-driven hydrologic regime for Slocan River near Crescent Valley (08NJ013). Green line is the maximum discharge, the blue line is the minimum discharge, and the red line is the 2018 discharge.

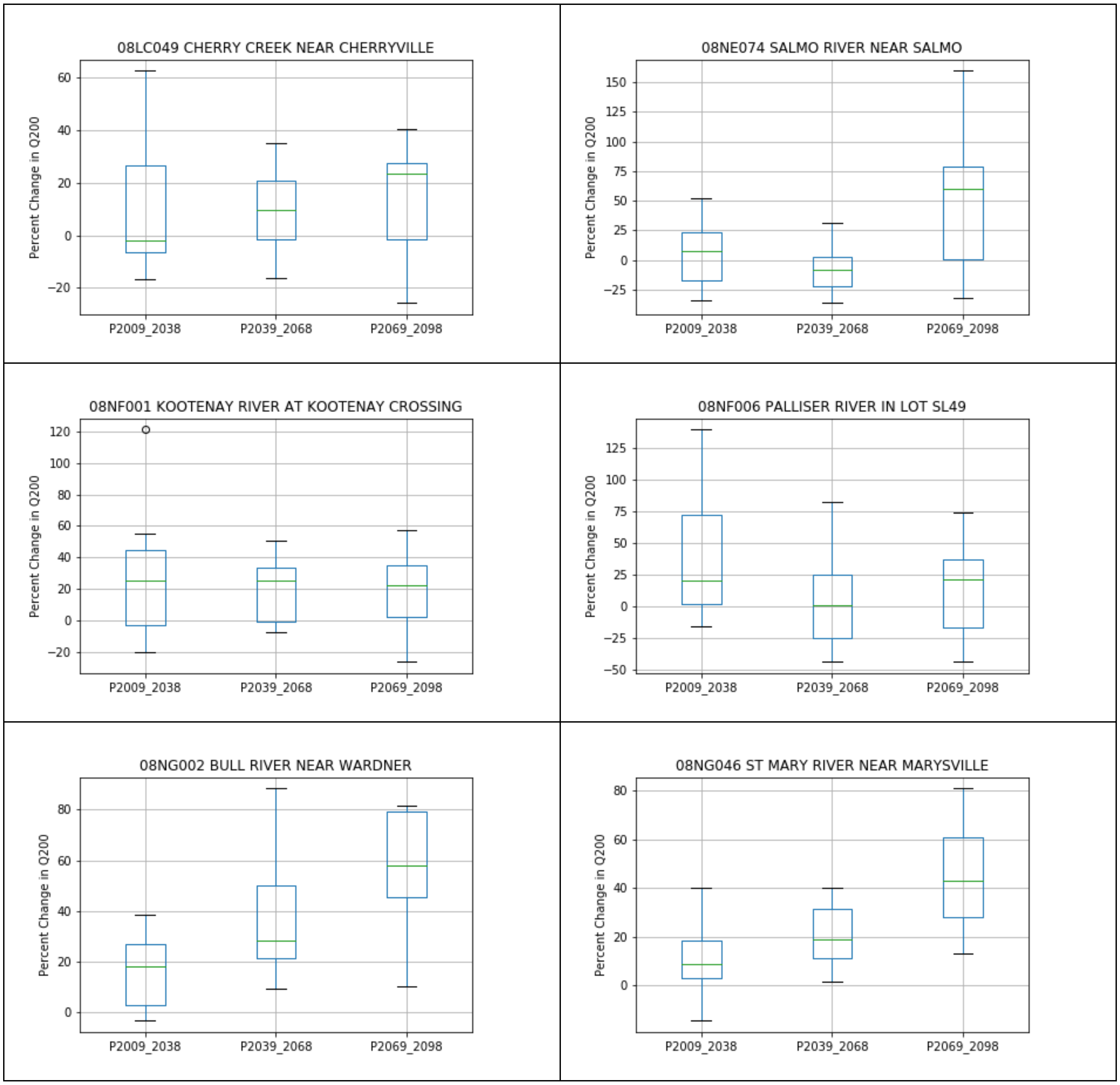

Figure D-12a. Boxplots of the PCIC Hydrological Stations and their change in the magnitude of the 200-year flood for the three periods examined compared to the 1955-2009 historical period. Boxplots represent the interquartile range from the ensemble of 8 GCM models.

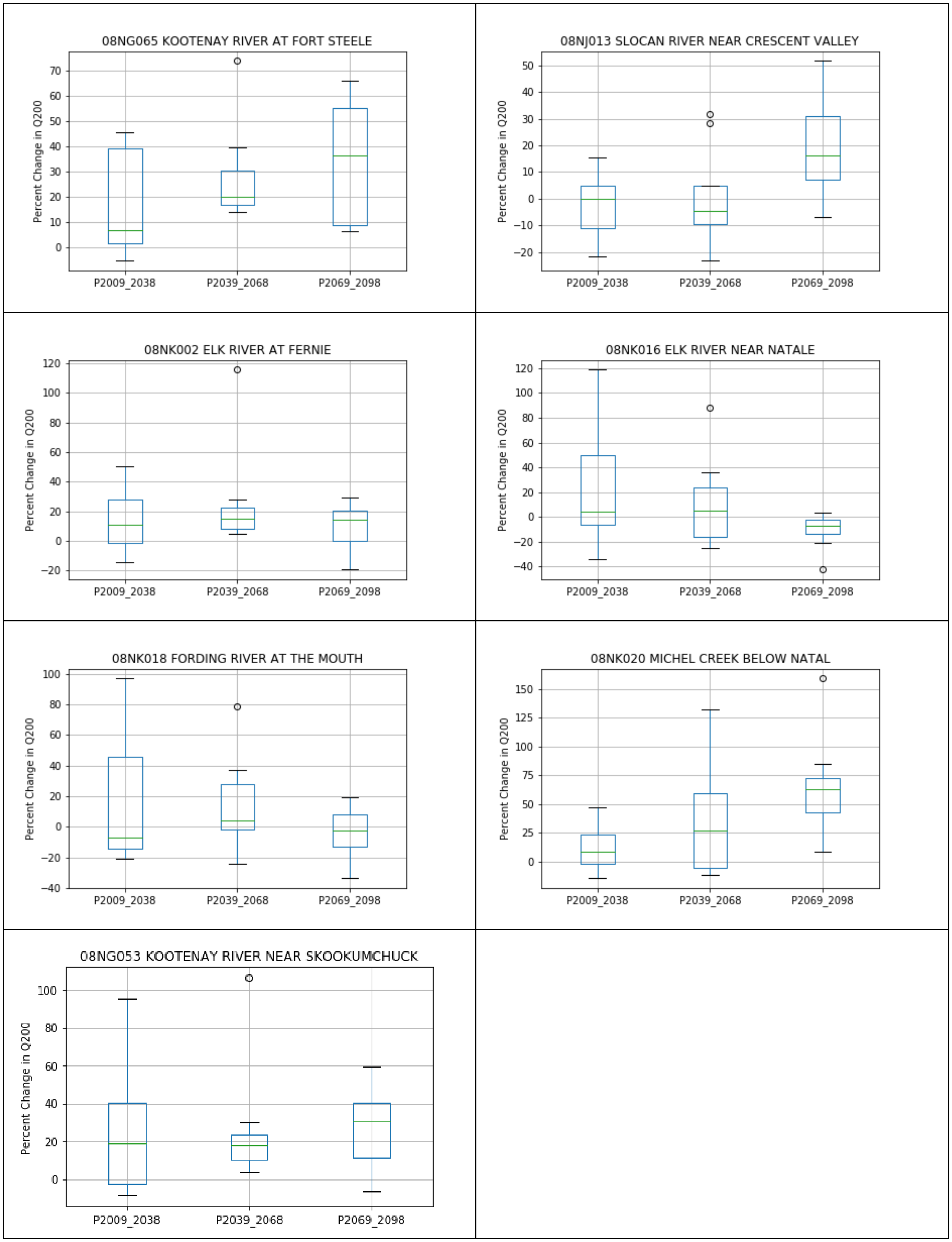

Figure D-12b. Boxplots of the PCIC Hydrological Stations and their change in the magnitude of the 200-year flood (continued).

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APPENDIX E
HYDRAULIC ASSESSMENT METHODS

E.1. INTRODUCTION

This appendix describes the approach used to develop a hydraulic model to estimate flood inundation extents for 20-, 50-, 200-, and 500-year return period floods in the Goat River study area. The following sections describe the methods used to develop the hydraulic model including model selection, model domain, scenarios and sensitivity analyses.

E.2. MODELLING SOFTWARE

Modelling results, including water surfaces profiles, water depths and flow velocities, were estimated using HEC-RAS version 5.0.7 hydraulic model. HEC-RAS is a public domain hydraulic modelling program developed and supported by the United States Army Corps of Engineers (Brunner & CEIWR-HEC, 2016). This version of HEC-RAS supports both one-dimensional (1-D) and two-dimensional (2-D) hydraulic modelling.

For this study, a 2-D hydraulic model was selected. The 2-D model is suited for locations like the Goat River which have multiple channels within a wide floodplain. The 2-D model also provides more detailed resolution of flow depths and velocities than a 1-D model. A 2-D model also removes some of the subjective modelling techniques which are involved in the development of 1-D models such as defining ineffective flow areas, levee markers, and cross-section orientation.

A limitation of 2-D models in HEC-RAS is the modelling of bridges. Currently, the 2-D model cannot model high-flows (e.g., when the water surface elevation is greater than the low cord of the bridge). Incorporation of bridge piers can be accomplished within the 2-D model but at significant computational cost. To address this, 1-D models were created at the bridges to compare the water surface elevations obtained from the 2-D models.

E.3. MODEL DOMAIN AND BOUNDARY CONDITIONS

The model domain covers an 11 km section of Goat River (Figure E-1) starting at the Goat River Dam at the upstream end. The downstream end of the model domain extends to include approximately 2.7 km of the Kootenay River at the confluence of the Goat River.

The upstream boundary for Goat River was set as a steady-state inflow hydrograph. Single-station flood frequency analysis (FFA) was used to estimate peak discharge for the gauged Goat River (Appendix C). The downstream boundary was set to the 20-year return period discharge and stage (water level) on the Kootenay River. Historical streamflow data from the Kootenay River at Porthill (08NH021) station, located 17 km upstream from the Goat River and Kootenay River confluence, was pro-rated to the confluence to provide an estimate of the 20-year return period discharge. This prorated flow was introduced as a steady state inflow hydrograph upstream of the Goat River confluence.

The downstream boundary condition of the model was initially set to the stage of the 20-year flow along the Kootenay River. The stage was then gradually increased over 30% of the simulation time to include the design flow from the Goat River. The downstream boundary stage was held steady for the final 70% of the simulation time to achieve a steady-state solution.

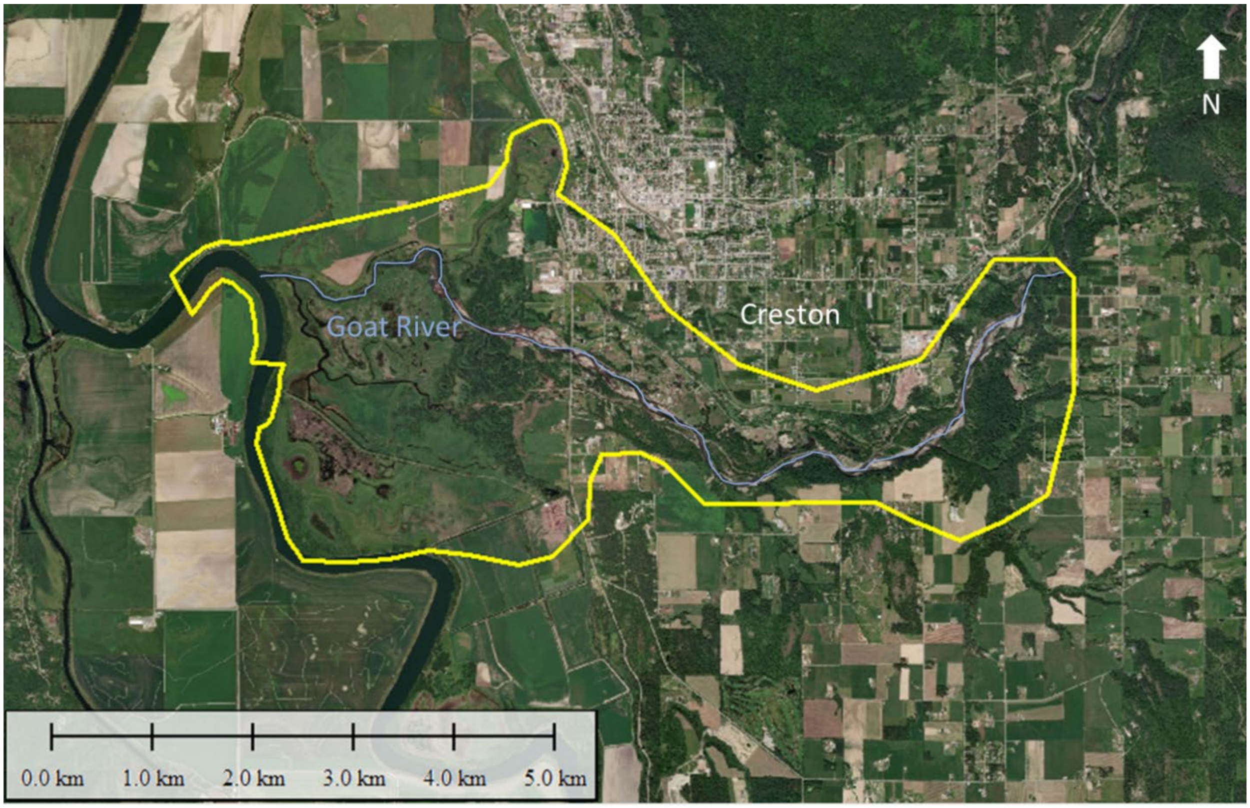


Figure E-1. Goat River study area modelling domain.

E.4. HYDRAULIC ROUGHNESS

As common with many hydraulic models, HEC-RAS 2D uses the Manning's roughness coefficient (Manning's n) to represent the hydraulic flow roughness. Measured flow and water level data for high-flow events were not available for Goat River, and therefore the model is uncalibrated. The in-channel Manning's n values were selected using data collected from a grain size sample (Wolman count) conducted on the surface of a gravel bar downstream of the Highway 21 bridge. The results of the Wolman Sample are shown in Figure E-2 and Table E-1.

The Manning's n values on the floodplain were selected with guidance from the literature and using empirical equations. Manning's n values for floodplain areas were based on land cover types (Figure E-3) with Manning's n values for each land cover type from Chow (1959). The spatial land cover distributions were imported from digital land cover maps from the North American Land Change Monitoring System (NRCan, 2019).

Table E-1. Goat River bar surface grain size distribution downstream of Hwy 21 Bridge (from Wolman count).

Grain Size	Goat River
Location	200 m downstream (west) of north Highway 21 bridge
Number of stones measured	109
D95 (mm)	127
D90 (mm)	116
D84 (mm)	105
D75 (mm)	90
D50 (mm)	64
D15 (mm)	40
D5 (mm)	33

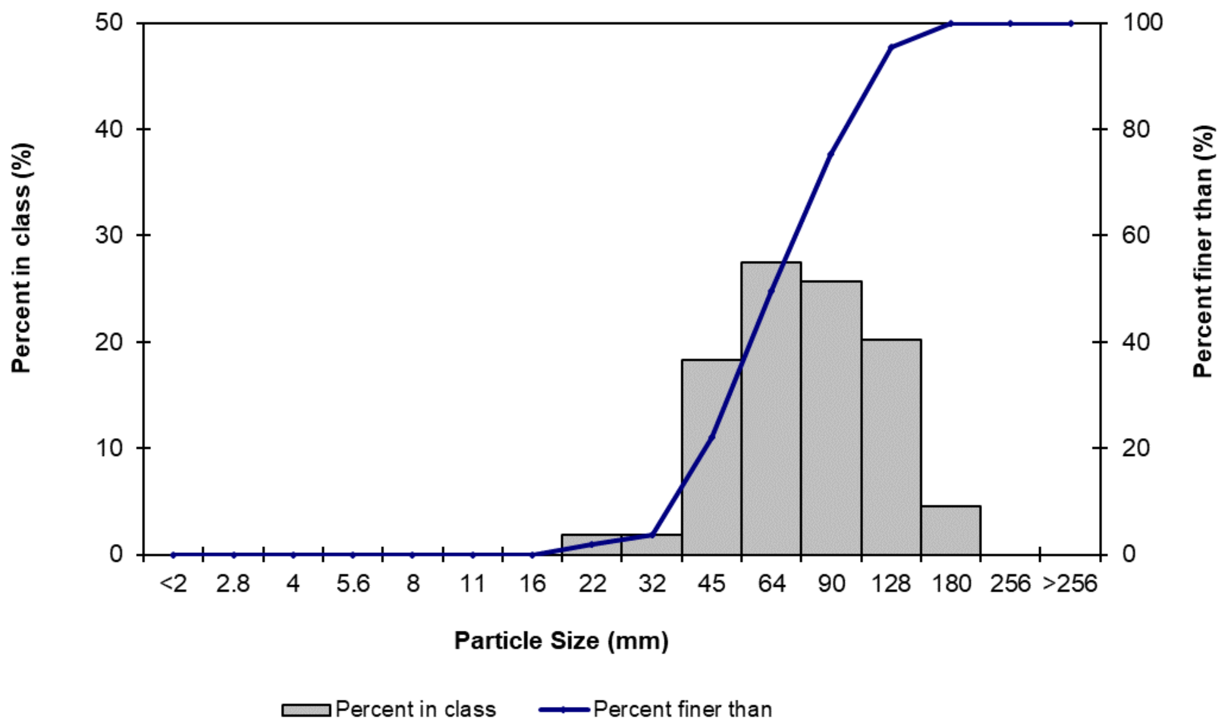


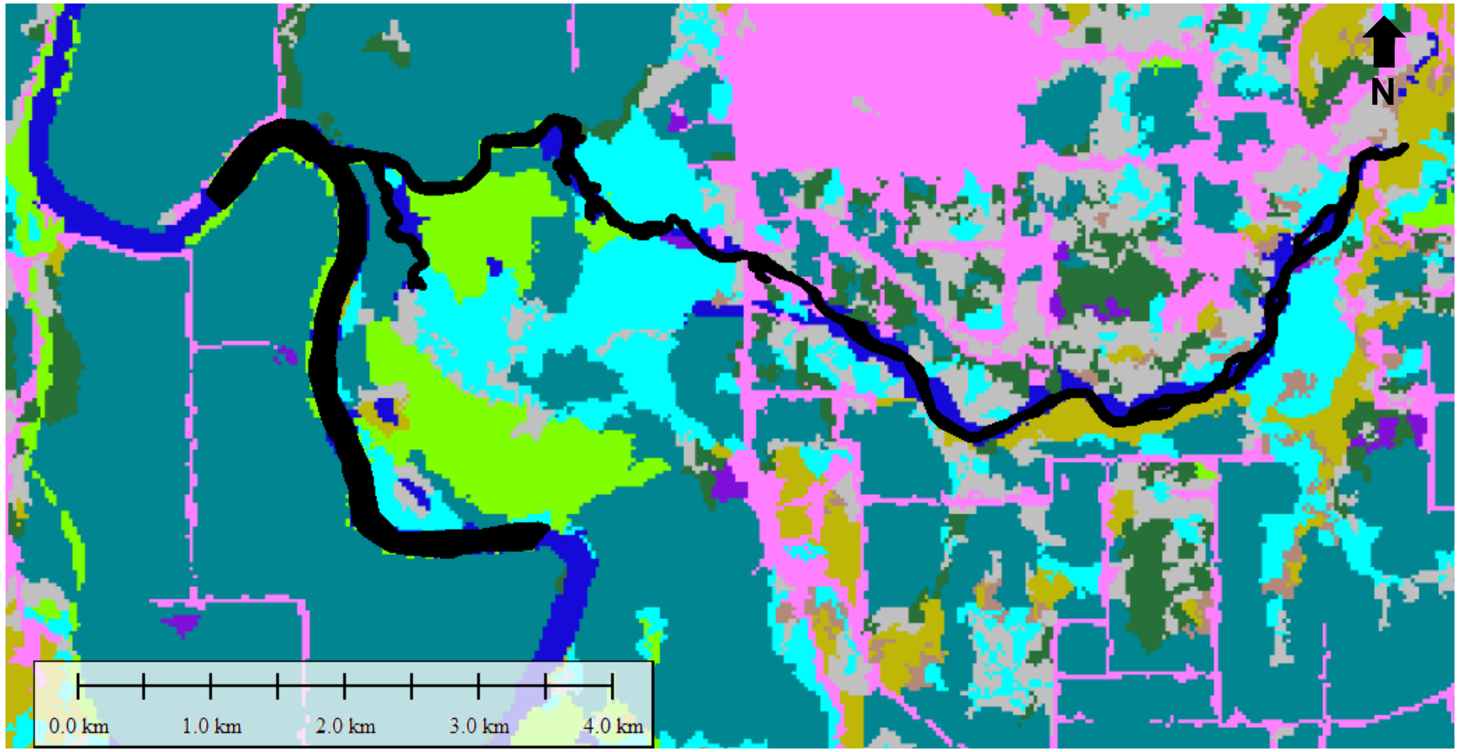
Figure E-2. Goat River surface grain size distribution downstream of Hwy 21 Bridge (from Wolman count).

The Wolman sample data was used in conjunction with the following equation to determine the in-channel Manning's n value (Lane and Carlson, 1953):

$$n = \frac{d_{75}^{\frac{1}{6}}}{66.86}$$

where d_{75} is the sediment diameter (in mm) of which 75% of the material is finer. This equation is based off a study conducted in the San Luis Valley canals, which were paved with cobbles.

Based on the results of the calculation, a value of 0.032 was selected for the in–channel Manning's n. A sensitivity on the model results to the Manning's n is provided later in Section E.7 of this appendix.



Land Class	Manning's N	Color
1. Temperate or sub-polar needleleaf forest	0.1	
2. Temperate or sub-polar broadleaf deciduous forest	0.1	
3. Mixed Forest	0.1	
4. Temperate or sub-polar shrubland	0.07	
5. Temperate or sub-polar grassland	0.035	
6. Wetland	0.044	
7. Barren Lands	0.044	
8. Urban and Built-up	0.025	
9. Water	0.044	
10. Main Channel	0.032	

Figure E-3. Land cover types and associated Manning's n values.

E.5. MODEL MESHING

The HEC-RAS software for 2D modelling uses an irregular mesh to simulate the flow of water over the terrain. Irregular meshes are useful for development of numerically efficient 2D models to allow refinement of the model in locations where the flow is changing rapidly and/or where additional resolution is desired. With 2D models the objective is to define a model with sufficient accuracy and resolution that minimizes model runtime.

The default cell geometries created by HEC-RAS are rectangular, but other geometries can be selected to suit the problem under consideration. Within HEC-RAS, a 2D mesh is generated based on the following inputs:

- The model perimeter (the model domain or extent of the model)
- Refinement areas to define sub-domains where the mesh properties (e.g., mesh resolution) is adjusted.
- Breaklines to align the mesh with terrain features which influence the flow such as dikes, ditches, terraces and embankments. HEC-RAS provides options to adjust the mesh resolution along breaklines if the modeler chooses.

From these inputs, HEC-RAS generates the mesh consisting of computational points at the cell centroid and the faces of the cells. The mesh was cleaned and checked for errors such a cell having more than 8 faces and gaps in the mesh.

E.5.1. Initial Mesh Development

For the Goat River Study area, a base model resolution of 20 m was selected. A refinement region was created upstream of the Highway 21 bridge with a 15 m mesh. Another refinement region with a 10 m mesh was created north of the dikes, upstream of the Hwy 21 bridge. Breaklines were placed along the top of all dikes, and along the top of Highway 21. Breaklines were also placed in areas where supercritical flow was observed after the first model run, to reduce numerical error. These breaklines had resolutions ranging from 2 to 8 m and had between 5 and 7 repeats. Additional breaklines were also added in areas where ‘leakage’ was noted between cells. Leakage is a result of the terrain features not aligning with cell faces and/or cells that are too large and allows water to non-physically flow between cells.

E.5.2. Mesh Refinement

The final mesh consisted of 140,000 computational cells with an average cell face length of 13 m and average cell area of 144 m^2. An example of the mesh developed is given in Figure E-4.

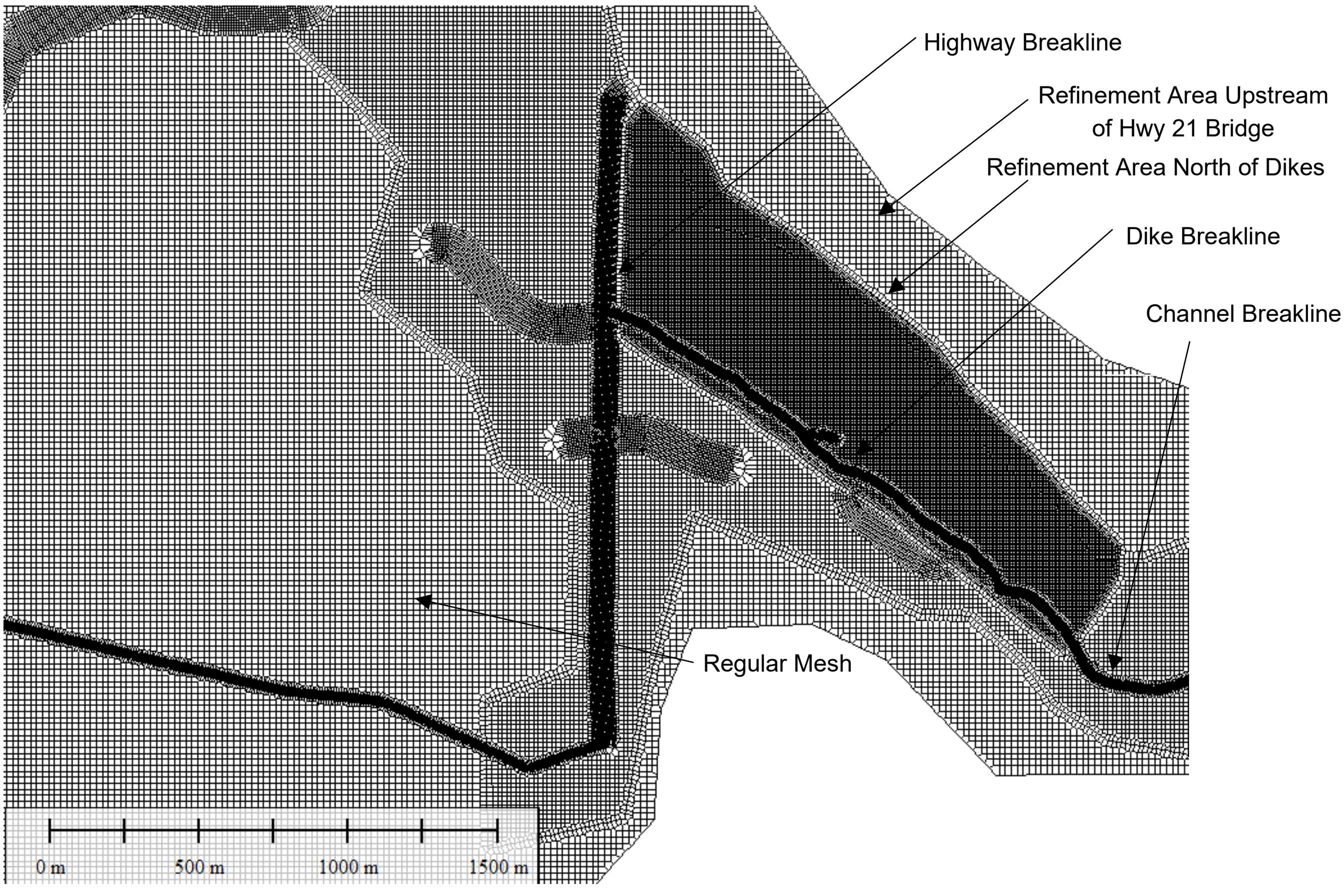


Figure E-4. Example of the mesh used for the model showing the breaklines and refinement areas.

E.5.3. Hydraulic Structures

Flow through the north and south Highway 21 bridges was analyzed with the HEC-RAS 1-D incorporating the bridge and pier dimensions (Table E-2). The results of the HEC-RAS 1-D model for the 500-year peak discharge are presented in Figures E-5 and E-6.

Table E-2. Bridge dimensions surveyed by Explore Survey Inc., July 2019.

Bridge	Top deck elevation (m)	Bottom deck elevation (m)	Pier Thickness (m)	Number of Piers	Shape of Piers	Deck Span (m)	Deck Width (m)
Highway 21 north	542.8	540.5	0.8	3	Rectangular Concrete	73.6	12.2
Highway 21 south	544.0	542.7	0.7	2	Rectangular Concrete	34.9	13.3[1]

Note:

1. Value measured from Google Earth by BGC, February 12, 2020.

The North Highway 21 bridge would have approximately 0.8 m of freeboard for the 500-year event (Figure E-5), while the South Highway 21 bridge would have more than 2.0 m (Figure E-6). As a result, the presence of the bridge decks would not affect the design water levels, and the bridge decks for the north and south Highway 21 bridges were removed from the topographic model for the HEC-RAS 2-D model.

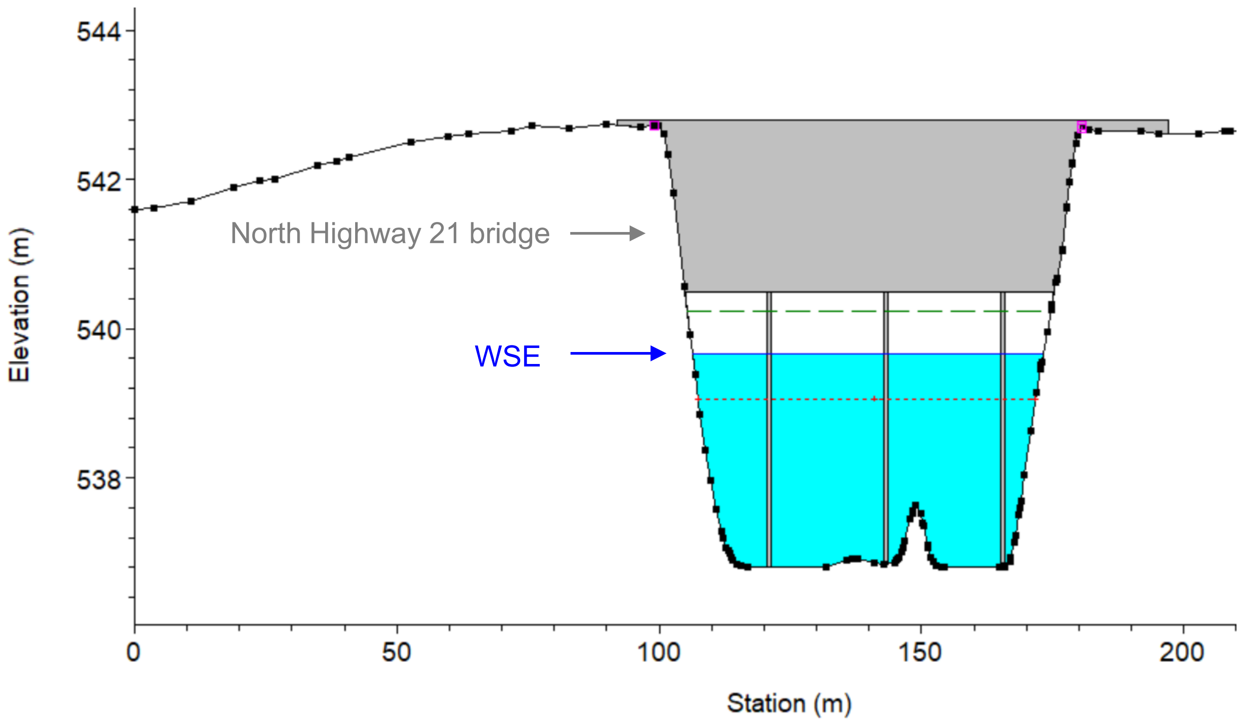


Figure E-5. 1-D HEC-RAS modelled 500-year peak discharge under the Highway 21 bridge (north).

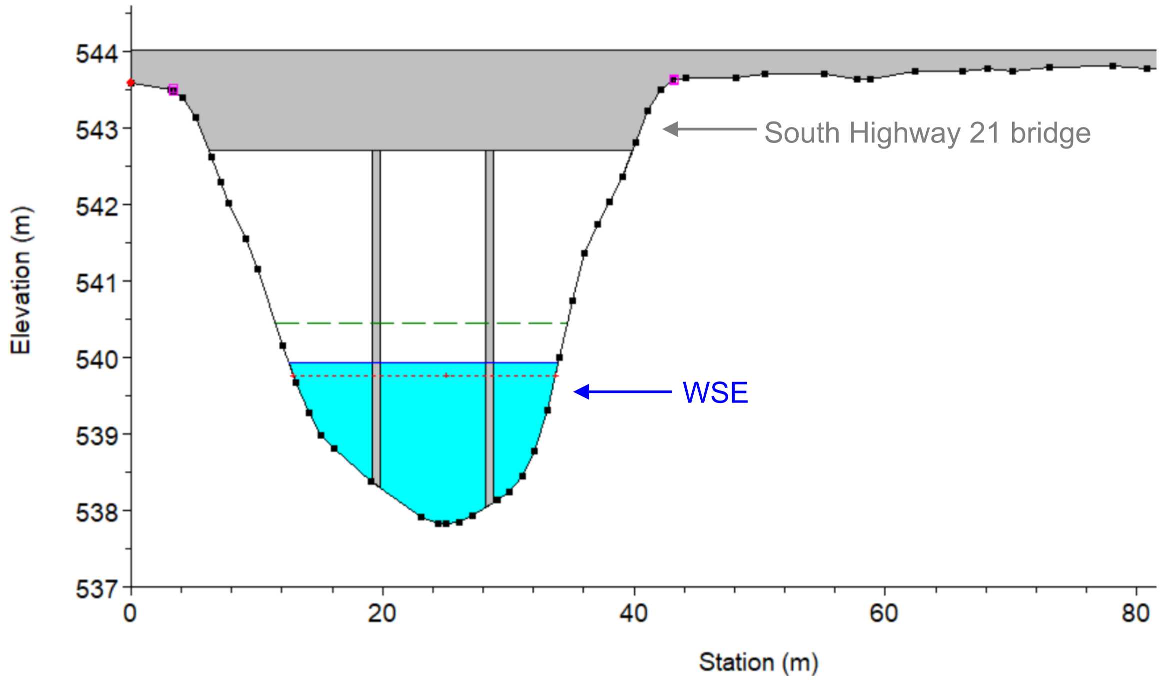


Figure E-6. 1-D HEC-RAS modelled 500-year peak discharge under the Highway 21 bridge (south).

Although the bridge piers can cause energy loss and an increase in water levels, a comparison of the 1D results (which includes the piers) and 2D results (no piers) demonstrates at these bridges that the effect of the piers on the water levels is of the order of 15 cm, or less (Figure E-7, Figure E-8).

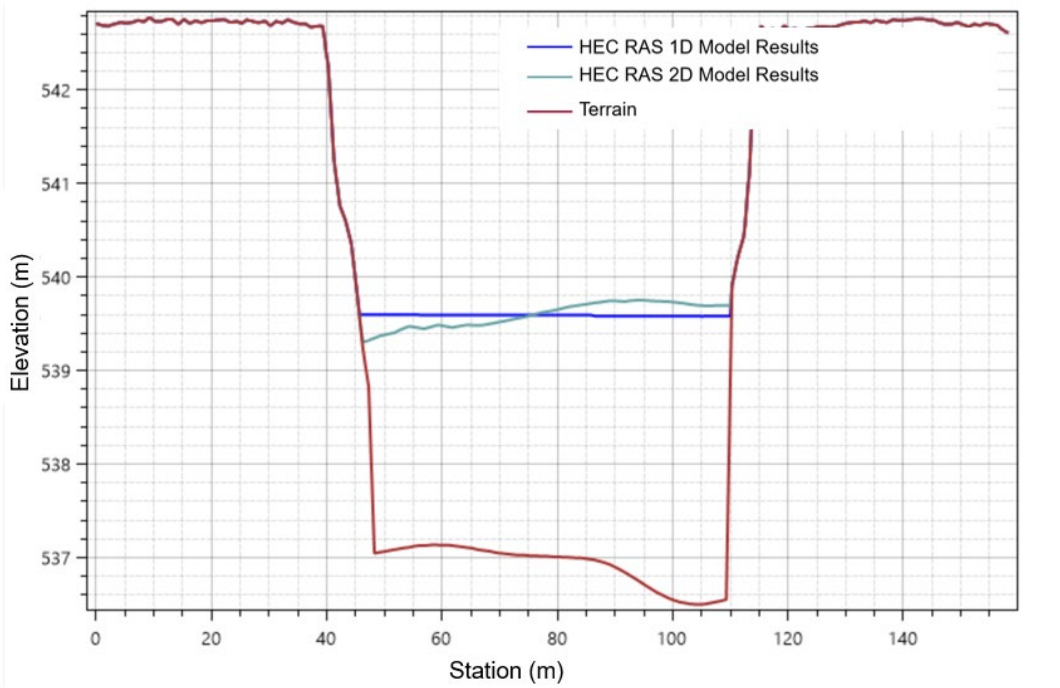


Figure E-7. Modelled 500-year flow under the Highway 21 North bridge for the 1D HEC-RAS model compared to the 2-D HEC-RAS model.

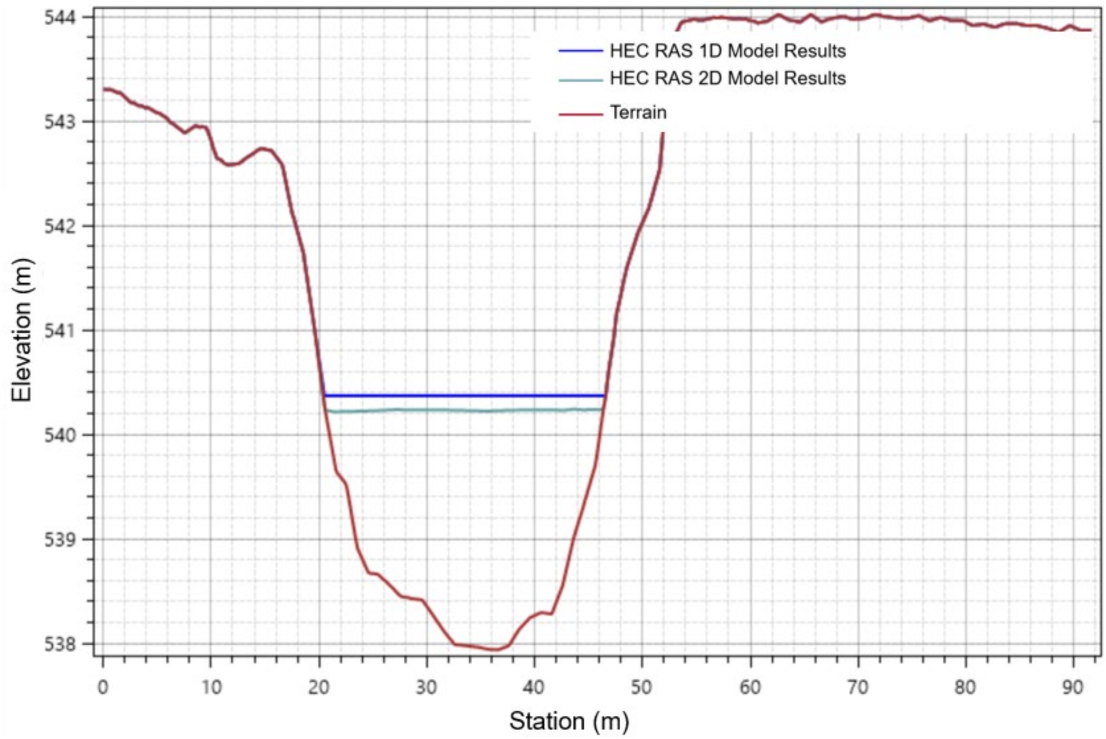


Figure E-8. Modelled 500-year flow under the Highway 21 North bridge for the 1D HEC-RAS model compared to the 2-D HEC-RAS model.

E.5.4. Simulation Settings

The hydraulic model described above was run using a Courant controlled time step. The initial time step was 0.2 seconds, and the maximum Courant number was 2. The model was run for 10 hours using the diffusion wave equation. The results of this were saved and used as an initial condition for the model which was then run for 9 hours using the full momentum equation. The full momentum equations provide accurate representation of flow dynamics especially where sharp contraction, expansions or changes in flow direction are observed. However, as the diffusion wave equation is less computationally heavy, using diffusion wave initially helped prevent numerical errors. A steady state of flow was reached after 6 hours using the full momentum equation.

E.6. MODELLING SCENARIOS

Scenarios were run for 20, 50, 200 and 500-year flood events. A summary of the modeled events is given in Table E-3. Sensitivity analysis was performed on the results of the 200-year peak discharge for Manning’s n.

Table E-3. Modelled scenarios

Scenario	Discharge at Upstream Boundary (m^3/s)	In- Channel Manning's n
20-year flow	464	0.032
50-year flow	520	0.032
200-year flow	595	0.032
200-year (+20% Manning's n)	595	0.038
200-year flow (-20% Manning's n)	595	0.026
500-year flow	640	0.032

E.7. SENSITIVITY ANALYSIS

Since the models are uncalibrated, a sensitivity analysis for Manning's n was performed. For the 200-year flood event two additional scenarios with a "high" Manning's n scenario with main channel's Manning's n value increased by 20% (n=0.038), and a "low" Manning's n scenario with main channel's Manning's n value decreased by 20% (n=0.026).

For the high Manning's n scenario the water surface elevation (WSE) was found to change by -2.0 cm to +12 cm in both the main channel and the floodplain. For the low Manning's n scenario, the WSE was found to change by +2.0 to -13 cm in both the main channel and the floodplain. The change in the WSE along the channel thalweg of the Goat River is shown in Figure E-9.

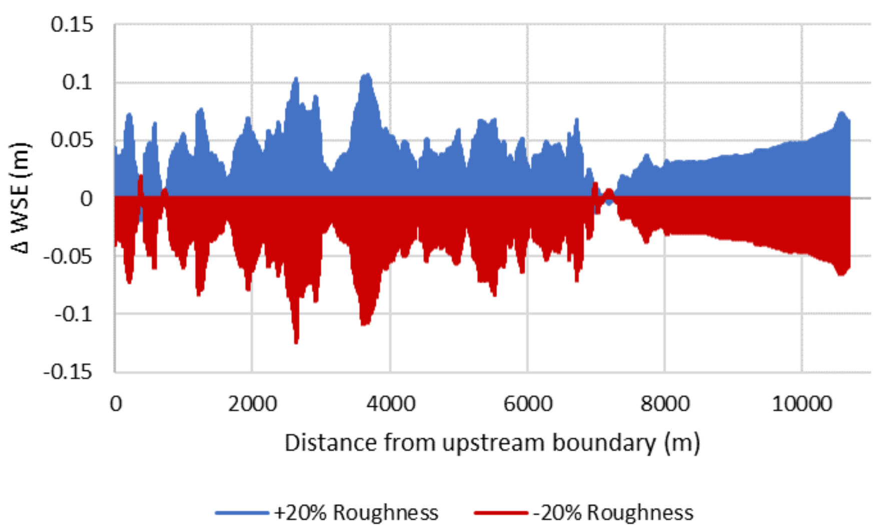


Figure E-9. Change in water surface elevation (WSE) along the channel thalweg for the "high" and "low" roughness sensitivity scenarios.

The effect of Manning's n on flood inundation extent is shown in Figure E-10 and Figure E-101. While decreasing Manning's n by 20% has a limited effect on the predicted extent of the flood plain, increasing Manning's n by 20% results in a slight increase in the predicted flood extent on the northern side of Goat River above the Hwy 21 bridge. A summary of changes to WSE at key locations is provided in Table E-4.

Table E-4. Summary of changes to water surface elevation (WSE) at key locations.

Location Description	Easting NAD 83 Zone 11	Northing NAD 83 Zone 11	Average WSE (m) n=0.026	Average WSE (m) n=0.032	Average WSE (m) n=0.038
Upstream model boundary (fan apex)	540017	5438294	575.33	575.33	575.33
Dike upstream of Highway 21	536207	5435806	545.54	545.50	545.57
Flow under Highway 21 Bridge (north)	534876	5436670	539.54	539.49	539.60
Downstream model boundary (outlet to Kootenay River)	531886	5437406	535.60	535.58	535.65

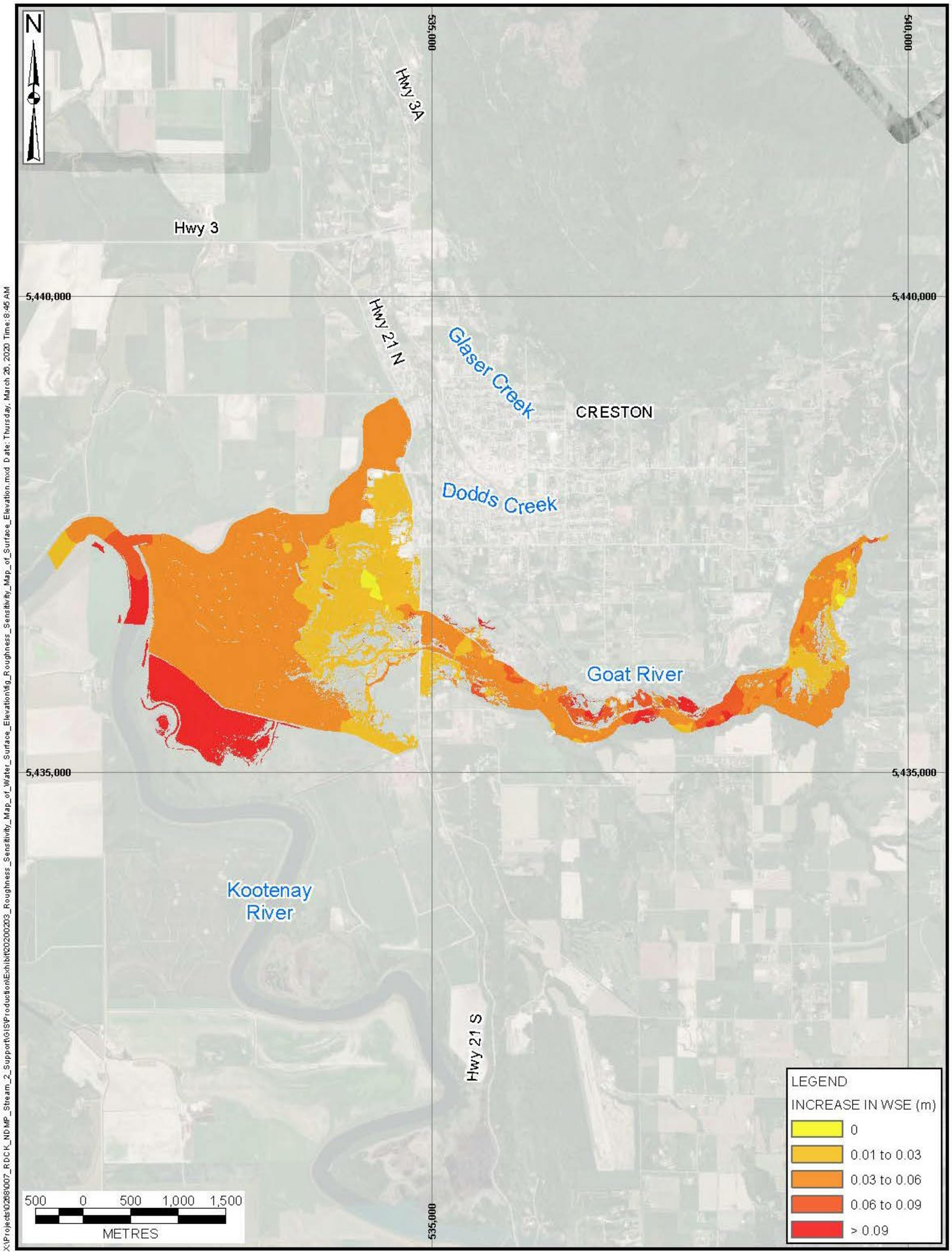


Figure E-10. Change in WSE for 20% increase in Manning's n.

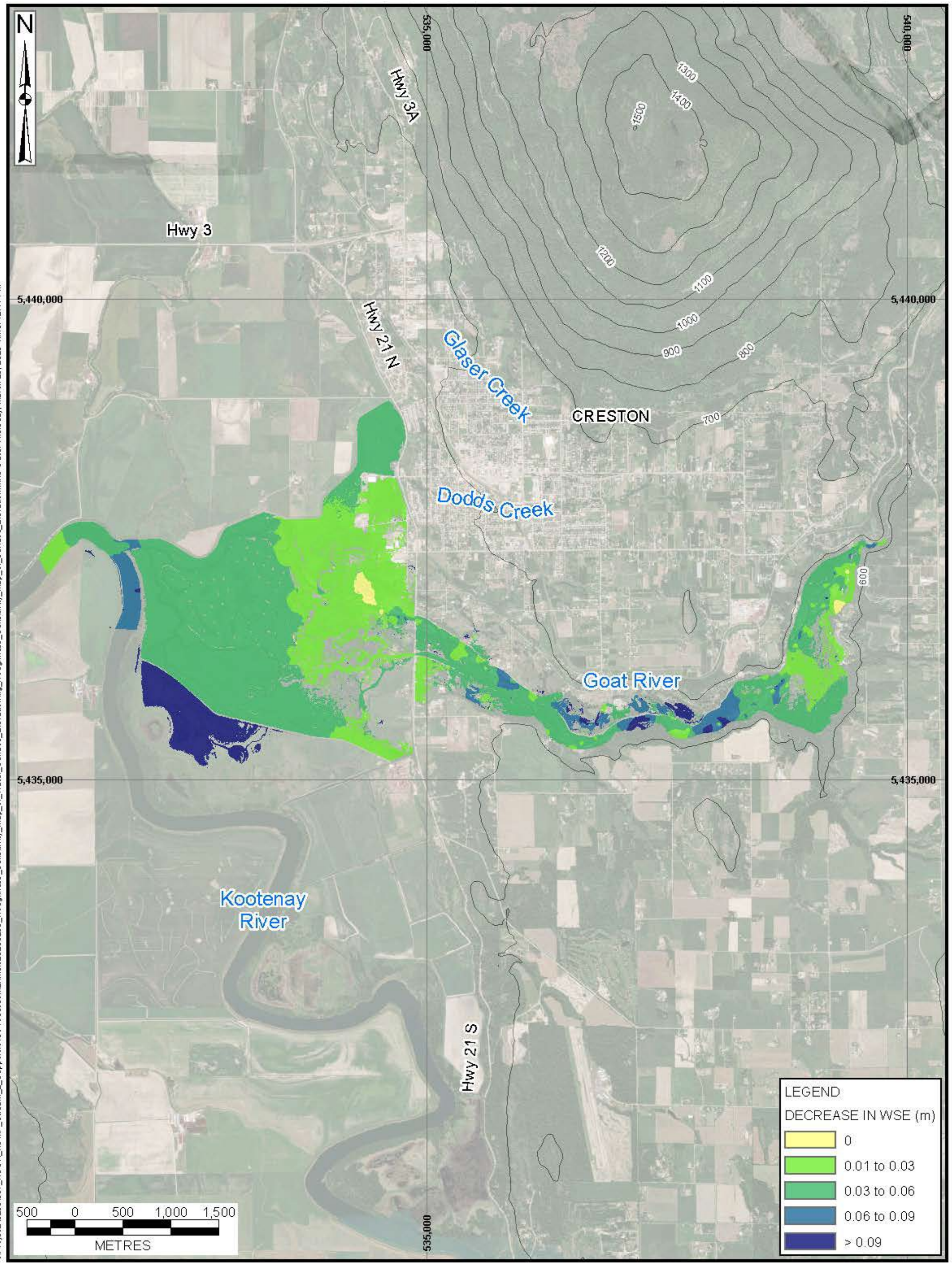


Figure E-11. Change in WSE for the "low" Manning's n scenario (20% decrease).

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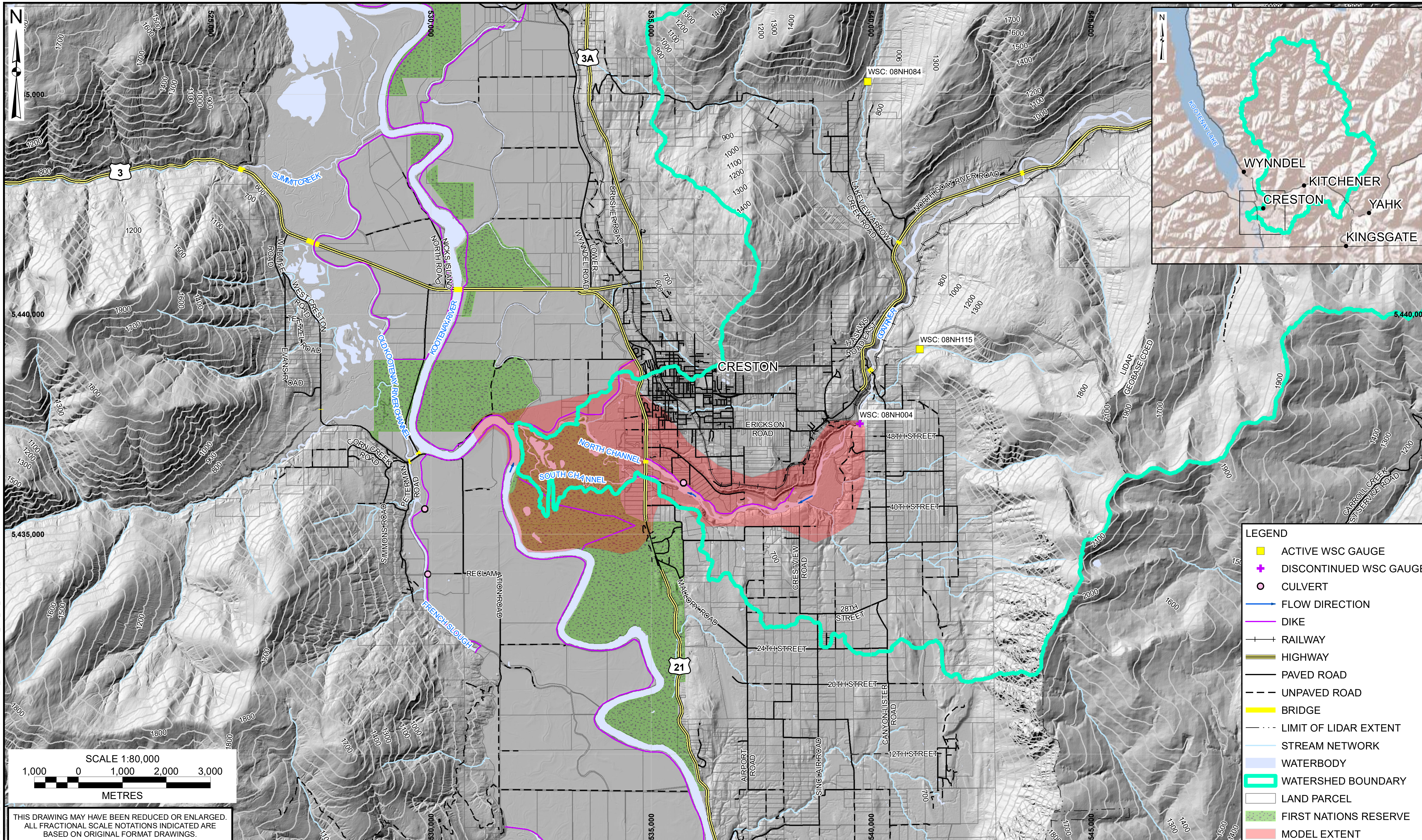

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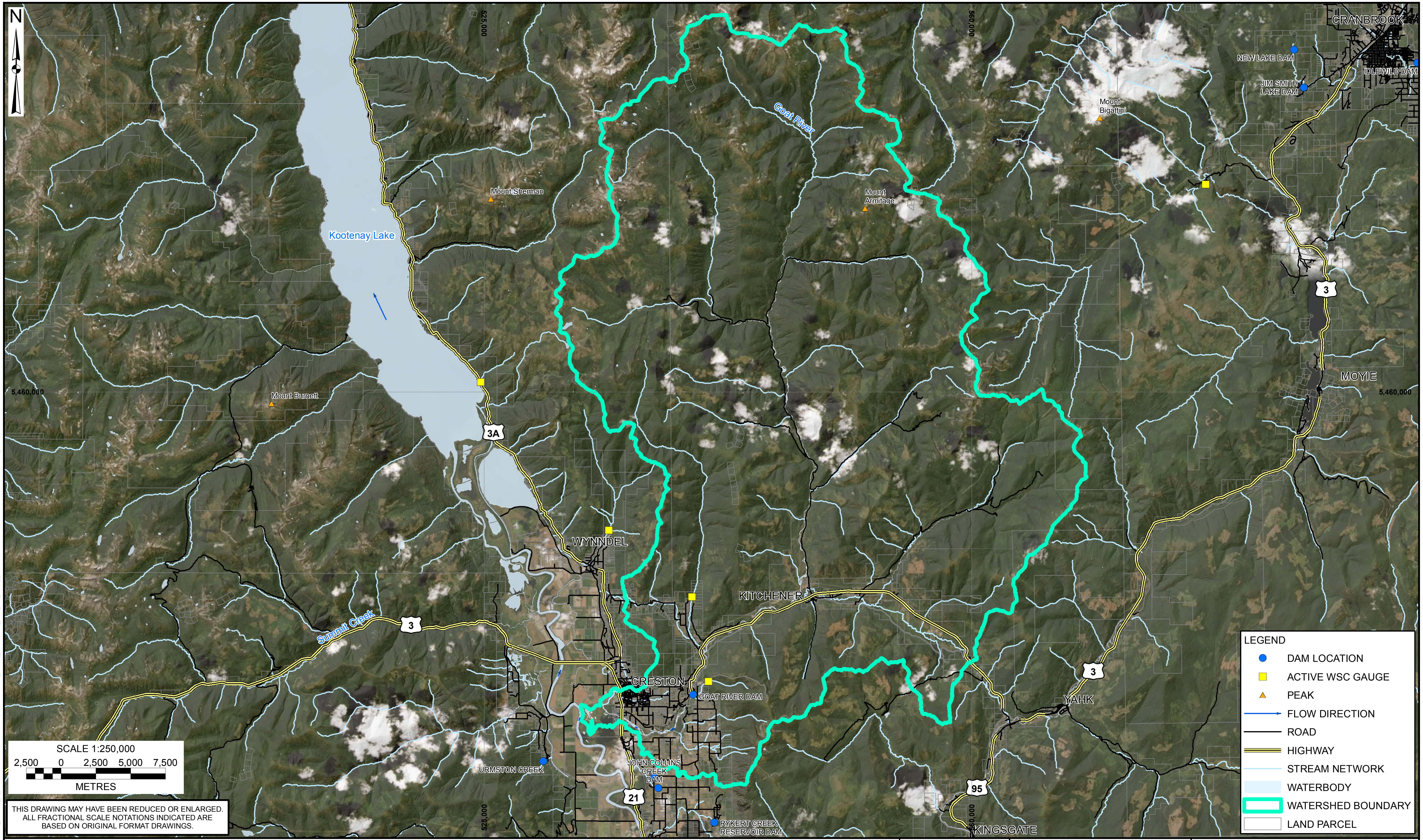

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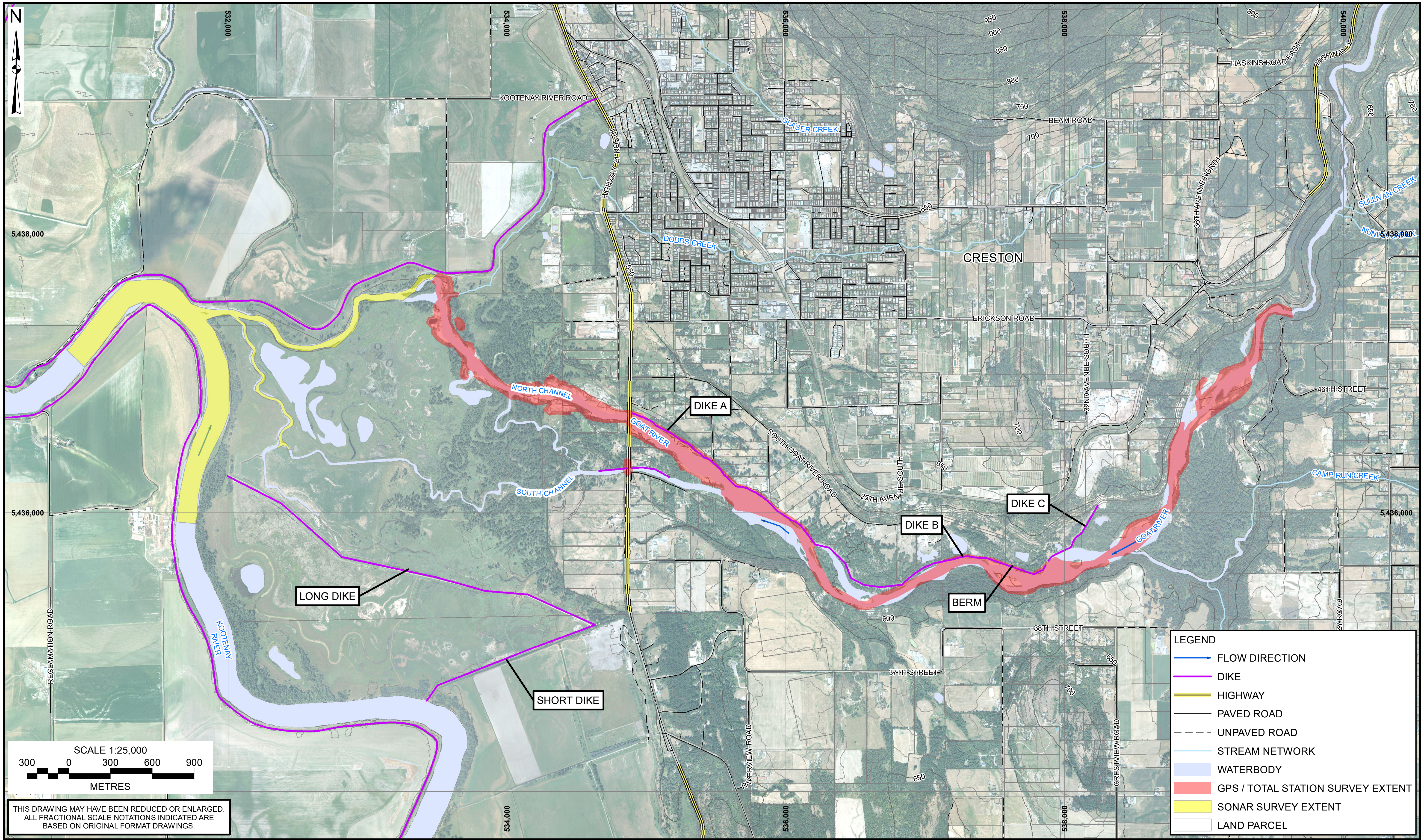

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5. SURVEY DATED AUGUST 9-11, 2019, AND PROVIDED BY MIDWEST SURVEYS INC. SURVEY DATA HORIZINTAL DATUM IS NAD83 (CSRS) 2010, VERTICAL DATUM IS CGVD 2013.
6. DIKE LOCATIONS FROM FLOOD PROTECTION WORKS: STRUCTURAL WORKS DATASET PROVIDED BY BC MFLNRO (2017).
7. SURVEY GPS EQUIPMENT USED IS TRIMBLE R10 GNSS. TOPOGRAPHIC EQUIPMENT USED IS LEICA TCR 403 AND TRIMBLE S3 ROBOTIC TOTAL STATION. SONAR EQUIPMENT USED IS ODOM ECHOTRAC CV-100 (TRANSDUCER).
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PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY GOAT RIVER

TITLE: SURVEY LOCATIONS

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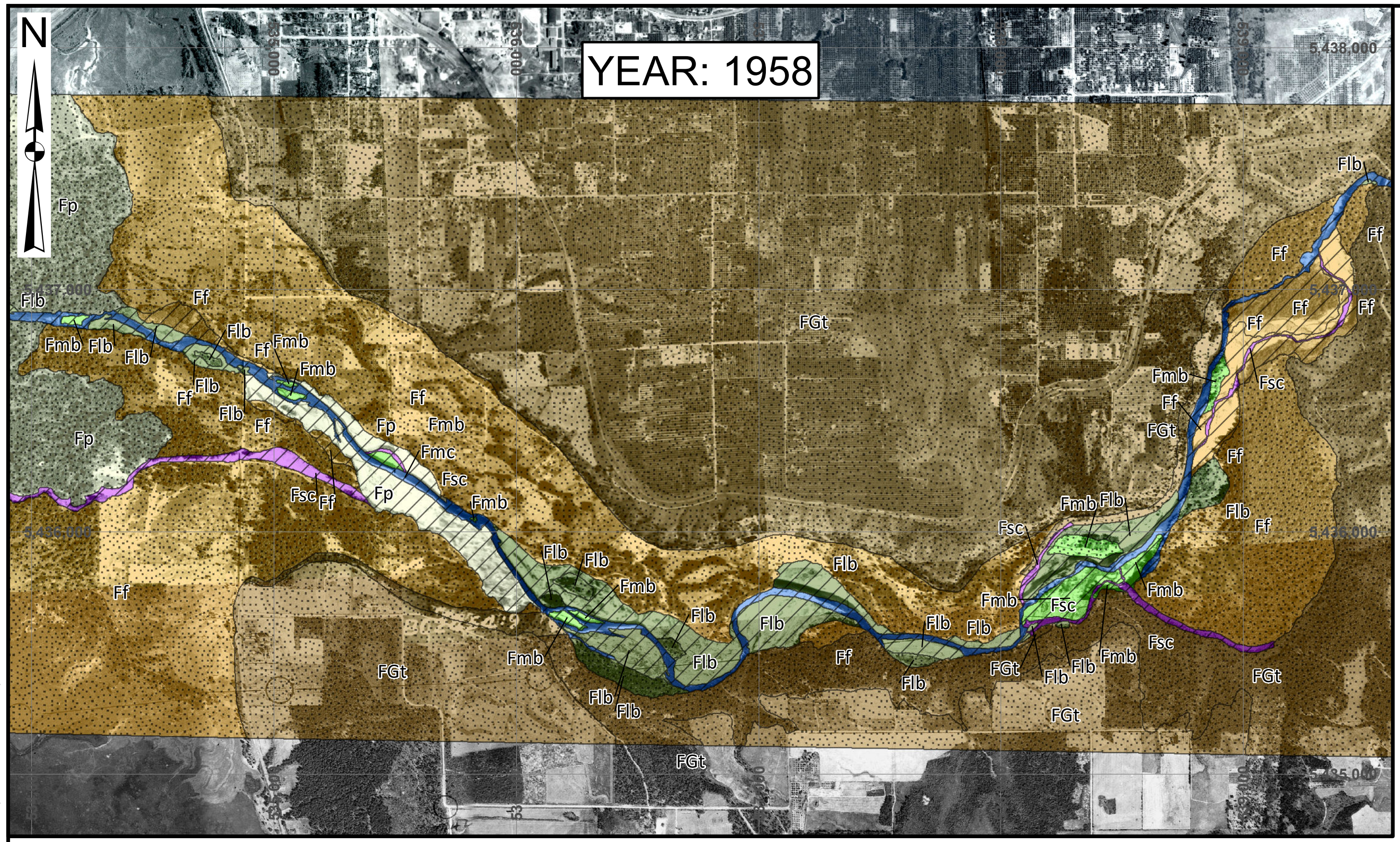

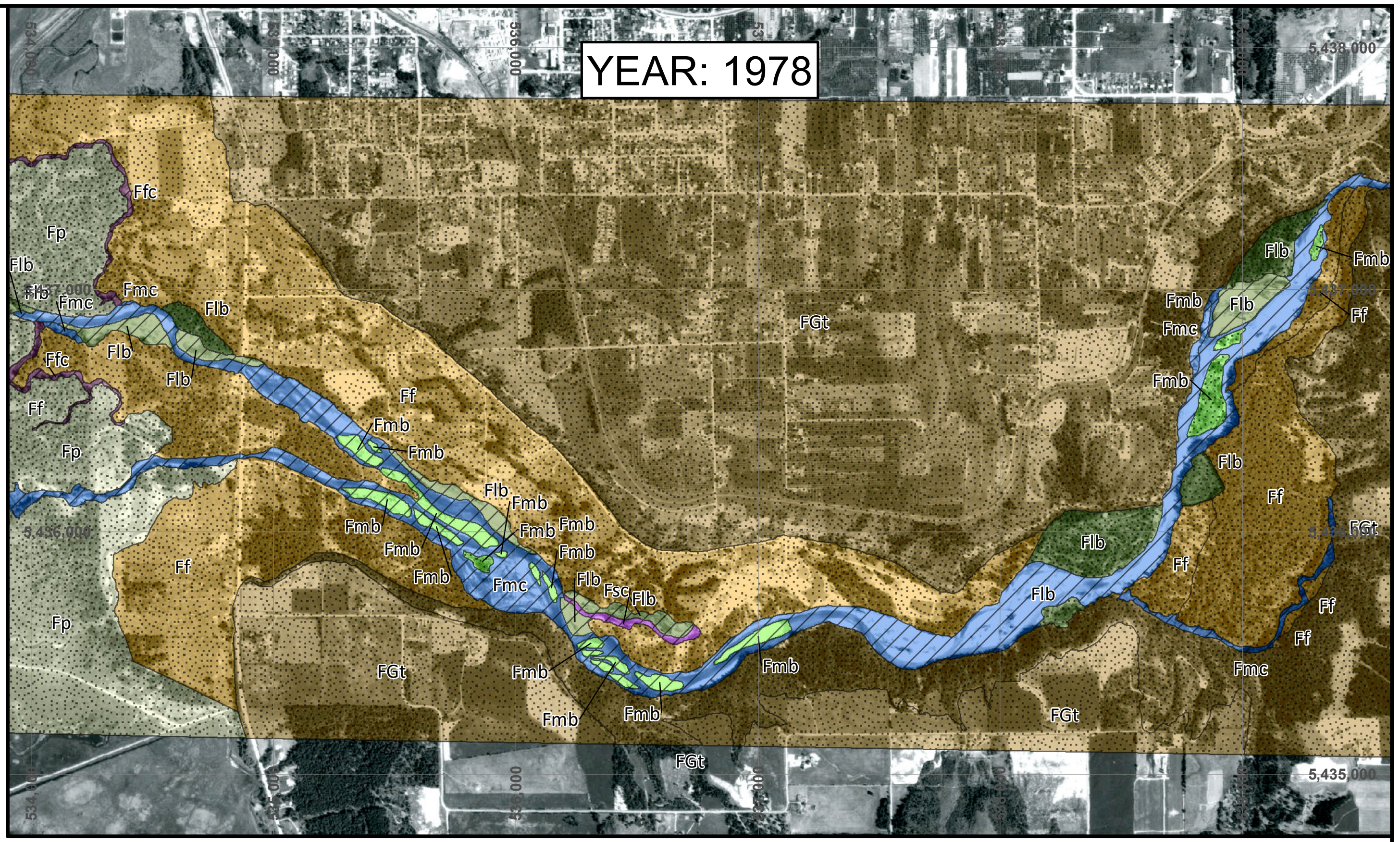

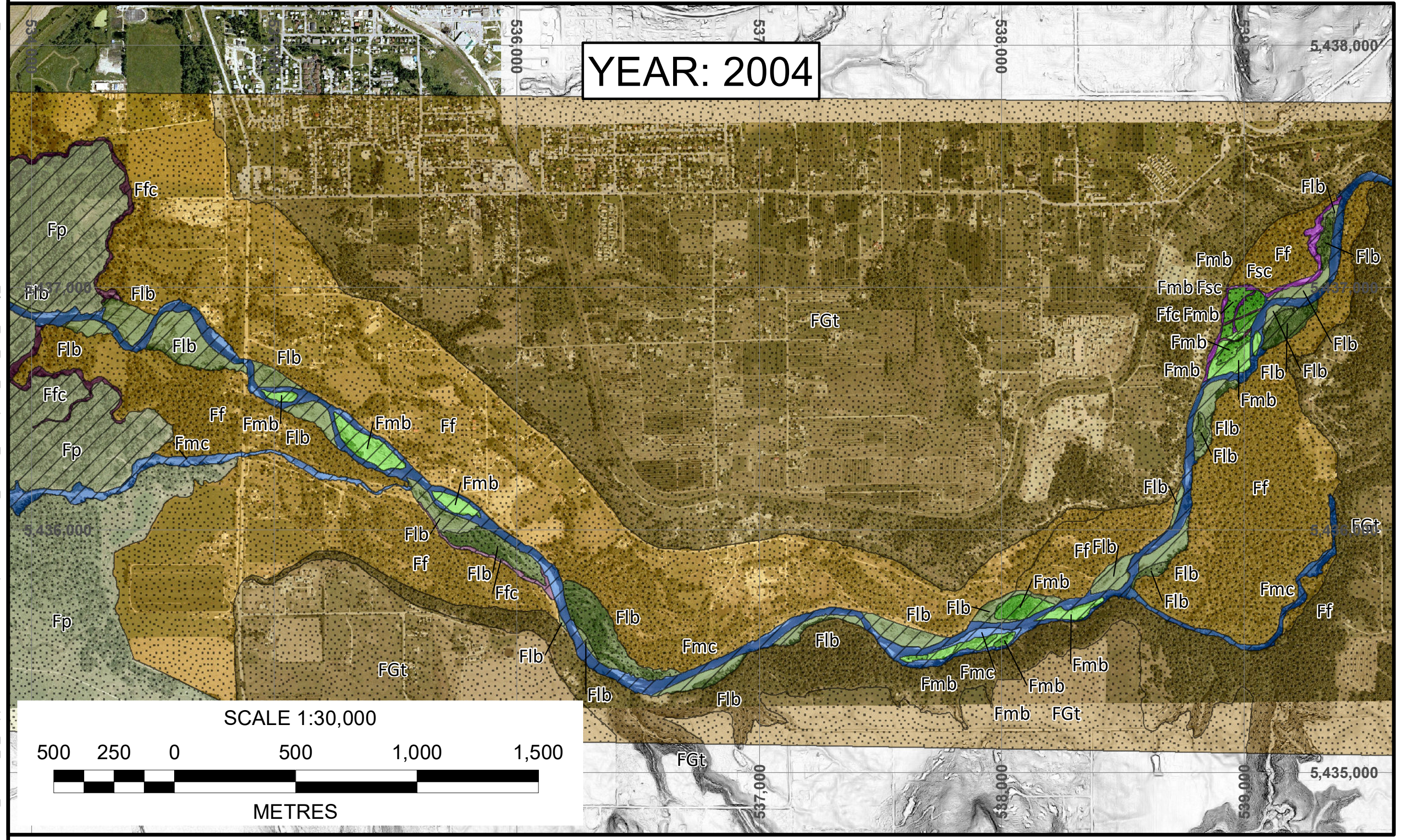

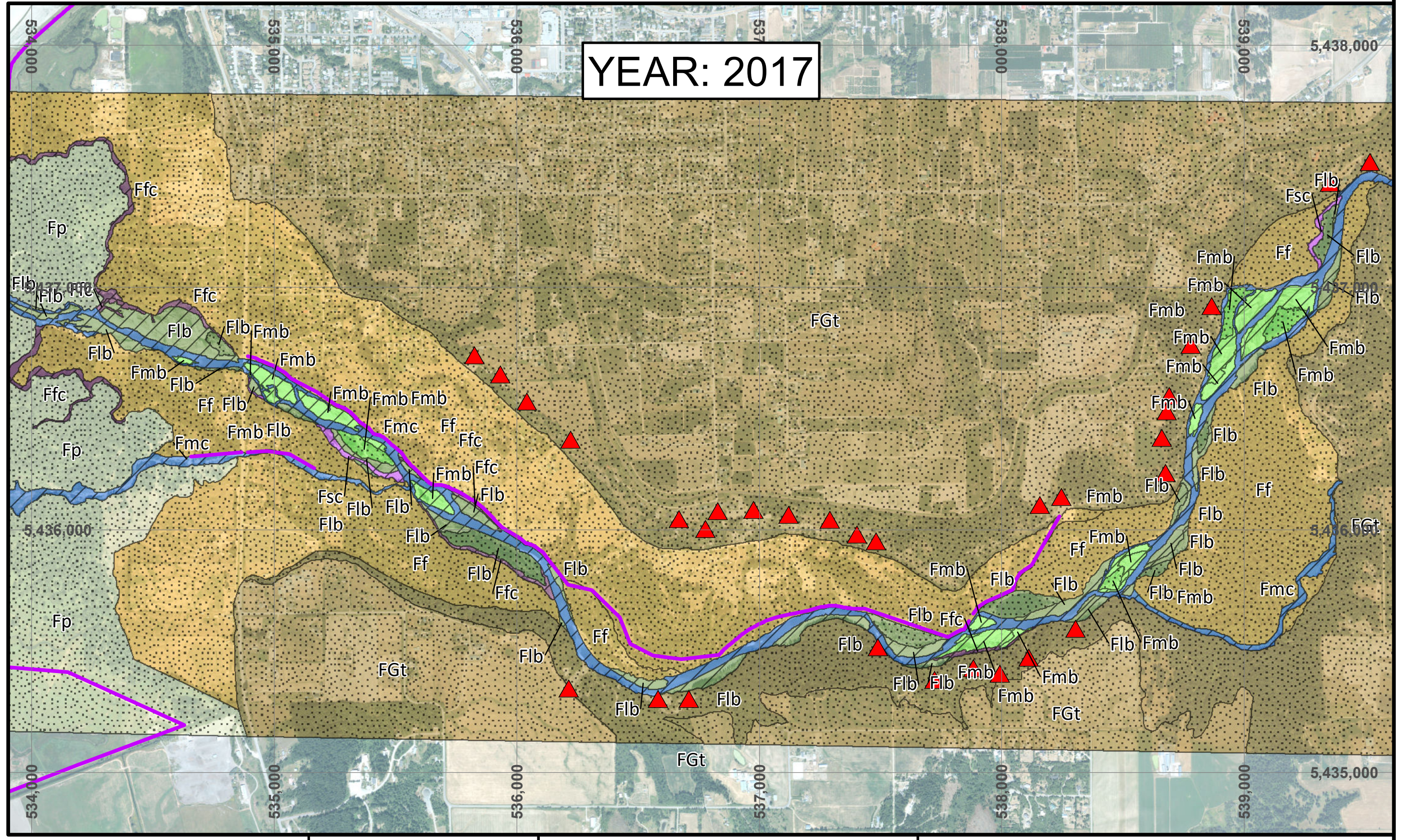

NOTES:

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3. BASE TOPOGRAPHIC DATA BASED ON LIDAR PROVIDED BY REGIONAL DISTRICT OF CENTRAL KOOTENAY DATED 2018.
4. COORDINATE SYSTEM IS NAD 1983 UTM ZONE 11N. VERTICAL DATUM IS UNKNOWN.
5. DIKE LOCATIONS FROM FLOOD PROTECTION WORKS: STRUCTURAL WORKS DATASET PROVIDED BY BC MFLNRO (2017).
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LEGEND

MAIN-CHANNEL (Fmc)	MID-CHANNEL BAR (Fmb)	TERRACE (GLACIOFLUVIAL) (FGt)	ACTIVITY LEVEL
SIDE-CHANNEL (Fsc)	LATERAL AND POINT BARS (Flb)	CANYON (Rs)	ACTIVE
FLOOD-CHANNEL (Ffc)	ALLUVIAL FAN/DELTA (Ff)	LAKE (L)	DORMANT
BACK-CHANNEL (Fbc)	FLOODPLAIN (Fp)	UNCLASSIFIED (U)	GROUND MOVEMENT LOCATION
ABANDONED-CHANNEL (Fac)	TERRACE (FLUVIAL) (Ft)		DIKE

SCALE:	1:30,000
DATE:	MAR 2020
DRAWN:	MW
CHECKED:	ES/VC
APPROVED:	RM

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT: REGIONAL DISTRICT CENTRAL KOOTENAY

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY GOAT RIVER

TITLE: AIR PHOTO COMPARISON

PROJECT No.:	DWG No:
0268-007	04

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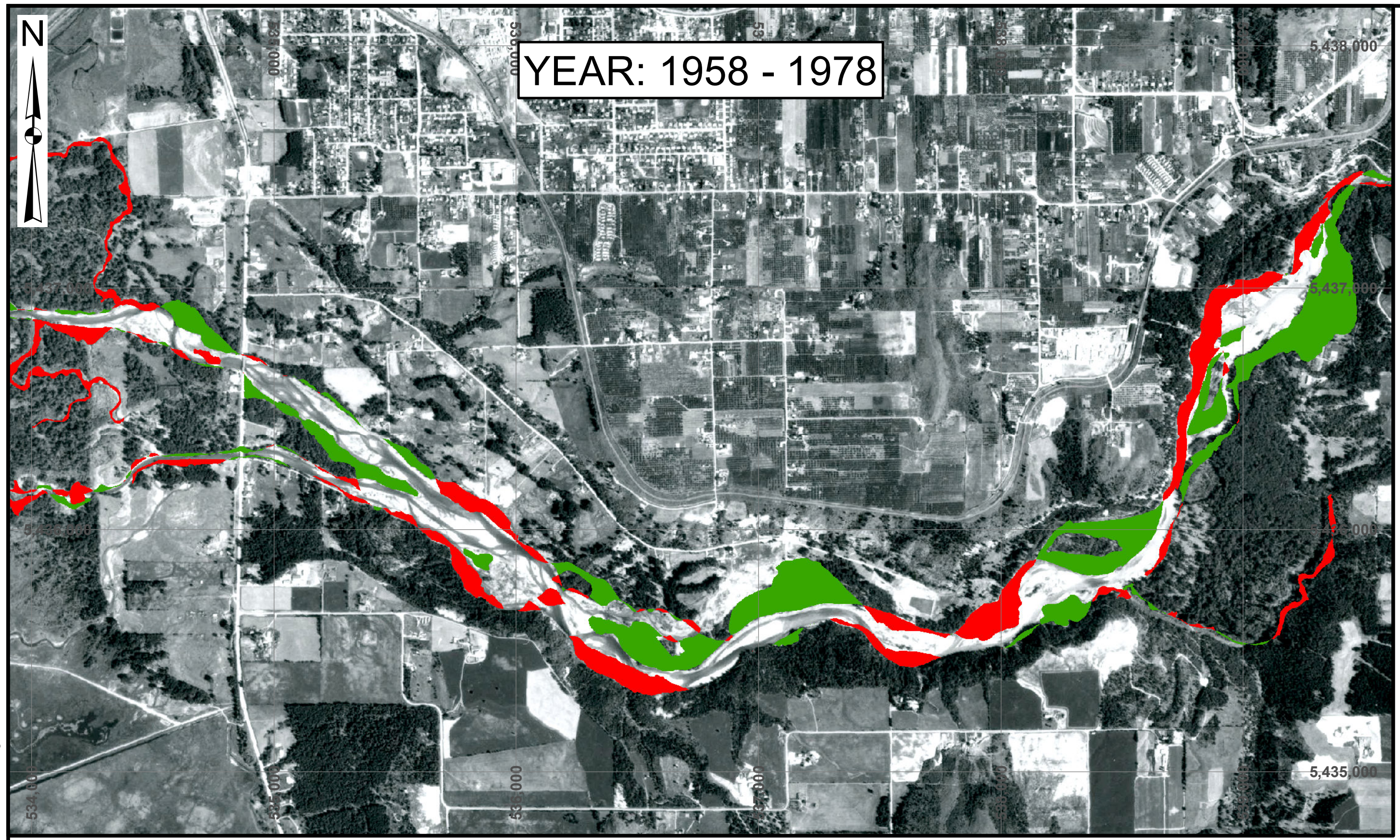

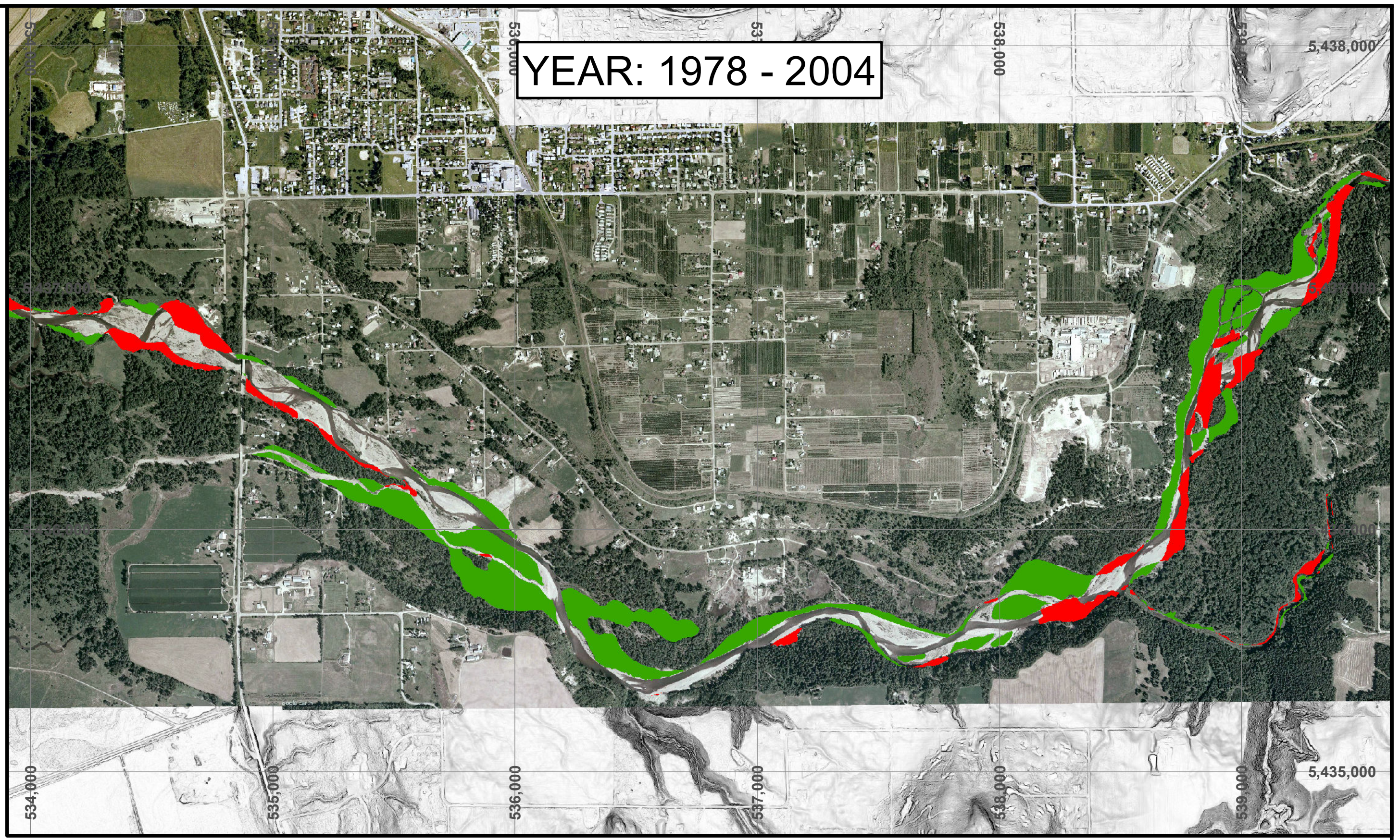

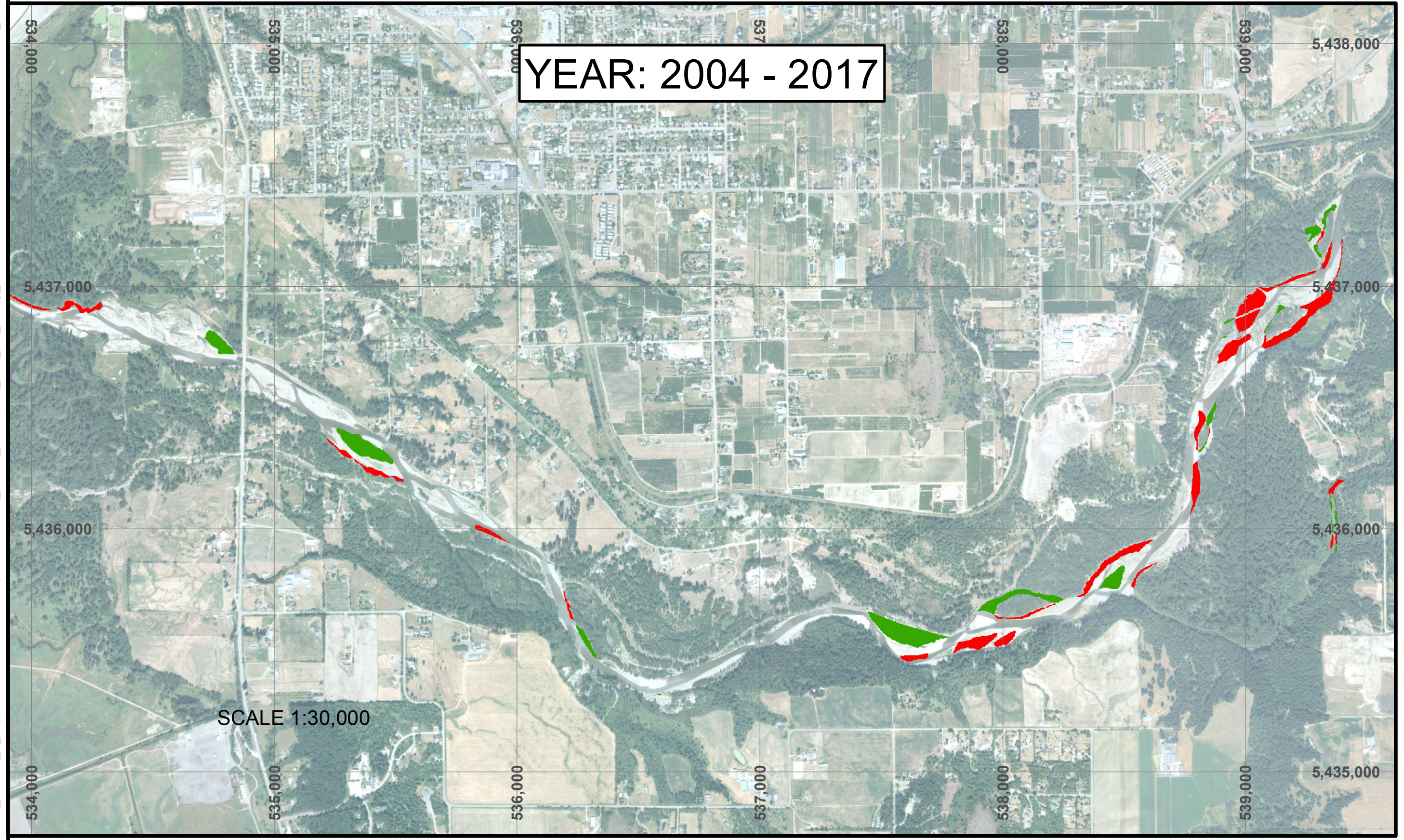

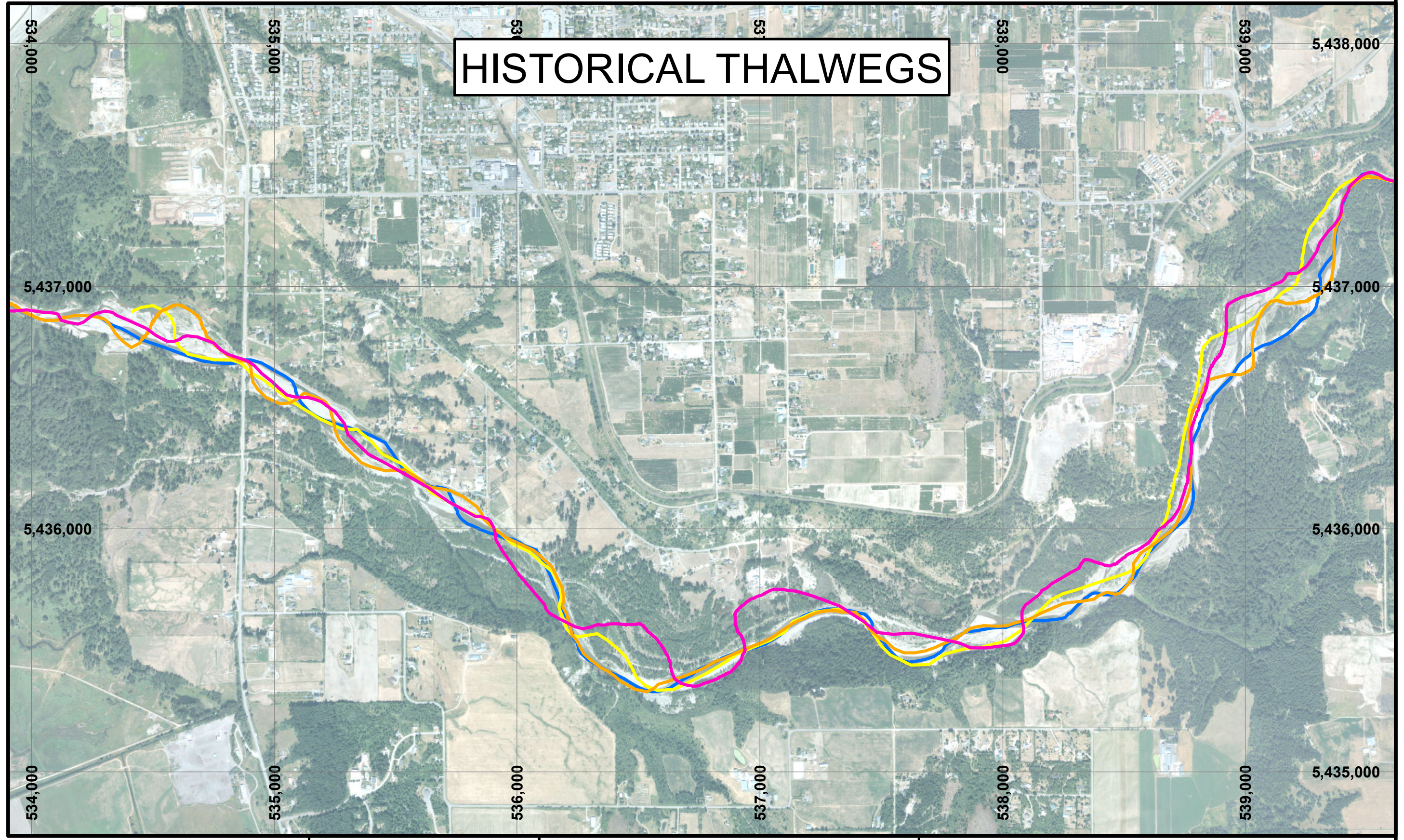

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LEGEND

HISTORICAL THALWEG (YEAR)
- 1958
- 1978
- 2004
- 2019

BANK EROSION, CHANNEL MIGRATION
DEPOSITION, STABILIZATION

SCALE:	1:30,000
DATE:	MAR 2020
DRAWN:	MW
CHECKED:	ES/VC
APPROVED:	RM

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:
REGIONAL DISTRICT CENTRAL KOOTENAY

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY
GOAT RIVER

TITLE: HISTORICAL CHANNEL CHANGE

PROJECT No.:	DWG No:
0268-007	05

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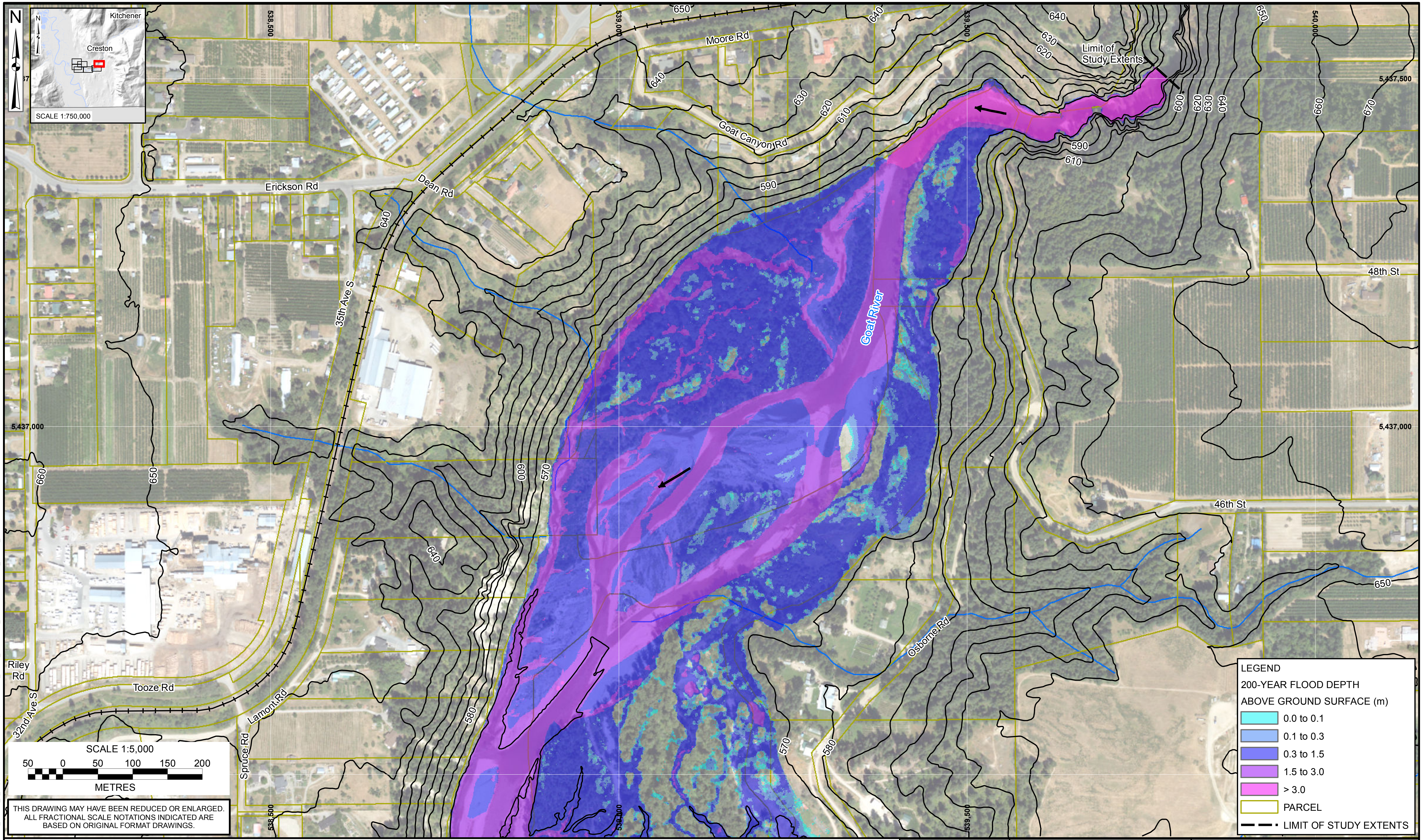

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DATE:	MAR 2020
DRAWN:	LL
CHECKED:	PG, HS
APPROVED:	RM

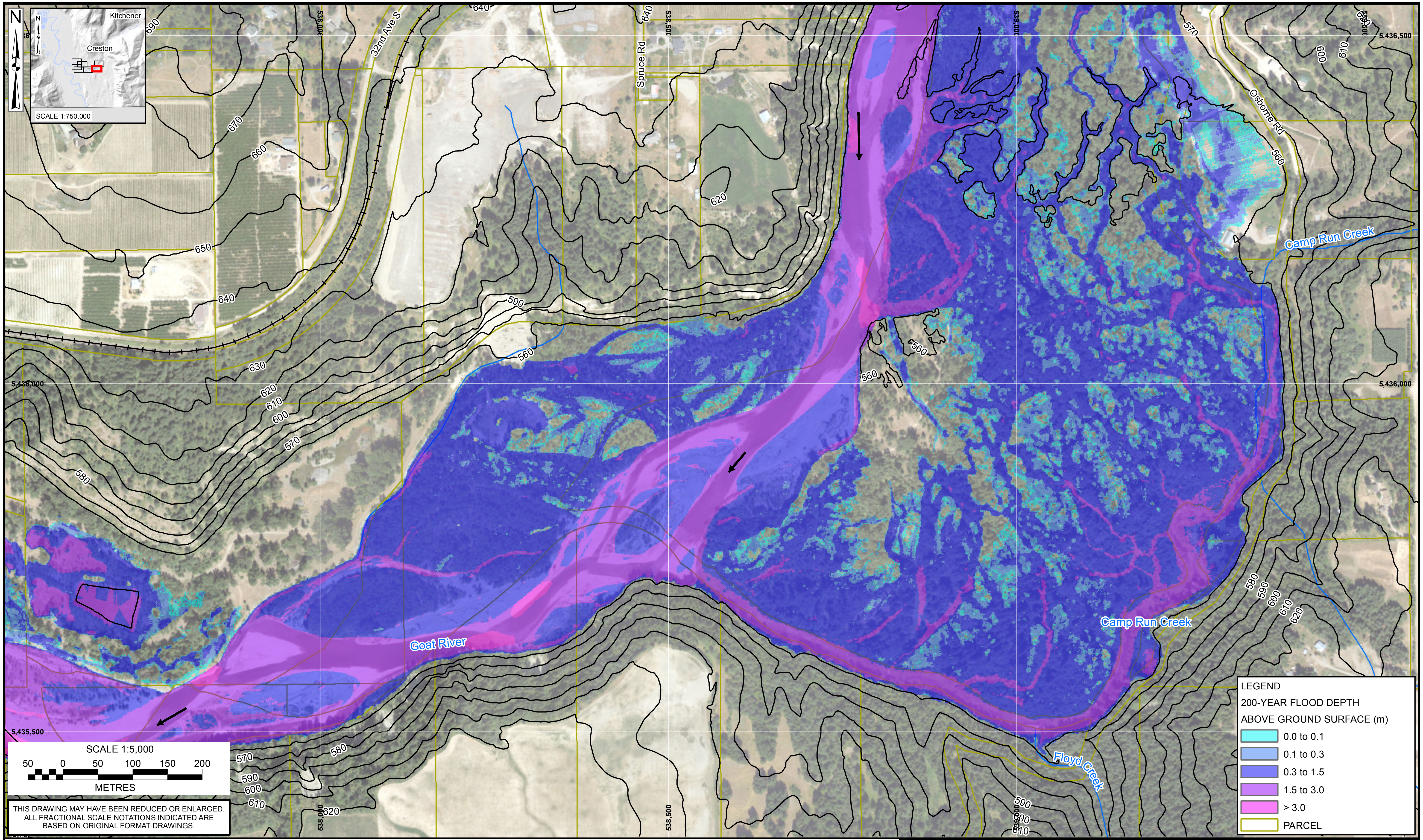
BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:

PROJECT:
RDCK FLOODPLAIN AND STEEP CREEK STUDY
GOAT RIVER

TITLE:
200-YEAR FLOOD HAZARD
(SHEET 1 OF 7)

PROJECT No.:	DWG No:
0268 007	06



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DRAWN:	LL
CHECKED:	PG, HS
APPROVED:	RM

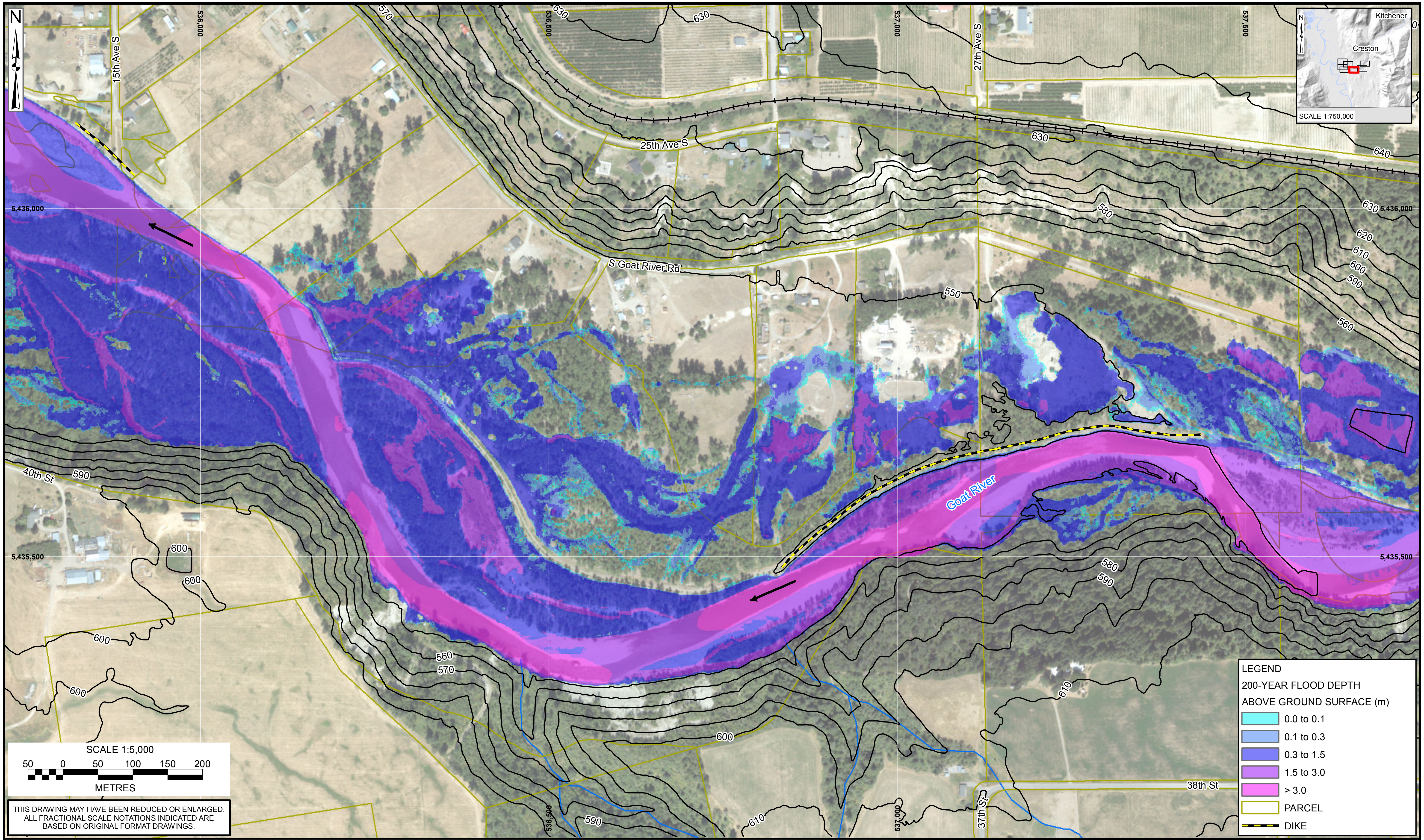
BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:

PROJECT:
RDCK FLOODPLAIN AND STEEP CREEK STUDY
GOAT RIVER

TITLE:
200-YEAR FLOOD HAZARD
(SHEET 2 OF 7)

PROJECT No.:	DWG No:
0268 007	06



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APPROVED:	RM

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY GOAT RIVER

TITLE: 200-YEAR FLOOD HAZARD (SHEET 3 OF 7)

PROJECT No.:	DWG No:
0268 007	06

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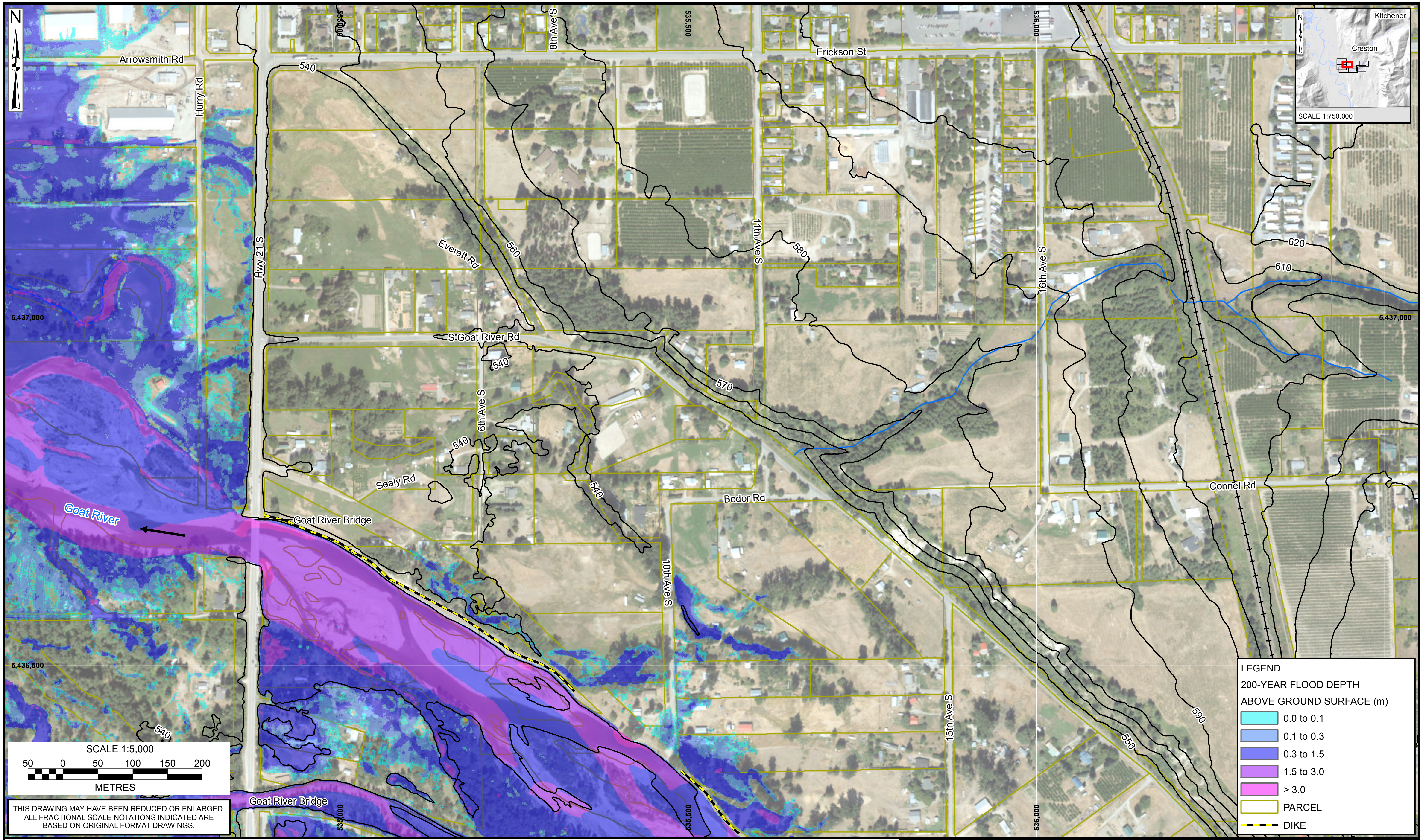

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DATE:	MAR 2020
DRAWN:	LL
CHECKED:	PG, HS
APPROVED:	RM

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT: REGIONAL DISTRICT CENTRAL KOOTENAY

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY GOAT RIVER

TITLE: 200-YEAR FLOOD HAZARD (SHEET 4 OF 7)

PROJECT No.: 0268 007

DWG No: 06

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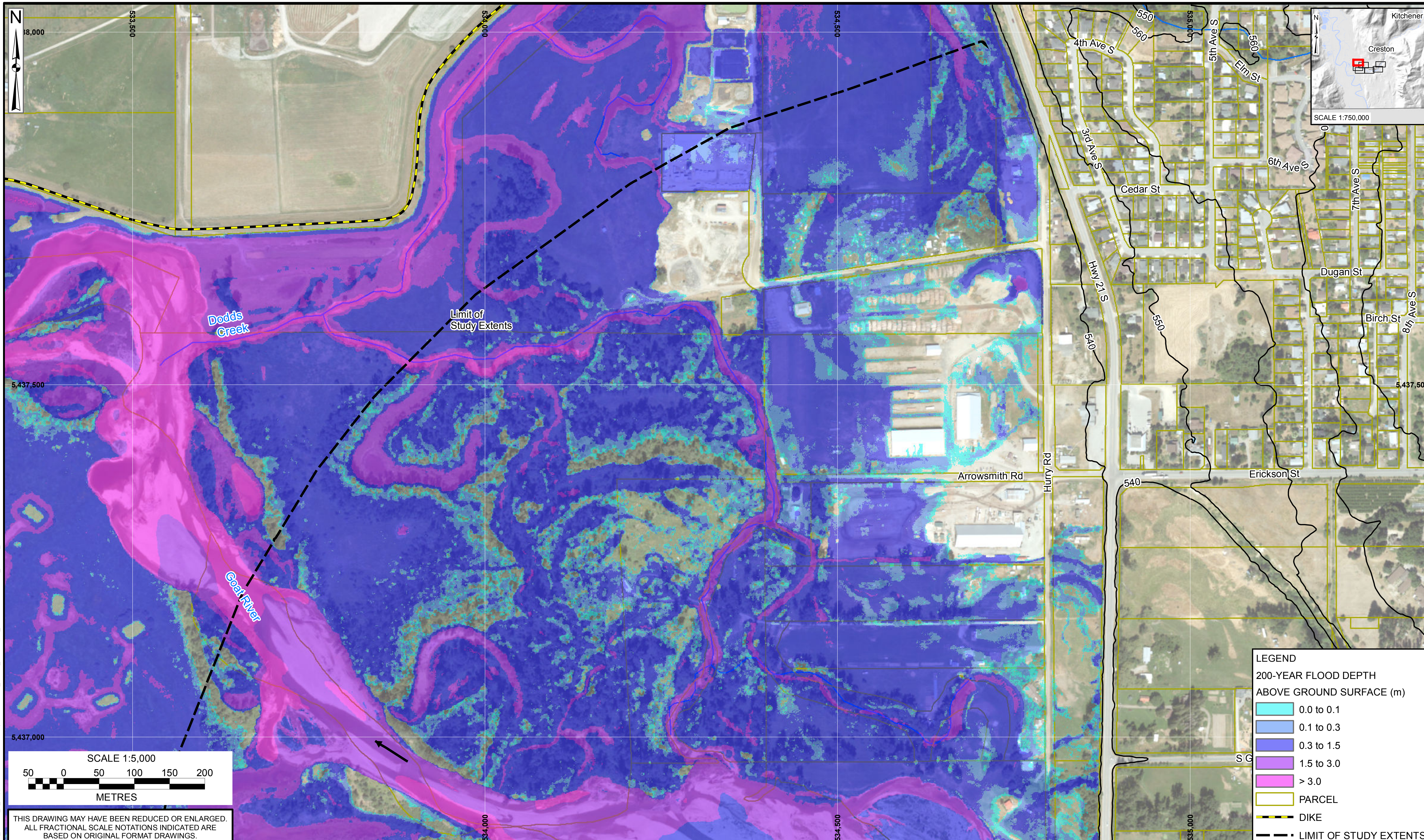

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DATE:	MAR 2020
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APPROVED:	RM

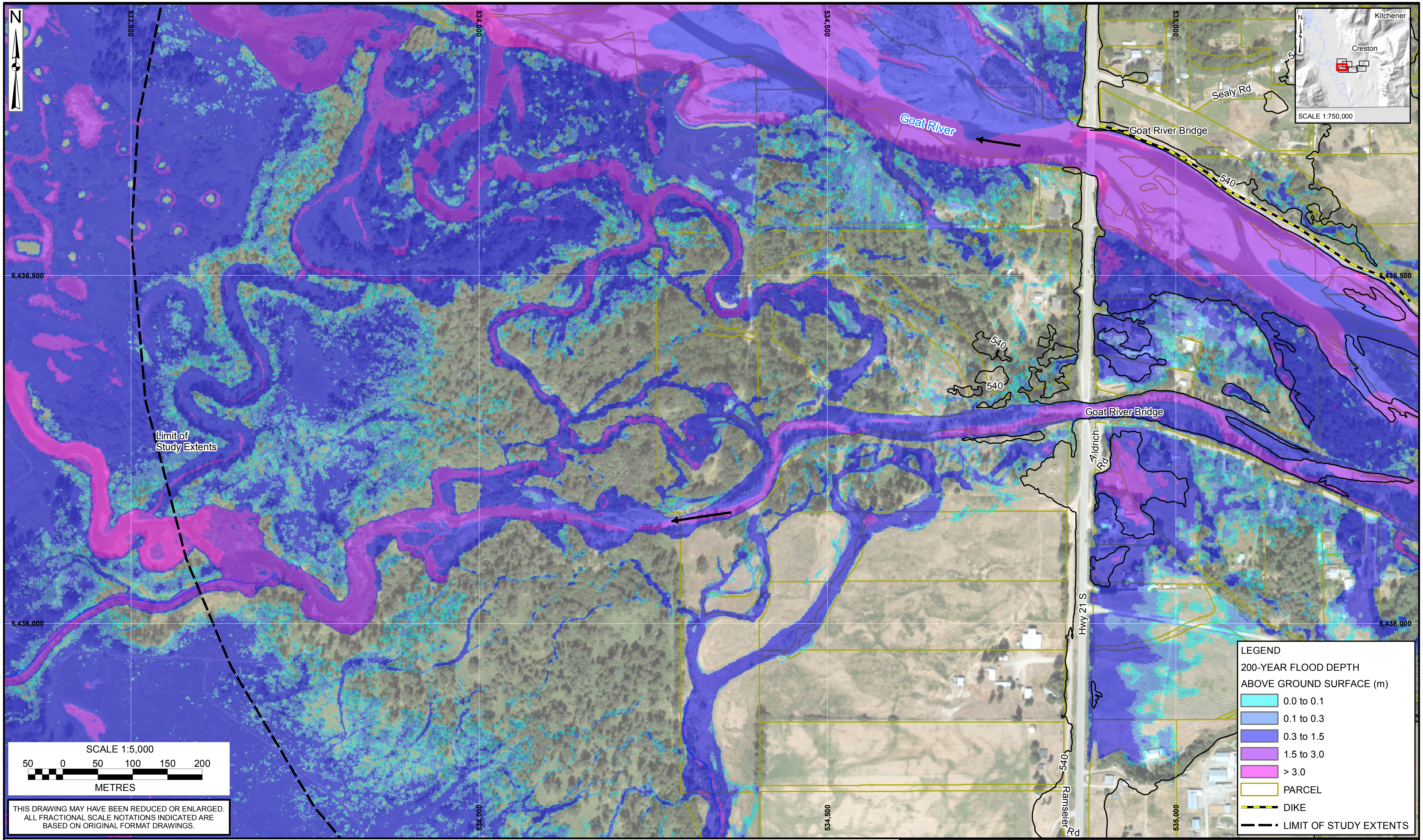
BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY GOAT RIVER

TITLE: 200-YEAR FLOOD HAZARD (SHEET 5 OF 7)

PROJECT No.:	DWG No:
0268 007	06



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CLIENT:

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY GOAT RIVER

TITLE: 200-YEAR FLOOD HAZARD (SHEET 6 OF 7)

PROJECT No.:	DWG No:
0268 007	06

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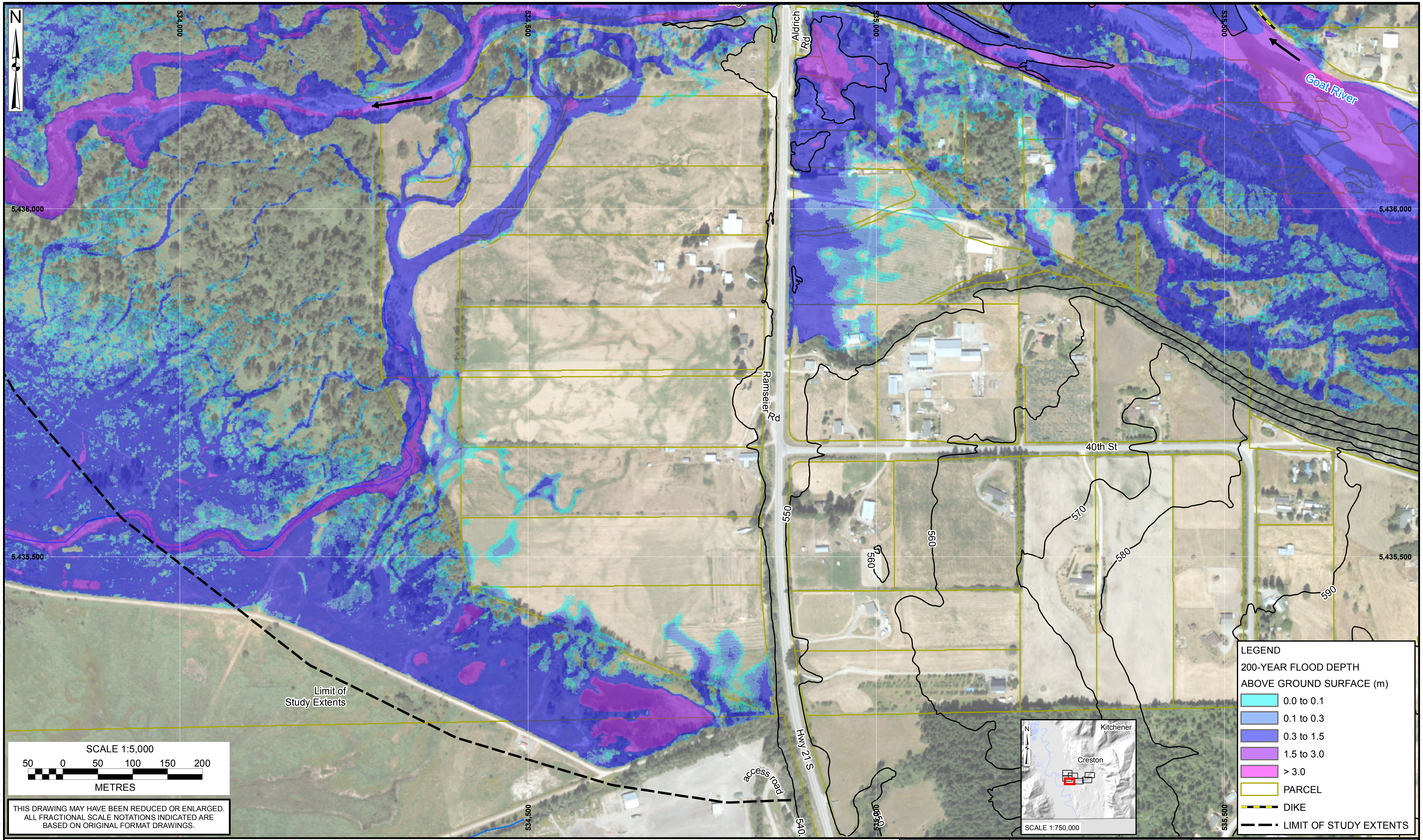

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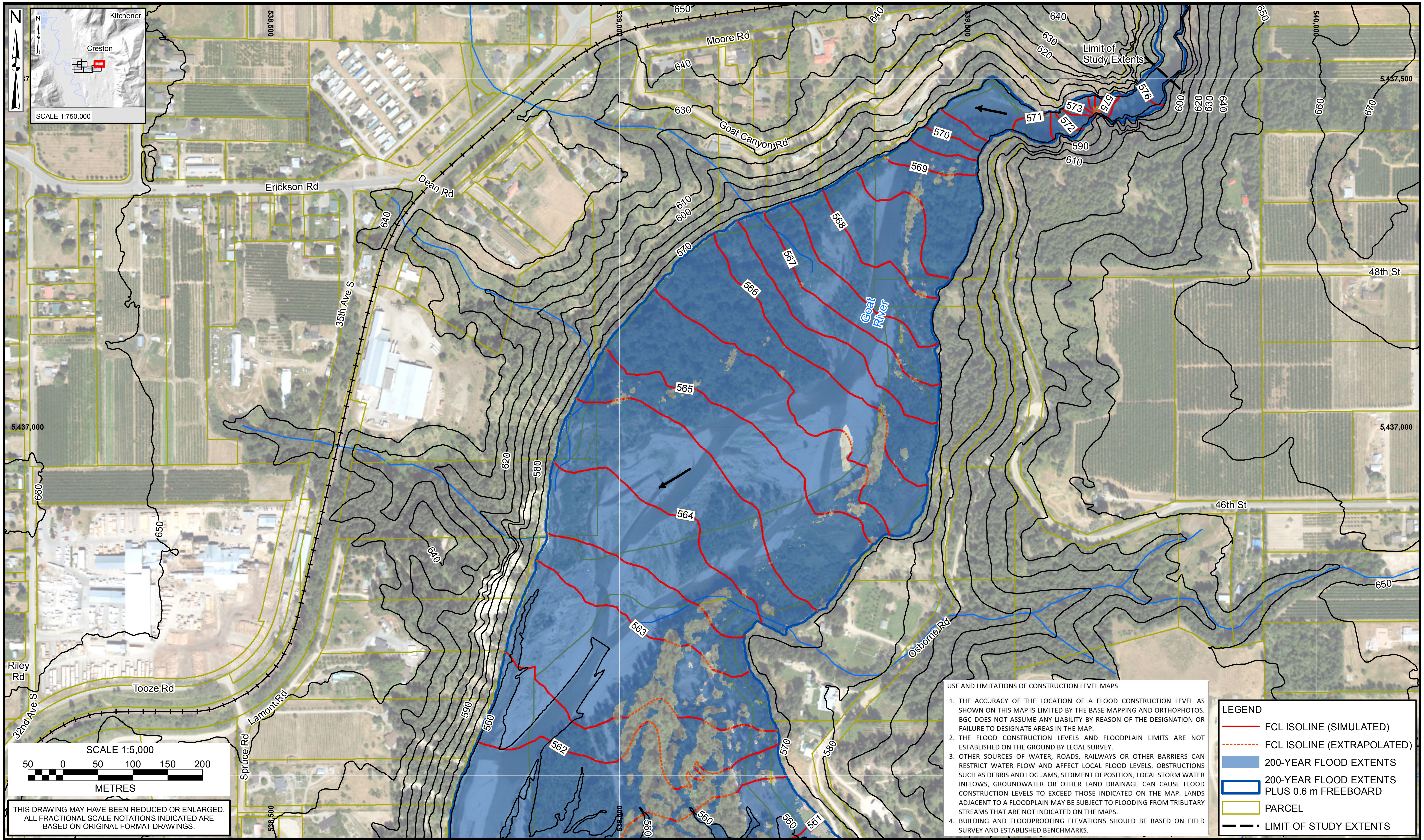
BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:

PROJECT:
RDCK FLOODPLAIN AND STEEP CREEK STUDY
GOAT RIVER

TITLE:
200-YEAR FLOOD HAZARD
(SHEET 7 OF 7)

PROJECT No.:	DWG No:
0268 007	06



USE AND LIMITATIONS OF CONSTRUCTION LEVEL MAPS

1. THE ACCURACY OF THE LOCATION OF A FLOOD CONSTRUCTION LEVEL AS SHOWN ON THIS MAP IS LIMITED BY THE BASE MAPPING AND ORTHOPHOTOS. BGC DOES NOT ASSUME ANY LIABILITY BY REASON OF THE DESIGNATION OR FAILURE TO DESIGNATE AREAS IN THE MAP.
2. THE FLOOD CONSTRUCTION LEVELS AND FLOODPLAIN LIMITS ARE NOT ESTABLISHED ON THE GROUND BY LEGAL SURVEY.
3. OTHER SOURCES OF WATER, ROADS, RAILWAYS OR OTHER BARRIERS CAN RESTRICT WATER FLOW AND AFFECT LOCAL FLOOD LEVELS. OBSTRUCTIONS SUCH AS DEBRIS AND LOG JAMS, SEDIMENT DEPOSITION, LOCAL STORM WATER INFLOWS, GROUNDWATER OR OTHER LAND DRAINAGE CAN CAUSE FLOOD CONSTRUCTION LEVELS TO EXCEED THOSE INDICATED ON THE MAP. LANDS ADJACENT TO A FLOODPLAIN MAY BE SUBJECT TO FLOODING FROM TRIBUTARY STREAMS THAT ARE NOT INDICATED ON THE MAPS.
4. BUILDING AND FLOODPROOFING ELEVATIONS SHOULD BE BASED ON FIELD SURVEY AND ESTABLISHED BENCHMARKS.

LEGEND

- FCL ISOLINE (SIMULATED)
- FCL ISOLINE (EXTRAPOLATED)
- 200-YEAR FLOOD EXTENTS
- 200-YEAR FLOOD EXTENTS PLUS 0.6 m FREEBOARD
- PARCEL
- LIMIT OF STUDY EXTENTS

NOTES:
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SCALE:	1:5,000
DATE:	MAR 2020
DRAWN:	LL
CHECKED:	PG, HS
APPROVED:	RM

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:

REGIONAL DISTRICT CENTRAL KOOTENAY

PROJECT:
RDCK FLOODPLAIN AND STEEP CREEK STUDY
GOAT RIVER

TITLE:
200-YEAR FLOOD CONSTRUCTION LEVEL
(SHEET 1 OF 7)

PROJECT No.:	DWG No:
0268 007	07

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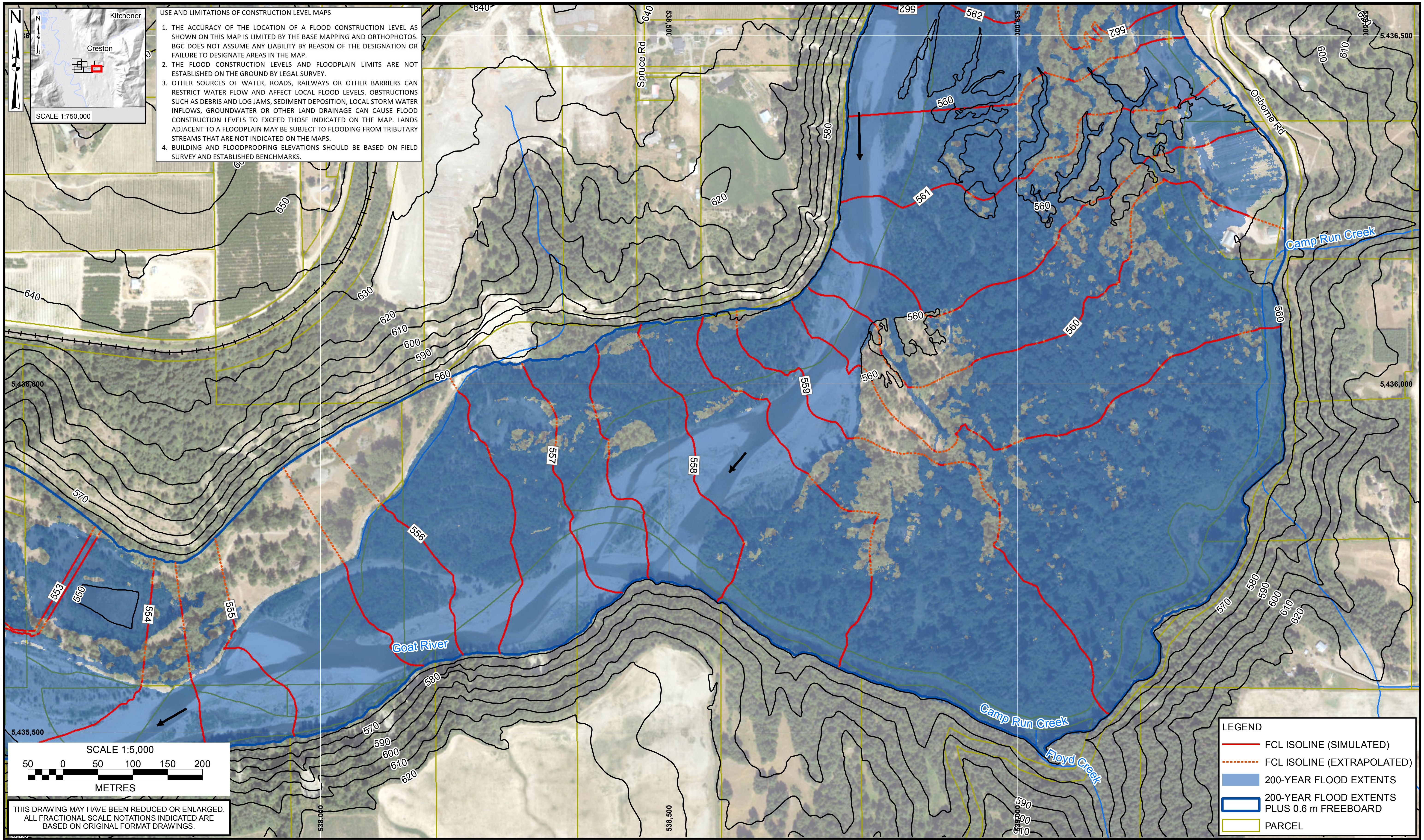

USE AND LIMITATIONS OF CONSTRUCTION LEVEL MAPS

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THIS DRAWING MAY HAVE BEEN REDUCED OR ENLARGED. ALL FRACTIONAL SCALE NOTATIONS INDICATED ARE BASED ON ORIGINAL FORMAT DRAWINGS.

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4. PROJECTION IS NAD 1983 UTM ZONE 11N. VERTICAL DATUM IS CGVD2013.
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CHECKED:	PG, HS
APPROVED:	RM

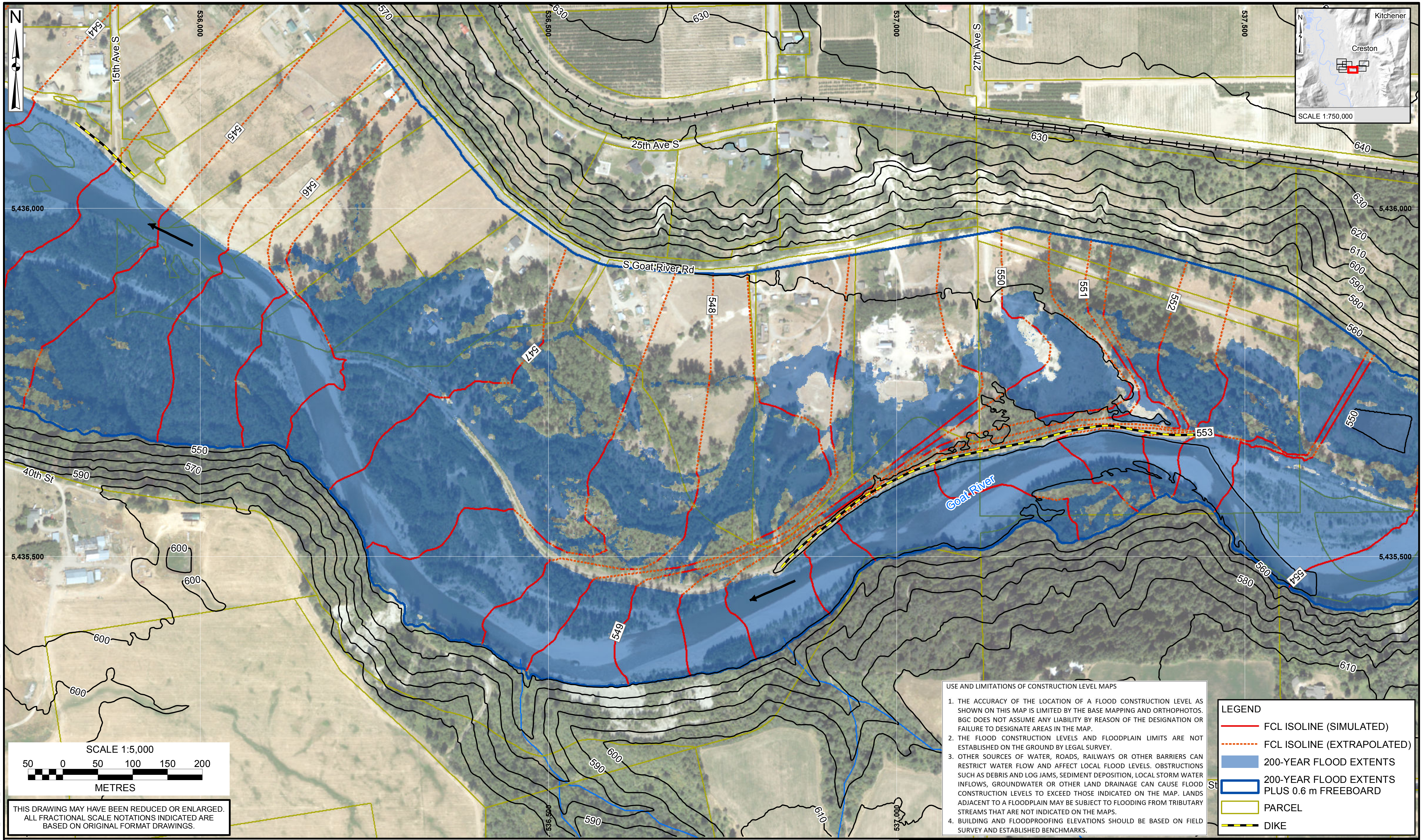
BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY GOAT RIVER

TITLE: 200-YEAR FLOOD CONSTRUCTION LEVEL (SHEET 2 OF 7)

PROJECT No.:	DWG No:
0268 007	07



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BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:

PROJECT:
RDCK FLOODPLAIN AND STEEP CREEK STUDY
GOAT RIVER

TITLE:
200-YEAR FLOOD CONSTRUCTION LEVEL
(SHEET 3 OF 7)

PROJECT No.:	DWG No:
0268 007	07

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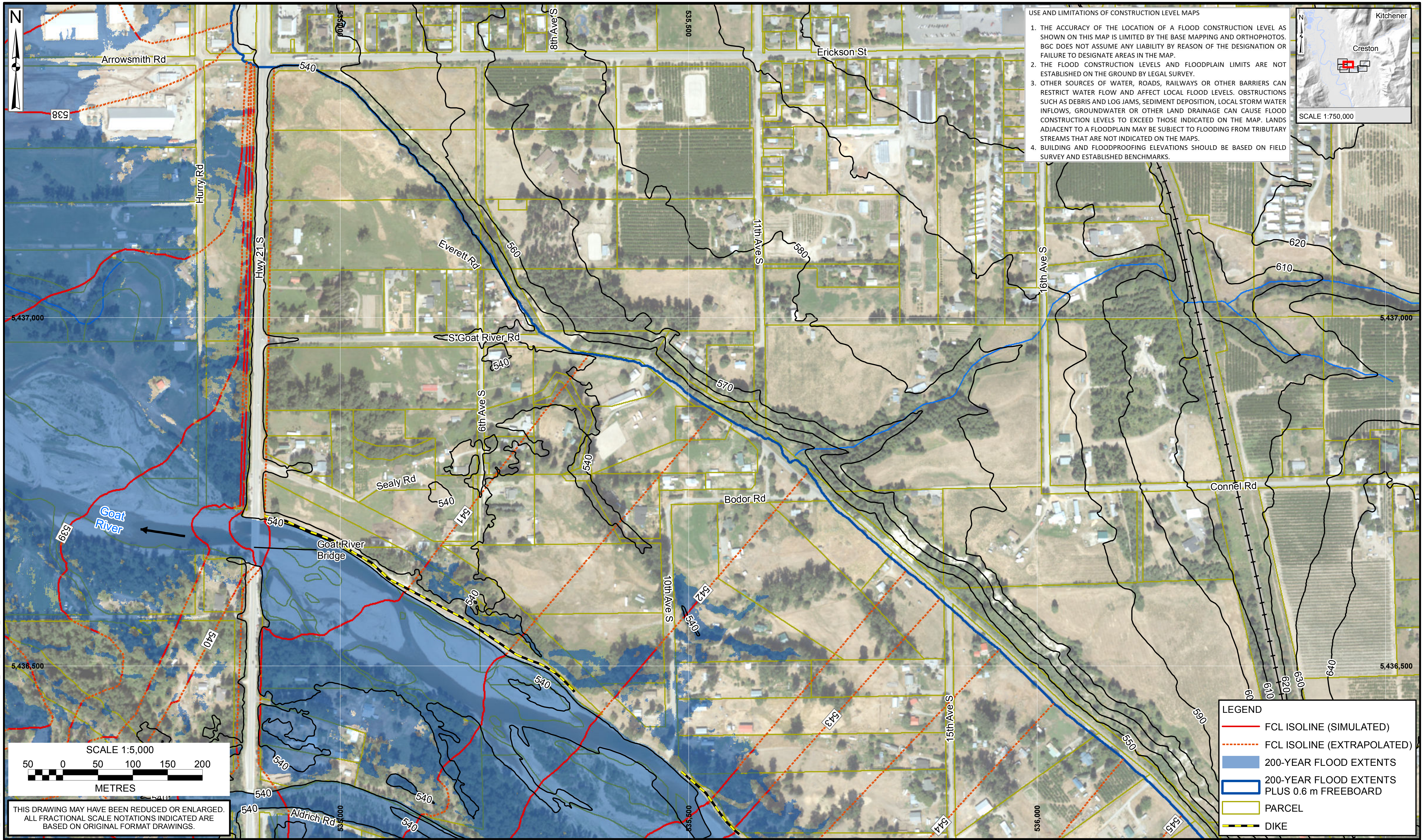

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CLIENT:

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY GOAT RIVER

TITLE: 200-YEAR FLOOD CONSTRUCTION LEVEL (SHEET 4 OF 7)

PROJECT No.:	DWG No:
0268 007	07

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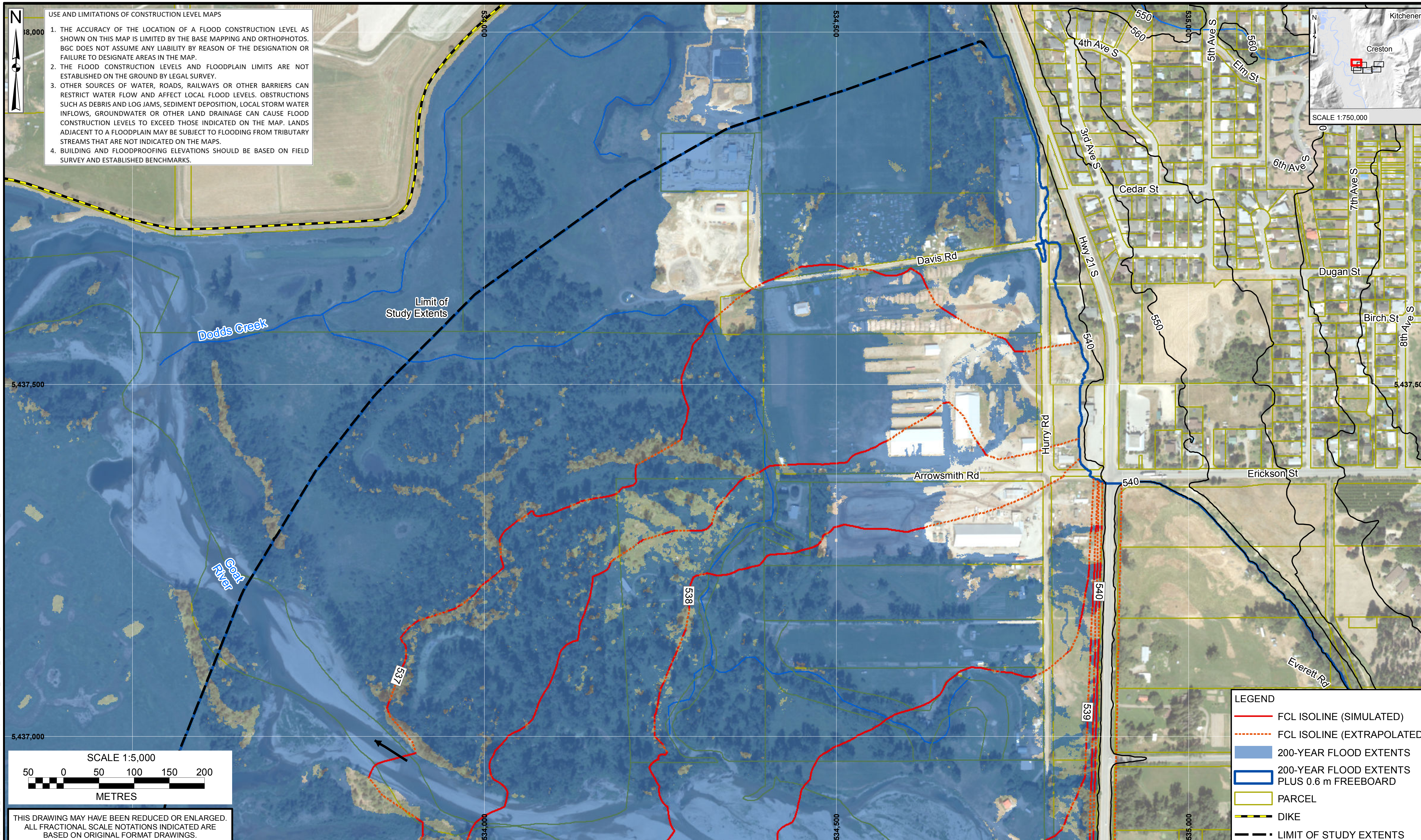

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CLIENT:

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY GOAT RIVER

TITLE: 200-YEAR FLOOD CONSTRUCTION LEVEL (SHEET 5 OF 7)

PROJECT No.:	DWG No:
0268 007	07

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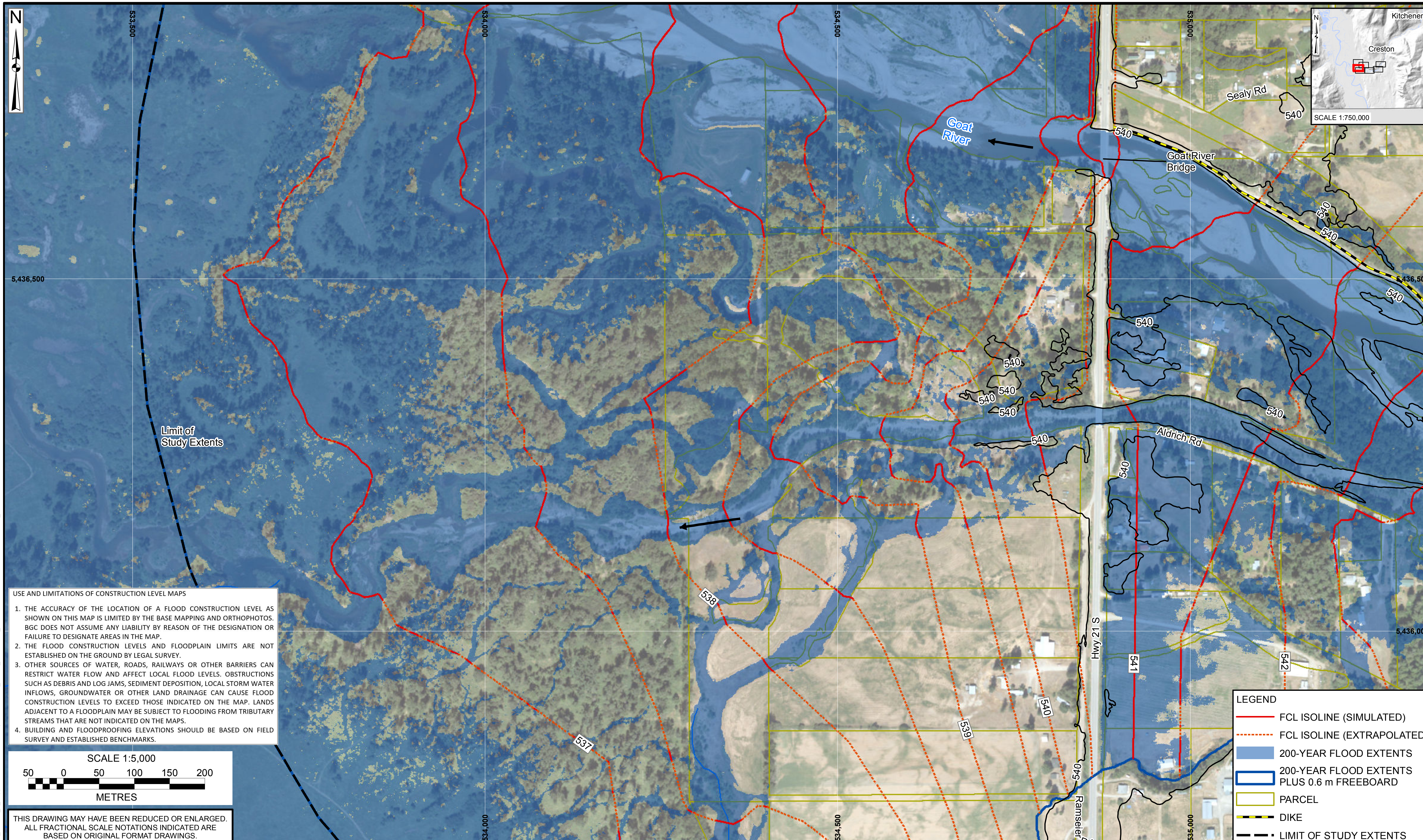

USE AND LIMITATIONS OF CONSTRUCTION LEVEL MAPS

1. THE ACCURACY OF THE LOCATION OF A FLOOD CONSTRUCTION LEVEL AS SHOWN ON THIS MAP IS LIMITED BY THE BASE MAPPING AND ORTHOPHOTOS. BGC DOES NOT ASSUME ANY LIABILITY BY REASON OF THE DESIGNATION OR FAILURE TO DESIGNATE AREAS IN THE MAP.
2. THE FLOOD CONSTRUCTION LEVELS AND FLOODPLAIN LIMITS ARE NOT ESTABLISHED ON THE GROUND BY LEGAL SURVEY.
3. OTHER SOURCES OF WATER, ROADS, RAILWAYS OR OTHER BARRIERS CAN RESTRICT WATER FLOW AND AFFECT LOCAL FLOOD LEVELS. OBSTRUCTIONS SUCH AS DEBRIS AND LOG JAMS, SEDIMENT DEPOSITION, LOCAL STORM WATER INFLOWS, GROUNDWATER OR OTHER LAND DRAINAGE CAN CAUSE FLOOD CONSTRUCTION LEVELS TO EXCEED THOSE INDICATED ON THE MAP. LANDS ADJACENT TO A FLOODPLAIN MAY BE SUBJECT TO FLOODING FROM TRIBUTARY STREAMS THAT ARE NOT INDICATED ON THE MAPS.
4. BUILDING AND FLOODPROOFING ELEVATIONS SHOULD BE BASED ON FIELD SURVEY AND ESTABLISHED BENCHMARKS.

SCALE 1:5,000

50 0 50 100 150 200

METRES

THIS DRAWING MAY HAVE BEEN REDUCED OR ENLARGED. ALL FRACTIONAL SCALE NOTATIONS INDICATED ARE BASED ON ORIGINAL FORMAT DRAWINGS.

LEGEND

- FCL ISOLINE (SIMULATED)
- FCL ISOLINE (EXTRAPOLATED)
- 200-YEAR FLOOD EXTENTS
- 200-YEAR FLOOD EXTENTS PLUS 0.6 m FREEBOARD
- PARCEL
- DIKE
- LIMIT OF STUDY EXTENTS

NOTES:
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BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT: REGIONAL DISTRICT CENTRAL KOOTENAY

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY GOAT RIVER

TITLE: 200-YEAR FLOOD CONSTRUCTION LEVEL (SHEET 6 OF 7)

PROJECT No.: 0268 007

DWG No: 07

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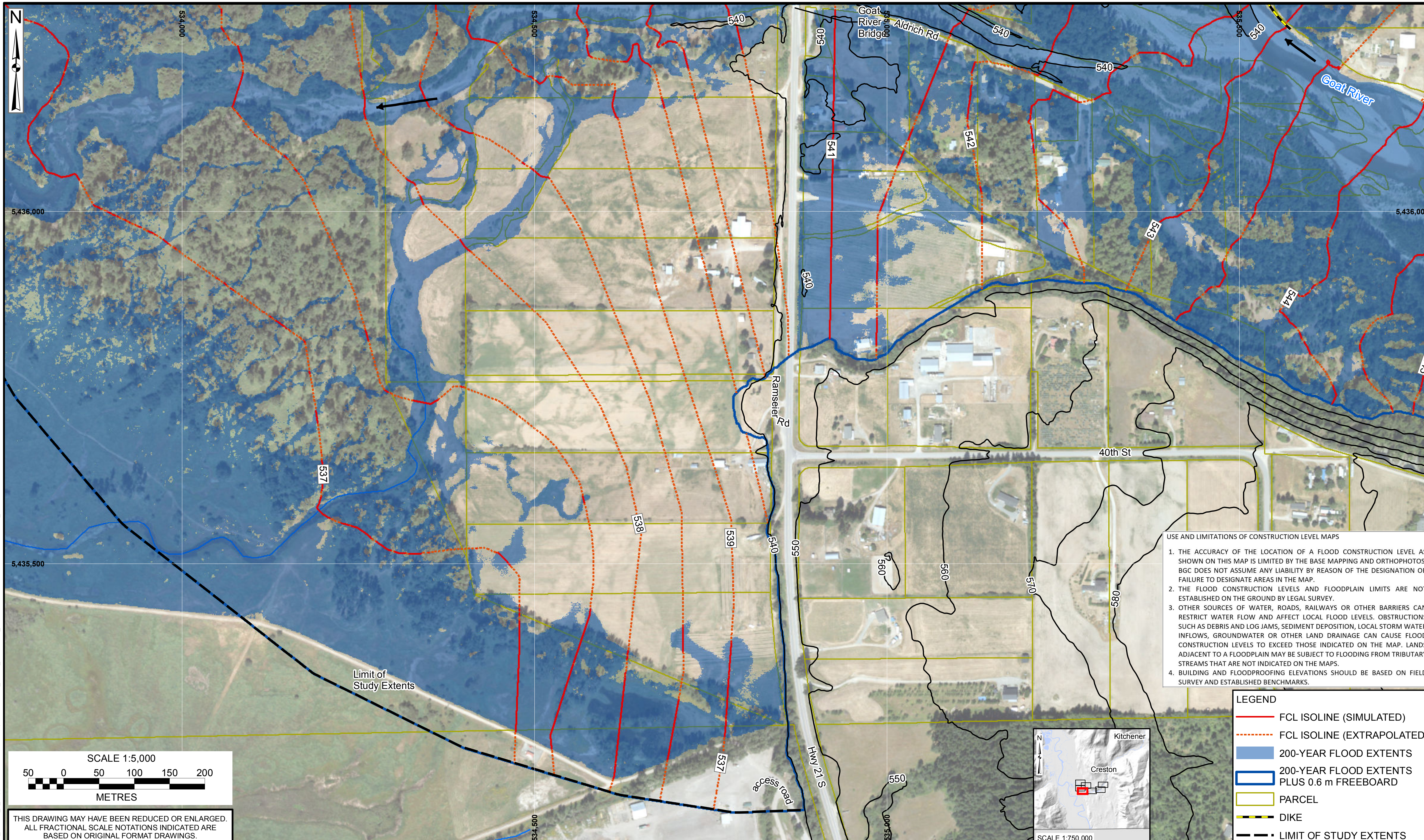

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USE AND LIMITATIONS OF CONSTRUCTION LEVEL MAPS

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4. BUILDING AND FLOODPROOFING ELEVATIONS SHOULD BE BASED ON FIELD SURVEY AND ESTABLISHED BENCHMARKS.

LEGEND

- FCL ISOLINE (SIMULATED)
- FCL ISOLINE (EXTRAPOLATED)
- 200-YEAR FLOOD EXTENTS
- 200-YEAR FLOOD EXTENTS PLUS 0.6 m FREEBOARD
- PARCEL
- DIKE
- LIMIT OF STUDY EXTENTS

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CLIENT:
REGIONAL DISTRICT OF CENTRAL KOOTENAY

PROJECT: RDCK FLOODPLAIN AND STEEP CREEK STUDY GOAT RIVER

TITLE: 200-YEAR FLOOD CONSTRUCTION LEVEL (SHEET 7 OF 7)

PROJECT No.:	DWG No:
0268 007	07

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