SQUAMISH – LILLOOET REGIONAL DISTRICT FLOOD HAZARD MAPPING AND RISK ASSESSMENT UPPER SQUAMISH

FINAL REPORT

Prepared for:

SQUAMISH - LILLOOET
REGIONAL DISTRICT

Squamish – Lillooet Regional District

26 November 2018

NHC Ref. No. 30003329

nhc
northwest hydraulic consultants
water resource specialists

SQUAMISH – LILLOOET REGIONAL DISTRICT
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Prepared for:

Squamish – Lillooet Regional District
Pemberton, BC

Prepared by:

Northwest Hydraulic Consultants Ltd.
Vancouver, BC

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CREDITS AND ACKNOWLEDGEMENTS

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The following NHC personnel participated in the project:

- Will Skitmore and various field staff (Survey)
- Wil Hilsen and Andrew Nelson (Geomorphic Analysis)
- Alex Anderson (Hydrologic Analysis)
- Arian Cueto Bergner and Donnie Jones (Hydraulic Modelling)
- Madalyn Ohrt (GIS and Mapping)
- Julie Van de Valk (Risk Analysis)
- Dale Muir (Project Review)
- Rosemarie Tirshman and Carla Bracken (Document Review)
- Todd Bennett (Project Management).

Pierre Friele, with Cordilleran Geoscience, assisted with the geomorphic assessment.

EXECUTIVE SUMMARY

Squamish River Valley Flooding

The Squamish River is at major river systems in the Squamish - Lillooet Regional District (SLRD) that is subject to frequent flooding. Vulnerability and hence risk of flooding in the upper Squamish River Valley is increasing as development is expanding. This risk has been emphasized with occurrence of some of the largest floods within 60 years of record occurring in recent years; 2015 and 2016.

Typically, the largest flood flows in southwestern British Columbia are the result of intense low-pressure weather systems, or atmospheric rivers occurring in fall and early winter. When originating over the Hawaiian tropics, these storms are often referred to as the Pineapple Express, bringing warm, high moisture air towards British Columbia's coastline. The storms may linger for several days and are particularly troublesome when preceded by early snowfall, leading to rapid melt in combination with heavy rains.

Floodplain Map Development

Floodplain mapping is paramount for estimating the extent and depth of different magnitude floods, developing appropriate flood emergency response measures, and planning for future flood resistant development and infrastructure. SLRD received funding from Emergency Management B.C. Disaster Mitigation Program to be used for developing floodplain mapping, risk assessment, and flood mitigation planning. NHC has carried out the work as described in this report. The project has made several major advances in knowledge and provides significant new tools to support flood management in the Squamish Valley. This report describes the work in detail, with main components and related benefits summarized here.

NHC conducted hydrologic analyses to estimate Squamish River design flows corresponding to the 20- through 500-year flood events, including projected climate change effects. To support the hydraulic modelling and subsequent floodplain mapping, NHC used LiDAR (Light Detection and Ranging) data combined with NHC surveyed data, collected by both foot and by boat in 2017 and 2018, of the Squamish River. A numeric hydraulic model was developed, calibrated to 2015, 2016, and 2017 high flow events as well as the low flow water surface elevation collected during the 2017/2018 survey, and then applied to simulate water levels corresponding to boundary water levels and design inflows (e.g. 50-, 100-, 200-, and 500-year floods, plus the 200-year incorporating projected climate change).

NHC also carried out an investigation to evaluate geomorphic hazards that could further influence the flood hazard and understanding of processes and state of the Squamish River. This work is described in Squamish River Geomorphology and Hydrogeomorphic Hazards, appended to the end of this report. The effects of sediment supply and debris floods damming the river and subsequently leading to a sudden outwash flood, were evaluated as part of the hydraulic modelling.

From study of the flood hazard, several types of floodplain map products were produced showing:

- Geomorphic hazards,
- Flood inundation limits,
- Flood depth,
- Flood Construction Levels (FCLs), a suggested minimum level for construction, and
- Flood hazard maps showing a rating based on flood depths and velocities.

Floodplain Map Use

The up-to-date floodplain maps provide valuable opportunities for improving flood safety and emergency response in the valley. Sharing the results and educating key authorities, stakeholders, and the public, SLRD will help reduce potential loss-of-life and damages during future extreme flood events.

Planning new development away from high hazard areas and implementation of the Squamish River FCLs will lead to more flood resilient development. Access and egress routes requiring improvement can readily be identified and the location of temporary evacuation areas determined. Consideration should also be given to relocating or floodproofing existing housing and other development in extreme flood hazard areas.

The Squamish River channel is highly dynamic and future climate change projections have sizable uncertainty; subsequently the hydraulic model and mapping will likely need to be updated over time. Considering the ongoing aggradation, the river channel should be monitored and re-surveyed approximately every 10 years, and after large sediment deposition/aggradation events, and the hydraulic model updated following substantial changes in the channel or climate projections.
During future flood events, the position, elevation, and timing of high water marks should be surveyed to allow for future model calibration.

This study shows that:

- Almost all of the valley is subject to geomorphic hazards.
- A potential outbreak flood from an upstream landslide blocked river could reach populated areas within a few hours and raise the floodplain water surface by several meters within some portions of the floodplain.
- At the 50-year flood event and above, most of the valley floor is flooded, with typical depths of 1 to 2 m within the inundated area.
- When areas are inundated, much of inundated areas have a high hazard rating and classified as dangerous for most to all people.
- Flood inundation affects all four receptors evaluated; people, the economy, the environment, and culture within the upper Squamish River Valley.
- Natural geomorphic changes at the Squamish-Cheakamus confluence could potentially cause an increased water surface extending upstream nearly to populated areas at river kilometer 30.

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1 INTRODUCTION

The Squamish River floodplain is subject to recurring flooding as well as development pressure. The Squamish - Lillooet Regional District (SLRD) requested the mapping of flood hazards and the assessment of hydrotechnical risks within the Upper Squamish Valley to clearly and concisely inform preparation or updating of emergency management plans and development criteria.

1.1 General Setting

The Squamish River Basin, a watershed of approximately 3,800 km^2, flows from and through the southern Coast Mountains, passing by the community of Brackendale and the District of Squamish (DOS) in British Columbia, Canada before reaching Howe Sound (Figure 1). The confluences with the Cheakamus and the Mamquam Rivers, two major tributaries to the Squamish, are located upstream and downstream, respectively, from these two developed areas. Land use in the basin is dominated by forestry and subalpine to alpine wilderness.

This Upper Squamish Valley flood hazard study evaluates potential geomorphic and river hydraulic flood hazards for the 27 km of the Squamish River upstream from the Cheakamus River; that is the SLRD-DOS boundary. The information from this SLRD study is complemented by the downstream Squamish River Integrated Flood Hazard Management Plan (DOS, 2017), to form a continuous assessment of the Squamish River system.

1.2 Scope of Work

The current report presents the main tasks completed within the Flood Hazard Mapping and Risk Assessment project for the Upper Squamish Valley. The project's scope of work addressed all items outlined in the request for proposals and was segmented into discrete tasks for a systematic approach to completing the project. These tasks include the following:

- Data Acquisition
- Hydrologic Analysis
- Geomorphologic Hazard Analysis
- Flooding Hazards Analysis
- Consequences Assessment
- Flood Hazard Mitigation

1.3 Risk Analysis Team

Northwest Hydraulic Consultants Ltd. (NHC) was engaged by SLRD to complete the project. A team of experienced NHC specialists led each technical component of the project with the support of junior and intermediate staff. Cordilleran Geoscience was also incorporated into the team to bring additional local knowledge on tributary hazards.

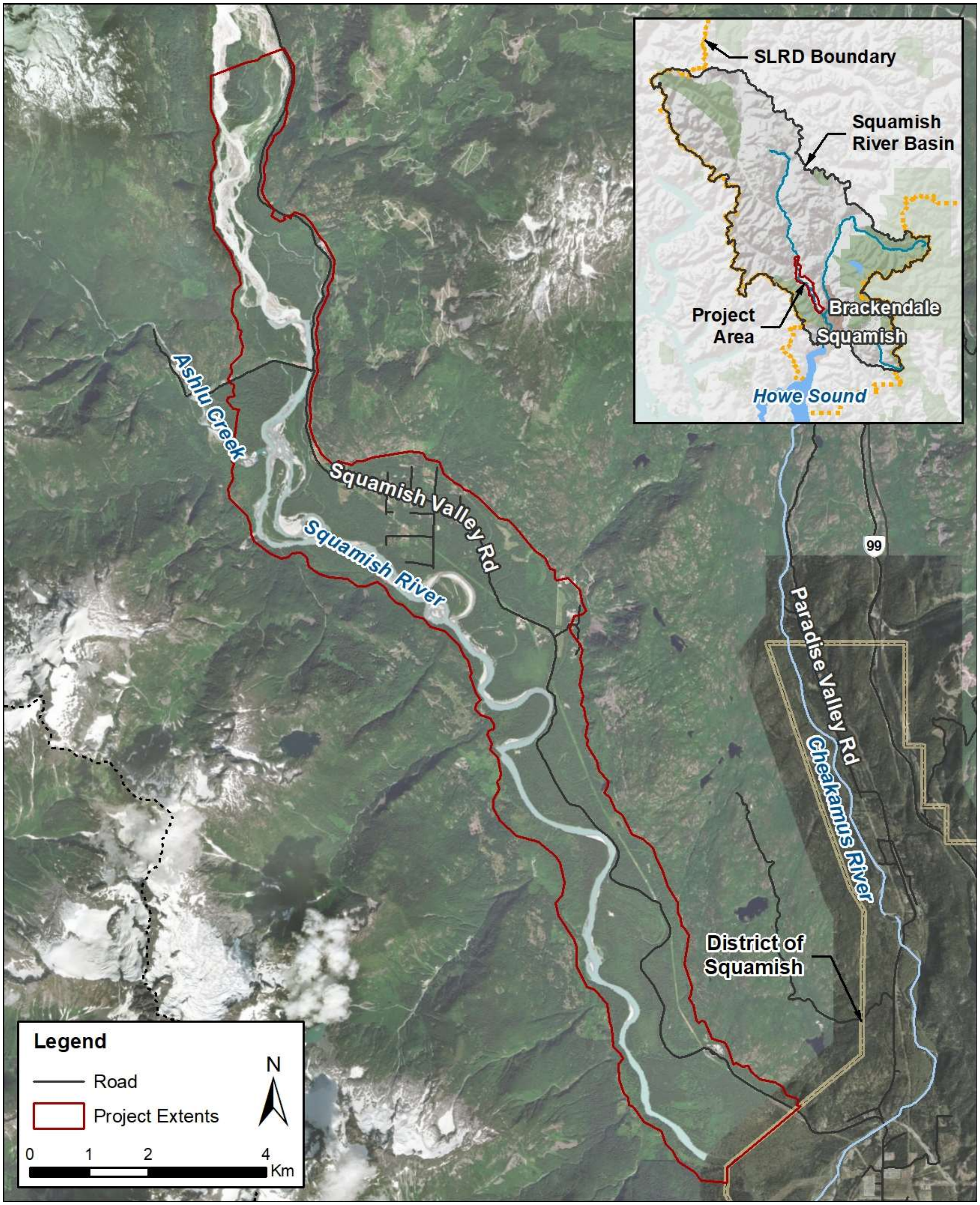


Figure 1 Project location and watershed map

1.4 Vertical Datum

The CGVD2013 datum was used for modelling and mapping for this project as Canada has adopted CGVD2013 as official datum and the province is in the process of migrating to this new datum. All elevation data and geographic information presented in this report uses this datum.

2 DATA ACQUISITION

At the onset of the project, NHC collected and consolidated available information on past floods, past debris events from the tributaries, historic air photos, and additional value components including pertinent studies, reports, and previously collected data including LiDAR data collected along the upper Squamish River. NHC reviewed relevant guidelines, most notably provincial Engineers and Geoscientists BC (EGBC, formerly APEGBC) flood hazard assessments (EGBC, 2018) and mapping guidelines (APEGBC, 2017). During this phase, NHC met with SLRD's steering committee to discuss the available information, scope, schedule, and deliverables. Data acquired during this study included 2016 Emergency Management BC (EMBC) LiDAR and orthophotos.

2.1 Survey

The quality of a floodplain map is directly related to the survey data used to develop the model and map the inundation. To maintain control of the quality of the data, the river survey and ground verification survey was conducted using NHC crews and NHC owned, maintained, and calibrated equipment. Survey cross-section locations, many matching the approximate location of the 1983 flood study, were identified to capture channel changes and channel splits around islands or large bars. In total, 37 cross-sections along a 25 km reach of river were surveyed with a section spacing ranging from 500 to 1000 m. A 25 km long profile of bed and water surface elevations was also surveyed along the thalweg of the upper Squamish River to support interpolation between surveyed sections and validation of the model during its development. The extent of the bathymetric and topographic surveys is presented in Figure 2.

The river bathymetric survey was initiated in November 2017 but could not be completed due to low water levels that prevented safe navigation along the upper Squamish River. The survey was completed in the spring of 2018 over the span of five days (April 27th to May 4th, 2018). The survey was performed using the following equipment:

- Trimble R10 and R8 GNSS RTK GPS rover receivers,
- Nikon Nivo 5" total station,
- Trimble R10 GNSS RTK GPS base receiver w/ Trimble TDL 450 35-watt radio,
- Trimble TSC3 and TSC2 controllers w/ Trimble Access field software,
- Trimble Business Center desktop software,
- Ohmex Sonarmite 200 kHz sounder sounding at 2 Hz,
- Panasonic CF31 Toughbook w/ Intel I5 processor,
- Hypack 2017 hydrographic software

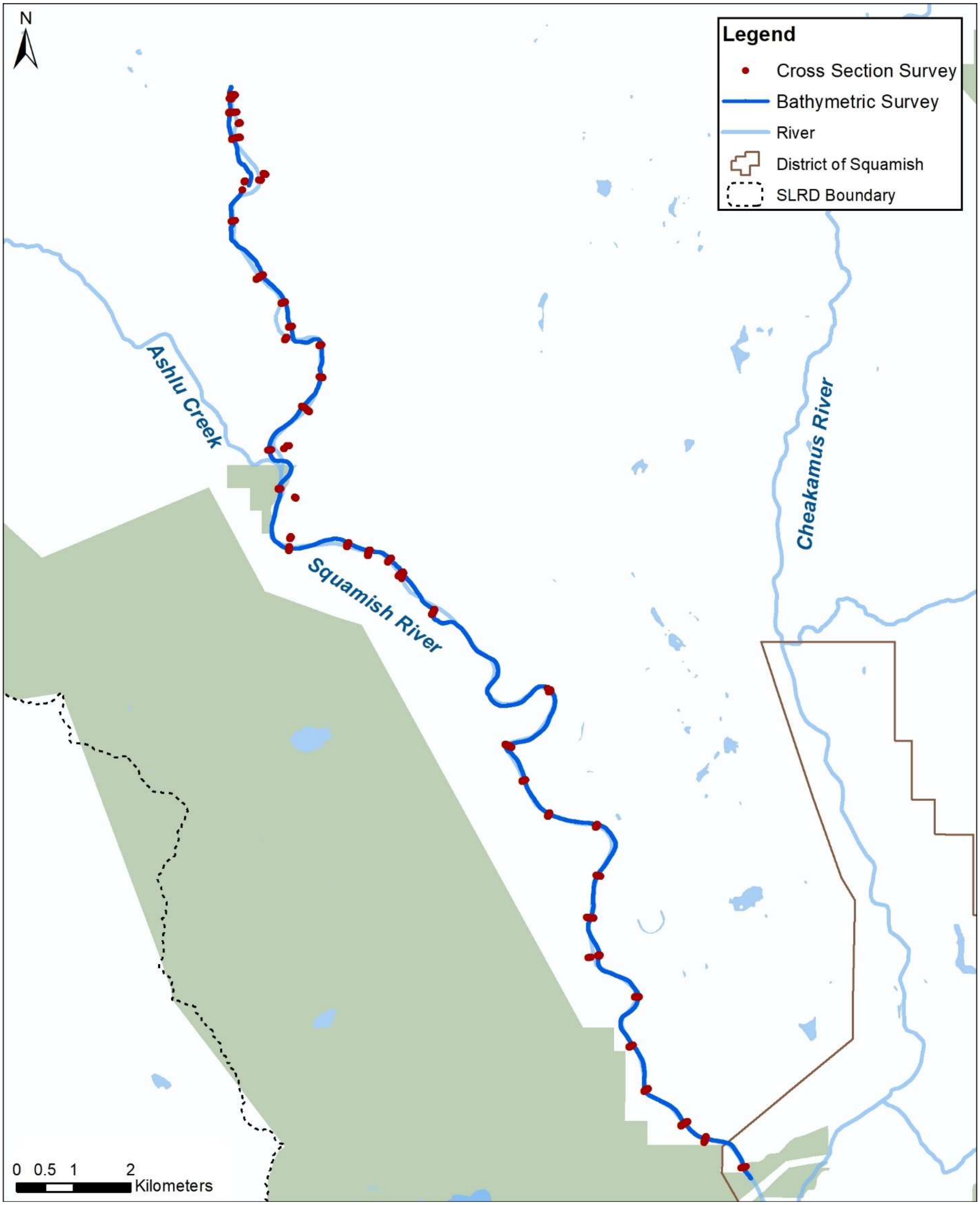


Figure 2 Survey extent of the bathymetric survey

Survey control was established at the onset of each survey (fall 2017 and spring 2018) with benchmarks surveyed daily to provide confidence in combining multiple days of survey. Overbank data points were collected where there was clear coverage and consistent elevation to provide checkpoints for ensuring consistency between the field survey and the LiDAR data. While on the river, identifiable high-water marks (such as staining or suspended debris) and current edge of water marks were surveyed to assist in model calibration.

Bathymetry was conducted using a 16-foot shallow draft boat equipped with survey grade RTK GPS, sounder, and field laptop with Hypack hydrographic software. Each day of the survey, QA/QC tests were conducted on the GPS, sounder, and software systems to ensure measurement dependability and synchronization. Ground shot elevations on the river bed were compared to bed elevations generated by the hydrographic software. These were in the order of +\- 5 cm.

Overbank data points were collected where there was clear coverage and consistent elevation to provide checkpoints for ensuring consistency between the field survey and the LiDAR data. Moreover, since the available LiDAR was recorded at relatively high-water levels, bathymetric cross-sections were extended by ground based topographic means when required to fill any gaps between available LiDAR and survey bathymetry. To achieve this on the river, a LiDAR boundary background file was used to ensure these points were taken within the LiDAR survey limits.

Total station surveys were used to survey the Ashlu Bridge structure and tie in Water Survey of Canada (WSC) hydrometric benchmarks. In both instances, temporary control was established using RTK GPS, which the total station was then set up on. The bridge deck, low chord, abutment, and pier structures were all surveyed with the total station off of geodetic control. WSC benchmarks, at Squamish River Brackendale gauge 08GA022, were tied in to obtain an accurate shift to a vertical geodetic datum (CGVD2013) from the local WSC vertical datum, so this historical data could be integrated into the model.

All survey data uses projection NAD 83 (CSRS) UTM zone 10 North. All elevations are in metres and use CGVD2013 as the vertical datum. The geoid model applied is CGG2013a.

2.2 Site Reconnaissance

A detailed site reconnaissance was conducted over the length of the study reach. Existing conditions were observed and photos taken on May 2, 2018. Selected photos (Figure 3) from this effort are presented in the Photo Log section of this report and show examples of river conditions (during low flow), channels, overbank vegetation, river bar material, and bank erosion. Observations from the site reconnaissance supported definition of modelling parameters as well as the identification and understanding of geomorphic form, process, and hazards. Figure 3 shows the location where these photos were taken.

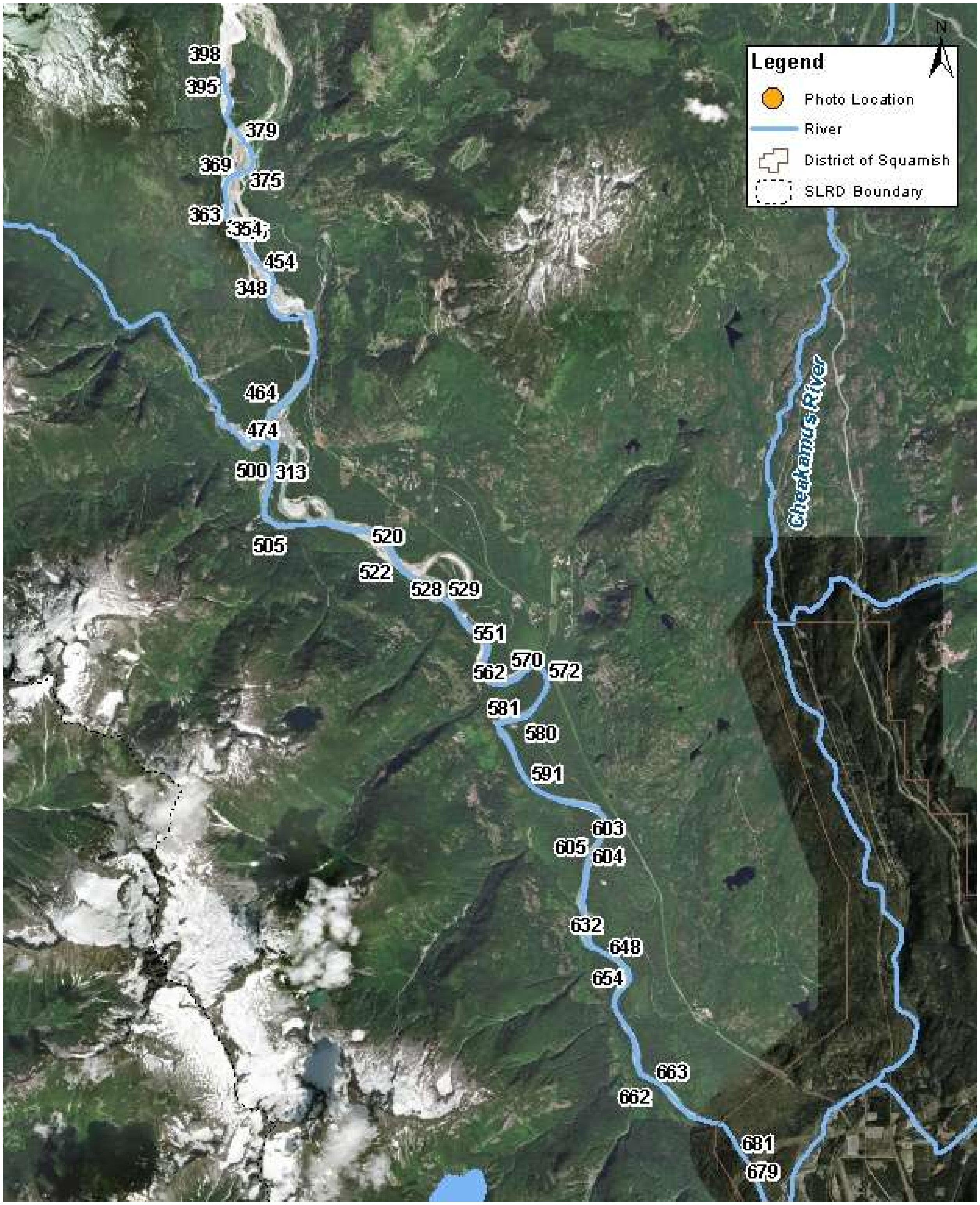


Figure 3 **Location of field photos**

3 HYDROLOGIC ANALYSIS

3.1 Contemporary Design Flow

WSC has been monitoring the Squamish River at the downstream end of the study site near the community of Brackendale since 1922, with nearly continuous record of flow and level since 1955. This hydrometric station (08GA022) is located approximately 2.5 km upstream of the confluence with the Cheakamus River. The Brackendale gauge was used as a proxy for flow into the hydraulic model given the relatively small percent of additional contributing area within the study area. A series of design flow events, based on average return period (inverse of annual probability of exceedance), was calculated (Table 3.1) by applying statistical computer software (USACE, 2010) and using the annual instantaneous peak discharge data record dating from 1956 to 2015 at the Squamish-Brackendale gauge.

Table 3.1 Peak design flow events

Return Period (years)	Design flow (m^3/s)	Design flow with increase for climate change (m^3/s)
2	1,300	1,600
10	2,100	2,500
20	2,400	2,900
50	2,900	3,500
100	3,200	3,800
200	3,700	4,400
500	4,300	5,200

3.2 Climate Change Projection

EGBC recommends a 10% increase in design peak flows to account for climate change when no trend is evident in the record, and a 20% increase when a trend is evident (EGBC, 2018). However, in hybrid rain/snow areas, such as the Squamish River and surrounding region, changes in peak flows are likely to be more similar to a threshold change than a simple increasing trend. As the climate warms, more annual peak flows are expected to occur as fall rain or rain-on-snow events and less as more typical spring freshet events. Fall rain-on-snow events are typically larger than spring events, and the most extreme of these are driven by atmospheric river weather events, which Radic (2015) found are likely to increase in frequency in the future. Thus, we recommend use of the higher 20% safety factor to account for climate change in this area.

4 GEOMORPHOLOGIC HAZARD ANALYSIS

Channel morphology is the study of the channel planform, cross-section, and longitudinal profile to understand the relationship between the spatial and temporal channel form and channel processes. Over time, channel form and processes in the Squamish River are undergoing natural changes as the river adjusts to changes in the flow and sediment regime. Hydrotechnical hazards along the upper Squamish River can be influenced or directly result from changes in the channel; such as through fluvial processes of erosion, aggradation, channel migration, avulsion, and indirect effects of landslides and debris flows that may reach the Squamish River both upstream and downstream of the project area. Landslides or debris flows deliver substantial volumes of sediment and wood debris to the Squamish River; these may then translate down valley as lahars (i.e., mobilization, transport, and deposition of wet volcanic debris)—a process not evaluated here—or block the valley. Partial or complete valley obstruction can cause backwater flooding upstream of the blockage and outburst flooding downstream if the blockage suddenly fails. The geomorphic setting and hazards are discussed in detail within Appendix A, *Geomorphology and Hydrogeomorphic Hazard*. A summary of this information is provided below.

4.1 Channel Morphology

The upper Squamish River flows through a glacially-carved valley with a broad and relatively flat valley bottom. The river has a wandering gravel bed channel morphology in the upper portion of the project reach that transitions to a meandering channel morphology in the lower portion of the project area. Wandering channel morphology represent an intermediate morphologic condition between meandering and braided rivers. Wandering channels are steeper, with more active bank erosion and bar deposition, higher bedload transport rates, and more frequent channel avulsions than meandering rivers of similar discharge. This typology is often characterized by wide, active, multi-channel, sedimentation zones separated by more stable sinuous single thread reaches.

The upper portion of the study reach has two to three main channel threads that branch around relatively stable vegetated islands. The channels are typically braided with low water flow paths divided around gravel bars. There is a high load of large wood debris in the channel, and most islands and bars lie behind naturally-formed apex jams. In addition to the main active channel, several large accessory channels cut across the floodplain.

The downstream, meandering, portion of the study reach, is a consistently single-thread channel with relict channels and oxbow features in the floodplain. Channel migration hazards include both gradual lateral movement of individual meanders and avulsion forming new channels cutting across the floodplain. Both migration mechanisms lead to bank erosion and can threaten adjacent infrastructure. Channel migration rates generally decrease from upstream to downstream along the study reach. Avulsion hazards are expected to be larger and more probable in the upstream portion of the study. Aggressive lateral channel migration primarily occurs through the wandering reach and in the upstream portion of the meandering reach.

4.2 Landslide Caused River Blockages and Outbreak Floods

There is a threat of landslides and debris flows from the flank of Mount Cayley that may deliver large sediment pulses to the Squamish River. These have historically resulted in river blockage that impounded water, causing backwater flooding upstream. In some cases, the blockages may have suddenly failed, causing a subsequent outbreak flood, with a deluge of water and debris flowing downstream. Landslide-caused river blockages have been documented for the upper Squamish River within the Cayley River, Elaho River, Turbid Creek, Avalanche Creek, and Endurance Creek valleys. It is estimated that the recurrence interval for a 25 to 40 m high debris blockage of the Squamish River is about 1,000 years. The potential outwash flood from a blockage failure is assessed in the Flood Hazard Analysis section.

The Squamish-Cheakamus river confluence, at river kilometer (RK) 12, as measured upstream from the river mouth, is near the downstream limit of the potential confluence zone. The base level for the lower portion of the project reach could be affected by the dynamics of the Cheekeye and Cheakamus Rivers, and each has the potential to deliver a slug of sediment that cannot be readily transported downstream by the Squamish River. Avulsions of the Cheakamus River could shift the confluence upstream (estimated to be up to RK 13), increasing the base bed level elevation on the river and increasing flood water surface elevations upstream. A potential increase in the base level is estimated to range between 1.5 to 5 m. The effects of these blockages on the upstream river channel were evaluated as part of the hydraulic assessment and are discussed in the Flood Hazard Analysis section.

5 FLOOD HAZARD ANALYSIS

A flood hazard analysis was completed for the study area by constructing and calibrating a numerical hydraulic model, and then applying the model to aid in defining flood hazards. This report section discusses the model development and calibration results. Flood hazard mapping is discussed later in Section 7.

5.1 Model Development

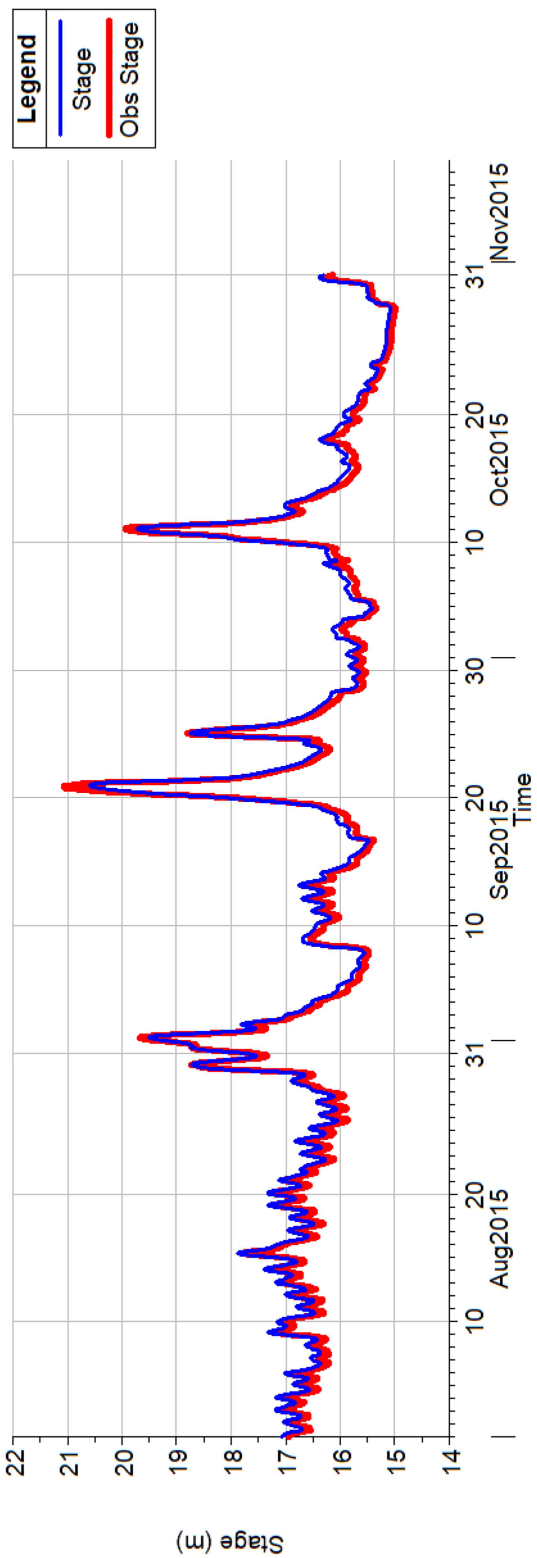
The upper Squamish River was modelled using HEC-RAS (USACE, 2016). HEC-RAS is a freely available hydraulic modelling software program developed by the USACE. A one-dimensional hydraulic model was created using the surveyed bathymetric data and overbank 2016 LiDAR data to define approximately 80 channel cross-sections between RK 40 and RK 13 (near the study limit). Approximately 30 additional cross-sections were added from RK 30 to RK 0, using a combination of overbank 2016 LiDAR data and best available channel geometry from prior 1970s hydraulic modelling, to extend the model to Howe Sound and help define downstream boundary conditions (more recent hydraulic modelling through the DOS was not available at the time of this study). A fixed downstream tidal condition was specified for all simulations. Sensitivity analyses were conducted to show that the selected downstream boundary condition (i.e. coastal water level at Howe Sound), did not have a significant effect on stage within the study area. Evaluation of other model parameters showed that the main channel roughness was one of the most significant factors controlling the simulated water surface elevation, with overbank roughness having very little affect (when varied between a value of 0.10 and 0.20).

5.2 Model Calibration

The upstream inflow to the hydraulic model was specified based on shifting hydrometric station 08GA022 (Squamish near Brackendale) by about five hours, this time value was adjusted during calibration to match hydrograph shape at the gage site, to account for the travel time between the upstream end of the model and the gauge location. The hydraulic model was calibrated to the low flow water surface elevations collected during the survey (below 100 cms for 2017 survey dates, and between 200 and 400 cms for 2018 survey dates) and to the 2015, 2016, and 2017 high flow events using the Brackendale gauge as shown in Figure 4 through Figure 9 (thicker red lines are observed gauge data and thinner blue lines are simulated results). For the 2015 event, calibration also utilized five observed flooding photos (personal communication, Malcolm Schulz, Ministry of Forests, Lands, and Natural Resource Operations, 24 October 2017).

Calibration consisted of adjusting mostly channel roughness and ineffective flow areas so that simulated results matched as best possible the observed condition for first low flow (Figure 10 through Figure 12 showing the surveyed elevation, orange dots, and the simulated water surface profile, blue lines, at the beginning and ending of the survey period) then making further refinements for the larger 2015, 2016, and 2017 events. During the calibration it was found that simulated results improved by adding an inflow at the Ashlu Creek (determined based on scaling drainage areas), and then reducing the upstream flow accordingly. Low flow generally matches the survey profile, on average being within a few tenths of meters with a maximum difference between simulated and observed of 1 m.

The event hydrograph figures show the comparison between observed and simulated stage and flow at the Brackendale gauge. The hydrograph timing of rising and falling periods matches well for both stage and flow. For the time series simulation of the three peak flow periods, simulated stage is slightly high at lower flows (order of tenths of meters) and a little low for highest peak flows (less than 0.5 m difference). Comparing the measured gauge rating curve to the simulation output showed similar results. Calibration was stopped at this point given the sparsity of observed high water data and thus rationale for any further modifications. Model calibration refinement should be conducted when data from high flow events are collected. Other uncertainties affecting the models ability to precisely represent the observed water surface include that the model assumes a fixed bed, that model geometry comes from bathymetric and topographic data dated from several different years (e.g. 2017 and 2018 bathymetric survey data and earlier dated LiDAR data), and therefore is an approximate representation of the real channel geometry, and this is a reach scale planning level model that does not represent the smaller scale details such as independent flow splits, large wood complexes affecting hydraulics, etc. The resulting model is suitable for identifying and assessing reach scale flood risk, but may require further refinement for localized hydraulic assessment or design.



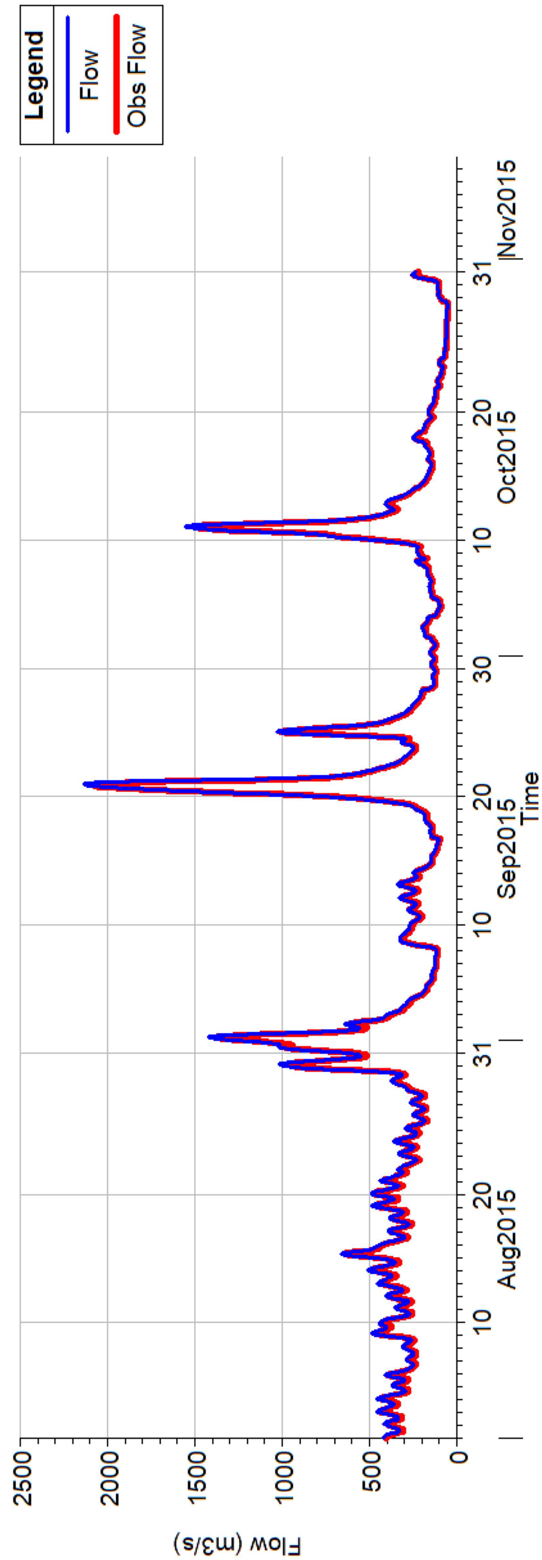


Figure 4 2015 observed and simulated stage

Figure 5 2015 observed and simulated flow

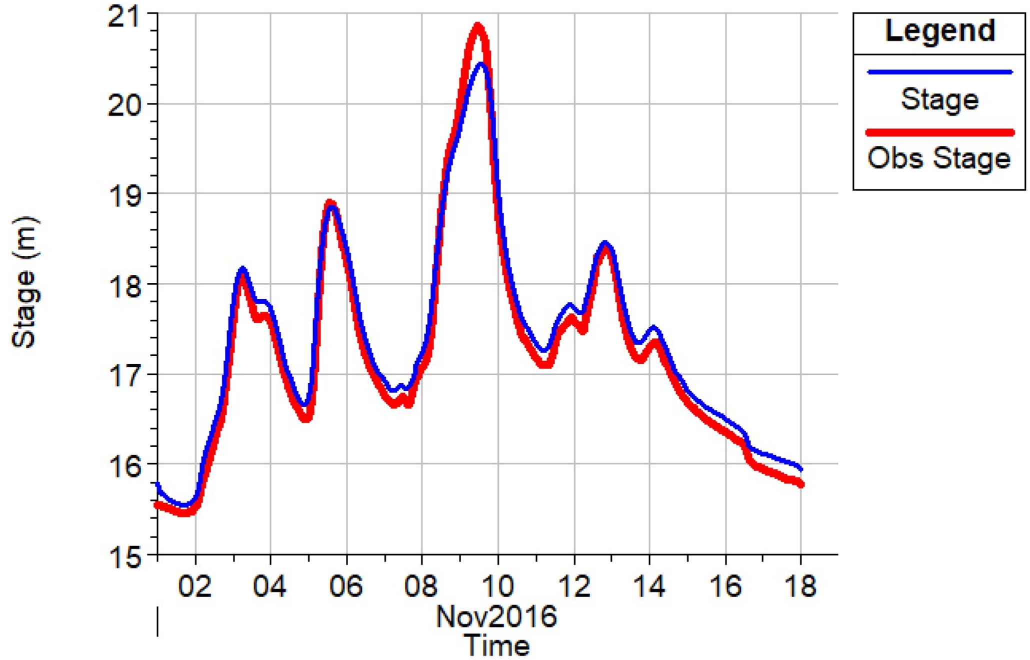


Figure 6 November 2016 observed and simulated stage

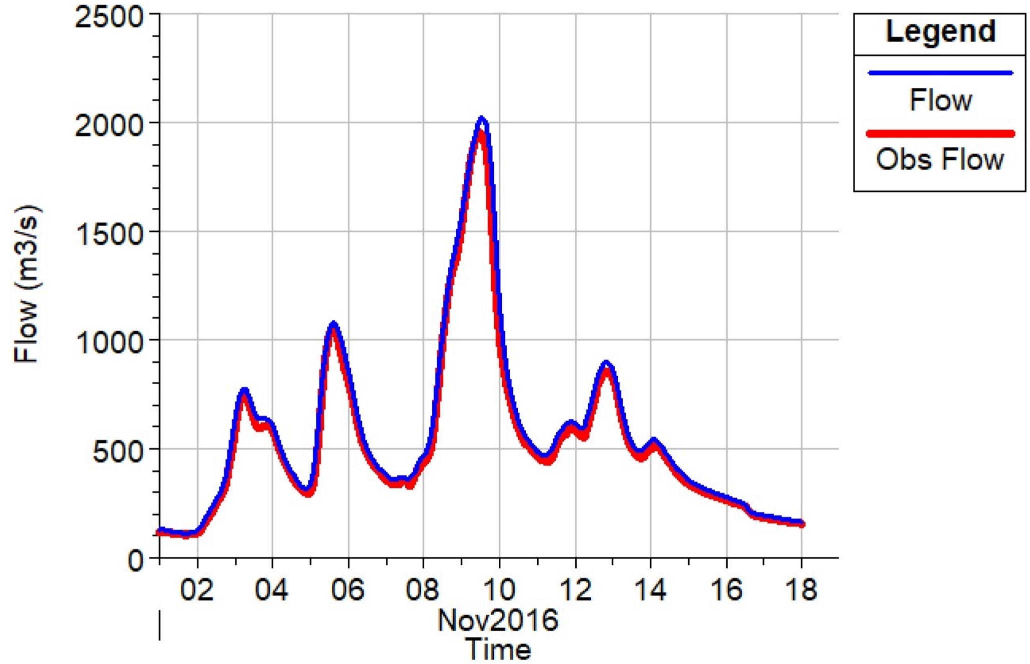


Figure 7 November 2016 observed and simulated flow

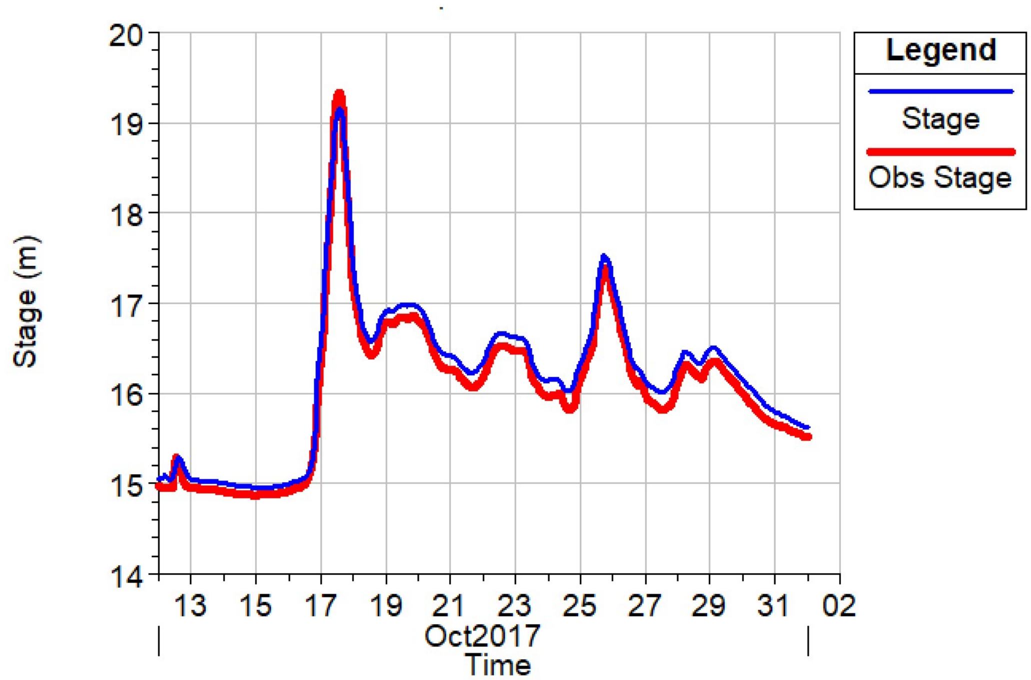


Figure 8 October 2017 observed and simulated stage

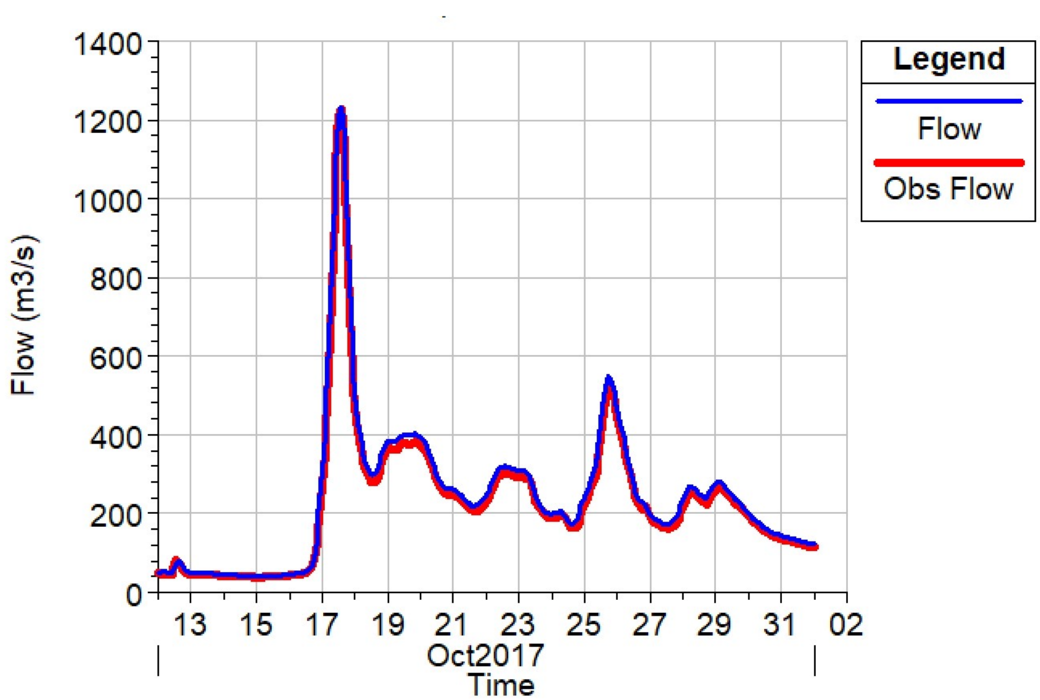


Figure 9 October 2017 observed and simulated flow

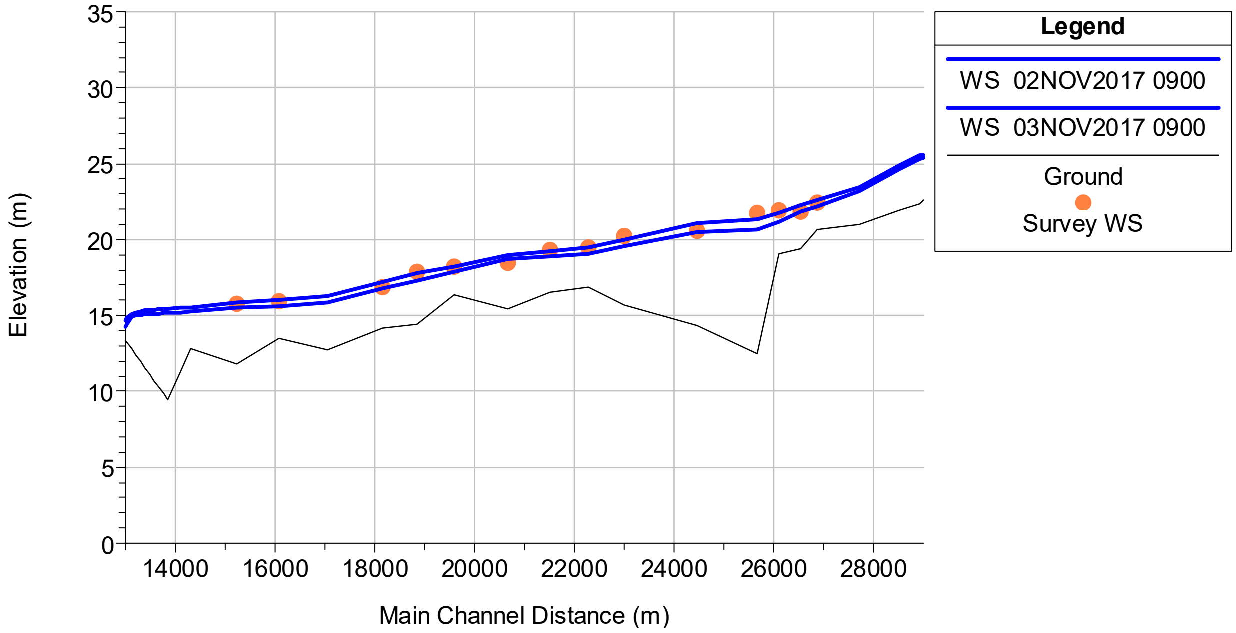


Figure 10 Simulated low flow water surface (WS) calibration to 2017 survey

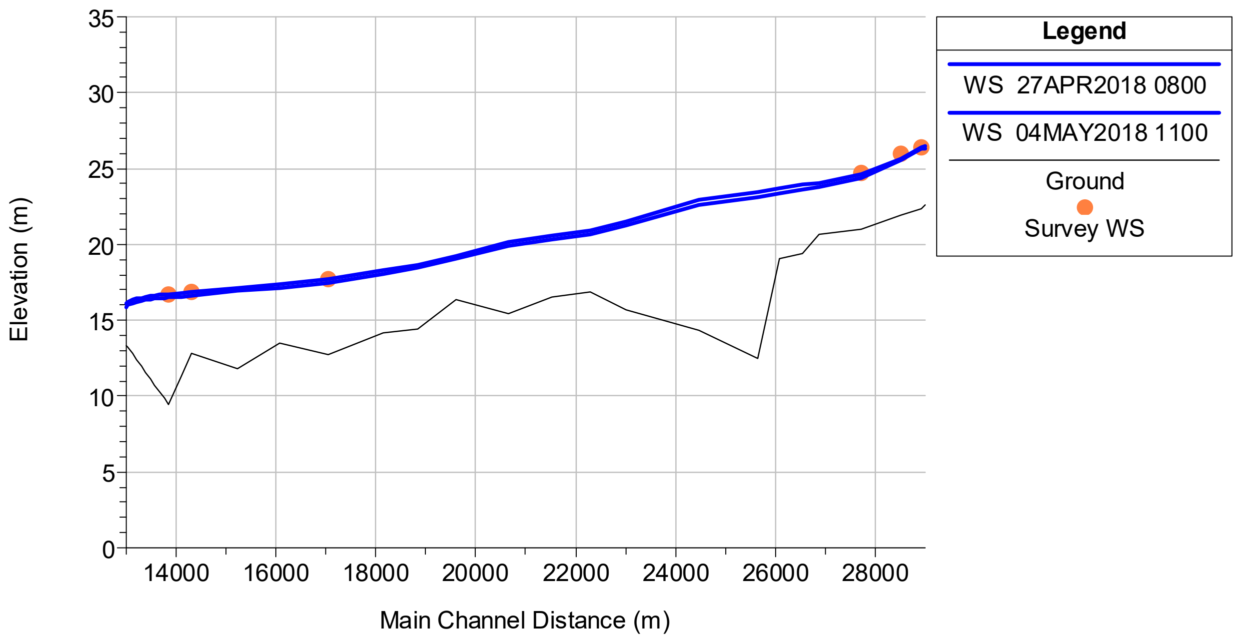


Figure 11 Simulated low flow water surface (WS) calibration to 2018 survey in the lower reach portion

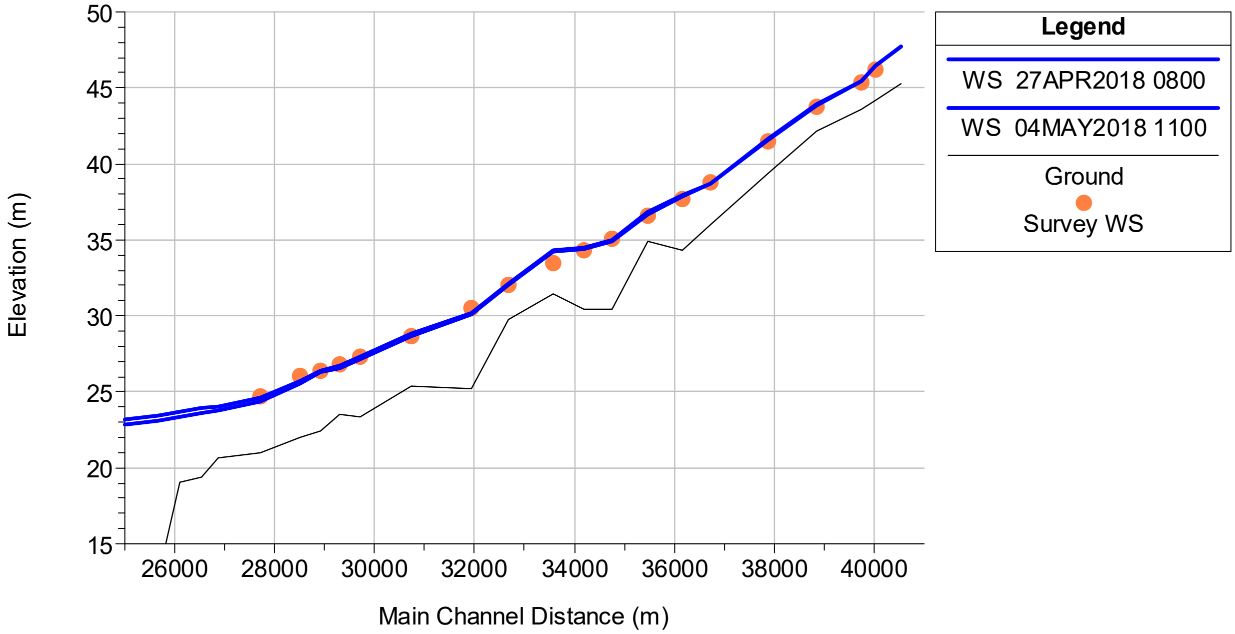


Figure 12 Simulated low flow water surface (WS) calibration to 2018 survey in the upper reach portion

5.3 Breach Analysis of Upstream Landslide Blocked River

As discussed in the Geomorphology and Hydrogeomorphic Hazard Appendix A, landslides have historically occurred within the basin, leading to blockage of the Squamish River. Based on the historic record, blockages of 25 m and 40 m high were simulated in the hydraulic model near the Turbid Creek confluence, and then failed with subsequent modelling of the outburst of water propagating downstream. Sensitivity of peak flow and delay to peak flow was asses for various failure shapes and breach durations. The shortest failure times simulated were 15 and 30 minutes, for 25 m and 40 m high landslide blockages, respectively.

The simulated results of an outburst flood from a potential landslide failure, occurring in the area around Turbid Creek, and blocking the river, are presented in Table 5.1. Results are tabulated at the upstream and downstream end of the study area, as well as near RK 30, just upstream of where much of the existing development is located. A variety of failures were simulated; results for simulations with the shortest travel time are shown in the table. Simulation results show that a large, catastrophic flood, of a magnitude comparable with those estimated to have occurred within the last 1000 years, would cause inundation flooding in excess of the 500-year event throughout the study area.

Table 5.1 Summary of one simulated outburst flood resulting from a 40 m high landslide blockage on the Squamish River near the Turbid Creek confluence during a low flow event

River Kilometer/Location	Peak Stage (m)	Peak Increase in Water Surface Elevation (m)	Time of Arrival after Failure (hours)	Time to Peak after Failure (hours)
RK 40	55	6	1	1.5
RK 30	37	5	1.5	2.5
RK 12	24	4	3	5.5

5.4 Hydraulic Impact of Bed Level Change at Cheakamus Confluence

The hydraulic model was used to simulate modified water surface elevations from bed form change at the Cheakamus River confluence (Section 4.2). For these tests, a range of flows were simulated with a debris flow extending across the Squamish River channel. The largest simulated effects were water surface increases of up to two to three meters between the confluence and RK 24, depending on the volume and duration evaluated, then dropping to insignificant increases by RK 29 for all events.

6 RISK ASSESSMENT

A risk assessment was completed for the study area to evaluate the impacts of the different flood hazard scenarios simulated. This report section discusses the risk assessment approach, data sources, findings, conclusions, and limitations.

6.1 Approach

For this assessment, the consequences of a variety of hazard scenarios were estimated qualitatively and quantitatively based on the impacts to four receptor classes; i) people, ii) economy, iii) environment, iv) culture. The quantitative assessment is limited by available data but provides a representative indication of the risk associated with various flood events. The qualitative assessment was based on an understanding of the valley and the estimated impacts of a flood scenario. This section of the report describes the approach taken in the risk assessment by first defining terminology and the relationships between concepts (Figure 13), then describing the estimation process and data sources used.

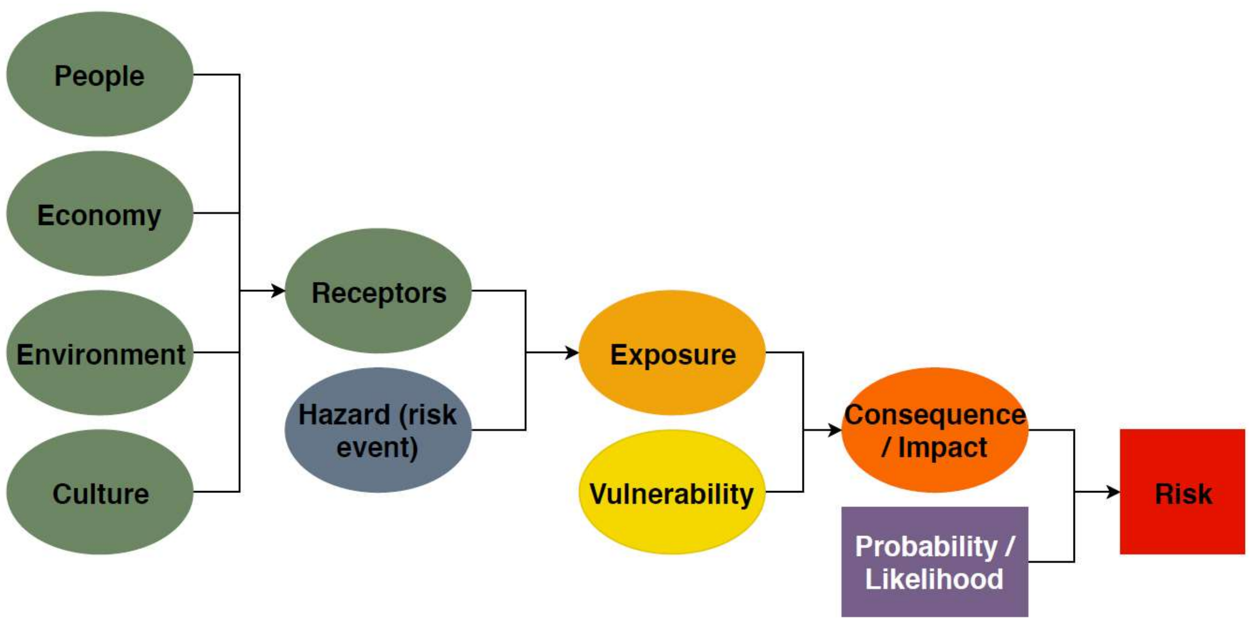


Figure 13 Terminology and Concept Diagram

6.2 Terminology Definitions

Receptors

Receptors are the valued components potentially affected by a flood event. Receptors can be considered at varying levels of complexity, from simple understandings of building and resident locations, to a complex understanding including psycho-social health and economic linkages.

Hazard

A hazard is "a process, phenomenon, or human activity that may cause loss of life, injury, or other health impacts, property damage, social and economic disruption or environmental degradation" as defined by the United Nations report on terminology relating to disaster risk reduction (United Nations, 2016). For this project, the hazard is the flooding (inundation, water depth, and water velocity) that occurs during a particular flow event on the upper Squamish River.

Exposure

Exposure is the receptors potentially at threat from the hazard; that is, "the people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas" (United Nations, 2016). To determine which receptors are exposed, receptor locations are overlaid with hazard areas. For example, buildings that are in the floodplain are identified.

Vulnerability

Vulnerability is the measure of how susceptible a receptor is to a certain hazard or event; extent of impact of the hazard on the receptor. Vulnerability is determined by "physical, social, economic and environmental factors or processes which increase the susceptibility of a receptor to the impact of hazard" (United Nations, 2016). The most commonly considered vulnerability for flood events is the vulnerability of buildings within the floodplain. Buildings can be analyzed through depth-damage curves that identify the expected level of damage based on flood depth. Such curves are specific to a particular building type.

Consequence

Consequence is the impact of the disaster; that is the sum of total negative effects and total positive effects. Effects can include economic, human, and environmental impacts; with human impacts potentially including physical effects (such as loss of life, injuries, diseases), mental effects (such a post traumatic stress disorder), and social effects (such as displacement, socio-economic redistribution, altered community engagement). In addition to direct consequences, there can be indirect consequences. Examples of indirect consequences is loss of future investment or reduced tourism due to enhanced perception of the risk following an event.

For the purpose of risk assessment to flood events, consequence is often focused on economic loss. For example, the projected flood depth of a building or group of buildings (exposure) is used with the depth-damage curve for the given building type or construction type (vulnerability) and the value of the building in the floodplain to calculate expected economic loss (consequence).

Indirect impacts to people due to the flood event may include: psychosocial impacts due to trauma associated with the event, temporary relocation and rebuilding, and impacts to people connected to those directly affected.

Probability

The probability is the likelihood or chance an event is to occur within a particular time period. The time period considered is often a single year, the annual exceedance probability (AEP), the design life of the infrastructure, or some planning horizon. For flood events, probability is most often expressed as the average period between reoccurrence of the same or larger flood event; which is equivalent to the inverse of the AEP. Table 6.1 presents a comparison of probability for a range of time horizons assuming no changes in hydrology or hydraulics (i.e. stationary analysis).

Table 6.1 Probability of exceedance for range of design life

Design Event	Probability of Exceedance within 1 year (AEP)	Probability of Exceedance within a 50-year period	Probability of Exceedance within a 100-year period
20-year	5.0%	92%	99%
50-year	2.0%	64%	87%
100-year	1.0%	39%	63%
200-year	0.5%	22%	39%
500-year	0.2%	10%	18%

Risk

In casual conversation, risk is often used to express probability of loss or to define a particular hazard. However, risk and loss analysis adopt a definition of risk as a function of, or the combination of, the likelihood of an event and its consequences (California Natural Resources Agency, 2018). Typically, risk is presented in a matrix form comparing probability and consequence for a range of receptors.

6.3 Project Methods and Data Sources

This section identifies how these definitions were applied in the context of this project. Receptors in all four categories were considered for this project through a combination of quantitative and qualitative analysis. The flood hazard was mapped for each scenario combining depth, velocity, and a debris factor. Exposure was determined based on the receptors present in the hazard area for each flood scenario. Exposure information was combined with receptor vulnerability to estimate the scenario consequence. The consequences associated with each probability event were then outlined in a risk matrix.

This risk assessment is generally complementary to assessments done previously for the lower Squamish River as part of the Squamish Integrated Flood Hazard Management Plan (River Flood Risk Mitigation Options dated September 2017). The previous assessment made use of the US Federal Emergency Management Agency (FEMA) GIS-based risk model HAZUS to assess economic consequences and risk. The Upper Squamish Valley does not have a high density of population or buildings, limiting the applicability of the HAZUS approach. An alternative approach was applied as presented in the following sub-sections.

6.3.1 People

Population information is based on the 2011 Canadian census as adapted and analyzed by Natural Resources Canada (NRCan). The population data is based on data published at the census dissemination area (DAUID) level and has been refined by NRCan to cover settled areas (SAUID). This refinement used Statistics Canada land cover information collected through the Landsat remote sensing program. This land cover information was originally classified to study agricultural land loss through analyzing land cover change over time. This analysis was adapted to restrict DAUID polygons to settled areas through removing areas with limited populations; such as, forests, wilderness areas, parks, and agricultural land. This output was refined in rural and remote areas by using NRCan CanVec data, which identifies structures and inhabited areas. The statistics for a given DAUID were then distributed over the settled areas using a weighted average based on the Night Light Development Index (NLDI) (in contrast to applying a uniform density). The NLDI identifies the concentration of lights seen at night and was developed by the National Oceanic and Atmospheric Administration (NOAA)'s National Centres for Environmental Information. Areas with greater concentrations of light at night were assigned a higher portion of the population.

The vulnerability of the population was approximated through a social vulnerability index (SVI) developed by NRCan with SAUID spatial units. The SVI developed by NRCan is a combination of indices of economic, population, health, and built environment. As the built environment index is specific to an earthquake hazard, it is removed from the analysis for this project, and the SVI is only based on the economic, population, and health indices.

The SVI is calculated differently for each community archetype. Community archetypes are developed to capture the differences in the effects of community type on social vulnerability. Community archetypes are developed as follows: Urban Metropolitan Centre; Urban Agglomeration Area (Pop>10,000) with administrative subdivisions; Urban Agglomeration Area (Pop>10,000) with no administrative subdivisions; Exurban Regional District with strong metropolitan influence; Exurban Regional District with moderate metropolitan influence; Rural District with weak metropolitan influence; and Rural District with no metropolitan influence. The Upper Squamish Valley is identified as an Exurban Regional District with strong metropolitan influence.

Each SVI input factor is normalized with a min-max approach between 0 and 1, with 1 being the highest vulnerability. To develop the economic, social, and community health indexes that form the overall SVI, each component index is developed through combining factors using weights specific to each community archetype and developed based on a principal component analysis (PCA). The social index is derived from 20 variables related to age, family characteristics, language, education, etc. The economic index is derived from 8 variables related to household income, individual income, employment status, etc. The community health index is derived from 13 variables related to illness, access to health care, quality of life, etc. The three component indexes are then combined, equally weighted.

6.3.2 Economy

The consequence to building structures and contents was assessed quantitatively using the Rapid Risk Evaluator (ER2) Flood tool. ER2 Flood is a tool developed by the University of New Brunswick and is commonly used to provide estimates of flood consequences in Canada. Based on building characteristics (quality, occupancy type, foundation type, year built, number of stories, presence of a basement, and garage size), repair costs and contents value are estimated. ER2 bases its estimate on a percent damage derived from modelled flood depth and the building characteristics. Buildings and building characteristics were identified through air photo examination and a desktop study. When information about the building was unknown, consistent assumptions based on local knowledge were used. Residential buildings were assumed to be 2-story, single family dwellings with a slab on grade foundation, built around the year 2000 with no basement and a 1-car garage. Valuations for building structure and contents were first identified by the tool and then adjusted if appropriate based on local knowledge.

A qualitative analysis of the exposure of roads was completed through overlaying the roads and the floodplain for each event. A qualitative assessment of other economic impacts was completed based on local knowledge and a desktop study.

6.3.3 Environment

Several datasets from GeoBC were used to determine the environmental assets in the area including: BC Parks and Ecoreserves; identified critical habitat areas; conservation lands; and local and regional greenspaces. An exposure level quantitative assessment of critical habitat areas, and a consequence level qualitative assessment was done. The quantitative assessment overlaid the hazard areas with the various environmental assets.

6.3.4 Cultural

Information about the cultural value of the area is qualitative. The reserve boundaries for the Squamish First Nation were downloaded from GeoBC and other resources were identified through local knowledge and a desktop study.

6.4 Findings

6.4.1 People

The population exposed to flood events was determined based on the census data adapted by NRCan as described in Section 6.3.1. This population in the census data represents the resident population and does not account for additional people who may be recreating or camping in the area. The number of people exposed during each flood scenario is shown in Table 6.2. With timely evacuation, these people could be removed from direct harm due to a flood event; however, this represents the number of people who would be displaced in the aftermath of the flood. A more detailed analysis of capacity and use of facilities in the area is required to determine additional population exposed. The SVI index of the resident population is 0.3, which represents fairly low social vulnerability.

Table 6.2 Resident population exposed in each flood scenario

Flood Scenario	Population Exposed
20-year	30
50-year	90
100-year	110
200-year	140
500-year	190

6.4.2 Economy

There are over 80 structures identified in the floodplain in the study area. These buildings have uses including residential, industrial, commercial, and agricultural. Damage due to flood events was estimated using the ER2 tool as outlined in Section 6.3.2. Damage to structure and contents was estimated for each return period flood and aggregated by building use type (Table 6.3). Damages are primarily residential and increase with the severity of the flood event. Values are estimates based on reference values and some manual corrections, and only reflect direct impact to the structure and its contents.

Table 6.3 Damage by building type (all costs in $)

Building Type		10-year	20-year	50-year	100-year	200-year	500-year
Residential	Structure	205,000	276,000	778,000	1,358,000	1,880,000	2,811,000
	Contents	69,000	185,000	936,000	1,580,000	2,014,000	2,988,000
	Total	274,000	460,000	1,715,000	2,938,000	3,894,000	5,799,000
Industrial	Structure	201,000	301,000	301,000	423,000	436,000	1,078,000
	Contents	301,000	452,000	452,000	737,000	873,000	2,687,000
	Total	502,000	753,000	753,000	1,159,000	1,309,000	3,765,000
Commercial (Inc. Hospitality)	Structure	83,000	95,000	242,000	341,000	511,000	595,000
	Contents	633,000	1,110,000	1,080,000	1,147,000	1,437,000	1,573,000
	Total	715,000	1,205,000	1,321,000	1,488,000	1,949,000	2,168,000
Agriculture	Structure	-	151,000	654,000	833,000	1,115,000	1,259,000
	Contents	134,000	806,000	1,317,000	1,360,000	1,511,000	1,581,000
	Total	134,000	957,000	1,971,000	2,193,000	2,626,000	2,841,000
All Building Types		**1,625,000**	**3,375,000**	**5,760,000**	**7,778,000**	**9,778,000**	**14,573,000**

The Upper Squamish Valley has limited infrastructure. There are no health facilities, education facilities, community facilities, potable water systems, sewage collection, and no first responder facilities located in the valley or directly impacted by the flood event. Communications infrastructure is limited, but its exact extent is unknown. Residents and businesses up the Upper Squamish Valley largely rely on household well water. There is electrical infrastructure including a transmission line, which runs from the town of Squamish up into the valley and numerous distribution systems to buildings.

There is a main road through the Squamish Valley called the Squamish Valley Road, and several minor roads. Table 6.4 identifies the length of road affected in each flood event. In addition to the road length that would be directly affected in a flood event, interruption of access along the road would cause significant disruption. This road is the only mode of access for local residents, to the hydropower project, to recreation sites and to a significant network of forest service roads and active logging. This network would be inaccessible during a flood event and during time required to make repairs from damage due to flooding.

There are also two government recreation sites past the study area that are accessed through the Squamish Valley Road.

Table 6.4 Length of road flooded in each flood scenario (all roads)

Flood Scenario	Length of Road Flooded (km)
20-year	4
50-year	14
100-year	19
200-year	22
500-year	26

Economic activity in the area is primarily forestry, local businesses, power generation, and recreational tourism. There are numerous active forest operations that are accessed off of the Squamish Valley Road. A flood event would eliminate access to these operations for the duration of the event and longer for any road repairs.

There are several local businesses in the valley including a children's camp, a private campground, meditation retreat centres, a feed and supply store, farms, and a horse farm and guiding centre. These businesses and others may have property damage during a flood event and would be interrupted during the flood event and post flood reconstruction.

The Cheakamus Generating Station is in the floodplain and inundated by any events with a return period of 50 years or higher. The Ashlu Creek Generating Plant, while not directly affected by flooding, is accessed from the Squamish Valley Road. The Cheakamus Generating Station may experience damage due to the flooding, and both plants may face difficulties staffing operations during a flood event and subsequent road repair.

Flood events will also impact recreational tourism in the area and established recreation sites. During a flood and for the duration of repairs, paid recreation such as guided river rafting trips, horseback tours, guided ski touring, etc., will be unable to operate or travel through the valley. These operations may also experience damage to equipment, campsites, or trails they use in their operations. Non-paid recreation such as ski touring, four-wheel driving, climbing, mountaineering, camping, hiking, or biking that occurs in or through the valley may also be impacted through temporary or permanent loss of campsites, trails, and access. While these activities do not directly contribute to the economy within the Upper Squamish Valley, they increase tourism and spending in the area. There are two official, government-run recreation sites in the floodplain – the High Falls (5.5 km) Recreation Site and the Anderson Beach Recreation Site. These recreation sites would both experience flooding that could damage park signs, trails, camping areas, and other built facilities.

In addition to the direct effects discussed above, there are also indirect effects associated with each of these impacts. Indirect effects include effects to the regional economy due to a flood through loss of recreational tourism, etc.

6.4.3 Environment

While flooding is a natural process, it would have effects on the environment of the Upper Squamish Valley. Numerous flora and fauna reside in the valley, and critical habitat areas for the Marbled Murrelet are located within the floodplain. Table 6.5 identifies the area of critical Marbled Murrelet habitat exposed in each flood scenario. The critical habitat dataset includes both final and proposed critical habitat for at risk species listed on Schedule 1 of the federal Species at Risk Act (SARA). To determine the impact of the flooding on the habitat area and on the local population of the species at risk, an assessment by a biologist would be required.

Table 6.5 Area of critical habitat flooded for each flood scenario

Flood Scenario	Marbled Murrelet Critical Habitat Affected (ha)
20-year	82
50-year	113
100-year	119
200-year	122
500-year	130

The Tantalus Provincial Park is located on the west side of the Squamish River. Park access is usually by helicopter from Squamish, or by driving up the Squamish valley crossing the Squamish River. While the park will not be directly affected by a flood event, access to the park will be impacted.

6.4.4 Cultural

The area is the traditional, ancestral home to the Squamish First Nation. The Squamish First Nation have used the Squamish River valley for thousands of years. The area was and is used by the Nation for living, hunting, gathering, fishing, ceremonial significance, and recreation. The Squamish First Nation reserve Cheakamus Number 11 covers much of the floodplain and the Skowishin Number 7 reserve is located within the floodplain. The Skowishin Graveyard 10 is located along the Squamish Valley Road; however, it will not be affected in any of the flood scenarios. No specific sites were identified as culturally significant as the Squamish First Nation have identified the entire valley to be of cultural significance. Table 6.6 identifies the area of each reserve flooded in each flood scenario.

Table 6.6 Area of reserve flooded for each flood scenario

Flood Scenario	Skowishin # 7 (ha)	Cheakamus # 11 (ha)
20-year	21	330
50-year	30	330
100-year	30	330
200-year	30	330
500-year	30	330

There is also significant cultural value for the wider Squamish community associated with the recreation that occurs in the floodplain. While impacts to people and the economy associated with the recreation are quantified above, the recreation in this valley is also culturally important to many residents.

There are various religious and spiritual institutions located in or accessed through the floodplain. The Queen of Peace Monastery is in the valley and is a spiritual institution for the Contemplative nuns of the Order of Preachers. The valley also contains several meditation and yoga retreats and institutions.

6.5 Limitations

The following limitations were associated with the analysis:

- No geomorphic hazards were considered (such as erosion, avulsion, degradation), only flood hazards.
- The analysis is limited to available receptor data. Accuracy limitations associated with the receptor data limits the accuracy of the analysis.
- Assumptions about building characteristics were made and no sensitivity testing was done.
- Only direct consequences were analyzed, indirect consequences in each category exist but their analysis was beyond the scope of this analysis.

7 HAZARD MAPPING

Results from the geomorphic and hydraulic analyses were used for the mapping. This study considered a range of geomorphic and hydraulic hazard scenarios, from the 2-year through the 500-year flood events, the latter which were addressed through numerical hydraulic modelling. The produced maps follow provincial floodplain mapping guidelines and standards (i.e. EGBC). It is important to note that the development of new floodplain maps can result in substantial pressures on local municipalities as no-build zones or FCLs become greater or different than those previously applied. Several types of maps were produced:

- Geomorphic hazards.
- Flood inundation limits.
- Flood depth maps.
- Flood construction levels.
- Flood hazard maps showing a rating based on flood depths and velocities

7.1 Geomorphic Hazards

This study provides a qualitative overview of some of the geomorphic hazards in the upper Squamish Valley. As shown on the Geomorphic Hazard maps, there are several current issues as well as longer term concerns. Based on 2016 orthoimages (recognizing that the Squamish is a very dynamic river and thus conditions may have changed in the two years since these images were taken), the river is very near the Squamish Valley Road in several locations, and thus the road is likely currently threatened, or soon to be threatened, by bank erosion. Examples are near the RK 40 side channel, between RK 34 and 35, RK 24.5 and, where existing bank armouring was observed on 24 October 2017, RK 20.5. The "Highest Hazard Zone" (see technical Appendix A for a detailed description) indicates that the roadway may be attacked by the river in several other locations within the next 50 years. Recent channel migration rates are estimated to be between 6 to 17 m/year, depending on location, with extreme values possibly as high as 10 times that in channel bends during a single flood season that experiences large floods. The Geomorphic Hazard maps also show debris fan hazards within the upper Squamish Valley.

7.2 50-Year through 500-Year Inundation and Flood Depths

Maps have been provided for the larger design events, comparing contemporary 50-, 100-, 200-, and 500-year inundation limits, based on results from the hydraulic modelling, as well as depth of flooding in the overbanks from comparing the simulated water surface to ground elevations. Water surface elevations were determined by linearly interpolating between cross-sections to create a two-dimensional surface, and then this was intersected with the LiDAR data, with the portion of the water surface above the LiDAR data defining the inundated area.

The 50-year simulation reaches the valley wall at many spots, and therefore little variation is seen in the lateral extent of flooding at these locations. The simulations show that properties near RK 28.5 to 29, depending on their exact location, appear to either experience both direct flooding or water backing up from downstream into lower topographic areas.

Flood depth maps were developed by subtracting the LiDAR elevation from the simulated water surface elevation. The colour shading references the description listed in Table 7.1, adapted from the national standard in Japan (EXCIMAP, 2007). Floodplain depths typically vary from roughly up to 1m for the 50-year event, to 2 m or more for the 500-year event.

Table 7.1 Flood depth description

Flood Depth (m)	Description
0 to 0.5	Most houses are dry; walking in moving water or driving is potentially dangerous; basements and underground parking may be flooded, potentially causing evacuation.
0.5 to 1.0	Water on ground flood; basements and underground parking flooded, potentially causing evacuation; electricity failed; vehicles are commonly carried off roadways.
1.0 to 2.0	Ground floor flooded; residents evacuate.
2.0 to 5.0	First floor and often roof covered by water, residents evacuate.
> 5.0	First floor and often roof covered by water, residents evacuate.

7.3 Flood Construction Level

The floodplain modelling was also used to develop a traditional floodplain map that presents the area of inundation and a minimum FCL. This map was based on the 200-year design event adjusted for projected climate change and freeboard set to 0.6 m. Analysis frequently uses 0.6 m above the instantaneous as an acceptance of the level of confidence in the results. This approach was considered appropriate for the project area due to the potential for geomorphic changes prior to or during a flood event and the sparsity of calibration data in developing the hydraulic model. The freeboard was added to the calculated water level to account for local variations in water level (i.e. super elevation, turbulence, surging), as well as for the precision or confidence in the data and assessment.

7.4 Flood Hazard

Flood Hazard Rating values were computed for the 50- and 200-year events using the following equation cited by EGBC (EGBC, 2018, Clarke, 2005):

HR = d x (v + 0.5) + DF, where

- HR = flood hazard rating;
- d= depth of flooding (m);
- v = velocity of floodwaters (m/s); and
- DF = debris factor (= 0, 0.5, 1 depending on probability that debris will lead to a significantly greater hazard)

For this application, velocity for the floodplain was determined by linearly interpolating the simulated average overbank velocity between cross-sections. Table 7.2 lists the different levels of flood hazard based on the UK DEFRA/Environmental Agency. Much of the 50- and 200-year inundated area throughout the valley has a "Significant" and "Extreme" hazard rating (Table 7.2) where the flooding is dangerous for most to all people.

Table 7.2 Flood Hazard Rating

Hazard Rating	Degree of Flood Hazard	Description
< 0.75	Low	**Caution** "Flood zone with shallow flowing water or deep standing water"
0.75 to 1.25	Moderate	**Dangerous for some** (i.e. children) "Danger: flood zone with deep or fast flowing water"
1.25 to 2.0	Significant	**Dangerous for most people** "Danger: flood zone with deep fast flowing water"
> 2.0	Extreme	**Dangerous for all** "Extreme danger: flood zone with deep fast flowing water"

8 HAZARD MITIGATION

The upper Squamish River is subject to several hazards as identified in this report, that could be addressed through structural and regulatory measures.

One of the most prominent hazards is flooding, highlighted by recent, relatively large floods in 2015 and 2016, and the flood hazard maps show that many properties within the upper Squamish Valley are flooded during the large design events. Regulatory mitigation can be used to put constraints on development (for example, preventing development of lands, limiting density, limiting type of development, and/or requiring site specific flood hazard assessments prior to rezoning or development) or for requiring detailed assessment and/or structural mitigations prior to development in flood hazard areas. Developing preparatory measures can also help mitigate these hazards, through emergency preparedness planning, evacuation route and safe zone identification, and public awareness campaigns. For structures within the flood hazard zones, first floor elevations can be raised (e.g. to or above the FCL) to reduce damage from flooding. Building relocation is another option to address flood hazards.

There is existing bank erosion threat, a natural occurring process through channel migration. However, when infrastructure is located close to a river, there is a potential hazard. These are locations where fish habitat-friendly bank protection can be designed and built. This is particularly important along the Squamish Valley Road, the one main road in and out of the valley.

There are currently no existing flood protection dikes along the upper Squamish River. Dikes can aid in flood protection, and if considered for the upper Squamish Valley they should be set back from rivers edge, as has been the recent trend versus the historical placement at the river banks, to allow for riparian habitat and natural channel processes.

The analysis and mapping for conducted for this report has provided a planning level assessment of the flood hazards within the upper Squamish River Valley. The next steps would build upon this work, further vetting these mitigation measures.

9 SUMMARY

The results of this study are intended to quantify and provide SLRD a better understanding of the upper Squamish River geomorphic and flood hazards. This report and the associated maps provide a basis for evaluating and mitigating hazards within the upper Squamish River Valley and for assessing and making informed decisions about future development within the basin. Based on the findings, the following conclusions are provided:

- Almost all of the valley is subject to geomorphic hazards.
- A potential outbreak flood from an upstream landslide blocked river could reach populated areas within a few hours and raise the floodplain water surface by several meters.
- At the 50-year flood event and above, most of the valley floor is flooded, with typical depths of 1 to 2 m within the inundated area.

- When areas are inundated, much of it has a high hazard rating and classified as dangerous for most to all people.
- Flood inundation affects all four receptors evaluated; people, the economy, the environment, and culture within the upper Squamish River Valley.
- Natural geomorphic changes at the Squamish- Cheakamus confluence could potentially cause an increased water surface extending upstream nearly to populated areas at RK 30.

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PHOTO LOG

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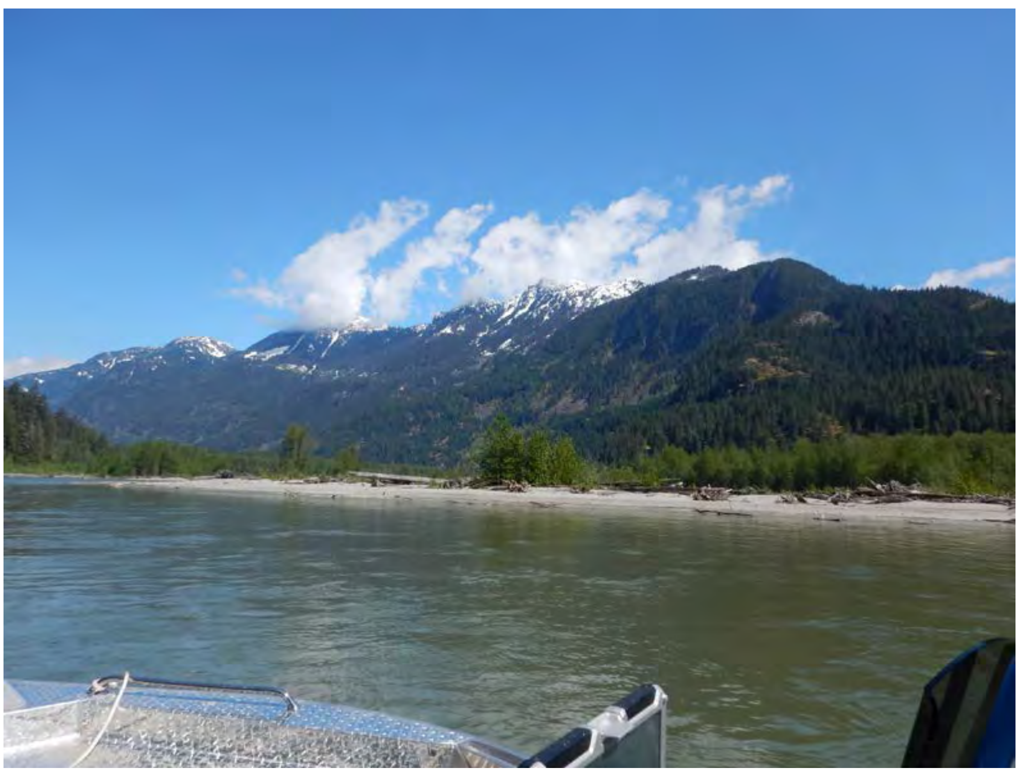

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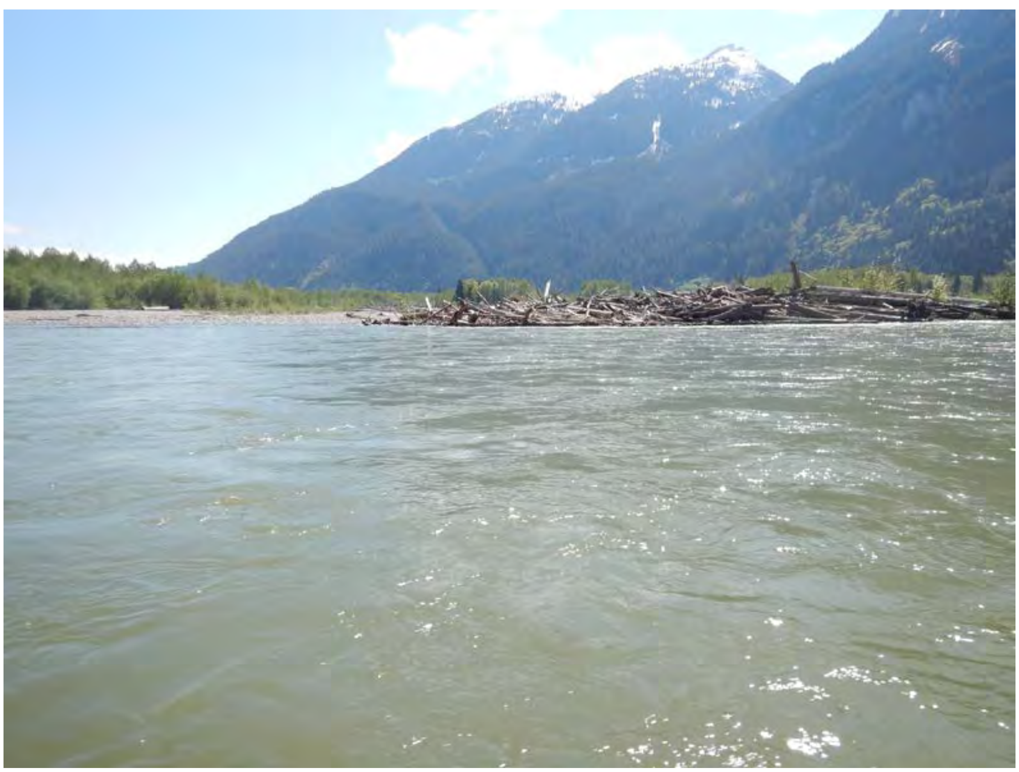

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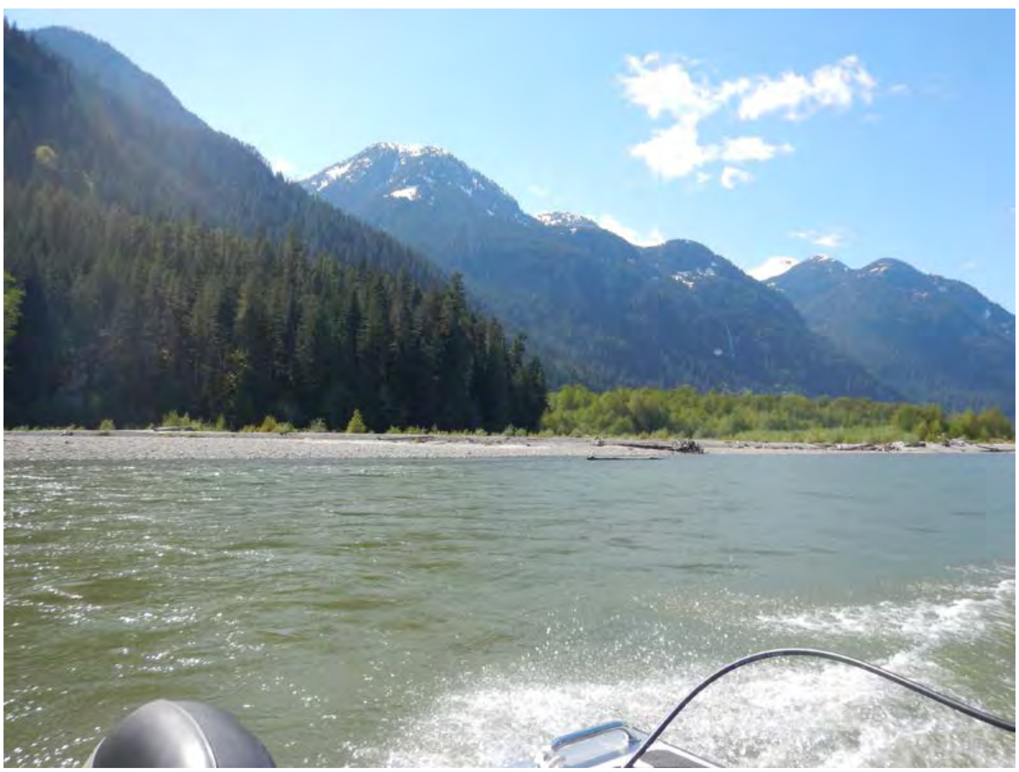

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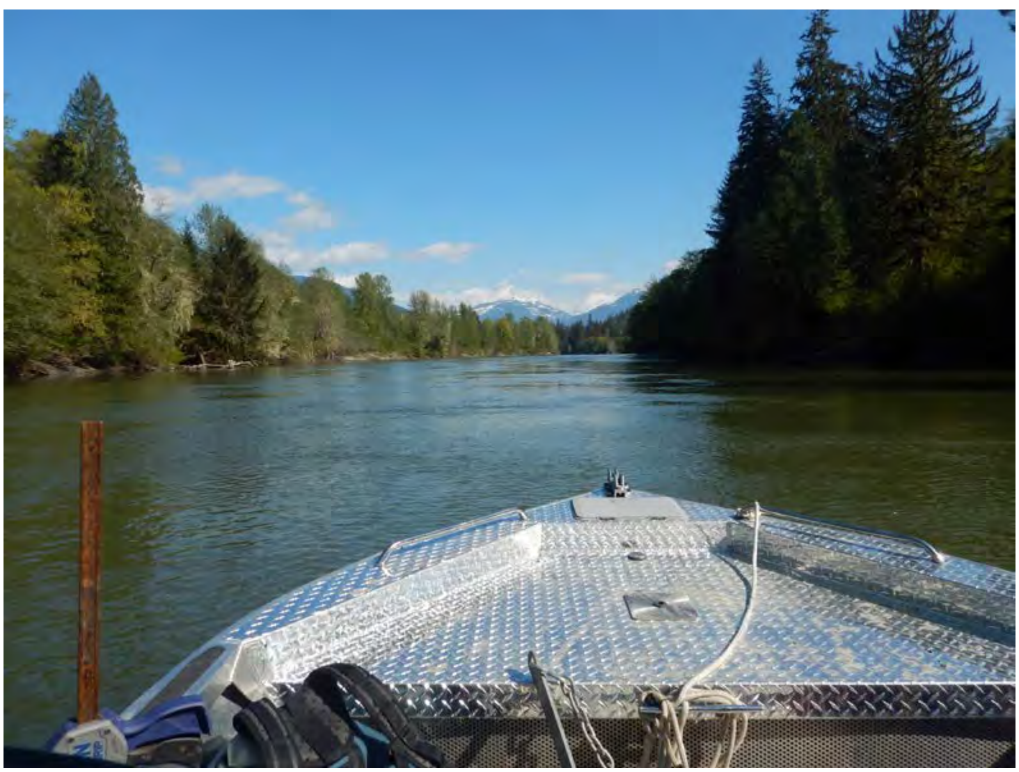

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50-Year through 500-Year Inundation
50-Year Flood Depth
100-Year Flood Depth
200-Year Flood Depth
500-Year Flood Depth
Flood Construction Level
50-Year Flood Hazard
200-Year Flood Hazard

General Notes:

1. Please refer to the accompanying SLRD: Flood Hazard Mapping and Risk Assessment - Upper Squamish Report (Issued on September 7, 2018) for important information concerning these maps.
2. Within the flood inundation areas shown on this map, there may be isolated pockets of high ground. To determine whether or not a particular site is subject to flooding, reference should be made to the computed flood levels in conjunction with site-specific surveys where detailed definition is required.
3. Non-riverine and local sources of water have not been considered, and structures such as roads, railways or barriers such as levees can restrict water flow and affect local flood levels. Channel obstruction, local storm inflow, groundwater seepage or other land drainage can cause flood levels to exceed those indicated on the map. Lands adjacent to a flooded area may be subject to flooding from tributary streams not indicated on the maps.
4. Line work for bridges and flood control structures is shown above flood inundation areas, in cases where bridges or flood control structures are inundated.

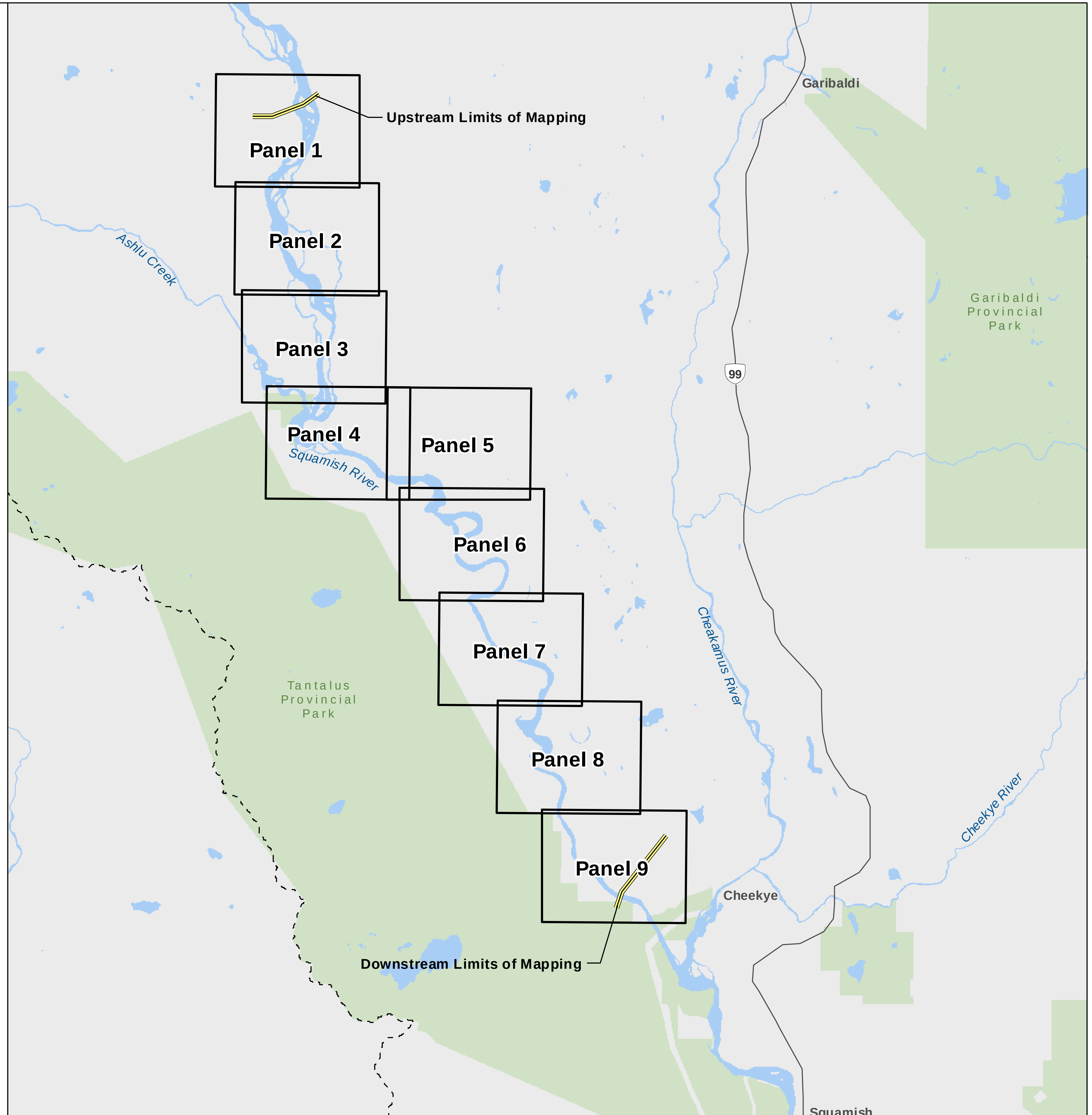
Definitions:

Flood Inundation Mapping - Delineates flood inundation areas, showing the extent of one or more flood scenarios under existing conditions. Depending on the particular flood scenario, the mapping may be divided into multiple zones. Flood inundation mapping is typically used for near real-time emergency response planning and operations.
Flood Inundation Area - The area inundated during a particular flood scenario under existing conditions. The flood inundation area may be divided into multiple zones, including areas inundated due to potential flood control structure failure and isolated areas that may become inundated due to groundwater seepage or other subsurface connections. Flood inundation areas may change as a result of future development or flow obstructions.
Flood Scenario - Water level conditions that describe a particular flood event. Flood scenario conditions represent discharge that produce water levels for a selected return period. The flood scenarios included with this map set include the 2-year, 200-year, and 500-year flood events.

Data Sources and References:

1. Channel imagery acquired by EMBC in 2016.
2. Valley wall imagery from ESRI 2013.

Horizontal Datum: NAD 1983 UTM ZONE 10N
Vertical Datum: CGVD 2013
Units: Metres



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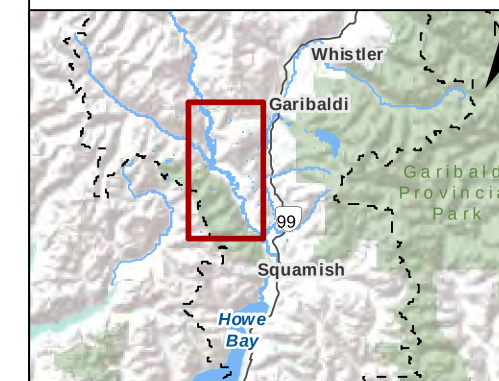

Legend

Map Panel
Squamish-Lillooet Regional District Boundary
Limits of Mapping

SCALE - 1:100,000
0 1,000 2,000 4,000 Metres
N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

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SQUAMISH RIVER
FLOOD HAZARD MAPPING

Index Map

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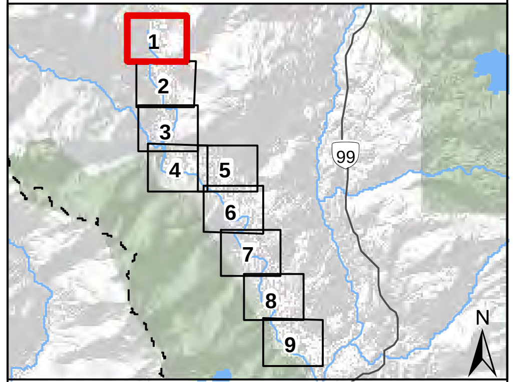

Legend

- River Km
- Road
- Limits of Mapping
- Tributary
- Tributary Creek Fans
- Modern Valley Bottom
- Highest Hazard Zone

2013 imagery from ESRI

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

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SQUAMISH RIVER
FLOOD HAZARD MAPPING

Geomorphic Hazards

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PANEL 1 OF 9

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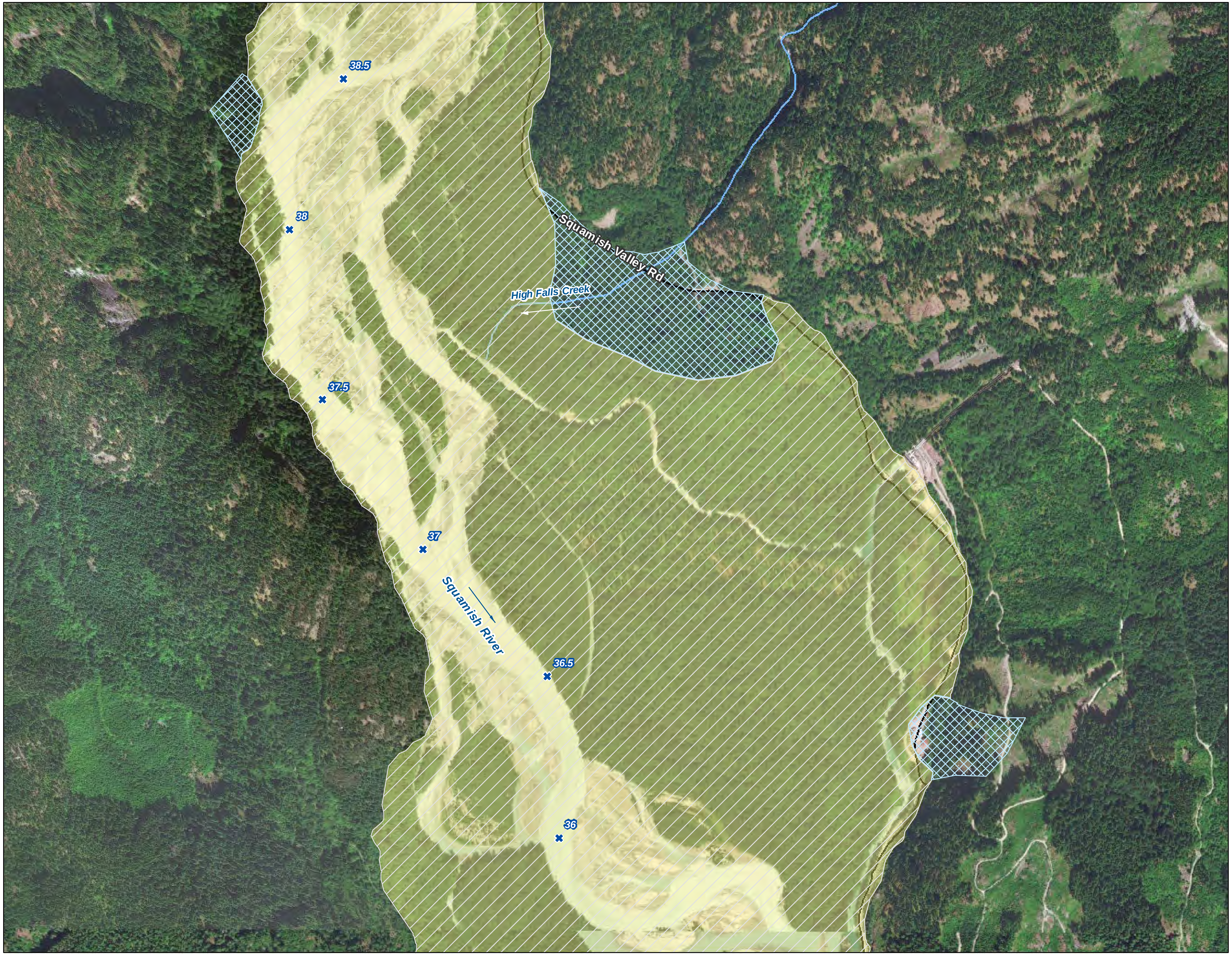

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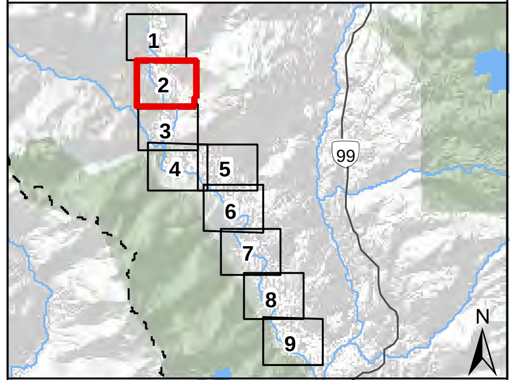

Legend

- River Km
- Road
- Limits of Mapping
- Tributary
- Tributary Creek Fans
- Modern Valley Bottom
- Highest Hazard Zone

2013 imagery from ESRI

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

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SQUAMISH RIVER
FLOOD HAZARD MAPPING

Geomorphic Hazards

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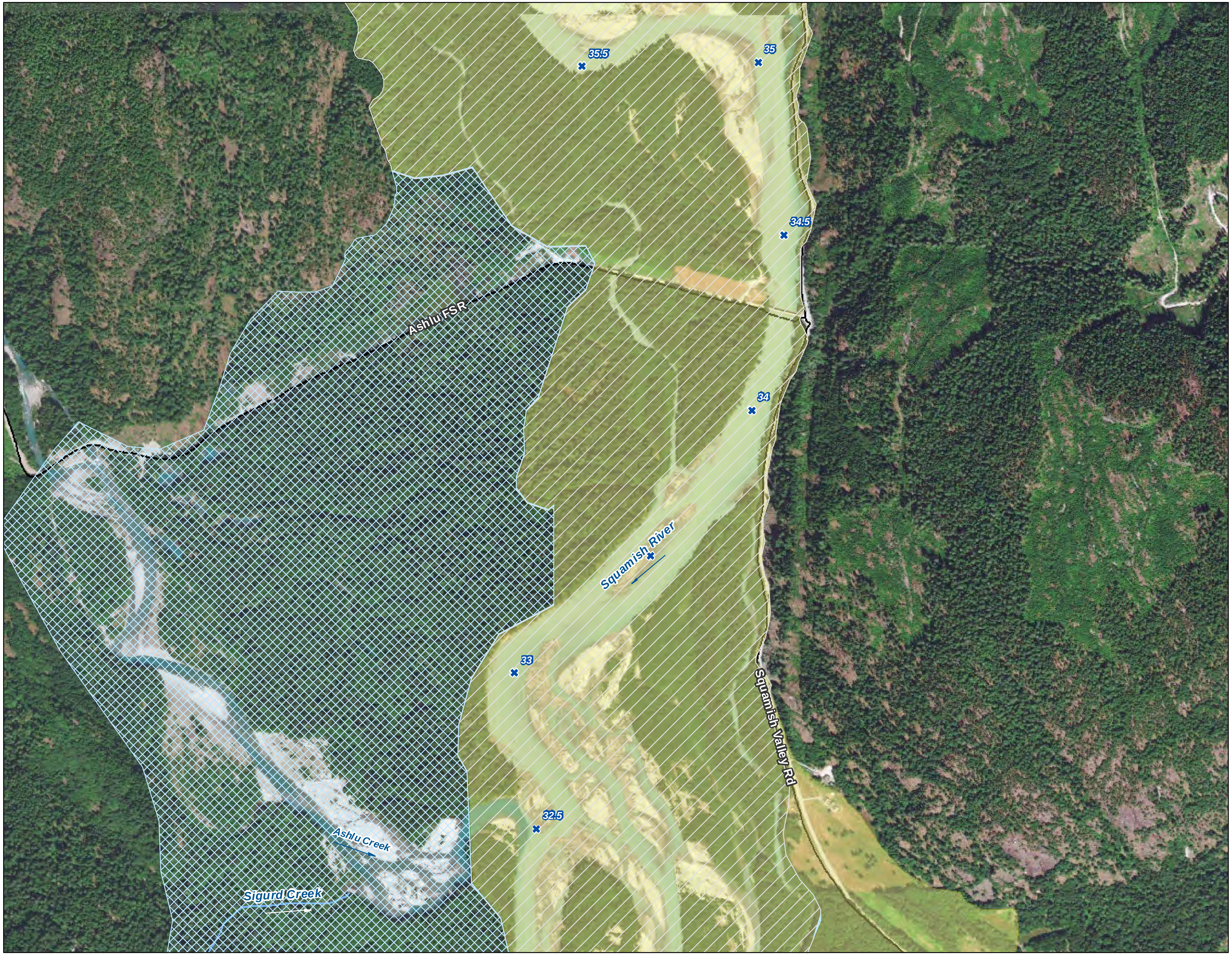

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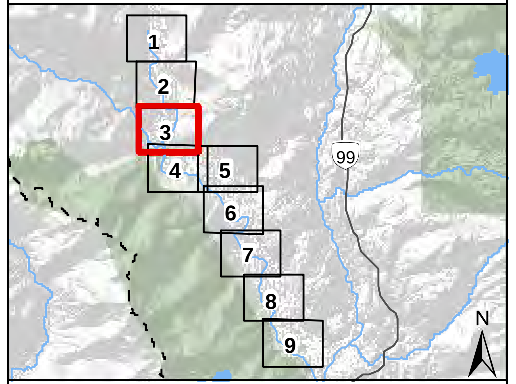

Legend

- River Km
- Road
- Limits of Mapping
- Tributary
- Tributary Creek Fans
- Modern Valley Bottom
- Highest Hazard Zone

2013 imagery from ESRI

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

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SQUAMISH RIVER
FLOOD HAZARD MAPPING

Geomorphic Hazards

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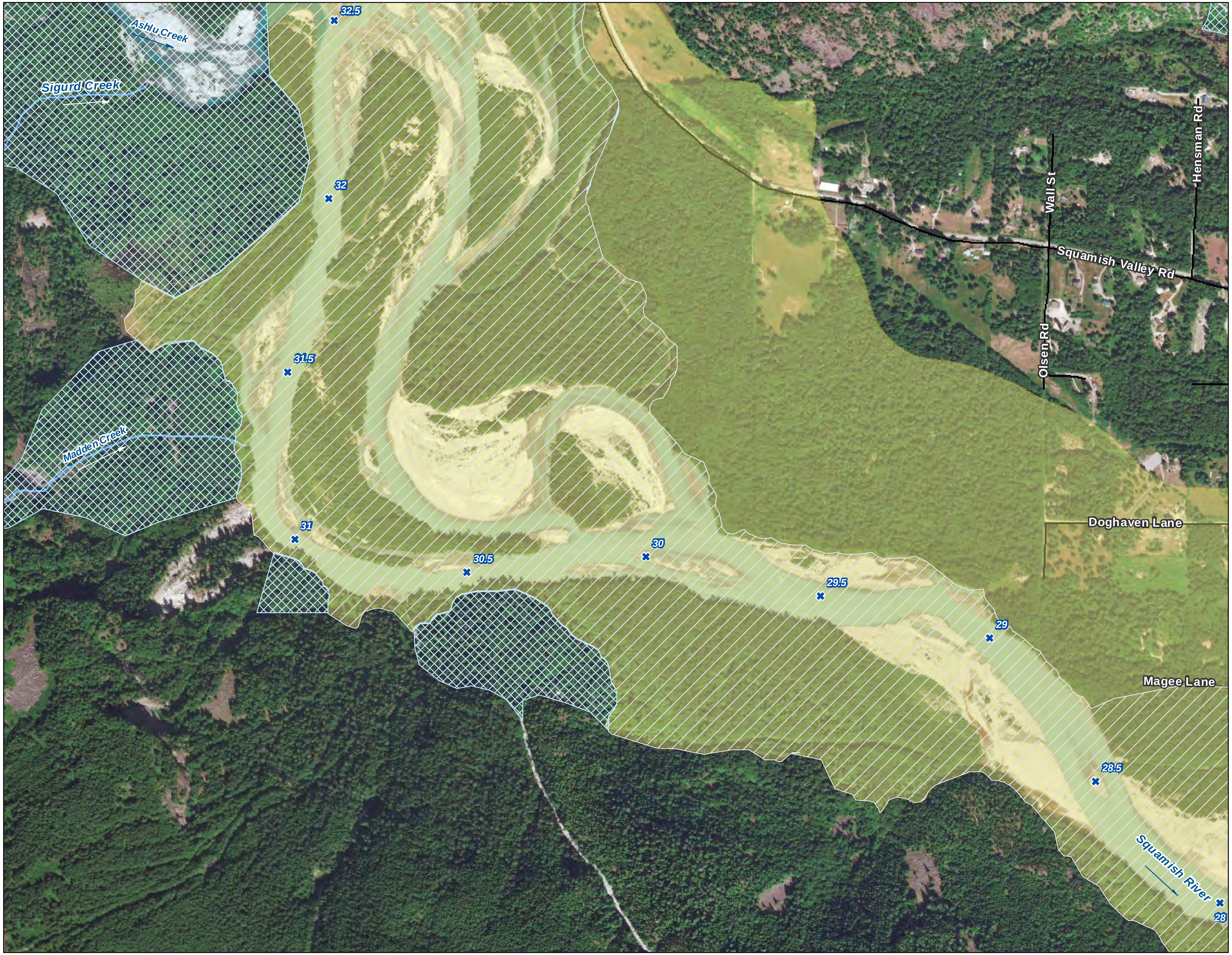

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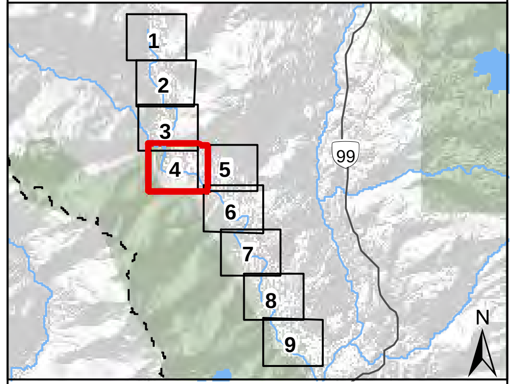

Legend

- River Km
- Road
- Limits of Mapping
- Tributary
- Tributary Creek Fans
- Modern Valley Bottom
- Highest Hazard Zone

2013 imagery from ESRI

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

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SQUAMISH RIVER
FLOOD HAZARD MAPPING

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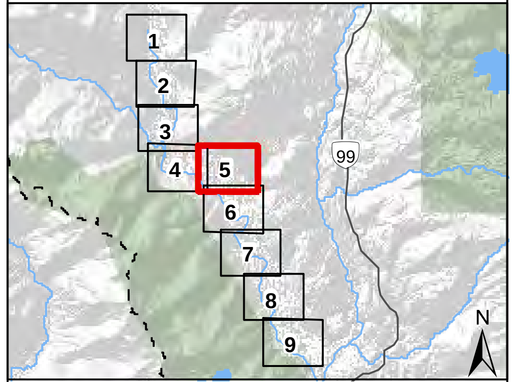

Legend

- River Km
- Road
- Limits of Mapping
- Tributary
- Tributary Creek Fans
- Modern Valley Bottom
- Highest Hazard Zone

2013 imagery from ESRI

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
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Geomorphic Hazards

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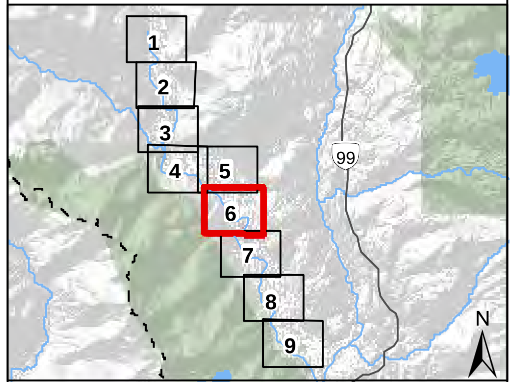

Legend

- River Km
- Road
- Limits of Mapping
- Tributary
- Tributary Creek Fans
- Modern Valley Bottom
- Highest Hazard Zone

2013 imagery from ESRI

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

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SQUAMISH RIVER
FLOOD HAZARD MAPPING

Geomorphic Hazards

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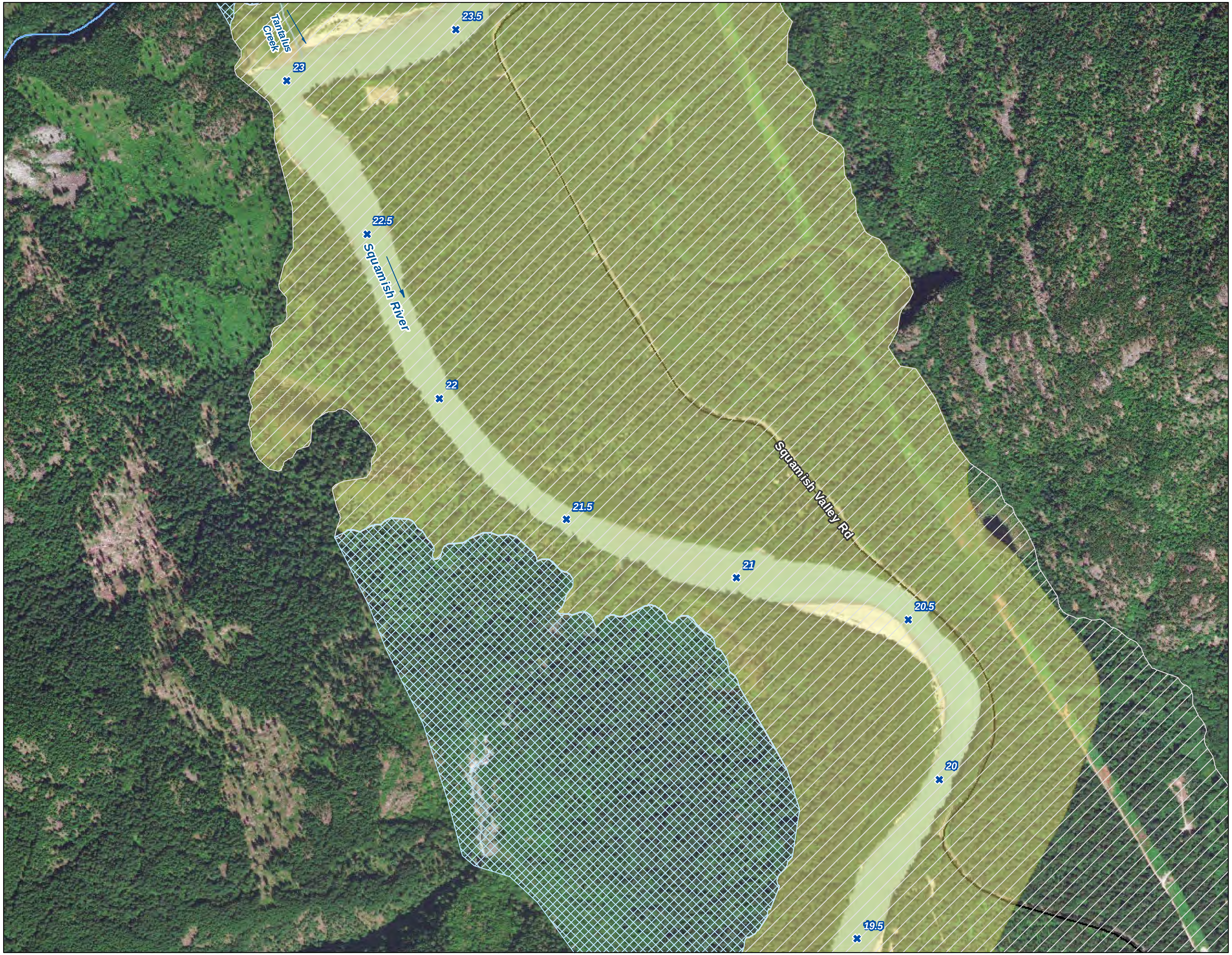

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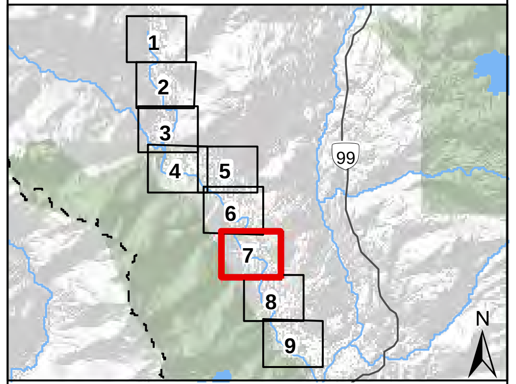

Legend

- River Km
- Road
- Limits of Mapping
- Tributary
- Tributary Creek Fans
- Modern Valley Bottom
- Highest Hazard Zone

2013 imagery from ESRI

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

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SQUAMISH RIVER
FLOOD HAZARD MAPPING

Geomorphic Hazards

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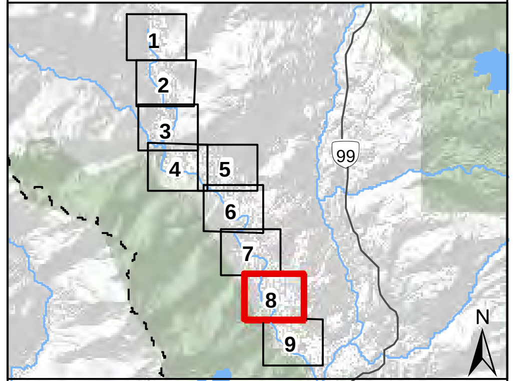

Legend

- River Km
- Road
- Limits of Mapping
- Tributary
- Tributary Creek Fans
- Modern Valley Bottom
- Highest Hazard Zone

2013 imagery from ESRI

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

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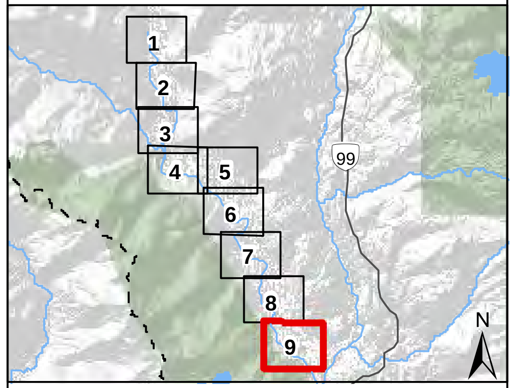

Legend

- River Km
- Road
- Limits of Mapping
- Tributary
- Tributary Creek Fans
- Modern Valley Bottom
- Highest Hazard Zone

2013 imagery from ESRI

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

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THB	MAO	THB

Job Number	Date
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SQUAMISH RIVER
FLOOD HAZARD MAPPING

Geomorphic Hazards

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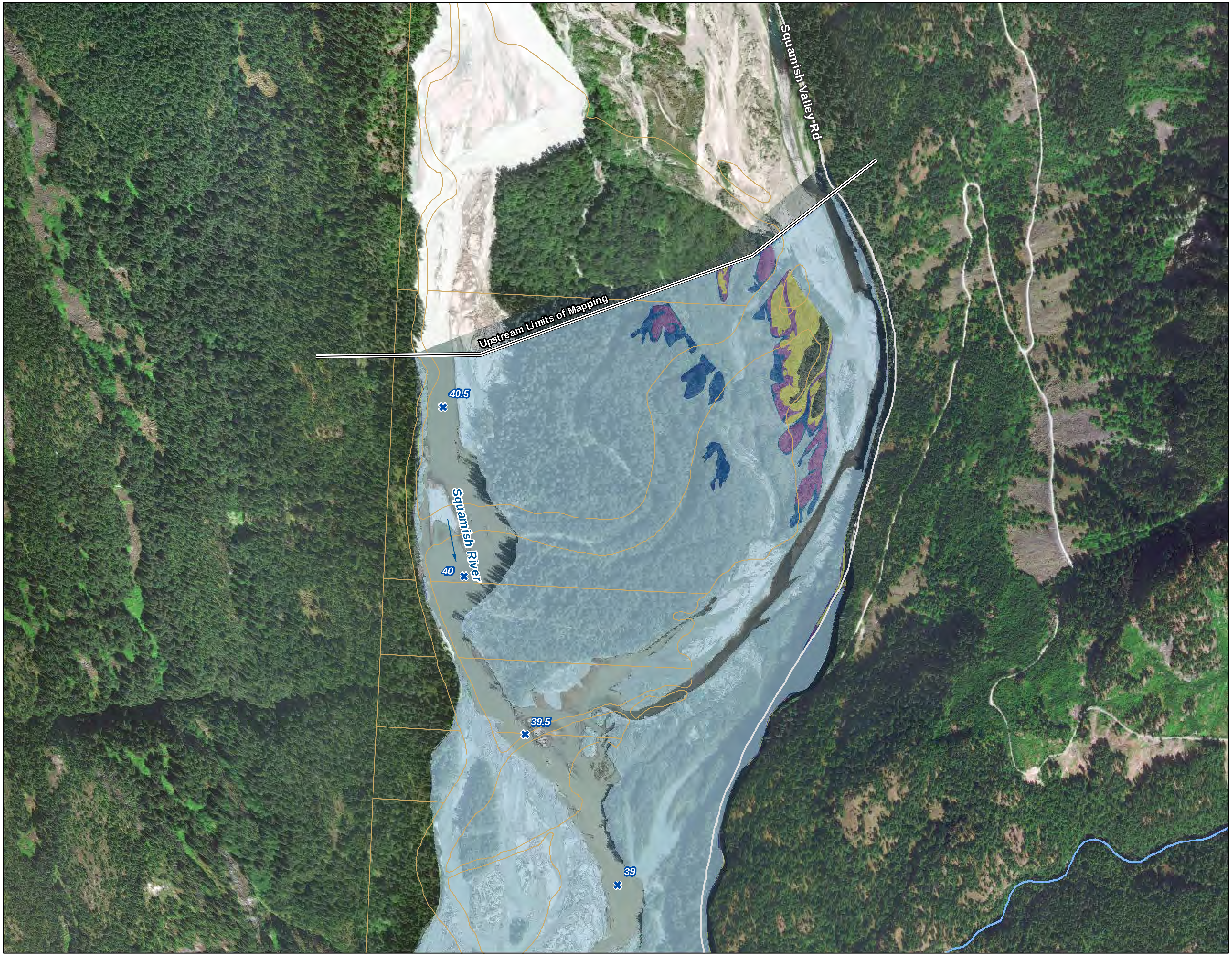

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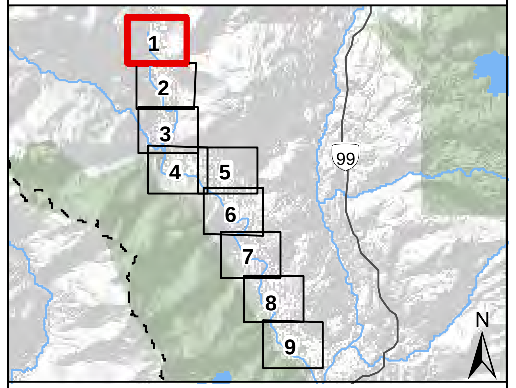

Legend

- River Km
- Critical Structure or Notable Public Feature
- Limits of Mapping
- Tributary
- Road
- Parcel Boundaries (2017)
- 50-Year Flood Inundation Extents
- 100-Year Flood Inundation Extents
- 200-Year Flood Inundation Extents
- 500-Year Flood Inundation Extents

2016 imagery in channel with 2013 valley wall imagery from ESRI

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

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THB	MAO	THB

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SQUAMISH RIVER
FLOOD HAZARD MAPPING
50-Year Through
500-Year Inundation

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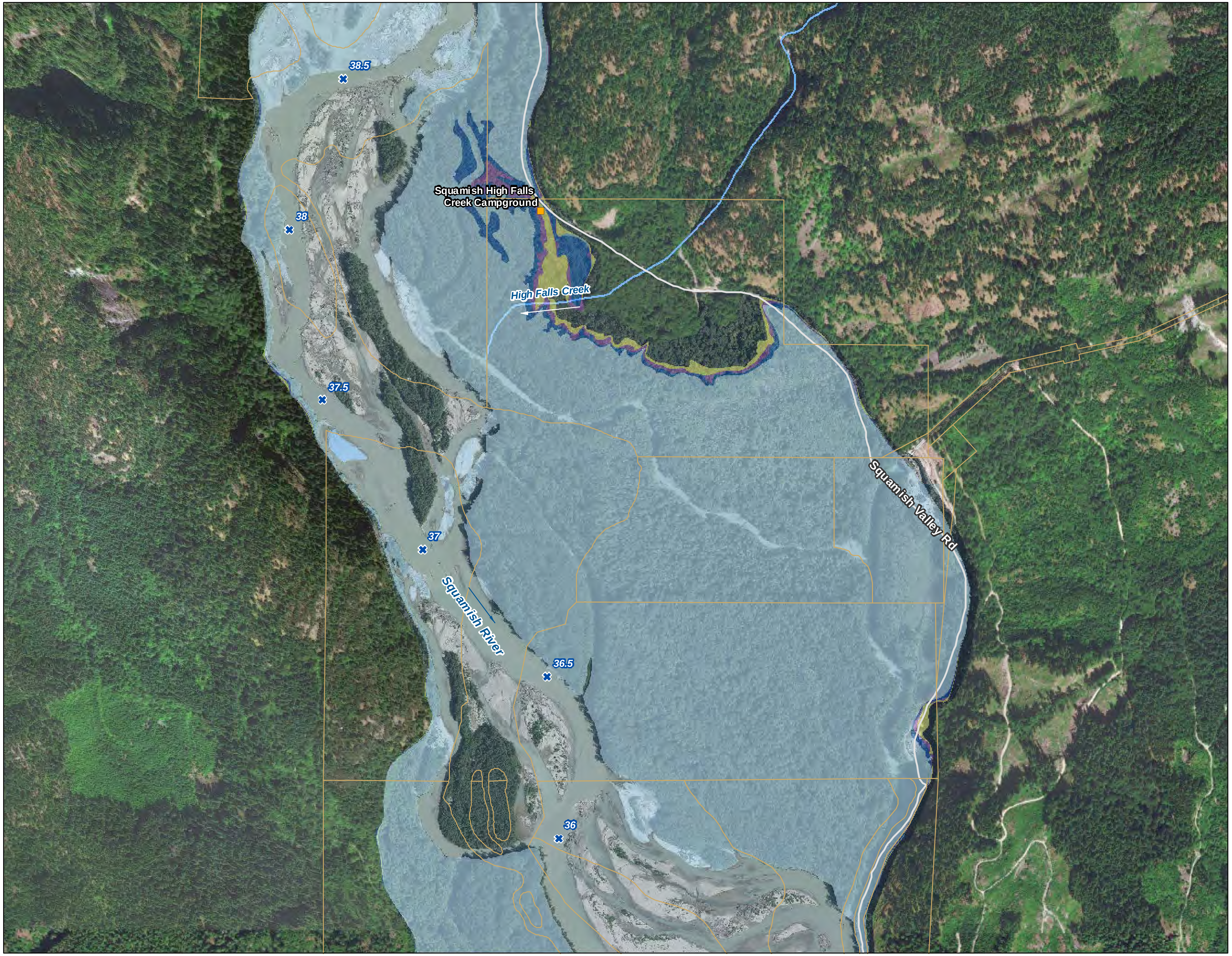

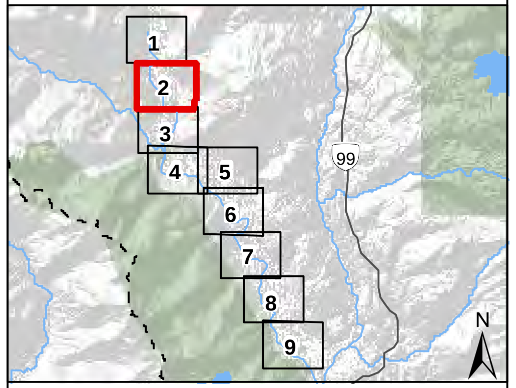

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Legend

- River Km
- Critical Structure or Notable Public Feature
- Limits of Mapping
- Tributary
- Road
- Parcel Boundaries (2017)
- 50-Year Flood Inundation Extents
- 100-Year Flood Inundation Extents
- 200-Year Flood Inundation Extents
- 500-Year Flood Inundation Extents

2016 imagery in channel with 2013 valley wall imagery from ESRI

SCALE - 1:10,000

0 100 200 400 *Metres*

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	*GIS*	*Reviewer*
THB	*MAO*	*THB*

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SQUAMISH RIVER
FLOOD HAZARD MAPPING
50-Year Through
500-Year Inundation

DRAFT

PANEL 2 OF 9

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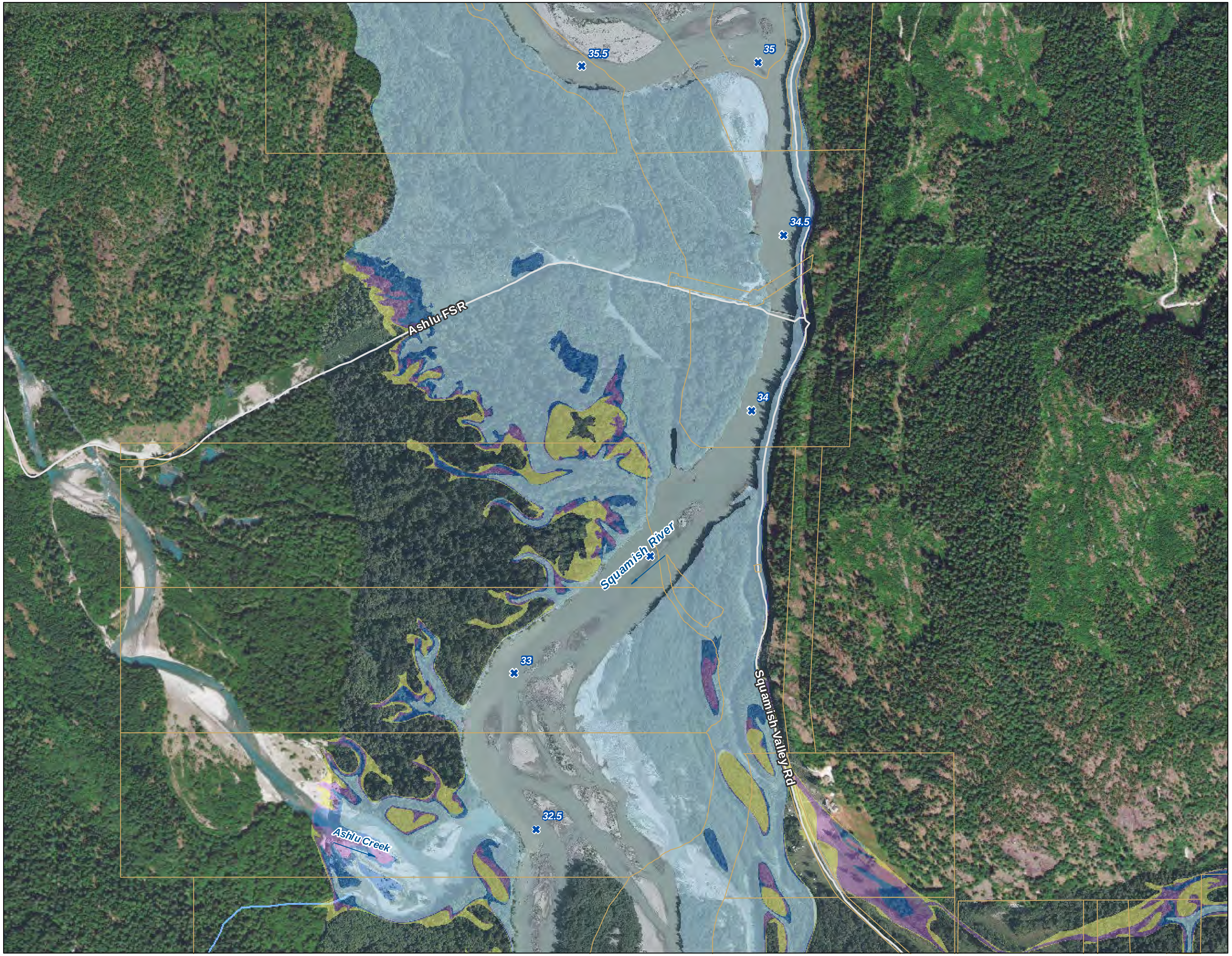

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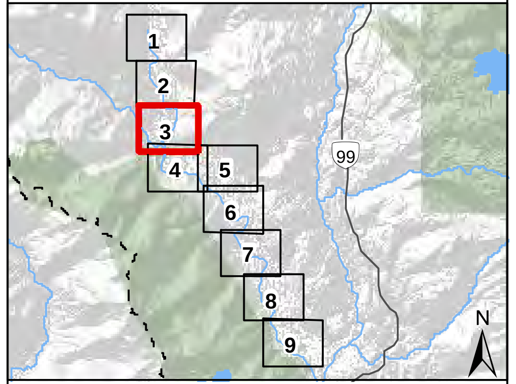

Legend

- River Km
- Critical Structure or Notable Public Feature
- Limits of Mapping
- Tributary
- Road
- Parcel Boundaries (2017)
- 50-Year Flood Inundation Extents
- 100-Year Flood Inundation Extents
- 200-Year Flood Inundation Extents
- 500-Year Flood Inundation Extents

2016 imagery in channel with 2013 valley wall imagery from ESRI

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

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SQUAMISH RIVER
FLOOD HAZARD MAPPING
50-Year Through 500-Year Inundation

DRAFT

PANEL 3 OF 9

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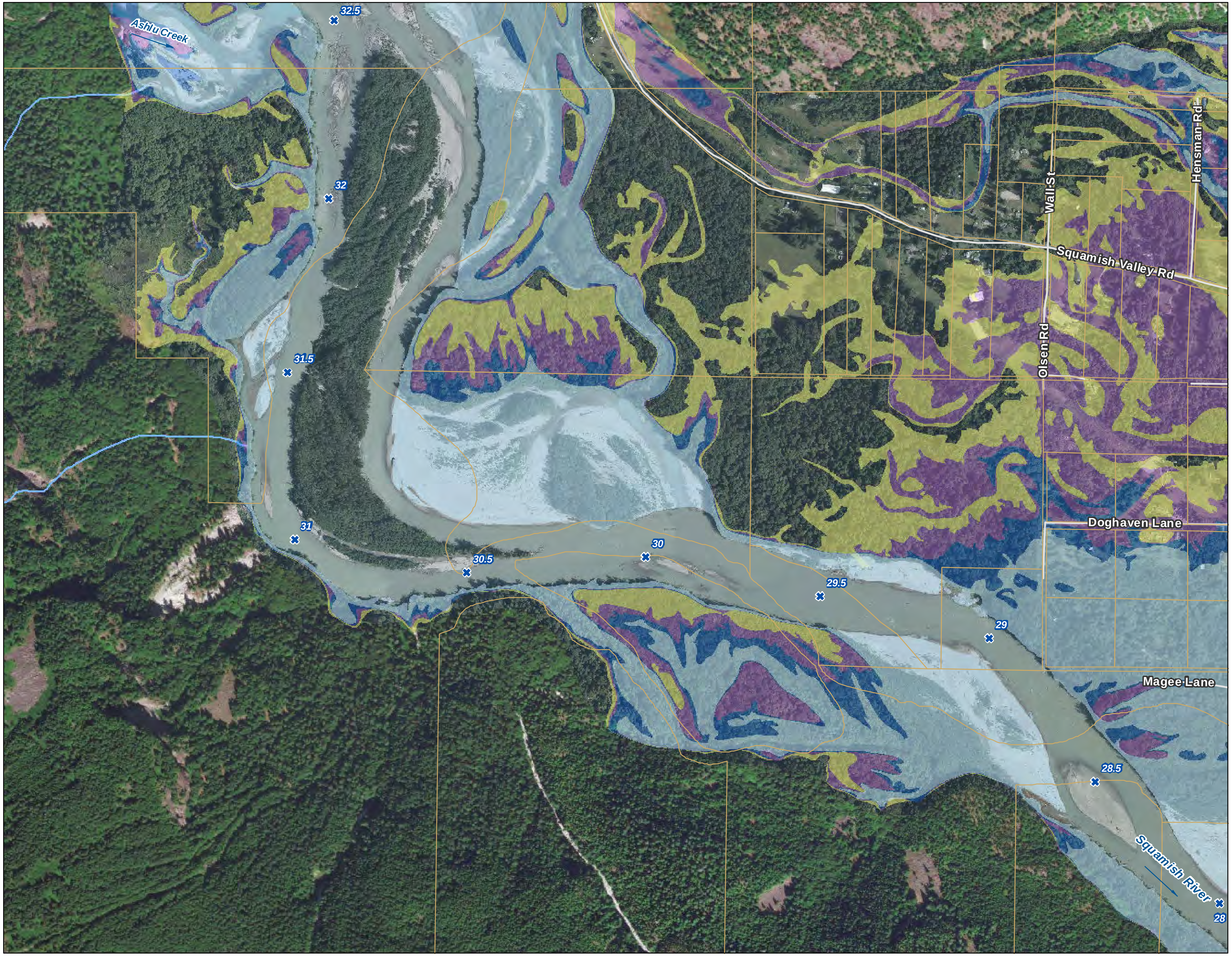

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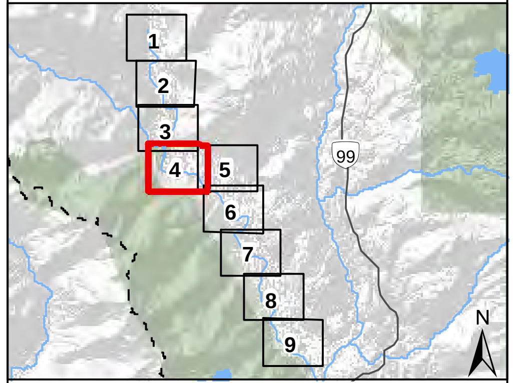

Legend

- River Km
- Critical Structure or Notable Public Feature
- Limits of Mapping
- Tributary
- Road
- Parcel Boundaries (2017)
- 50-Year Flood Inundation Extents
- 100-Year Flood Inundation Extents
- 200-Year Flood Inundation Extents
- 500-Year Flood Inundation Extents

2016 imagery in channel with 2013 valley wall imagery from ESRI

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

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SQUAMISH RIVER
FLOOD HAZARD MAPPING
50-Year Through 500-Year Inundation

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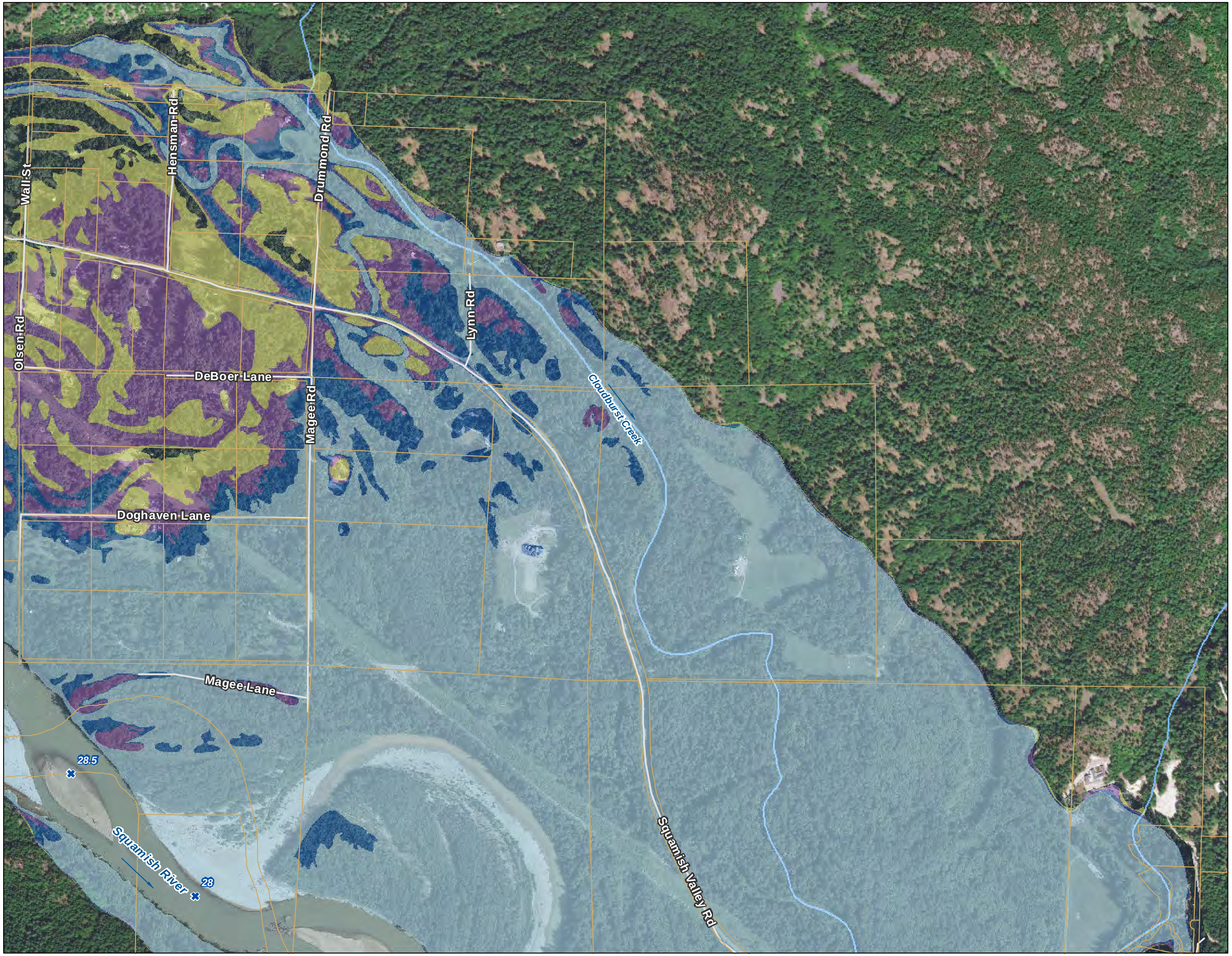
PANEL 4 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_InundationMapBook_20181125.mxd



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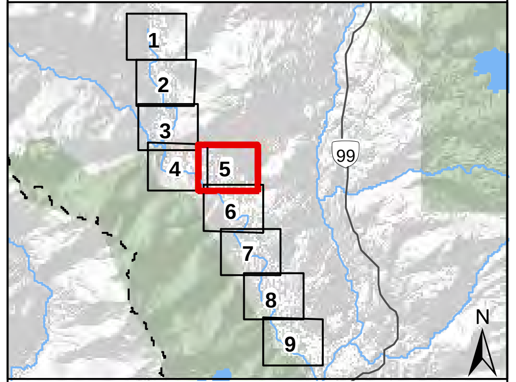

Legend

- River Km
- Critical Structure or Notable Public Feature
- Limits of Mapping
- Tributary
- Road
- Parcel Boundaries (2017)
- 50-Year Flood Inundation Extents
- 100-Year Flood Inundation Extents
- 200-Year Flood Inundation Extents
- 500-Year Flood Inundation Extents

2016 imagery in channel with 2013 valley wall imagery from ESRI

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

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SQUAMISH RIVER
FLOOD HAZARD MAPPING
50-Year Through
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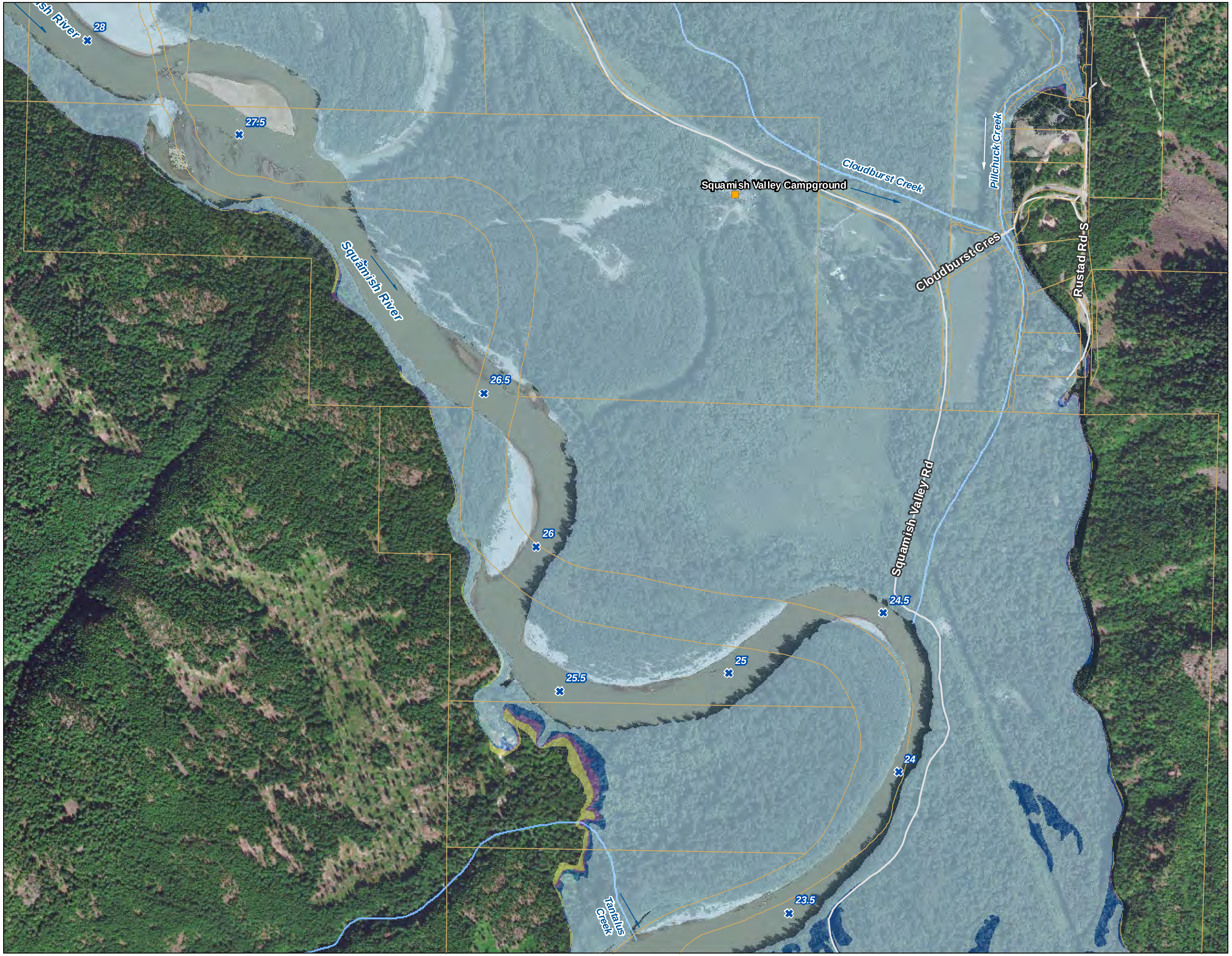
PANEL 5 OF 9

MAO; Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_InundationMapBook_20181125.mxd



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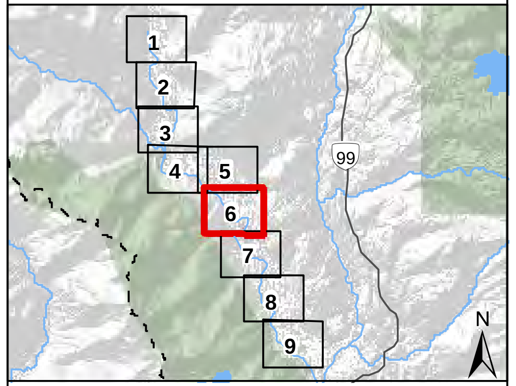

Legend

- River Km
- Critical Structure or Notable Public Feature
- Limits of Mapping
- Tributary
- Road
- Parcel Boundaries (2017)
- 50-Year Flood Inundation Extents
- 100-Year Flood Inundation Extents
- 200-Year Flood Inundation Extents
- 500-Year Flood Inundation Extents

2016 imagery in channel with 2013 valley wall imagery from ESRI

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

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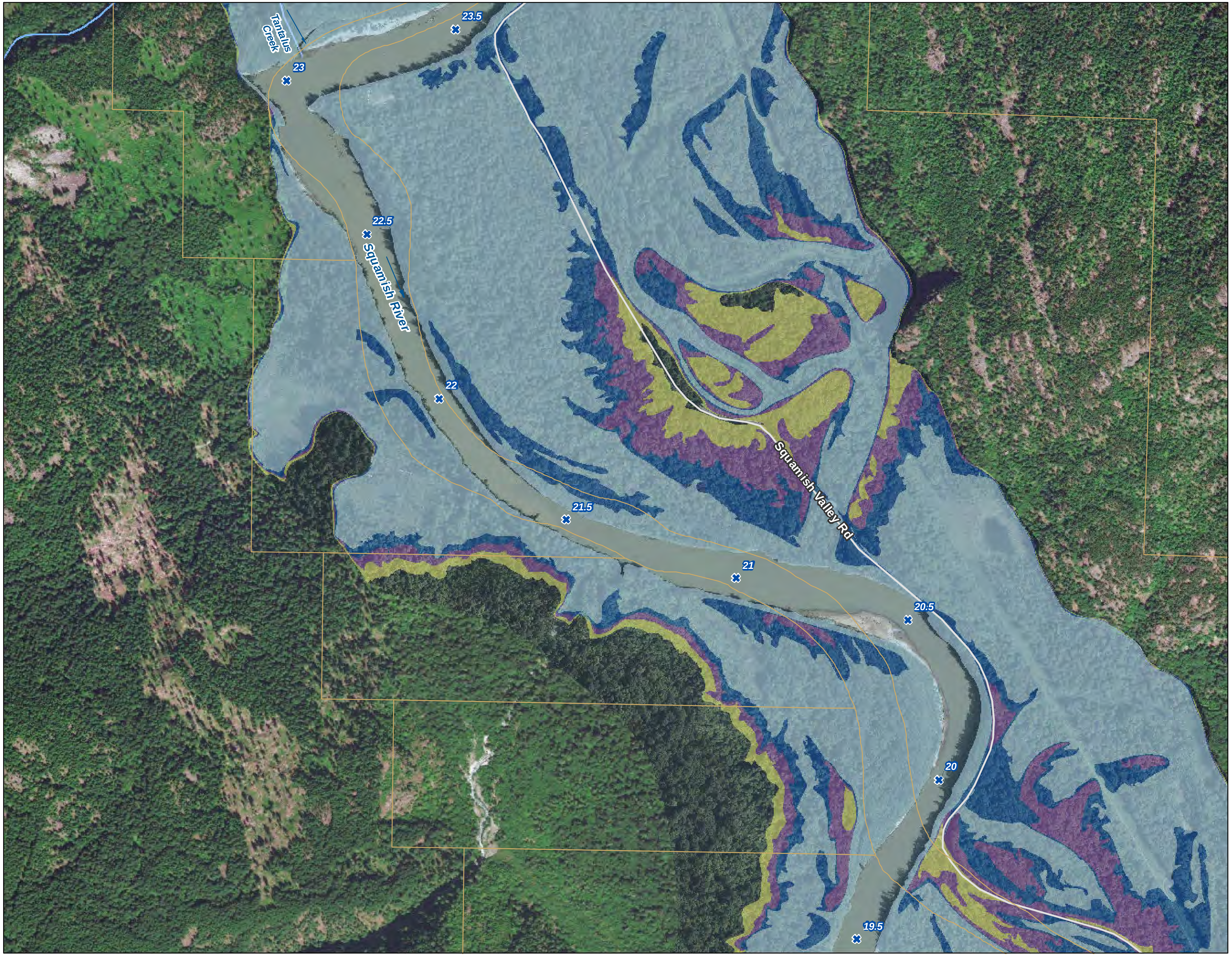
SQUAMISH RIVER
FLOOD HAZARD MAPPING
50-Year Through
500-Year Inundation

DRAFT

PANEL 6 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_InundationMapBook_20181125.mxd



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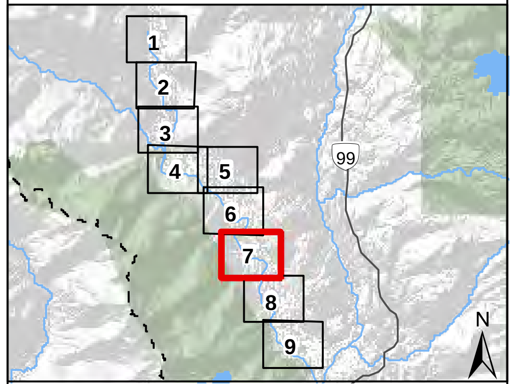

Legend

- River Km
- Critical Structure or Notable Public Feature
- Limits of Mapping
- Tributary
- Road
- Parcel Boundaries (2017)
- 50-Year Flood Inundation Extents
- 100-Year Flood Inundation Extents
- 200-Year Flood Inundation Extents
- 500-Year Flood Inundation Extents

2016 imagery in channel with 2013 valley wall imagery from ESRI

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

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SQUAMISH RIVER
FLOOD HAZARD MAPPING
50-Year Through
500-Year Inundation

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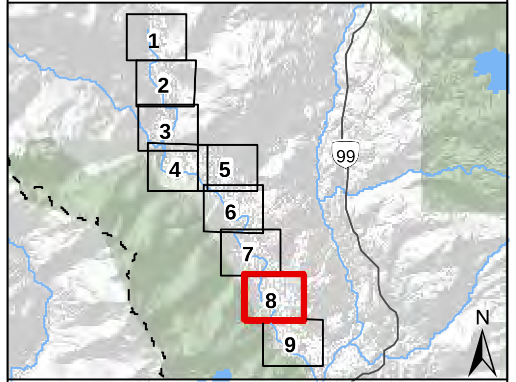


Legend

- River Km
- Critical Structure or Notable Public Feature
- Limits of Mapping
- Tributary
- Road
- Parcel Boundaries (2017)
- 50-Year Flood Inundation Extents
- 100-Year Flood Inundation Extents
- 200-Year Flood Inundation Extents
- 500-Year Flood Inundation Extents

2016 imagery in channel with 2013 valley wall imagery from ESRI

SCALE - 1:10,000

0 100 200 400 *Metres*

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	GIS	Reviewer
THB	*MAO*	*THB*

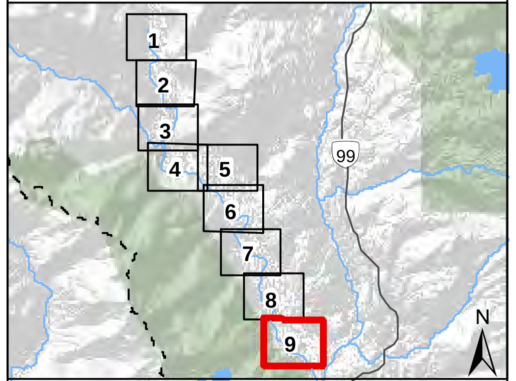
Job Number	Date
3003329	*26-NOV-2018*

SQUAMISH RIVER
FLOOD HAZARD MAPPING
50-Year Through
500-Year Inundation

DRAFT

Squamish - Lillooet
REGIONAL DISTRICT

nhc
northwest hydraulic consultants



Legend

- River Km
- Critical Structure or Notable Public Feature
- Limits of Mapping
- Tributary
- Road
- Parcel Boundaries (2017)
- 50-Year Flood Inundation Extents
- 100-Year Flood Inundation Extents
- 200-Year Flood Inundation Extents
- 500-Year Flood Inundation Extents

2016 imagery in channel with 2013 valley wall imagery from ESRI

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	GIS	Reviewer
THB	MAO	THB

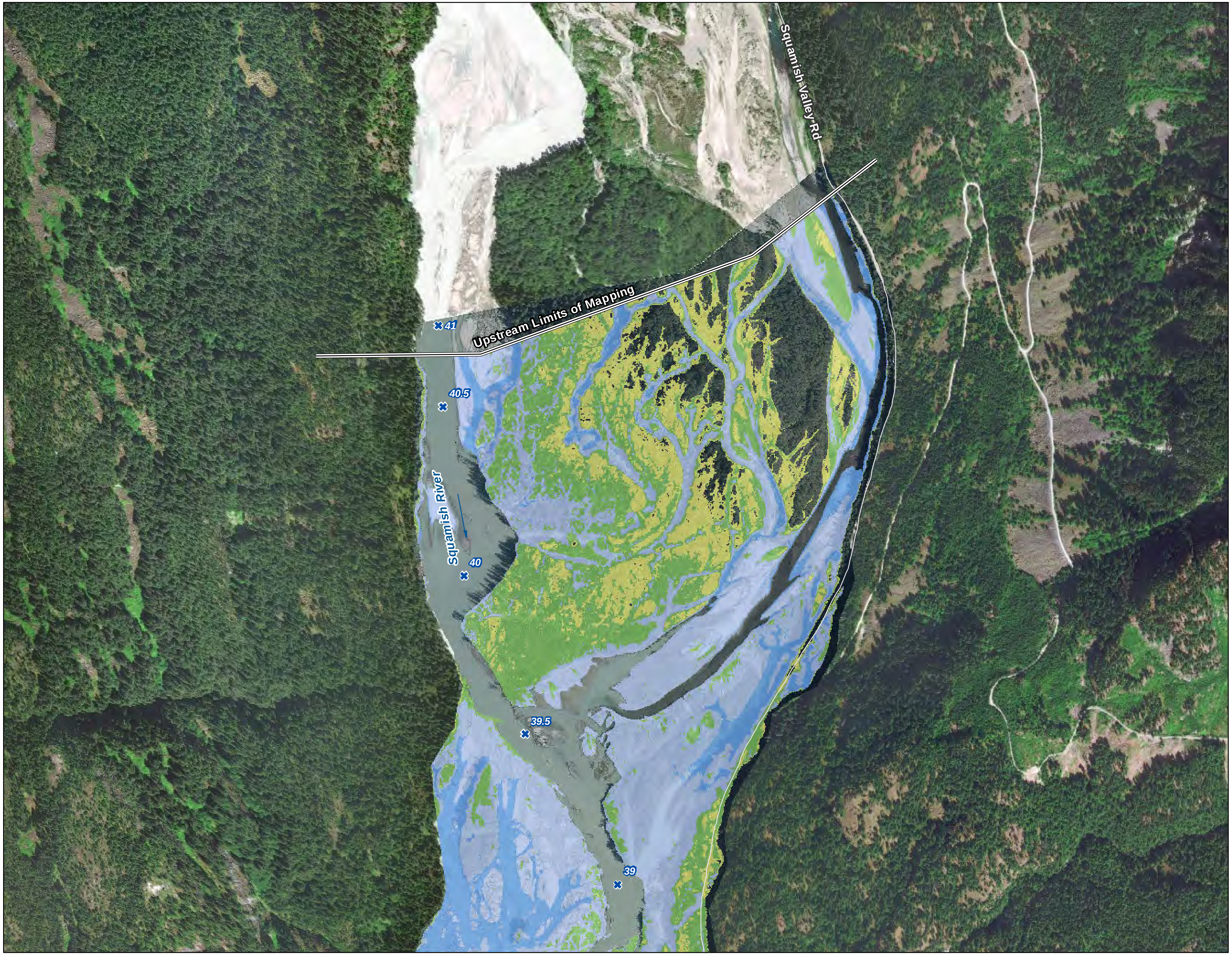
Job Number	Date
3003329	26-NOV-2018

SQUAMISH RIVER
FLOOD HAZARD MAPPING
50-Year Through
500-Year Inundation

DRAFT

PANEL 9 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_InundationMapBook_20181125.mxd



Squamish - Lillooet
REGIONAL DISTRICT

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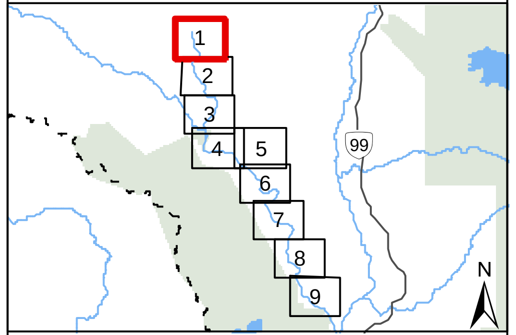
northwest hydraulic consultants



River Km

Road

Limits of Mapping

Depth (m)

0 - 0.5

0.5 - 1.0

1.0 - 2.0

2.0 - 5.0

>5.0

0-0.5m: Most houses are dry; walking in moving water or driving is potentially dangerous; basements and underground parking may be flooded, potentially causing evacuation.

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>5m: First floor and often roof covered by water; residents evacuate.

Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 *Metres*

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	*GIS*	*Reviewer*
THB	*MAO*	*THB*

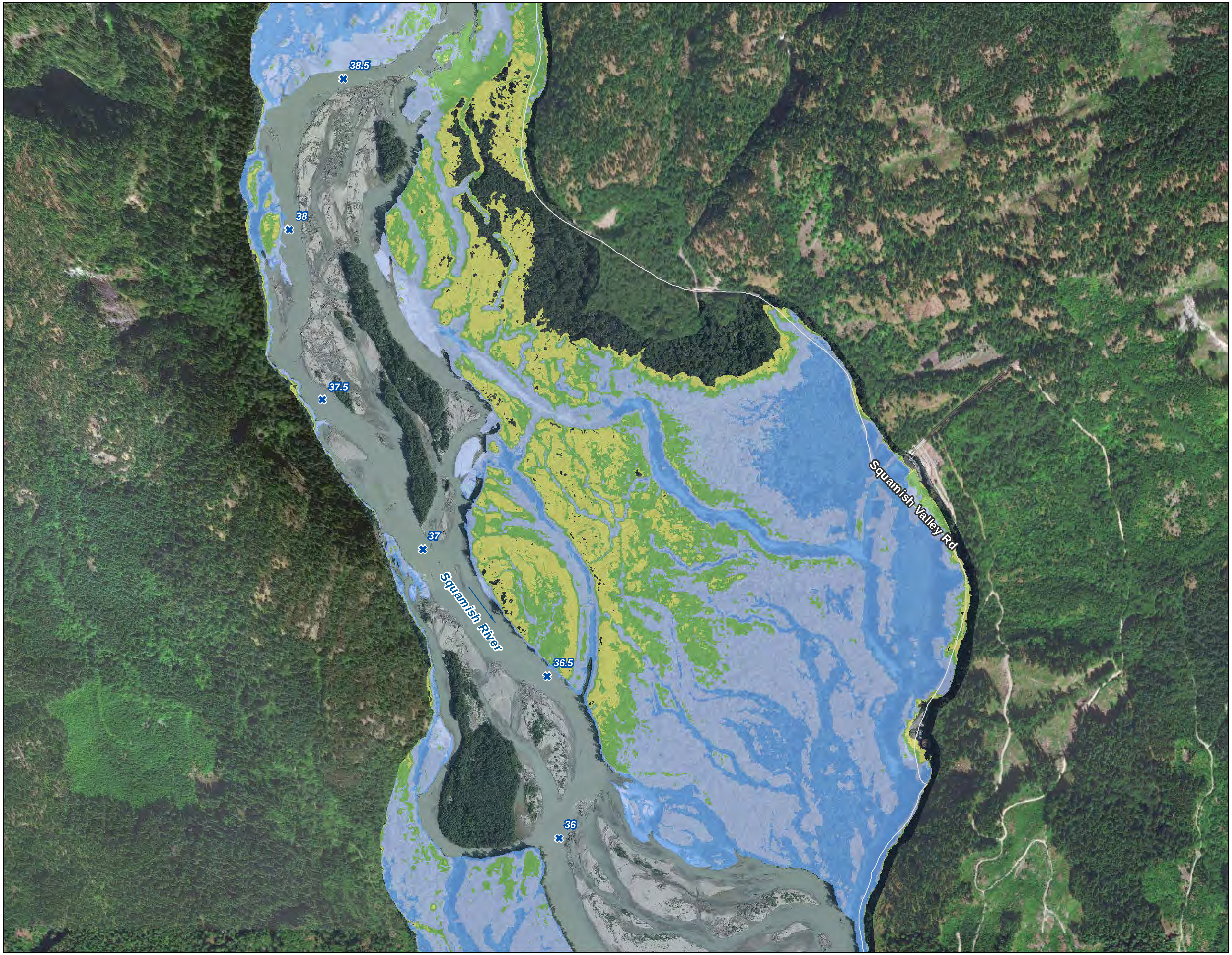
Job Number	*Date*
3003329	*26-NOV-2018*

SQUAMISH FLOOD HAZARD MAPPING

500-Year Flood Depth

SHEET 1 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_DepthMapBook_20181123.mxd



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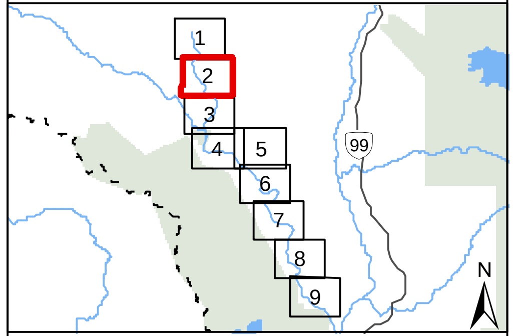

River Km

Road

Limits of Mapping

Depth (m)

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- 0.5 - 1.0
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Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

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Units: METRES

Engineer	GIS	Reviewer
THB	MAO	THB

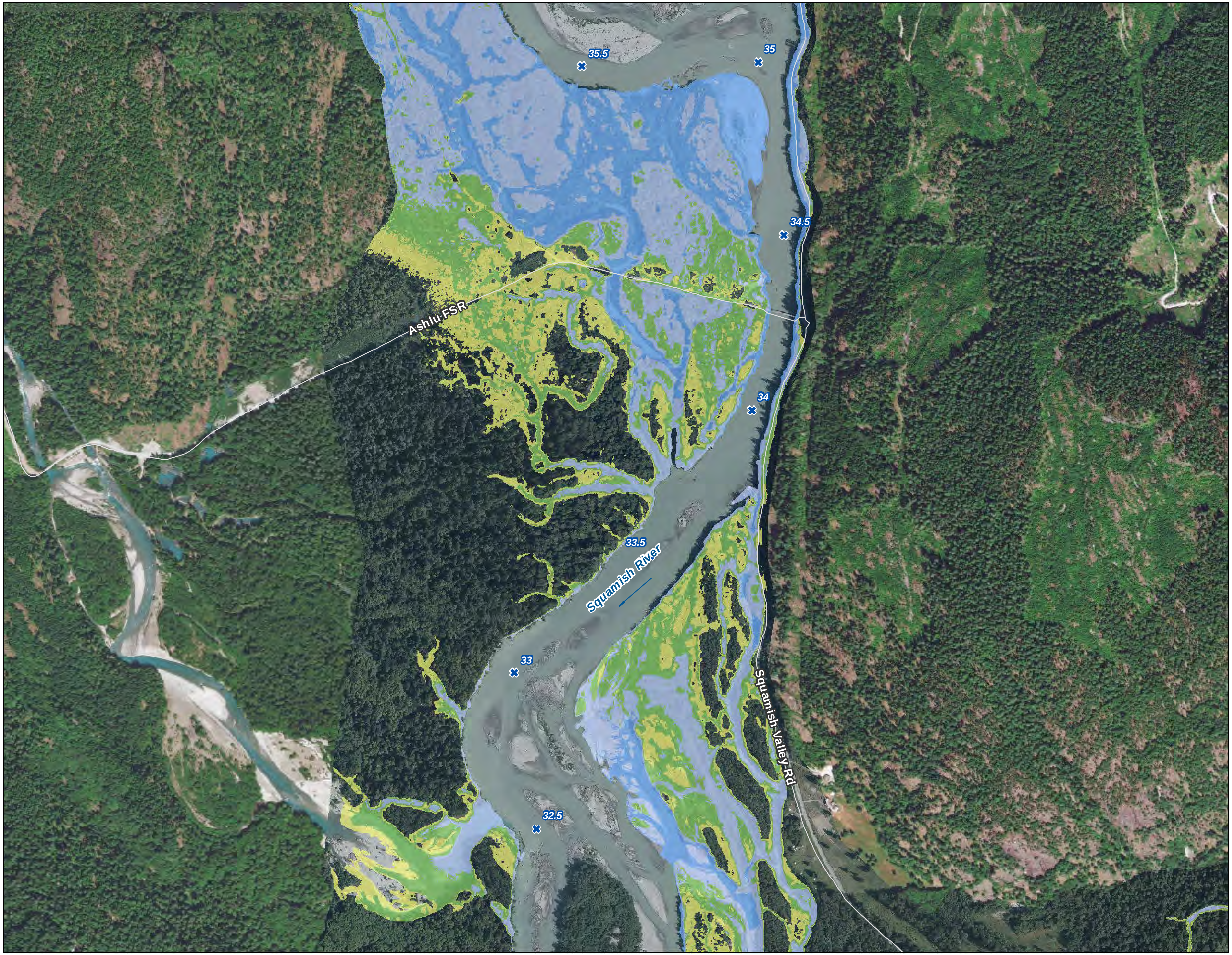
Job Number	Date
3003329	26-NOV-2018

SQUAMISH FLOOD HAZARD MAPPING

500-Year Flood Depth

SHEET 2 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_DepthMapBook_20181123.mxd



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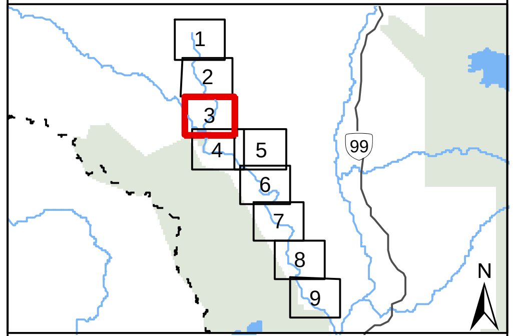

River Km
Road
Limits of Mapping

Depth (m)

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Data Sources: 2016 Orthoimagery

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Engineer	*GIS*	*Reviewer*
THB	*MAO*	*THB*

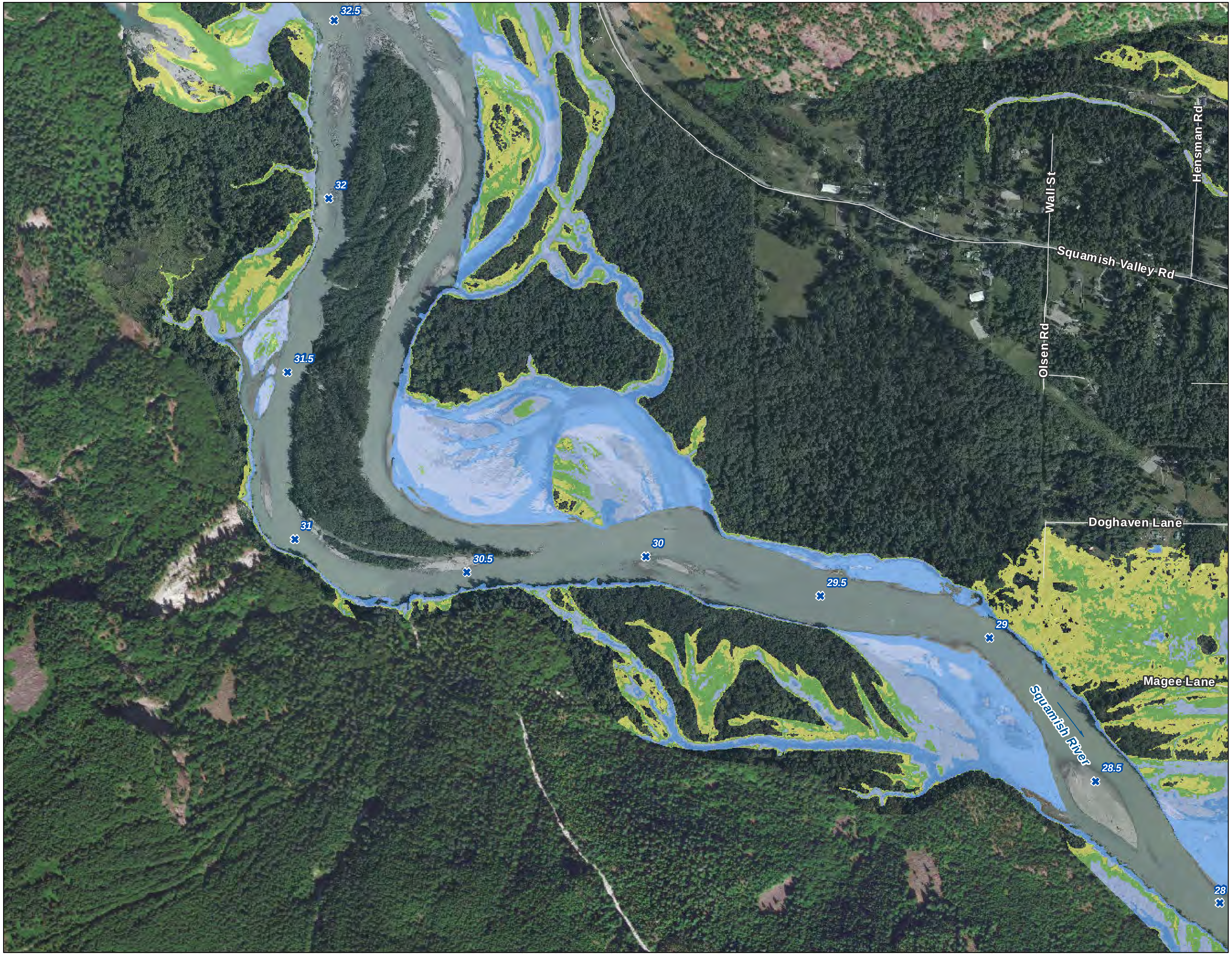
Job Number	*Date*
3003329	*26-NOV-2018*

SQUAMISH FLOOD HAZARD MAPPING

500-Year Flood Depth

SHEET 3 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_DepthMapBook_20181123.mxd



Squamish - Lillooet
REGIONAL DISTRICT

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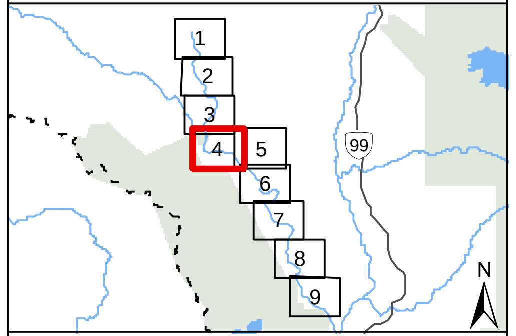

River Km
Road
Limits of Mapping

Depth (m)

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Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000
0 100 200 400 Metres
N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	GIS	Reviewer
THB	MAO	THB

Job Number	Date
3003329	26-NOV-2018

SQUAMISH FLOOD HAZARD MAPPING

500-Year Flood Depth

SHEET 4 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_DepthMapBook_20181123.mxd

Squamish - Lillooet
REGIONAL DISTRICT

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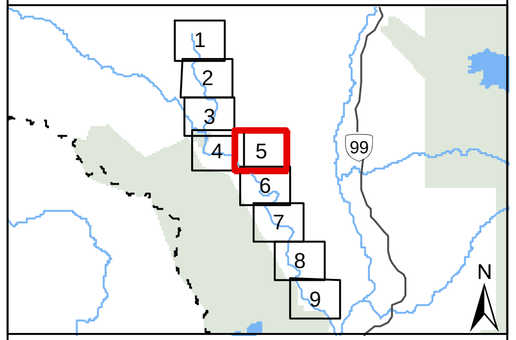

River Km
Road
Limits of Mapping

Depth (m)

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Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

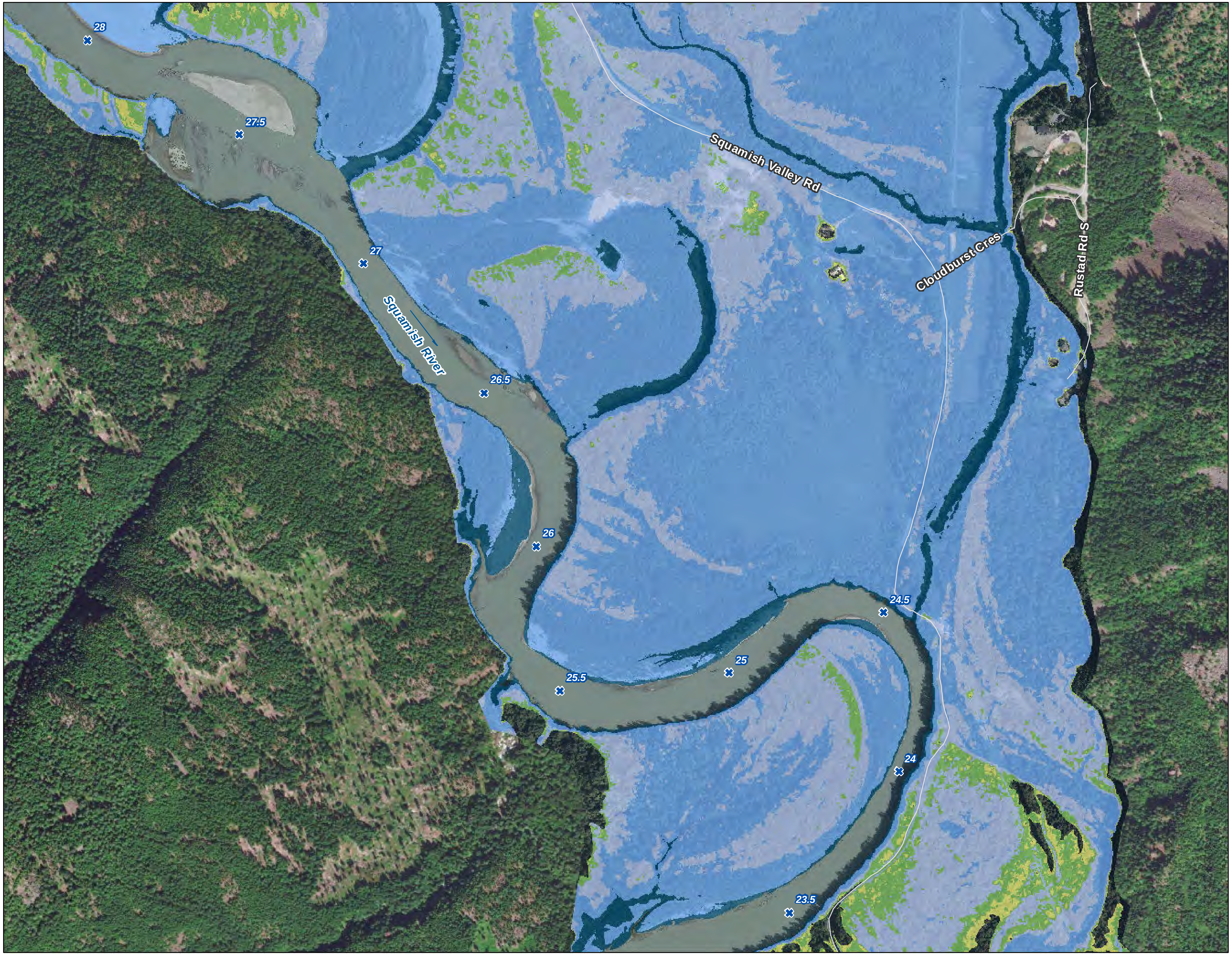
Engineer	GIS	Reviewer
THB	MAO	THB

Job Number	Date
3003329	26-NOV-2018

SQUAMISH FLOOD HAZARD MAPPING

500-Year Flood Depth

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_DepthMapBook_20181123.mxd



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REGIONAL DISTRICT

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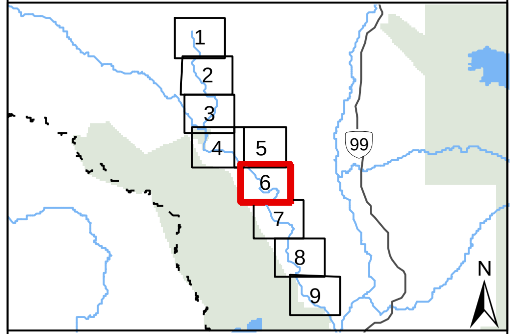

River Km

Road

Limits of Mapping

Depth (m)

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0.5 - 1.0

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Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 *Metres*

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

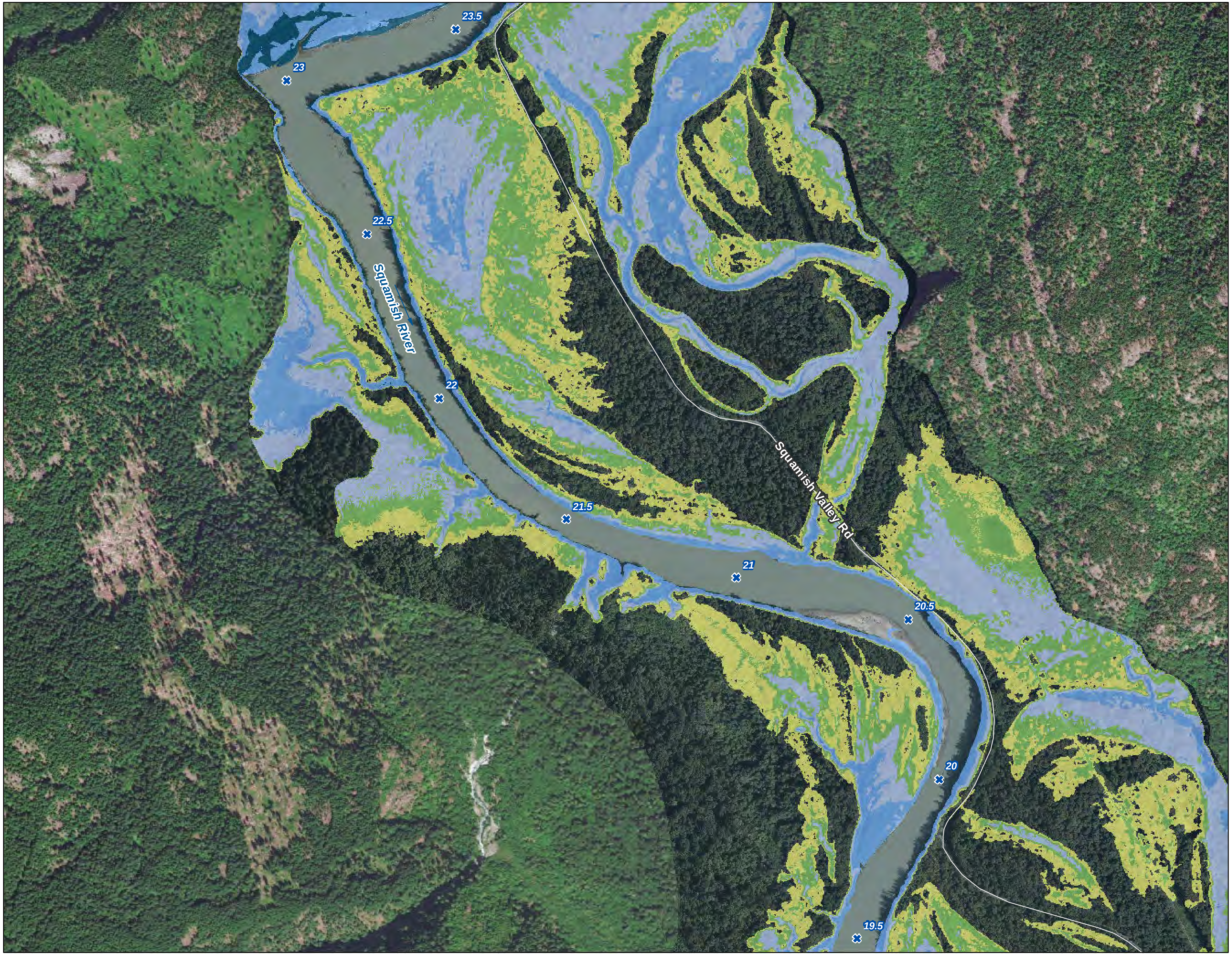
Engineer THB	*GIS* MAO	*Reviewer* THB
Job Number 3003329	*Date* 26-NOV-2018	

SQUAMISH FLOOD HAZARD MAPPING

500-Year Flood Depth

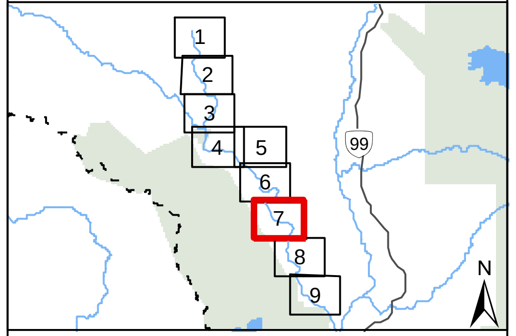
SHEET 6 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_DepthMapBook_20181123.mxd



Squamish - Lillooet
REGIONAL DISTRICT

nhc
northwest hydraulic consultants



River Km

Road

Limits of Mapping

Depth (m)

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- 0.5 - 1.0
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Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	GIS	Reviewer
THB	MAO	THB

Job Number	Date
3003329	26-NOV-2018

SQUAMISH FLOOD HAZARD MAPPING

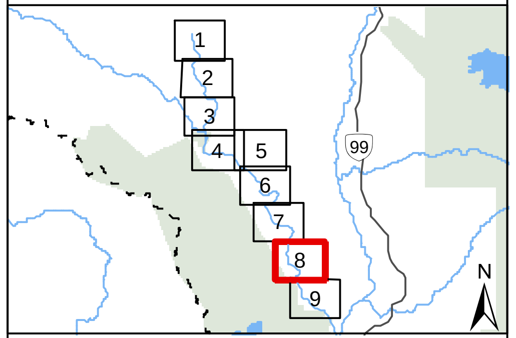
500-Year Flood Depth

SHEET 7 OF 9

MAO: Q:\3003329_SURD_Flood_Hazard_Map\95_GIS\MXD\Figures\Squamish_DepthMapBook_20181123.mxd

Squamish - Lillooet
REGIONAL DISTRICT

nhc
northwest hydraulic consultants



River Km

Road

Limits of Mapping

Depth (m)

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Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 *Metres*

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	*GIS*	*Reviewer*
THB	*MAO*	*THB*

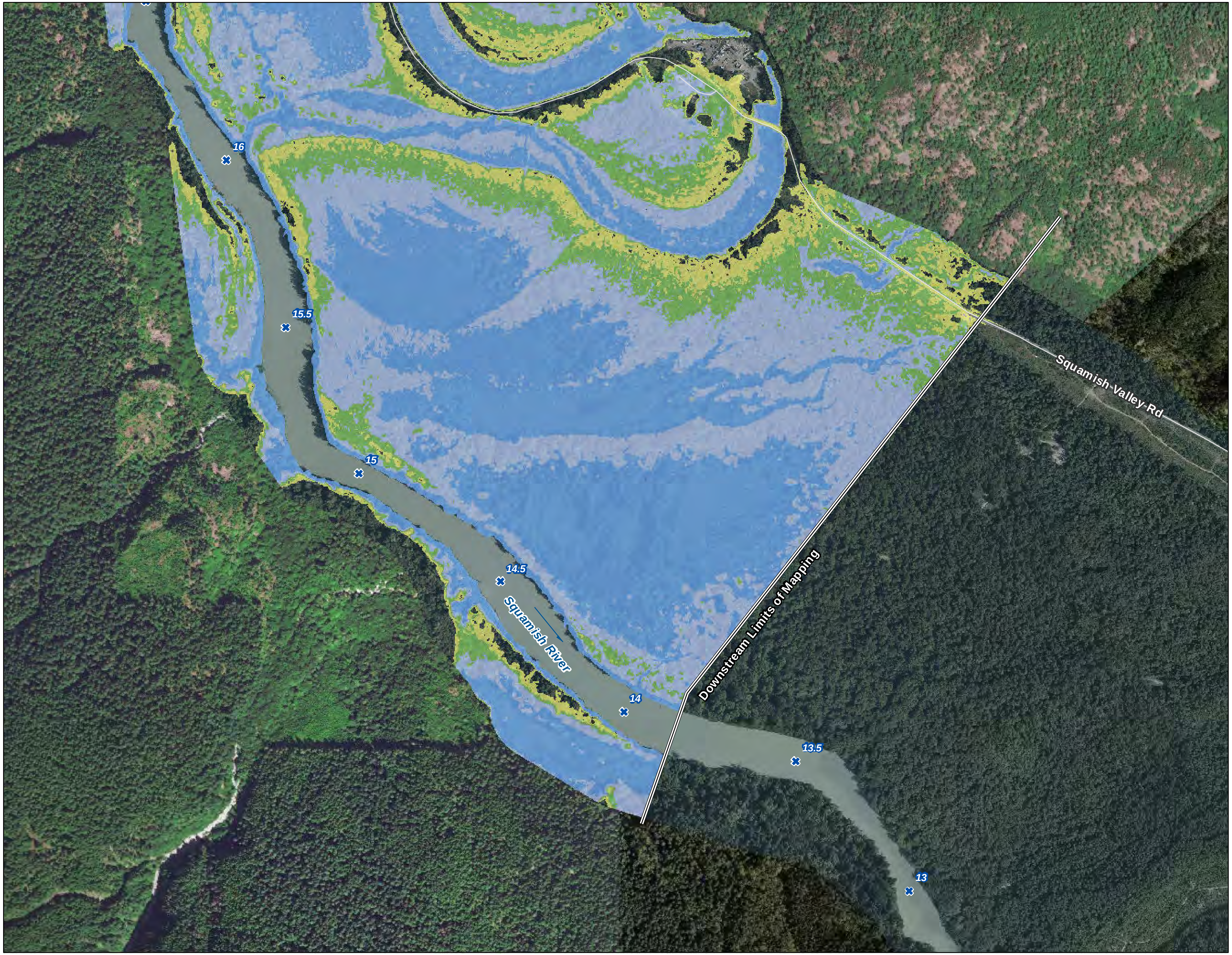
Job Number	*Date*
3003329	*26-NOV-2018*

SQUAMISH FLOOD HAZARD MAPPING

500-Year Flood Depth

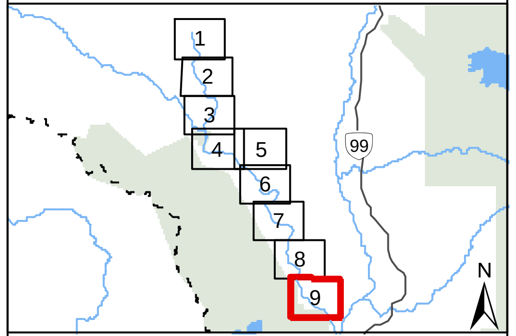
SHEET 8 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_DepthMapBook_20181123.mxd



Squamish - Lillooet
REGIONAL DISTRICT

nhc
northwest hydraulic consultants



River Km
Road
Limits of Mapping

Depth (m)

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- 0.5 - 1.0
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Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000
0 100 200 400 Metres
N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	GIS	Reviewer
THB	MAO	THB

Job Number	Date
3003329	26-NOV-2018

SQUAMISH FLOOD HAZARD MAPPING

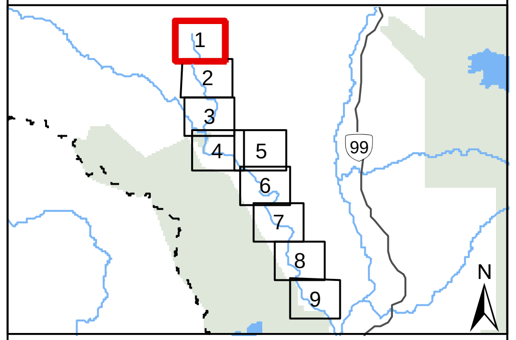
500-Year Flood Depth

SHEET 9 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_DepthMapBook_20181123.mxd

Squamish - Lillooet
REGIONAL DISTRICT

nhc
northwest hydraulic consultants



River Km

Road

Limits of Mapping

Depth (m)

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Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 Metres

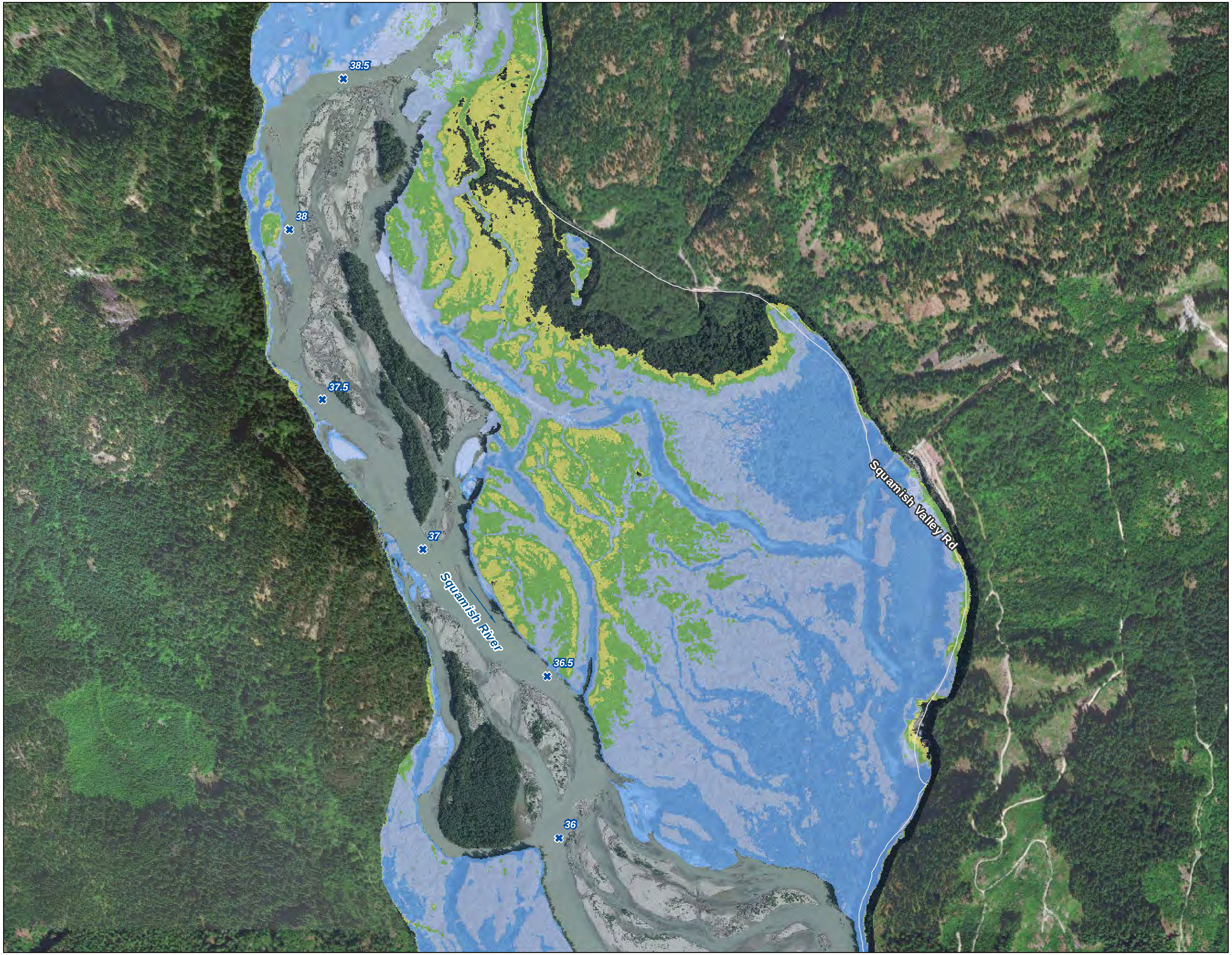
N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer THB	*GIS* MAO	*Reviewer* THB
Job Number 3003329	*Date* 26-NOV-2018	

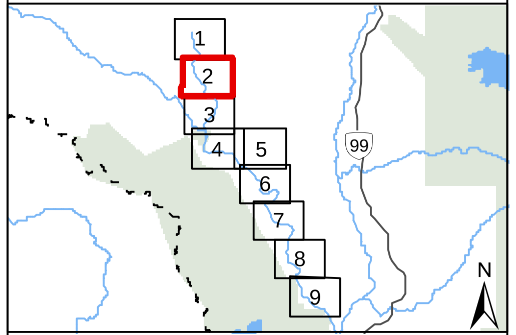
SQUAMISH FLOOD HAZARD MAPPING

100-Year Flood Depth



Squamish - Lillooet
REGIONAL DISTRICT

nhc
northwest hydraulic consultants



River Km
Road
Limits of Mapping

Depth (m)

0 - 0.5
0.5 - 1.0
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Engineer	*GIS*	*Reviewer*
THB	*MAO*	*THB*

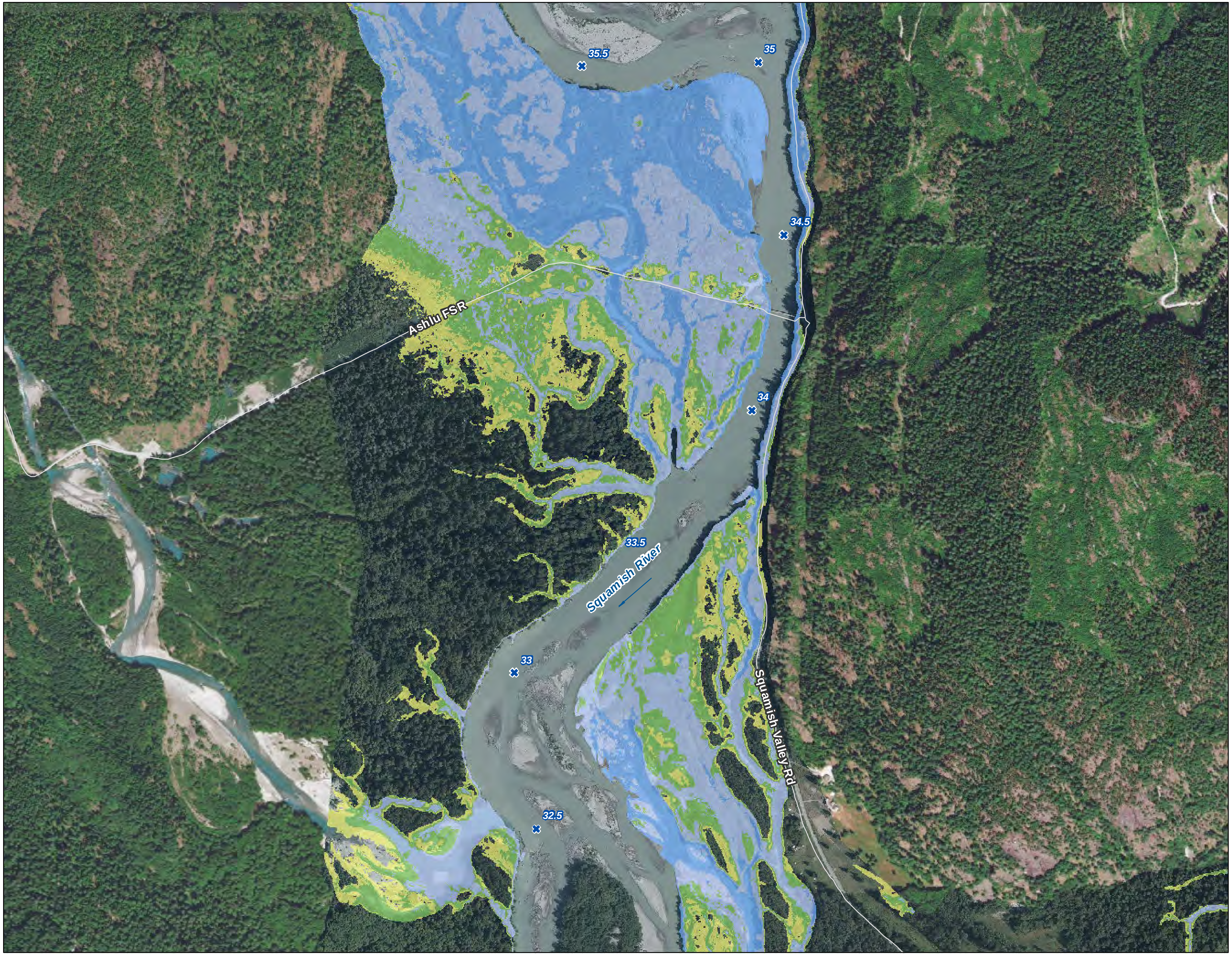
Job Number	*Date*
3003329	*26-NOV-2018*

SQUAMISH FLOOD HAZARD MAPPING

100-Year Flood Depth

SHEET 2 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map95_GIS\MXDs\Figures\Squamish_DepthMapBook_20181123.mxd



Squamish - Lillooet
REGIONAL DISTRICT

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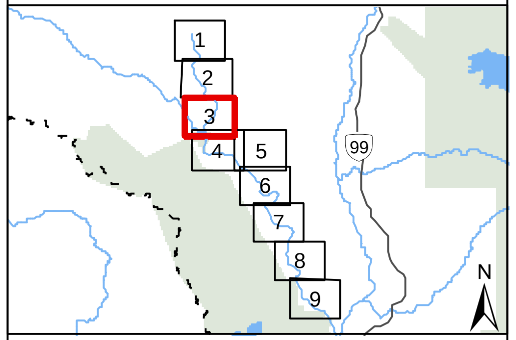
northwest hydraulic consultants



River Km
Road
Limits of Mapping

Depth (m)

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Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 *Metres*

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Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

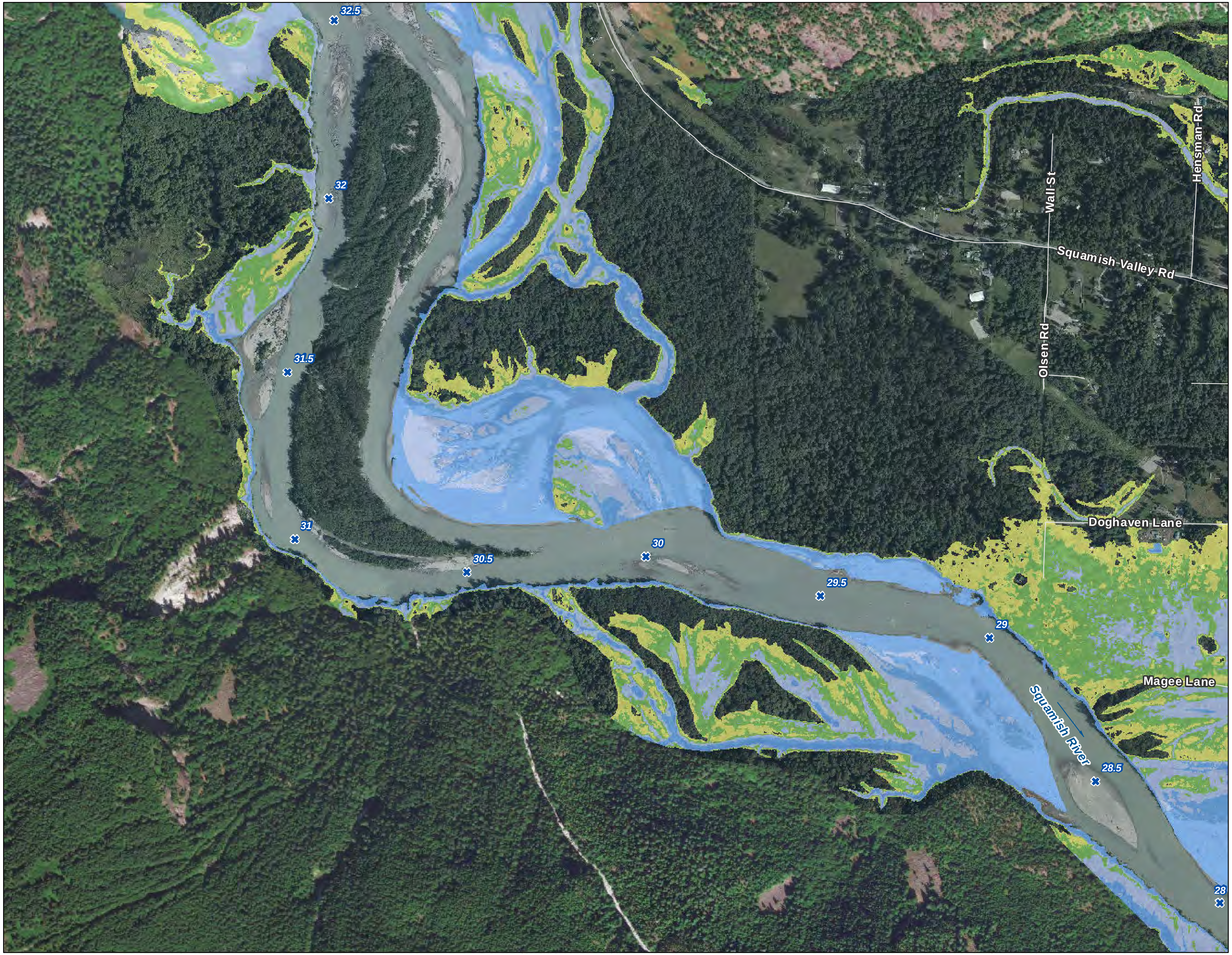
Engineer THB	*GIS* MAO	*Reviewer* THB
Job Number 3003329	*Date* 26-NOV-2018	

SQUAMISH FLOOD HAZARD MAPPING

100-Year Flood Depth

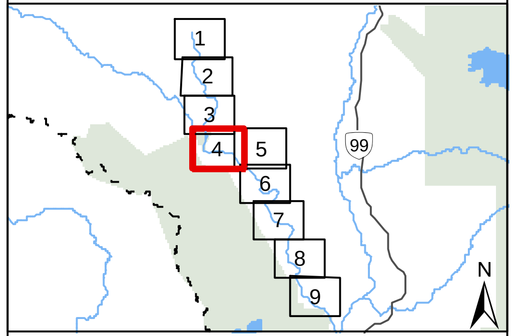
SHEET 3 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_DepthMapBook_20181123.mxd



Squamish - Lillooet REGIONAL DISTRICT

nhc northwest hydraulic consultants



River Km

Road

Limits of Mapping

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Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	GIS	Reviewer
THB	MAO	THB

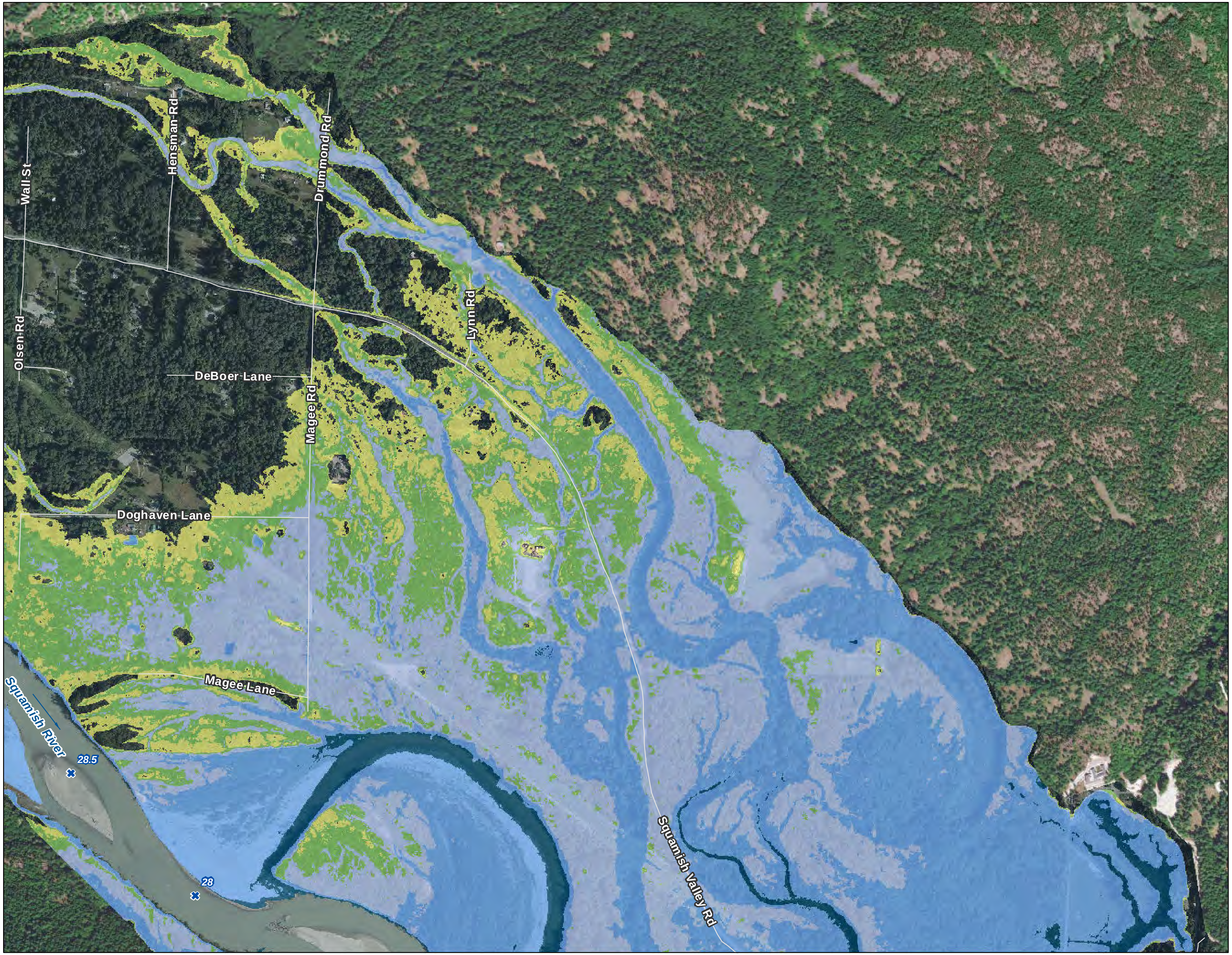
Job Number	Date
3003329	26-NOV-2018

SQUAMISH FLOOD HAZARD MAPPING

100-Year Flood Depth

SHEET 4 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_DepthMapBook_20181123.mxd



Squamish - Lillooet
REGIONAL DISTRICT

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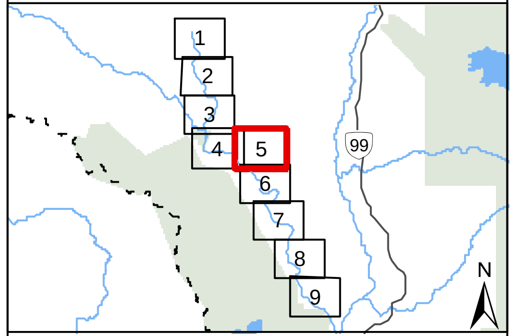

River Km
Road
Limits of Mapping

Depth (m)

0 - 0.5
0.5 - 1.0
1.0 - 2.0
2.0 - 5.0
>5.0

0-0.5m: Most houses are dry; walking in moving water or driving is potentially dangerous; basements and underground parking may be flooded, potentially causing evacuation.
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Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	GIS	Reviewer
THB	MAO	THB

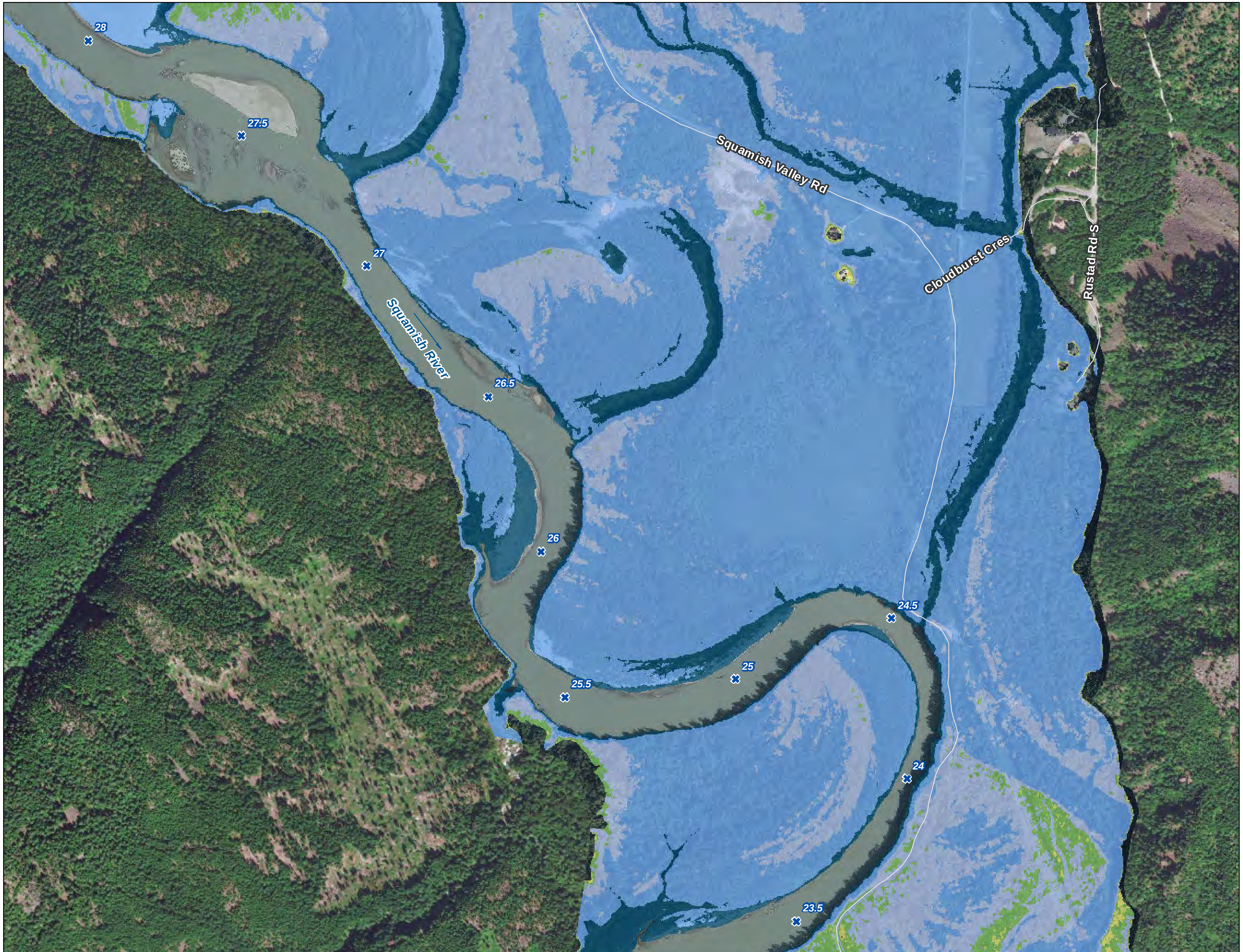
Job Number	Date
3003329	26-NOV-2018

SQUAMISH FLOOD HAZARD MAPPING

100-Year Flood Depth

SHEET 5 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_DepthMapBook_20181123.mxd



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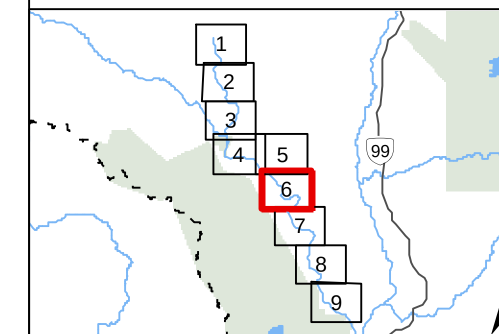

River Km

Road

Limits of Mapping

Depth (m)

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0 - 0.5
0.5 - 1.0
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0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	*GIS*	*Reviewer*
THB	*MAO*	*THB*

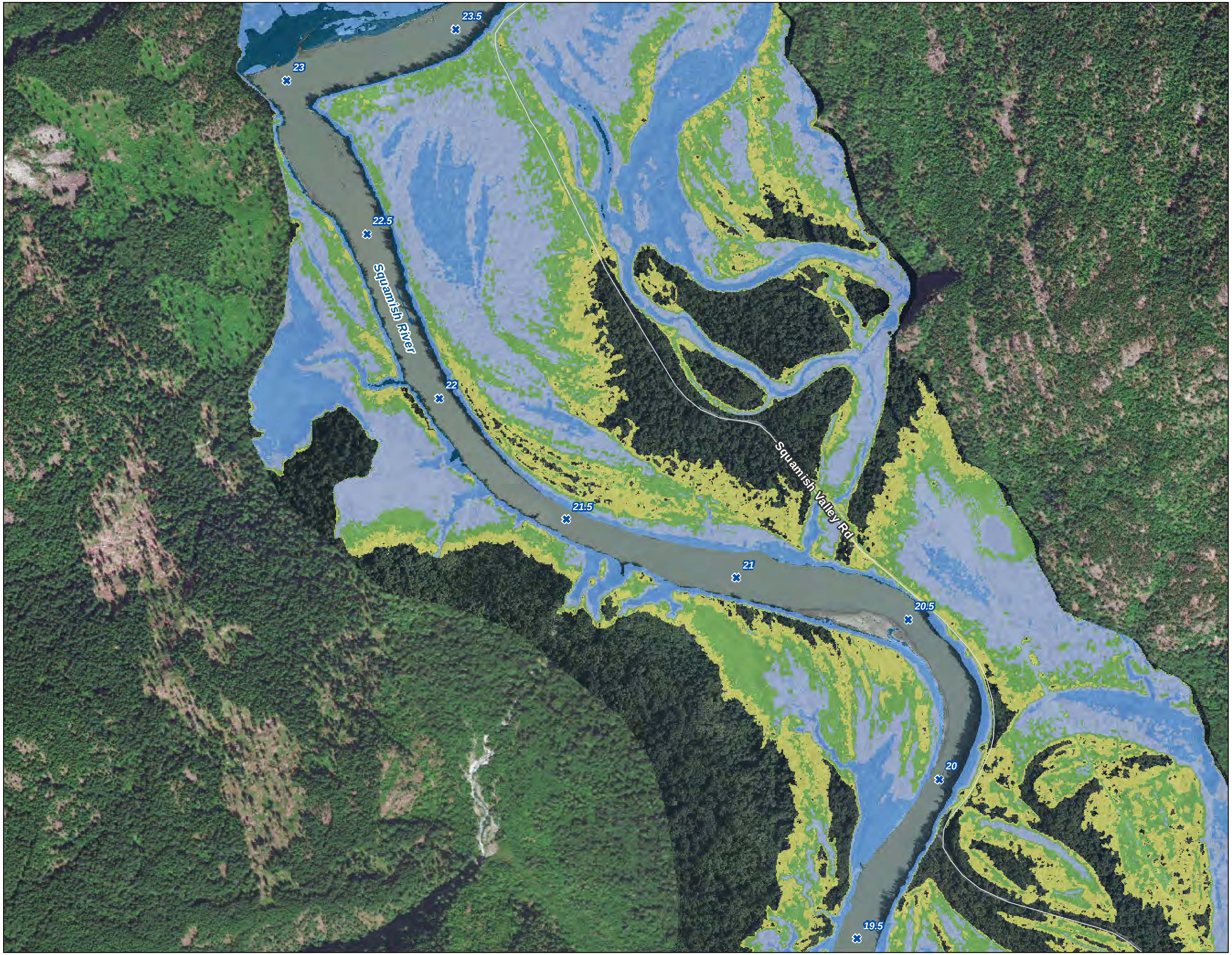
Job Number	*Date*
3003329	*26-NOV-2018*

SQUAMISH FLOOD HAZARD MAPPING

100-Year Flood Depth

SHEET 6 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_DepthMapBook_20181123.mxd



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REGIONAL DISTRICT

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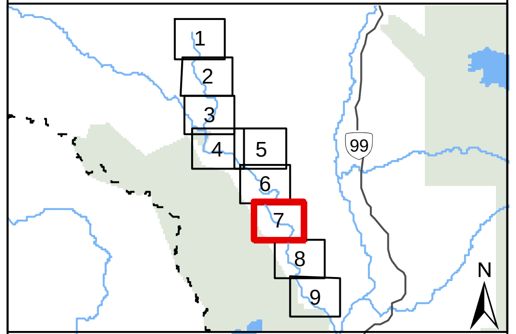

- ✖ River Km
- Road
- Limits of Mapping

Depth (m)

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- 0.5 - 1.0
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Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 *Metres*

N

Coordinate System: NAD 1983 UTM ZONE 10N
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Engineer	*GIS*	*Reviewer*
THB	*MAO*	*THB*

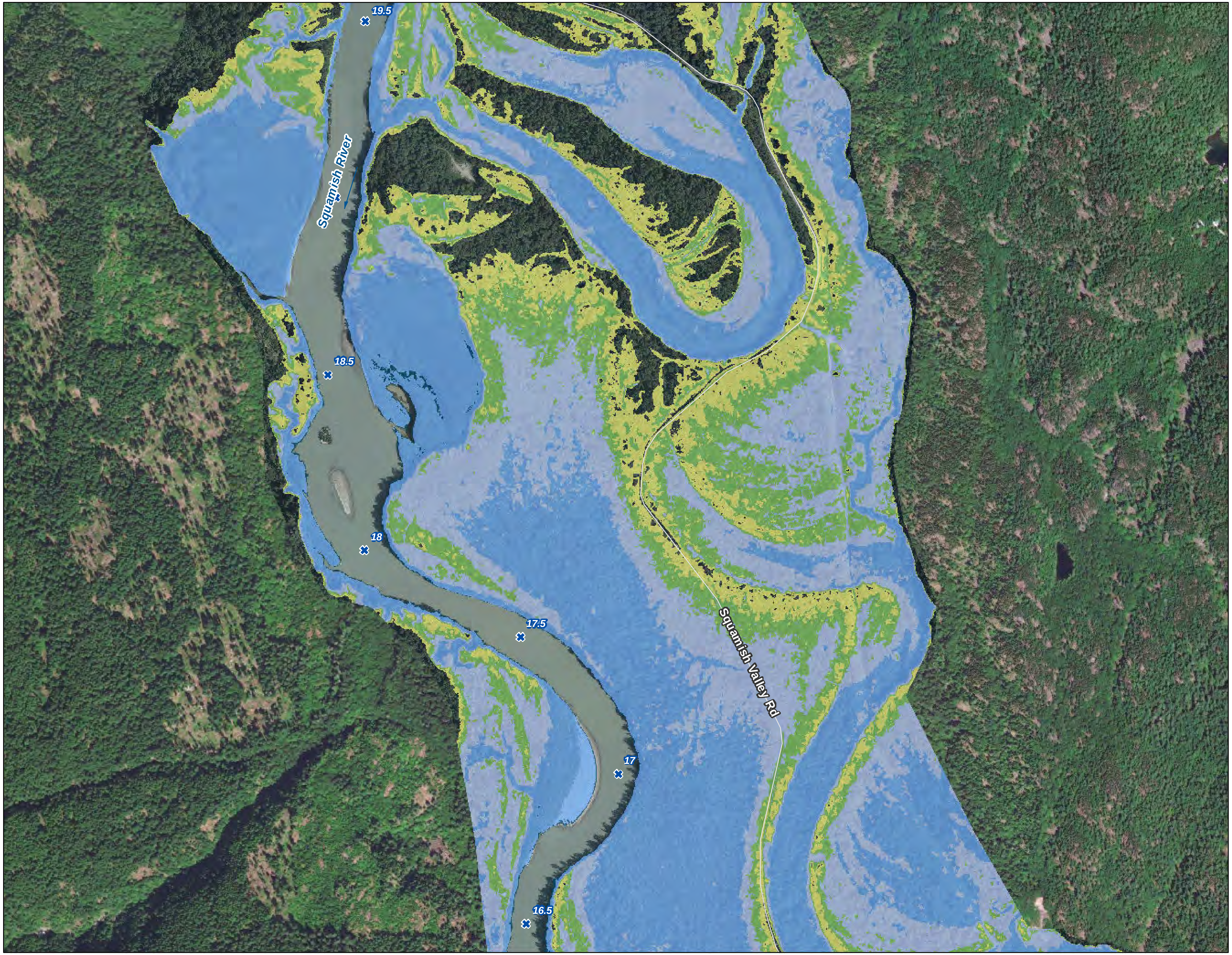
Job Number	*Date*
3003329	*26-NOV-2018*

SQUAMISH FLOOD HAZARD MAPPING

100-Year Flood Depth

SHEET 7 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_DepthMapBook_20181123.mxd



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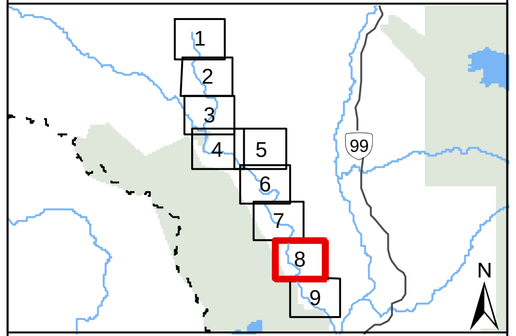

River Km

Road

Limits of Mapping

Depth (m)

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0.5 - 1.0

1.0 - 2.0

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Engineer	*GIS*	*Reviewer*
THB	*MAO*	*THB*

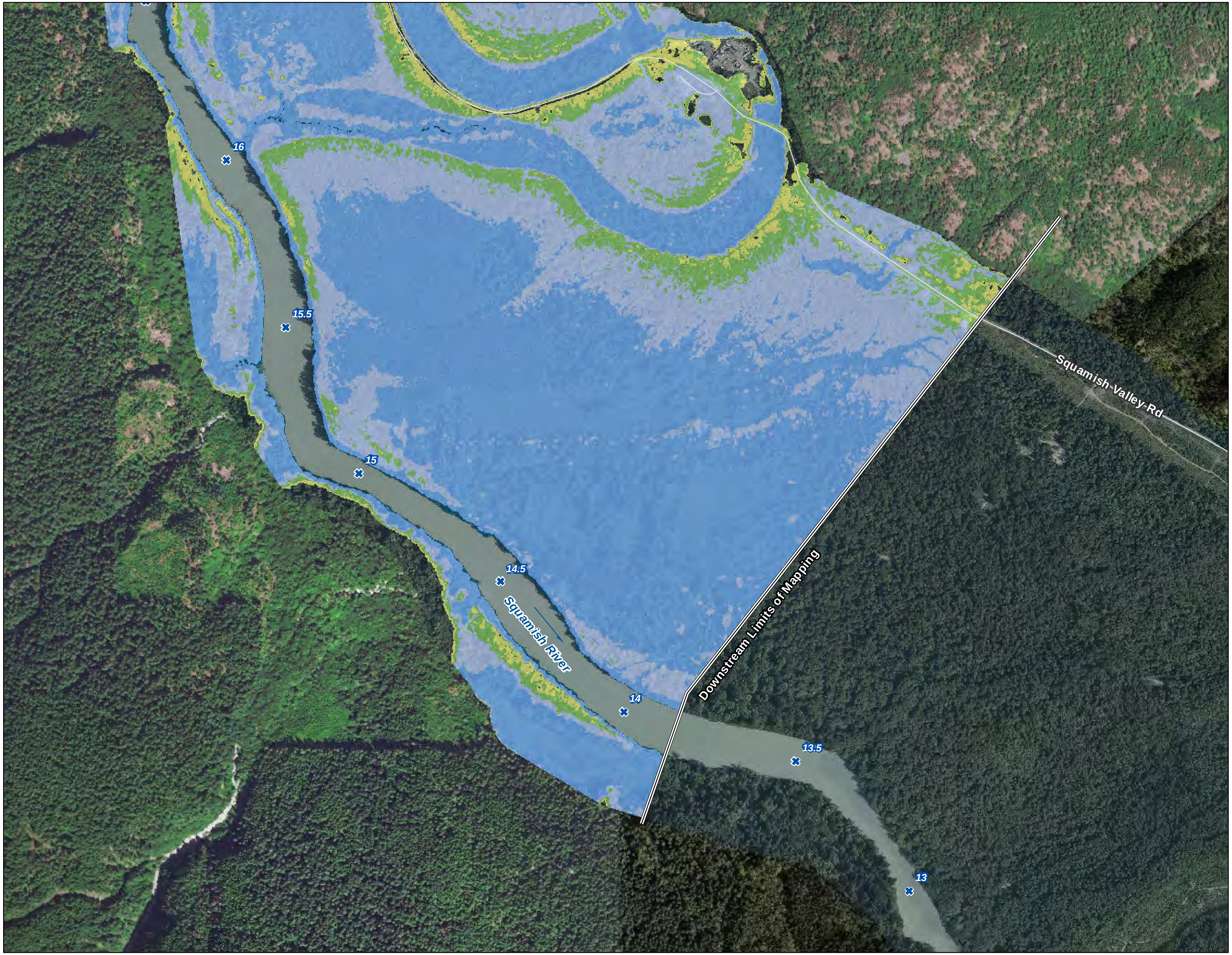
Job Number	*Date*
3003329	*26-NOV-2018*

SQUAMISH FLOOD HAZARD MAPPING

100-Year Flood Depth

SHEET 8 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_DepthMapBook_20181123.mxd



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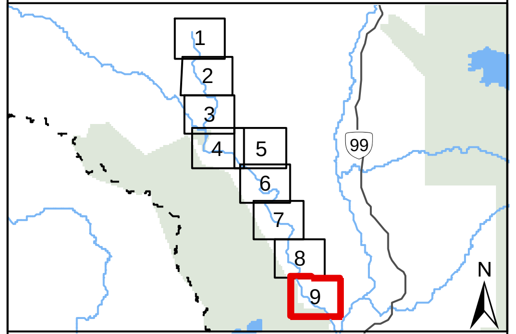

River Km
Road
Limits of Mapping

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Please refer to General Notes on Map Index Sheet

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Engineer	GIS	Reviewer
THB	MAO	THB

Job Number	Date
3003329	26-NOV-2018

SQUAMISH FLOOD HAZARD MAPPING

100-Year Flood Depth

SHEET 9 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_DepthMapBook_20181123.mxd

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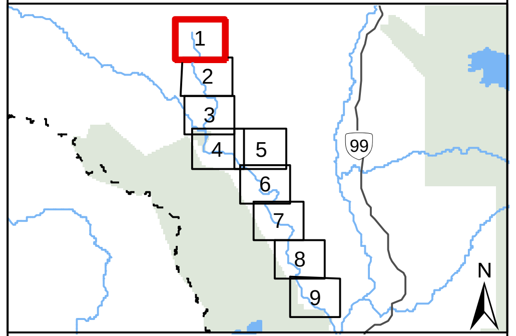

River Km
Road
Limits of Mapping

Depth (m)

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Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	*GIS*	*Reviewer*
THB	*MAO*	*THB*

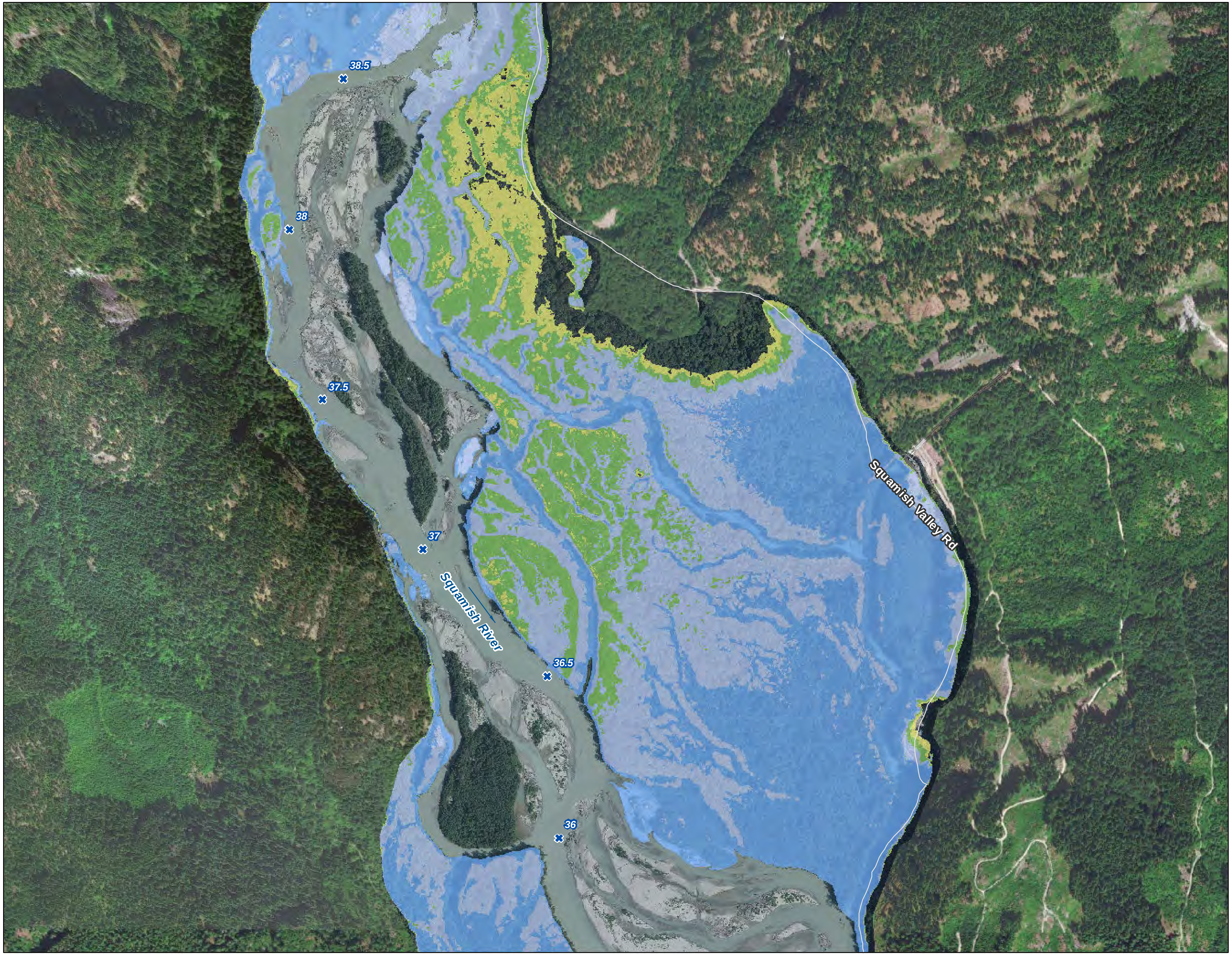
Job Number	*Date*
3003329	*26-NOV-2018*

SQUAMISH FLOOD HAZARD MAPPING

200-Year Flood Depth

SHEET 1 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_DepthMapBook_20181123.mxd



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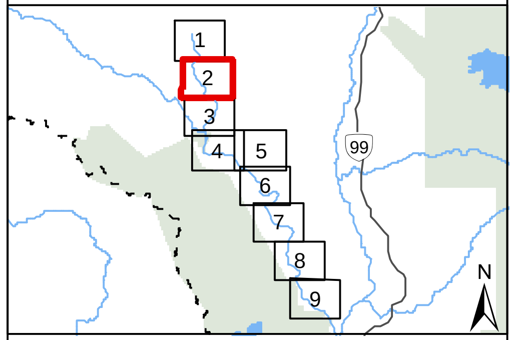

River Km
Road
Limits of Mapping

Depth (m)

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Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 *Metres*

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	*GIS*	*Reviewer*
THB	*MAO*	*THB*

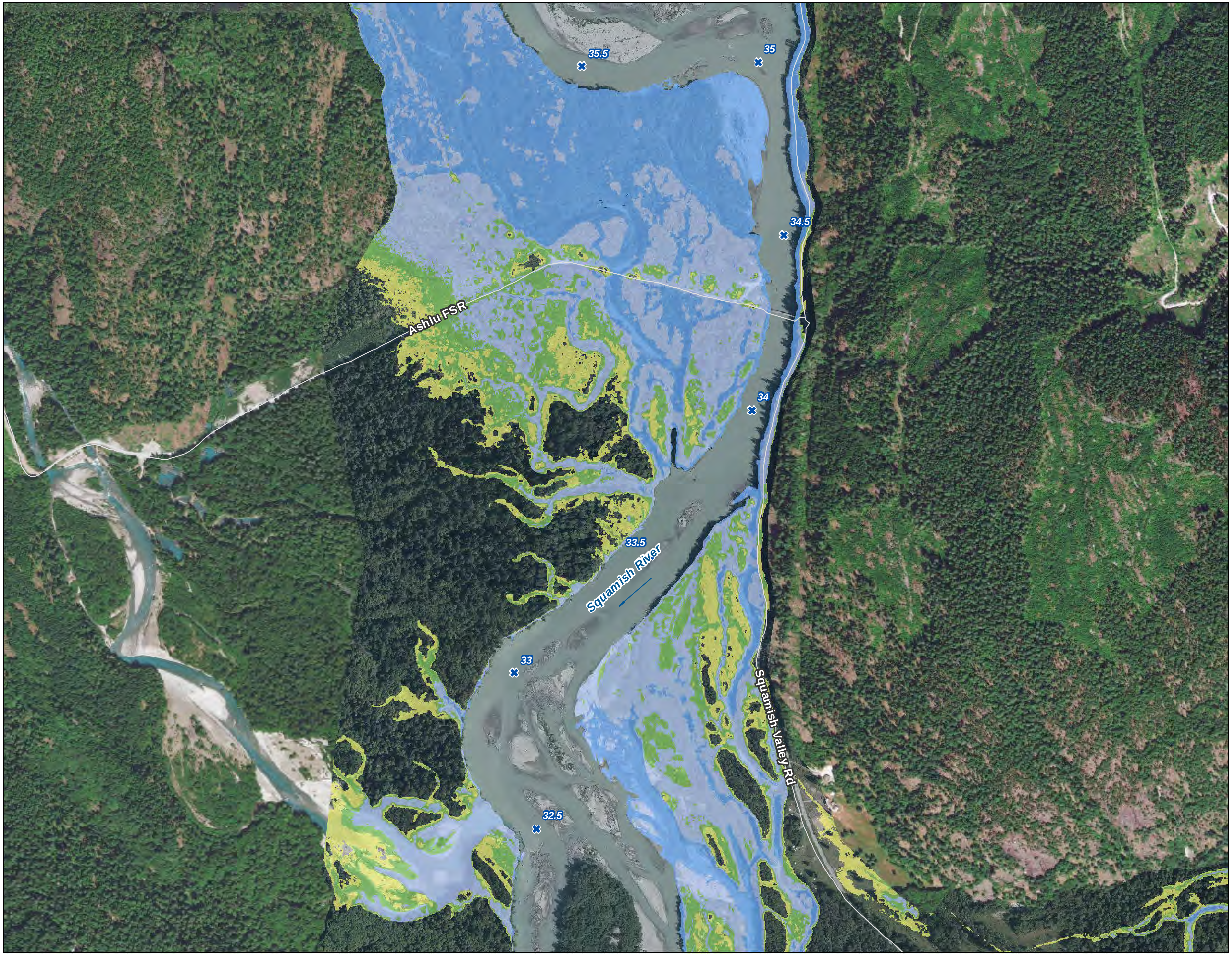
Job Number	*Date*
3003329	*26-NOV-2018*

SQUAMISH FLOOD HAZARD MAPPING

200-Year Flood Depth

SHEET 2 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_DepthMapBook_20181123.mxd



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REGIONAL DISTRICT

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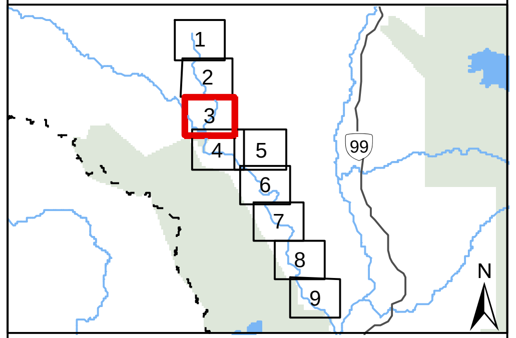

River Km

Road

Limits of Mapping

Depth (m)

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Please refer to General Notes on Map Index Sheet

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0 100 200 400 *Metres*

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	*GIS*	*Reviewer*
THB	*MAO*	*THB*

Job Number	*Date*
3003329	*26-NOV-2018*

SQUAMISH FLOOD HAZARD MAPPING

200-Year Flood Depth

SHEET 3 OF 9

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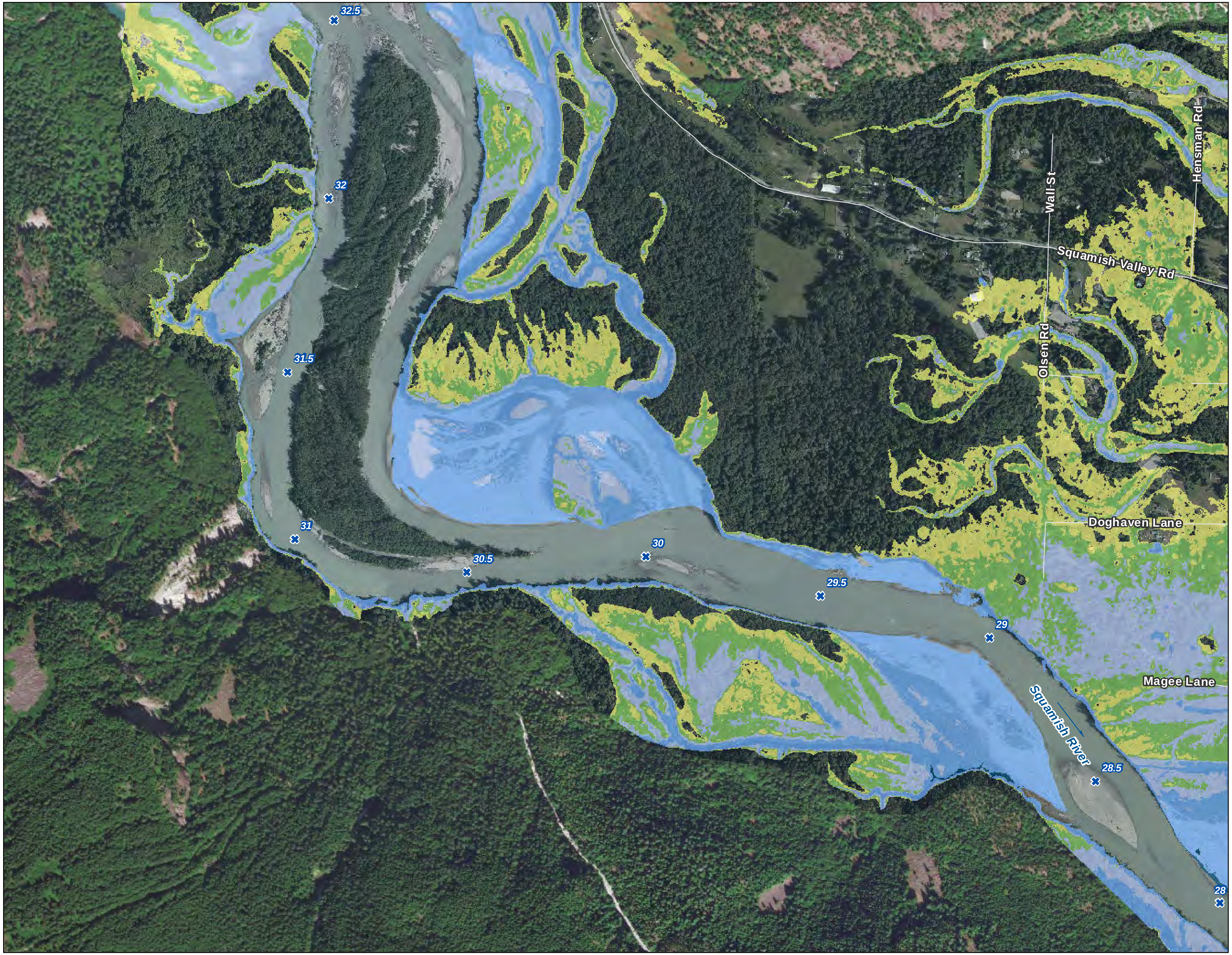

Squamish - Lillooet
REGIONAL DISTRICT

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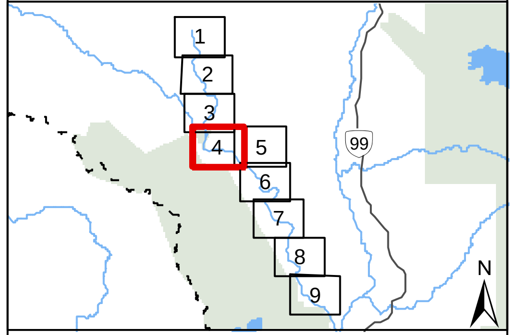

- River Km
- Road
- Limits of Mapping

Depth (m)

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Engineer	GIS	Reviewer
THB	MAO	THB

Job Number	Date
3003329	26-NOV-2018

SQUAMISH FLOOD HAZARD MAPPING

200-Year Flood Depth

SHEET 4 OF 9

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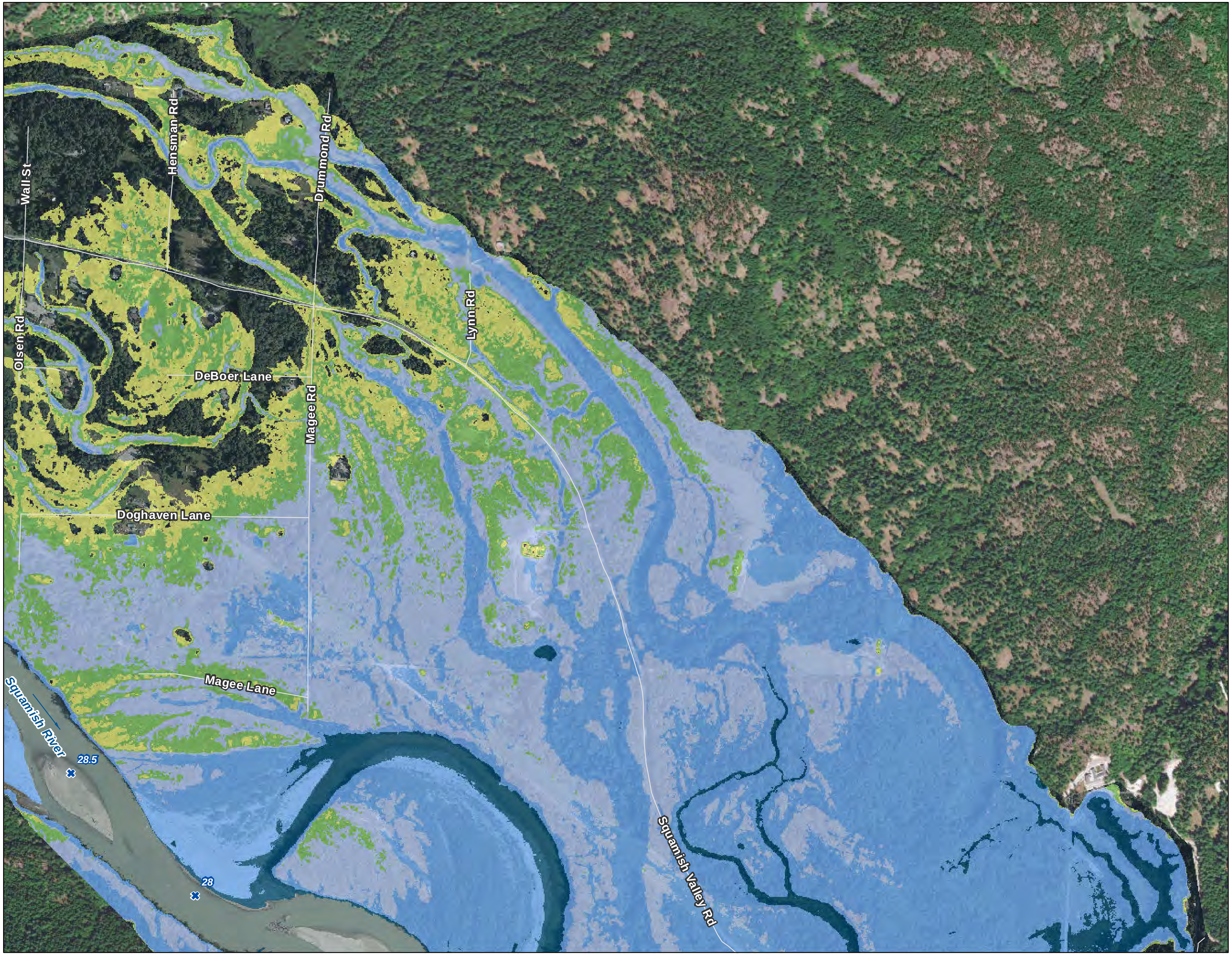

Squamish - Lillooet
REGIONAL DISTRICT

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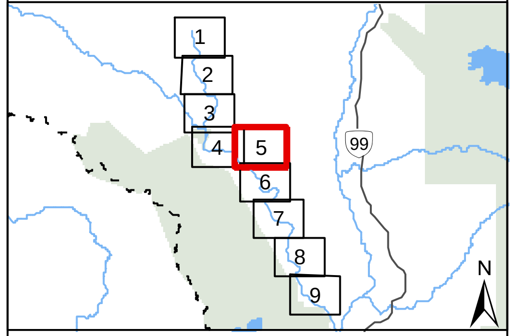

River Km
Road
Limits of Mapping

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Engineer	*GIS*	*Reviewer*
THB	*MAO*	*THB*

Job Number	*Date*
3003329	*26-NOV-2018*

SQUAMISH FLOOD HAZARD MAPPING

200-Year Flood Depth

SHEET 5 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_DepthMapBook_20181123.mxd

Squamish - Lillooet
REGIONAL DISTRICT

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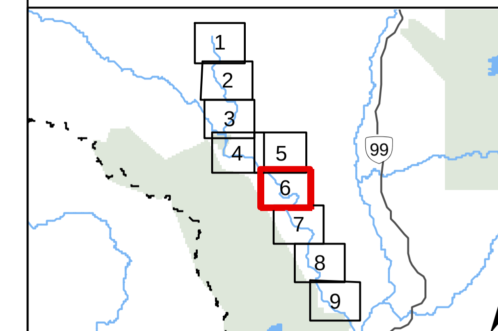

River Km
Road
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Engineer	GIS	Reviewer
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3003329	26-NOV-2018

SQUAMISH FLOOD HAZARD MAPPING

200-Year Flood Depth

SHEET 6 OF 9

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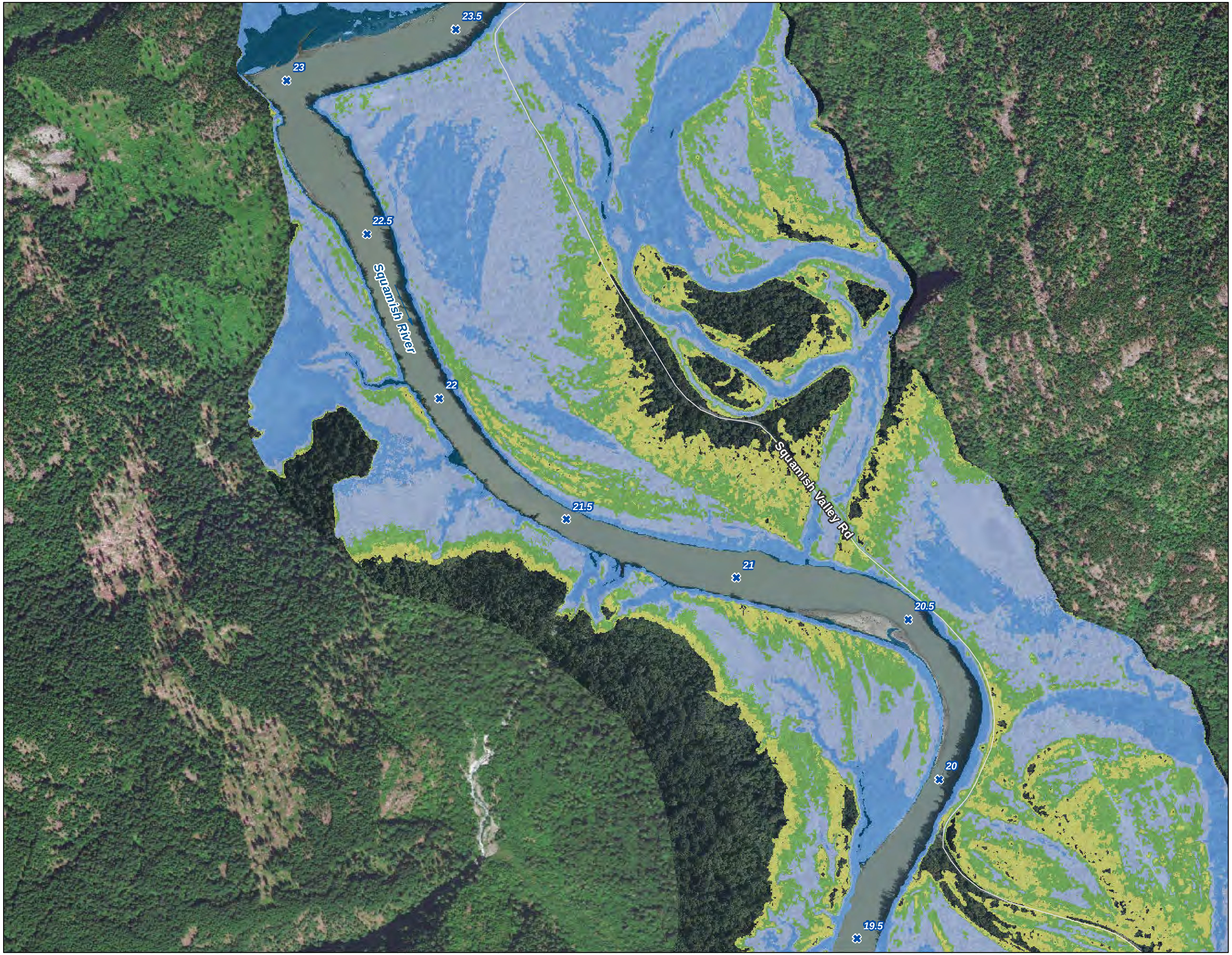

Squamish - Lillooet
REGIONAL DISTRICT

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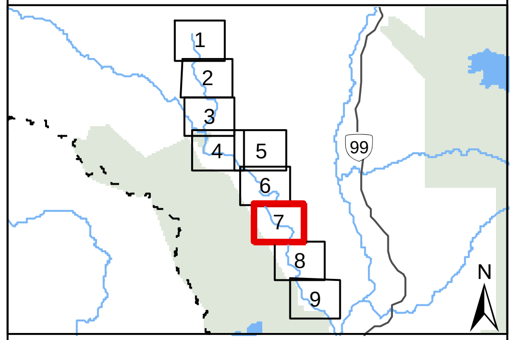

River Km

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Engineer	GIS	Reviewer
THB	MAO	THB

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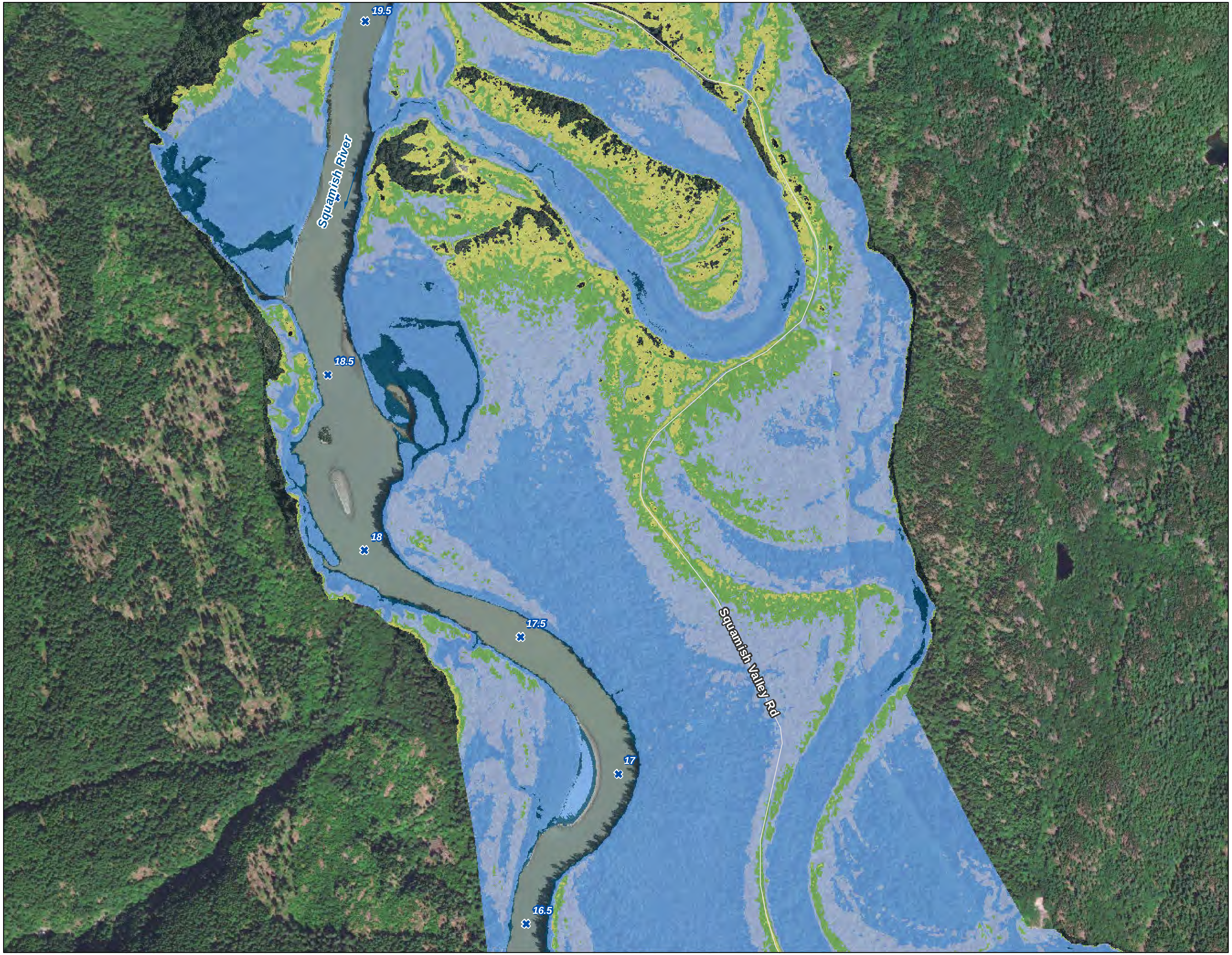
3003329	26-NOV-2018

SQUAMISH FLOOD HAZARD MAPPING

200-Year Flood Depth

SHEET 7 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_DepthMapBook_20181123.mxd



Squamish - Lillooet
REGIONAL DISTRICT

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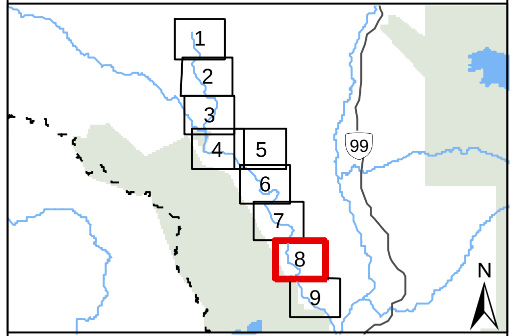

River Km
Road
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Engineer THB	*GIS* MAO	*Reviewer* THB
Job Number 3003329	*Date* 26-NOV-2018	

SQUAMISH FLOOD HAZARD MAPPING

200-Year Flood Depth

SHEET 8 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_DepthMapBook_20181123.mxd

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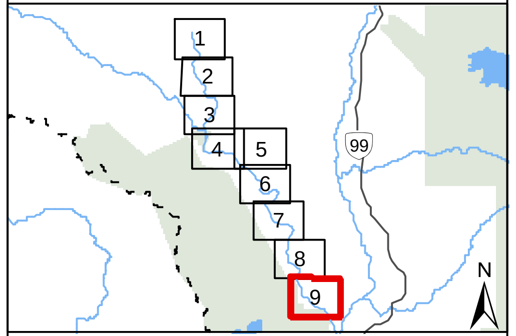

River Km

Road

Limits of Mapping

Depth (m)

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0.5 - 1.0

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>5m: First floor and often roof covered by water; residents evacuate.

Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	GIS	Reviewer
THB	MAO	THB

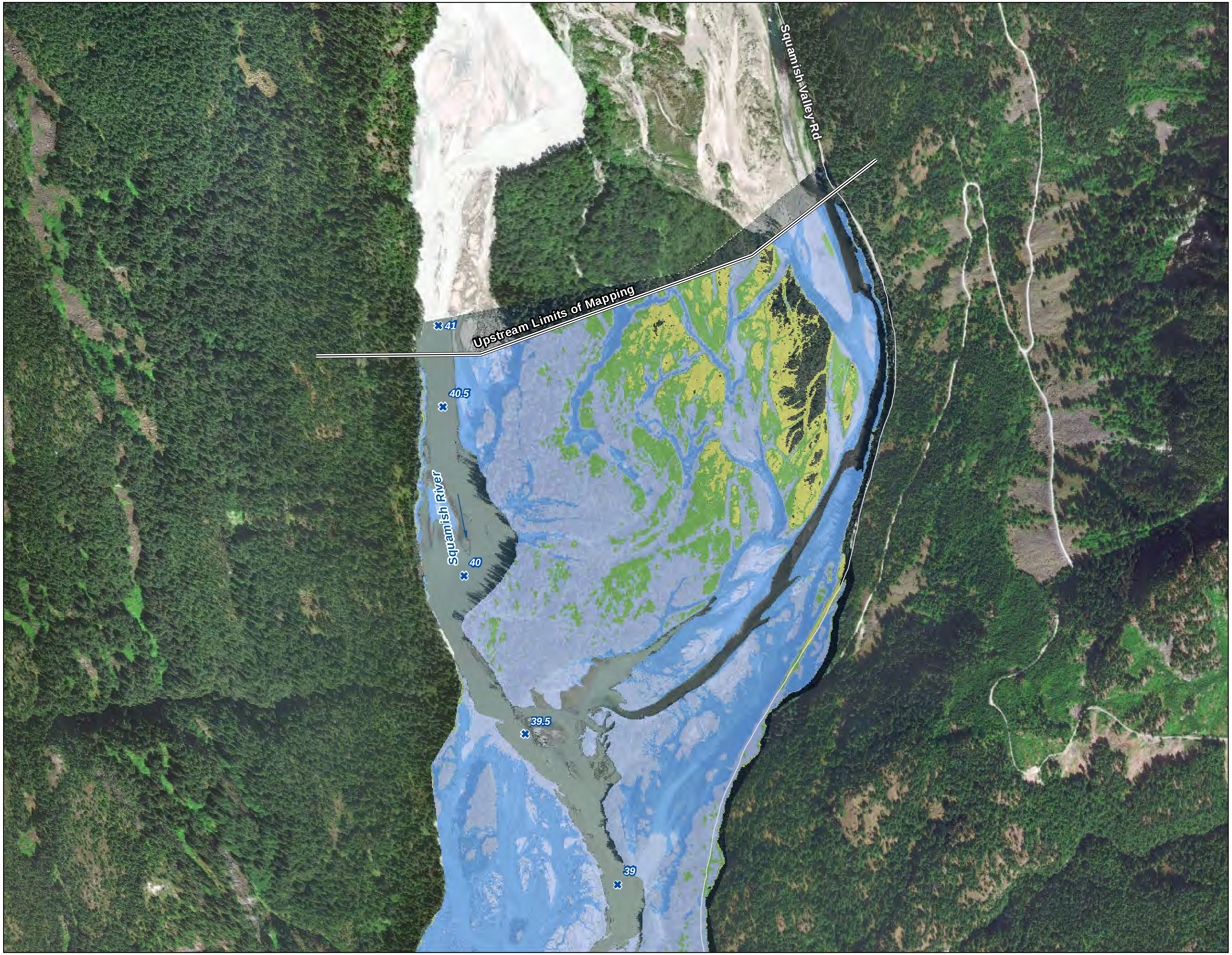
Job Number	Date
3003329	26-NOV-2018

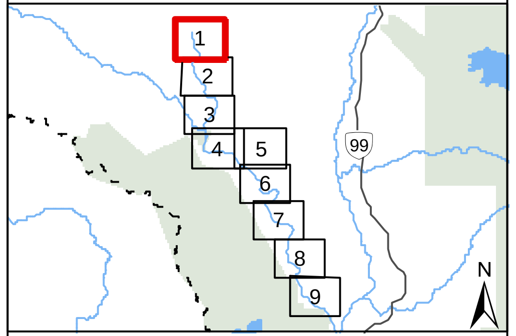
SQUAMISH FLOOD HAZARD MAPPING

200-Year Flood Depth

SHEET 9 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_DepthMapBook_20181123.mxd





- River Km
- Road
- Limits of Mapping

Depth (m)

- 0 - 0.5
- 0.5 - 1.0
- 1.0 - 2.0
- 2.0 - 5.0
- >5.0

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Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	GIS	Reviewer
THB	MAO	THB

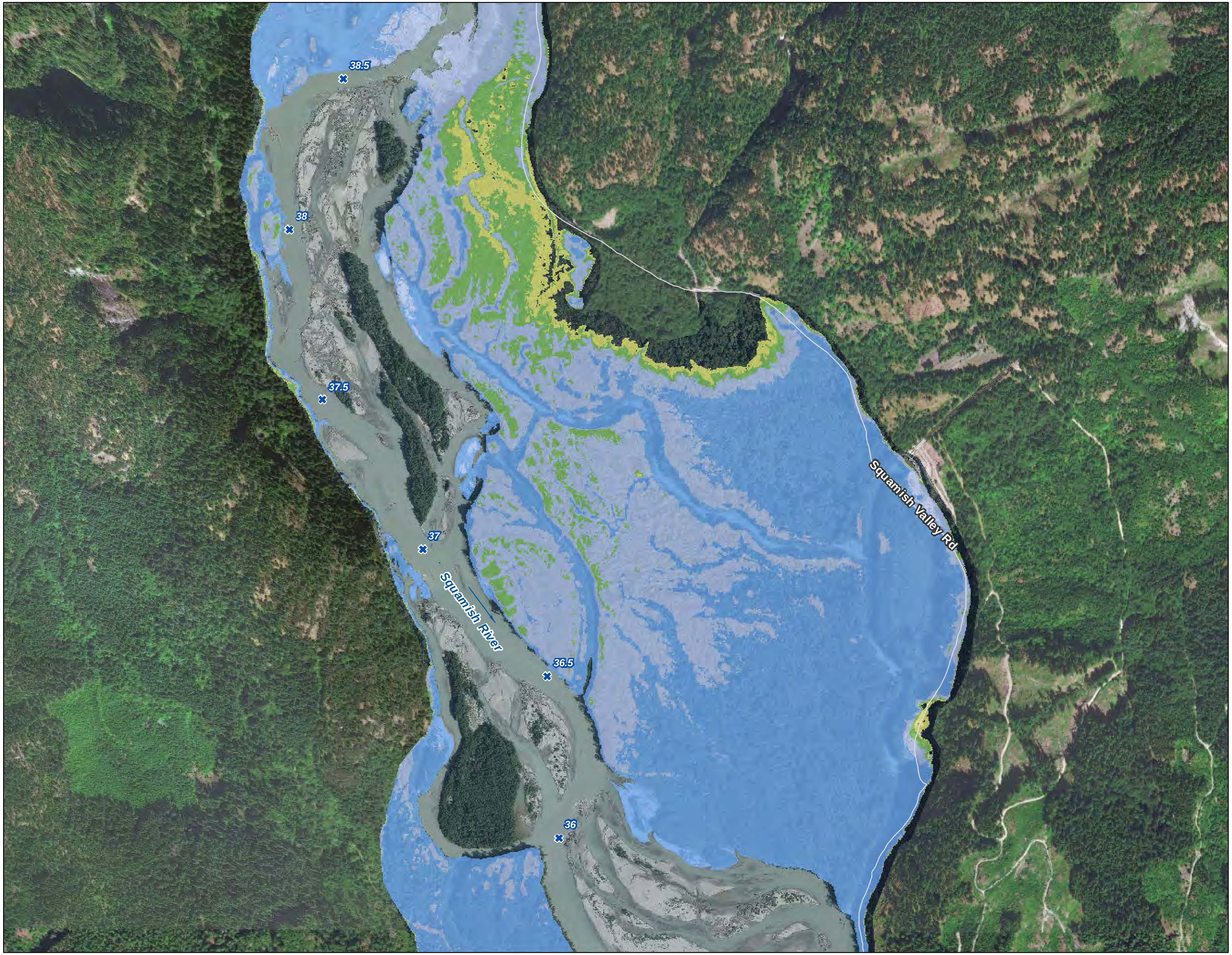
Job Number	Date
3003329	26-NOV-2018

SQUAMISH FLOOD HAZARD MAPPING

500-Year Flood Depth

SHEET 1 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_DepthMapBook_20181123.mxd



Squamish - Lillooet REGIONAL DISTRICT

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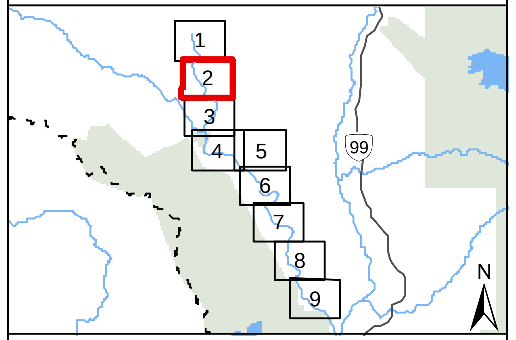

- River Km
- Road
- Limits of Mapping

Depth (m)

- 0 - 0.5
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Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	GIS	Reviewer
THB	MAO	THB

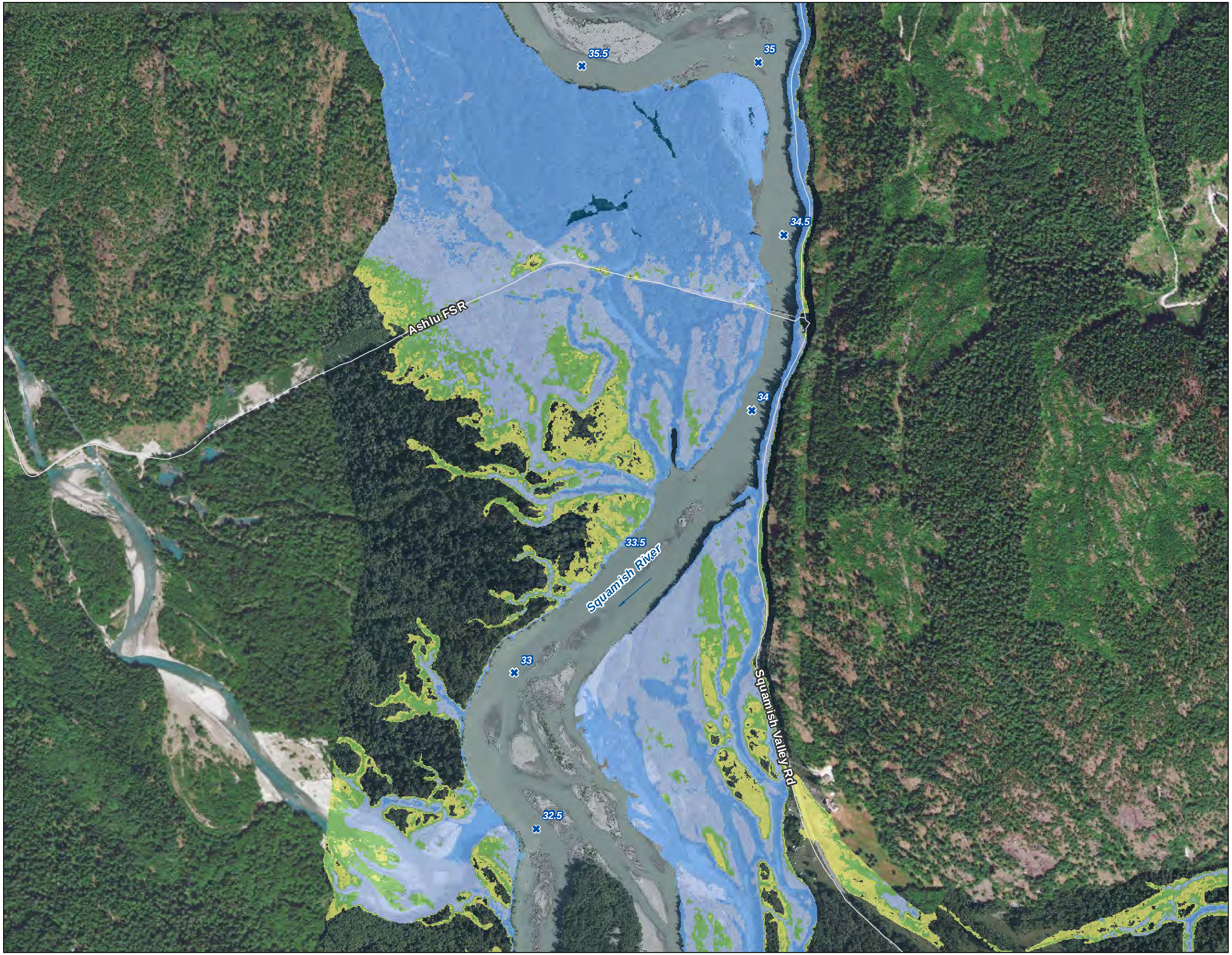
Job Number	Date
3003329	26-NOV-2018

SQUAMISH FLOOD HAZARD MAPPING

500-Year Flood Depth

SHEET 2 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_DepthMapBook_20181123.mxd



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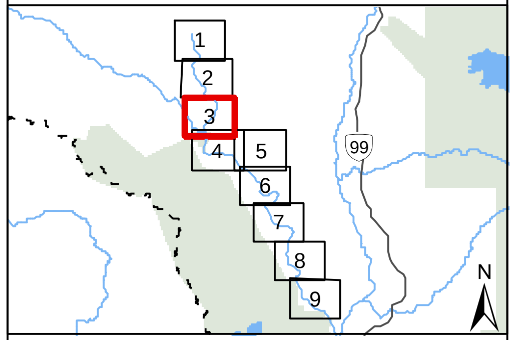

River Km

Road

Limits of Mapping

Depth (m)

0 - 0.5
0.5 - 1.0
1.0 - 2.0
2.0 - 5.0
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Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

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Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

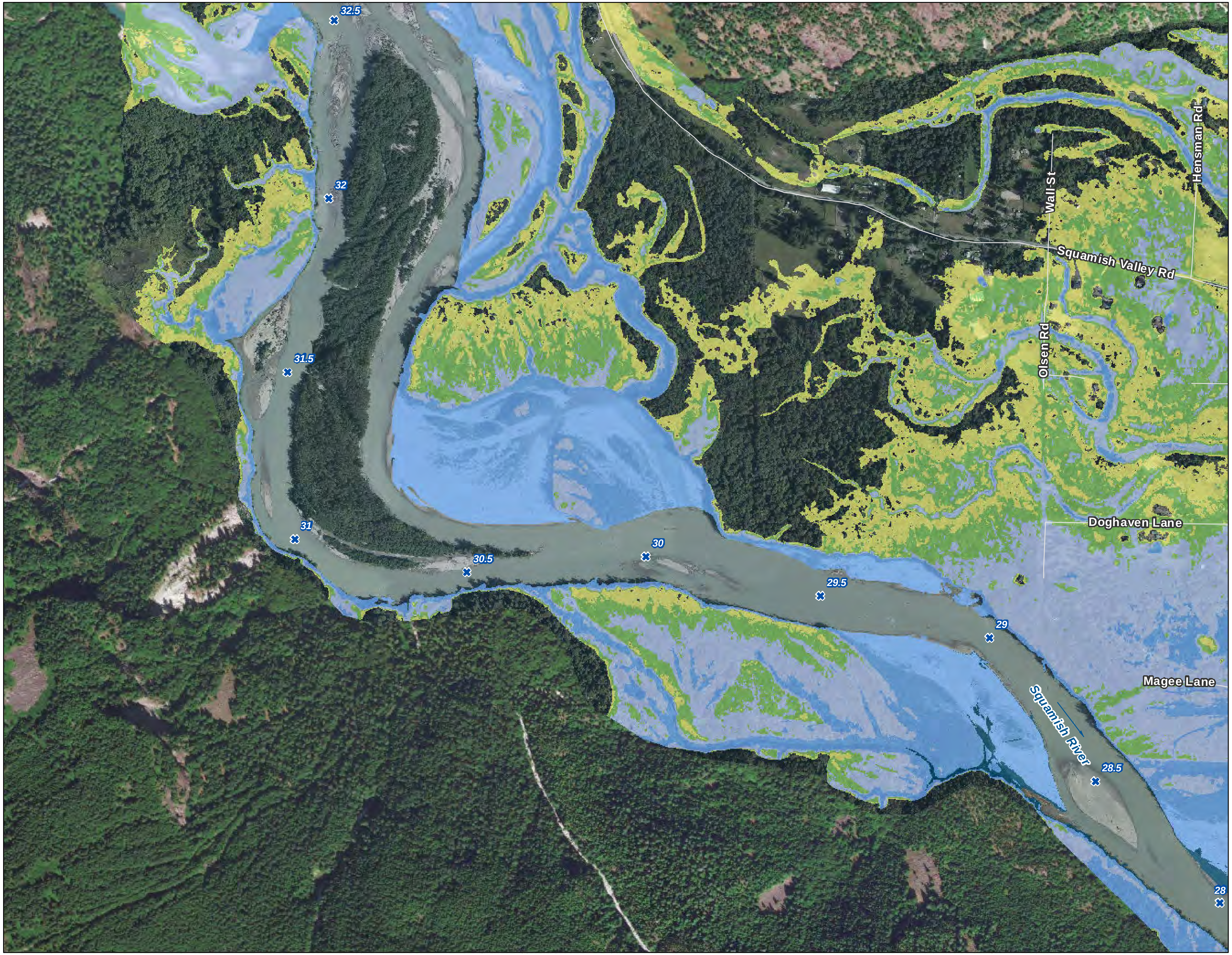
Engineer	GIS	Reviewer
THB	MAO	THB

Job Number	Date
3003329	26-NOV-2018

SQUAMISH FLOOD HAZARD MAPPING

500-Year Flood Depth

SHEET 3 OF 9



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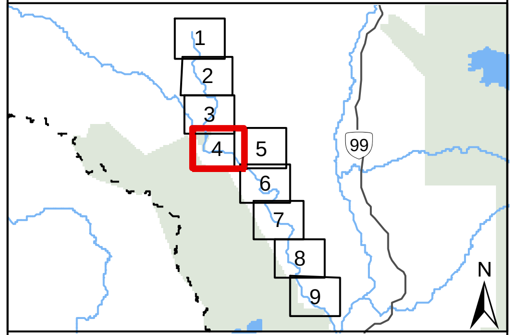

River Km
Road
Limits of Mapping

Depth (m)

- 0 - 0.5
- 0.5 - 1.0
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Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

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0 100 200 400 Metres

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Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

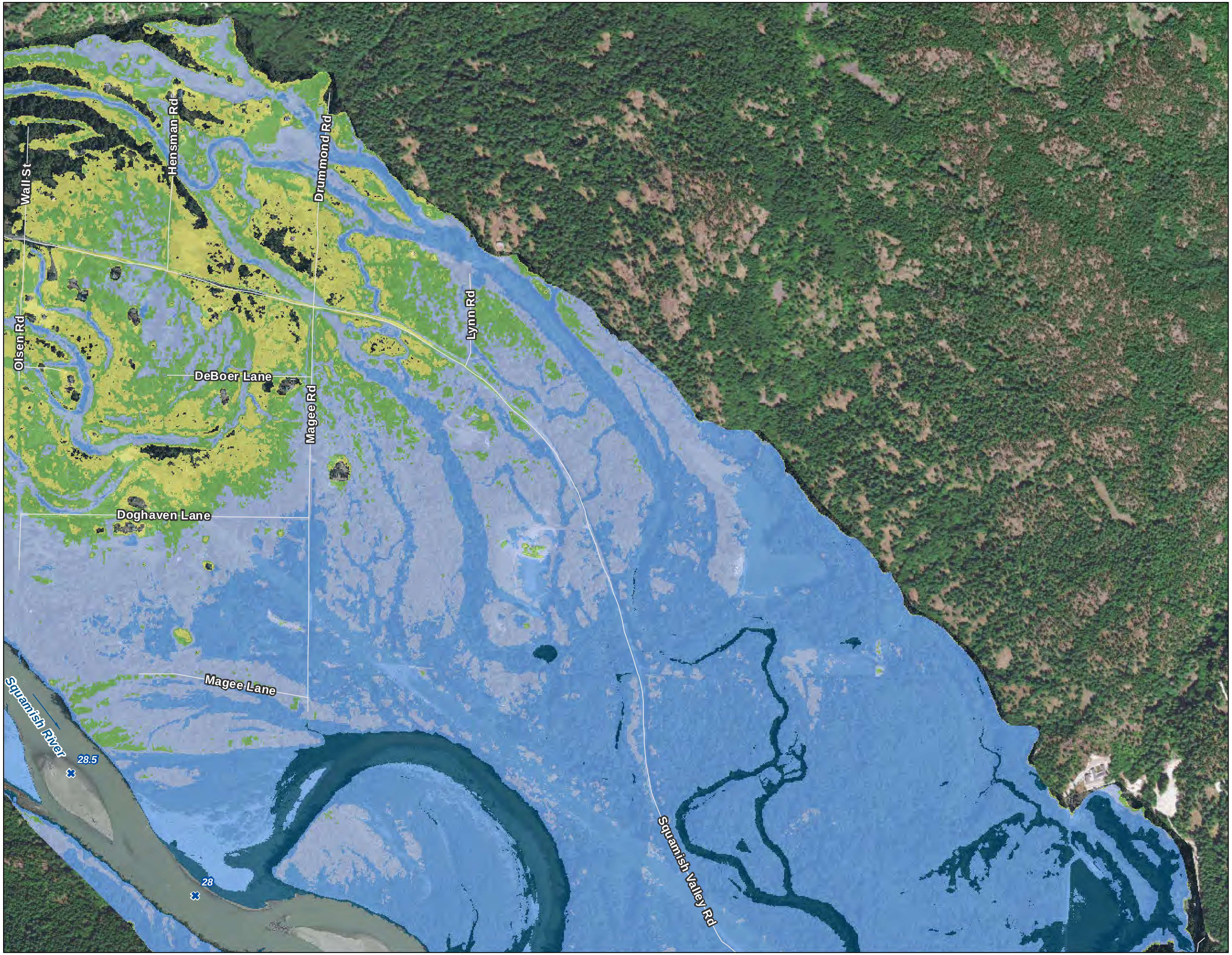
Engineer	*GIS*	*Reviewer*
THB	*MAO*	*THB*

Job Number	*Date*
3003329	*26-NOV-2018*

SQUAMISH FLOOD HAZARD MAPPING

500-Year Flood Depth

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_DepthMapBook_20181123.mxd



Squamish - Lillooet
REGIONAL DISTRICT

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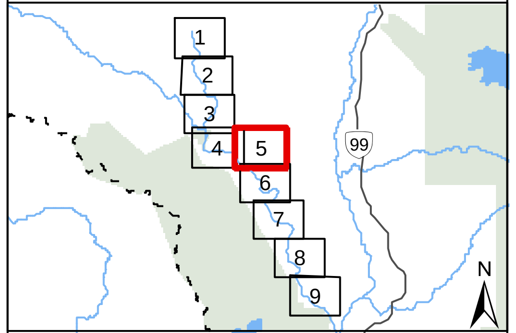

River Km

Road

Limits of Mapping

Depth (m)

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Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	GIS	Reviewer
THB	MAO	THB

Job Number	Date
3003329	26-NOV-2018

SQUAMISH FLOOD HAZARD MAPPING

500-Year Flood Depth

SHEET 5 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_DepthMapBook_20181123.mxd

Squamish - Lillooet
REGIONAL DISTRICT

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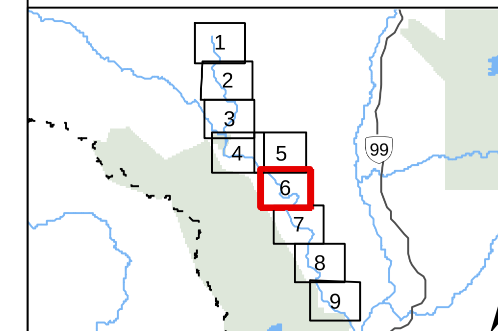

River Km

Road

Limits of Mapping

Depth (m)

0 - 0.5

0.5 - 1.0

1.0 - 2.0

2.0 - 5.0

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Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

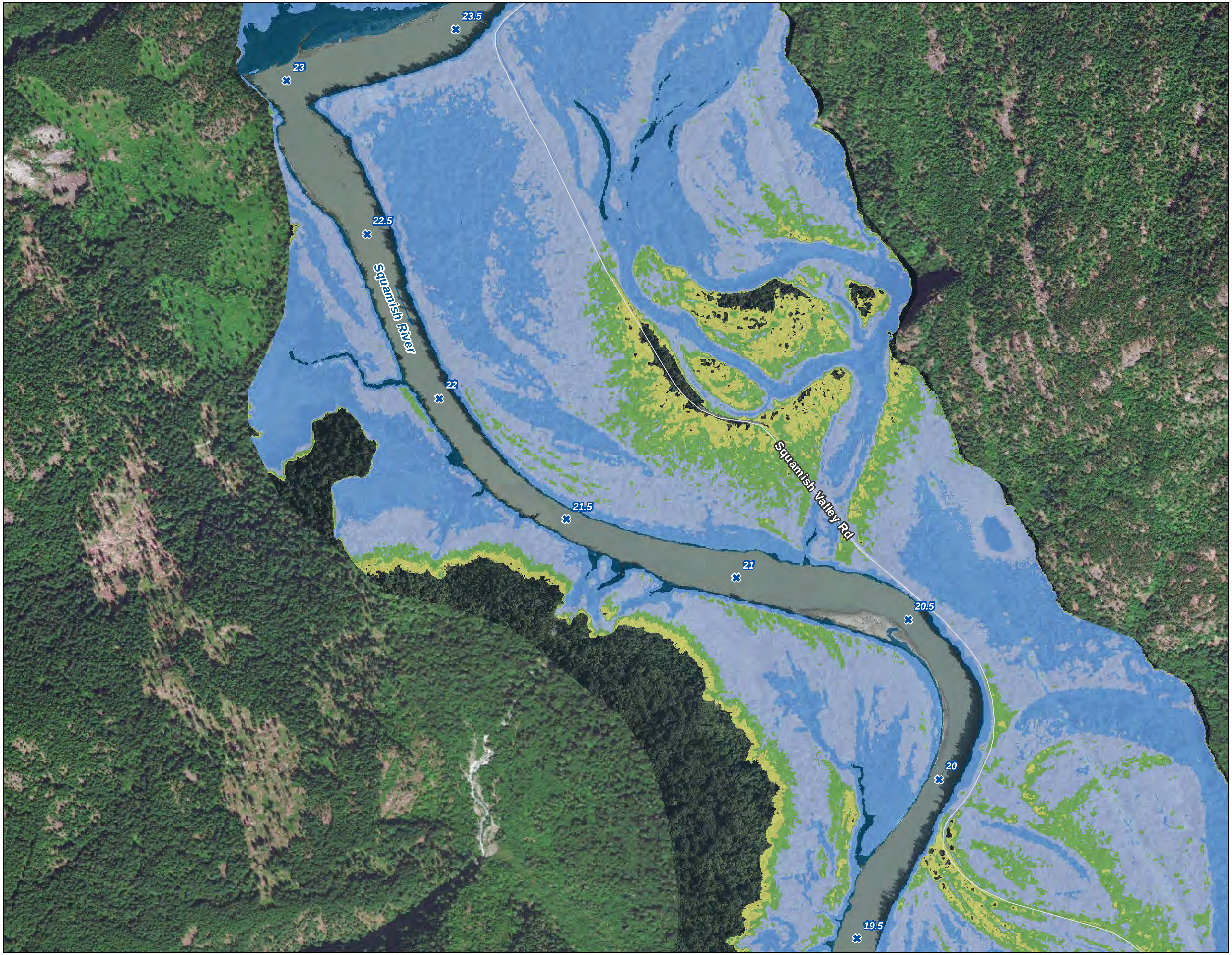
Engineer	*GIS*	*Reviewer*
THB	*MAO*	*THB*

Job Number	*Date*
3003329	*26-NOV-2018*

SQUAMISH FLOOD HAZARD MAPPING

500-Year Flood Depth

SHEET 6 OF 9



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REGIONAL DISTRICT

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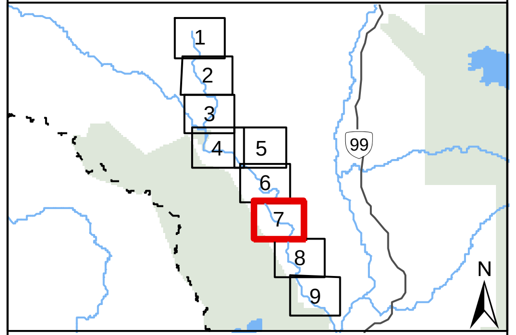

River Km
Road
Limits of Mapping

Depth (m)

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0.5 - 1.0
1.0 - 2.0
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Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	GIS	Reviewer
THB	MAO	THB

Job Number	Date
3003329	26-NOV-2018

SQUAMISH FLOOD HAZARD MAPPING

500-Year Flood Depth

SHEET 7 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_DepthMapBook_20181123.mxd

Squamish - Lillooet
REGIONAL DISTRICT

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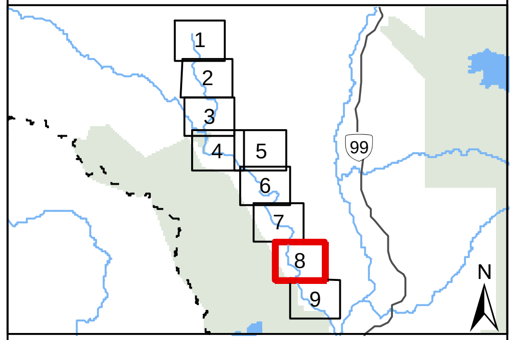

River Km

Road

Limits of Mapping

Depth (m)

0 - 0.5

0.5 - 1.0

1.0 - 2.0

2.0 - 5.0

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Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	*GIS*	*Reviewer*
THB	*MAO*	*THB*

Job Number	*Date*
3003329	*26-NOV-2018*

SQUAMISH FLOOD HAZARD MAPPING

500-Year Flood Depth

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_DepthMapBook_20181123.mxd

Squamish - Lillooet
REGIONAL DISTRICT

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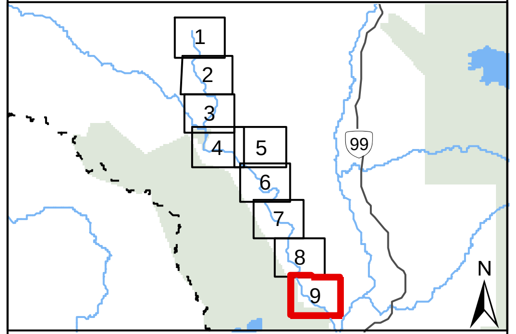

River Km

Road

Limits of Mapping

Depth (m)

0 - 0.5

0.5 - 1.0

1.0 - 2.0

2.0 - 5.0

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Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 *Metres*

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	GIS	Reviewer
THB	MAO	THB

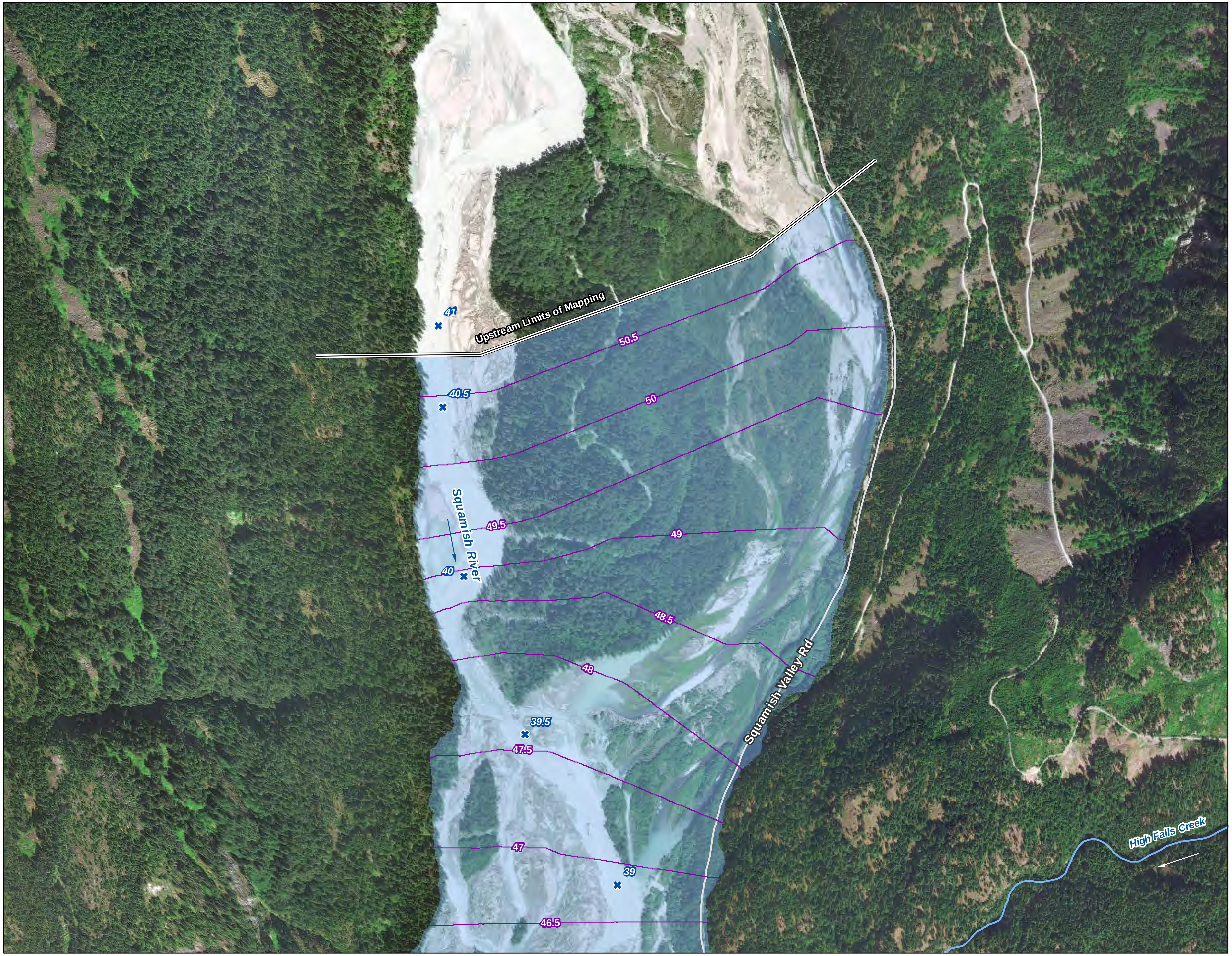
Job Number	Date
3003329	26-NOV-2018

SQUAMISH FLOOD HAZARD MAPPING

500-Year Flood Depth

SHEET 9 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_DepthMapBook_20181123.mxd



Squamish - Lillooet
REGIONAL DISTRICT

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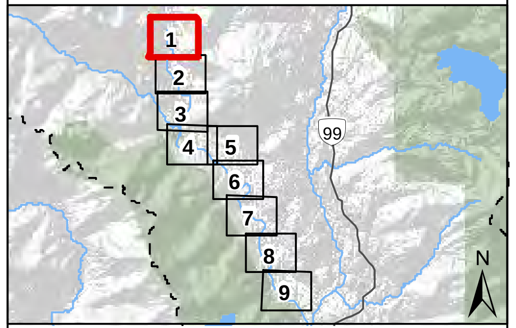


Legend

- River Km
- Tributary
- Road
- 200-year water surface elevation with 20% increase for climate change and 0.6 m freeboard
- Tributary Creek Fans
- 200-year inundation with 20% increase for climate change and 0.6 m freeboard

Source: 2016 imagery in channel with 2013 valley wall imagery from ESRI

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000
0 100 200 400 Metres
N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

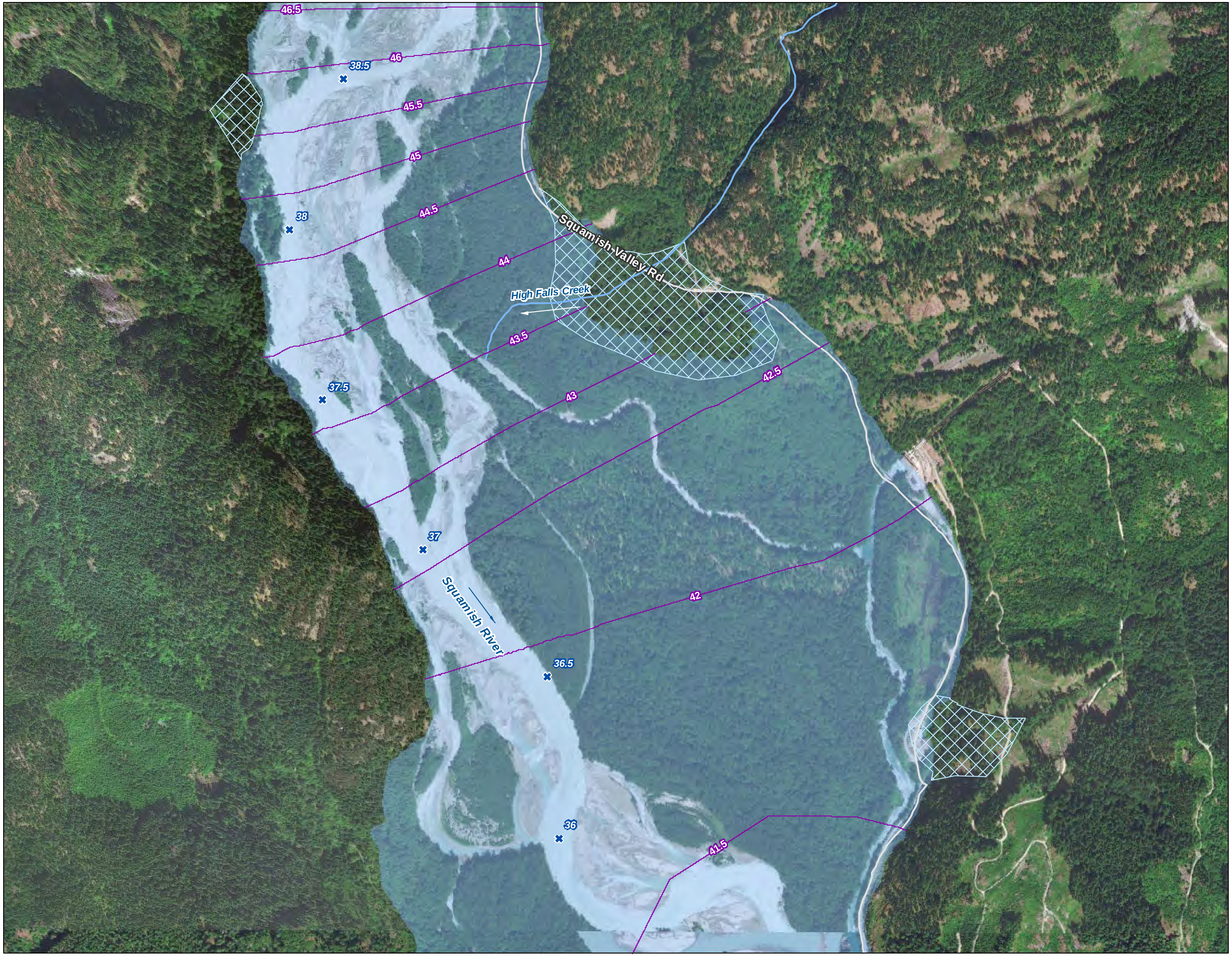
Engineer	GIS	Reviewer
THB	MAO	THB

Job Number	Date
3003329	26-NOV-2018

SQUAMISH RIVER
FLOOD HAZARD MAPPING

Flood Construction Level

PANEL 1 OF 9



Squamish - Lillooet
REGIONAL DISTRICT

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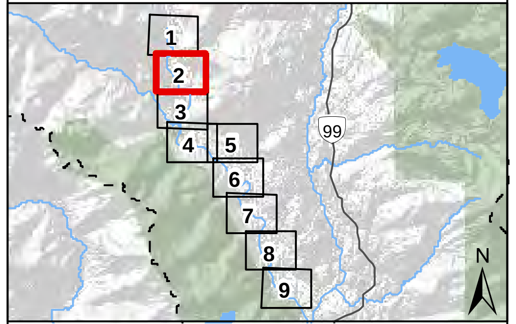


Legend

- 28 River Km
- Tributary
- Road
- 28 200-year water surface elevation with 20% increase for climate change and 0.6 m freeboard
- Tributary Creek Fans
- 200-year inundation with 20% increase for climate change and 0.6 m freeboard

Source: 2016 imagery in channel with 2013 valley wall imagery from ESRI

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000
0 100 200 400 Metres
N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	GIS	Reviewer
THB	MAO	THB

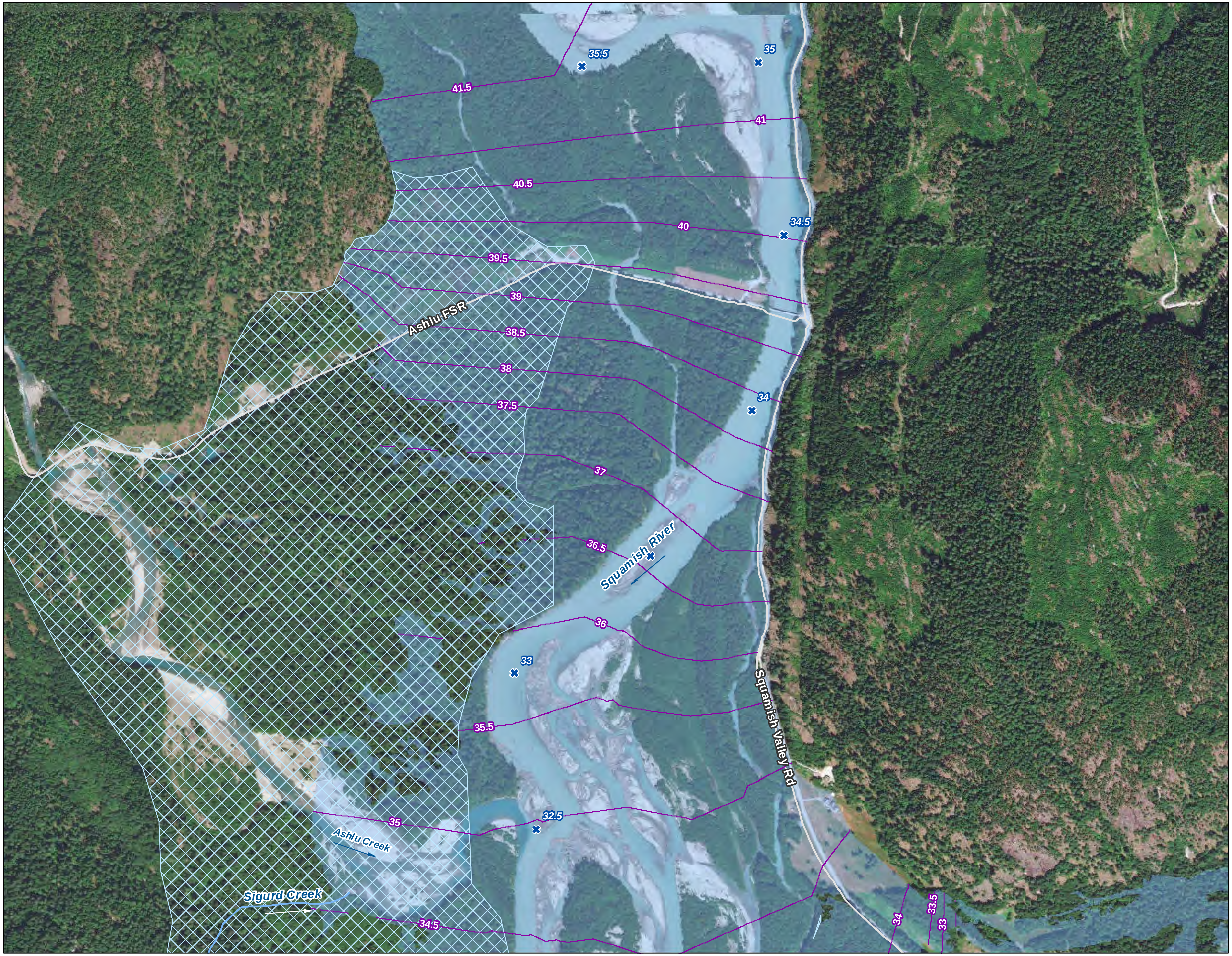
Job Number	Date
3003329	26-NOV-2018

SQUAMISH RIVER
FLOOD HAZARD MAPPING

Flood Construction Level

PANEL 2 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_FloodControlLevee.mxd



Squamish - Lillooet
REGIONAL DISTRICT

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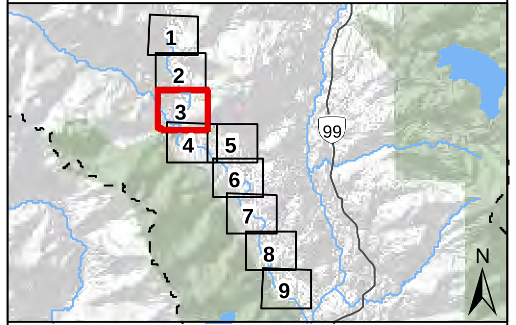


Legend

- 28 River Km
- Tributary
- Road
- 28 200-year water surface elevation with 20% increase for climate change and 0.6 m freeboard
- Tributary Creek Fans
- 200-year inundation with 20% increase for climate change and 0.6 m freeboard

Source: 2016 imagery in channel with 2013 valley wall imagery from ESRI

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000
0 100 200 400 Metres
N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

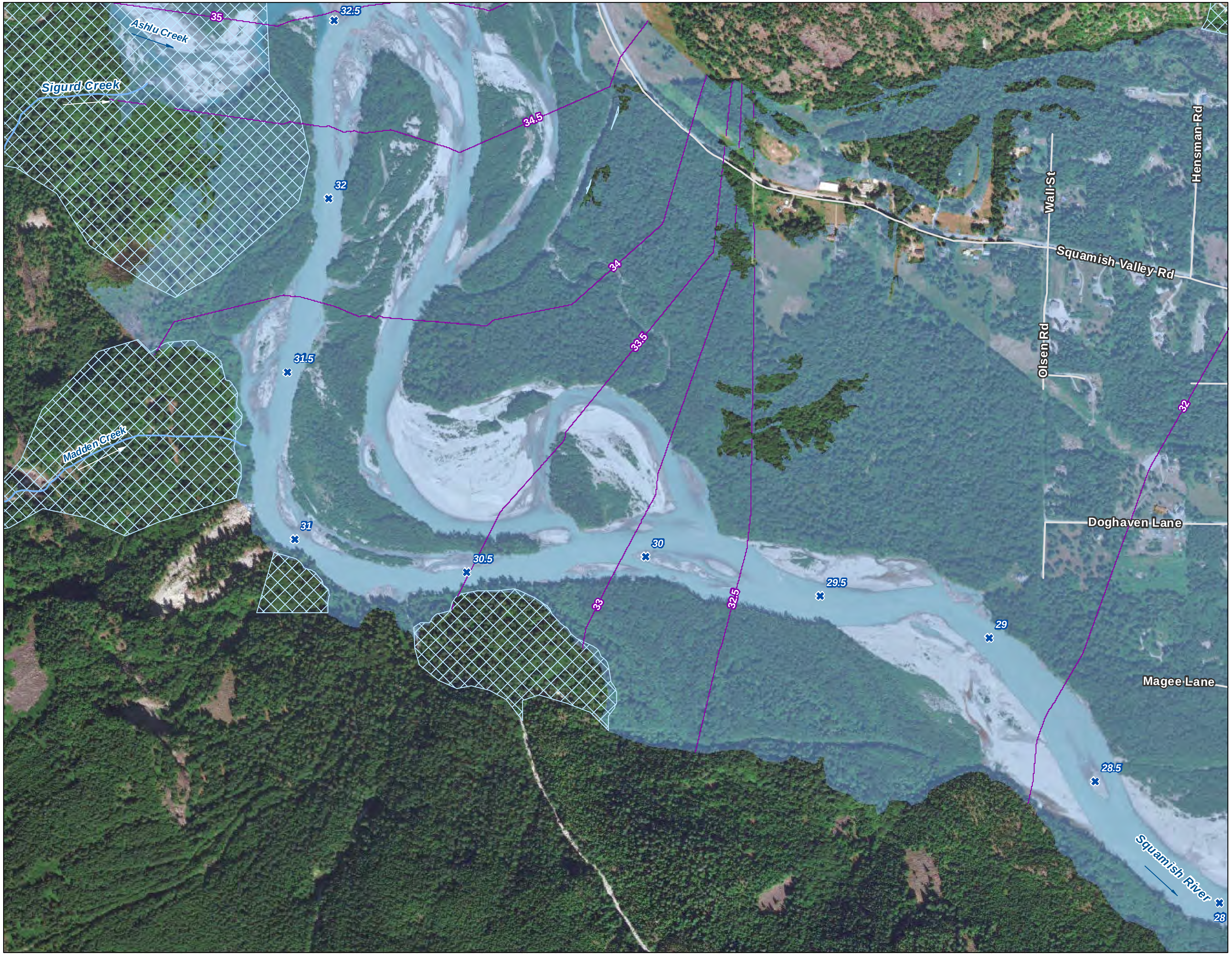
Engineer	GIS	Reviewer
THB	MAO	THB

Job Number	Date
3003329	26-NOV-2018

SQUAMISH RIVER
FLOOD HAZARD MAPPING

Flood Construction Level

PANEL 3 OF 9



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REGIONAL DISTRICT

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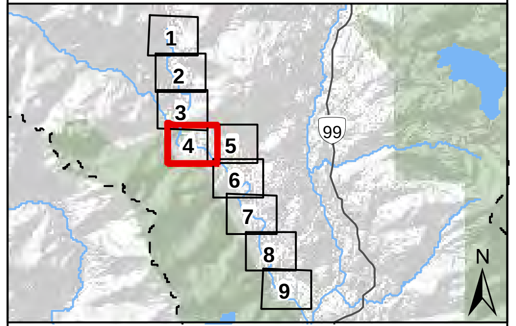


Legend

- 28 River Km
- Tributary
- Road
- 28 200-year water surface elevation with 20% increase for climate change and 0.6 m freeboard
- Tributary Creek Fans
- 200-year inundation with 20% increase for climate change and 0.6 m freeboard

Source: 2016 imagery in channel with 2013 valley wall imagery from ESRI

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000
0 100 200 400 Metres
N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

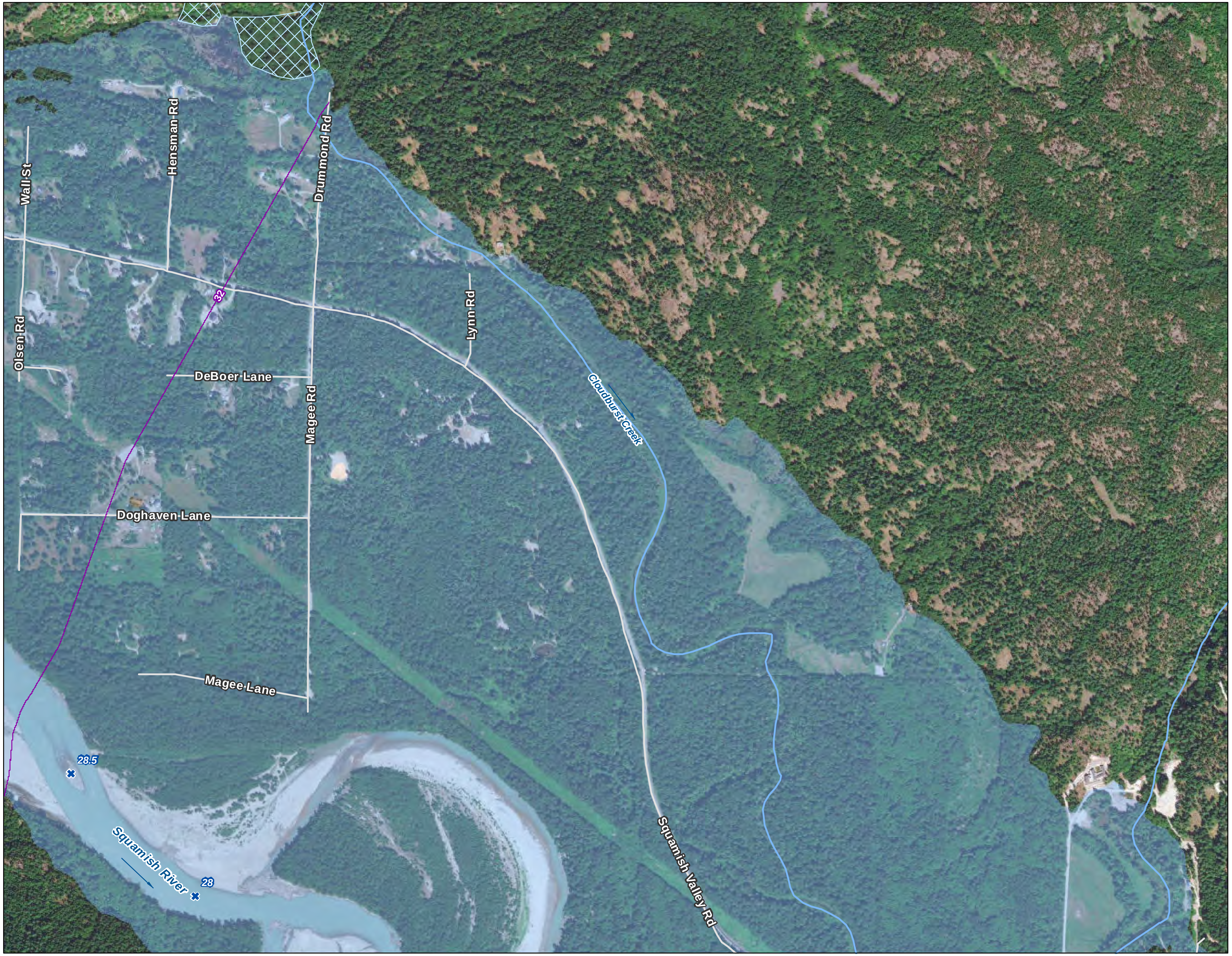
Engineer	GIS	Reviewer
THB	MAO	THB

Job Number	Date
3003329	26-NOV-2018

SQUAMISH RIVER
FLOOD HAZARD MAPPING

Flood Construction Level

PANEL 4 OF 9



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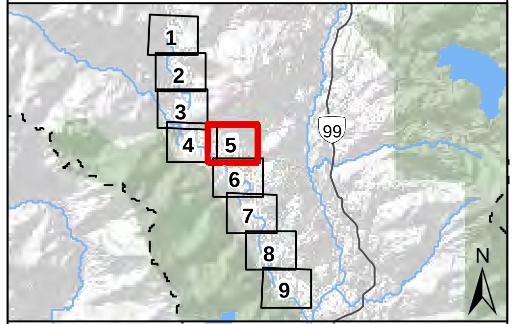


Legend

- 28 River Km
- Tributary
- Road
- 28 200-year water surface elevation with 20% increase for climate change and 0.6 m freeboard
- Tributary Creek Fans
- 200-year inundation with 20% increase for climate change and 0.6 m freeboard

Source: 2016 imagery in channel with 2013 valley wall imagery from ESRI

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	GIS	Reviewer
THB	MAO	THB

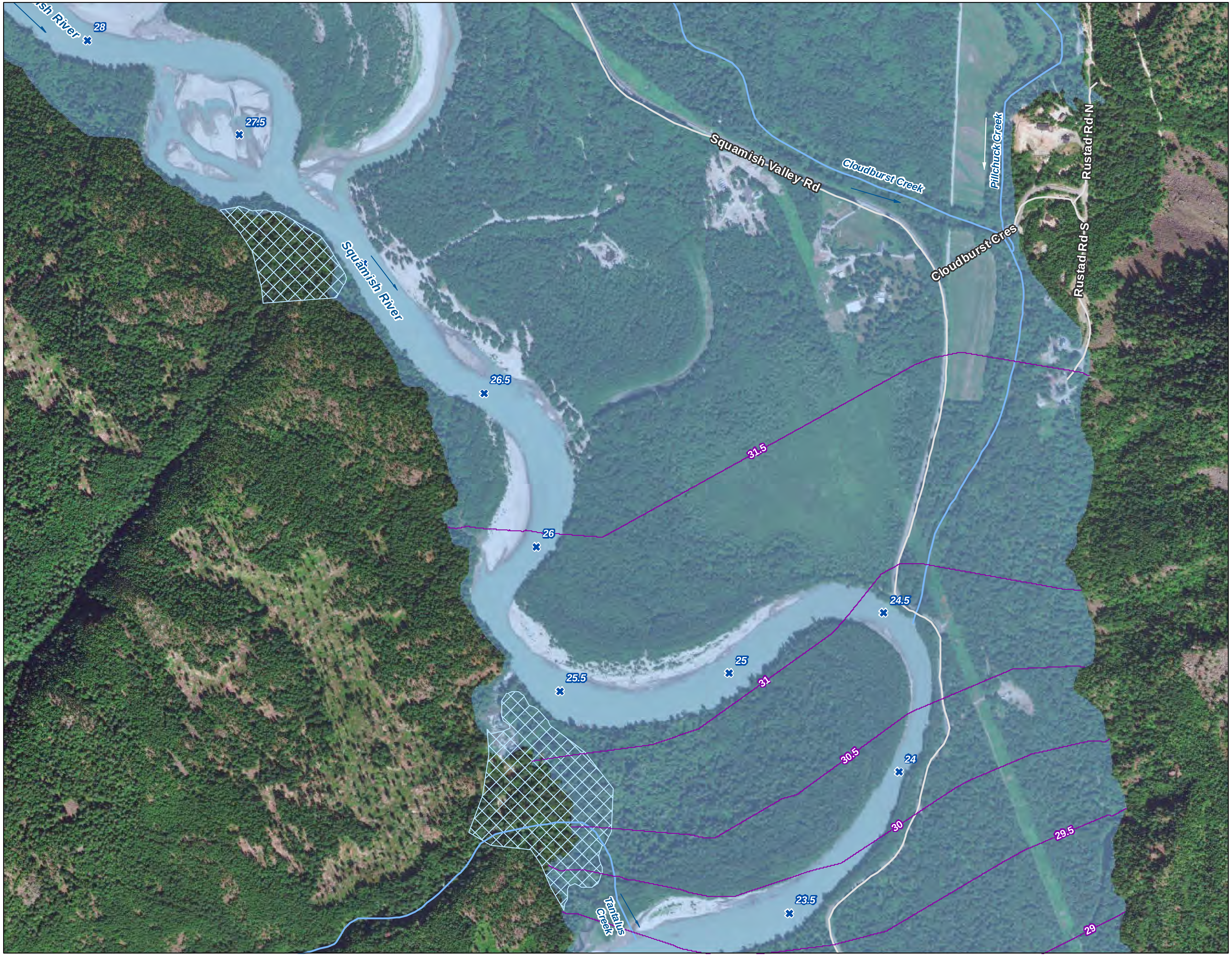
Job Number	Date
3003329	26-NOV-2018

SQUAMISH RIVER
FLOOD HAZARD MAPPING

Flood Construction Level

PANEL 5 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_FloodControlLevee.mxd



Squamish - Lillooet
REGIONAL DISTRICT

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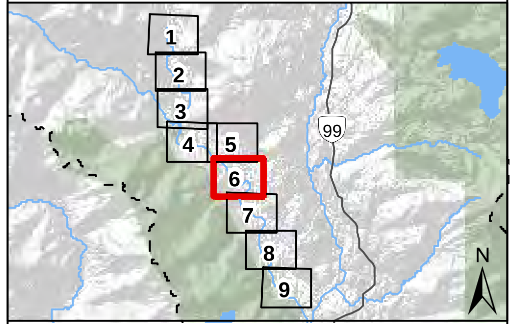


Legend

- 28 River Km
- Tributary
- Road
- 28 200-year water surface elevation with 20% increase for climate change and 0.6 m freeboard
- Tributary Creek Fans
- 200-year inundation with 20% increase for climate change and 0.6 m freeboard

Source: 2016 imagery in channel with 2013 valley wall imagery from ESRI

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000
0 100 200 400 Metres
N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	GIS	Reviewer
THB	MAO	THB

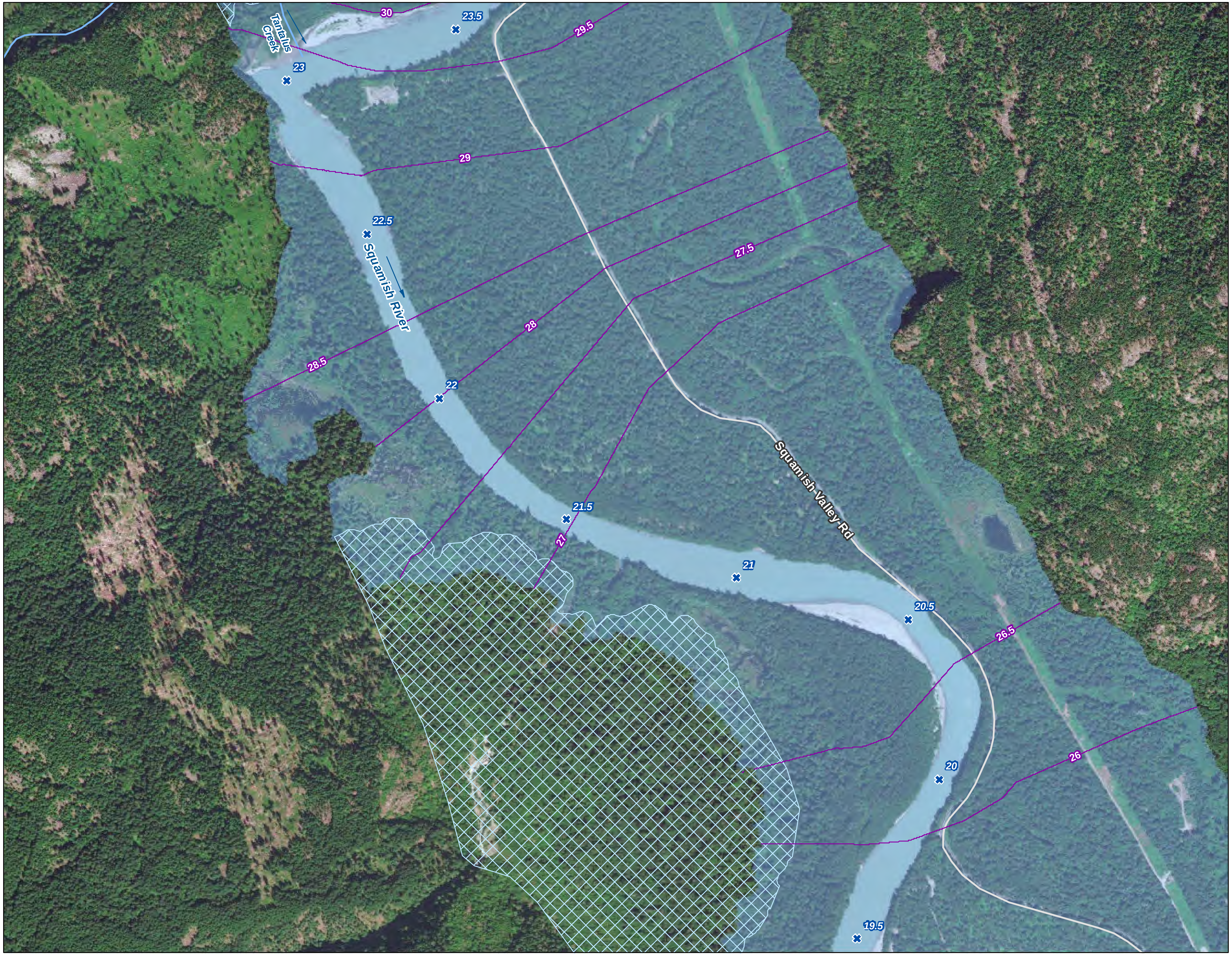
Job Number	Date
3003329	26-NOV-2018

SQUAMISH RIVER
FLOOD HAZARD MAPPING

Flood Construction Level

PANEL 6 OF 9

MAO Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_FloodControlLevee.mxd



Squamish - Lillooet
REGIONAL DISTRICT

nhc
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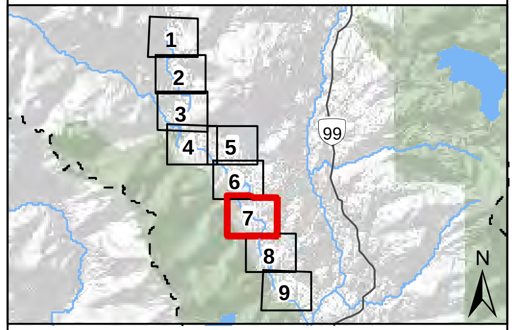

Legend

- River Km
- Tributary
- Road
- 200-year water surface elevation with 20% increase for climate change and 0.6 m freeboard
- Tributary Creek Fans
- 200-year inundation with 20% increase for climate change and 0.6 m freeboard

Source: 2016 imagery in channel with 2013 valley wall imagery from ESRI

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	GIS	Reviewer
THB	MAO	THB

Job Number	Date
3003329	26-NOV-2018

SQUAMISH RIVER
FLOOD HAZARD MAPPING

Flood Construction Level

PANEL 7 OF 9

Squamish - Lillooet
REGIONAL DISTRICT

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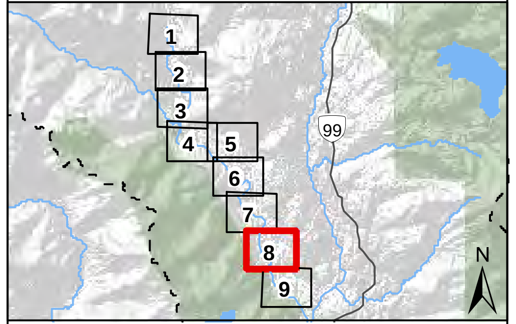
northwest hydraulic consultants



Legend

- 28 River Km
- Tributary
- Road
- 28 200-year water surface elevation with 20% increase for climate change and 0.6 m freeboard
- Tributary Creek Fans
- 200-year inundation with 20% increase for climate change and 0.6 m freeboard

Source: 2016 imagery in channel with 2013 valley wall imagery from ESRI

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	GIS	Reviewer
THB	MAO	THB

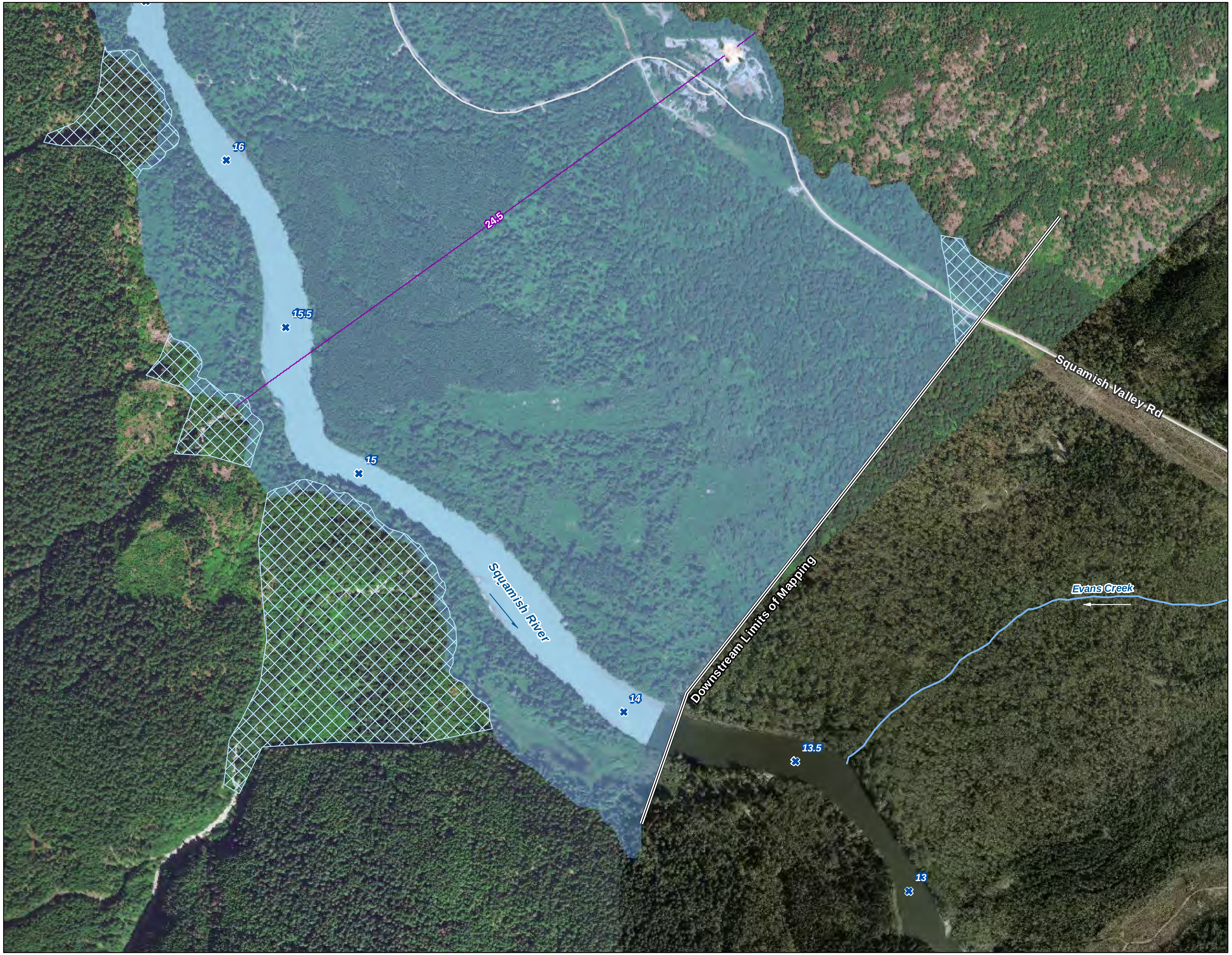
Job Number	Date
3003329	26-NOV-2018

SQUAMISH RIVER
FLOOD HAZARD MAPPING

Flood Construction Level

PANEL 8 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_FloodControlLevee.mxd



Legend

- River Km
- Tributary
- Road
- 200-year water surface elevation with 20% increase for climate change and 0.6 m freeboard
- Tributary Creek Fans
- 200-year inundation with 20% increase for climate change and 0.6 m freeboard

Source: 2016 imagery in channel with 2013 valley wall imagery from ESRI

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

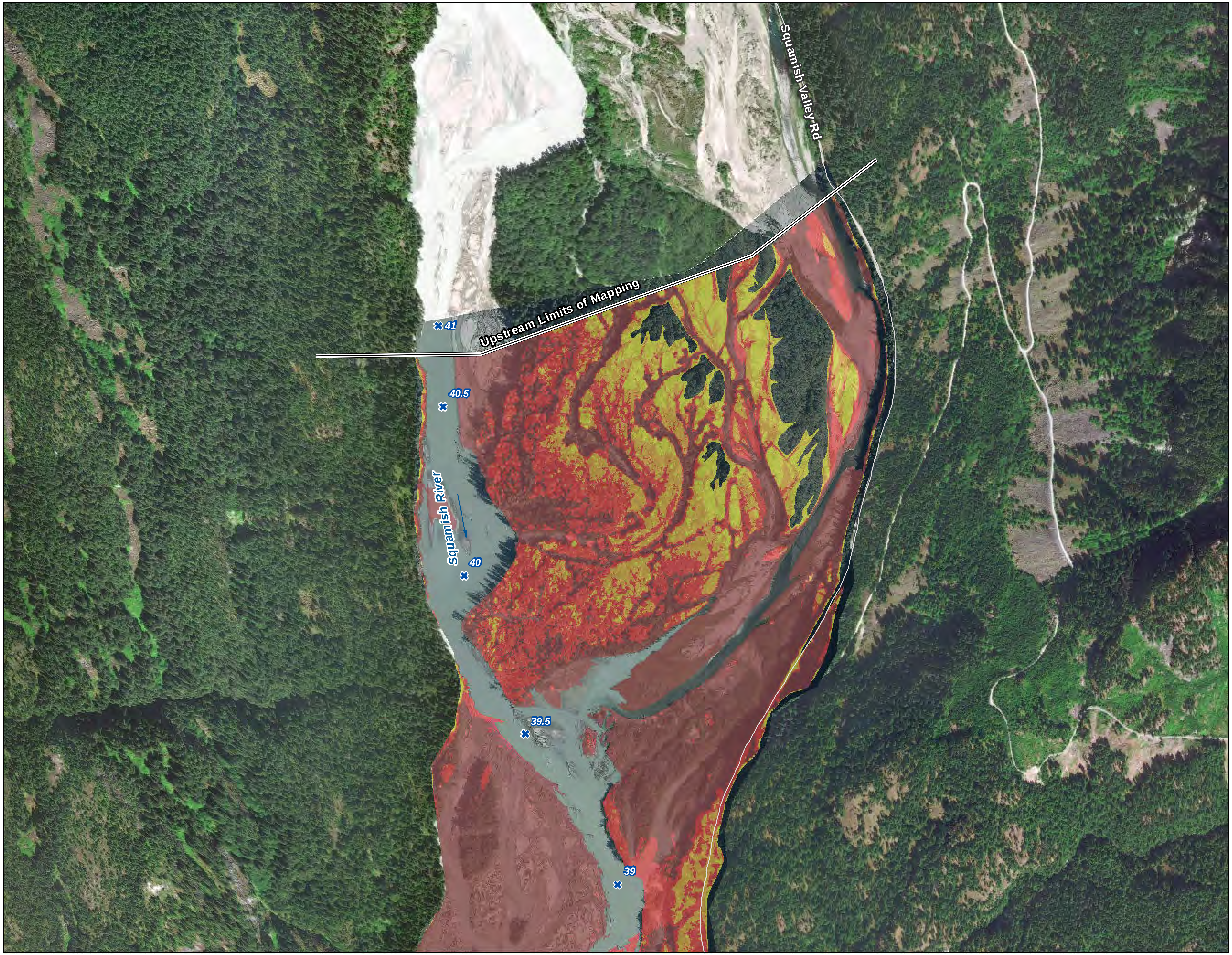
Engineer	GIS	Reviewer
THB	MAO	THB

Job Number	Date
3003329	26-NOV-2018

SQUAMISH RIVER
FLOOD HAZARD MAPPING

Flood Construction Level

PANEL 9 OF 9



Squamish - Lillooet
REGIONAL DISTRICT

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northwest hydraulic consultants

Limits of Mapping
River Km
Road

Hazard Ratimg (m*m/s)

Hazard Rating = (Depth x (Velocity +0.5)) + DF

< 0.75
0.75 - 1.25
1.25 - 2
> 2

Low: Caution - Flood zone with shallow flowing water or deep standing water.

Moderate: Dangerous for some (i.e. children) - flood zone with deep or fast flowing water.

Significant: Dangerous for most people - flood zone with deep, fast flowing water.

Extreme: Dangerous for all - flood zone with deep, fast flowing water.

Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 Metres

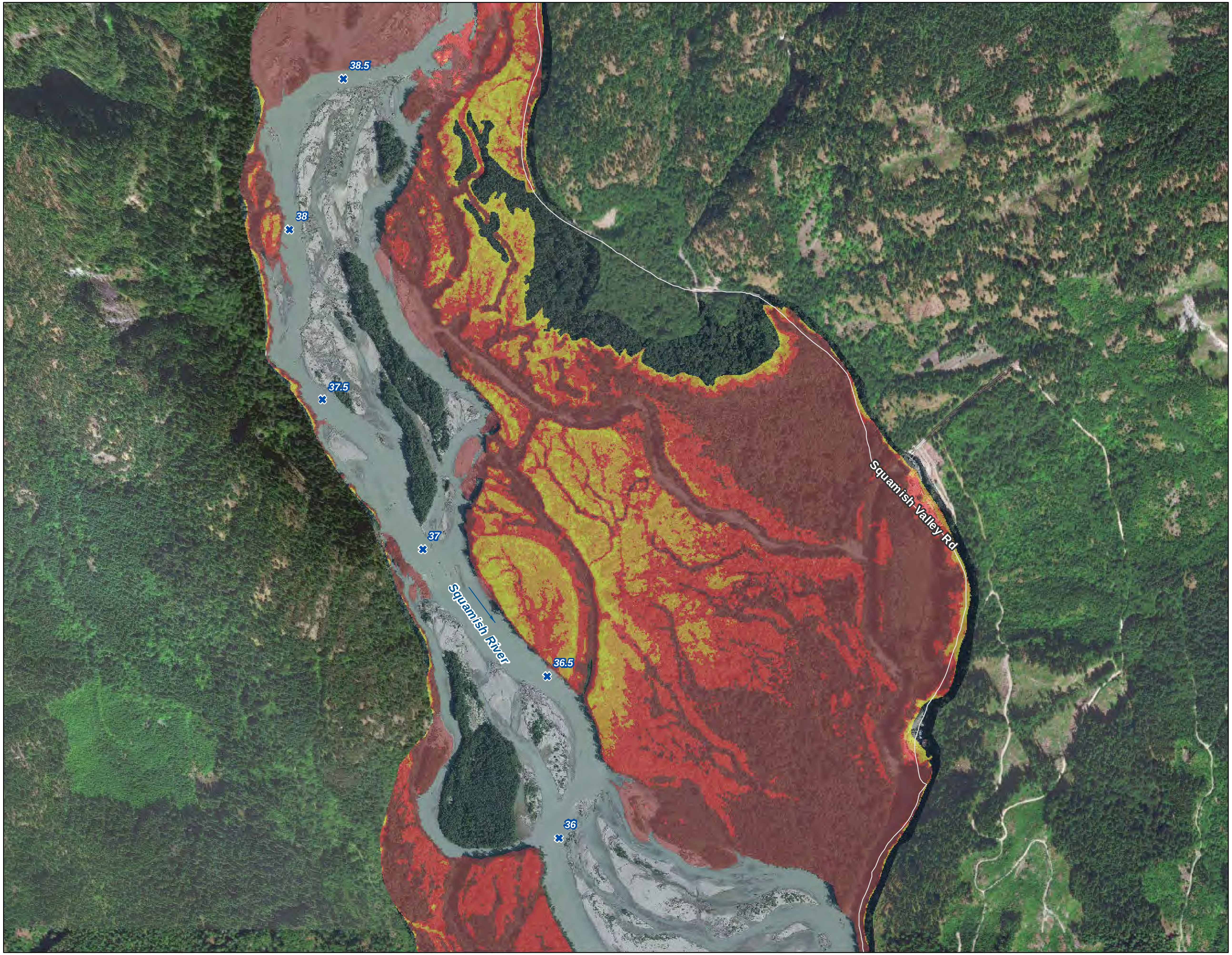
Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	GIS	Reviewer
THB	MAO	THB

Job Number	Date
3003329	26-NOV-2018

SQUAMISH FLOOD HAZARD MAPPING

50-Year Flood Hazard



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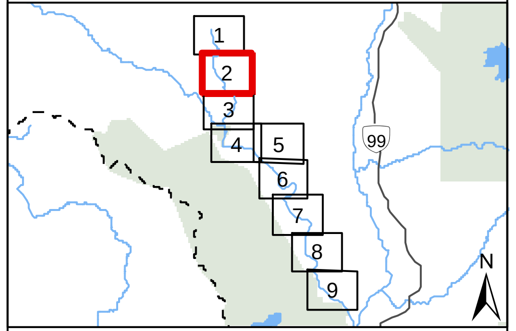

Limits of Mapping

River Km

Road

Hazard Ratimg (m*m/s)

Hazard Rating = (Depth x (Velocity +0.5)) + DF

- < 0.75
- 0.75 - 1.25
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Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	*GIS*	*Reviewer*
THB	*MAO*	*THB*

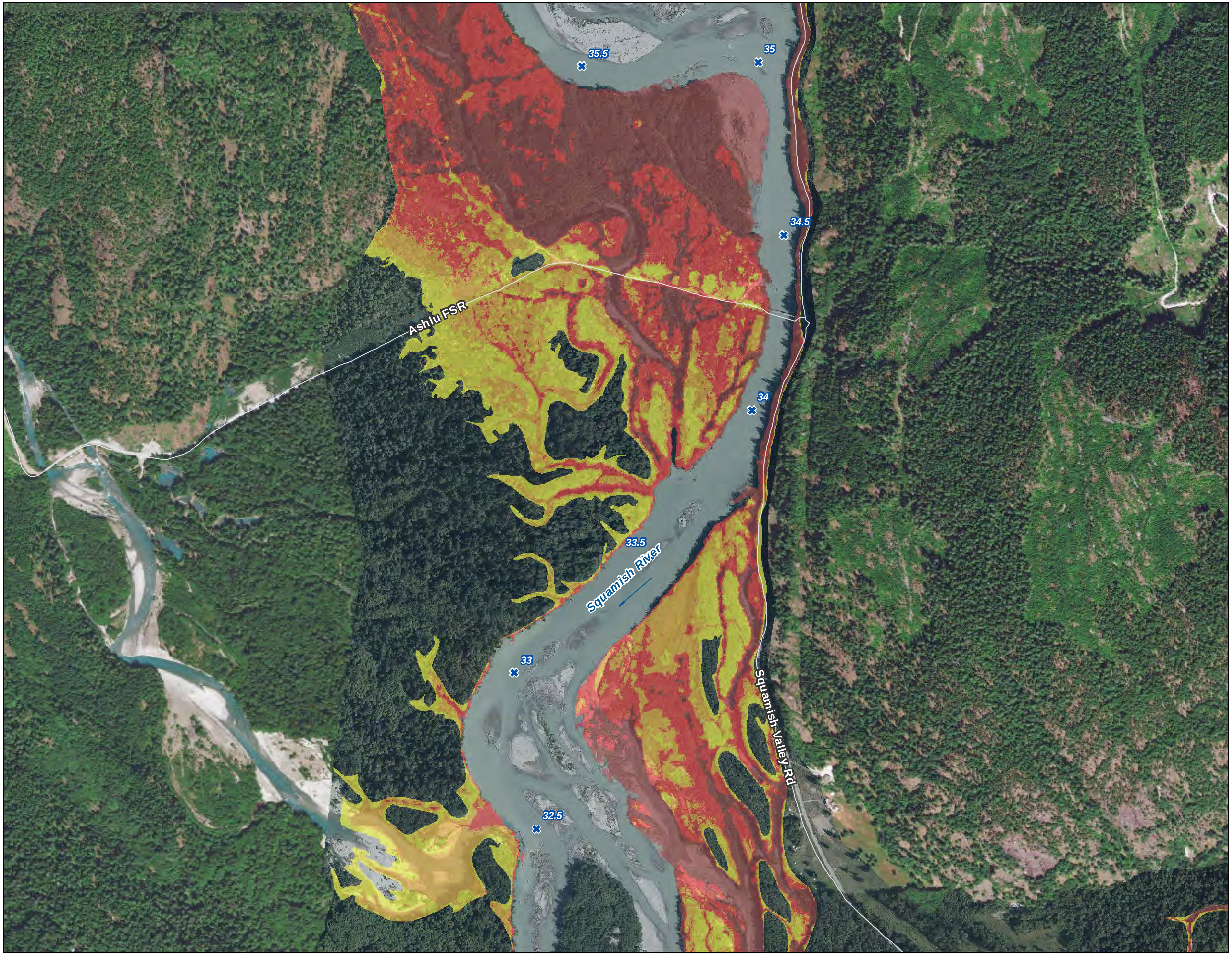
Job Number	*Date*
3003329	*26-NOV-2018*

SQUAMISH FLOOD HAZARD MAPPING

50-Year Flood Hazard

SHEET 2 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_FloodHazardMapBook_20181012.mxd



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REGIONAL DISTRICT

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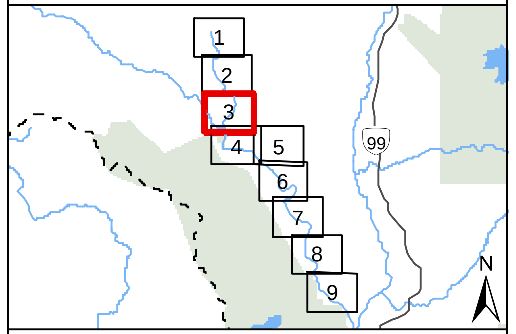

Limits of Mapping

River Km

Road

Hazard Ratimg (m*m/s)

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Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	GIS	Reviewer
THB	MAO	THB

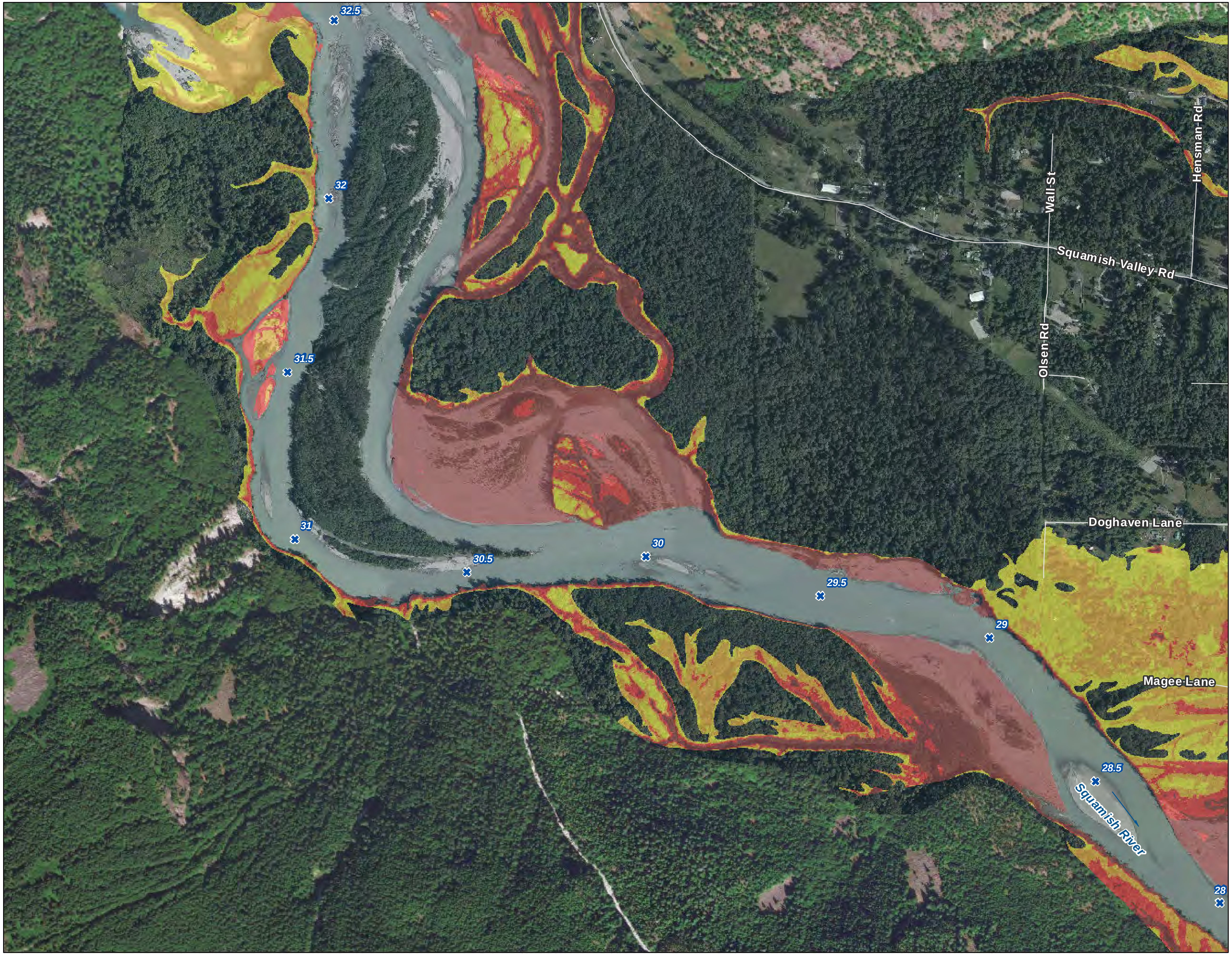
Job Number	Date
3003329	26-NOV-2018

SQUAMISH FLOOD HAZARD MAPPING

50-Year Flood Hazard

SHEET 3 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_FloodHazardMapBook_20181012.mxd



Squamish - Lillooet
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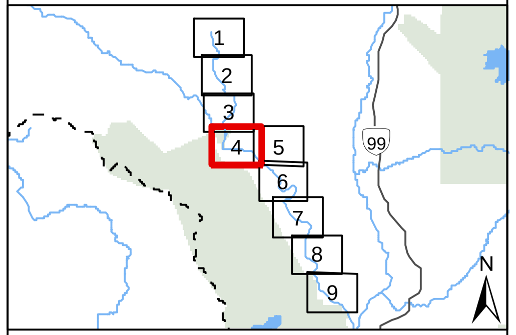

Limits of Mapping

River Km

Road

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0.75 - 1.25

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Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 *Metres*

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	*GIS*	*Reviewer*
THB	*MAO*	*THB*

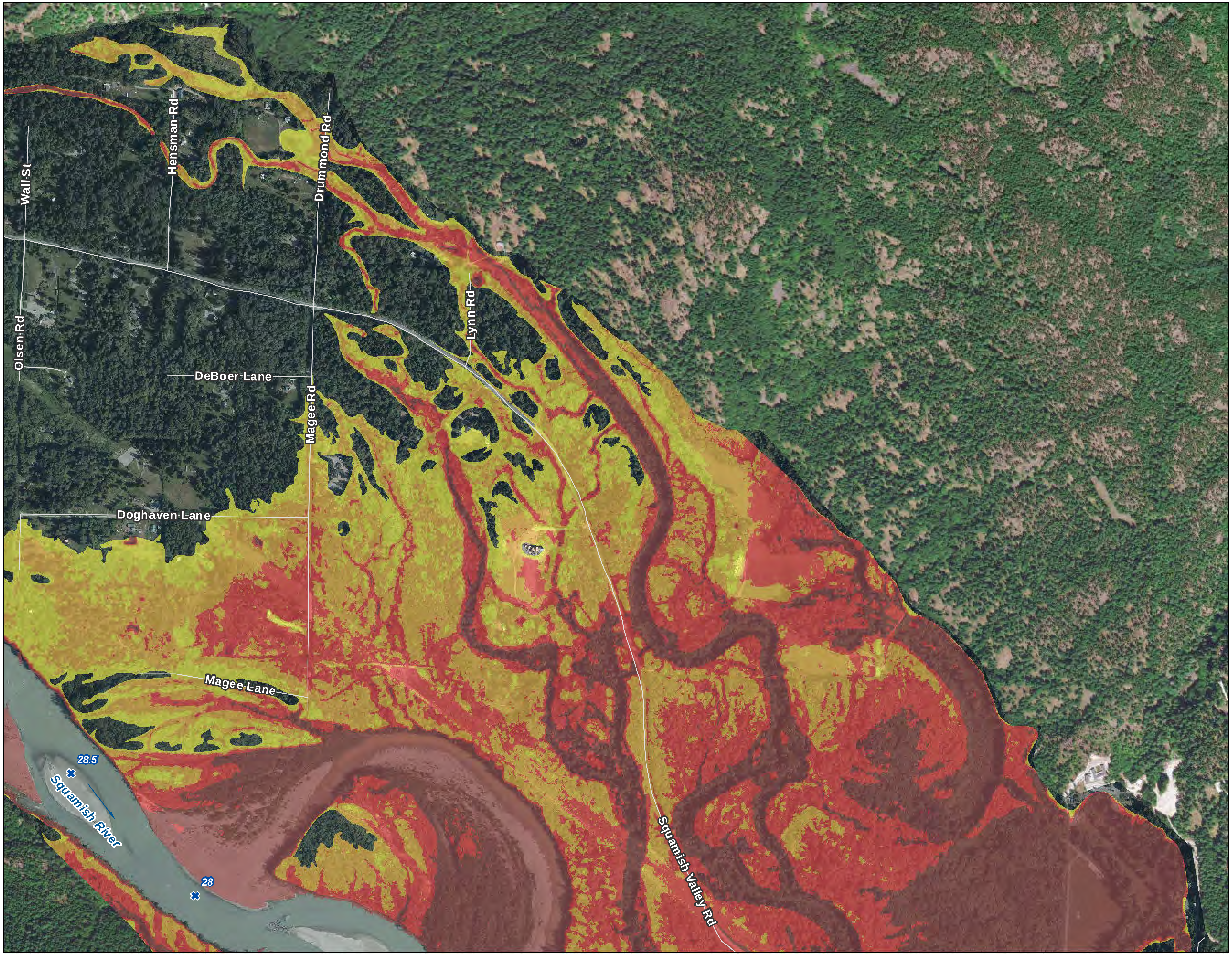
Job Number	*Date*
3003329	*26-NOV-2018*

SQUAMISH FLOOD HAZARD MAPPING

50-Year Flood Hazard

SHEET 4 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_FloodHazardMapBook_20181012.mxd



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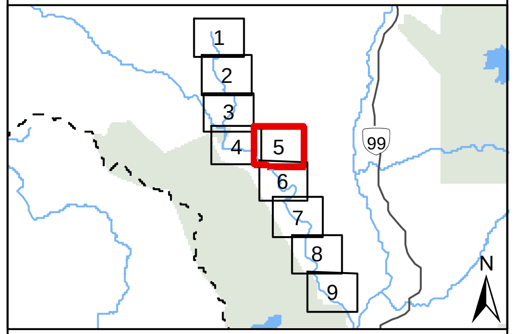

Limits of Mapping

River Km

Road

Hazard Ratimg (m*m/s)

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Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 *Metres*

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	*GIS*	*Reviewer*
THB	*MAO*	*THB*

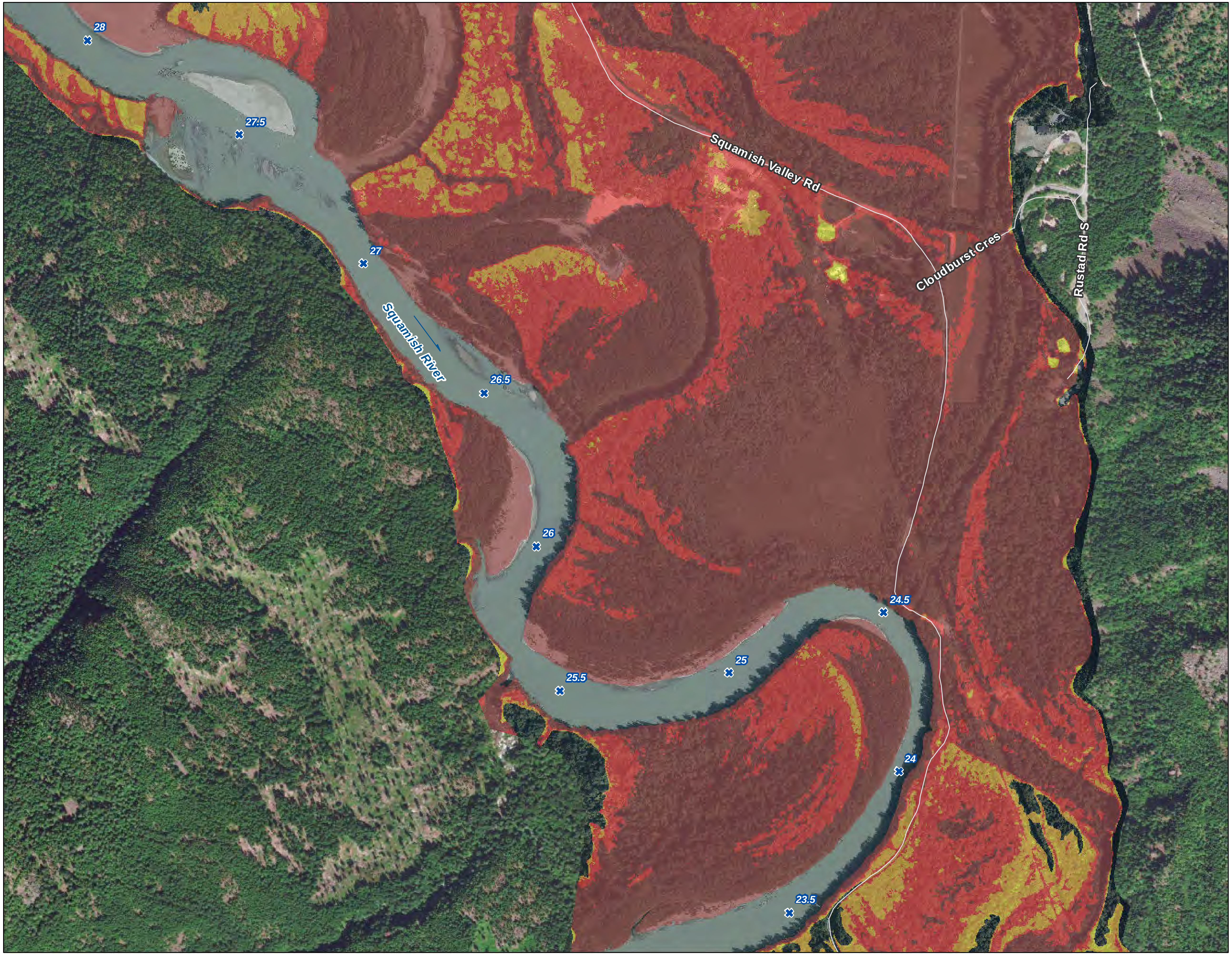
Job Number	*Date*
3003329	*26-NOV-2018*

SQUAMISH FLOOD HAZARD MAPPING

50-Year Flood Hazard

SHEET 5 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_FloodHazardMapBook_20181012.mxd



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REGIONAL DISTRICT

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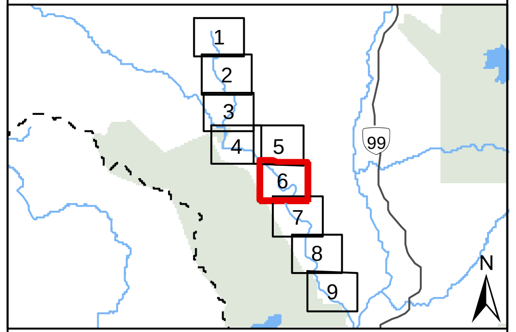

Limits of Mapping
River Km
Road

Hazard Ratimg (m*m/s)

Hazard Rating = (Depth x (Velocity +0.5)) + DF

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Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	GIS	Reviewer
THB	MAO	THB

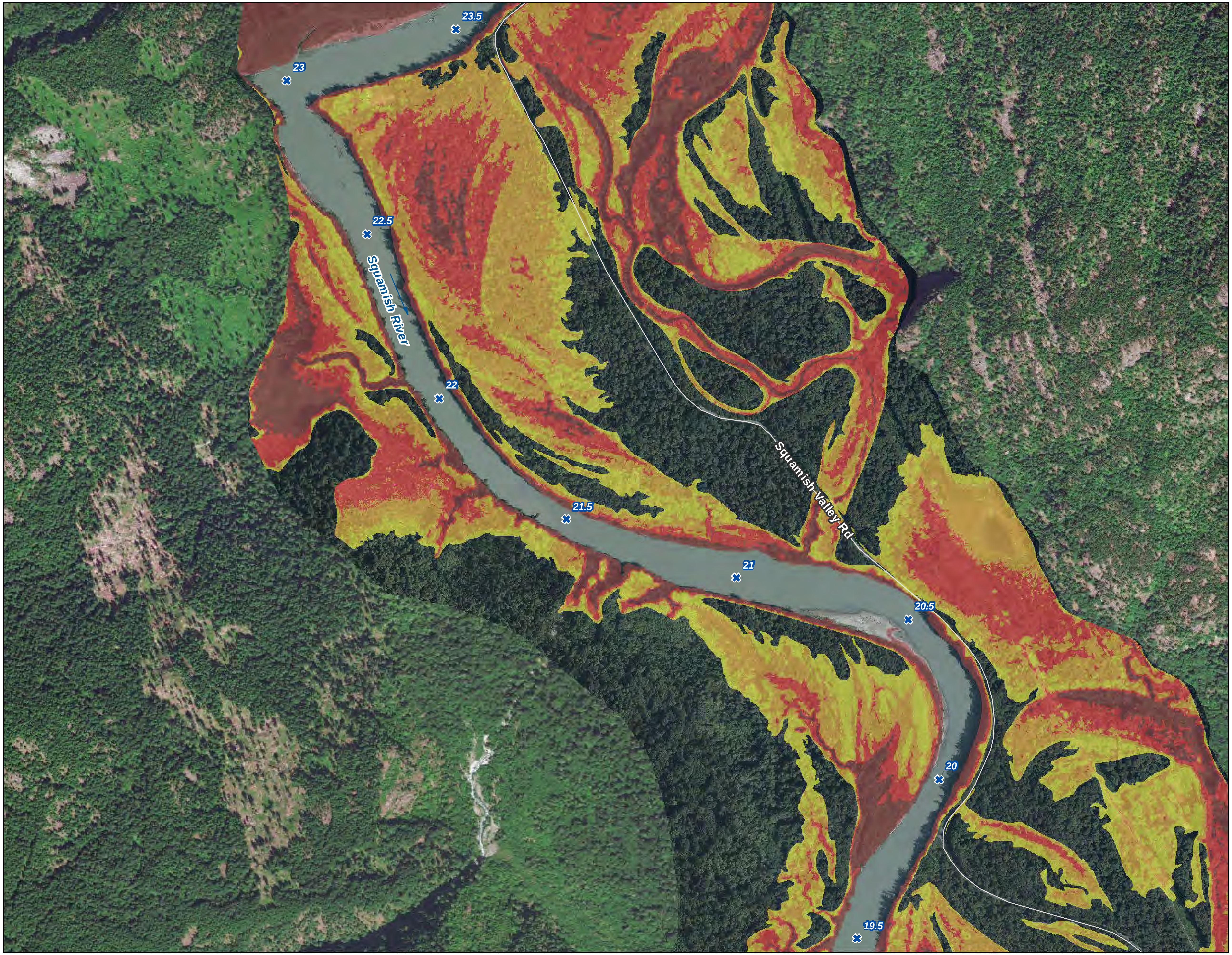
Job Number	Date
3003329	26-NOV-2018

SQUAMISH FLOOD HAZARD MAPPING

50-Year Flood Hazard

SHEET 6 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_FloodHazardMapBook_20181012.mxd



Squamish - Lillooet
REGIONAL DISTRICT

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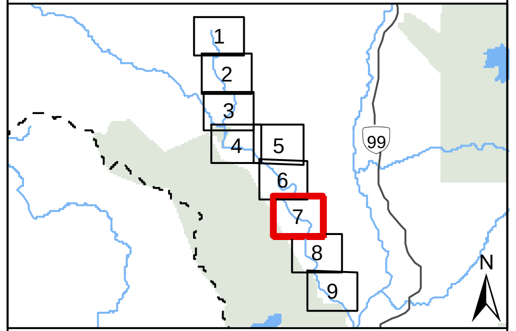
northwest hydraulic consultants



Limits of Mapping
River Km
Road

Hazard Ratimg (m*m/s)

Hazard Rating = (Depth x (Velocity +0.5)) + DF

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Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

N

0 100 200 400 *Metres*

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

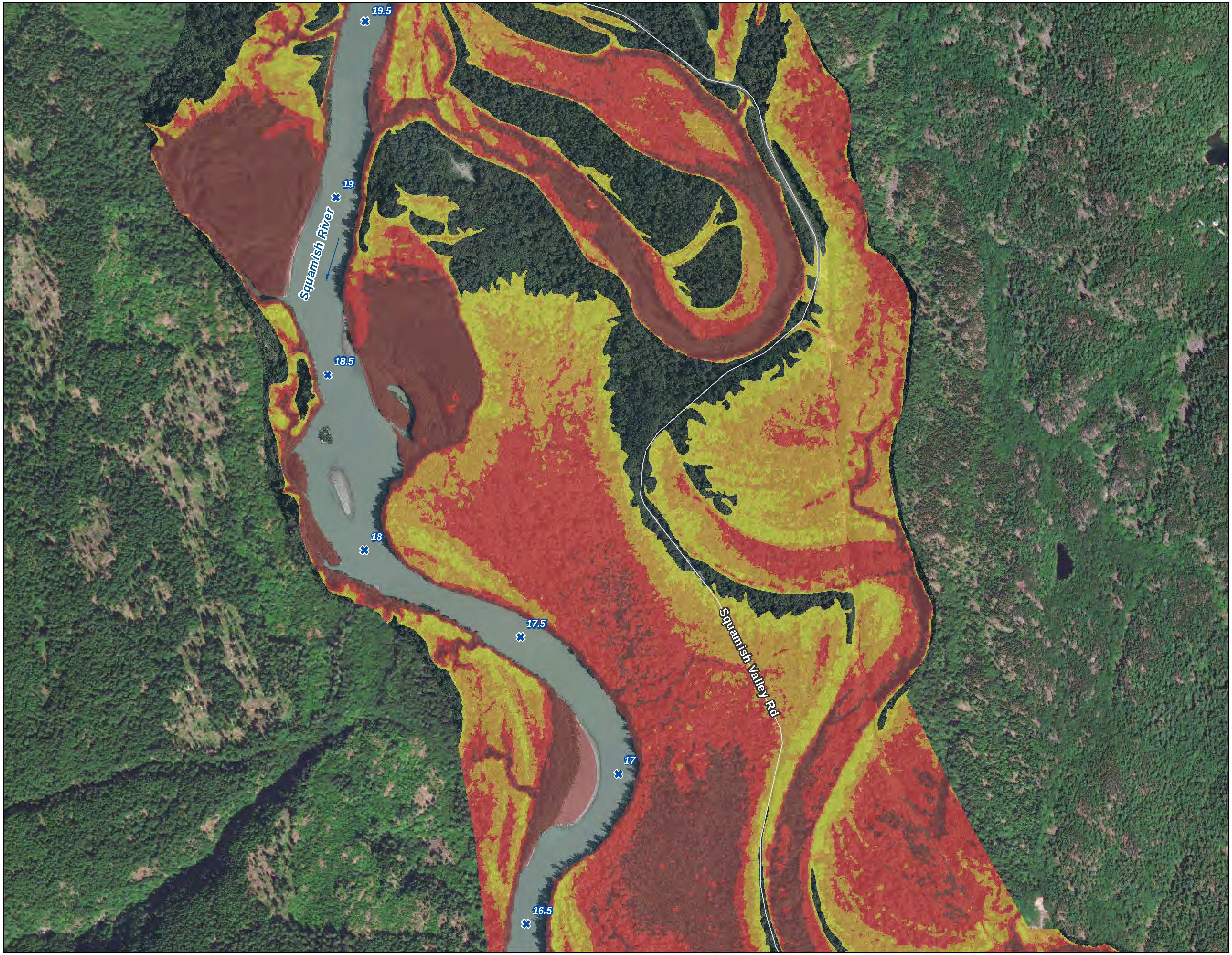
Engineer THB	*GIS* MAO	*Reviewer* THB
Job Number 3003329	*Date* 26-NOV-2018	

SQUAMISH FLOOD HAZARD MAPPING

50-Year Flood Hazard

SHEET 7 OF 9

MAO Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_FloodHazardMapBook_20181012.mxd



Squamish - Lillooet
REGIONAL DISTRICT

nhc
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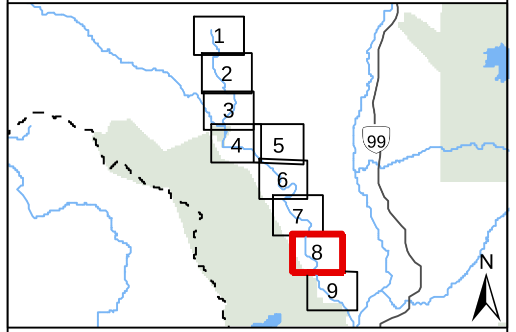

Limits of Mapping
River Km
Road

Hazard Ratimg (m*m/s)

Hazard Rating = (Depth x (Velocity +0.5)) + DF

- < 0.75
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- 1.25 - 2
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Data Sources: 2016 Orthoimagery

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SCALE - 1:10,000

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Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	GIS	Reviewer
THB	MAO	THB

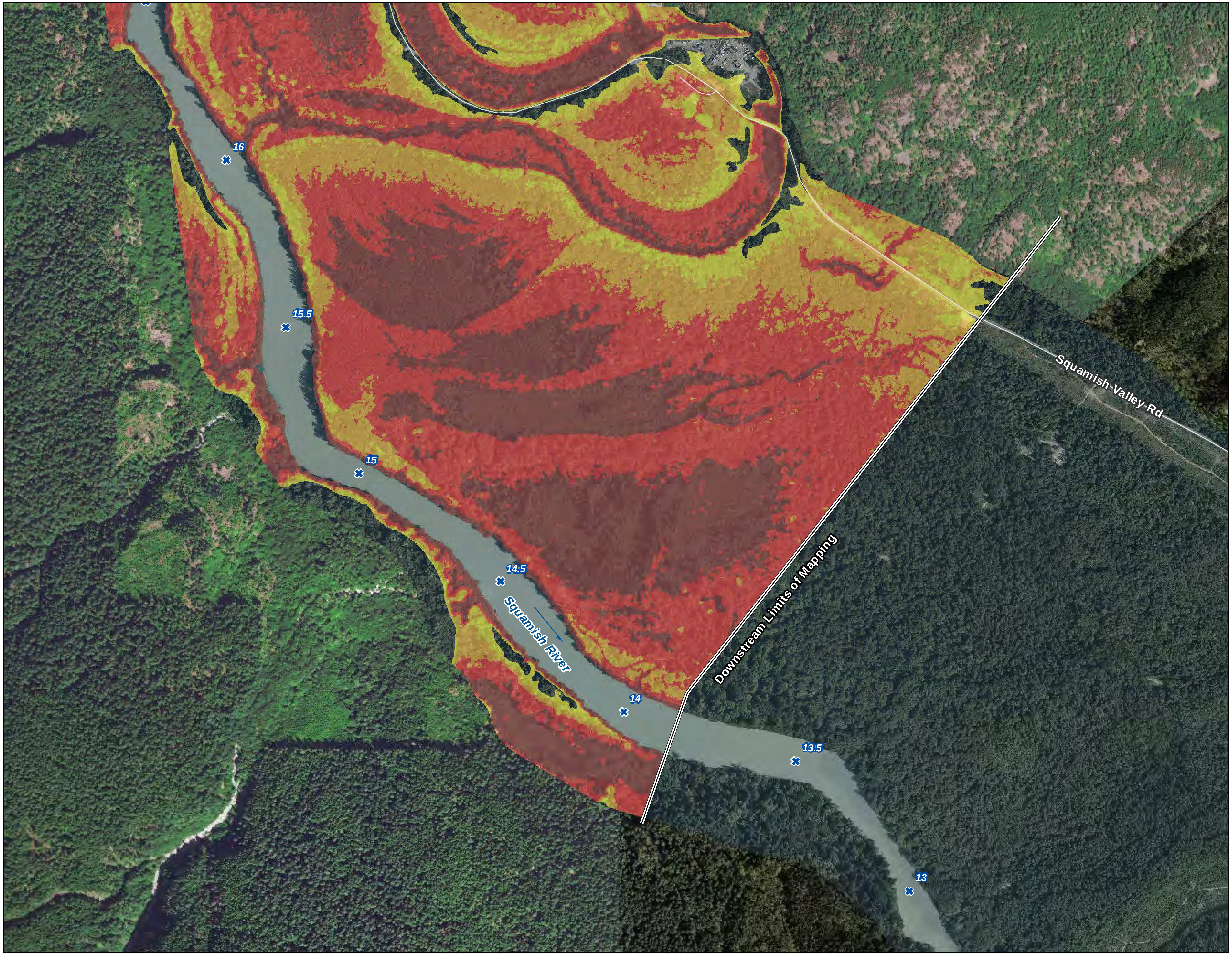
Job Number	Date
3003329	26-NOV-2018

SQUAMISH FLOOD HAZARD MAPPING

50-Year Flood Hazard

SHEET 8 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_FloodHazardMapBook_20181012.mxd



Squamish - Lillooet
REGIONAL DISTRICT

nhc
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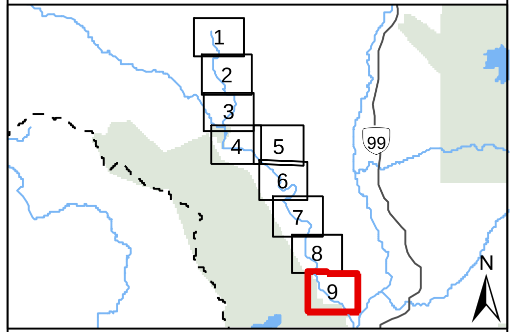

Limits of Mapping
River Km
Road

Hazard Ratimg (m*m/s)

Hazard Rating = (Depth x (Velocity +0.5)) + DF

- < 0.75
- 0.75 - 1.25
- 1.25 - 2
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Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 *Metres*

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	*GIS*	*Reviewer*
THB	*MAO*	*THB*

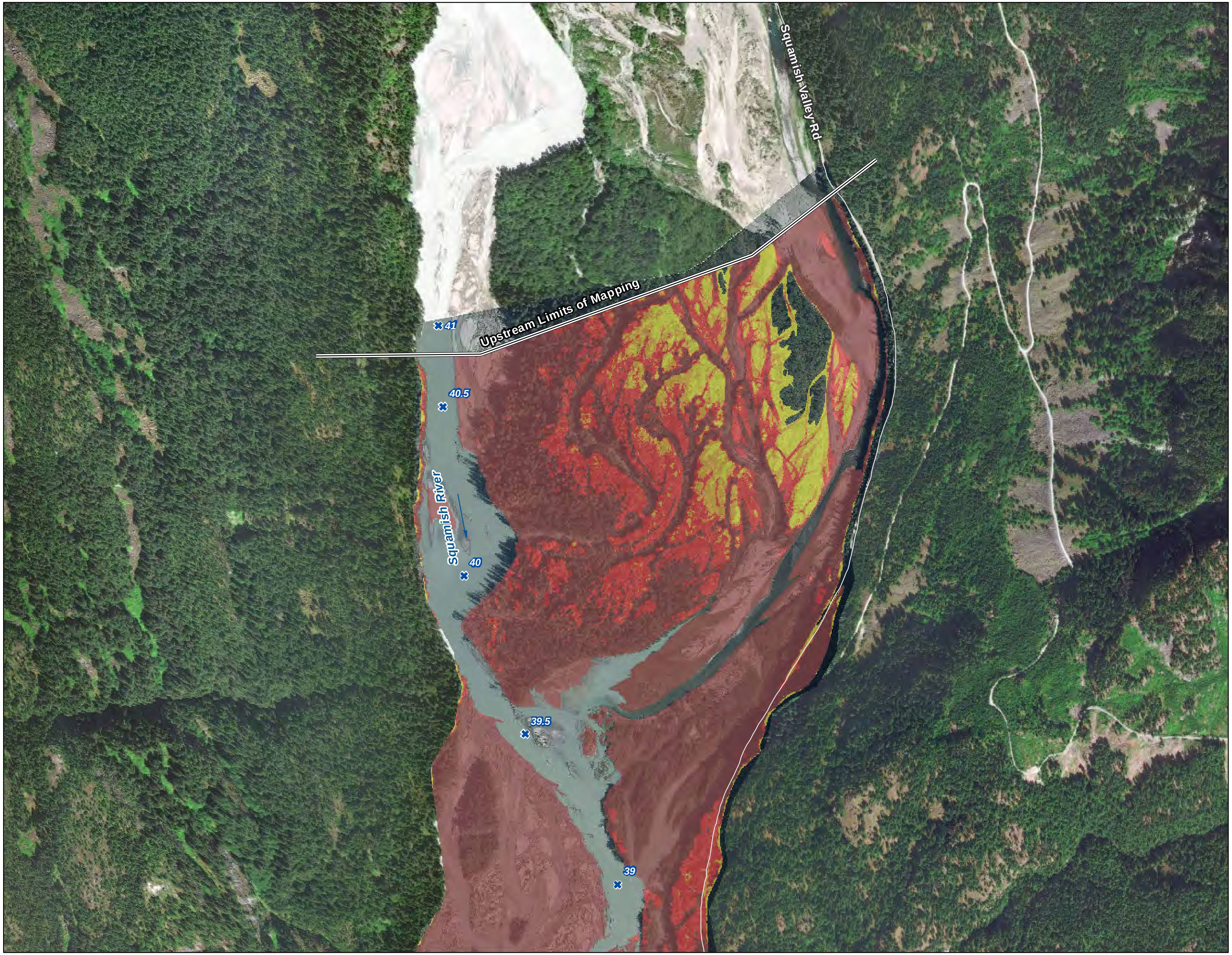
Job Number	*Date*
3003329	*26-NOV-2018*

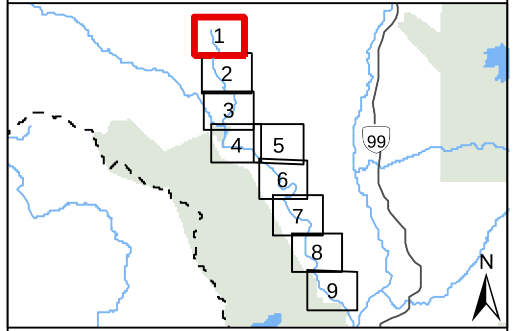
SQUAMISH FLOOD HAZARD MAPPING

50-Year Flood Hazard

SHEET 9 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_FloodHazardMapBook_20181012.mxd





Limits of Mapping
River Km
Road

Hazard Ratimg (m*m/s)

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Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	GIS	Reviewer
THB	MAO	THB

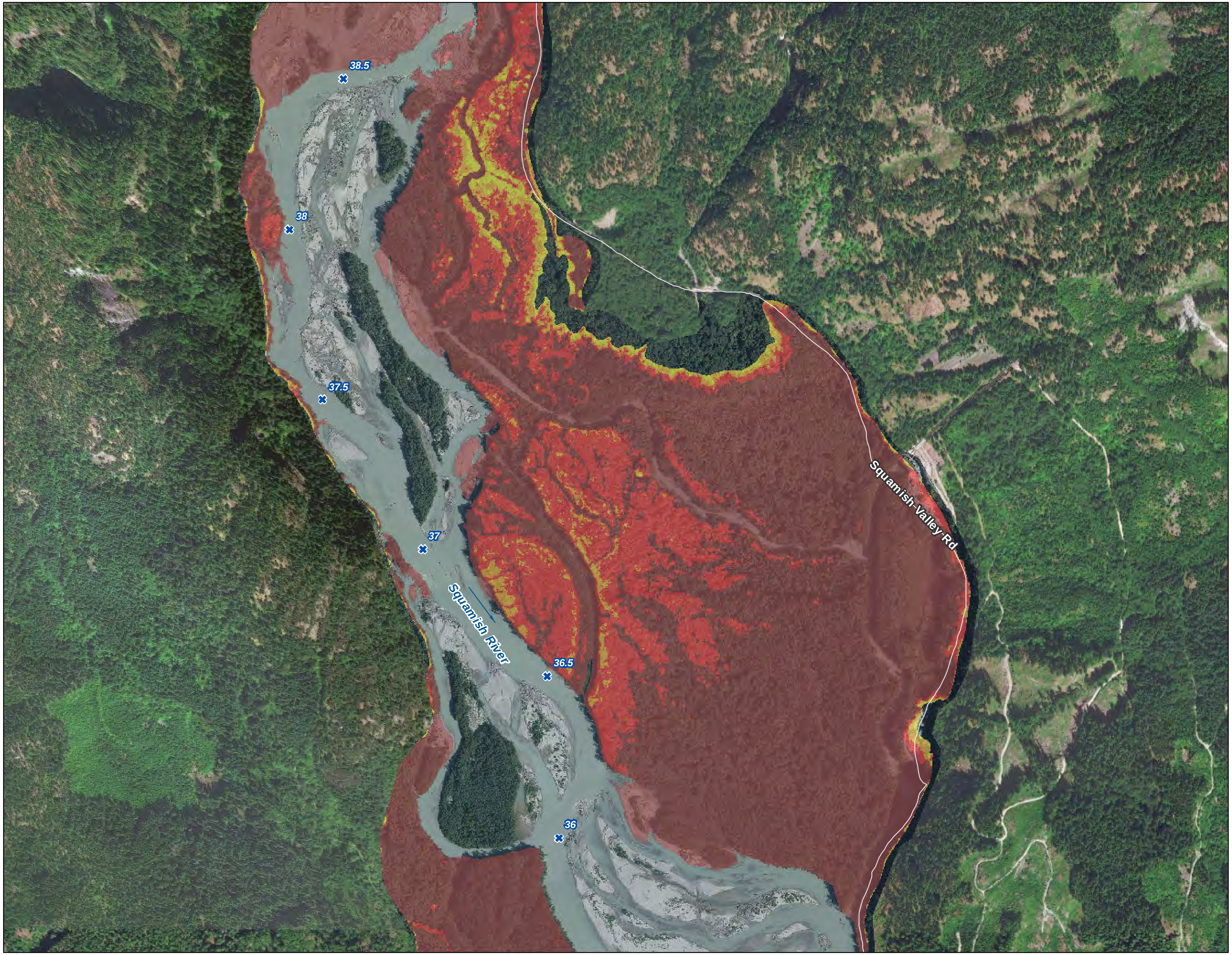
Job Number	Date
3003329	26-NOV-2018

SQUAMISH FLOOD HAZARD MAPPING

200-Year Flood Hazard

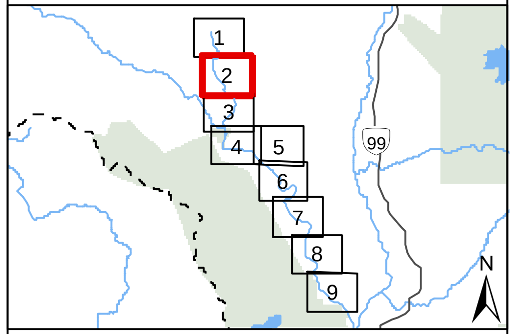
SHEET 1 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_FloodHazardMapBook_20181012.mxd



Squamish - Lillooet
REGIONAL DISTRICT

nhc
northwest hydraulic consultants



Limits of Mapping

River Km

Road

Hazard Ratimg (m*m/s)

Hazard Rating = (Depth x (Velocity +0.5)) + DF

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Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 Metres

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	*GIS*	*Reviewer*
THB	*MAO*	*THB*

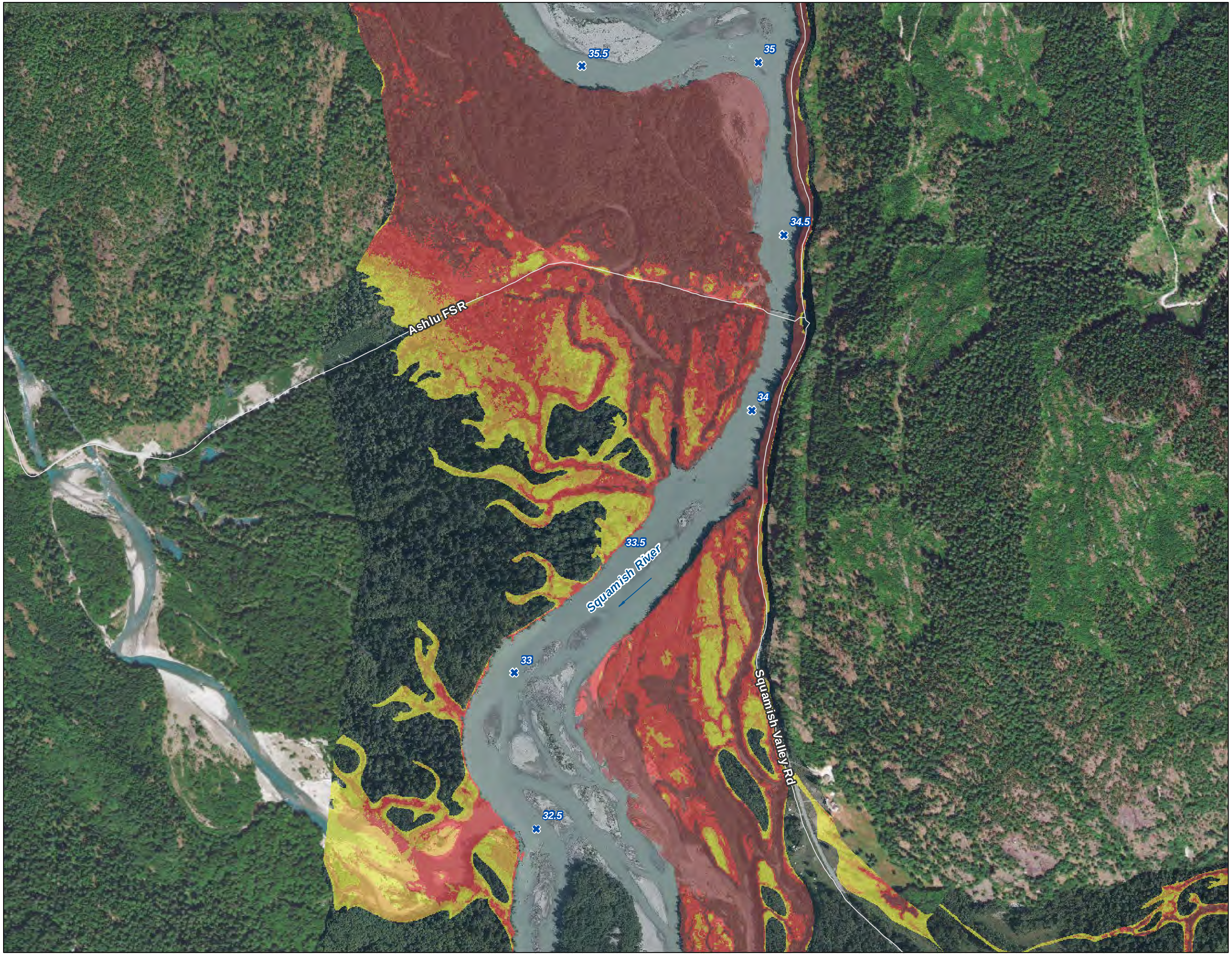
Job Number	*Date*
3003329	*26-NOV-2018*

SQUAMISH FLOOD HAZARD MAPPING

200-Year Flood Hazard

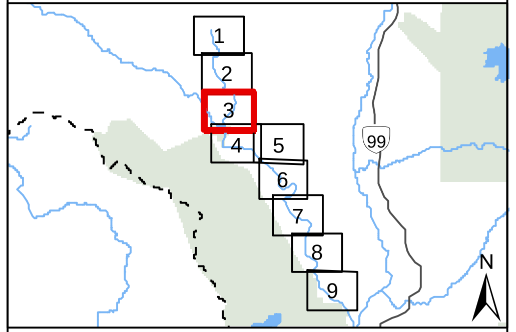
SHEET 2 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_FloodHazardMapBook_20181012.mxd



Squamish - Lillooet
REGIONAL DISTRICT

nhc
northwest hydraulic consultants



Limits of Mapping

River Km

Road

Hazard Ratimg (m*m/s)

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Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 *Metres*

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Engineer	*GIS*	*Reviewer*
THB	*MAO*	*THB*

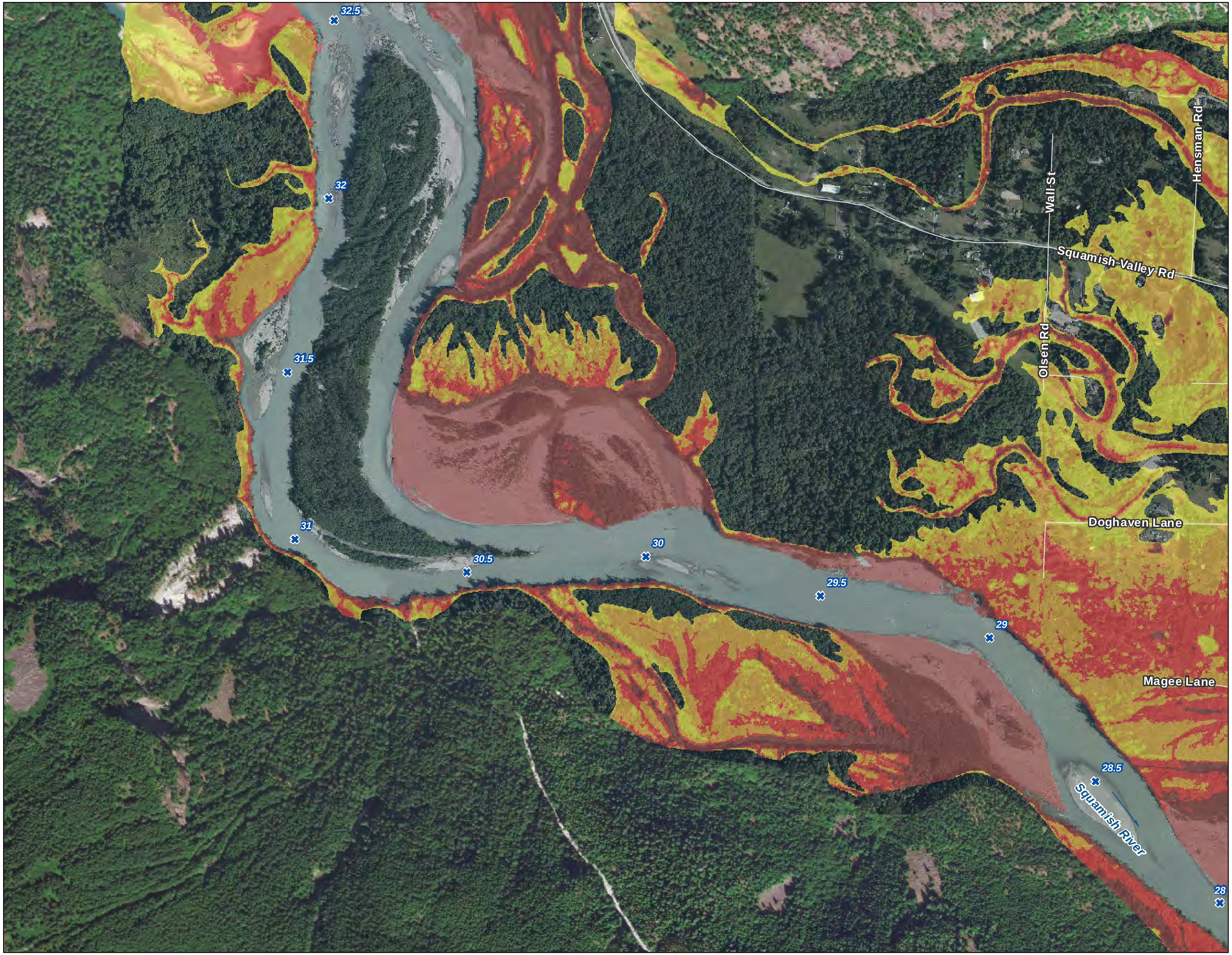
Job Number	*Date*
3003329	*26-NOV-2018*

SQUAMISH FLOOD HAZARD MAPPING

200-Year Flood Hazard

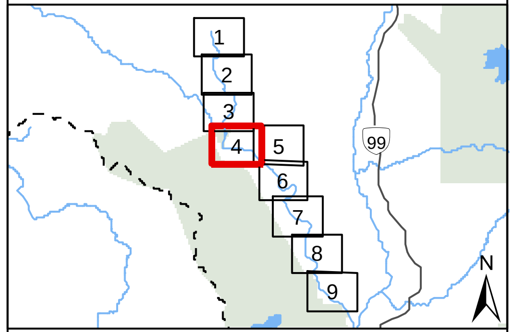
SHEET 3 OF 9

MAO, Q:\3003329_SLRD_Flood_Hazard_Map\95_GIS\MXDs\Figures\Squamish_FloodHazardMapBook_20181012.mxd



Squamish - Lillooet
REGIONAL DISTRICT

nhc
northwest hydraulic consultants



Limits of Mapping
River Km
Road

Hazard Ratimg (m*m/s)

Hazard Rating = (Depth x (Velocity +0.5)) + DF

- < 0.75
- 0.75 - 1.25
- 1.25 - 2
- > 2

Low: Caution - Flood zone with shallow flowing water or deep standing water.

Moderate: Dangerous for some (i.e. children) - flood zone with deep or fast flowing water.

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Extreme: Dangerous for all - flood zone with deep, fast flowing water.

Data Sources: 2016 Orthoimagery

Please refer to General Notes on Map Index Sheet

SCALE - 1:10,000

0 100 200 400 Metres

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Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

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THB	MAO	THB

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SQUAMISH FLOOD HAZARD MAPPING

200-Year Flood Hazard

SHEET 4 OF 9

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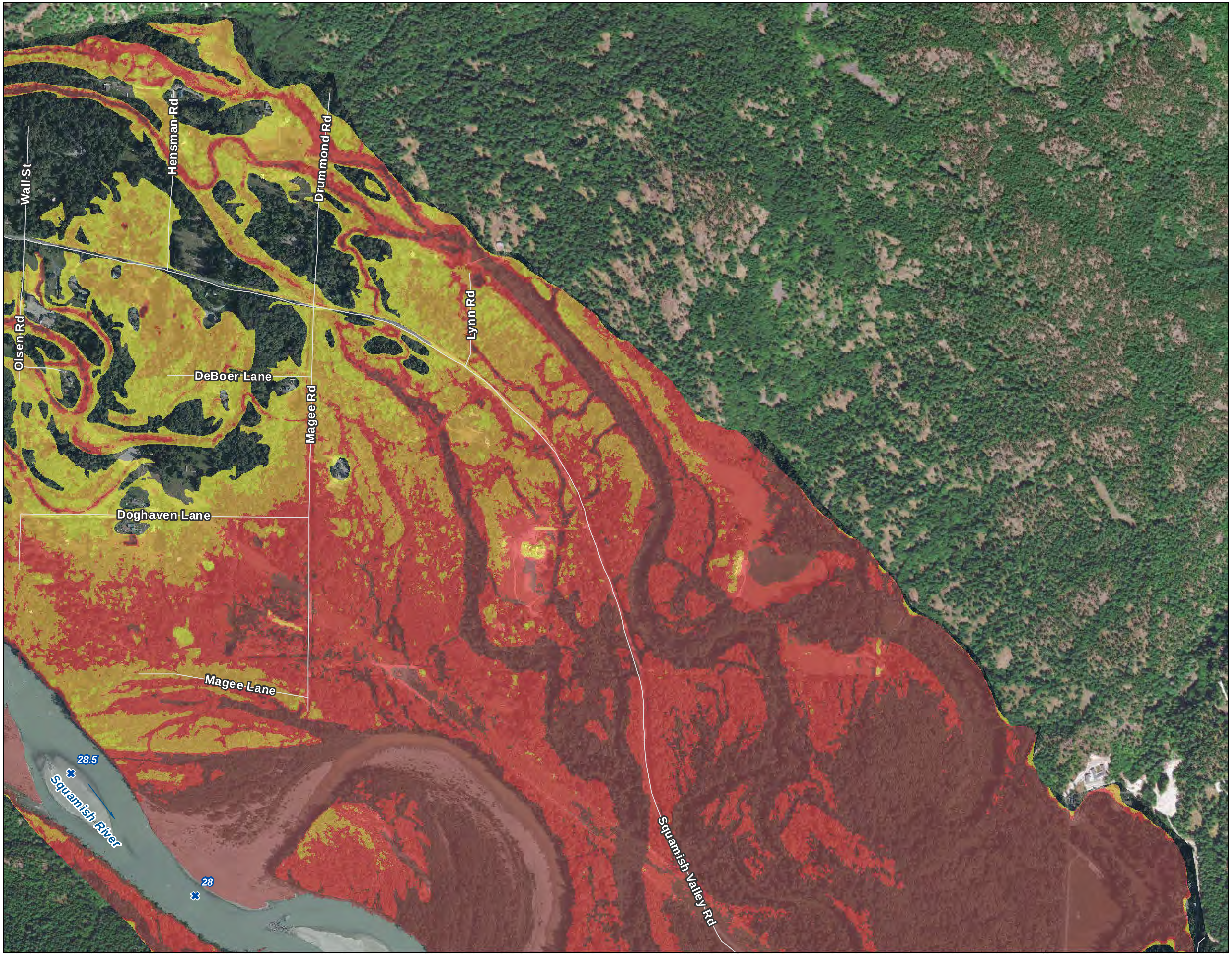

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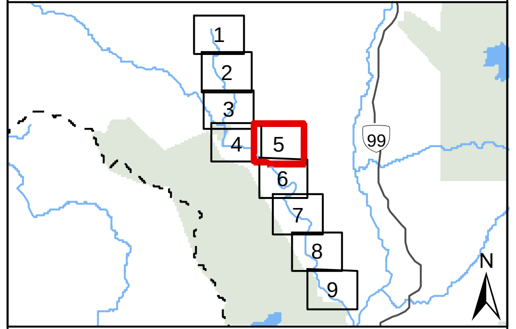

Limits of Mapping

River Km

Road

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Job Number	*Date*
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SQUAMISH FLOOD HAZARD MAPPING

200-Year Flood Hazard

SHEET 5 OF 9

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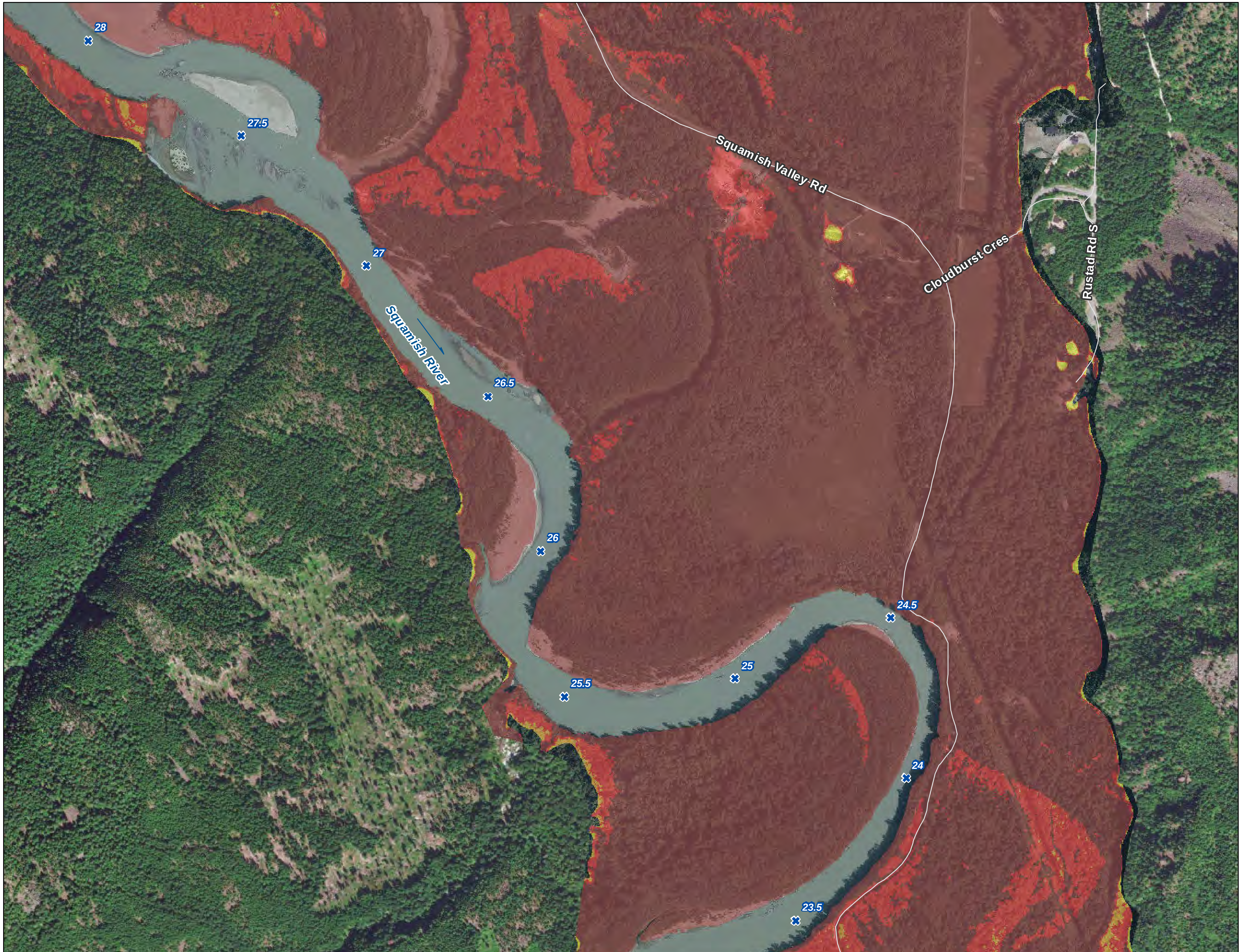

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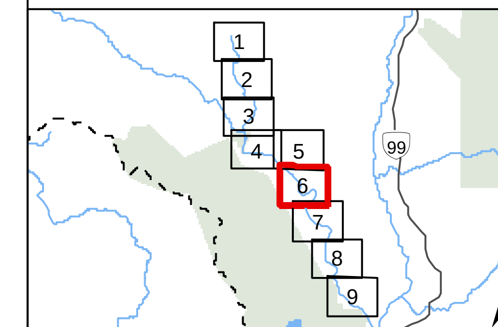

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SQUAMISH FLOOD HAZARD MAPPING

200-Year Flood Hazard

SHEET 6 OF 9

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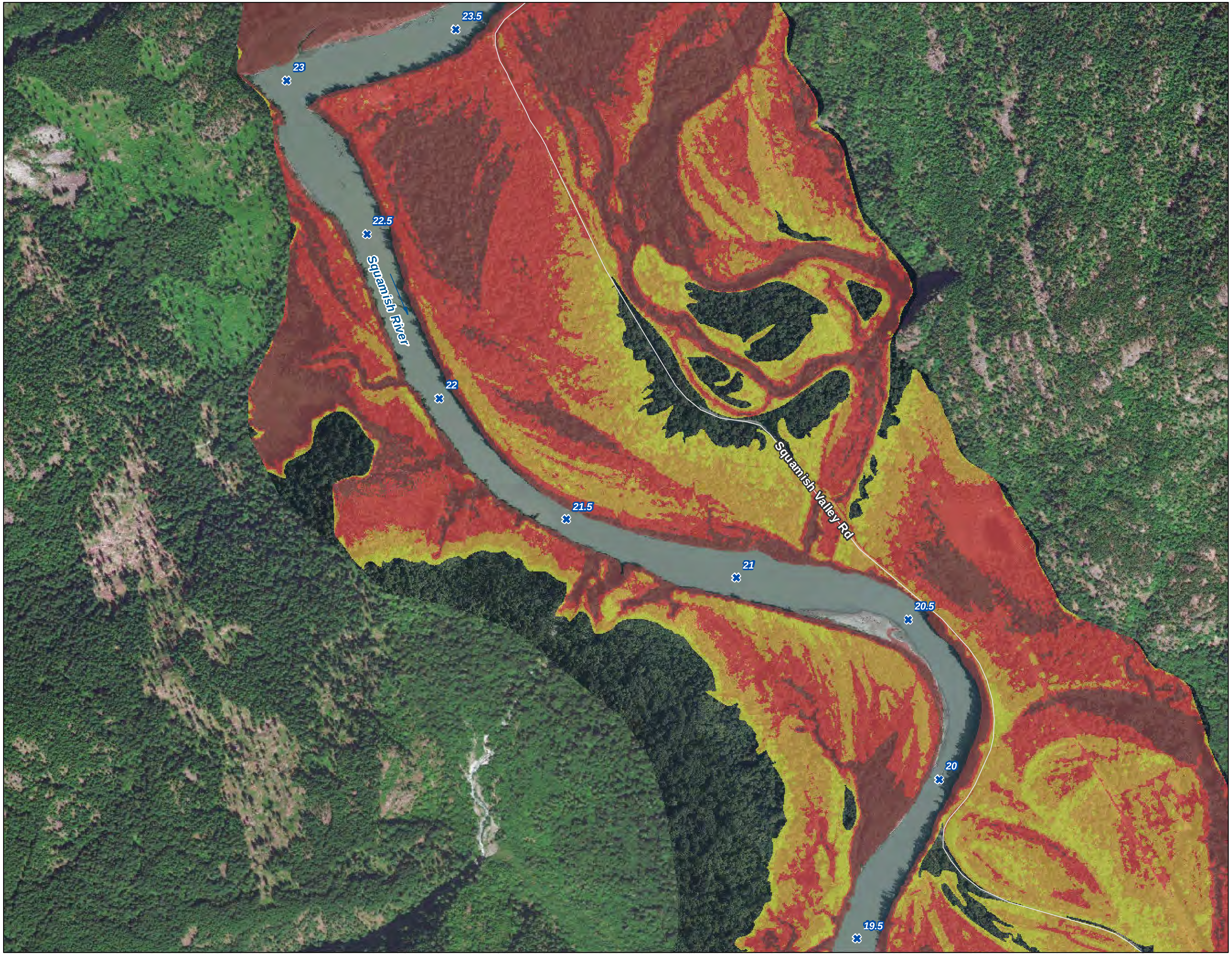

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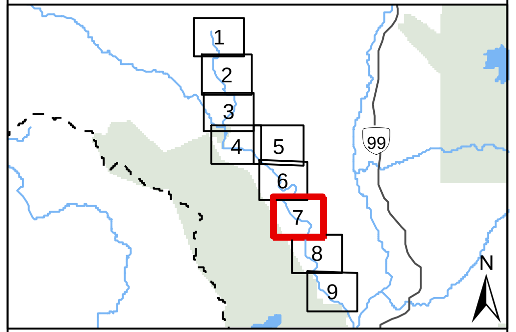

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SQUAMISH FLOOD HAZARD MAPPING

200-Year Flood Hazard

SHEET 7 OF 9

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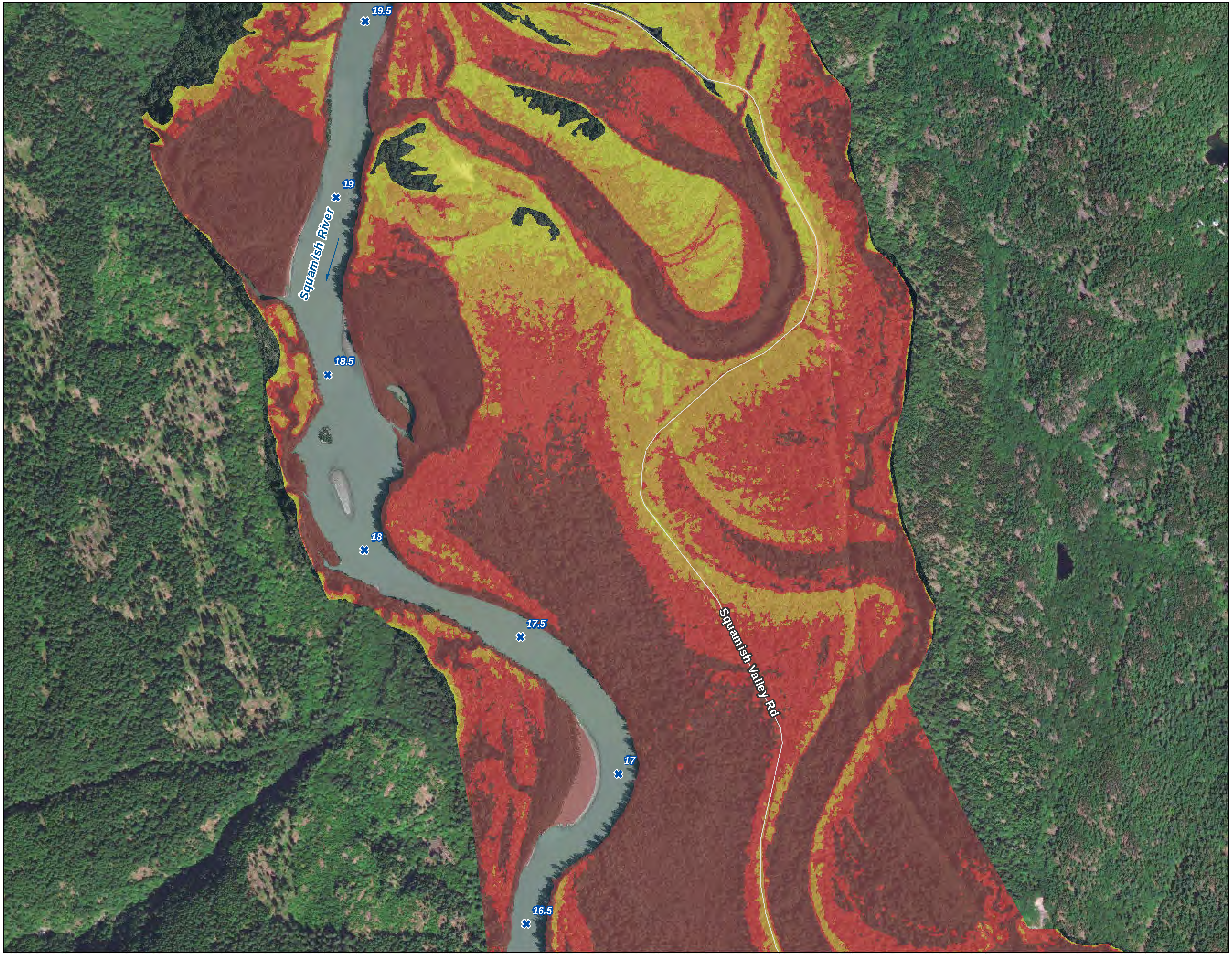

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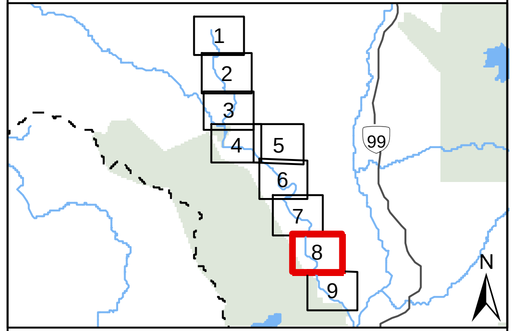

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SQUAMISH FLOOD HAZARD MAPPING

200-Year Flood Hazard

SHEET 8 OF 9

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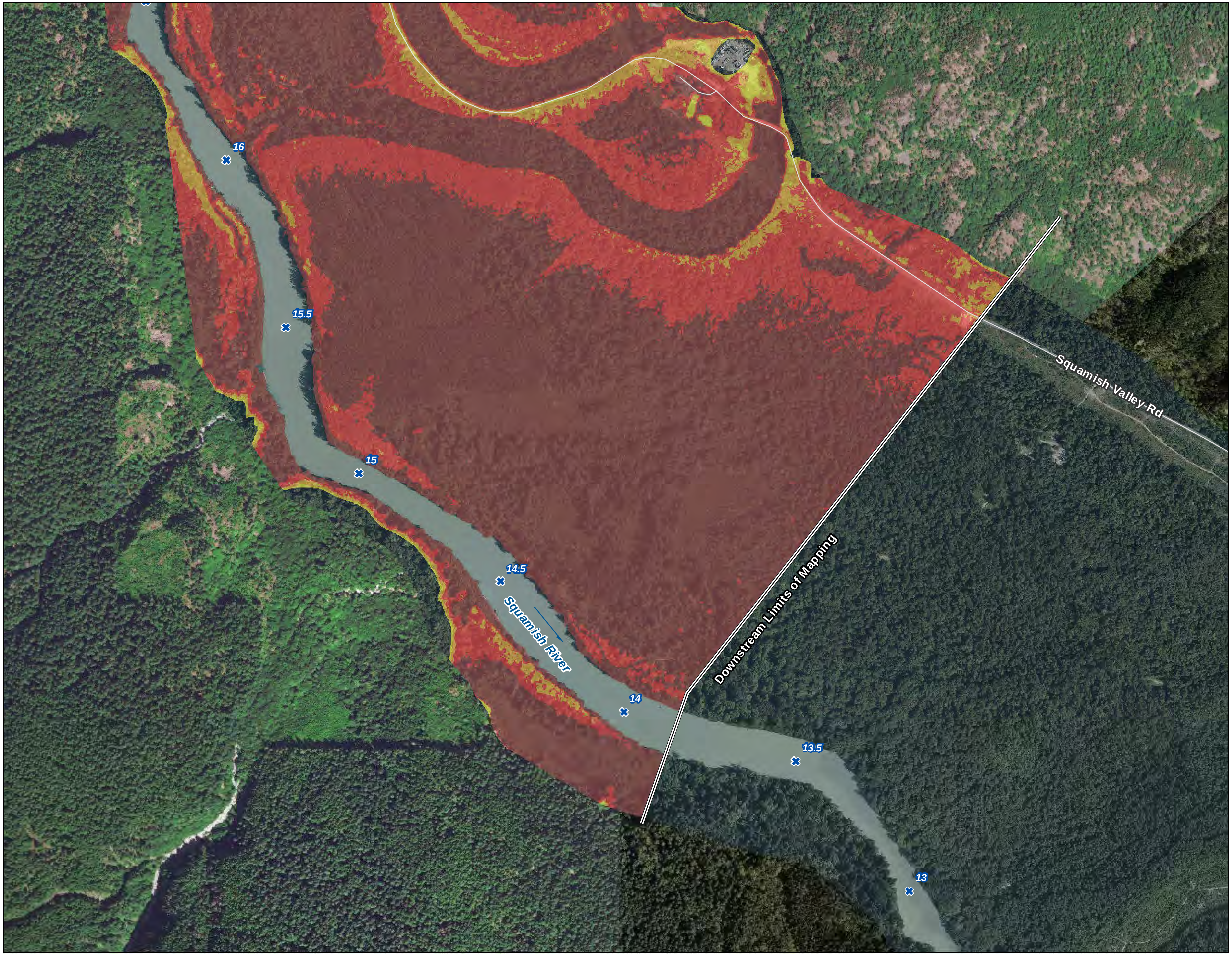

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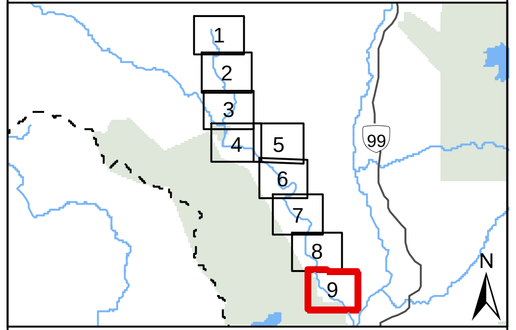

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0 100 200 400 *Metres*

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Units: METRES

Engineer	*GIS*	*Reviewer*
THB	*MAO*	*THB*

Job Number	*Date*
3003329	*26-NOV-2018*

SQUAMISH FLOOD HAZARD MAPPING

200-Year Flood Hazard

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APPENDIX A:
SQUAMISH RIVER GEOMORPHOLOGY AND HYDROGEOMORPHIC HAZARDS

FINAL REPORT

Prepared for:

Squamish - Lillooet Regional District
Pemberton, BC

Prepared by:

Northwest Hydraulic Consultants Ltd.
Vancouver, BC

9 September 2018

NHC Ref. No. 003003329

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Associate | Geomorphologist

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1 INTRODUCTION

In addition to hydroclimatic flooding driven by precipitation and runoff, hydrotechnical hazards along the upper Squamish River include hydrogeomorphic events that involve interaction of flowing water and sediment. These include changes in the channel bed configuration through fluvial processes of erosion, aggradation, channel migration, and avulsion; and tributary channel, fan, and valley slope processes. Landslides or debris flows and debris floods can deliver substantial volumes of sediment and wood to the Squamish River and may be capable of damming the channel and causing dam failure flooding. Some of these processes can alter the downstream base level of the riverbed, which can lead to long-term morphological changes to the channel. This appendix explains the geomorphic setting of the river basin, controls over these processes, and implications for flood management.

2 BASIN CONTEXT

2.1 Physiography

The Squamish River conveys flow and sediment from 3,800 km^2 of the southern Coast Mountains at its mouth (Figure 1 and Figure 2). Two tributaries, the Mamquam (360 km^2 basin area) and Cheakamus (1,100 km^2 basin area) join below the project area, leaving about 2,300 km^2 basin area at the downstream edge of the project area. Land use in the basin is dominated by forestry and subalpine to alpine wilderness. Lowlands are in the Coastal Western Hemlock Biogeoclimatic zone, elevations between approximately 1,000 m and 1,500 m are in the Mountain Hemlock zone, and areas above this include tundra (Alpine heather), bare rock, unstable paraglacial sediment, and glaciers, which cover about 16% of the basin. About 30% of the basin area lies within low elevation (<1,000 m) fluvially modified glacial valleys and about 25% is above 1,500 m.

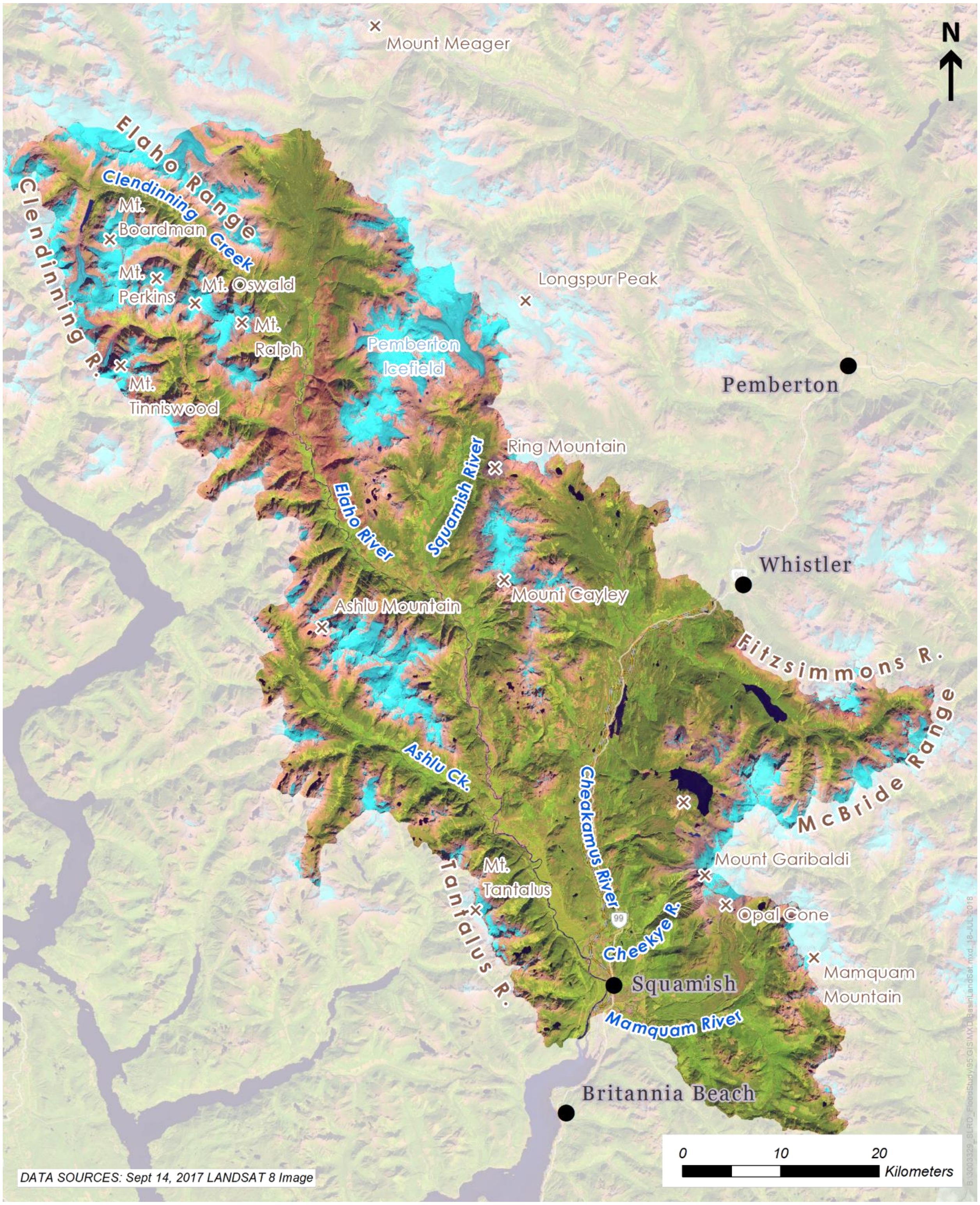


Figure 1: Late Summer (14 Sept 2017) Landsat image showing the Squamish River Basin.

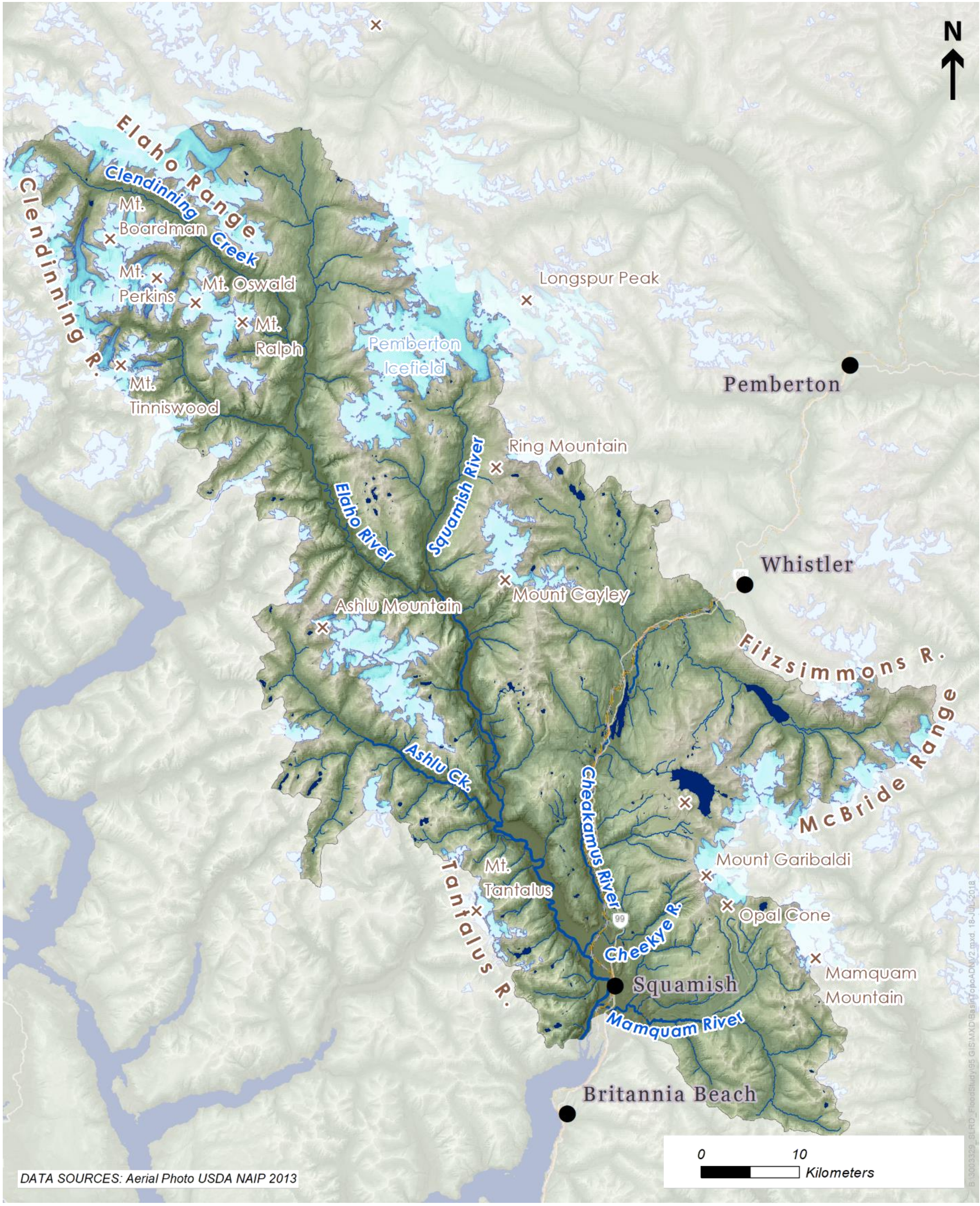


Figure 2: Topographic overview of the Squamish River Basin.

2.2 Geology

2.2.1 Bedrock Geology and Quaternary Volcanism

Bedrock geology of the Squamish River watershed (Figure 3) consists primarily of intrusive and metamorphic rocks of the Coast Plutonic Complex (Journeay and Monger 1994). North of Garibaldi Lake and within Callaghan River Valley is an area of older pendant rocks of the metavolcanic and metasedimentary Gambier Group. In the study area, these igneous and metasedimentary rocks are strong and form coarse grained colluvium. The Ashlu Creek thrust fault follows the trend of Ashlu River and then follows the Clowhom/Squamish River divide.

Of more limited extent, but much greater importance with respect to erosion and sedimentation are the volcanic rocks of the Garibaldi Volcanic Belt. These provide a disproportionate volume of sediment to the fluvial system; for example, Friele et al (2005) observed that while volcanic rocks make up 2% of the Lillooet River watershed, volcanic sediment makes up 25-75% of the bedload in the Lillooet River.

These volcanic rocks are part of the Cascade Volcanic Arc that includes other well-known volcanoes such as Mount St. Helens, Mount Rainier, and Mount Baker. Canadian volcanoes of the Cascade chain include Mount Garibaldi, Mount Cayley, and Mount Meager (Figure 2 and Figure 3). The Garibaldi Volcanic Belt is Quaternary in age and some landforms display features indicative of ice-contact volcanism (Hickson 1994; Kelman et al 2002), such as the ice dammed flows in Rubble and Culliton Creeks and the various flat topped volcanoes (e.g. Ring & Table Mountains) called Tuyas. Mount Cayley and Mount Garibaldi are composite volcanoes consisting of poorly lithified pyroclastic rocks and lavas. Mount Cayley last erupted some 300,000 years ago. Mount Garibaldi was active during the waning stages of the last glaciation some 14,000 years ago, erupting partly onto glacier ice (Mathews 1952). It subsequently became destabilized during deglaciation, leading to the formation of Cheekye Fan (Friele et al 1999; Friele and Clague 2005; Friele and Clague 2009). The last eruption occurred 9,000 to 10,000 years ago in the Opal Cone area on the southeast flank (Brooks and Friele 1992), forming the Ring Creek Lava Flow along Mamquam River. There has been no documented eruptive activity since that time.

Thus, the Quaternary volcanic centres of Mount Garibaldi and Mount Cayley form a small, but important, part of the Squamish River Valley. They cover local basement rock across unconformable, high-relief surfaces, and are weak and extremely unstable. Hydrothermal activity, which continues today at Mount Cayley (Hickson 1994), has cooked rock, producing clay-rich rock, weakening the edifice. Both Mount Cayley and Mount Garibaldi and other steep relief volcanic landforms remain vulnerable to large landslides, and where there is direct connectivity to stream channels, these volcanic landscapes are significant sediment sources to the Squamish River. Landslides from volcanic centres may spawn debris flows that travel tens of kilometers downstream from their source (Moore and Mathews 1978; Friele et al 2005).

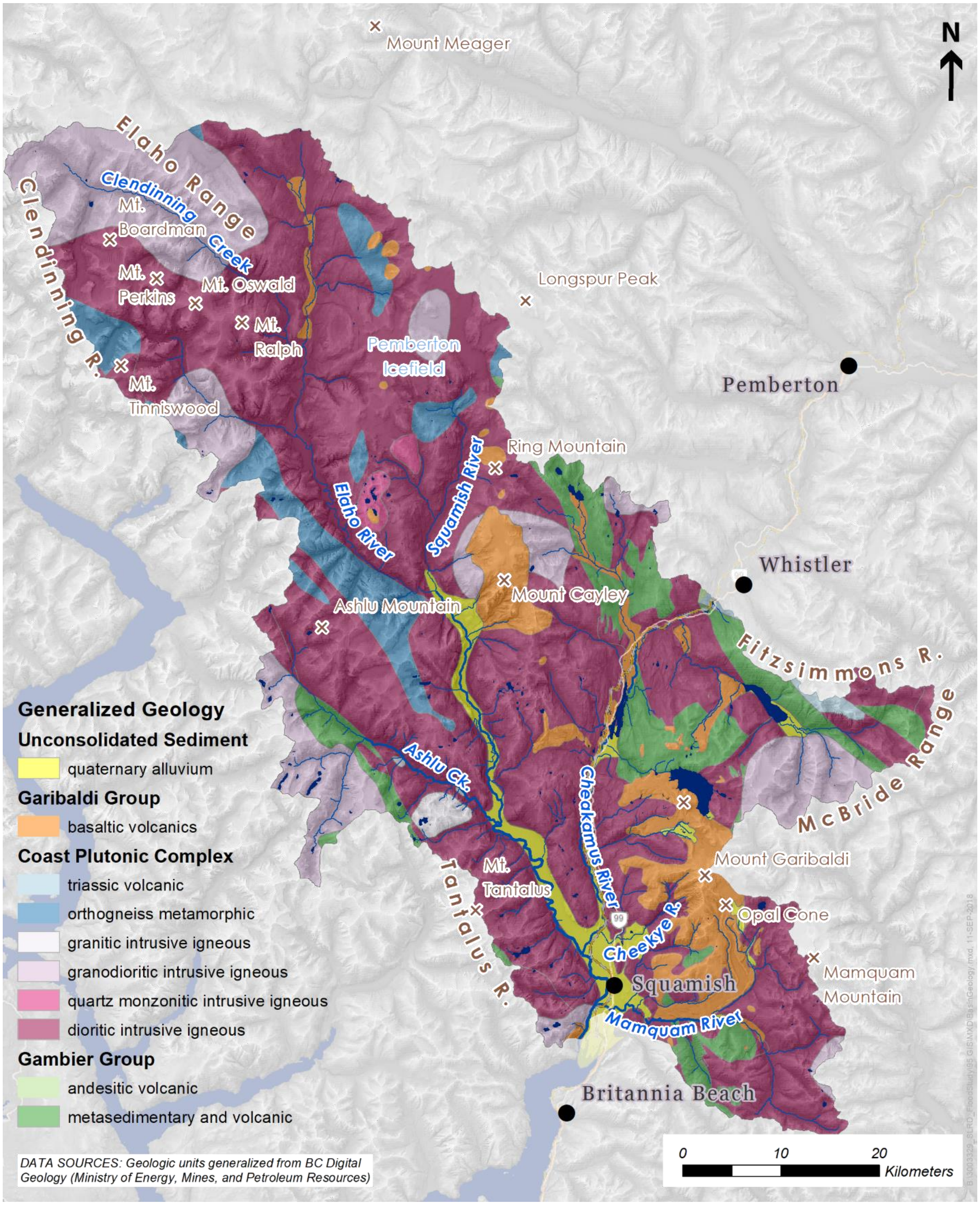


Figure 3: Generalized geology of the Squamish River Basin.

2.2.2 Pleistocene Glaciation

The Pleistocene is a geological epoch that began about 2.6 million years ago and lasted until about 11,700 years ago. It was a time when large parts of the earth surface were successively covered by great ice sheets, on cycles spanning about 100,000 years. During the Pleistocene, the entire Squamish River watershed, except the highest peaks, such as Mount Garibaldi and Mount Tantalus, was glaciated numerous times leaving rounded ridges and U-shaped valleys. The last, or Fraser Glaciation, reached its maximum extent about 15,000 years ago (Blaise et al 1990, Booth et al. 2003), and thereafter began a slow retreat. Subsequent to at least two minor readvances during deglaciation, lowlands of the Squamish Basin were deglaciated by 12,000 years ago (Friele and Clague 2002a, b).

During deglaciation, the supraglacial cone of Mount Garibaldi became destabilized and rock avalanche debris formed kame terraces against the thinning Squamish Valley glacier, and once the valley was ice free these unconsolidated materials from the west flank of Mount Garibaldi were redistributed to form the lower Cheekye Fan (Figure 4; Thurber-Golder 1993; Friele and Clague 2005). Lava flows from Mount Price in Garibaldi Park flowed down Rubble and Culliton Creeks and were dammed by the waning valley glacier in Cheakamus valley (Figure 4 inset; Mathews 1952). When the ice melted, tall lava cliffs were exposed. The lava cliffs along Rubble Creek are referred to as the Barrier, and a similar feature exists on Culliton Creek. These cliffs are sites of past and potential instability that could affect downstream areas.

2.2.3 Paraglacial Landsystem

The Squamish River must be understood in the context of the paraglacial landsystem, as the watershed contains numerous paraglacial landforms that have affected and continue to affect stream processes, including sediment supply, channel long profiles, and base level control.

Upon deglaciation, starting about 14,000 years ago, the landscape was gradually exposed, slopes scoured and modified by glacier erosion were debuttressed, and morainal and bedrock slopes were then in disequilibrium with subaerial conditions, leading to a period of enhanced sediment yield from these slopes. Glacial isostatic rebound imparted deep stresses in the earth crust, causing sheeting joints in near-surface bedrock slopes, gravitational distress leading to deep-seated instability on some bedrock slopes, and fractures extending deeper in the crust that triggered Quaternary volcanism.

This profound geomorphic response lasted thousands of years and extended through the deglacial and into the post glacial period. This dramatic response was first documented in the alluvial fans of the Fraser and Thompson River valleys in Interior British Columbia (Ryder 1971). There, Mazama tephra (~7ka BP) is found near the surface of alluvial fan sequences indicating most fan growth had occurred between ~7-12 ka BP. Church and Ryder (1972) coined this time of dramatic geomorphic response as the “paraglacial period”. Later, Church and Slaymaker (1989) recognized that paraglacial sediment was progressing as a pulse downstream along the larger rivers in British Columbia. This realization led to the expansion of the paraglacial paradigm from describing landform response, to describing landsystem response (Ballantyne 2002).

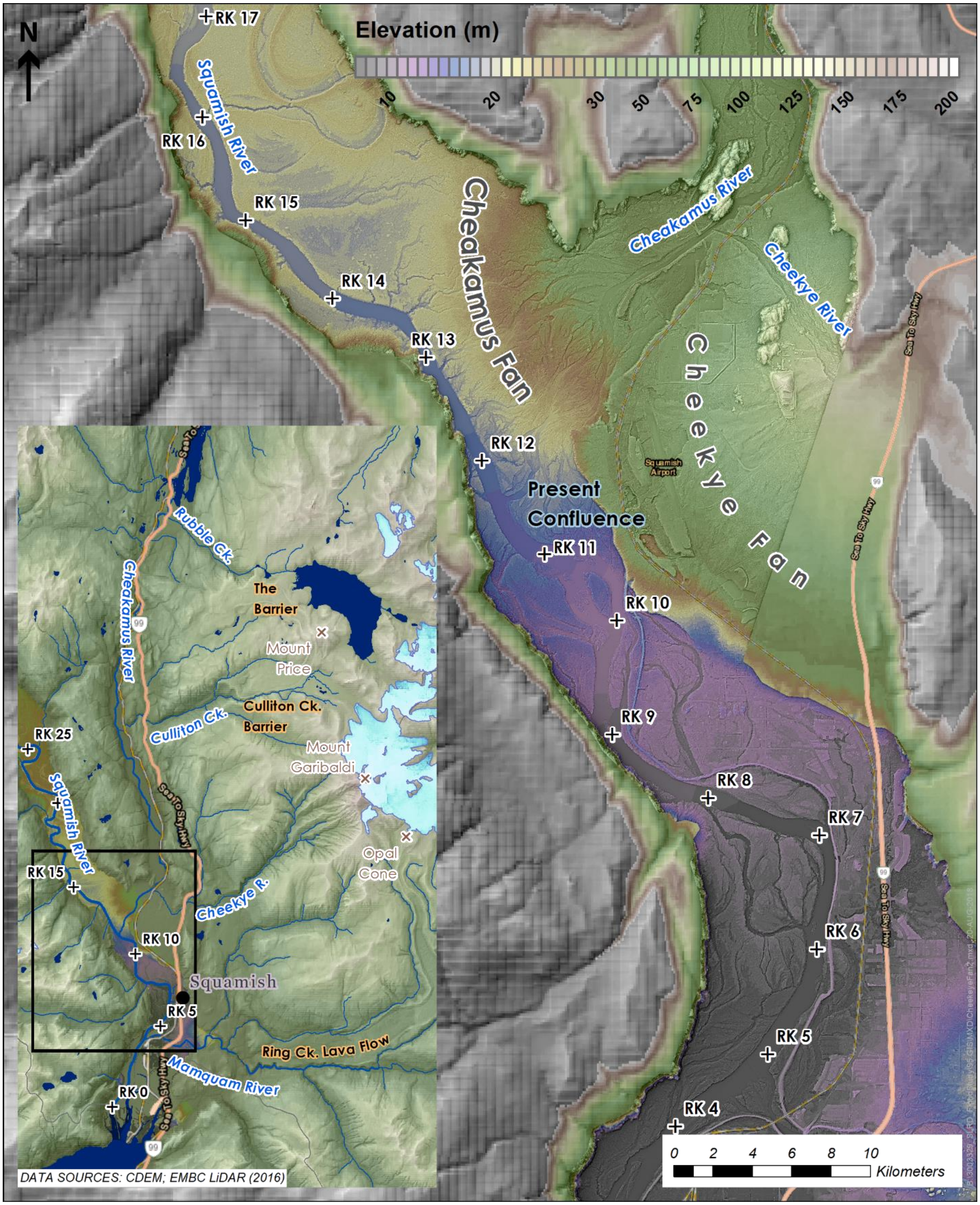


Figure 4: Detail of Cheakamus-Squamish River confluence area showing Cheekye Fan. Inset shows key features associated with Pleistocene volcanic activity and paraglacial instability around Mount Garibaldi.

Paraglacial Sediment Supply

The paraglacial sediment supply provides one of the best lines of evidence available to understand the relative degree of geomorphic activity in various tributary regions. Brooks (1994) mapped valley fill landforms in the tributary valleys of the Squamish River (Ashlu, Elaho, Cheakamus, Mamquam) and estimated the paraglacial sediment volume reworked from those deposits and transported to the Squamish River (Table 1). Ashlu, upper Squamish, and Mamquam Rivers all had similar specific yields of ~3.5×10^5 m^3/km^2; while Cheakamus and Elaho were 1 and 2 orders of magnitude less, respectively. The lower yields are attributed to within valley storage: Elaho upstream of the bedrock canyon, and Cheakamus within the lake and upstream of Rubble and Cheekye Fans.

The total volume of material transported to the Squamish River from tributaries provides an estimate of the sediment transport rate in the Squamish River, if normalized over the Holocene Period to account for the general decline in sediment transport following deglaciation described above. Taking the total transported volume and dividing by the duration of the Holocene (~10,000 yrs) suggests a typical annual bed material transport volume around 40,000 m^3/yr; however, this is likely a maximum estimate of the current rate. A substantial additional volume of material may have been supplied from landslides originating on Mount Cayley and Mount Garibaldi (see Section 3). Hickin (1989) estimated the modern sediment yield for the whole Squamish Basin based on surveyed sediment accumulation in the river's delta. This analysis indicated the modern rate is about $1.29 \mathrm{X} 10^6$ m^3/yr. This estimate includes suspended and wash load components and is much more than the bed material estimate based on valley erosion. This indicates the importance of hillslope and alpine sediment sources.

Table 1: Paraglacial sediment volume transported to Squamish River from tributary valleys.

Major tributary	Drainage basin area (km^2)	Volume (m^3)	Specific yield (m^3/km^2)	Comment
Ashlu	290	95×10^6	3.3×10^5	
Cheakamus	1100	54×10^6	4.9×10^4	Specified yield low due to storage in Cheakamus Lake and also upstream of Rubble and Cheekye Fans.
Elaho	1250	6×10^6	4.8×10^3	Top of Elaho Canyon, bedrock and 1900 yr BP rock avalanche debris form sill producing convex longprofile (Brooks 1994). In valley storage upstream of Elaho Canyon.
Mamquam	360	130×10^6	3.6×10^5	Volume reduced because sediments capped/preserved by Ring Creek lava flow (Brooks and Friele 1992).
Upper Squamish	350	130×10^6	3.7×10^5	Holocene rock avalanche 1840±60 yr BP caused backwater ponding, 500 m long temporary lake (Brooks 1994).
Total		415×10^6		

Paraglacial Cheekye Fan, Base Level Control and Ford/Lake Isolation

Cheekye Fan (Figure 4) is a large paraglacial alluvial fan underlying the neighbourhoods of Brackendale and Cheekye within the District of Squamish; it is formed by colluvial debris derived from the collapse of Mount Garibaldi. Subsequent to deglaciation, the Howe Sound Ford extended up valley as far as the Ashlu River confluence. By 7000 yr BP, Cheekye Fan prograded west across the ford to the opposite valley side, forming a sill at about 20-22 m above sea level (asl) and isolating a lake upstream (Hickin 1989; Fath et al 2018).

The lake would have received reworked glacial sediment from Elaho, Ashlu, and upper Squamish watersheds, which amounts to 231×10^6 m^3 (Brooks 1994), in addition to ongoing fluvial sedimentation. The lake was gradually filled, and by ~2000 yr BP it had transitioned from shallow ponds and wetlands to floodplain forest (Fath et al 2018). Modern fluvial processes throughout this reach consist of a meandering channel planform eroding fine lake and organic-rich wetland sediment and replacing this with channel, bar, and overbank facies.

In the early Holocene, base level control of the lake outlet at the Cheekye Fan was as high as 20-22 m asl. By about 3000 years BP, the sill level was likely 17–18 m asl. At that time, the lake may have extended as far north as 7–9 km above the upstream end of Cheekye Fan. Base level lowered to 15-16 m asl before 2300 years BP. Today base level is at 13 m asl, about 4–5 m lower than when the Squamish River was filling in the lake upstream of the fan (Fath et al 2018).

The modern base level of the upper Squamish River is controlled by Cheekye Fan and the Cheakamus River Fan on its northern margin (Figure 4). These features narrow the Squamish River and create a localized depositional zone, and the tributaries deliver substantial sediment loads to the mainstem. Avulsions and channel migration across the Cheakamus River Fan can vary the position of the confluence by about 4 km along the Squamish River. Most of the potential confluence zone is upstream of the present confluence position, which is at the extreme southern margin of the Cheakamus Fan (RK 10.8). The confluence has been at least about 1.5 km to the northwest of its current location sometime in the past century (Fath et al 2018). When the confluence is oriented more or less perpendicular to the west valley wall or further to the north on the fan, where Cheakamus Fan impounds the Squamish River more effectively, the Squamish River base level is more likely to rise due to sedimentation processes. The Squamish-Cheakamus River confluence is presently near the downstream limit of the potential confluence zone; therefore, future migration across the fan would likely increase the base level elevation on the river and could potentially increase flood water surface elevations for some distance upstream.

2.2.4 Future Base Level Variability

As described above, the base level for the lower portion of the Squamish River in the project reach is set by dynamics of the Cheekye and Cheakamus Rivers, which each have the potential to deliver larger caliber sediment than the Squamish River can readily transport downstream. The range that base levels may change from an avulsion of the Cheakamus River to a position further north on the fan can be estimated by considering two scenarios, both of which are based on the concept of dynamic equilibrium and assumption that the incoming quantity and caliber of sediments are proportional to the slope and discharge in a channel.

1) The present gradient of the Cheakamus River downstream from the fan apex represents an approximately equilibrium slope for its estimated incoming sediment load and discharge. The slope downstream of the Squamish River and Cheakamus River confluence should be less than that of the Cheakamus River because of the additional discharge from the Squamish River (which carries relatively small caliber bed material at this point). Therefore, the upper-bound estimate of a future Squamish River base level is estimated by considering a future confluence location that extends the Cheakamus River profile downstream from the fan apex along the shortest possible path to an intersection of the Squamish River at approximately RK 12.8. The slope profile of the fan surface grades to the same elevation as this projected channel profile, which suggests this scenario is probably more likely to occur than the following lower-bound estimate.

2) The present gradient of the Squamish River downstream of the Cheakamus River confluence is steeper than the profile upstream of the confluence. It represents an approximately equilibrium

slope given the incoming sediment load and discharge of both rivers. Because the Cheakamus River confluence is presently located at its most southerly possible position on the fan, it is far from the fan apex and the calibre and quantity of incoming load from the Cheakamus River may be smaller than if the channel were to avulse to a more northerly position. Therefore, a projection of the current slope profile of the Squamish from downstream of the Cheakamus confluence represents a lower-bound scenario for a future confluence location and Squamish River base level.

Figure 5 illustrates these geometric relationships. The lower-bound scenario projects the average Squamish River profile[1] upstream from the present confluence to the point where a Cheakamus River avulsion would have the biggest impact (by putting the confluence at approximately RK 13 at the point in closest proximity to the fan apex), and results in an estimated increase in the base level of about 1.5 m. The upper-bound scenario projects the existing Cheakamus profile and grade of the fan along the same worst case avulsion profile, and results in an estimated 3.5 m increase in the base level. This estimated base level range of 3.5 m above present day base level (13-16.5 m el.) is consistent with the base level variation over the last 2,300 years documented by Fath et al (2018).

Based on previous work to determine the frequency-magnitude relationship for Cheekye River debris flows (BGC Engineering Inc., 2008) and modeling of those flows (BGC Engineering Inc., 2007, 2014), it is possible that flows equivalent to or less than a 2,500 yr recurrence interval event may reach and directly or indirectly introduce sediment to the Squamish River. This type of event will increase sediment supply to the Cheakamus and may drive an aggradation or avulsion event on the Cheakamus Fan, the potential consequence of which has been assessed above. Some of the modeled 10,000 yr recurrence interval debris flow events reached the Squamish River with a sediment and debris depth up to about 5 m (BGC Engineering Inc., 2014), which could potentially impound the river to that height above the current Cheakamus confluence.

[1] Average profile of the reach between RK 8 up to the present confluence, at RK 11.5.

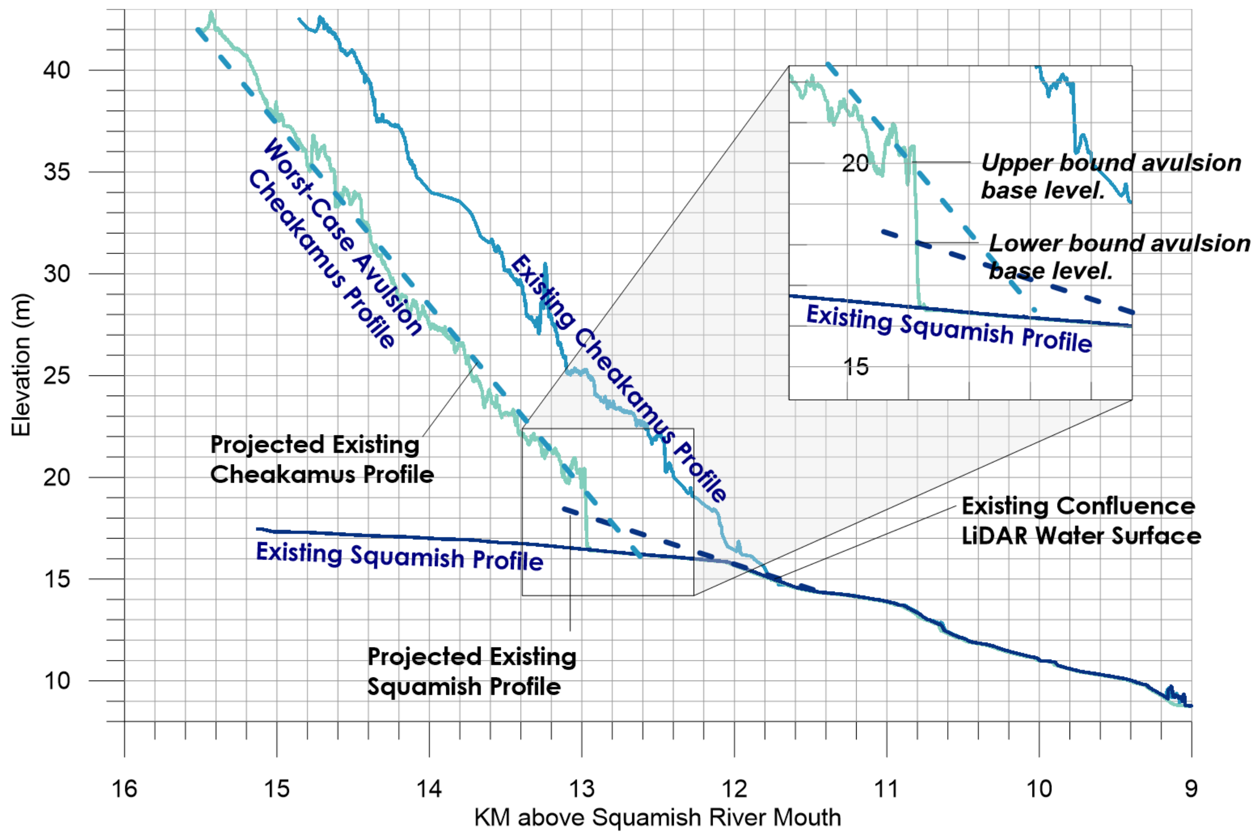


Figure 5: Water surface/ground profiles for Squamish River and possible Cheakamus River avulsion paths. The profile for the Squamish is the LiDAR water surface, which is about 2 m above the 13 m base level described by Fath et al (2018) at the present confluence. Changes illustrated are all relative to this water surface.

3 LANDSLIDES AND SEDIMENT SUPPLY

Stochastic landslide activity has shown to be a required component to explain Holocene sediment yield in BC rivers (Dadson and Church 2005). Landslides, particularly on the flanks of the weak volcanic edifices of Mounts Cayley and Garibaldi (Figure 3), deliver pulses of sediment to the fluvial system. Landslide-river impacts can have several dramatic consequences, such as:

- Barrier formation and upstream inundation. This has been documented for Squamish River upstream of both Cheekye Fan (Fath et al. 2018) and Cayley Fan (Evans and Brooks 1991);
- Direct or delayed sediment inputs causing increased rates of lateral channel migration (Hickin and Sichingabula, 1988; Cruden and Z-y., 1989; Wickert et al., 2013; Nelson and Dubé, 2016); or
- The formation and subsequent failure of landslide dams and the associated catastrophic outburst flood as occurred in 2010 at Mount Meager (Guthrie et al., 2012).

This section considers the occurrence of historic landslides from Mount Cayley and the potential for such slides to lead to landslide dam failures.

3.1 Historic Landslides

Our understanding of potential future landslides in the Squamish River basin is constrained by the distribution of historic events determined through both observation over approximately the past century and geological evidence. Jordan (1987) catalogued the impact of mass movement on stream channels in the Squamish and Lillooet River watersheds. He mapped and classified frequency and magnitude of rockfall, debris avalanche, debris flow, and debris flood processes affecting river channels. The most active watershed was Clendinning Creek in the upper Elaho Valley (Figure 2), with numerous active torrent channels having moderate sedimentation impact to the mainstem channel extending downstream to the Elaho River confluence.

Elsewhere in the Squamish River watershed there is a low density of debris flow within lower order subbasins. Some streams appear to support active fans, such as Blakney Creek in upper Squamish and Endurance Creek (Table 2) opposite Turbid Creek (see Figure 8 for locations). The Endurance Creek Fan was studied by Jakob (1996), and KWL (2003) reported an event during the Oct 18/19, 2003 flood. No debris volumes are provided, but typical events are likely 10^3-10^4 m^3 in volume. These streams are located far enough upstream, the events have small enough volumes, and their magnitude-frequency are not well enough studied; therefore, they can be factored into the present study as contributing to background sediment yield only.

Table 2: Debris flow events on Endurance Creek

Year	Data Source
1909	Jakob 1996
1920	Jakob 1996
1934	Jakob 1996
1962	Jakob 1996
1980	Jakob 1996
1984	Jakob 1996
1991	Jakob 1996
2003	KWL 2003

Two medium sized rockslide deposits have been dated: one 1900±60 yr BP (SFU 708) at the head of Elaho Canyon and another 1840±60 yr BP (SFU 682) within the upper Squamish (Figure 6). The coincidence of the timing of these events may be a dating artefact, but could also reflect a shared trigger, such as earthquake. The upper Squamish event formed a temporary blockage of the main channel causing lake sediments to accumulate up to 500 m upstream.

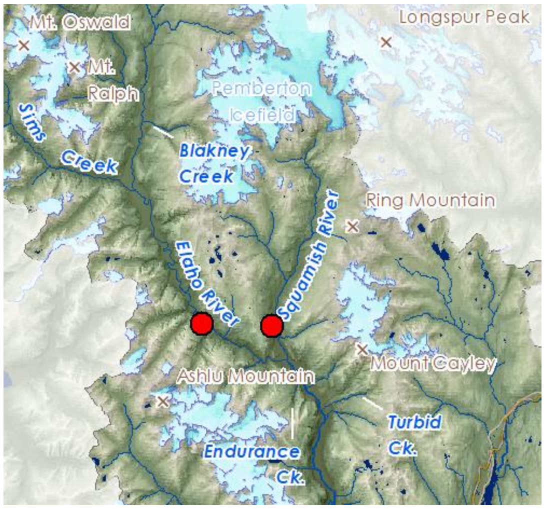


Figure 6: Detail from basin topographic overview showing locations of Elaho and Upper Squamish Rockslide Deposits (denoted in red) and select debris-flow influenced creeks.

The most important landslide impacts are sites where volcanic tributary subbasins affect the mainstem of the Squamish and Cheakamus Rivers; these are creeks on the west side of Mount Cayley, Rubble and Culliton Creeks, and the Cheekye River (Figure 2). Volcanic landslides are conditioned by many factors including slope relief, glacial oversteepening, debuttressing by glacier retreat, weak rock including structural controls and hydrothermal alteration, the presence of groundwater seepage, and time (see for example Roberti et al 2017).

Not all landslides are triggered in the same way (Jakob and Friele 2010). For instance, small debris flows may be caused by runoff mobilizing debris stored along channels, whereas large debris flows or rock avalanches may be derived from deep-seated slope failures (e.g., Clague & Souther 1982; Cruden & Lu 1992). Some landslides may occur without an apparent trigger, and others may be clearly triggered by phenomenon such as earthquake or intensive precipitation, or rapid snowmelt, or both.

3.1.1 Mount Cayley Landslides

Mount Cayley (Figure 7) is a volcanic centre located at approximately RK 60, 25 km upstream of the project reach within the Squamish River watershed (Figure 2 and Figure 3). Three creeks connect the massif to the Squamish River (Figure 8); these are impacted by two populations of landslides: smaller debris flows triggered by runoff; and deep seated slope failures. With respect to the more common smaller (<Class 4; Jakob 2005) events, a phenomenon observed at Meager Creek and Mount Cayley is that during long summer dry spells, as the edifice rock dries it becomes friable and ravels, with noticeable rockfall occurring during dry periods, then with first rains of fall debris flows are often triggered in gully channels where debris collected. This is exactly what happened in 2012, which had a 2-3 month long dry spell then rainfall starting in mid-October. When heavy rain came on Friday 12 October 2012, Jeff Fisher (Northwest Squamish Forestry) predicted a washout (Fisher, pers. comm.) and on Sunday 14 October 2012, the first of a series of washouts occurred. The same mechanism was attributed to the 17 October 2017 event. Typical precipitation intensities that trigger runoff generated landslides include >50mm/24 hr and >5mm/hr.

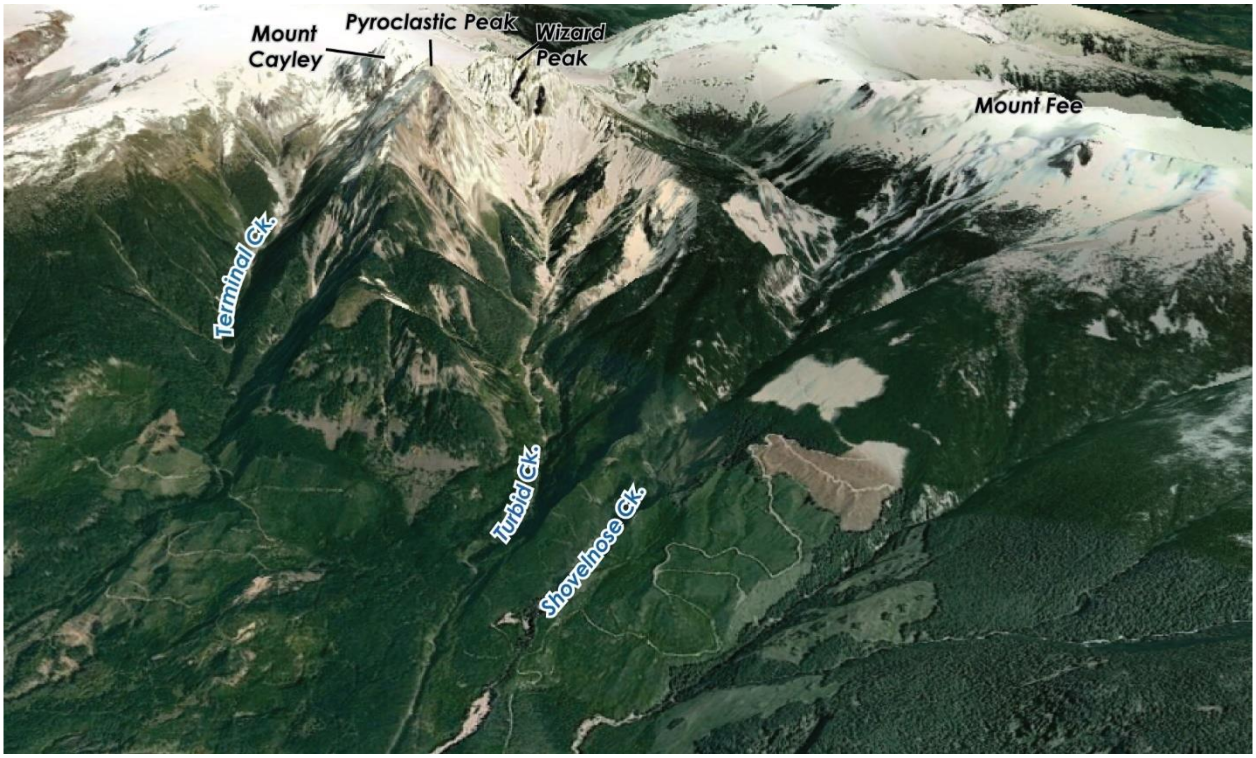


Figure 7: Oblique imagery projection (above) showing view of Mount Cayley from the southwest highlighting unstable cliffs bordering creeks. Oblique imagery data courtesy of Google Earth, DigitalGlobe CNES/Airbus, and Province of British Columbia

Catastrophic (>1 M m^3) failures have occurred during the period of historical observation: the 5 × 10^6 m^3 Dusty Creek landslide in 1963 (Clague and Souther 1982 and another 3.2 × 10^6 m^3 event from Mount Cayley in 1984 (Cruden & Lu 1992). In the prehistoric period, 7-8 catastrophic landslides at Mount Cayley have been directly dated by buried wood or inferred from backwater sediment accumulations (Evans and Brooks 1991; Brooks and Hickin 1991). The largest is the 4800 year old event that makes up the main body of the 14 m thick debris apron at the foot of the volcano (Figure 9); other large events have been dated to 3200, 1100, and 500 years ago, and Brooks and Hickin believe 4 other events occurred between 1100 and 500 years ago with similar magnitude to the 500 year old event. The debris avalanche deposits from these slides have a high matrix content (40-70%) and so Brooks and Hickin believe incision through the slide deposits would have been rapid. These slides formed landslide debris dams that impounded temporary lakes upstream as far as the Elaho River confluence (Figure 8). Table 3 lists details of the landslide dam geometry and impounded water volume for these historical events and several other theoretical landslide dams of arbitrary intermediate size with damming heights set at 5 m increments. The impounded volume and time to fill have important implications regarding the impact of downstream flooding that are evaluated in Section 3.2.

The 4800 year old debris avalanche from Mount Cayley was described as having a volume of 2-3 x 10^8 m^3 (Evans and Brooks 1991), resulting from edifice collapse of the western flank of Mount Cayley. Apart from damming rivers, these large scale volcanic debris flows have the potential to travel long distances downstream. For example, four edifice collapse events have been documented at Mount Meager and their deposits have been observed to be interstratified with floodplain sediments 32-65 km downstream within Pemberton Meadows (Friele et al 2005; Simpson et al 2006). By analogy, edifice collapse from Mount Cayley could affect the reach of the Squamish River upstream of Cheekye Fan. Due to infill of the Cheekye Fan-dammed lake and later floodplain aggradation, potential deposits of a large volcanic debris flow are not visible at the surface. Subsurface drilling would be required to document past events.

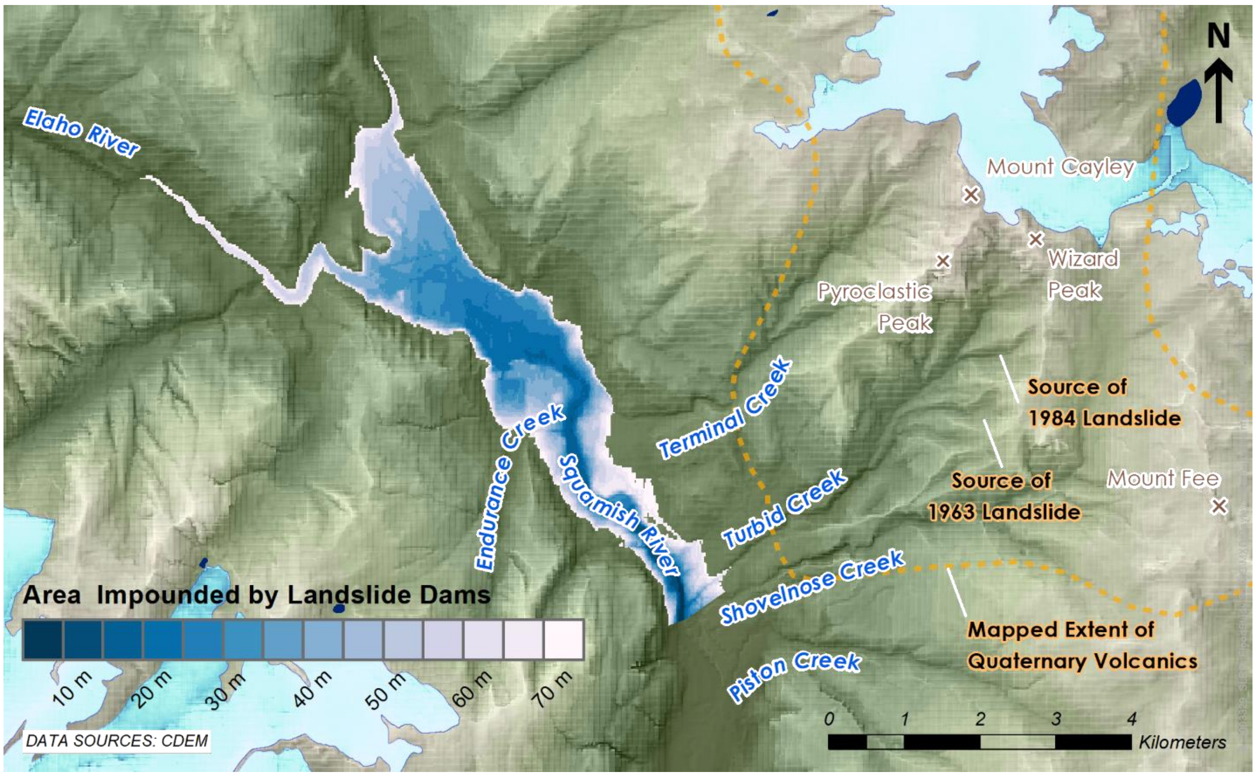


Figure 8: Mount Cayley Massif and adjacent Squamish River Valley showing principal peaks, creeks, landslide source areas, and potential areas of upstream impoundment for landslide blockages of varying depth.

Table 3: Landslide dam geometry and impoundment volume for several historical and theoretical events blocking the Squamish River at Turbid Creek (Figure 8).

Historical Event	Debris Dam Height (m)	Impounded Volume (m^3)	Time to Fill (~July Mean=500 $m^3\ s^{-1}$)	Time to Fill (Q 2-yr=1320 $m^3\ s^{-1}$)
--	5	1.3×10^6	45 mins	15 mins
--	10	5.7×10^6	2.5 hours	1.0 hours
--	15	1.3×10^7	7 hours	3 hours
--	20	2.3×10^7	13 hours	5 hours
500 BP +	25	3.7×10^7	21 hours	8 hours
--	30	5.9×10^7	1.4 days	12 hours
1100 BP	40	1.2×10^8	2.7 days	1.0 days
--	50	2.0×10^8	4.6 days	1.8 days
4800 BP	60	2.5×10^8	5.8 days	2.3 days

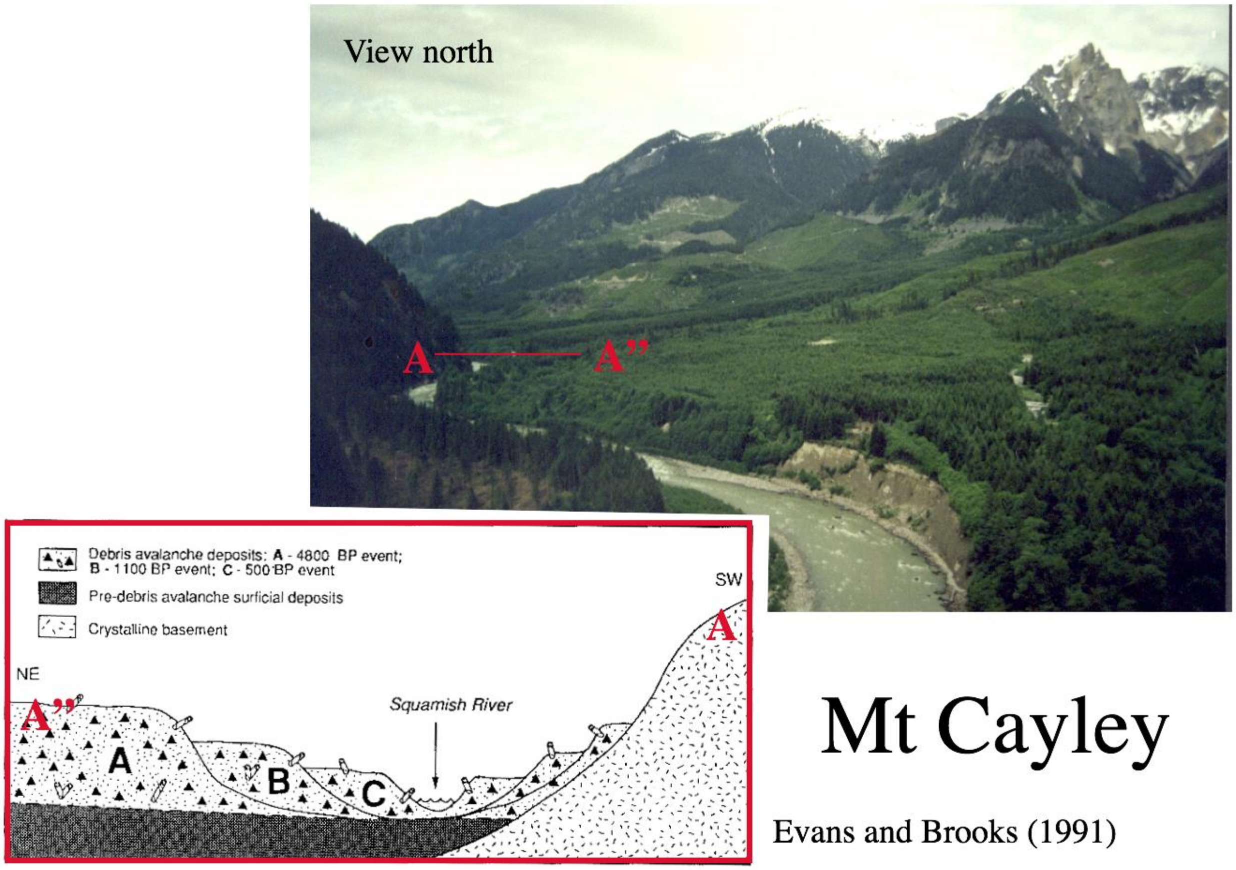


Figure 9: View upstream towards Mount Cayley showing debris apron filling the valley in the foreground, and the inset diagram showing a succession of incised landslide deposits.

The historic catastrophic landslides caused short-lived impoundments, at least twice in the last 100-years: in 1963 and in 1984 (Clague and Souther 1982; Cruden & Lu 1992). The 28 June 1984 event was described by Cruden and Lu (1992) as follows:

> *Approximately 3.2 million cubic metres of volcanics travelled 2.0 km down Avalanche Creek at velocities up to 35 m/s to dam the confluence of Avalanche and Turbid creeks. The breaking of the landslide dam caused an extremely fast debris flow. The velocity of the debris flow and associated wind gusts, up to 34 m/s, caused superelevations, hurled rocks and wood through the air, uprooted trees, and spattered mud 16 m up trees. The debris flow removed the logging road bridge and road approaches at the mouth of Turbid Creek, blocked the Squamish River during surges, and introduced huge quantities of sediment to the Squamish River.*

The height of the landslide dams on the Squamish River are not reliably reported for either event, but one anecdotal report (Braidwood, n.d.) suggests the 1984 event dam was approximately 6 m high. A list of historic debris flow activity since 1963 at Turbid Creek (Table 4) has been compiled from various sources, notably from Jakob (1996) with more recent events provided by Jeff Fisher and Malcolm Schulz

(Cordilleran 2012). The information on large historic events (i.e., 1963, 1984) was summarised by Evans and Savigny (1994).

Table 4: Historic turbid creek debris flow events

Year	Date	Trigger	Volume (m3)	Data Source
1963	July	--	5,000,000	Clague & Souther 1982
1967	--	--	--	Weldwood in Jakob 1996
1972	--	--	--	Weldwood in Jakob 1996
1978	--	--	--	Weldwood in Jakob 1996
1984	28-Jun	Rain	3,200,000	Jordan 1987; Cruden and Lu 1989
1984	08-Oct	Rain	500,000	Jordan 1987
1987	--	--	--	Weldwood in Jakob 1996
1991	--	--	--	Weldwood in Jakob 1996
1993	29-Jul	Rain	300,000	Jakob 1996
1995	04-Aug	Heat	--	Jakob 1996
1997	--	--	--	Friele
2003	18-Oct	Rain	100,000	KWL 2003
2005	08-Jul	Rain	10,000	Cordilleran 2005
2010	06-Aug	Heat	100,000	Jeff Fisher
2012	14-Oct	Rain	--	Jeff Fisher
2012	19-Oct	Rain	--	Jeff Fisher
2012	21-Oct	Rain	--	Jeff Fisher
2012	04-Nov	Rain	--	Jeff Fisher
2013	30-Aug	Rain	--	Jeff Fisher
2014	29-Jun	Rain	20,000 to 40,000	Shelly Higman
2015	20-Sep	Rain	--	Malcolm Schulz
2016	17-Jul	Rain	75,000 (MS approx)	Gino Fournier
2016	18-Jul	Rain	75,000 (MS approx)	Gino Fournier
2016	17-Sep	Rain	20,000 (MS approx)	Malcolm Schulz
2016	07-Nov	Rain	<10,000 (MS approx)	Malcolm Schulz
2017	17-Oct	Rain	<20,000 (MS approx)	Malcolm Schulz
2017	22-Nov	Rain on snow	<20,000 (MS approx)	Malcolm Schulz

Note that the event list for Turbid Creek[2] is not complete: Weldwood records may not have been comprehensive; Interfor (1995-2006) did not keep records; and Jeff Fisher has not provided details of all events since 1995. Nevertheless, over the 54 year record, there have been 27 recorded events with an average of 1 every 2-3 years. In some years there are multiple (2-4) events, while the longest gap is 6-years, which might be a fault of poor record keeping. The return period for small rain/runoff type events

[2] Note that the local names and formal names are different: On NTS maps Turbid Creek is identified on the channel called Mud Creek in local usage. This report refers to formal naming convention.

is likely <1-5 years, or very high (Table 4). Turbid Creek is classified as a transport-limited system (Jakob 1996), implying that debris supply is infinite and events may occur whenever climate conditions or other triggers allow. Clearly Turbid Creek forms the greatest point sediment source to the Squamish River upstream of Cheakamus River.

Since 2010, it appears that there may be more frequent washout events at Turbid Creek, occurring almost annually, often in close succession. In 2012 and 2016, four events occurred in one year. It is not known if this increase in frequency is real, or if it is a result of more consistent reporting in the news media, despite no formal recording procedure by industry or government. Alternatively, it could be related to flushing of debris following the larger (100,000 m^3) 2010 event, or possibly precursor to a larger failure.

As well as Turbid Creek, the other creeks draining the west slope of Mount Cayley (Figure 8) are debris flow prone. For example, Jakob (1996) reports that Terminal Creek has had an average debris flow recurrence interval of 1/11 per annum over the last 119 years, as deduced from historic records and dendrochronology. The Terminal Creek record has been recently updated by Malcolm Schulz, starting in 2014, with annual events since then, including two in 2016 (Table 5).

Table 5: Historic terminal creek debris flow events

Year	Date	Trigger	Volume (m3)	Data Source
1875	--	--	--	Jakob 1996
1909	--	--	--	Jakob 1996
1916	--	--	--	Jakob 1996
1935	--	--	--	Jakob 1996
1942	--	--	--	Jakob 1996
1958	--	--	--	Jakob 1996
1965	--	--	--	Jakob 1996
1967	--	--	--	Jakob 1996
1981	--	--	--	Jakob 1996
1984	--	--	--	Jakob 1996
1990	--	--	--	Jakob 1996
		1990-2014 gap in record		
2014	20-Oct	Rain	--	Jeff Fisher
2014	06-Nov	Rain	--	Jeff Fisher
2014	08-Dec	Rain or rain on snow	--	Malcolm Schulz
2015	20-Sep	Rain	--	Malcolm Schulz
2016	17-Jul	Rain	5,000 (approx)	Cordilleran 2016
2016	07-Nov	Rain	--	Malcolm Schulz
2017	22-Nov	Rain on snow	<20,000 (approx)	Malcolm Schulz

There is no long-term record for Shovelnose Creek or the next creek south, but they are partially underlain by volcanic bedrock. Abundant debris flow deposits are present along upper reaches of Shovelnose Creek (Souther and Dellechaie, 1984) and the basin has similar characteristics to Turbid

Creek (Figure 7 and Figure 8), suggesting a high likelihood of future debris flow events originating in that basin as well. KWL (2003) notes a debris flood occurred on Shovelnose and a debris flow on Piston Creek in 2003; fresh deposits from these events are visible in aerial photos collected in 2009 and satellite imagery indicates some bed mobilizing event occurred on Shovelnose Creek in 2015 or 2016. No details about magnitude are available.

3.1.2 Magnitude Frequency Model for Mount Cayley Landslides

In summary, the magnitude-frequency model for Mount Cayley landslides (lumping all channels for simplicity) can be expressed as in Table 6 and Figure 10.

Table 6: Magnitude frequency model for mount cayley landslides

Volume (m^3)	Squamish R. Impoundment Height (m)	Recurrence Frequency (years)	Evidence	Source
10^4-10^5		1	Essentially annual since 1963	Table 4 and Table 5
10^5-10^6		15	At least 4 in 50 yrs	Table 4 and Table 5
10^6-10^7	5-10 m	50	2 events in historic record	Clague and Souther 1982 Cruden and Lu 1989
10^7-10^8	25-40 m	1000	3200, 1100, 500, possibly 4 additional events between 1100 and 500 years ago	Evans and Brooks 1991; Brooks and Hickin 1991
10^8-10^9	50-70 m	5000	4800 year event	Evans and Brooks 1991

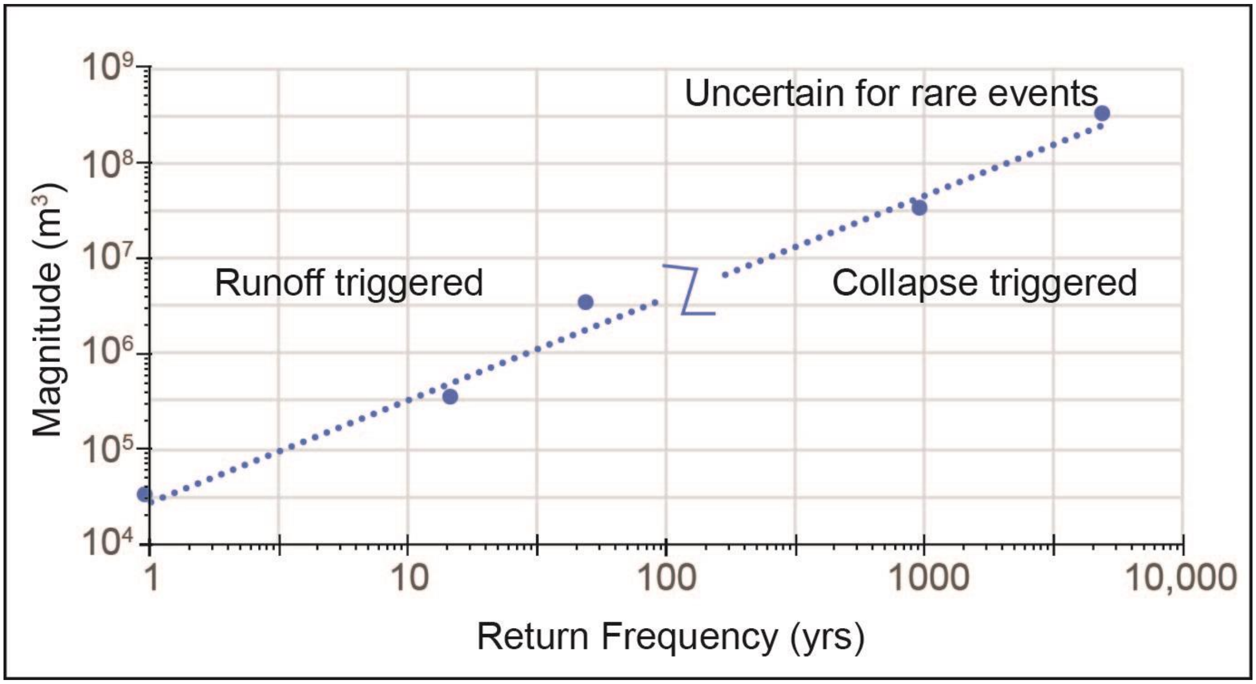


Figure 10: Magnitude-frequency curve for Mount Cayley Landslides. Magnitudes are plotted as midpoint of each class cited in Table 6. The prehistoric record, for event frequencies >100 years is very uncertain.

3.2 Landslide Dam Failures

Given the narrow constriction formed by Squamish River incision through historic debris at the base of Mount Cayley (Figure 8), it is highly likely that any significant landslide or large debris flow will form a dam impounding the Squamish. Formation of a dam, however, does not necessitate its ultimate catastrophic failure; indeed impoundments behind many landslide dams remain for a long period of time —forming lakes— or drain slowly as the channel incises through the deposit over a period of days to weeks without releasing an outburst flood. Therefore, the magnitude-frequency curve for landslides may not translate directly to a frequency for landslide-dam outburst floods.

3.2.1 Local Historic Events

Landslides from Mount Cayley have caused temporary blockages of the Squamish River, at least seven to eight times in the prehistoric period (Brooks and Hickin 1991) and twice in the last 100 years (Clague and Souther 1982; Hickin and Sichingabula 1988). Such blockages cause interruptions to the flow of the Squamish River, can impound water and raise water levels behind the dam, and the landslide barriers have the potential to fail rapidly, leading to outburst floods affecting downstream reaches, as happened in 2010 in the Lillooet River headwaters following the collapse of Mount Meager in Capricorn Creek (Guthrie et al 2012).

1963 Dusty Creek landslide

Investigation of daily flow records from the Cheakamus and Squamish Rivers at Brackendale reveals no clear indication of a flood pulse on the Squamish related to a landslide dam failure in 1963; likely —if a failure occurred— the flow impact was short enough to not be recorded in daily averaged data.

1984 Turbid Creek Event

The 28 June 1984 event on Turbid Creek (see section 3.1.1) highlights the potential for this hazard. This landslide directly affected the Squamish River (Jordan 1987; Cruden and Lu 1992), resulting in temporary damming and a detectable flow pulse at Brackendale (Figure 11; Jordan 1987). Later in the year, on 8 October 1984, the landslide was followed by a 30-year return flood (2610 m^3/s). This reworked the landslide debris and caused major braiding of the Squamish River between Mount Cayley and Ashlu River (Hickin and Sichingabula, 1988).

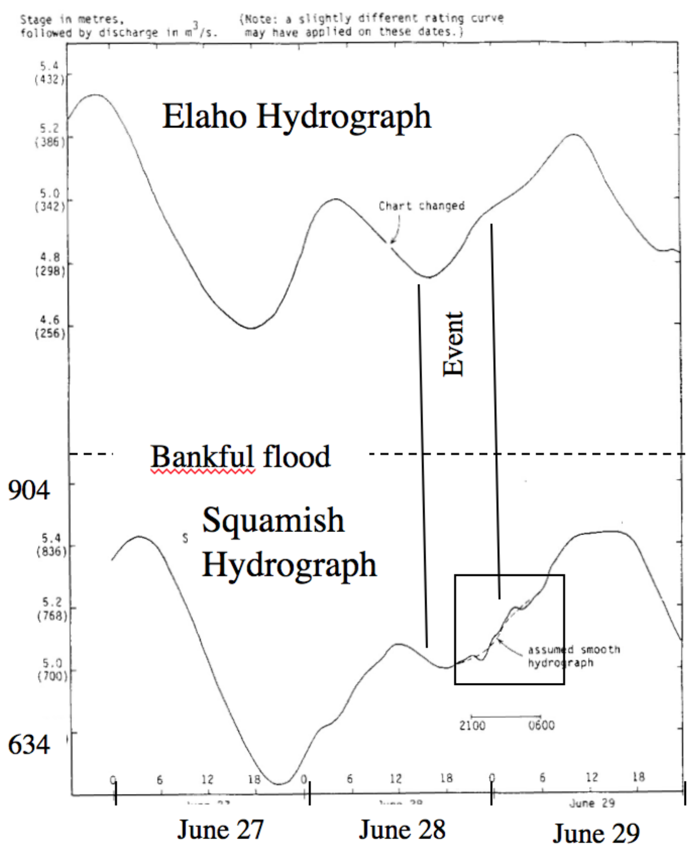


Figure 11: Elaho and Squamish River hydrographs June 1984 (from Jordan 1987).

2003 Turbid Creek Event

KWL (2003) suggested that the 2003 Turbid Creek landslide may have caused surge on the Squamish River, but no follow up data or discussion was provided. Hourly Water Survey of Canada flow data from the 'Squamish River at Brackendale' hydrometric station is plotted in Figure 12 and shows an unusual hydrograph for the peak of the flow event that occurred during the landslide.

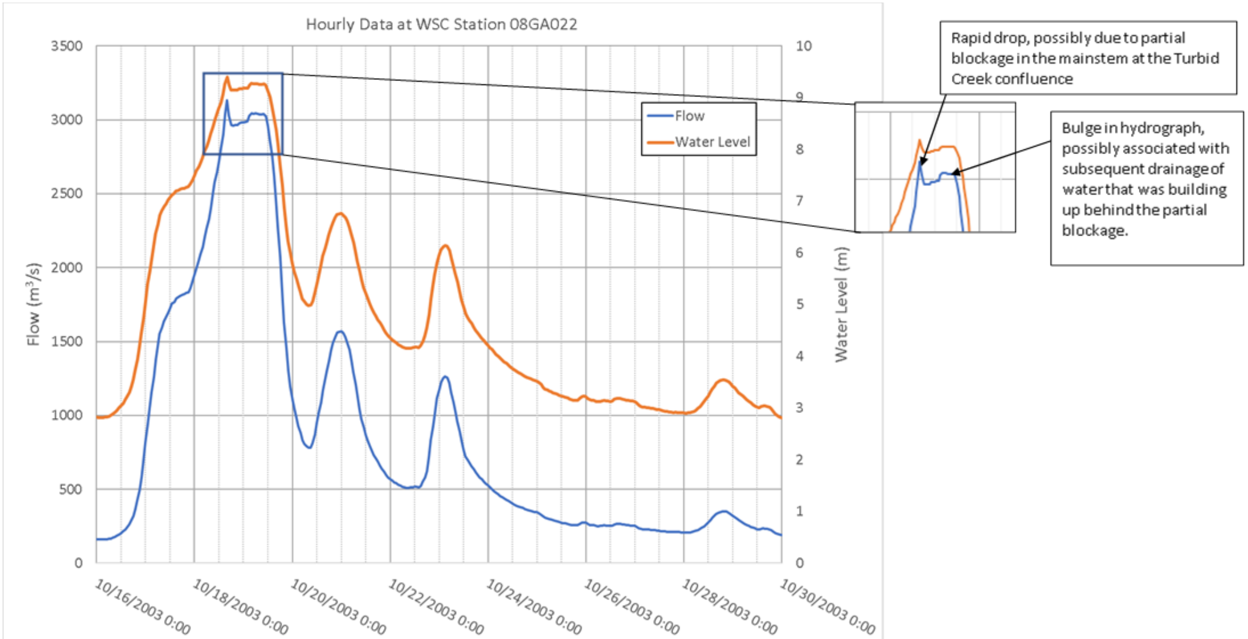


Figure 12: Hydrograph for 18 October 2003 flood showing unusually irregular flood peak profile that is potentially linked to occurrence of a dam-failure flow pulse.

Prehistoric Mount Cayley Events

A recent study of Squamish River floodplain sediments between Cheakamus River and about RK 24 (Fath 2014, 2018) did not discern any evidence for prehistoric outburst flood in the last 3000 years of the available sediment record. However, there was evidence of significant channel aggradation about 1100 years ago, and this was tentatively attributed to downstream reworking of sediment introduced by the 1100 BP Mount Cayley landslide event (Table 2); similar to the post-1855 response on Cheakamus River (Clague et al 2003).

Based on the prehistoric record, the approximate return frequency of large landslides capable of blocking the Squamish River to the point that large impoundments develop is about 1/500 years (Section 3.1.1). Not all landslide barriers become incised, and of those that are, not all are breached rapidly with ensuing high peak discharges. Finally, not all occur when the river flow is high. A recent local example is the outburst flood resulting from the Aug 2010 Capricorn landslide that impounded 3 million m^3 of water when flow on the Lillooet River was at relatively low stage. Attenuation of the flood wave resulted in water levels only reaching bankfull condition, with no overbank flooding of settled areas located 40 km downstream. Potential flood impacts of landslide dam failure are explored more in Section 3.2.

1855-56 Rubble Creek Event

The “Barrier” on Rubble Creek has suffered at least two major collapses in post-glacial time (Hardy et al 1978; Clague/Friele unpublished data). The most recent event occurred in 1855-56 resulting in a large rock avalanche that reached the Cheakamus River and transformed into a debris flow that traveled down the Cheakamus River into the Cheakamus Canyon (Moore and Mathews 1978). Recently, Clague et al (2003) documented 1-2 m of channel aggradation along lower Cheakamus River in the vicinity of the North Vancouver Outdoor School. This aggradation event occurred over a 25 year long period immediately following the 1855-56 Barrier collapse, indicating a delayed sediment pulse with dramatic effect on fluvial processes. Recent radiocarbon dating of sediment exposed in a fresh road cut at Rubble Creek indicates that the earlier "Barrier" collapse occurred shortly after 6645±20 yr BP (UCI-6645) (Clague/Friele, unpublished, Figure 13).

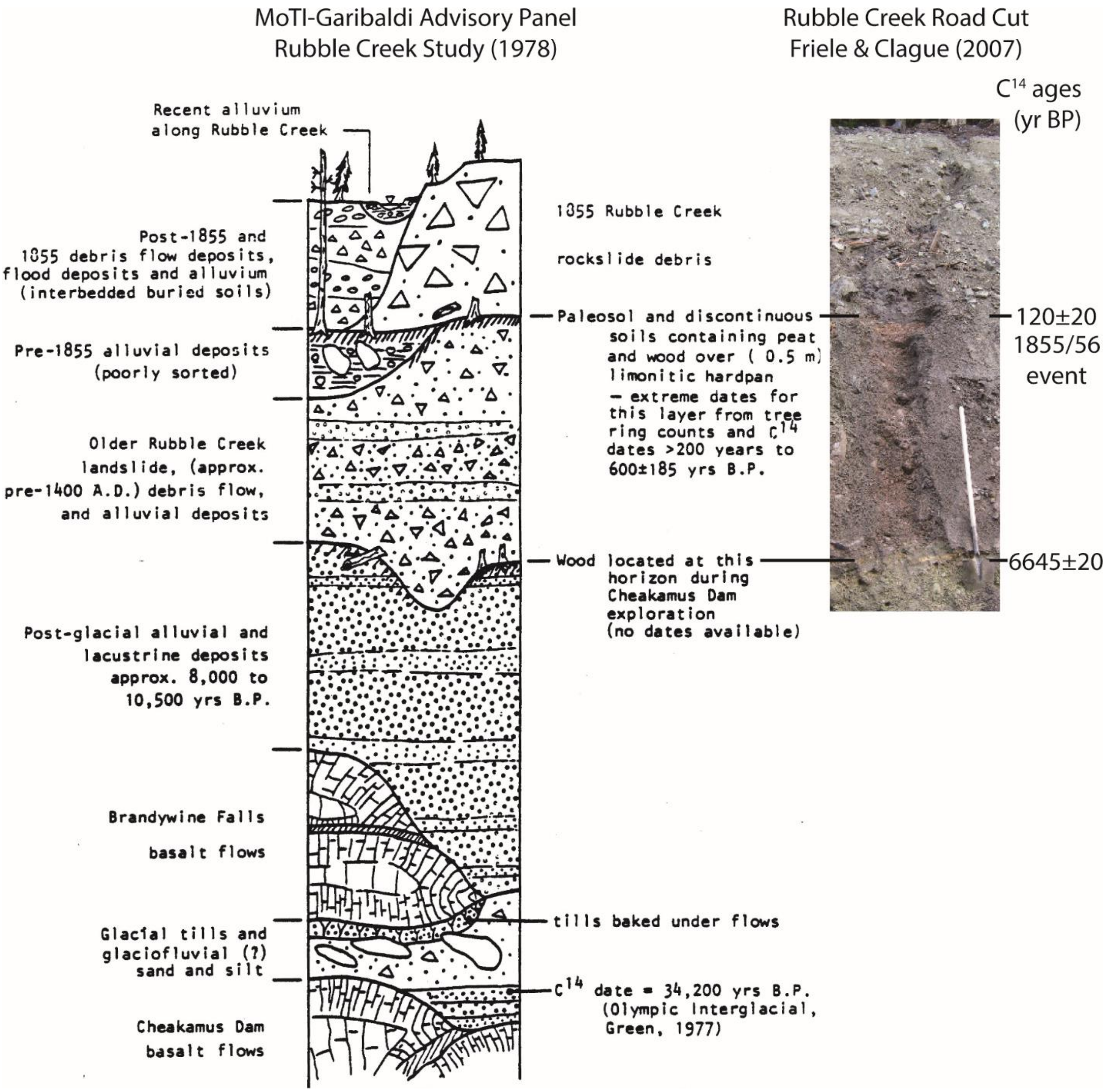


Figure 13: Stratigraphy of Rubble Creek Fan from Hardy (1978) and Friele/Clague (unpublished).

Culliton Creek

A similar history and set of downstream consequences might be expected from the Culliton Creek "barrier". River sections on river right and river left, just upstream of Culliton Creek Fan provide evidence on the frequency of blockage of Cheakamus River at Culliton Creek. There is a 4 m tall exposure on the right (west) bank located just upstream of Culliton Creek. Here at river level is 1 m of very poorly sorted gravel, similar in character to the surface unit upstream in this reach. This unit is capped by a 3 m thick sequence of bedded silty fine sand. There are four discrete silty fine sand beds, the surface of each defined by a buried soil horizon, or paleosol. Charcoal fragments from within the lowest sand bed yielded an age of 5415±20 yr BP (UCI-45015) and charcoal from the paleosol capping this bed yielded an age of 3520±20 (UCI-45014)(Clague/Friele, unpublished data). Each silt unit with capping paleosol is interpreted to represent a landslide dam event, and there are four since 5400 yr BP, suggesting an average recurrence interval of channel blockage of about 1300 years.

On the left (east) side of the channel, the exposed bank (Figure 14) is 8 m tall revealing 3.5 m of sandy gravel overlying a 2.5 m thick, bedded sand unit with beds having a steep (20º) upstream dip. The dipping sands overly 2 m thick sequence of horizontally bedded sands extending to river level. Charcoal fragments from the basal fines have been dated to 4020±30 yr BP (Beta- 483551) (Friele, unpublished). The upstream dipping sand beds are interpreted as foreset beds deposited in a small delta formed in a pond upstream of the 4020 yr old blockage at Culliton Creek.

Figure 14: View of left bank Cheakamus River, just upstream of Culliton Creek. Flow left to right. Note basal fines interpreted as backwater sediments, dated to 4020±30 yr BP, overlain by upstream dipping foreset beds and capped by topset alluvial fan gravels.

3.2.2 Landslide Dam Failure Probability, Discharge, and Rate

Previous Work on Squamish River

A potential landslide dam breach at Mount Cayley was modeled by Woods (1987). Modeling of this sort is based on many assumptions and the analysis is fraught with uncertainty. Nevertheless, the exercise demonstrated that "even a modest blockage that erodes rapidly could achieve peaks close to the 1/200 year flow if coincident with the annual peak flood". Whereas, a flood resulting from rapid breach of a more extensive channel spanning dam could equal or exceed twice the 200-year flood level. Apparently, a similar modeling exercise was undertaken by KWL for a proposed subdivision (Magee) in the upper Squamish, but this report is not publicly available for review.

Dam Failure Probability

A large dataset of 84 landslide dams and their ultimate fate was collated by Ermini and Casagli (2003), who used the information to develop a geomorphological dimensionless index capable of effectively discriminating stable landslide blockages from those that rapidly failed. Because it is based on modest input data requirements, it can be applied to evaluate the expected fate of various Mount Cayley landslide scenarios. The dimensionless blocking index (DBI) relates three parameters: Dam volume (V_d), dam height (H_d), and catchment area (A_b), as follows:

$$DBI = log\left(\frac{A_b \times H_d}{V_d}\right)$$

so that dam volume, which controls the dam's self-weight, is the primary stabilizing parameter and dam height and catchment areas are the primary destabilizing factors. Dam height relates to the dam slope downstream and energy of overtopping waters available to incise through the dam, while watershed area relates to the expected discharge and stream power and –indirectly– dam shape. Ermini and Casagli (2003) found that values of DBI > 2.75 typically correspond to stable landslide dams, values between 2.75 and 3.08 are uncertain, and values < 3.08 are typically unstable (Figure 15).

DBI was calculated for the three largest landslide classes listed in Table 6, with a range of estimates based on potential variability in the landslide dam geometry. These results are presented in Table 7 and overlain on Figure 15 (as points identifying the central estimate with error bars indicating the range between the best case and worst case estimates) and show how larger landslides are more likely to result in stable landslide dams than smaller events:

- The 50 yr event is predicted to be unstable for both the worst case and central estimate, and has an uncertain fate for the best case estimate.
- The 1000 yr event is predicted to be unstable for the worst case estimate, is uncertain for the central estimate, and is predicted to be stable for the best case estimate.
- The 5000 yr event is predicted to be uncertain for the worst case estimate and stable for the central and best case estimates.

From the standpoint of landslide dam failure flood hazard, the worst-case scenario is, therefore, likely a relatively moderate (50-500 yr recurrence interval) landslide event and not the largest millennial-timescale recurrence interval flank collapse events. It is important to note, however, that these larger flank collapses can evolve into long-runout volcanic debris flows (See Section 3.1.1) posing a separate and significant hazard to the downstream valley. The fact that larger landslides are more prone to produce stable dams may account for the longer term impoundments that occurred following the largest slides evidenced by the accumulated backwater sediments mapped by Evans and Brooks (1991).

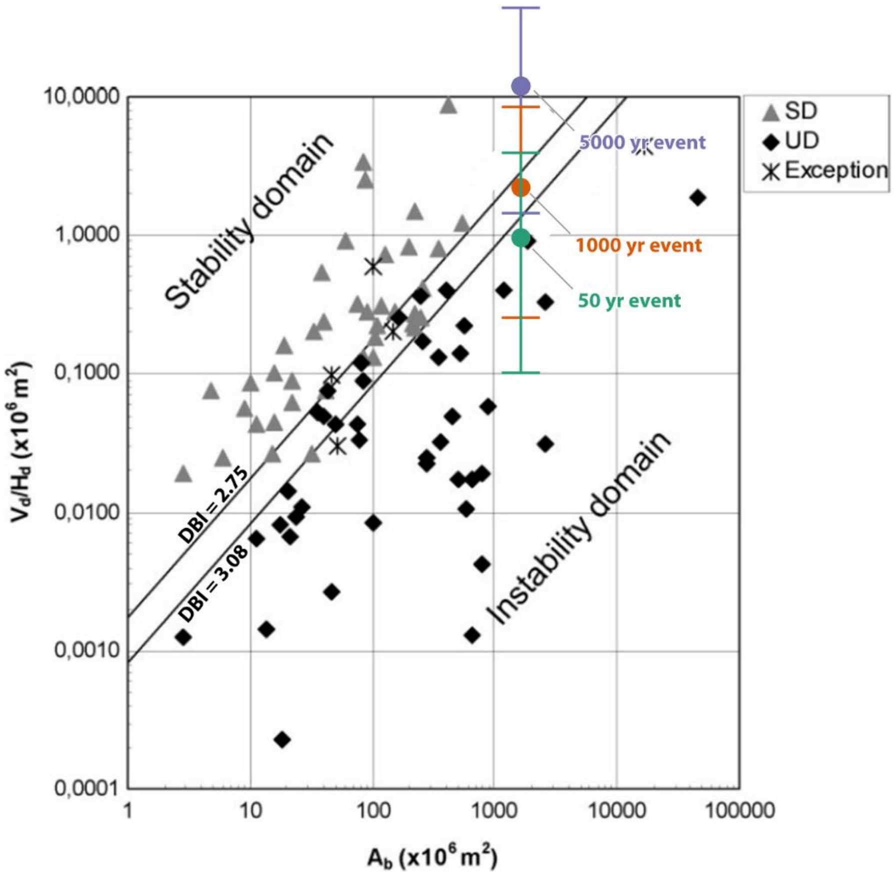


Figure 15: Ermini and Casagli's (2003): Dimensionless blockage index plotted over their dataset of 84 global landslide dam events. Values for potential Mount Cayley landslide dams are overlain.

Table 7: Computed dimensionless blocking index values for large potentially valley-damming landslides at Mount Cayley.

Volume (m^3)	Squamish R. Impoundment Height (m)	Recurrence Frequency (years)	Dimensionless Blocking Index* worst case	central estimate	best case
10^6-10^7	5-10 m	50	4.23	3.25	2.93
10^7-10^8	25-40 m	1000	3.83	2.89	2.62
10^8-10^9	50-70 m	5000	3.07	2.15	1.93

*** worst case DBI calculated as minimum class landslide volume paired with maximum impoundment height, central estimate calculated as geometric mean of the landslide volume range paired with mean of the height range, and best case calculated as maximum class landslide volume paired with minimum impoundment height.**

Dam Failure Discharge and Duration

Unstable landslide dams may fail rapidly, suddenly releasing a large volume of impounded water, or may fail more slowly, over the course of days to weeks, resulting in a modest increase to downstream baseflow conditions. Walder and O'Connor (1997) describe a method for predicting peak outflow discharge and the rate of landslide dam failure. Their method is based on a simple physically based model of dam failure (see the original paper for details) parameterized by values that, in the case of Mount Cayley landslides, can be estimated in advance or applied from experience elsewhere. Specifically, it requires estimates of the drop in water level (d), water volume released (V_0), and rate of vertical breach erosion (k).

Here we assume 'd' to be the whole landslide dam height, which is a conservative assumption based on the relatively fine-grained nature of historic slide deposits and anticipated limited potential for armor development. In other typical landslide dam failure cases $0.5H_d < d < H_d$. (Walder and O'Connor, 1997), the volume of water released is based on values listed in Table 3. The vertical break erosion rate (k) is unknown for historic events at the site but events in other regions have been described as typically ranging between 10 and 100 m/h (Walder and O'Connor, 1997), and so these values are used to bracket this evaluation. Discharges exceeding the 100-year recurrence interval hydroclimatic flood (3100 m^3/s) can be generated by failure of 15 to 20 m high landslide blockages. Blockages of this height are likely to form from landslide events with a 100 to 500 yr recurrence interval (section 3.1.2) and may be either stable or unstable.

Table 8: Computed peak discharge (Q_p) from various landslide-dam failure scenarios depending on dam height and erosion rate.

Debris Dam Height (m) (assumed to be d)	Impounded Volume (m^3) (assumed to be V_0)	Peak Discharge ($m^3 s^{-1}$) depending on Erosion Rate k (m/h)			
		k = 10	k = 25	k = 50	k = 100
5	1.3×10^6	320	340	340	340
10	5.7×10^6	1500	1800	1900	1900
15	1.3×10^7	2700	4400	5200	5300
20	2.3×10^7	5000	7800	9200	11000
25	3.7×10^7	7000	12000	16000	18000
30	5.9×10^7	9000	17000	24000	28000
40	1.2×10^8	14000	25000	41000	54000
50	2.0×10^8	18000	44000	66000	89000
60	2.5×10^8	20000	47000	70000	110000

Walder and O'Connor's model can also be used to estimate the time to peak discharge (t_p) and generate an approximate flood hydrograph based on the assumption of a triangular hydrograph with the estimated peak discharge and duration of $2V_0/Q_p$. Time to peak discharge values are shown in Table 9. Routing of example flood surges and implications for downstream flood hazards are documented in the accompanying main report.

Table 9: Estimated time to peak discharge (t_p) values from various landslide-dam failure scenarios depending on dam height and erosion rate.

Debris Dam Height (m) (assumed to be d)	Impounded Volume (m^3) (assumed to be V_0)	Time to Peak Discharge (min) depending on Erosion Rate k (m/h)			
		k = 10	k = 25	k = 50	k = 100
5	1.3×10^6	30	12	6	3
10	5.7×10^6	60	24	12	6
15	1.3×10^7	90	36	18	9
20	2.3×10^7	123	48	24	12
25	3.7×10^7	139	60	30	15
30	5.9×10^7	158	86	36	18
40	1.2×10^8	191	104	48	24
50	2.0×10^8	218	118	60	30
60	2.5×10^8	228	124	78	36

4 CHANNEL GEOMORPHOLOGY

The previous sections have emphasized the potential for geomorphic processes to abruptly—and possibly catastrophically—alter the supply of sediment or water to the project reach. This section focuses on geomorphic processes that are expected to occur under normal sediment supply and flood regimes over the coming decades. These may cause the channel to shift its position, both laterally and vertically, which may change flood water levels or directly erode land with consequences for valley bottom development.

4.1 Profile, Channel Hydraulics, and Sediment Mobility

The profile of the Squamish River and its tributaries is plotted on Figure 16 and shows they are punctuated with distinct higher gradient steps in between lower gradient concavities where the gradient decreases in the downstream direction. This is characteristic of channels that flow through recently glaciated landscapes (Brardinoni and Hassan 2006) and/or are affected by landslide-river interruption (Hewitt 1998; Korup 2006). The project reach (Figure 17)—between the confluence with the Cheakamus River at about RK 11 and a point up valley at approximately RK 41—grades to base level set by the Cheekye Fan. As described in Section 2.2.3, the fan initially formed an impoundment at approximately 22 m elevation, but fluvial incision during the Holocene has lowered this elevation to about 13 m at the present. As discussed in Section 2.2.4, if the Cheakamus River were to shift northerly on its fan, then the base level of the Squamish River at the confluence could be raised as much as 3.5 m, similar to base level some 2300 years ago as reconstructed by Fath et al (2018). Large floods or sediment introduced by high-moderate frequency debris flows from Cheekye Fan could trigger lateral instability on Cheakamus Fan and increase in base level on the Squamish River. If such an event were to occur, it is likely that some sort of intervention would be executed. Alternately, mitigation of debris flow hazard on Cheekye Fan might reduce this risk.

The channel slope declines from about 0.25% at the upstream boundary of the project area to about 0.03% just above the confluence of the Cheakamus River. Slope declines consistently through the upper portion of the profile, decreasing from about 0.25% at RK 41 to about 0.15% at RK 30. Between RK 30 and RK 28, about where the channel crosses the upstream boundary of the area that had been impounded by Cheekye Fan, the slope drops abruptly to about 0.06%. This transition marks the boundary between a wandering channel morphology in the upper project reach and meandering channel morphology in the downstream portion of the project reach. The slope of the meandering reach gradually declines from about 0.06% at its upstream boundary to about 0.03% at its downstream edge. The channel is convex as it crosses the Cheakamus River alluvial fan, and so slope increases in the lowest portion of the project area.

Shear stress, which is a function of channel depth and slope, also declines in the downstream direction, but less rapidly than slope because depth generally increases from upstream to downstream. In the upper wandering reach, shear stress is sufficient to move medium-sized cobble, but it drops abruptly at the transition from wandering to meandering planform morphology, and the channel appears to lack the competence to transport cobble sized sediment downstream of RK 28. Field observations of the sediment texture (Figure 18) support this inference: cobble sized material accounts for about 20% of the bed surface at the pebble count collected at the upstream edge of the project area (RK 48), but only about 5% of the bed surface both at the sample locations immediately downstream of the transition (RK 27.4) and near the downstream edge of the project area (RK 18).

Normalized shear stress is a measure of sediment mobility that is computed as the ratio of modelled shear stress to the critical shear stress needed to transport the 84 percentile of the channel bed material (D_{84}). The D_{84} was estimated at each model cross-section by interpolating the bed mainstem material samples collected at RK 40.8, 27.4, and 18. Computed normalized shear stress is relatively high (values of 1 to 2) through the project area across the range of evaluated flood flows. Notable areas with lower (<1 to ~1) normalized shear stress occur at approximately RK 36, at the head of the meandering reach, and just above the confluence with the Cheakamus River. Based on the observed pattern of slope, shear stress, and normalized shear stress, substantial and persistent aggradation may be expected around the transition from wandering to meandering channel morphology and across the lower portion of the meandering reach, as shown in Figure 17.

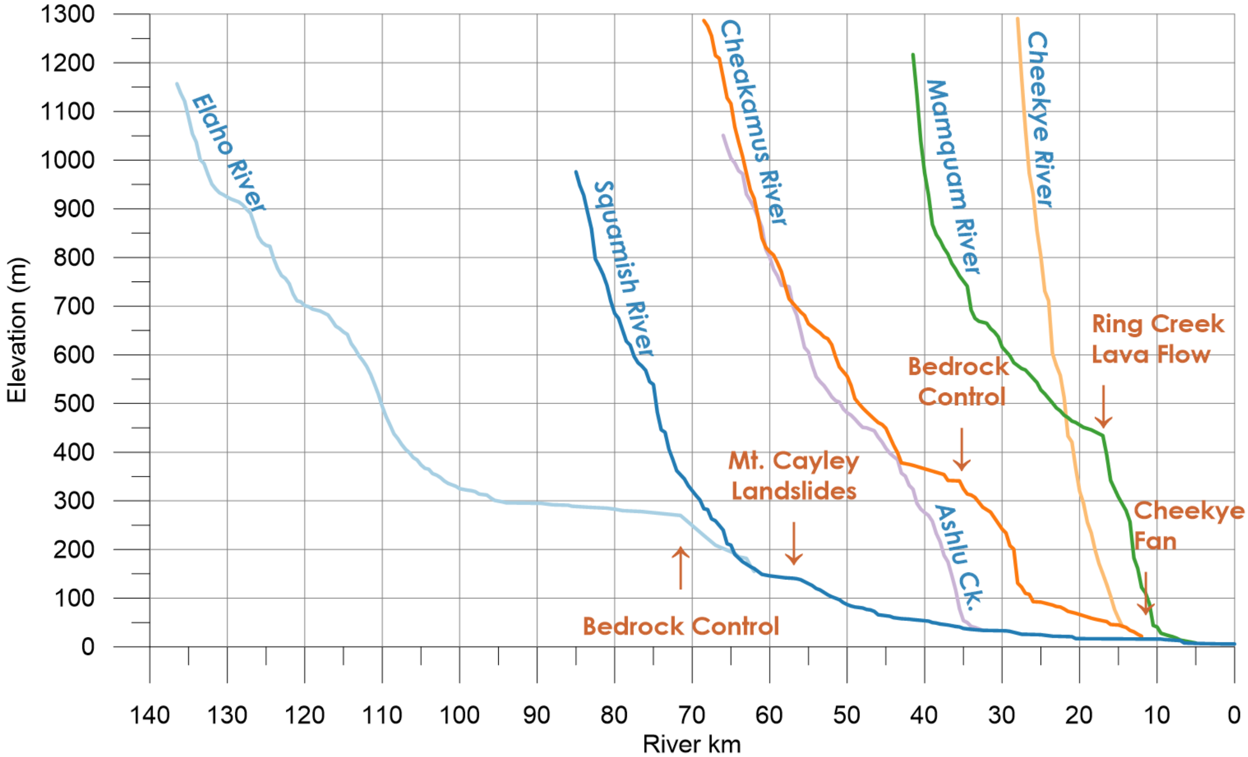


Figure 16: Profile of the Squamish River and its main tributaries.

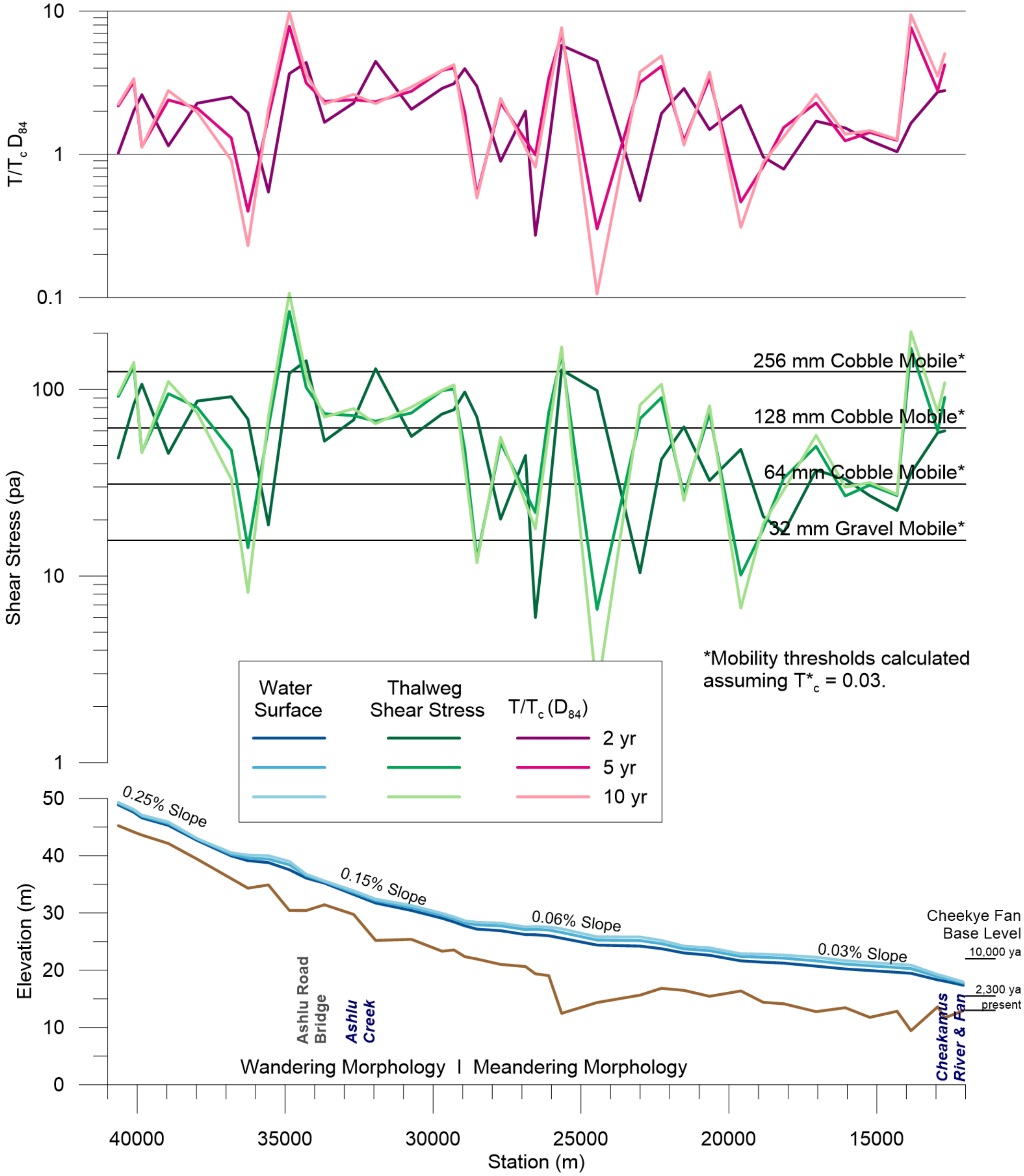


Figure 17: Detailed profile of Squamish River through project area showing surveyed thalweg profile and modeled water surface elevation, shear stress, and normalized shear stress for select flows.

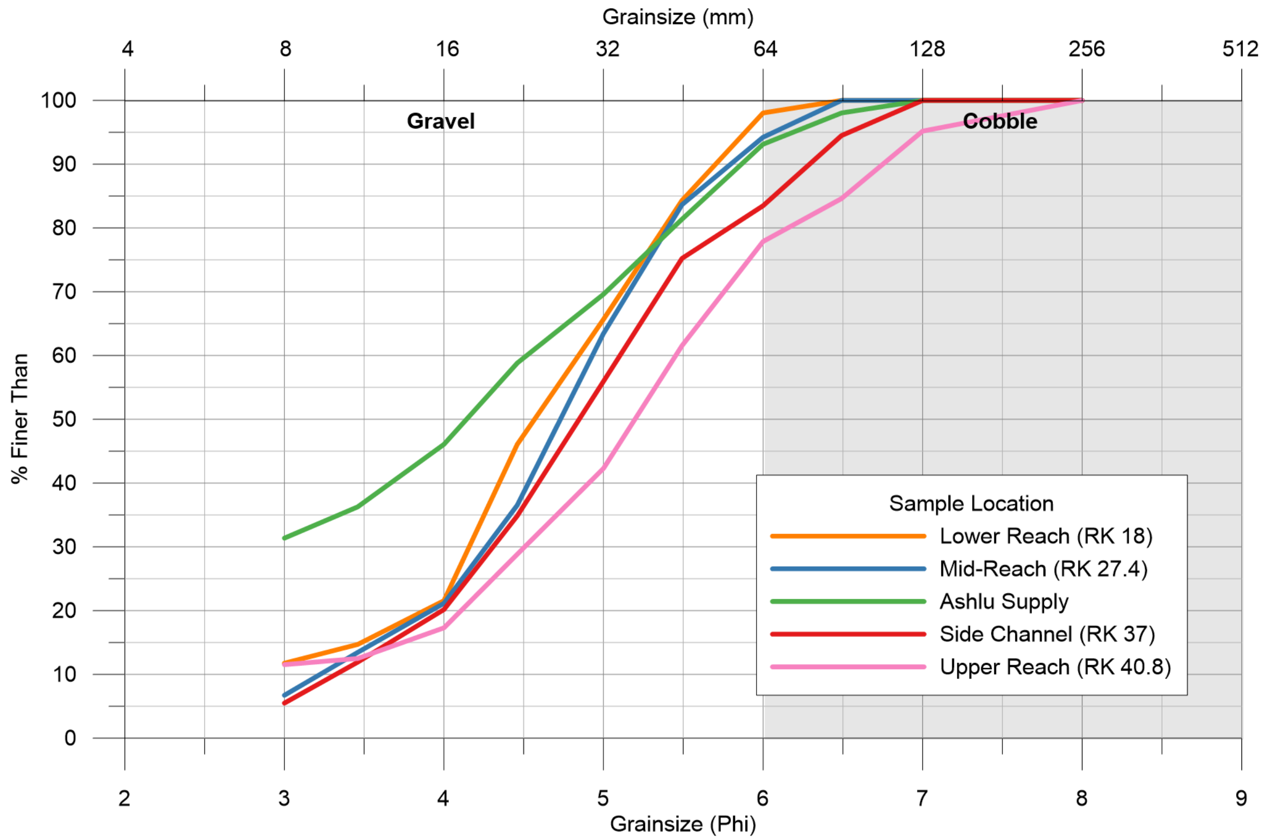


Figure 18: Surface Grain size Distributions Throughout Project Area

4.2 Project Area Reaches

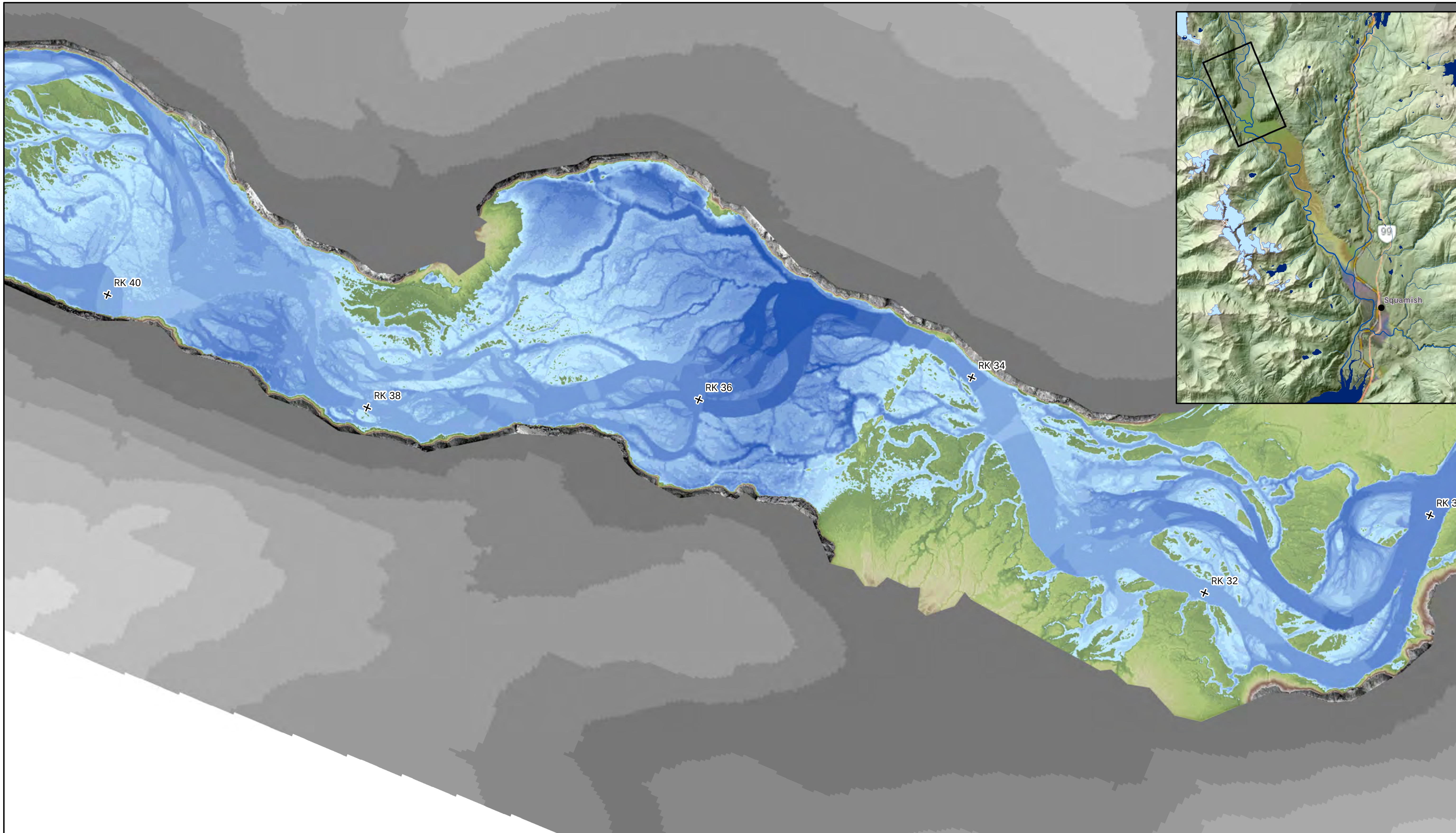
The project area encompasses two distinct reaches of the Squamish River. Each of these reaches has distinct river processes and channel form that result in different morphodynamic patterns and hydrogeomorphic hazards. This section discusses these processes and related hazards resulting from typical climate-driven floods and variability in sediment supply, not the extreme hydrogeomorphic events evaluated in Section 3.

4.2.1 Wandering Reach (RK 30-40.6)

The upstream reach has a wandering morphology characterized by a 400 to 600 m wide active channel split into two to three channel threads (Figure 19). These threads anabranch around relatively stable vegetated islands and are typically braided with low water flow paths divided around gravel bars (Figure 19, inset). There is a high load of large wood debris in the channel, and most islands and bars lie behind naturally-formed apex jams. In addition to the main active channel, several large (10-30 m wide) accessory channels cut across the floodplain. One segment of the channel in this reach—between about RK 34 and 35—abuts the left valley wall and is much narrower, flowing through an approximately 100 m wide single thread with a substantial accessory channel that is presently cutting across the right bank floodplain.

The pattern of channel migration in the wandering reach is characteristic of rivers with this planform morphology. Individual, sinuous channels migrate laterally and aggrade vertically until another path across the floodplain becomes more hydraulically favorable, leading to a new channel forming in an avulsion that divides the flow or causes partial or complete abandonment of the former main channel. Some large islands can also form behind large wood jams, further dividing the channel into multiple branches. Channel migration hazards in this reach include both gradual lateral movement of individual meanders and avulsion forming new channels cutting across the floodplain. Any portion of the floodplain in this reach is subject to the possibility of a channel avulsion, but low-elevation paths offering a shorter link down valley are particularly vulnerable.

Bauch and Hickin (2011) present detailed data (including earlier work by Sichingabula, 1985) describing the channel migration history of approximately the downstream 4 km of the wandering reach (RK 30 – 34). Their data show that the long-term average bank erosion rate in the reach has been about 11 m/yr, but that the period from the mid-1980s to 2009 had a faster erosion rate (17 m/yr) than the earlier period from 1951 through 1987, which had an erosion rate of about 8 m/yr. Individual bends, however, have migrated at rates up to about 50 m/yr, much faster than this reach-averaged rate. Between 1951 and 2009, bank erosion has substantially exceeded the rate of floodplain accretion, and so the average active channel width has increased by about 180 m.



Floodplain Elevation Relative to 2-yr Water Surface (m)

Depth: -2.5, -2, -1.5, -1, -0.5, 0

Height Above: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10

SCALE - 1:20,000

0 100 200 300 400 500 600 700 800 Meters

N

Coordinate System: NAD83 UTM ZONE 10N
Units: METERS

Job: 0300375 | Date: 01-JAN-2000

Squamish River Geomorpology
Wandering Reach
Morphology

Figure 19

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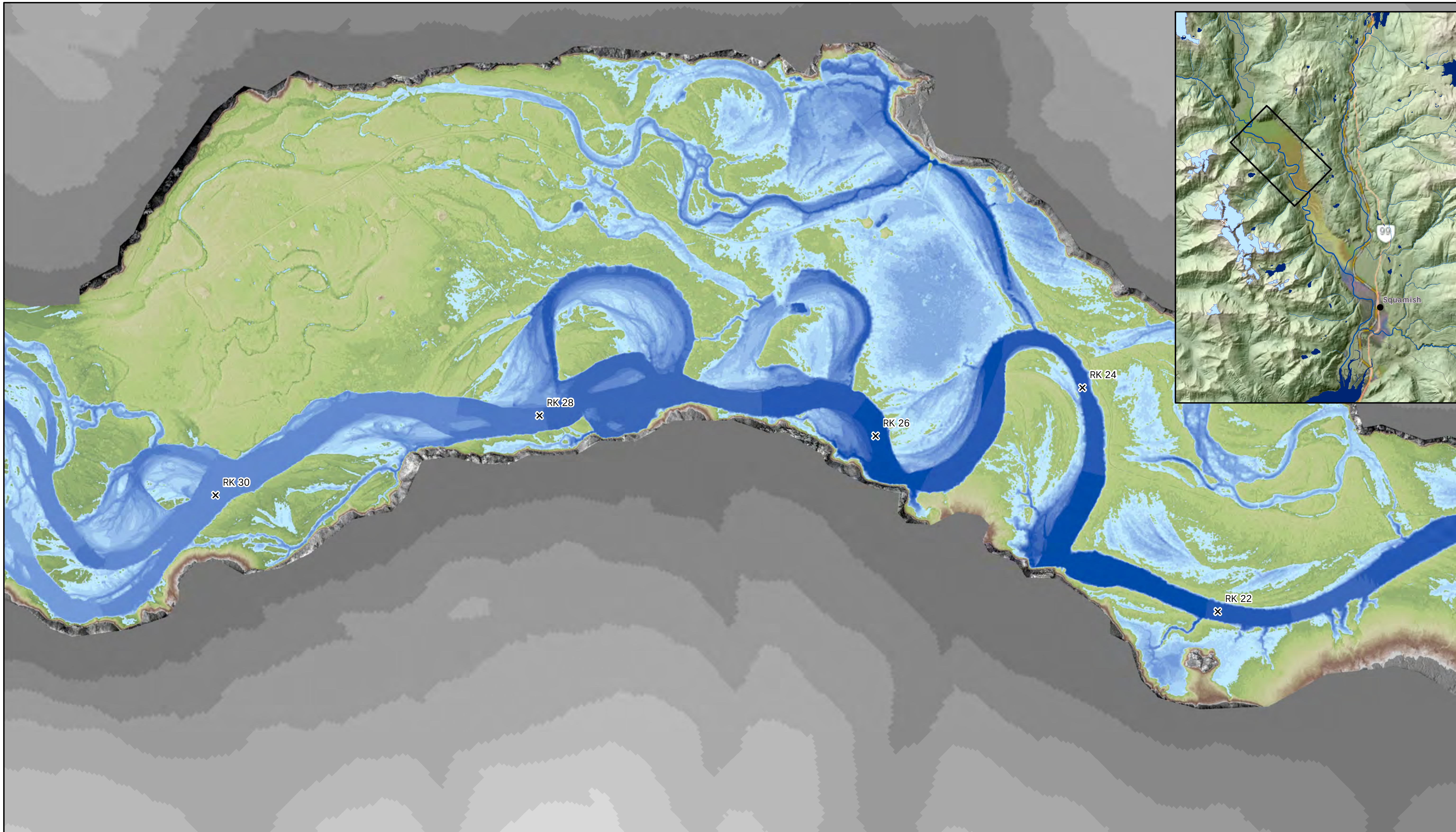
4.2.2 Meandering Reach (RK 13-30)

The downstream reach (Figure 20 and Figure 21) has a meandering planform with a consistently single-thread channel that is about 200 m wide. Large relict channels and oxbow features (including lakes) are present across the valley bottom. In the upstream portion of the meandering reach (RK 20 to 30), these include both channel scars with similar geometry to the present-day river and large (30 to 60 m wide) accessory channels that appear to have been abandoned by relatively downcutting. Downstream, channel scars across the floodplain consistently have similar geometry to the present-day river. Prominent alluvial ridges are present along channel features, suggesting overbank sedimentation is typically concentrated near the river channel.

The pattern of channel migration in this reach is characterized by gradual meander amplification and down-valley translation followed by chute or neck cut offs across the inside of the meander. In contrast to the wandering reach upstream, the abandoned channels often have path lengths much longer than the newly formed avulsion channel and so they do not persist as a part of the active channel network, but become isolated by formation of natural levees along the preferred channel path. Bauch and Hickin (2011) also examined channel migration rates in the reach and present data for two sub reaches, one extending from approximately RK 23 to 29 (their Reach C) and the other from about RK 17.5 to 21.5 (their Reach B). The furthest downstream portion of the project area (RK 12-17) has been extremely stable over the historic record, with very little bank erosion and channel migration. Restricted lateral channel mobility in this area has resulted in the formation of deep flood basins isolated from the channel by natural levees. Slower lateral channel migration in this reach is a consequence of higher relative bank strength due to cohesive bank material described by Fath et al. (2018), local bank protection provided by riprap, and lower bed material transport and accumulation rates compared to upstream. Riprap that has been placed along the channel may locally exacerbate lateral erosion of non-armored banks.

Bauch and Hickin (2011) show that the average erosion rate along the upper portion of the meandering reach has been about 11 m/yr (1951-2009 period), while it has been substantially slower—5 m/yr—along the lower portion of the reach (1959-2009 period). As with their observation for the wandering reach, erosion rates have accelerated in the meandering reach since the mid-1980s, increasing from about 8 to 15 m/yr in the upstream portion of the reach and from about 3 to 6 m/yr in the downstream portion of the reach. Individual bends typically migrate laterally at rates of 20 to 40 m/yr; however, large floods in 1990 and 1991 produced exceptional migration rates at freely migrating meanders of 50 to 150 m over single flood seasons. In the upper portion of the meandering reach, bank erosion has substantially exceeded floodplain accretion, resulting in about a 90 m increase in the active channel width between 1951 and 2009, while in the downstream portion, there has been little change in the active channel width.

Increased erosion rates and channel widening in the project area are correlated with an increase in the intensity of autumn-season storms and floods, and show that the channel is sensitive to decadal-scale hydrologic variability (Bauch and Hickin, 2011). The upstream-to downstream pattern of increasing responsiveness to floods suggests that the pattern of channel migration and widening is a function of bed material transport rate, which is presumed to decrease through the project area due to movement of material into storage along the channel.



Floodplain Elevation Relative to 2-yr Water Surface (m)

Depth: -2.5, -2, -1.5, -1, -0.5, 0

Height Above: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10

SCALE - 1:20,000

0 100 200 300 400 500 600 700 800 Meters

N

Coordinate System: NAD83 UTM ZONE 10N
Units: METERS

Job: 0300375 *Date: 01-JAN-2000*

Squamish River Geomorpology
Upper Meandering Reach
Morphology

Figure 20

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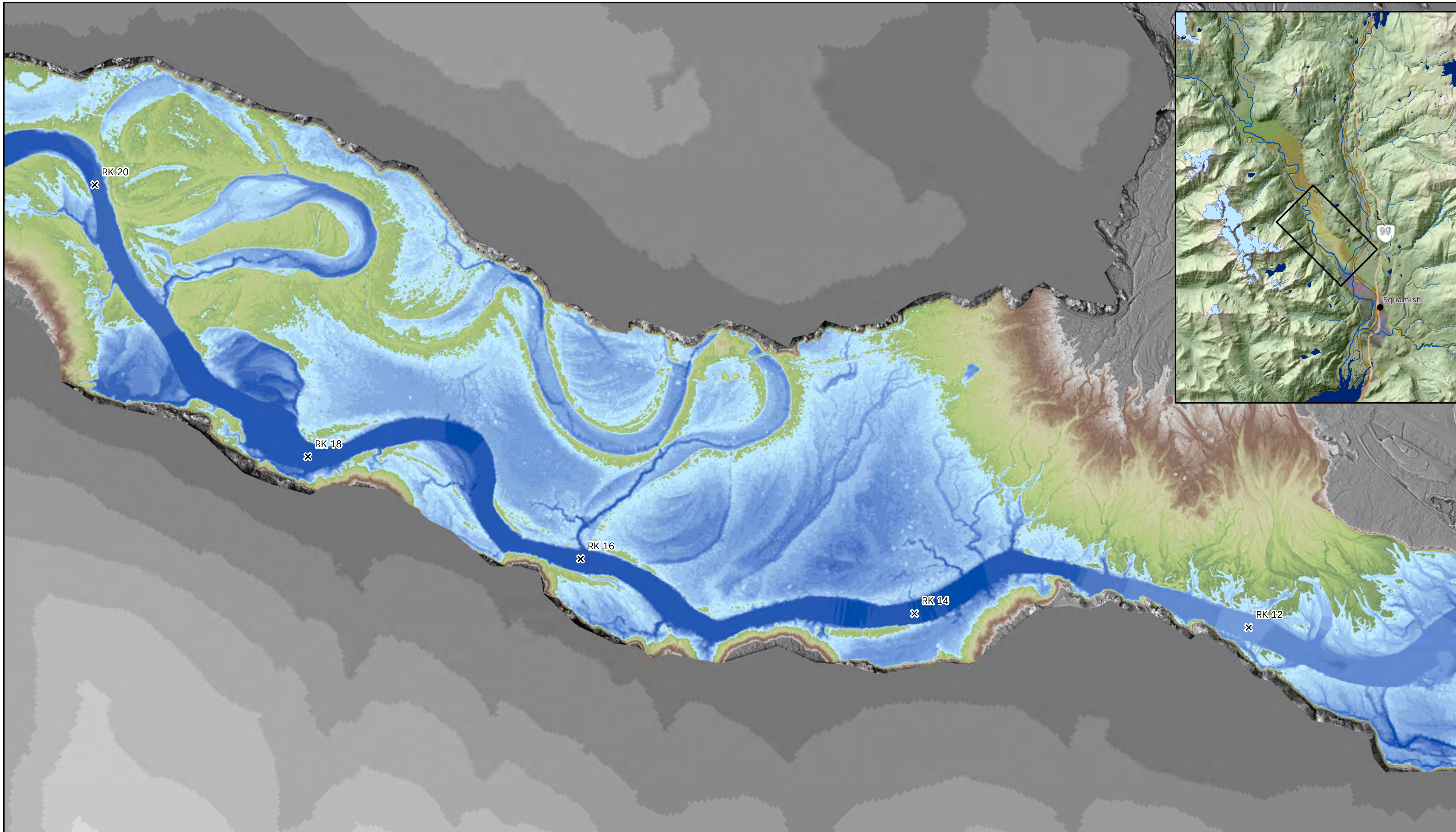

Floodplain Elevation Relative to 2-yr Water Surface (m)

Depth -2.5 -2 -1.5 -1 -0.5 0

Height Above 1 2 3 4 5 6 7 8 9 10

SCALE - 1:20,000

0 100 200 300 400 500 600 700 800 Meters

N

Coordinate System: NAD83 UTM ZONE 10N
Units: METERS

Job: 0300375

Date: 01-JAN-2000

Squamish River Geomorpology
Lower Meandering Reach
Morphology

Figure 21

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4.3 Channel Migration Zone Delineation

The Channel Migration Zone (CMZ) for the Squamish River was mapped following the planning level CMZ (pCMZ) delineation procedure described by Olson et al. (2014). This procedure involves determination of several components of the CMZ, as follows.

- The Modern Valley Bottom, which is defined as "the area where channel migration has occurred in the current climatic and hydrologic regime, which is assumed to encompass the last several thousand years (Olson et al., 2014 p. 19)." This unit can be delineated on the basis of the extent of fluvial landforms on the geomorphic surface where the channel currently actively migrates. It is by definition inclusive of—but greater than— the historical area of channel occupancy. In the case of the Squamish River, floodplain channels, meander scrolls, alluvial splay deposits, and Oxbow Lakes and depressions provide abundant evidence of lateral channel migration encompassing most of the valley bottom. In the meandering reach, meander scrolls are becoming over-printed on the finer grained lacustrine valley fill.
- The Erosion Hazard Area is the second core component of the pCMZ. This unit is added to the modern valley bottom to account for potential future valley widening caused by channel migration. Olson et al. recommend that the width of the erosion hazard area be determined on the basis of valley margin erodibility and probability of the channel impinging against the valley wall. Valley margin erodibility is a function of the composition of the valley wall material and height of the valley wall. In the pCMZ framework, the probability of channel impinging on the valley wall is a function of the ratio of the modern valley bottom width to the meander (or braid) belt width and distance between the modern valley bottom margin and active channel (Figure 22). The widths applied for this delineation are listed in Table 10. Due to the highly competent nature of the plutonic bedrock in the glacially-scoured valley walls, a width substantially narrower than recommended by Olson et al. (2014) was applied to areas where presence of competent bedrock could be confidently inferred from LiDAR texture and/or aerial photos.
- In addition to the core CMZ for the Squamish River, described by the above two zones, tributary creek fans are areas where avulsions or migration of tributary streams are expected to occur and where some erosion of the fan toe due to migration of the Squamish River may also occur. Debris flows from tributary streams may also impact some of the delineated fans. The toes of tributary fans were mapped from available LiDAR data, but this did not typically extend upslope to the fan apex. The extent of fans upslope of LiDAR data coverage was delineated based on aerial photo interpretation and should be considered very approximate —detailed mapping based on full coverage of LiDAR data or ground based mapping should be completed before any local land use decision is made on-or-near mapped alluvial fans outside of the area of LiDAR coverage.

Results of the delineation are mapped in Figure 23 through Figure 25. The channel migration zone delineated with this method essentially spans the entire valley bottom. Therefore, in addition to the pCMZ units described above, a highest hazard migration area was mapped to delineate the portion of the main valley bottom susceptible to avulsions or within the existing or recently occupied meander belt and a buffer around this into the alluvial valley bottom—which includes both the main valley bottom and alluvial terraces—equivalent to the average lateral channel migration over a 50 year timespan, based on the long-term measured lateral migration rates described by Bauch and Hickin (2011).

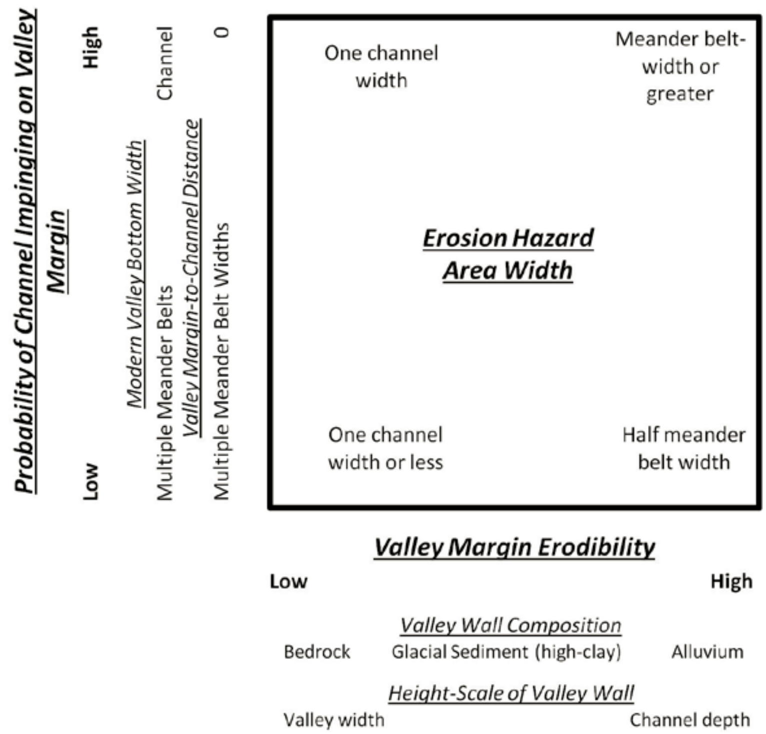
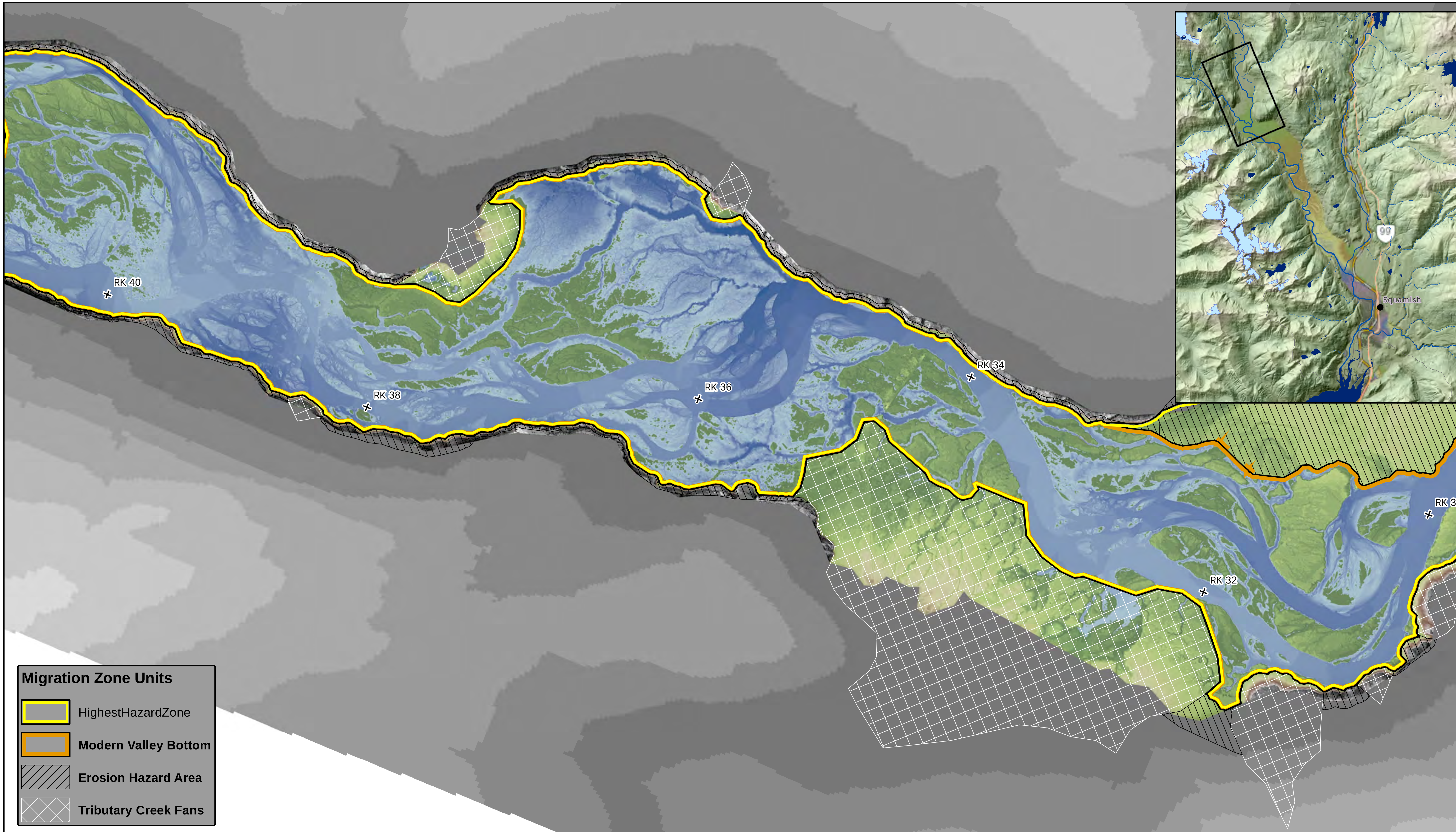


Figure 22: Olson et al.'s (2014) paradigm for determining width of the erosion hazard area.

Table 10: Rules used to determine erosion hazard area width for Squamish River pCMZ delineation.

Reach	Interpreted Valley Wall Composition	Valley Wall Height Scale	Modern Valley Bottom Width	Valley Margin to Channel Distance	Selected EHA Buffer
Wandering Reach	Plutonic Bedrock	Valley Width	Channel	Adjacent to less than a braid belt width	<< 1 channel width (25 m)
	Colluvium				~ 1/2 channel width (100 m)
Meandering Reach	Plutonic Bedrock	Valley Width	Channel to meander belt width	Adjacent to meander belt width	<< 1 channel width (25 m)
	Colluvium				~ 1/2 channel width (100 m)
	Alluvium	Channel-Depth	Channel to meander belt width	Adjacent to Channel	Meander belt width (1000 m)



Floodplain Elevation Relative to 2-yr Water Surface (m)

Depth: -2.5, -2, -1.5, -1, -0.5, 0

Height Above: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10

SCALE - 1:20,000

0 100 200 300 400 500 600 700 800 Meters

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Coordinate System: NAD83 UTM ZONE 10N
Units: METERS

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Squamish River Geomorpology
Wandering Reach
pCMZ

Figure 23

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Floodplain Elevation Relative to 2-yr Water Surface (m)

Depth -2.5 -2 -1.5 -1 -0.5 0

Height Above 1 2 3 4 5 6 7 8 9 10

SCALE - 1:20,000

0 100 200 300 400 500 600 700 800 Meters

Coordinate System: NAD83 UTM ZONE 10N
Units: METERS

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Squamish River Geomorpology
Upper Meandering Reach
pCMZ

Figure 24

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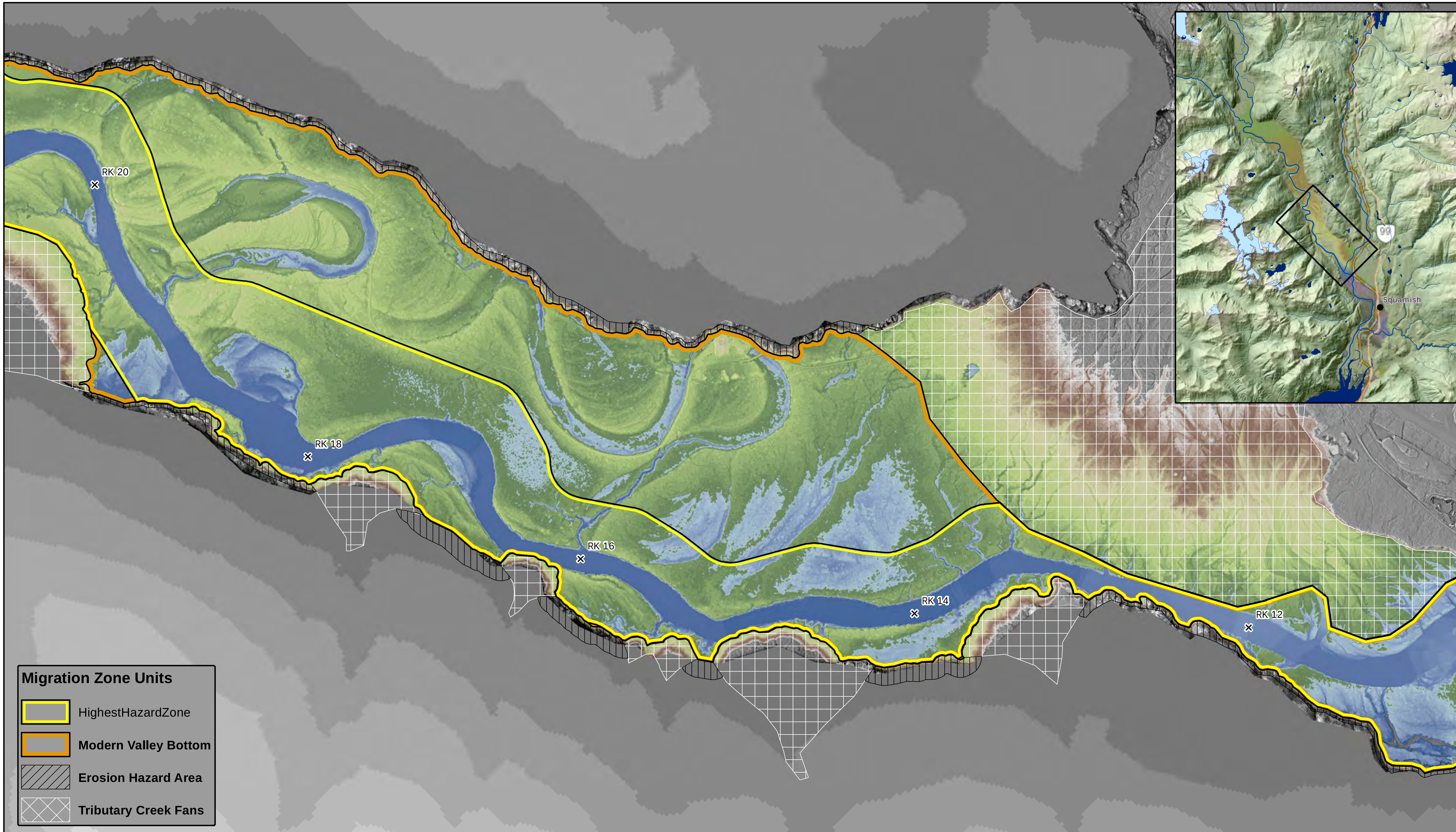

Floodplain Elevation Relative to 2-yr Water Surface (m)

Depth -2.5 -2 -1.5 -1 -0.5 0

Height Above 1 2 3 4 5 6 7 8 9 10

SCALE - 1:20,000

0 100 200 300 400 500 600 700 800 Meters

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Coordinate System: NAD83 UTM ZONE 10N
Units: METERS

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Squamish River Geomorpology
Lower Meandering Reach
pCMZ

Figure 25

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