Photo source: NHC 2019

Birkenhead and Green River Floodplain Mapping and Risk Assessment

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All participants who contributed to the data collection in the Risk Assessment.

In addition to the authors and reviewers of the report, the following NHC personnel participated in the study:

- Julie Van De Valk — Flood Risk Specialist, NHC
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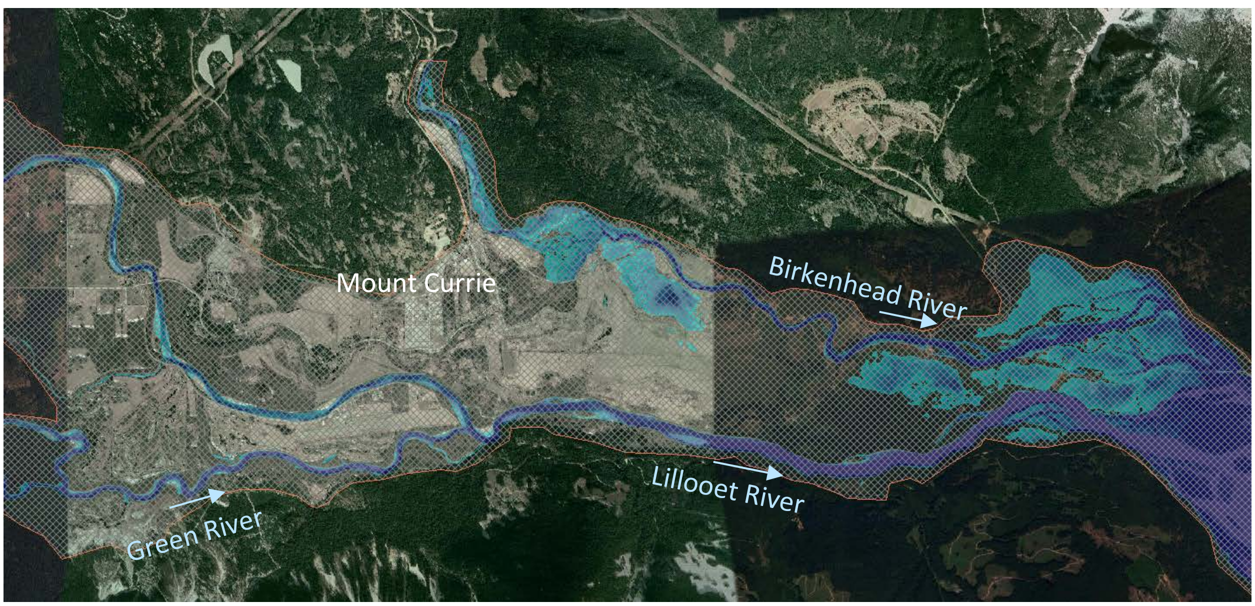
- Christine McKim — CAD Specialist, NHC
- Shane McConachie — GIS Analyst, NHC
- Chris Long — Principal, NHC

EXECUTIVE SUMMARY

A long history of flooding and exposure to flood hazard led Lil̓wat Nation to develop floodplain maps for the Birkenhead and Green Rivers. The study area covered 12 km of the Birkenhead River (starting from the outlet at Lillooet Lake) and 9 km of the Green River (starting at the confluence with Lillooet River). In order to accurately model the Lil̓wat Nation lands, the Lillooet River was included in the study as well.

For the Lil̓wat Nation, the new maps replace previous maps from 1991 and provide additional information for the shared floodplain with the Lillooet River. In 2018, Pemberton Valley Dyking District (PVDD) commissioned NHC to develop floodplain maps for Lillooet River. These maps remain valid for the Lillooet Valley. However, Lil̓wat Nation elected to include an allowance for climate change impacts on flows for their maps and the new, slightly more conservative maps developed in this study, apply to Lil̓wat Nation interests. Up-to-date floodplain mapping is important since rivers change over time. This is particularly true in the Pemberton Valley where climate change is increasing the peak flows on the rivers and sediment aggradation is occurring.

The project was carried out by Northwest Hydraulic Consultants Ltd (NHC). At the start of the project, Lil̓wat Nation members met with representatives from NHC to describe past flooding problems and discuss what was most important to the Lil̓wat Nation.



Study Area (hatched area represents the hydraulic model domain)

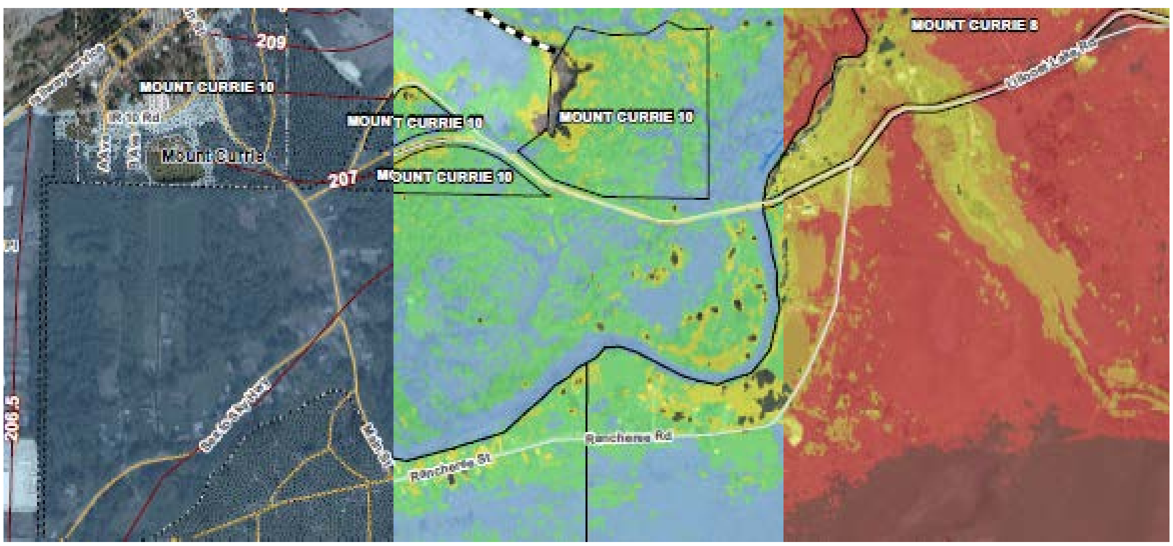
Why are floodplain maps useful?

Floodplain maps help you prepare for future floods. They show how high waters will rise during a very large flood and how much land will be under water. The maps help you plan where to safely build, how high to put livable floor space and ensure that buildings can be accessed during flood waters. The maps are also helpful during large flood events for emergency response and the evacuation of people from vulnerable areas.

How are floodplain maps developed?

Floodplain mapping projects involve several steps. First the rivers need to be surveyed and the topography of the floodplain captured by "Light Detection and Ranging" (Lidar). This information is used for developing a Digital Elevation Model (DEM). The DEM is then input into a numerical hydraulic model. Various flood flows are estimated based on recorded flows in the region, and these are used in the hydraulic model to estimate corresponding flood levels. Based on the simulated flood levels, maps are developed. The report "Birkenhead and Green River Floodplain Mapping and Risk Assessment" describes the different technical steps in detail.

Three types of maps were developed: 1) 200 year Designated Floodplain Maps showing flood extents and Flood Construction Levels (FCLs) including a freeboard allowance; 2) 50, 100 and 200 year Depth Maps; and, 3) 50, 100 and 200 year Flood Hazard Rating maps, showing the combination of flow velocities and depths. The 200 year flood refers to a flood that is estimated to occur once in 200 years on average or has a 0.5% probability of occurring in any one year. Map samples are shown below with detailed mapping included in the main report.



Sample sections of the 200 year Designated Floodplain map, 200 year Depth Map and 200 year Flood Hazard Rating Map

What are the main results of the mapping study?

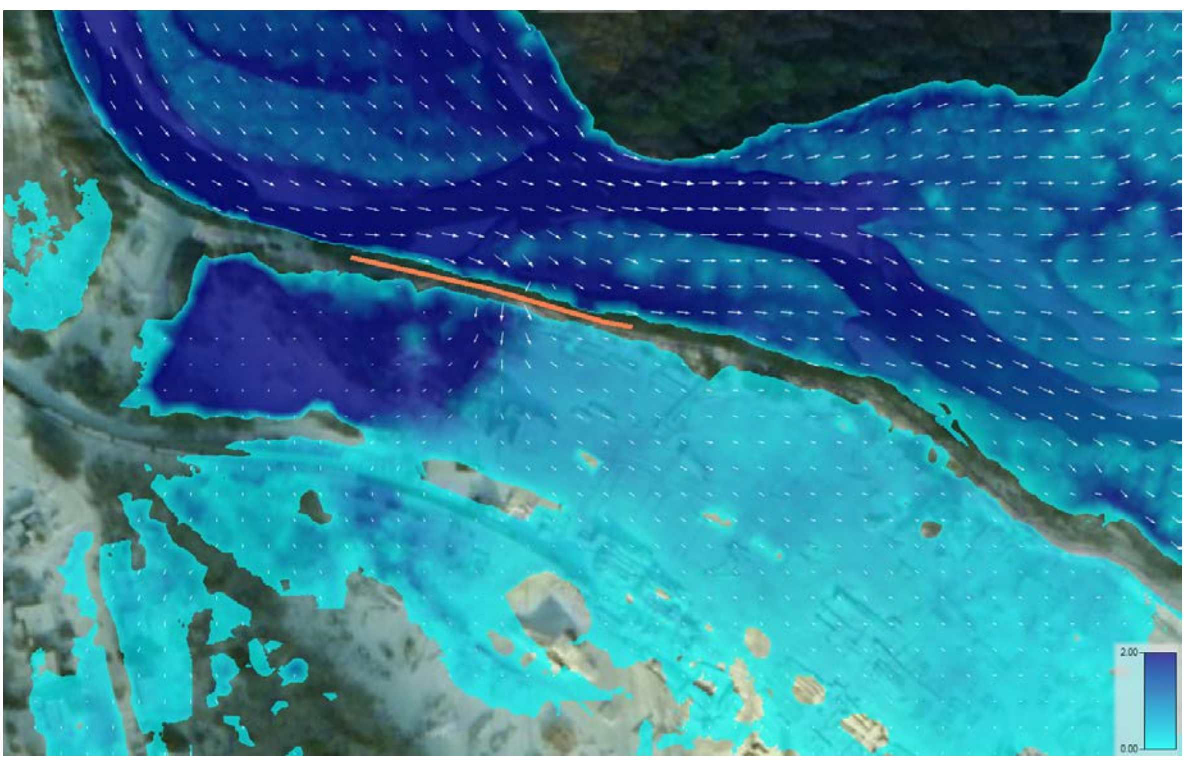
The NHC (2018) study suggested that the Green or Birkenhead River watersheds are likely sensitive to climate change impacts because they are in the rain-snow transition zone. The current 200 year flood estimate for the Green and Birkenhead Rivers are 656 m^3/s and 628 m^3/s. As based on EGBC guidelines and analyses of peak flow trends, climate change may increase the flood peak estimate to 820 m^3/s and 786 m^3/s by the end of century. These flows were used for developing the mapping.

Large-scale channel straightening and lowering of Lillooet Lake in the 1950's was carried out and over time, a number of dikes and berms were built (including the Poleyard Dike). Despite these flood mitigation measures, the Lillooet Valley continues to be at high risk of flooding. Considering apparent increases in peak flows and reduced channel capacity due to aggradation, flood hazards are expected to increase with time.

Development of the floodplain has resulted in a much less complex network of river channels and has substantially reduced the active channel area on the floodplain. Over time, channel sedimentation will further infill the river, particularly while material from the Mount Meager landslide moves through the river system. This will increase the channel bed elevation relative to elevation of the adjacent floodplain, increasing the potential for dike overtopping and severity of flooding. It will also reduce the flood carrying capacity of the channel, increasing the potential for localized channel erosion and other instabilities in some channel reaches. With no other flood mitigation options, channel management will need to be part of the long term flood management program.

Hydraulic modelling showed that overtopping of the Poleyard dike may begin at about the 50 year flood level. The dike breaches simulated in the hydraulic model would have significant impact on Mount Currie, inundating many areas on the floodplain within a few hours. Corresponding flow velocities would be very high and flood hazard ratings are categorized as significant or extreme in several locations.

It is clear from the risk and exposure assessment, as well as the community consultation, that consequences of flooding have already been experienced multiple times. The occurrence of the 200 year design flood, incorporating an allowance for the projected end-of-century climate change, would have severe impacts on people, economy, infrastructure, environment, and culture within the Nation. A high proportion of buildings are exposed to the design flood and so mitigating residential flood risk should be a priority. In addition, road access within the community and externally is severely affected and so response, continuity as well as any recovery plans should address this.



Hydraulic model output for the 200 year flood with a dike breach (location shown in orange).

What are the next steps?

It is recommended that an up-to-date flood emergency response plan be developed, taking into account the increased flood hazards. It would be beneficial for Lílwat Nation to coordinate their plan with Village of Pemberton, Squamish Lillooet Regional District and Pemberton Valley Dyking District. Depending on the location and nature of a dike breach, the response time before hazardous flows block roads and reach developed areas may be as little as 15 minutes (e.g., in Mount Currie just inside Poleyard dike).

It is recommended that the designated floodplain maps be adopted for the Birkenhead and Green Rivers and that the FCLs shown on the mapping be applied to future Lílwat Nation development. Major development should be avoided or limited in high hazard areas of the floodplain. If development is essential, it must be built to withstand flood waters (buildings raised on fill or stilts and with flood and erosion protection applied). Generally, protection measures in the area need to be improved. It is recommended that:

- Local authorities review the depth and hazard rating maps and identify areas where flooding would have major impacts on existing development. Consideration should be given to relocating or floodproofing housing and other development in critical areas.
- MOTI and other agencies be encouraged to identify areas where road and rail access/ egress can be improved to allow transport during high floods.
- Consideration be given to ensuring access to higher elevation areas in the valley that residents/ domestic animals can quickly be evacuated to.
- Phase 1 of the Poleyard Dike upgrade project is presently underway to upgrade the existing dike and extend it upstream to the edge of the railway right of way. Future phases should be completed to tie the dike into the railway grade at the upstream end, and to extended it farther downstream.

A full list of recommendations and conclusions can be found in Section 7.

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1 INTRODUCTION

Recently updated floodplain mapping prepared for Lillooet River (NHC 2018) showed that the Pemberton Valley is subject to considerable flood hazard and that the level of protection offered by present diking is lower than previously believed. Main reasons for this are: 1) sedimentation caused by the 2010 Mount Meager landslide leading to increased aggradation in the Lillooet River channel; and, 2) a shift in the hydrologic regime resulting in higher flood flow estimates. These two changes also have an impact on the Birkenhead and Green Rivers and their adjoining floodplain.

The 2018 Lillooet River Floodplain Mapping project included the Birkenhead and Green Rivers but did not specifically model tributary design floods, instead focussing on the Lillooet River 200 year flood. The estimated Flood Construction Levels (FCL) and flood hazard levels correspond to the Lillooet River and may be exceeded along the Birkenhead and Green Rivers during local events. Based on the Lillooet River study, breaching of the Poleyard Dike in Mount Currie could have severe impacts on the community. Over time, climate change is expected to increase flood flows and exacerbate flood hazards. Consequently, Lílwat Nation has recognized an urgent need for floodplain mapping and flood risk assessment for the Birkenhead and Green River design floods.

1.1 Background Information

A number of man-made changes were introduced to the lower Lillooet and Birkenhead rivers in the late 40's and early 50's; these are, straightening the rivers, constructing dikes and altering the Lillooet Lake inlet (Weatherly and Jakob, 2014). The rivers' joint floodplain is low-lying and, had these changes not been made, the majority of the floodplain would likely still be undeveloped due to frequent inundation and lateral movement.

At the top of the Birkenhead River alluvial fan the Birkenhead River shifts direction by nearly 90 degrees from the south to the east and then continues to flow down the north side of the fan. In 1950, the Poleyard Dike was constructed across the fan cutting off a portion of the original main channel and conveying flow to the east. In 2003, a debris jam formed downstream of the Poleyard Dike which resulted in the main channel infilling and flow spilling into a network of side channels. In 2014, approximately 12,000 m^3 of sediment was removed to improve the channel capacity and reduce the potential for historical channels to become more active, which could threaten the Mount Currie.

1.1.1 Historical Flooding

The Lílwat Nation has a long living memory of flooding in the Pemberton Valley before settlers arrived. The oral traditions of a First Nation allow warnings for future events to be passed down through the generations so that descendants can be prepared. Lílwat Nation has its own flood story that tells of a great flood that came, and how the Lílwat people survived by tying their canoe to the mountain peak with cedar and willow tree rope (Attila Nelson, 2019).

In more recent terms, the Water Survey of Canada (WSC) has been recording water level and flow on the Lillooet River near Pemberton since 1914 (WSC gauge 08MG005). There have been four floods past

45 years that either set records at the local gauge or caused damage to the Pemberton Valley (e.g., breaching/overtopping dikes or causing property damage). The Birkenhead River was gauged from 1945 to 1971 (WSC gauge 08MG008) so many of the floods experienced in the valley are not reflected in this gauge record. The Lillooet and Birkenhead Rivers can flood at the same time or they can flood independently of each other. The Green River typically floods when the Lillooet River does. The largest floods typically occur in the fall on the Lillooet River and are associated with rain-on-snow events. Larger floods on the Birkenhead River tend to occur in spring. Some major previous events are:

- Fall of 1984, flood of Lillooet and Birkenhead rivers, several dikes failed with evacuation of Mount Currie and Village of Pemberton (KWL, 2002) (1,310 m^3/s max. instantaneous flow estimated at WSC gauge 08MG005).
- Late summer 1991, flood of Lillooet and Birkenhead Rivers as well as Lillooet Lake reaching a historic high (1,410 m^3/s max. instantaneous flow estimated at WSC gauge 08MG005).
- Fall of 2003, flood of Lillooet and Birkenhead Rivers where Pemberton Valley and Lil̓wat Nation was cut off from Whistler and the Lower Mainland by a washout of the Hwy 99 bridge on Rutherford Creek (a tributary to the Green River and Lillooet River) (1,490 m^3/s max. instantaneous flow estimated at the WSC gauge 08MG005, flood of record).
- Spring 2013, flood of Birkenhead River, Poleyard Dike was raised as part of emergency measures during event (no measurement of flow on Birkenhead River was recorded to our knowledge).
- Fall of 2016, flood of Lillooet and Birkenhead Rivers (peak flow estimated by of 956 m^3/s on the Lillooet River at the WSC 08MG005 gauge near Pemberton, preliminary estimate).

The 2003 flood is about a 50 year flood based on the previous study of the river (NHC, 2018).

1.2 Project Objectives

The primary objectives of the project are to:

1. Estimate the 200 year design flows for the Birkenhead and the Green Rivers (present and end-of-century climate conditions).
2. Modify the Lillooet River hydraulic model developed by NHC (2018) to include the additional bathymetry for the Birkenhead, surveyed as part of previous project for Pemberton Valley Dyking District.
3. Simulate the Birkenhead and Green River 200 year design flood profiles. Identify potential Poleyard Dike breach locations and subsequent flood progression.
4. Using the model results, develop corresponding floodplain maps, flood depth maps and flood hazard maps for the Birkenhead and Green Rivers for present climate conditions. Outline the impacts of end-of-century climate change impacts.
5. Complete the flood risk assessment described in the project terms of reference.
6. Communicate results of the study with the community and work with Líl̓wat Nation to identify next steps for flood mitigation and adaptation.

1.3 Terms of Reference

The terms of reference developed by Lil̓wat Nation and outlined during a meeting between the Nation and NHC on 10 January 2019, consists of two main parts:

Part 1: Floodplain mapping:

a. Update the hydrology for the Birkenhead and Green Rivers to estimate the 200 year design flows on each river. Consider potential impacts of climate change on the design flows.

b. Refine the previously developed hydraulic model of the Lillooet River (NHC 2018) to simulate the 200 year Birkenhead and Green River floods (present and end-of-century flow conditions).

c. Develop floodplain, flood depth and flood hazard maps in accordance with Engineers and Geoscientists in BC (EGBC) floodplain mapping standards.

d. Summarize and communicate the results.

Part 2: Flood risk assessment:

The purpose of the risk assessment is to help the community understand the impacts of the design flood event on the Lillooet, Birkenhead and Green Rivers. Understanding the impacts of the design flood will help inform future flood risk reduction plans. The risk assessment will be done in partnership with the Lil̓wat Nation and include significant community input. The assessment will focus on the following factors:

- *Impact to population;*
- *Effects on sites of cultural significance;*
- *Economic impact due to damages or disruption; and*
- *Environmental consequences such as contamination or habitat destruction.*

Data will be gathered from available sources, field investigations by the project team and the Lil̓wat; and through a series of workshops with the Lil̓wat Nation. NHC is committed to helping develop capacity within the Lil̓wat Nation for this type of work and incorporate local knowledge. We will support the Lil̓wat Nation with collection of attribute data and facilitate community meetings related to the flood risk assessment. Tasks will include:

- *Spatially identifying hazard areas using GIS overlays.*
- *Quantitatively and qualitatively estimating the vulnerability of assets and the consequences of flooding as follows:*
  - *To determine the impact to people, population information will be overlaid with hazard mapping to quantify potential displacement, injury and death.*
  - *To determine cultural impacts, effects of flooding on known cultural sites will be estimated and qualitatively described through community consultation.*

- *To quantify economic impact, damages to buildings and infrastructure will be estimated using approximate depth-damage relationships. Economic disruption will be approximated based on potential disruption times.*
- *Environmental impacts will be estimated by identifying inundated potential contamination sources and sensitive habitat areas.*

Results will be presented to the community at a meeting with nation staff and/or the public. High, medium and low risk areas will be identified. This information can be used for developing a risk reduction strategy and future emergency management planning (not part of the present project) to highlight evacuation routes and safe zones.

Due to the Covid-19 global pandemic, certain objectives identified in the risk assessment and community engagement could not be completed due to lockdowns, restrictions on gatherings, and safety concerns. Where possible, online meetings were held, and the risk assessment was completed remotely. To compensate the reduction in community engagement, additional channel surveys of the Birkenhead River and desktop based geomorphologic analysis of historical air photos was completed to help provide additional information on the river and support future works such as the Poleyard Dike upgrade and Birkenhead River channel management activities.

2 HYDROLOGY

The region surrounding the Pemberton Valley is situated on the eastern side of the Coast Mountains along a transition between the very moist Coast Mountains and dry interior of BC. Within this transition zone connecting the vastly different hydroclimates of BC's coastal and interior regions, there is considerable spatial and temporal variation in hydrology. Overall the hydrology in this area is snowmelt dominant. However, depending on the watershed, hydrology regimes may also be rainfall dominant, rain-snow hybrid, snow-glacier, and rain-snow-glacier hybrid (Eaton and Moore, 2010). In some places these may also change over time based on medium (e.g. El Nino Southern Oscillation, Pacific Decadal Oscillation) and long term (e.g. climate change) climate trends, as well as short-term variations in weather from year to year (Fleming et al., 2007). While annual peak flows are generally expected to occur during the spring freshet due to snowmelt processes, it is not uncommon for peak flows to be generated at different times and magnitudes as a result of other processes such as heavy rainfall, rain-on-snow flooding, and rain-on-glacier flooding.

The fact that peak flows can be caused by many different processes, fluctuate based on climate modes at multiple scales, and vary widely from watershed to watershed, greatly complicates the process of flood frequency analysis. When floods are generated by multiple different physical processes, the statistical assumption that the peak flow series can be represented by a single distribution is violated. However, performing a separate flood frequency analysis on each type of flood generation process is often inviable unless ample historical data from each type of peak flow are available, which is most often not the case.

This report is concerned with determining design flows for the Green and Birkenhead Rivers, two major tributaries to the Lillooet River, between Pemberton and Lillooet Lake. In addition to the complexities regarding flow frequency analyses for watersheds in this area, limited historical flow data are available for the Green and Birkenhead Rivers, with no data from recent years.

NHC (2018) noted that around 1975, the hydrologic regime of the Lillooet River near Pemberton shifted from snowmelt-dominant to rain-snow hybrid; this shift was attributed to the Pacific Decadal Oscillation and long-term climate change. With no flow data for the Green and Birkenhead Rivers after 1975, it is difficult to be certain if and how their hydrology would have been influenced by the climatic changes that shifted the hydrology of the upstream Lillooet River. As such, NHC has taken on a multi-faceted spatial investigation to attempt to fill these gaps.

2.1 Overview of Watersheds

The Lillooet River straddles the Central and East South Coast Mountains hydrologic zones (CSCM and ESCM, respectively). The Green River flows into the Lillooet River from the south and Birkenhead River drains into Lillooet Lake, having a joint floodplain with the Lillooet River over its downstream end.

The Green River watershed, situated southwest of the Pemberton Valley within the CSCM, is warmer and wetter than the Lillooet River watershed as it has greater exposure to coastal rainstorms and atmospheric rivers. It receives the most year-round precipitation and has a median basin elevation lower than either the Birkenhead or Lillooet (1480 m). The Birkenhead River watershed, located northeast of the Pemberton Valley toward the eastern boundary of the coast mountains, has most of its area within the ESCM with the remainder in the Fraser Plateau hydrologic zone. Conditions are driest here due to terrain shading effects and climatic influence from the interior plateau.

The WSC gauges used to assess the hydrology of each watershed are summarized in Table 2.1. Figure 2.1 displays the location of the watersheds and gauges.

Table 2.1 WSC Gauge Details. Watershed areas delineated by NHC.

Name	WSC ID	Watershed Area (km^2)	Record Period	Daily Record Length (years)	Median Elevation (m.a.s.l.)
LILLOOET RIVER NEAR PEMBERTON	08MG005	2086	1914 – 2017	99	1656
GREEN RIVER NEAR PEMBERTON	08MG003	830	1913 – 1951	39	1480
BIRKENHEAD RIVER AT MOUNT CURRIE	08MG008	641	1945 – 1971	27	1568

2.1.1 Previous Study: Lillooet River at Pemberton

Prior to 1975, Lillooet River peak flows occurred primarily in the spring or summer, driven by snowmelt during the spring freshet. Since then, many annual peaks have still occurred in the summer, but the highest floods have shifted towards fall and early winter. The fall/winter peaks are primarily caused by major rain-on-snow floods.

1975-1976 was considered to be a transition from a cold phase to a warm phase in the Pacific Decadal Oscillation (PDO; Fleming et al. (2007)), which may partly explain the shift in the Lillooet River hydrology from a snow-dominant to rain-snow hybrid peak flow regime. While this warm phase was supposed to have ended around 1998, there is no indication that the hydrology regime has correspondingly reverted. It is hypothesized that the shift back to the PDO cold phase was negated by warming trends for the Lillooet River, attributed to climate change. It is unclear if the same hydrologic shift has taken place in the watersheds of the Green and Birkenhead Rivers.

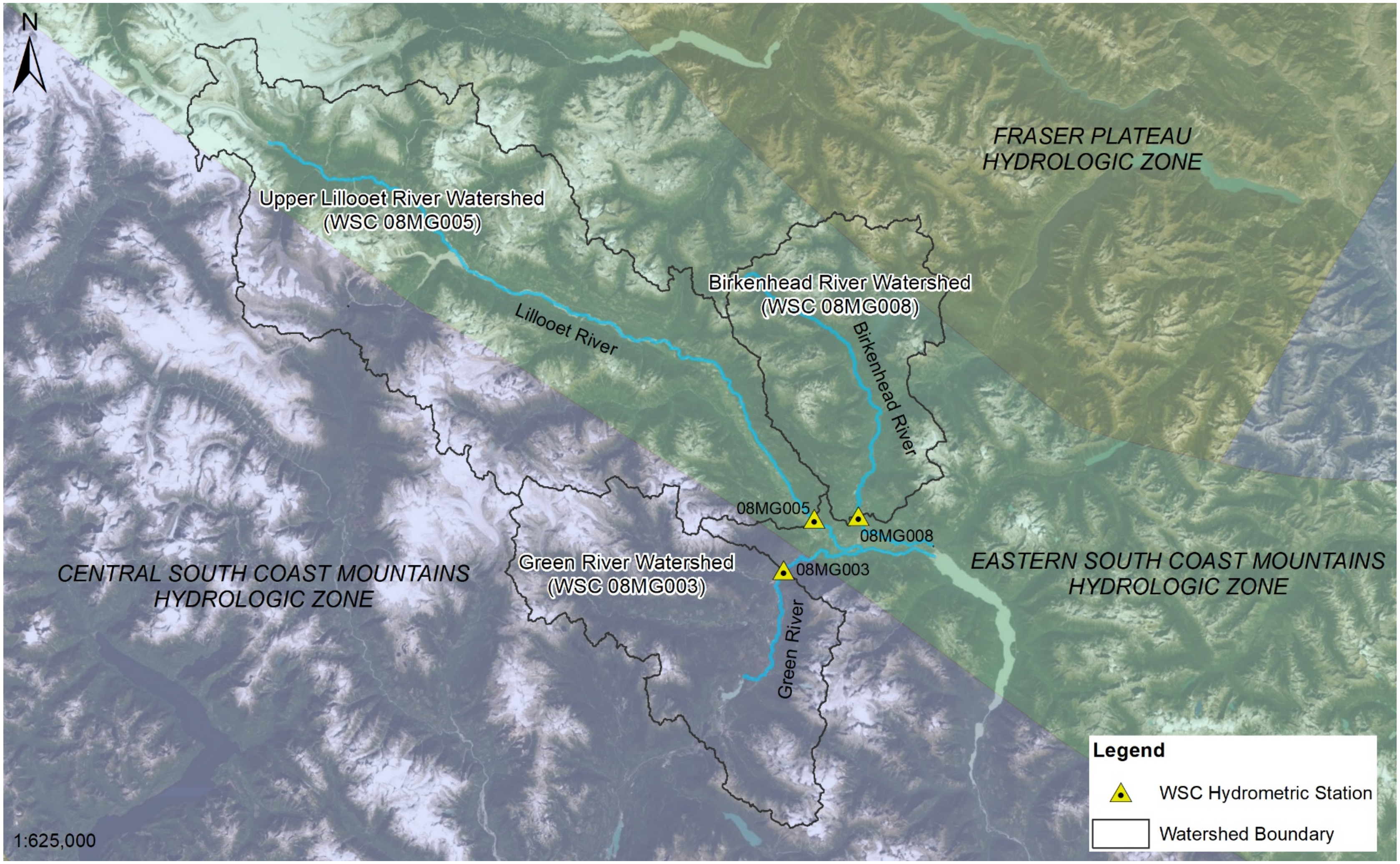

Figure 2.1 Overview of the Green, Lillooet, and Birkenhead watersheds, WSC gauge locations, and hydrologic zones.

2.2 Spatial Data Investigation

To investigate if hydrologic shifts have taken place in the in the Green and Birkenhead Rivers, and fill flow data gaps, NHC completed a spatial data investigation using GIS to compare various physical characteristics of the Lillooet, Green, and Birkenhead watersheds.

2.2.1 Precipitation

Average monthly precipitation for each watershed is plotted in Figure 2.2. It is clear that the Green River watershed receives the most annual precipitation while the Birkenhead River watershed receives the least, but overall the annual precipitation pattern is consistent across all three watersheds. The majority of annual precipitation occurs in the winter, while summers are very dry. This illustrates the important influence of snow hydrology within all three watersheds and implies snowmelt dominant or rain-snow hybrid hydrologic regimes.

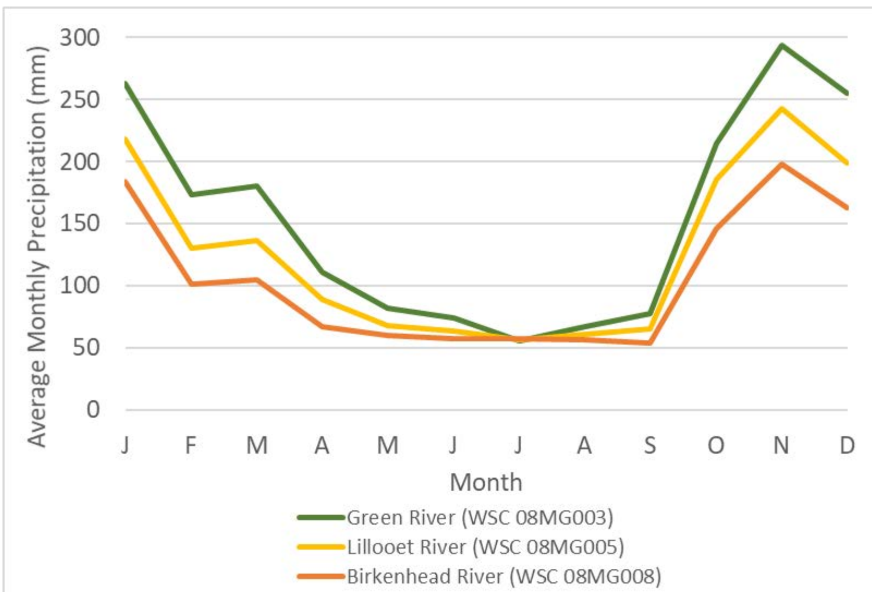

Figure 2.2 Mean Monthly Precipitation for the Green, Birkenhead, and Lillooet Watersheds (1981-2010;(PCIC, 2020))

Figure 2.3 displays the mean annual precipitation (MAP) distribution in the region surrounding the Pemberton Valley, from the ClimateWNA analysis (Wang et al., 2012). Moving across the Coast Mountains from southwest to northeast, annual precipitation decreases due to terrain shading impacts and lack of coastal influences (and thus increasing influence of drier interior air masses). The Lillooet River watershed appears to straddle the transition between the relatively wet Green River watershed and dry Birkenhead River watershed on either side of it. Due to the greater total precipitation, lower median elevation (Table 2.1), and location nearer to warm Pacific air masses, the Green River is expected to experience more peak flows due to rainfall (or rain-on-snow) than for the other two watersheds.

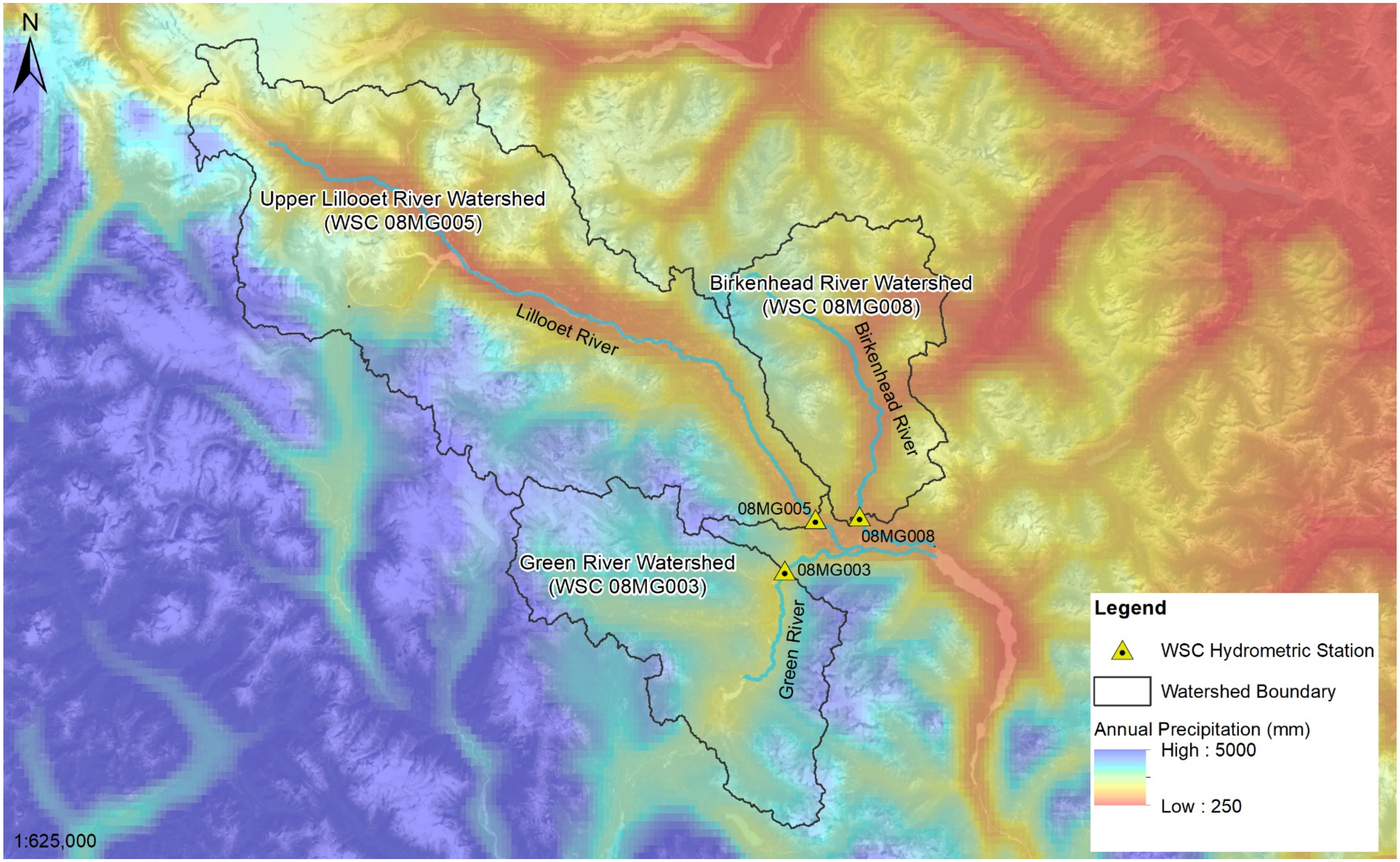

Figure 2.3 Average annual precipitation distribution (1981-2010) of the Green, Lillooet, and Birkenhead watersheds. Data obtained from ClimateWNA (Wang et al., 2012).

2.2.2 Glacial Coverage

Figure 2.4 shows the glacial coverage within each of the three watersheds. Lillooet River has the greatest glacial coverage at 17 percent, followed by Green River with 7 percent coverage, and Birkenhead River with 1 percent coverage. This variation in glacier coverage is indicative of differences in tendency to store precipitation (in the form of snow or ice) and overall topographical properties. Though the Green River has a lower median elevation than the Birkenhead or Lillooet Rivers (Table 2.1), the watershed hypsometry (area-elevation distribution) in Figure 2.5, suggests that the Green River contains slightly more area at the highest elevations than the Birkenhead River.

Glacial coverage is important for understanding the likelihood of rain-on-glacier peak flows in the late summer. The second greatest flood on record for the Lillooet River occurred on August 31, 1991 and was presumed to be a rain-on-glacier flood, where rain fell directly on exposed glacier ice. This flood was the flood of record for a number of watersheds in the Sea-to-Sky region of BC, from Squamish to Pemberton (NHC, 2018; WSC, 2020), likely including the Green River, though the gauge was not active at the time.

The minimal glacierization of the Birkenhead River watershed is likely indicative of two things: 1) the watershed does not receive enough precipitation to create significant glacier coverage, and 2) a late summer rain event, such as the August 1991 flood would not be as enhanced by glacier melt as in the other watersheds. However, there may still be some effect of the 1% glacierization of the Birkenhead River watershed. Trubilowicz et al. (2013) found a signal of glacier influence on a watershed hydrograph was evident with watersheds containing glacier coverage as low as 0.5%.

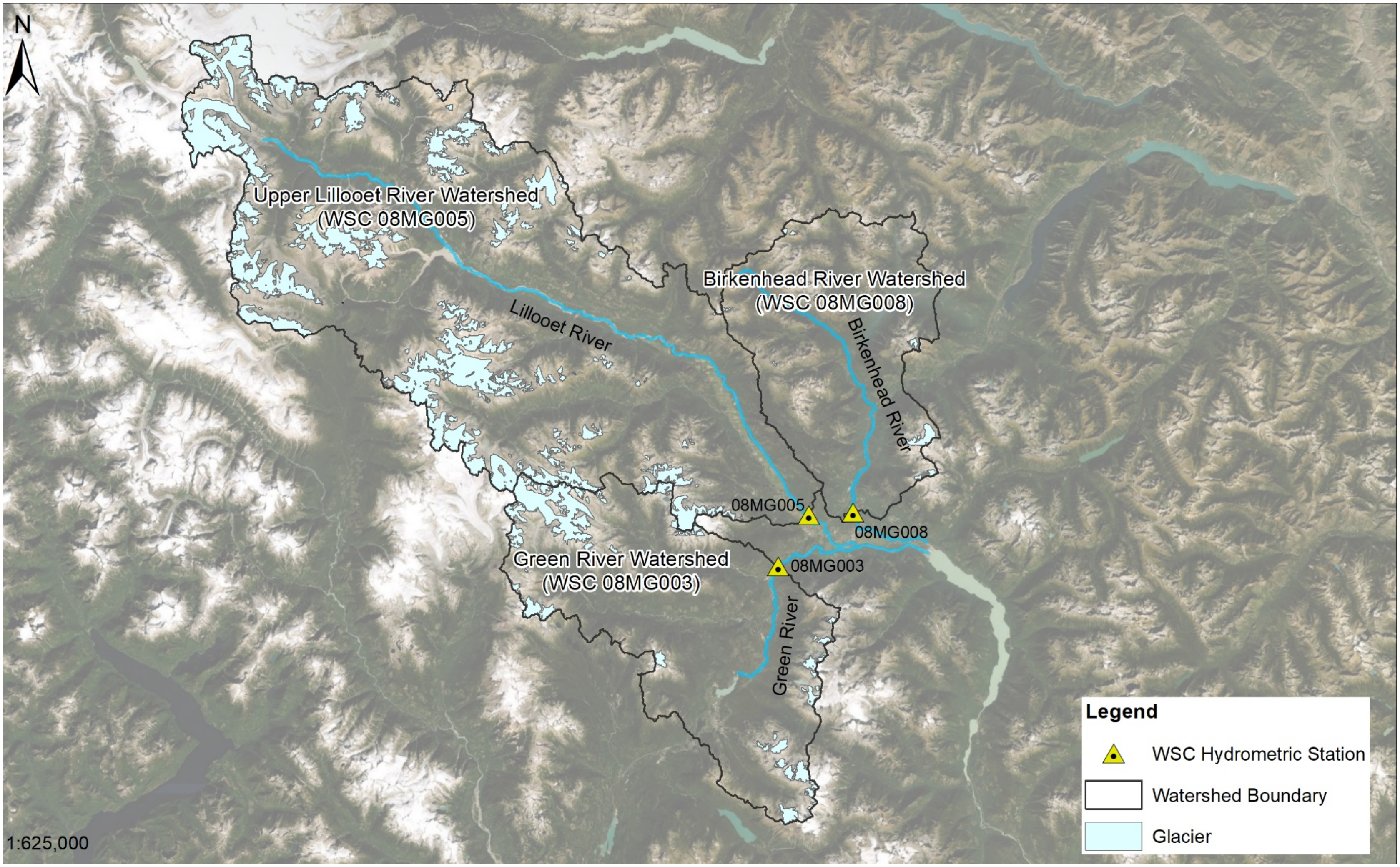

Figure 2.4 Glacial coverage of the Green River, Lillooet River, and Birkenhead River watersheds.

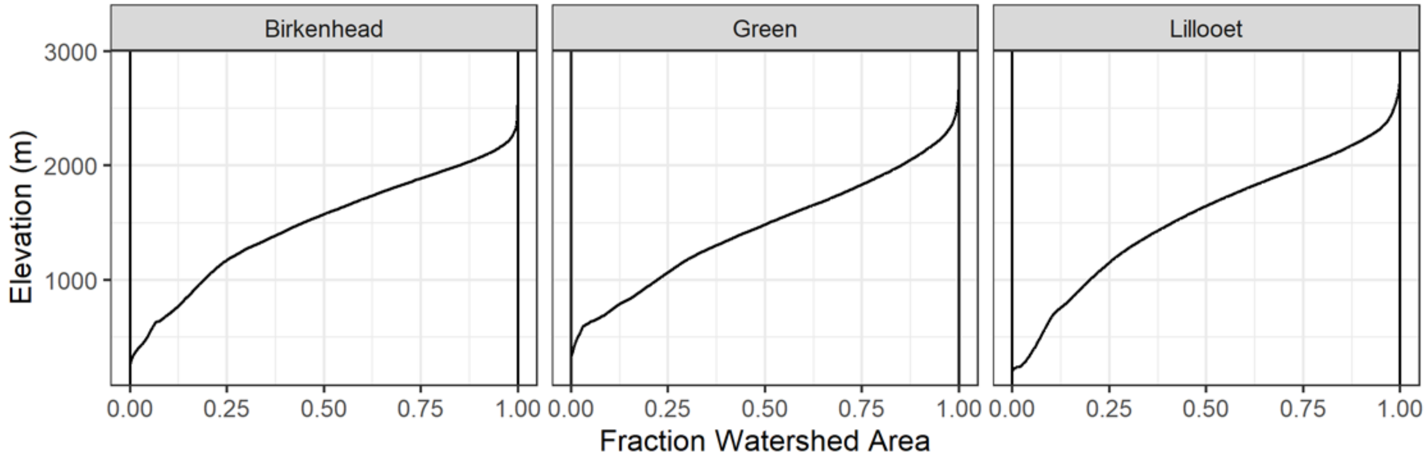

Figure 2.5 Watershed hypsometric curve comparison. Elevation obtained by the 'elevatR' package for the statistical programming language 'R' (Hollister and Shah, 2017; Hornik, 2016).

2.2.3 Biogeoclimatic Zones

The Biogeoclimatic Ecosystem Classification program groups ecologically similar sites based on climate, soils, and vegetation (Ministry of Forests, Lands and Natural Resource Operations, 2020). As climate, soils, and vegetation are primary controls on the hydrology of a watershed, biogeoclimatic zonation can be indicative of differences in hydrology. Figure 2.5 displays the biogeoclimatic zones throughout the three watersheds and the surrounding region; the figure shows that the biogeoclimates of the Green River and Birkenhead River watersheds are very different. The Green River watershed is made up of the Coastal Mountain-heather Alpine, Mountain Hemlock, and Coastal Western Hemlock zones, while the Birkenhead River watershed contains the Interior Mountain-heather Alpine, Engelmann Spruce – Subalpine Fir, Interior Douglas-fir, and Coastal Western Hemlock zones. The Lillooet River watershed shares the biogeoclimatic zones present in both tributary watersheds but is more prominently represented by the zones present in the Green River watershed. Table 2.2 summarizes the climate characteristics of the biogeoclimatic zones.

Table 2.2 Biogeoclimatic Zone Climate Characteristics of the Green River, Lillooet River, and Birkenhead River Watersheds

Biogeoclimatic Zone	Climate Characteristics	Watersheds
Coastal Mountain-heather Alpine (BC Ministry of Forests and Range, 2006)	• Strong coastal influence • Heavy and prolonged snowfall • Deep snowpack • Most land area occupied by glaciers	Green, Lillooet
Mountain Hemlock (BC Ministry of Forests, 1997b)	• Strong coastal influence • Short, cool summers and long, wet winters • 70 percent of precipitation is snow • Deep snowpack	Green, Lillooet
Coastal Western Hemlock (BC Ministry of Forests, 1999)	• Strong coastal influence • Very wet (rain and snow) • Cool summers, mild winters	Green, Birkenhead, Lillooet
Interior Mountain-heather Alpine (BC Ministry of Forests and Range, 2006)	• Dry due to high altitude • Warm summers (relative to other alpine zones)	Birkenhead, Lillooet
Engelmann Spruce – Subalpine Fir (BC Ministry of Forests, 1998)	• Short, cool summers and long, cold winters • Heavy snowfall • Deep snowpack	Birkenhead, Lillooet
Interior Douglas Fir (BC Ministry of Forests, 1997a)	• Warm, short summers and cool winters. • Very dry	Birkenhead, Lillooet

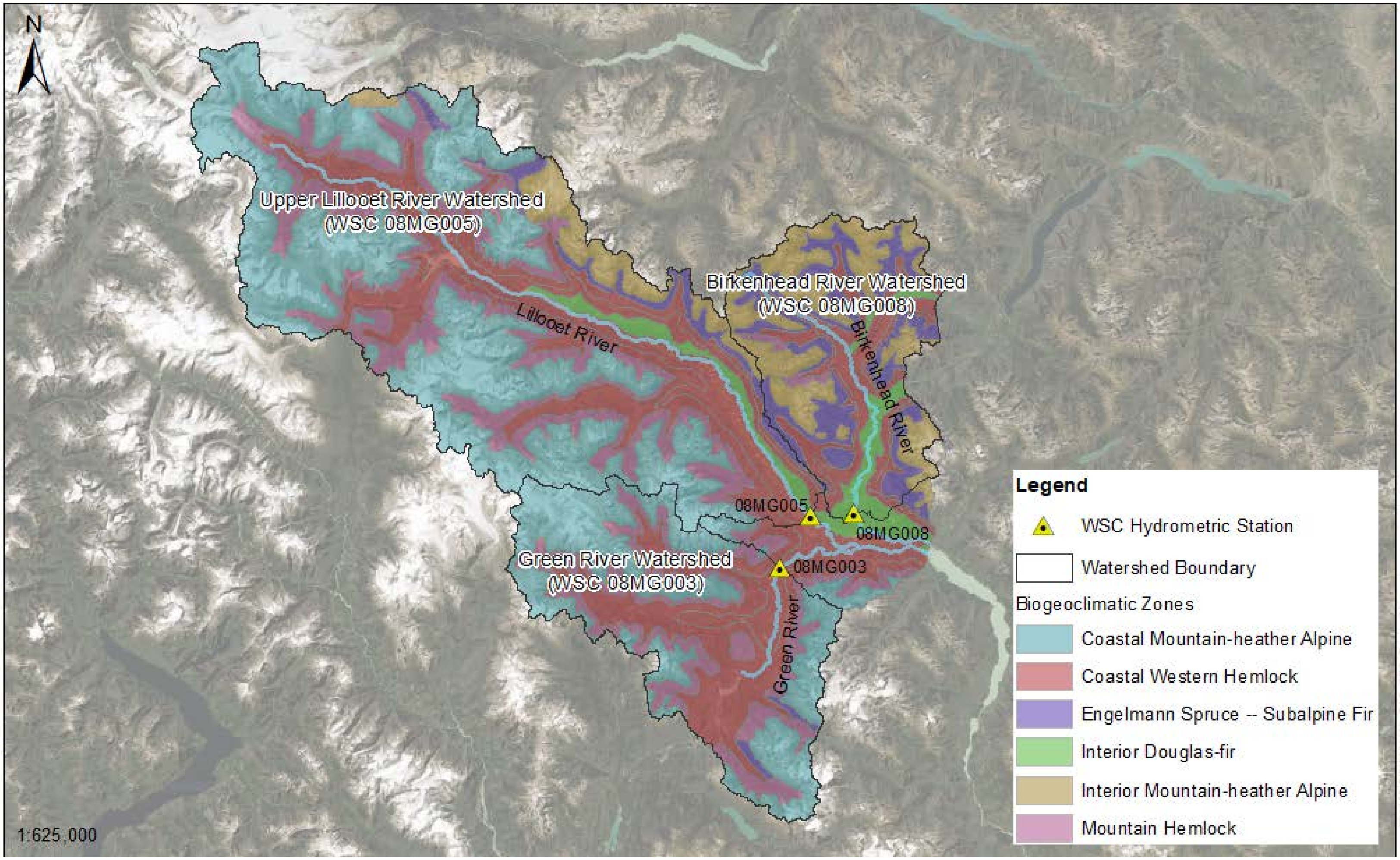

Figure 2.6 Biogeoclimatic zones of the Green River, Lillooet River, and Birkenhead River watersheds

2.2.4 Watershed Flow Correlation

As a final analysis, we investigated correlations between the gauges, by season (Figure 2.7), for overlapping periods to further evaluate the possibilities to extend the data record. For spring (i.e., snowmelt) peak flows, the Lillooet River showed relatively strong correlation with the Birkenhead River (Pearson R = 0.79)[1] and poor correlation with the Green River (R = 0.45). Conversely, for winter peak flows (rain or rain-on-snow), the Lillooet River gauge showed a poor correlation with the Birkenhead River (R = 0.18) and a strong correlation with the Green River (R = 0.72). These mixed results, along with the spatial analysis and evidence of changing Lillooet River regime, led us to conclude that record extension was inappropriate.

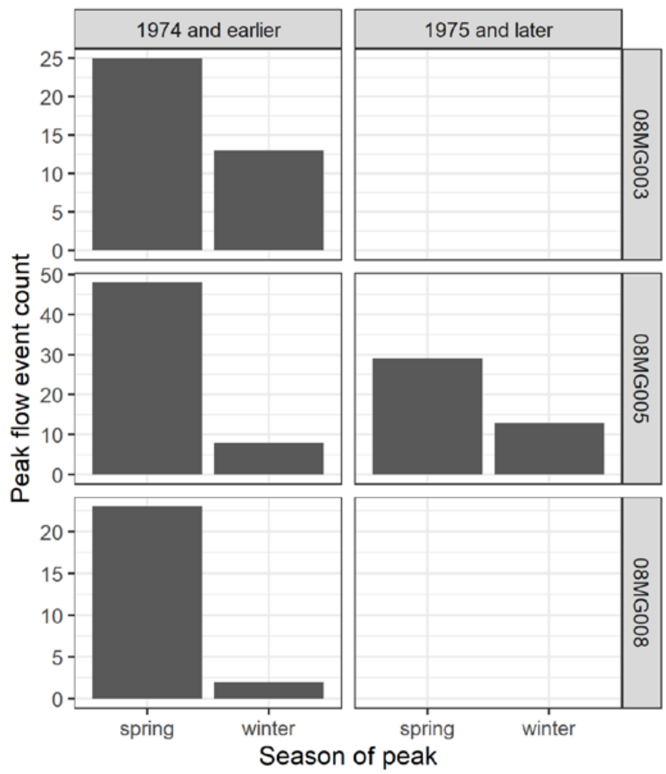

Figure 2.7 Distribution of peak flows (maximum daily average) by season for Green River (08MG003), Lillooet River (08MG005), and Birkenhead River (08MG008). Seasons defined as in Waylen and Woo (1983). Blank panels indicate no data is available (gauge deactivated).

[1] The Pearson correlation coefficient (Pearson R) is a measure of linear correlation between two sets of data.

2.2.5 Watershed Comparison Conclusions

The previous section investigated the relationships between the Lillooet River (gauged to the present) and the deactivated gauges on Green River and Birkenhead River. It is evident from the spatial data investigation that the Green River, Birkenhead River, and Lillooet River watersheds all have distinct features that influence their unique hydrologic characteristics. The Green River watershed has a full coastal regime, with mixed influences of rain, snow, and glaciers. The Birkenhead River watershed is a drier watershed, experiencing less total precipitation and less precipitation as rain, which results in a different ecological composition. The Lillooet River is positioned in the transition between these two.

Because of these different watershed characteristics, we cannot assume the findings of a changing peak flow regime on the Lillooet River after 1975 (NHC 2018) would similarly apply to the Green or Birkenhead Rivers. Green River has shown a rain-snow hybrid regime since before 1975 for the years where data was available (Figure 2.6). Even if the dominance of rainfall in the Green River flow regime increased as it did in the Lillooet River watershed, it is not certain weather or to what extent peak flow patterns would have changed. In contrast, the Birkenhead River experiences substantially lower mean annual precipitation (Figure 2.3) and was historically strictly snowmelt dominant (Figure 2.6). Additionally, there is very little glacierization in the Birkenhead River compared to either the Lillooet River or Green River. This suggests that the peak flow regime on the Birkenhead River would not change similarly to the Lillooet River.

2.3 Design Flow Calculation

Design flows for the Green River and Birkenhead River watersheds were calculated using instantaneous peak flows for the two gauges. Two complicating factors necessitated the calculation of multiple peaking factors to infill missing instantaneous peak flows using maximum daily flows:

1. Only daily flow data are available for WSC 08MG008 – Birkenhead River at Mt. Currie.
2. The peak flow type (either spring freshet or winter rain/rain-on-snow) likely means that a different daily -> instantaneous peaking factor is required for each season.

Thus, rank-rank correlation was used to compute four peaking factors: spring/summer and fall/winter (as defined in Waylen and Woo (1983)) for the 08MG003 and 08MG005 gauges. As the WSC only published one instantaneous annual maximum per year, having enough data for calculation of both a spring and fall peaking factor is dependent on a mixture of peak flow seasons for a gauge, and is thus only applicable to mixed regimes.

The results from the 08MG005 – Lillooet River near Pemberton peaking factors were applied to the Birkenhead River gauge. While we have discussed that the watersheds of the two gauges display notable differences, this gauge is still the best available option for transferring peaking factors, as they share a watershed boundary. The peaking factors are summarized in Table 2.3.

Table 2.3 Peaking factors calculated from rank-rank regression of instantaneous and daily annual maxima, separated by season and gauge. The number of observations used in the relationship are shown in parenthesis.

Gauge	Spring/Summer	Fall/Winter
08MG003 – Green River	1.09 (12)	1.12 (4)
08MG005 – (Applied to 08MG008 – Birkenhead River)	1.11 (45)	1.16 (10)

Though regression-based record extension was deemed inappropriate (see Section 2.2.4), we included an estimate of the October 2003 flood on the Green River based on scaling the observation from the Lillooet River. We only included this estimate for the Green River, as the 2003 flood was a fall flood, and fall floods displayed a strong correlation between the Lillooet and Green, yet a poor correlation between the Lillooet and Birkenhead Rivers. We scaled the 2003 Lillooet River instantaneous flow to the area of the Green River watershed using the area-based scaling as in Sumioka (1998):

$$Q_u = Q_g \left(\frac{A_u}{A_g}\right)^b$$

where Q_u and Q_g are the flows, of any desired return period, for an ungauged and gauged site, A_u (and A_g) are the watershed areas of the ungauged and gauged sites, and b is a scaling exponent, which is often determined empirically. Eaton et al. (2002) recommended a generalized scaling exponent of 0.75 for all of British Columbia, with values increasing in more coastal regions. Thus, we used a scaling exponent of 0.85 in this analysis.

Area based scaling of the 1490 m^3/s 2003 peak flow on the Lillooet River gave an estimate of 677 m^3/s on the Green River. After adding an uncertainty band of +/- 20% to this number, we used this range in the frequency analysis for the Green River following the techniques of the USGS 'expected moments algorithm' which allows for formalized integration of uncertain observations outside the period of record (England Jr. et al., 2019).

After applying the peaking factors to each gauge and season, we performed frequency analyses. We applied the USGS' expected moments algorithm (EMA) to the Green River. EMA fits a log-Pearson Type III distribution to a series with a combination of observed points and 'historical' observations outside the period of record, in this case our estimate of the 2003 flow on the Green River. We used the expected moments algorithm in the USGS PeakFQ software (Veilleux et al., 2014), assuming that the 2003 flood was the flood of record for the gauge. Frequency analysis results are shown for the Green River in Figure 2.8.

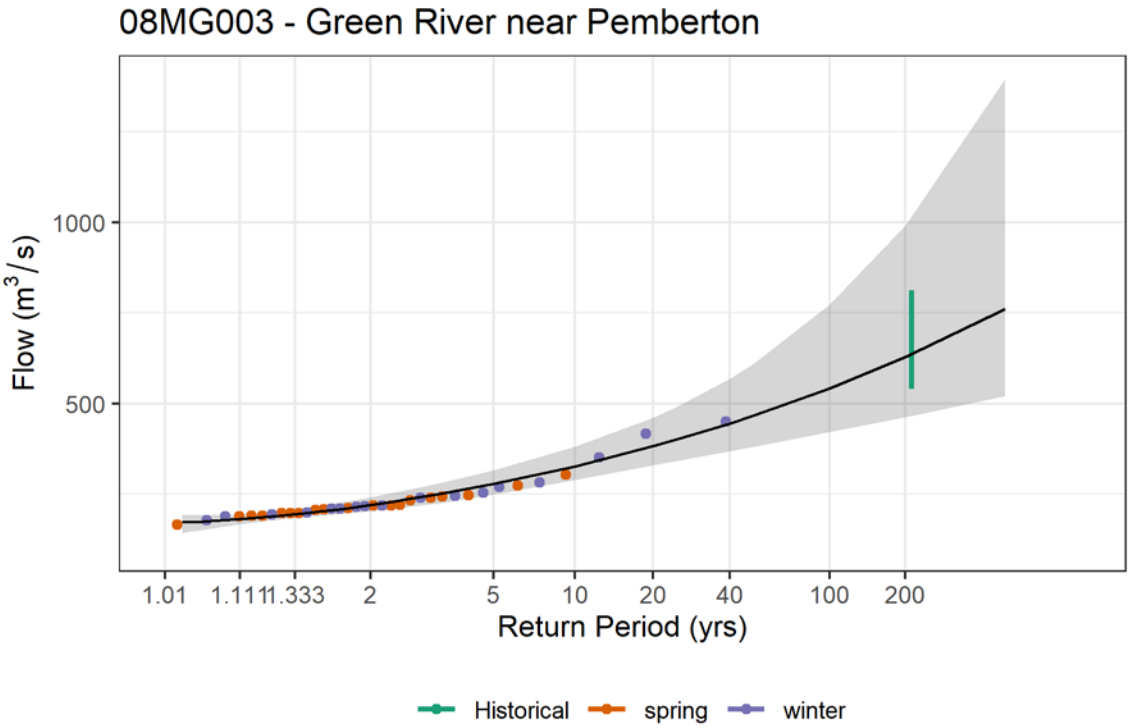

Figure 2.8 Frequency analysis results for the Green River near Pemberton. Floods are colored by the season of occurrence, as defined in Waylen and Woo (1983). 90% confidence bands are shown in grey. Green line indicates a range estimate for the 2003 flood.

For the Birkenhead River, we fit the generalized extreme value (GEV) distribution using l-moments with the statistical package 'lmomco' (Asquith, 2011) in the statistical programming language 'R' (Hornik, 2016). Frequency analysis results are shown for Birkenhead River in Figure 2.9 and Table 2.4.

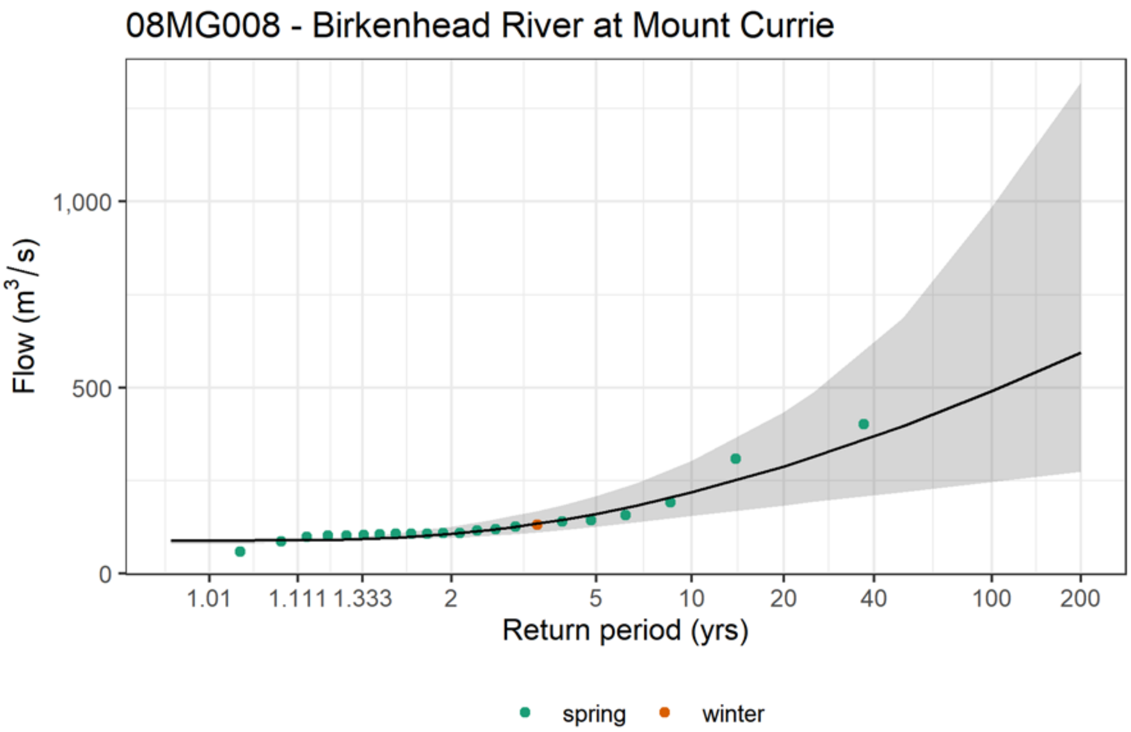

Figure 2.9 Frequency analysis results for the Birkenhead River near Mount Currie. Floods are colored by the season of occurrence, as defined in Waylen and Woo (1983). 90% confidence bands are shown in grey.

Table 2.4 Frequency analysis results for WSC 08MG003 (Green River near Pemberton) and 08MG008 (Birkenhead River at Mount Currie). RP = return period (years). Flow units given in m^3/s.

RP	08MG003	08MG008
2	220	108
5	278	162
10	327	219
20	382	288
50	467	397
100	542	491
200	628	594

2.4 Model inputs

Gauge design flows were then scaled to the inflow locations to the hydraulic model. As with the scaling of the 2003 flood for the Green River, design flows for model inputs were scaled using the area-based scaling as in Sumioka (1998) with an exponent of 0.85. As a conservative approach, we scaled the WSC gauges to the watershed area at the point where the Green and Birkenhead Rivers met the Lillooet River. These flows were then used at the top of the model reach for their respective rivers, 684 km^2 for Birkenhead River and 874 km^2 for Green River. This scaling results in the scaled inflows for the Green River model input in Table 2.5.

Table 2.5 Scaled design flows for input on the Green River and Birkenhead River using a 0.85 scaling exponent. RP = return period (years). Flow units given in m^3/s.

RP	Green	Birkenhead
2	230	114
5	291	171
10	342	231
20	400	305
50	488	420
100	567	519
200	656	628

2.5 Climate Change Impacts

The shift in the timing and magnitude of peak flows in the Lillooet River upstream of Pemberton is evidence of the sensitivity to climate modal shifts and climate change. Though the spatial analysis could not support applying these post-1975 changes to the Green or Birkenhead River directly, it is still likely that the watersheds are sensitive to climate change impacts.

Year-round rising temperatures are expected to result in increased total precipitation, increased rain to snowfall ratio, decreased winter snowpack accumulation, and glacier recession (Pike et al., 2010; Shrestha et al., 2012). As previously mentioned, the hydrology of this region is highly influenced by snow accumulation and melting processes and is thus expected to be significantly impacted by such climatic changes. Additionally, Radic et al. (2015) predicted that fall atmospheric rivers are expected to occur more often in a changing climate, introducing the possibility of more frequent extreme rainfall events. All these factors indicate that the region may shift to a wetter hydrologic regime, and rain-on-snow and rain-on-glacier peak flows may occur more frequently. Within the Lillooet River, peak flows in the fall/winter from rain-on-snow events and peaks flows in the late summer from rain-on-glacier events are generally greater in magnitude than the more common snowmelt-induced freshet peak flows. The greater occurrence of rain-on-snow and rain-on-glacier events in the region (including within neighbouring watersheds such as Green and Birkenhead) is expected to result in overall increasing peak flow trends.

There is an absence of data for the Green and Birkenhead Rivers from the last several decades, and thus it is not possible to assess how climate change may have already affected the peak flow hydrology of these watersheds, or if these watersheds were affected as much as the Lillooet River. However, it is reasonable to assume that watersheds in the rain-snow transition zone are likely to be some of BC's most sensitive watersheds to climate change impacts on peak flows.

NHC previously identified a trend towards increasing instantaneous peak flows on the Lillooet River (NHC, 2018). In these cases, EGBC recommends the application of a 20 percent increase to return period design flows in areas where increased flows are expected (EGBC, 2018). Due to lack of recent data and resulting uncertainty surrounding the current and future hydrologic conditions within the Green and Birkenhead watersheds, NHC recommends the application of a 25 percent increase to design flows; this will not only account for potential increased peak flows in the future, but also includes a safety factor to account for unknown potential peak flow increases that may have already occurred. Design flows for model input locations, including a 25% increase for potential recent and future climate change impacts, are shown in Table 2.6. It should be noted that significant uncertainty is associated with these estimates.

Table 2.6 Recommend design flows, for the hydraulic model inputs on the Green and Birkenhead Rivers, including a 25% safety factor accounting for climate change. RP = return period (years). Flow units given in m^3/s.

RP	Green	Birkenhead
2	288	142
5	364	214
10	427	289
20	500	381
50	611	525
100	708	649
200	820	786

3 GEOMORPHOLOGY

Pemberton Valley is a broad low lying floodplain, approximately 2 km wide and confined by steep mountainous terrain that rises up to 2,000 m above the valley floor. The basin is largely comprised of plutonic rocks, aside from the Mount Meager volcanic complex which is particularly prone to debris flows and episodic large landslide events or volcanic flank collapse (NHC, 2018). At the time that the large glacial ice sheets covering the region started to recede, in the order of 10,000 years ago, Lillooet Lake extended approximately 35 km farther upstream than present (Friele et al., 2005). Over time, sediment transport and deposition by the Lillooet River and tributaries has shifted the Lillooet Lake inlet down valley to its present location. The geomorphic assessment for this project focusses on channel processes on the floodplain that are a function of seasonal hydrologic conditions, hydraulic flow patterns, and considers longer term effects due to episodic introductions of large volumes of sediment into the river system (e.g., such as occurred on the Lillooet River as a result of the 2010 Mount Meager landslide). This study does not include an assessment of the hazard potential for these or other types of large magnitude and episodic events, such as glacial lake outburst floods or landslide dam outburst floods. Over time, changes in the glacial environment and upper watershed could alter the potential for these types of large geomorphic events to occur. Further assessment of the hazard potential in the upper watersheds of the Lillooet River (including Green R. and other tributaries) and Birkenhead River would be necessary to determine the risk and evaluate the need for a longer term monitoring program to detect and assess changing conditions over time.

Historically the river channels in the valley would have shifted laterally across the floodplain in response to patterns of river sediment deposition and erosion, complex channel flow patterns, and episodic influxes of relatively larger volumes of material from the mountains. Prior to large scale flood control and drainage works in the Pemberton Valley initiated by the Prairie Farm Rehabilitation Administration, the Lillooet River and tributaries generally exhibited an irregular meandering pattern with a complex network of channel branches. The distributary channel pattern on the floodplain would have conveyed water and sediment across the floodplain, building it up relatively slowly over time. Complex channel inter-connections would likely have provided similarly complex aquatic ecosystems and habitat connectivity.

Changes brought on by development of the valley have substantially changed the pattern and form of the river channels. Section 3.1 discusses changes to the Lillooet River and Green River planform. In general, the channels are substantially less complex now than they were in 1951 (based on comparison of available images). Diking and channel bank armouring has reduced the available area for these channels to occupy. Over time, as the channel bed levels build up with sediment it will increase the height of the channel relative to the floodplain. The build up of sediment in the confined channels will increase the potential for dike overtopping and channel instabilities. Section 3.2 and 3.3 discuss changes to the Birkenhead River since 1948.

The Poleyard dike serves to train the Birkenhead River along the northern-most portion of the alluvial fan. A flood channel that was originally constructed in the 1950's was re-excavated in 2014 following several years of reportedly worsening flooding (NHC, 2014b). Comparison of recent (2021) channel survey data with the post-2014 construction data indicates the channel may have filled in by as much as two thirds. Highway 99 has cut off several distributary channels and has confined the Birkenhead River to a relatively narrow floodplain between the highway and valley edge. The bridge crossing at the mouth of the Birkenhead River has narrowed the active channel area at the lake to approximately 15% of its 1948 width.

3.1 Lillooet River and Green River channel changes (1951 to 2016)

Figure 3.1 presents a 1951 air photo and a 2016 orthoimage to illustrate the channel changes that have occurred on the floodplain. By 1951 the railway had already been constructed, Arn Canal had been excavated, and dike construction and other drainage projects were underway. Between 1951 and 2016 the Lillooet River and Green River channel network has transitioned to a primarily single threaded channel network with occasional bars and islands.

The 1951 Lillooet River channel split into several distributary channels, described below.

- At the top of the image shown is a distributary channel that branches off the mainstem (labelled Lillooet R. North), cutting across the north side of the floodplain. A channel branch off the Lillooet River North channel used to convey water and sediment into Grandmother Slough before draining into the Birkenhead River. The remainder of the Lillooet R. North branch channel flow would have returned to the Lillooet River mainstem, at the present day location of the North Arm outlet channel.
- Approximately 2 km downstream of the present day Highway 99 crossing over the Lillooet River were two 1951 Lillooet River channel branches. The middle branch channel was approximately aligned with the present day channel. The southern channel (labelled Lillooet R. South) cut across the south side of the floodplain, eventually flowing in an alignment that is now part of the lower reach of the Green River. The confluence of the Green River (south branch) and Lillooet River south branch channel in the 1951 image was approximately 2.4 km upstream of the present confluence of the Green and Lillooet Rivers.
- Approximately 5 km upstream of Lillooet Lake, a 1951 Lillooet River distributary channel branch cut across the north side of the floodplain and joined the Birkenhead River (labelled Lillooet River distributary). Approximately 3 km upstream of Lillooet Lake was another 1951 distributary channel that connected the Lillooet and Birkenhead Rivers (outside of the extents of the figure).

In 1951, the Green River flowed into the Pemberton Valley from the southwest. Downstream of Nairn Falls Provincial park the Green River was laterally unconfined. The 1951 channel was multi-branched and spread across the floodplain over a distance of more than 1 km in places. The Green River north branch channel joined Pemberton Creek, approximately 700 m upstream of the present day confluence between Pemberton Creek and the Lillooet River.

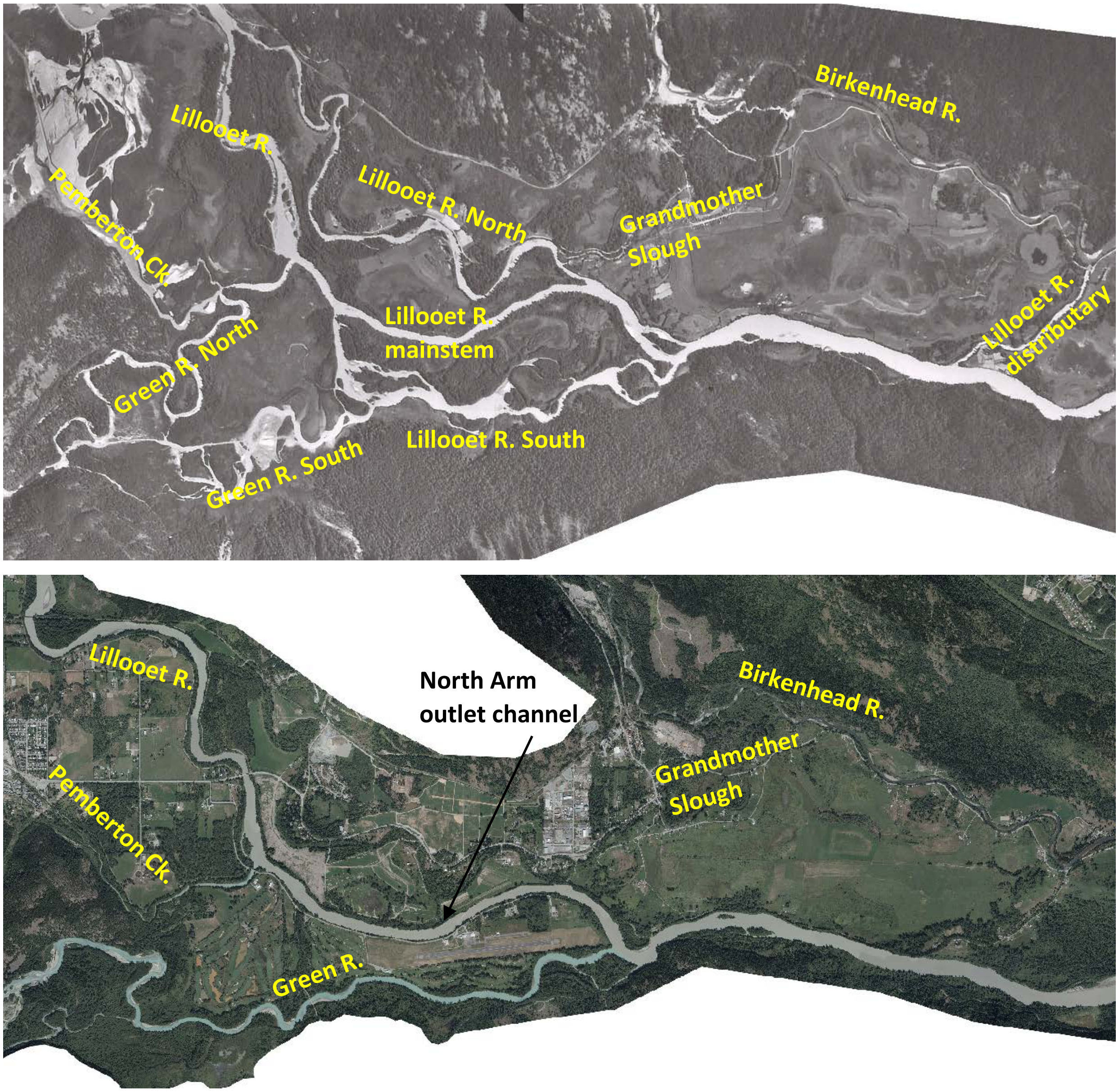

Figure 3.1 1951 air photo (UBC Geography) and 2016 ortho-imagery (Emergency Management BC).

3.2 Birkenhead River at Poleyard Dike channel changes (1948 to 2016)

In the reach upstream of Mount Currie IR10, the Birkenhead River is presently confined to a channel that is a few hundred metres wide, becoming unconfined as it flows onto the floodplain. Over time the Birkenhead River has formed an alluvial fan where the channel gradient becomes lower and coarser sediment is deposited by the river. Alluvial fans are potentially unstable landforms that form through an ongoing redistribution of flow and sediment across the fan surface. This fan building process often occurs during flood events or other conditions that can result in a heavy sediment and debris load in the channel. Deposition of large volumes of sediment and debris in the channel can create conditions that increase the potential for a channel avulsion, whereby the channel suddenly changes course in response to a channel obstruction.

Figure 3.2 compares 1948 and 2016 images of the Birkenhead River at Mount Currie IR10. At the time of the 1948 air photo, the Birkenhead River flowed farther to the south on the fan in a relatively wider channel with frequent overlapping bars. By 1948, a flood channel intended to convey flow farther to the north was already under construction. By comparison, the 2016 image shows how the channel has been trained along the northern part of the fan by the Poleyard dike, which was constructed in the 1950's. The flood channel was reconstructed in 2014 to reduce the frequency of flooding south of the channel and in response to near overtopping of the bank adjacent to the Continental Poleyard in 2013, which was mitigated by the construction of a berm downstream of the Poleyard dike under emergency conditions (NHC, 2014a).

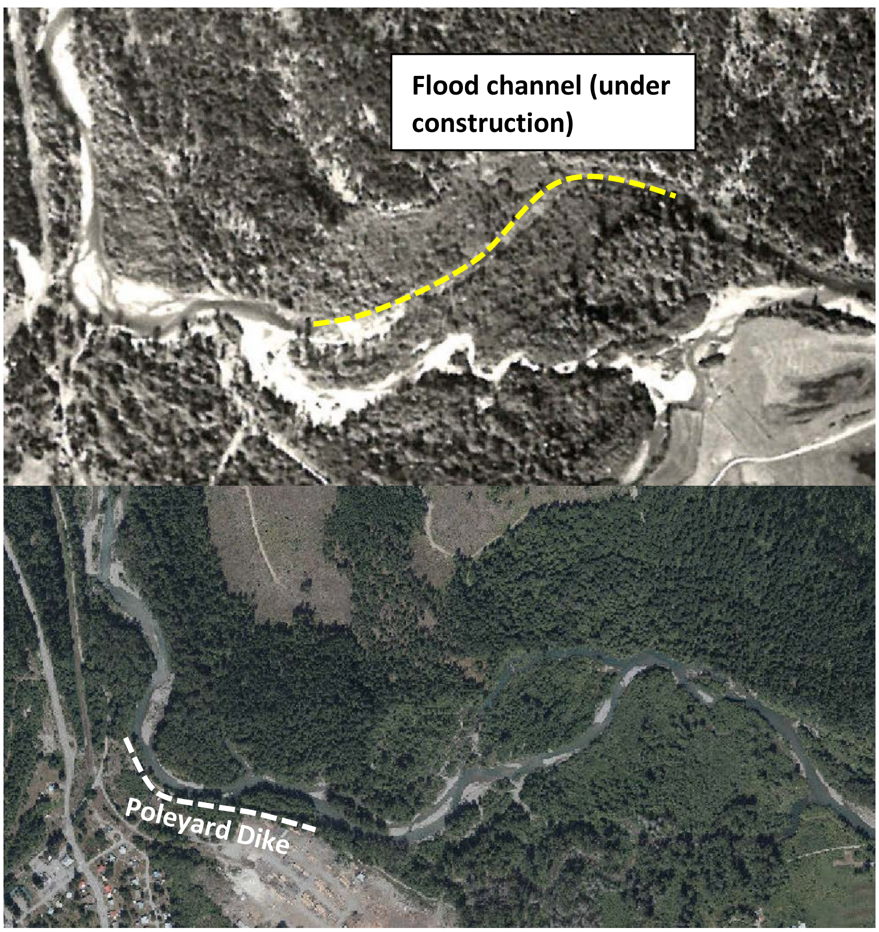

Figure 3.2 1948 air photo (UBC Geography) and 2016 ortho-imagery (Emergency Management BC).

The Birkenhead River channel pattern and position was digitized to map channel changes over time, using eight sets of air photos and the 2016 orthoimage. Figure 3.3 shows each of the channel configurations, overlaid from most recent to oldest.

By the 1960's the former main channel had largely filled in with sediment and established vegetation, and by the 1970's the excavated flood channel had started to develop bar features indicative of an actively mobile channel (NHC, 2014b).

Channel migration in the active fan area is ongoing; however, the active channel is narrow and confined to the north by the edge of the valley. The present-day channel runs along the toe of the Poleyard dike, and at its narrowest point the active channel zone is about 80 m in width. In the reach immediately upstream of the dike, the channel is building up with sediment and woody debris (Photo 3.1). This may be partly occurring in response to channel narrowing imposed by the construction of the dike. The former Birkenhead River main channel (i.e., prior to excavation of the flood channel) now conveys a relatively small amount of flow that feeds into Grandmother Slough before draining back into the Birkenhead River.

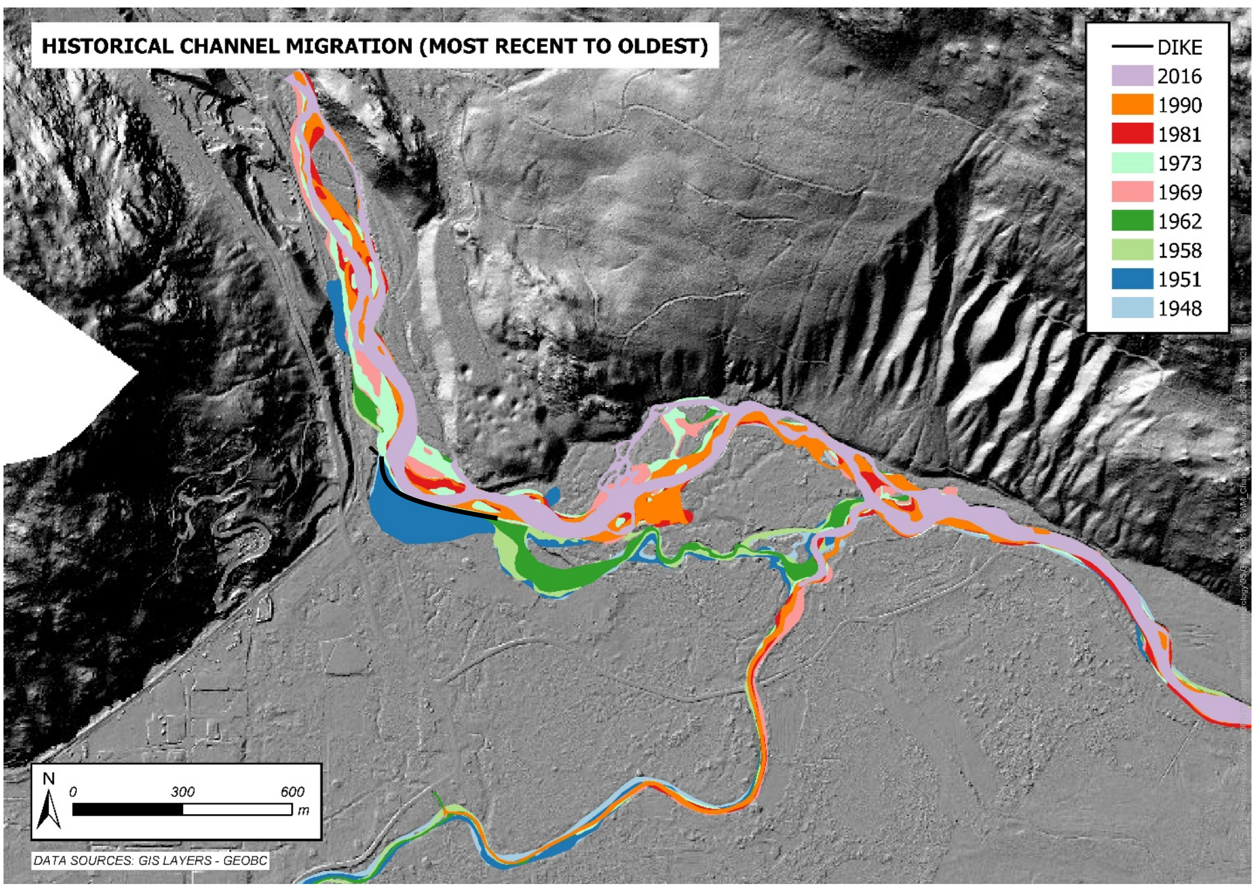

Figure 3.3 Historical channel migration (1948 to 2016).

Appendix A presents 16 channel cross sections; some that were originally surveyed in 2014 and some in 2019. All 16 sections were resurveyed again in March 2021 to evaluate channel changes. The cross sections generally indicate some degree of channel infilling in the reach upstream of the Poleyard dike with relatively little change in the diked reach and infilling in the reach downstream of the dike. The sections upstream of the Poleyard dike were not surveyed in 2014 and monitoring at these locations is limited to a two year period. Channel changes often occur sporadically during higher flow events. The river is not gauged and no flow records are available. As such, the observed channel changes (or lack thereof) may not represent longer term conditions.

Downstream of the Poleyard dike, a review of channel changes at a single cross section (which represents the flood channel that was excavated in 2014) indicates approximately 1 metre of infilling. In context, the 2014 excavation generally targeted depths of approximately 1.5 metres (NHC, 2014b). Assuming the infilling at the representative cross section represents conditions at other locations along the channel, this would equate to approximately two-thirds of the channel infilling. For context, this proportion of infilling would represent somewhere in the order of 8,000 m^3 of the 12,000 m^3 that was removed in 2014.

Photo 3.1 Downstream view of the Birkenhead River, approximately 300 m upstream of the Poleyard dike (November 2020).

3.3 Birkenhead River, from the Flood Channel to Lillooet Lake

Downstream of the flood channel located just downstream of the Poleyard dike, the Birkenhead River is confined to a narrow floodplain that ranges between 400 m and less than 100 m in width. Figure 3.4 compares the 1948 and 2016 imagery. By 1948 the highway was already under construction, cutting across the floodplain. The bridge at Lillooet Lake had not yet been constructed and the active Birkenhead River channel at the lake was over 500 m wide, and comprised of a network of distributary channels. At the time, these channels would have carried water and sediment between the Lillooet and Birkenhead Rivers. The channel was generally wider overall and included islands in the lower reach.

Once constructed, the highway became a major controlling feature on the floodplain. The 2016 image highlights the changes to the channel and floodplain. The present-day channel is considerably narrower and less complex. Side channels that formerly flowed along the north side of the islands have filled in with sediment and vegetation and the outlet to the lake is limited to a single bridge opening width that is in the order of 70 m, or less than 15% of its former width. Hardening of the right (south) channel bank along the highway with riprap has resulted in a substantially narrowed active channel zone. Over time, gravel bar formations in the channel reach downstream of the Poleyard dike are reducing the channel's flood carrying capacity and increasing the potential for channel instabilities (NHC, 2017). The channel is eroding portions of the left (north) channel bank, and with ongoing sedimentation and if no changes are made along the south side of the river, it is anticipated that this erosional process will continue.

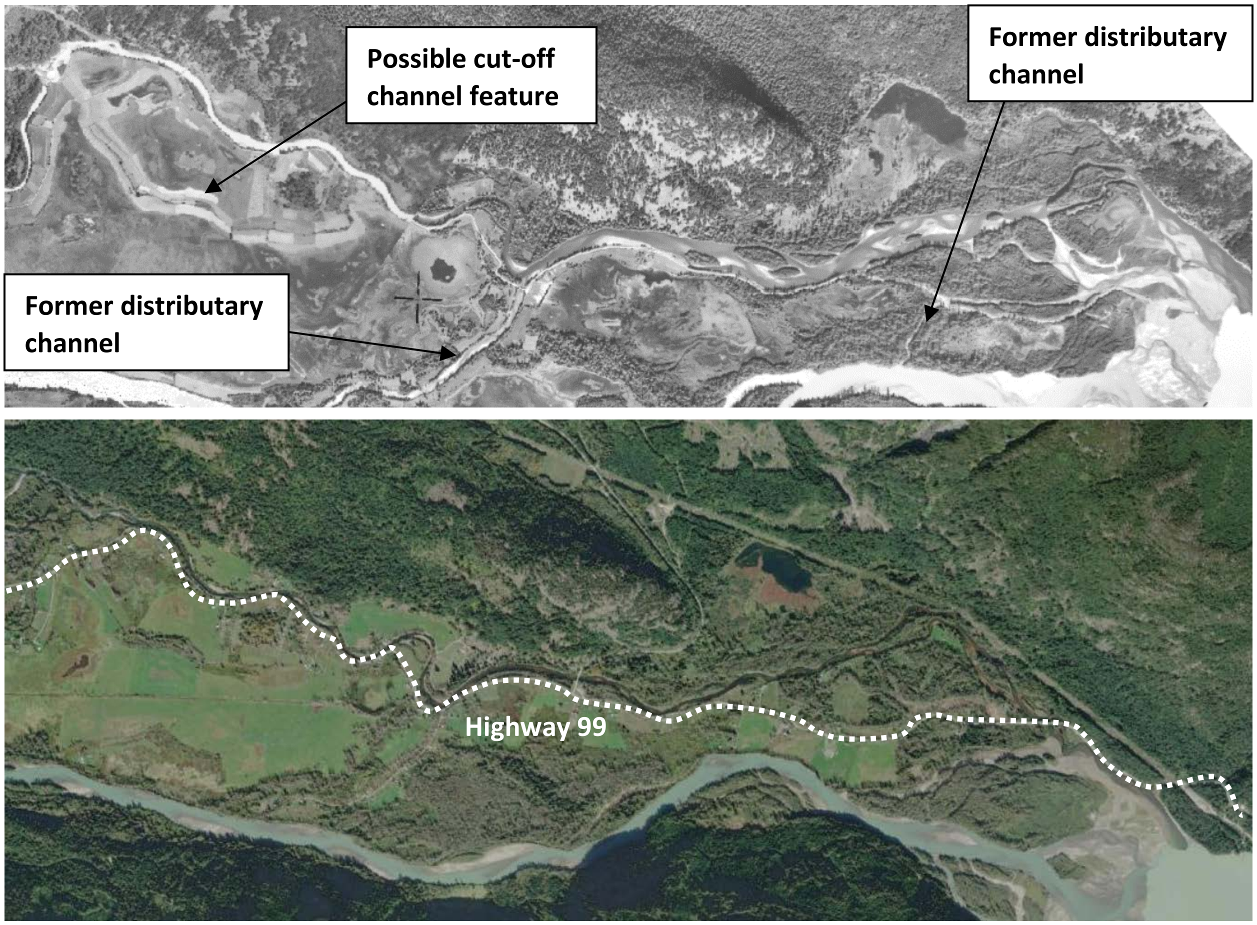

Figure 3.4 1948 air photo (UBC Geography) and 2016 ortho-imagery (Emergency Management BC).

4 HYDRUALIC MODELLING

A hydraulic model was developed in the NHC (2018) Lillooet River study to simulate the 50, 100, 200 year and 200 year + climate change design floods and estimate corresponding flood levels and extents within the study area. The hydraulic model from the previous study was used and adapted for the Birkenhead and Green Rivers to provide flood levels and extents. This section describes the various tasks carried out and results obtained. Key steps included: 1) Update of a Digital Elevation Model (DEM); 2) update of a hydraulic model; 3) calibration and validation of the model; 4) performing model runs and reviewing results; 5) modelling dike breaches and reviewing results; and, 6) reviewing model limitations.

4.1 DEM Update

NHC (2018) developed a DEM, or model geometry for the Lillooet River and tributaries, by combining the 2017 channel surveys, the 2017/2018 dike surveys, and the 2016 and 2009 LiDAR. The DEM prioritized most recent channel/ dike surveys and the 2016 LiDAR. The 2009 LiDAR was only used to fill any voids in the 2016 floodplain topography, typically limited to the outer edges of the DEM (less than

30% of the final terrain). See (NHC, 2018)for details on bathymetry data surveyed. The Birkenhead channel was extended upstream and updated near Poleyard dike to include 2019 survey data collected in the Pemberton Mitigation Study (NHC, 2020).

The DEM for the river channels was derived from the bathymetric surveys listed above. The US Bureau of Reclamation Bathymetric Interpolation Tool was employed to interpolate a continuous surface from the surveyed points. Breaklines were used liberally to shape the channel topography as needed. In areas of sparse data (such as upstream of Km 44 on Lillooet River, downstream of Km 0 on Lillooet Lake, upstream of Km 2.5 on Miller Creek, upstream of Km 10 on the Birkenhead River and upstream of Km 4 on Pemberton Creek) the riverbed was interpolated using available data and professional judgement. Dikes were introduced into the digital terrain by linearly interpolating surveyed dike crest elevations and assigning a uniform width of 6 m.

4.2 Model Software and Update

The Lillooet, Birkenhead and Green River flows are partly confined by dikes, roads and valley walls. There are secondary channels that have aggraded but become active during flood flows. Channel meander remnants from the channel-straightening in the 1950's may also carry some flow. Shallow bars and islands are frequently overtopped during high flow events, adding channel roughness and complexity to the hydraulics. Many of the dikes are expected to overtop during extreme flow events. Tributary channels provide additional complexity and confluence configurations are influenced by flow magnitudes.

Due to the very complicated floodplain, NHC (2018) built a 2D model for the valley to provide a more accurate representation of hydraulic conditions. HEC-RAS2D software developed by the U.S. Army Corps of Engineers Hydrologic Engineering Center (HEC) was used. The hydraulic model was updated for this study from Version 5.0.4 to 5.0.7 (the current full version at the time of the study).

4.3 Calibration and Validation

Model calibration is a critical step of hydraulic model development. It involves gradual refinement of model parameters to ensure simulated water levels match observed levels for a particular flood event. Typically, model parameters include channel roughness, floodplain roughness, and timing of hydrograph routing, but can also include approximation of channel blockages, scour, or degradation that may have occurred during a particular event. Once the coefficients have been fine-tuned, the model is used for simulating a second independent flood event with known flows and observed water levels to validate that the calibrated model is suitable for events other than just the calibrated event.

For the Birkenhead River, the amount, spatial extent, and accuracy of flow and water level data from past floods somewhat limit the model calibration and validation. The 2003 flood was used for primary model calibration and the 2019 data obtained during the river survey was used for model validation. The calibration, validation and comparison model runs are described below.

4.3.1 Roughness Coefficients

Hydraulic roughness coefficients, represented by Manning's n-values, strongly influence the computed profile. Care must be exercised to assign appropriate values based on observed highwater marks, technical literature and professional judgement.

For a 1D model the roughness factors account for friction losses resulting from surface roughness, vegetation, channel irregularities (variations in cross section size and shape), obstructions (stumps, roots, logs, isolated boulders) and channel alignment (degree of meandering). In a 2D model much of the friction losses (variations in channel shape and alignment) are accounted for in the momentum equation and consequently Manning's n-values are generally lower.

The roughness values determined for the Lillooet River and other tributaries were based on the NHC (2018) calibration. For the present work, Birkenhead and Green Rivers were divided into reaches with similar channel bed material, sectional geometry, and plan form. Each reach was then assigned an initial roughness value for the in-channel portion of the reach. These initial roughness values were assigned based on field observations of channel bed composition and verified with values referenced in the literature (A Strickler, 1923; Bathurst, 1985; Brownlie, 1981; Engelund and Hansen, 1967; Jarrett, 1984; Limerinous, 1970; Maynord et al., 1991; van Rijn, 1984; Wong and Parker, 2006).

The overbank portion of the model mesh developed for the Lillooet River Study (NHC, 2018) was not changed for the present study. The overbank was assigned roughness values using aerial imagery and professional judgment.

Following the calibration process, the Manning's n channel roughness coefficients listed in Table 4.1 were updated for the Birkenhead and Green Rivers.

Table 4.1 Channel roughness values used in hydraulic modelling

River	Reach	Manning's Coefficient (n)
Green River:	Lillooet River to Km 6.5	0.04
	Upstream of Km 6.5	0.05
Birkenhead River:	Mouth to Km 8	0.03
	Upstream of Km 8	0.05

4.3.2 High Flow Calibration

For optimum calibration results, observed high water marks (HWMs) should be obtained at flows approaching the design flow magnitude. HWM observations should also be recent, corresponding to the channel and floodplain geometries used in the model. On the Lillooet River, there were numerous channel changes that have taken place since the flood of record in 2003 (including the Meager Slide, 2010), the event was deemed unsuitable for calibration despite having extensive highwater information at a very high flow (1490 m^3/s). However, there was no major sediment supply change on the Birkenhead or Green River since that flood. While the data is old and there have likely been channel shifts, the floodplain on the whole has been fairly stable and is likely unchanged and so the 2003 flood was used for calibration. There is uncertainty regarding the vertical datum used for surveying the 2003 HWMs so the data was converted to the current datum using best judgement. Unfortunately, there were no HWMs collected during the 2016 flood for the Birkenhead and Green Rivers and this more recent flood could not be used.

The 2003 flood was used for calibration; results are included in Figure 4.1 and Figure 4.2. Based on the calibration, the simulation provides a good match to the 2003 HWMS in the Birkenhead River. The agreement between observed and simulated water levels has a mean absolute error of 0.15 m. However, there was limited information for the Green River and the one HWM available was 0.57m higher than the simulated flood level. This point is likely a localized high water level, not captured in the model, but without any other points to compare to, it is difficult to validate. Overall, differences between observed HWMs and the simulated water levels are likely due to:

- Bed level changes. The 2003 Flood occurred 18 years ago and the channel has likely changed since then (Section 3). During the flood, the channel bed may have lowered due to general and local scour. The model geometry has a fixed bed.
- Uncertainty in datum. The HWMs were surveyed in a local unspecified datum and the assumed conversion may be incorrect.
- Potential discrepancies in observed water levels. The HWMs were surveyed after the flood receded. The HWMs vary for a particular location and may be affected by local features.

Despite the model potentially over-predicting water levels to some degree, the channel roughness values were not further adjusted for the following reasons:

- The roughness values selected are at either the low or high end of plausible values for the channel form, bed texture, and channel slope based on referenced literature and past modelling experience.
- There is some uncertainty with the accuracy of the 2003 HWMs.
- The model assumes a fixed bed and scour during high floods cannot specifically be modelled.

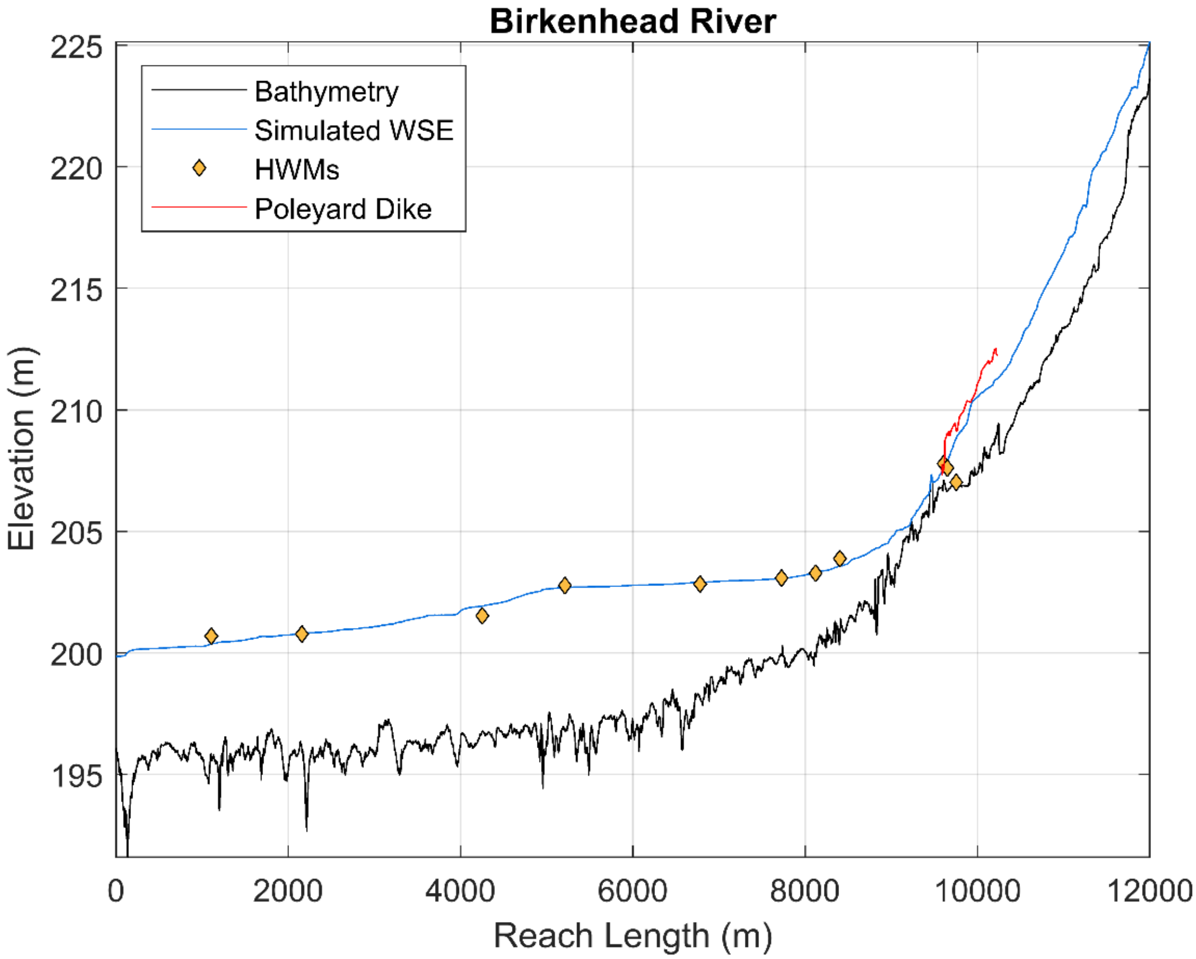

Figure 4.1 Calibration Profile Plot of Birkenhead River

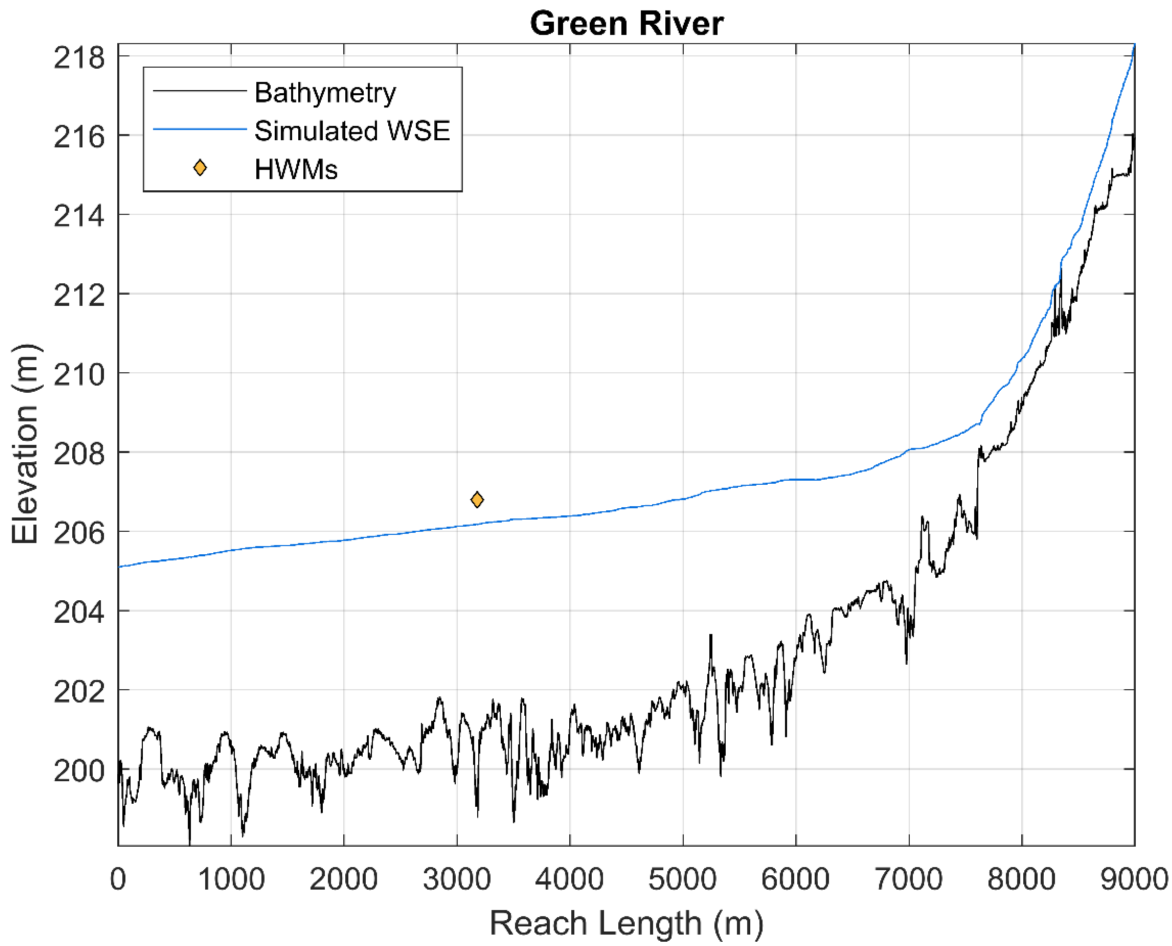

Figure 4.2 Calibration Profile Plot of Green River

4.3.3 2019 Validation

For model validation, NHC selected the flow conditions observed during the 2019 field surveys, on September 04. The validation was completed for the Birkenhead River based on the limited available data. No Validation was completed for the Green River. Water level data was available for the cross sections surveyed, starting near the Poleyard Dike and continuing about 2 km upstream. The river was flowing approximately between 8-11 m^3/s (based on survey estimates), dropping slightly over the course of the day.

The model has good agreement with the observed data in the lower half of the model and not as strong agreement in the upper half of the model. The model tends to underestimate the WSE in the upper portion of the model (overall a mean absolute error of 0.27 m). Spatially, there was good agreement with the surveyed points at the sides of the river. Differences between the modelled and observed profiles can be attributed to:

- Unknown flow on the Birkenhead River. Without a gauge or an accurate rating curve, the flows used are only estimates. The larger difference in the validation in the upper portion of the model was likely caused by a higher flow in the morning diminishing through the day and the estimate is more accurate for the lower portion of the surveyed reach.
- Local variation in channel geometry and WSE. The Birkenhead River has gravel bars, side channels and debris in the river all of which can cause the local water level to vary greatly from one side of the river to the other.

4.3.4 Calibration Summary

Based on the NHC (2018) study, the calibration, validation and comparison for the Lillooet model indicate the model may, to some extent, over-predict water levels. However, the additional calibration for the Birkenhead River does not show a tendency to over or under predict and the model was adopted for simulating the required design runs.

4.4 Model Runs and Results

In BC, floodplain mapping is typically developed for the 200 year flood. In addition to the 200 year Birkenhead and Green River floods, the 50 and 100 year floods were also modelled, as well as the estimated end-of-century 200 year flood, increased due to climate change impacts.

The Birkenhead and Green River flows used in the modelling are assumed to be coincident with the 50, 100 and 200 year floods on the Lillooet River. This is a conservative assumption but the shared inundated floodplains between the Green, Birkenhead and the Lillooet are wide enough that the additional flood waters do not significantly raise the water surface elevation in the floodplain (< 0.1 m near the Green River and < 0.2 m near the Birkenhead). The floodplain mapping developed in Section 5 is specifically for the Birkenhead and Green Rivers.

To develop floodplain maps, design profiles must first be simulated using the calibrated hydraulic model. The present diking is extensively over-topped and consequently likely to breach. In Mount Currie behind the Poleyard dike, a breach would have significant impact on the village. For the Birkenhead River regulatory mapping, dike breach modelling was performed to estimate overbank flow velocities and flood hazards for breached conditions. The analysis of dike breaches is described in Section 4.5.

4.4.1 Boundary Conditions

To simulate the selected design floods, appropriate boundary conditions (inflows and lake levels) had to be specified.

Estimated 50, 100 and 200 year design flows are listed in Table 2.5Table 4.2. Also included, is the 200 year flood estimate corresponding to the end of the century. The gauged flows were scaled based on watershed area (Section 2.3) to represent inflows at the upstream end of the Birkenhead and Green River model reaches.

Table 4.2 Peak flow estimates for the Birkenhead and Green River.

Return Period (Yr)	Green River (m^3/s)	Birkenhead River (m^3/s)
50	488	420
100	567	519
200	656	628
200+Climate Change	820	786

The downstream boundary condition, or the Lillooet Lake level, was set at the coincident return period (i.e. the 50 year design flow was run with the 50 year lake level). The climate change scenario was run with a 200 year lake level. Lake levels are listed in Table 4.3.

Table 4.3 Peak lake level estimates for the WSC Lillooet Lake gauge (08MG020).

Return Period (Yr)	Lake Level Estimate (m) (CVGD 2013)
50	199.65
100	199.93
200	200.20

The WSC lake records were converted to CGVD2013 to match the modelled data (subtract 169.55 m to convert local datum) (NHC, 2018).

4.4.2 Design Profiles

For potential Poleyard dike upgrades, simulated design flood profiles are plotted in Figure 4.3. Full profiles for the Birkenhead, Green and Lillooet River are attached in Appendix B. The profiles represent the water surface elevation at the centre of the river channel during the peak of the flood.

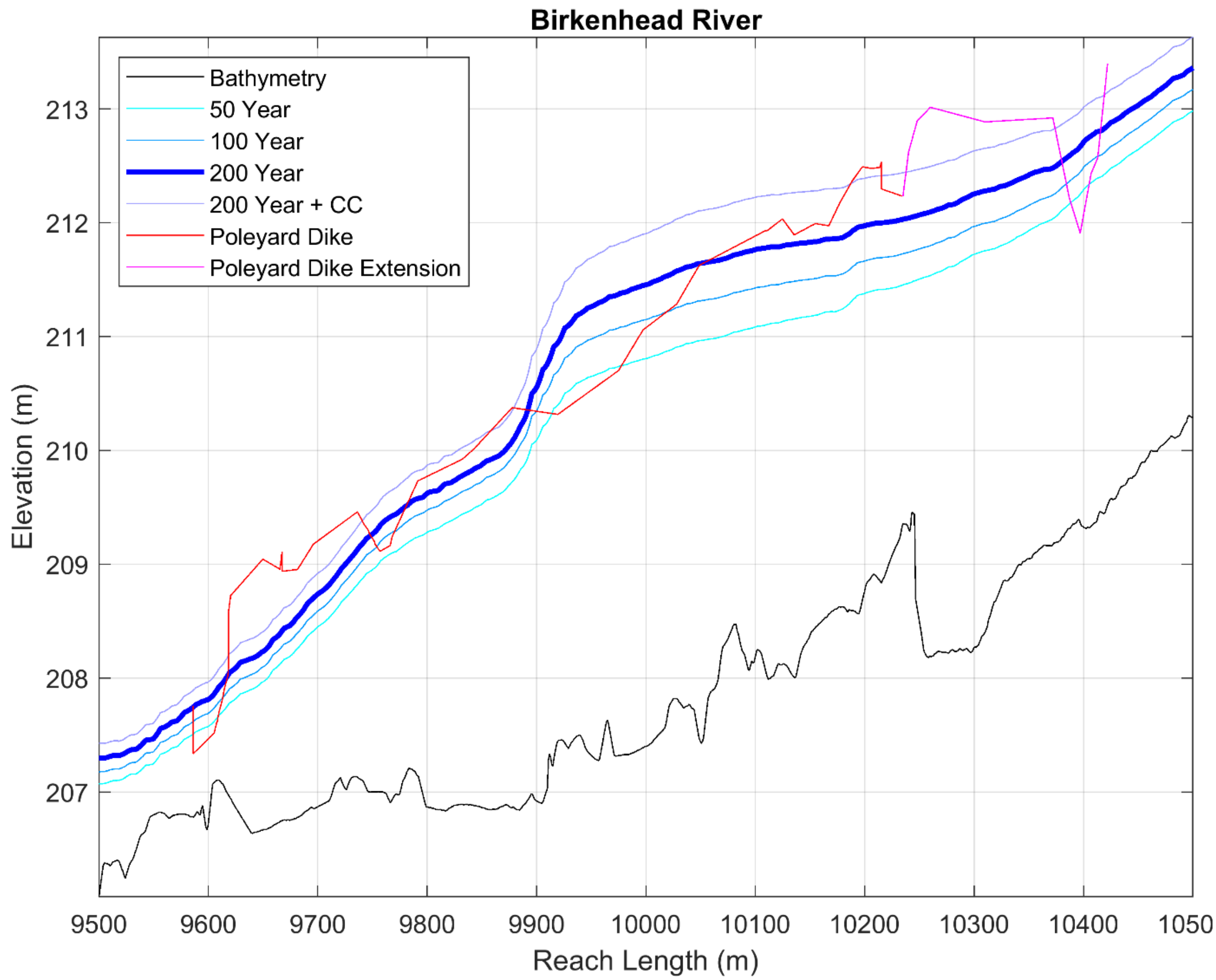

Figure 4.3 Birkenhead River design profile (no freeboard allowance) and Poleyard dike.

4.4.3 Model Sensitivity

Model sensitivity analysis was completed by NHC (2018) and was only updated for channel roughness on the Birkenhead and Green Rivers. The roughness conditions were tested with upper and lower limits of +/- 20%. When the roughness parameters were increased by 20%, the WSE increase within the channel was typically less than 10 cm. Similar results were found for the roughness decrease of 20%.

4.4.4 Progression of the 200 Year Flood Simulation

An animated video of the simulated 200 year flood + climate change was developed and provided to Lil̓wat Nation as a digital file. To prepare for emergency response measures it is important to have an understanding of the possible sequence of floodplain inundation, dike overtopping and impacts on access routes. Please note that the pattern and sequence of flooding could vary significantly from the simulated event shown in the video, and would depend on tributary inflows, dike breach locations and many other factors.

Highway 99, a key access/egress route for the area, becomes extensively inundated during the 200 year flood. The first location to overtop is near the mouth of the Birkenhead River. The 200 year lake level is the cause of highway inundation early on during the flood. Next, water overtops the highway east of Mount Currie, where the road bends along the Birkenhead River, cutting off access to the east. In this area,the Birkenhead River is the cause of flooding. The Lillooet River first overtops the highway directly east of the Highway 99 Lillooet River Bridge. East of the bridge water begins to spill over the road and into the floodplain cutting off Mount Currie's access to the west. This may occur when the flow at the WSC gauge is approximately 1150 m^3/s. Highway 99 through Pemberton becomes inaccessible as the area dikes breach or overtop.

4.5 Dike Breach Modelling

The hydraulic modelling showed that during the simulated 200 year flood, the Birkenhead flood flows overtop the Poleyard dike. For the floodplain and hazard mapping, the overtopped Poleyard dike was assumed to breach due to erosion of the crest. Dike breach modelling was carried out to develop an understanding of the flood progression and timing of inundation resulting from a localized failure. It is emphasized that dikes may fail well before overtopping due to seepage, piping, slippage or other modes of failure. These other types of failures were not modelled.

For an overtopping failure, the process is generally initiated by a head-cutting erosion process on the downstream side of the embankment as a shallow stream of water flows over the dike crest. As the depth of flow increases above the dike crest, the surface vegetation is generally removed and the embankment starts to erode very rapidly. Once water levels on both sides of the embankment equalize or the breach invert reaches the elevation of the floodplain, the rate of erosion slows down or stops.

For overtopping failures of the Poleyard dike, a final breach bottom width of 100 m at the elevation of the floodplain and an estimated breach formation time of one hour were used. The final shape of the breach was assumed to be trapezoidal in shape with 2H:1V side slopes. This assumed configuration is roughly based on observed failures during the 2003 flood (Ayers Dike and Ryan River Dike).

4.6 Model Limitations and Uncertainties

Some uncertainty is associated with all hydraulic model outputs and accuracy limitations should be kept in mind. The output from the Lillooet River HEC-RAS2D hydraulic model is limited by the capabilities of the DEM, the hydraulic modelling and breach assumptions made.

4.6.1 DEM

The limitations and assumptions associated with the DEM include:

- The 2016 LiDAR surveyed by EMBC did not cover the full extents of Lillooet Valley so the 2009 LiDAR was used to fill in the gaps (roughly 30% of the entire DEM). The older LiDAR may contain inaccuracies caused by river channel shifts and other changes in the floodplain.
- For all the channels, a smoothing algorithm and professional judgement was applied to develop the surface geometry between survey points.

- During the bathymetric surveys, the Lillooet channel bed was partly mobile, with dunes of material visible in the data. The mobile bed conditions likely introduced some inaccuracies.
- Although specified to contain bare-earth data, the LIDAR used for developing the DEM may contain some artificially high points, especially in areas where the vegetation is dense, creating unrealistic “dry spots” for some floodplain model runs.
- Culverts, ditches/canals and other drainage features were not specifically modelled.

4.6.2 HEC-RAS2D

For the 2D unsteady flow computations, the software used the full 2D Saint-Venant equations. The 2D computational cells were pre-processed in order to develop detailed hydraulic property tables based on the underlying terrain. (This allowed for larger cells to be partially wet with the correct water volume based on the modelled water surface and DEM resolution). Although RAS2D is a sophisticated modelling tool, it has several basic assumptions and limitations:

- The model assumes a fixed geometry for the channel and floodplain in spite of bank erosion, scour, deposition and potential avulsions taking place during high flows. Over time, channel aggradation is possible in these channels, which will result in higher water levels for a given flow condition.
- The absence of blockages, such as debris jams at bridge crossings and debris plugs at floodplain openings, is assumed.
- Dike breaches, other than those specifically modelled, are assumed not to occur. For the breaches that have been modelled, actual breach locations, parameters and opening sizes may vary.
- The model is as accurate as its calibration. The 200 year design flood is considerably larger than the calibration event and the calibrated roughness coefficients may not be representative of the higher flow. Some overprediction was observed on the Lillooet River but not on the Birkenhead River so roughness coefficients were not reduced as it was felt that the values applied represent lower bound coefficients.
- At the start of a flood simulation, the model floodplain is assumed to be dry although there may already be water in the form of localized ponding and runoff from precipitation. Also, a multi-peaked hydrograph may cause more severe flooding than the event simulated.

4.6.3 Dike Breaching

Some limitations and assumptions associated with the dike breach modelling include:

- The dike breach results are based on individual model runs and specific dike breach locations. The dikes may breach in any location and multiple dikes may breach at once. The actual pattern, extent and timing of breach floods may vary significantly from those assumed.
- For detailed breach assessments, geotechnical modelling of the dikes is carried out to develop suitable breach parameters. The breach parameters specified for this project are based on

historic breaches but parameters for future failures could vary (e.g. the breach could open faster or slower, wider or more narrow than specified).

4.6.4 Summary Statement

Although a number of limitations were identified with the different hydraulic modelling components, the results have followed state-of-the-art modelling procedures and are considered sufficiently accurate for updating the design profile, preparing up-to-date floodplain mapping and other required mapping products. It is recommended that the floodplain mapping described in Section 5 replace the mapping from 1990.

5 FLOOD MAPPING

5.1 Flood Map Products

Three types of map products were produced:

- Designated floodplain maps depicting 200 year flood levels plus climate change plus a freeboard allowance.
- Flood depth maps for the 50, 100 and 200 year plus climate change floods.
- Flood hazard maps showing a Hazard Rating based on flood depths and flow velocities.

The approaches for developing the mapping and the maps produced are described below.

5.2 Designated Floodplain Maps

The simulated 200 year plus climate change water surface was mapped at 1:10,000 scale on the 17 sheets (11”x17”) that are included in the map section of this report. Freeboard, discussed in Section 5.2.1, was added to the simulated water level surface, and the combined surface was then mapped over the DEM and projected across the floodplain to delineate flood extents. The maps show flood extents with and without freeboard allowance. With freeboard included, the maps indicate the minimum level for construction at a certain point within the floodplain, referred to as the Flood Construction Level (FCL). The maps include isolines or lines corresponding to equal FCLs, generally in 0.5 m or 1 m increments.

Lílwat First Nation has the authority to regulate new development in flood hazard areas. The new mapping could be designated by the Lílwat First Nation to become the official floodplain mapping for the Birkenhead and Green River.

GIS deliverables for the flood mapping are described in Appendix C.

5.2.1 Freeboard Requirements

Freeboard is added to provide a safety factor. The freeboard accounts for local variations in water level (such as standing waves, super-elevation at the outside of river bends, local turbulence) and uncertainty in the flood level simulations. Historically in British Columbia, the minimum freeboard allowance applied has been the greater of 0.3 m above the instantaneous (peak) flood event or 0.6 m above the daily flood event. For some rivers, freeboard should be increased to 1 m or more, to address greater uncertainty in the assessment or concerns regarding sediment deposition, debris blockages or ice jams (MWLAP, 2004).

In recent years, a minimum freeboard of 0.6 m has been frequently used with an instantaneous event[2], as suggested in recent provincial guidelines for sea dikes (BC Ministry of Environment (BC MOE), 2011) and as discussed in the EGBC professional practice guideline for floodplain mapping (APEGBC, 2017).

Considering the potential for bed level changes in the Birkenhead and Lillooet River and the uncertainty of climate change on future flood flows, a minimum freeboard allowance of 0.6 m is recommended. Monitoring should be carried out over time to assess for channel changes and potential impacts to flood levels.

The Lil̓wat Nation may wish to define a higher level of protection for certain infrastructure or facilities, such as dikes, major transportation routes, hospitals, emergency response centers, communications centers, residences for the elderly, or schools.

5.3 Flood Depth Maps

The flood depth maps were developed using the water surfaces simulated in the model without a freeboard allowance. The DEM surface was subtracted from the water level surface to show the flood depths across the floodplain. The flood depth maps are shown on seven 11”x17” sheets at 1:20,000 scale, as included in the map section of this report.

The flood depth maps correspond to the 50, 100 and 200 year floods plus climate change on the Birkenhead and Green River. The colour shading references the criteria listed in Table 5.1, adapted from the national standard in Japan (EXCIMAP, 2007).

Inundation durations were not mapped. Durations are highly sensitive to the flood hydrograph, dike breaching, and drainage patterns experienced. For the depth mapping, dike breaches were not considered.

A comparison of the different return period flood depth maps show remarkably little increase in flood extents between the 50 and 200 year floods but significant increases in depth. This is to be expected,

[2] A brief set of examples of use of a minimum of 0.6 m freeboard above the instantaneous flood flow within BC include flood hazard study and mapping in Prince George, the lower Fraser River, Maple Ridge, Squamish, and North Vancouver (FLNRORD and NHC, 2014; KWL, 2014, 2017; NHC, 2008, 2016).

considering the valley is relatively flat and has steep valley walls. During floods with a return period exceeding 50 years, most of the valley floor is flooded.

Table 5.1 Flood Depth Criteria

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 floor; 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.

5.4 Flood Hazard Maps

For the flood hazard maps, a velocity surface was extracted from the model and (as per the Flood Hazard Rating equation shown in Table 5.2) multiplied by the depth surface to create a hazard rating surface. This surface was then mapped over the DEM as shown on the seven 11"x17" sheets at 1:20,000 scale in the map section.

Similar to the depth mapping, the 50, 100 and 200 year plus climate change return period floods were mapped, allowing for dike breaching when overtopping occurs on the Poleyard dike.

Table 5.2 lists the different levels of flood hazard based on the UK DEFRA/Environmental Agency (2005).

For many parts of the floodplain the hazard rating increases significantly from the 50 to 200 year flood. Some of the highest flood hazard ratings (i.e. "Significant" and "Extreme") apply to relatively large areas of the lower part of the Valley from Lillooet River Km 25 (just upstream of the Miller Creek confluence) to Lillooet Lake.

Table 5.2 Flood Hazard Ratings

Hazard Rating depth * (velocity + 0.5) (m·m/s)	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 2.5	Significant	**Dangerous for most people** "Danger: flood zone with deep fast flowing water"
> 2.5	Extreme	**Dangerous for all** "Extreme danger: flood zone with deep fast flowing water"

6 RISK ASSESSMENT

The flood risk assessment for Lílwat Nation was completed to help the community understand the consequences of the design flood event for the rivers and lake in the study area. An assessment of the consequences of a large flood can help to inform risk reduction plans and build resilience from such events.

The risk assessment for Lílwat Nation included consideration of the consequences of flooding for People, Economy, Infrastructure, Environment, and Culture. Areas of importance and specific assets were identified using provincial datasets and community input. The consequences of flooding for each category were assessed for the design flood as described in Section 2.5. The design flood is a 200 year flow with climate change on the Green River, the Birkenhead River, and the Lillooet River along with a 200 year return period lake level for Lillooet Lake. This would be a very large flood event and would affect the entire community.

This section summarizes the results of the risk assessment and community consultation completed as part of the project. The area included in the exposure assessment is shown in Figure 6.1

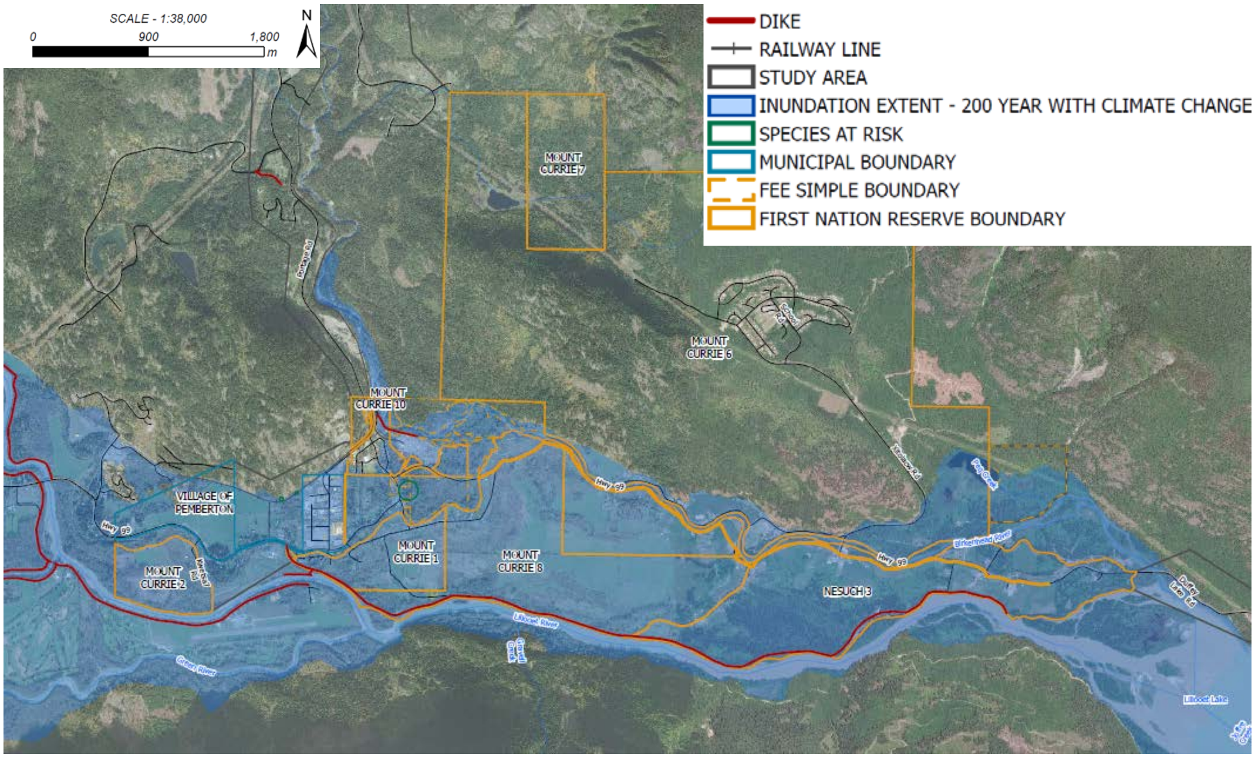

Figure 6.1 Area of Lil̓wat Nation study area exposed to design flood

The flood exposure is used as a proxy for flood risk. This means that the exposure to flooding was assessed for one event, the design flood. This approach was selected, as the design event would be used for mitigation design and risk reduction decision making. A probabilistic risk assessment could be completed with the hazard extents of multiple return periods in the future if it is determined that it would add value.

6.1 Exposure Assessment

For the exposure assessment two areas were considered, the extent of Lil̓wat Nation Reserves and a larger area of interest which includes fee simple lands adjacent to the reserves. This larger area of interest was used so that infrastructure and properties used by Lil̓wat Nation off-reserve would be included in the assessment. The exposure assessment was completed for consequences to People, Infrastructure, Economy, Environment, and Cultural areas as shown in Figure 6.2.

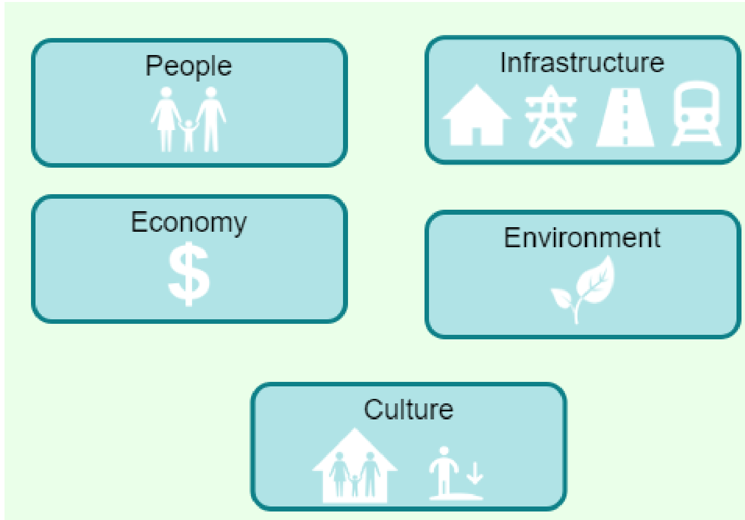

Figure 6.2 Categories of flood consequence assessed for Lil̓wat Nation

6.1.1 People

To assess the consequences of flooding for people, buildings were mapped and analyzed for their exposure and vulnerability to flooding. For this the Canadian buildings database from Microsoft was used (Microsoft, 2019). The baseline database was improved on and added to with comparisons using satellite imagery. In addition, a survey of buildings on reserve and adjacent to the reserves was completed by Lil̓wat Nation member Willow Edmonds in March 2021. This survey enhanced the building database with building type information and records of the consequences of past events. The majority of buildings surveyed are timbre frame houses constructed either with concrete foundations, on concrete blocks, or on earth. Several buildings exposed to flooding have basements.

Table 6.1 Exposure of people in AOI and on reserves

Asset	Total AOI	Total Exposed in AOI	Total on Reserve	Total Exposed on Reserve
Buildings	553	414	276	233

It was found that 75% of buildings within the study area, and 84% of on reserve buildings, are exposed to the design flood. With a very high level of exposure for all buildings there would be severe consequences of the design flood for people with regards to direct safety, as well as damage to homes and businesses.

6.1.2 Economy

Economic consequences of flooding were assessed for damage to buildings. This was completed using flood depths from modelling and building information from the buildings survey. The highest maximum flood depth for a building within the study area is 3.4 m and the average maximum depth for exposed buildings is 0.9 m. Based on depth damage curves from Canadian guidelines (NRCan, 2021) for residential buildings the total damage was calculated for the AOI and buildings on reserve for the design flood using the max depth as shown in Figure 6.2.

Table 6.2 Exposure for economy in AOI and on reserves

Asset	Total Damage on AOI	Total Damage on Reserve
Buildings	$37M	$21M

6.1.3 Infrastructure

Flood consequences to infrastructure were assessed for road and rail infrastructure using provincial databases and the design flood hazard layers as shown in Table 6.3.

Table 6.3 Exposure of infrastructure in AOI and on reserves

Asset	Total AOI	Total Exposed in AOI	Total on Reserve	Total Exposed on Reserve
Railway	10.0 km	1.3 km	0.2km	0.04 km
Roads Total	51.4 km	25.6 km	25.7 km	12.7 km
Highway	5.1 km	3.9 km	1.1 km	1.1 km
Arterial Roads	9.2 km	7.5 km	0.6 km	0.6 km
Collector Roads	12.4 km	1.2 km	5.1 km	1.1 km
Local Roads	27.5 km	13.0 km	18.8 km	9.8 km

From the consultation it was determined that the road access is the primary concern for the Lílwat people. Road access to the town centre of Pemberton in particular, is a concern as this is the main supply for goods and services. This includes the highway from Mount Currie and the road up to the Village. The main access roads are inundated during the design flood. There is also a possibility of the highway bridge over the Birkenhead River being washout out in the design flood. While the floods could recede fairly quickly, access through this route might be limited for much longer time periods due repairs. Also 47% of the roads in the study area and 49% of roads on reserve would be flooded. This means that local circulation as well as external access would be disrupted.

6.1.4 Environment

Flood consequences for environment were assessed for sensitive habitat areas. This is used as a proxy for environmental flood consequences as sensitive habitats can be affected by contaminants transported by flood waters. Areas of species at risk were calculated for the study area and on reserve area as summarized in Table 6.4.

Table 6.4 Exposure of environment in AOI and on reserves

Asset	Total AOI	Total Exposed in AOI	Total on Reserve	Total Exposed on Reserve
Species at risk areas	0.03 km^2	0.02 km^2	0.03 km^2	0.02 km^2

Sources of contamination that would be a concern for these areas include gas stations, fuel storage, and agricultural pollutants transported from Pemberton and the Pemberton Valley upstream.

6.1.5 Culture

A severe flood would affect several important cultural areas and cultural assets. These were mostly documented qualitatively and some of the main sites affected include burial sites and cultural buildings. In particular the community cemetery has been affected by previous flooding and there is an interest in protecting this area from future damage.

6.2 Community Consultation

Community consultation for the risk assessment was completed virtually through several meetings and a survey including a public meeting for the community. It was planned to have several in-person sessions, however, due to the COVID-19 pandemic this was not possible. Through the virtual meetings the objectives of the risk assessment were shared along with the completed flood mapping, and input was gathered on areas of concern. In addition, impacts from previous floods were shared.

The consultation meetings and activities completed include the following:

- Meeting with Emergency Management Committee – Thursday February 25th 2021
- Public Meeting with Flood Bingo – Thursday March 18th 2021
- Building Survey by Willow Edmonds – March 2nd – 27th 2021

The objective of the public meeting was to share the results of the flood mapping project as well as gather input. To encourage participation, Flood Bingo was developed for this project as shown in Figure 6.3. This is a tool that could easily be re-used for any future engagement and named relevant terms throughout the public presentation.

Flood Bingo

Lillooet	FREE	Birkenhead	Evacuation	Safety
Dike	Inundation	Retreat	Flood Risk	Tributary
Recover	Green	Flow	Design Flood	Breach
Flood Story	Respond	Protect	Flood Map	Depth
Adapt	River	Prepare	Flood Event	Velocity

Figure 6.3 Public Meeting Flood Bingo Card

From the public meeting some of the indirect consequences of flooding were recorded including transportation access. With the design flood, the Líl̓wat Nation loses road access to Pemberton, which is an important center for accessing goods and services. There are some other services roads that can be used, however, the travel time with these is longer.

From the building and community survey it was recorded that impacts to the Líl̓wat community have included residential buildings being significantly affected. Some buildings with basements mention that the basement floods with every recorded flood. Three building residents reported having had septic seepage issues since the flood in 2003. Other residents mentioned that the water was waist deep in their trailer during the last flood. In one area, the flood water stayed in the area for three weeks before a trench was dug to drain it away.

7 CONCLUSIONS AND RECOMMENDATIONS

Based on the project findings, the following conclusions and recommendations are provided:

7.1 Conclusions

1. A number of significant floods on the Lillooet, Green and Birkenhead Rivers have occurred in the past (1984, 1991, 2003, 2013 and 2016). In the 1950s large-scale channel straightening and lowering of Lillooet Lake was carried out and over time, a number of dikes and berms have been

built (including the Poleyard Dike). Despite these flood protection measures, the Lillooet Valley continues to be at high risk of flooding. Considering apparent increases in peak flows and reduced channel capacity due to aggradation, flood hazards are expected to increase with time.

2. Previous floodplain mapping and flood profile work for the valley used a range of survey datum. Although, it was possible to convert some previous results to the present datum (CGVD2013), some inaccuracies may exist.
3. Development of the floodplain has resulted in a much less complex network of river channels and has substantially reduced the active channel area on the floodplain. Over time, channel sedimentation will result in more of a disequilibrium between the channel bed elevation and elevation of the adjacent floodplain, further increasing the potential for erosion, lateral channel migration and other channel instabilities, dike overtopping and severity of flooding. With no other flood mitigation options, channel management will need to be part of the long term flood management program.
4. The NHC (2018) study suggests a change in the flow regime of the Lillooet River starting roughly around 1975. Prior to 1975, the annual peak flow was typically freshet generated but over the past 45 years the extreme annual peaks tend to occur in the fall as a result of rain on snow events. The shift in the timing and magnitude of peak flows in the Lillooet River upstream of Pemberton is evidence of the sensitivity to climate modal shifts. Though the spatial analysis could not support applying these post-1975 changes to the Green or Birkenhead River directly due to absence of data, it is still likely that the watersheds are sensitive to climate change impacts because they are in the rain-snow transition zone. The current 200 year flood estimate for the Green and Birkenhead Rivers are 656 m^3/s and 628 m^3/s. As based on EGBC guidelines and analyses of peak flow trends, climate change may increase the flood peak estimate to 820 m^3/s and 786 m^3/s by the end of century.
5. The hydraulic model showed that the Poleyard dike would be overtopped during the 100 year and greater floods. Overtopping is imminent at 50 year flood level. The dike breach simulated would have significant impact on Mount Currie. Flood flows would inundate many areas on the floodplain within a few hours. Corresponding flow velocities would be very high and flood hazard ratings are categorized as significant or extreme in many locations.
6. Although the hydraulic model has a number of limitations, it is a useful tool developed by applying state-of-the-art techniques. The simulated flood extents are similar to those developed for the 1990 floodplain mapping. However, flood levels are generally much higher and FCL isoline patterns vary. The depth mapping developed shows depths of over 2 m for extended areas, resulting in inundation of the first floor of most housing in the valley.
7. It is clear from the risk and exposure assessment, as well as the community consultation, that the consequences of flooding have already been experienced in the community multiple times. The occurrence of the 200 year design flood with climate change would have severe consequences for people, economy, infrastructure, environment, and culture within the Nation.
8. A high proportion of buildings are exposed to the design flood and so mitigating residential flood risk should be a priority. In addition, road access within the community and externally is severely affected and so response, continuity as well as any recovery plans should address this.

7.2 Recommendations

1. An up-to-date flood emergency response plan should be developed, taking into account the increased flood hazards. It is recommended that the Líl̓wat Nation coordinate their plan with Village of Pemberton, Squamish Lillooet Regional District and Pemberton Valley Dyking District. Depending on the location and nature of a dike breach, the response time before hazardous flows block roads and reach developed areas may be as little as 15 minutes (in Mount Currie just behind Poleyard dike).
2. It is recommended that Líl̓wat Nation adopt the designated floodplain maps for the Birkenhead and Green Rivers and that the FCLs shown on the mapping be applied to future development.
3. It is recommended that major development be avoided or limited in high hazard areas of the floodplain. If such development is essential, it must be built to withstand flood waters ((buildings raised on fill or stilts and with flood and erosion protection applied).
4. It is recommended that the provincial River Forecast Centre be made aware of flood hazards in the Lillooet Valley and that the importance of accurate and timely forecasts be emphasized.
5. Protection measures in the area need to be improved. It is recommended that:
    - Local authorities review the depth and hazard rating maps and identify areas where flooding would have major impacts on existing development. Consideration should be given to relocating or floodproofing housing and other development in critical areas.
    - MOTI and other agencies be encouraged to identify areas where road and rail access/ egress can be improved to allow transport during high floods.
    - Consideration be given to ensuring access to higher elevation areas in the valley that residents/ domestic animals can quickly be evacuated to.
    - Phase 1 of the Poleyard Dike upgrade project is presently underway to upgrade the existing dike and extend it upstream to the edge of the railway right of way. Future phases should be completed to tie the dike into the railway grade at the upstream end, and to extended it farther downstream.
6. The hydraulic model must be updated over time. Considering the significant aggradation taking place, the Lillooet River channel should be monitored and re-surveyed every 5-10 years and the model updated as required. Major changes within the floodplain should be included in the model, such as raised dikes, roads or fill areas. (With a robust model readily available, updating portions of the DEM and hydraulic model is relatively straightforward.)
7. WSC is encouraged to install or re-activate gauges on the tributaries, currently not in operation. It is particularly important that a gauge be reinstalled on the Birkenhead River. In order of priority, the Green, Ryan and Miller watersheds should also be gauged.
8. Over time, apparent trends in observed peak flows should be monitored and potential changes in flows due to climate change be reviewed.
9. During large floods, high watermarks should be collected and corresponding flood flows observed to allow for future model calibration and validation updates.

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APPENDIX A

POLEYARD DIKE CHANNEL CROSS SECTION COMPARISON

NOTES:
- SEE SHEETS 2 AND 3 FOR CROSS SECTION COMPARISON
- 2016 ORTHOPHOTO PROVIDED BY CLIENT (FROM GeoBC)

LIL'WAT NATION
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REVISIONS

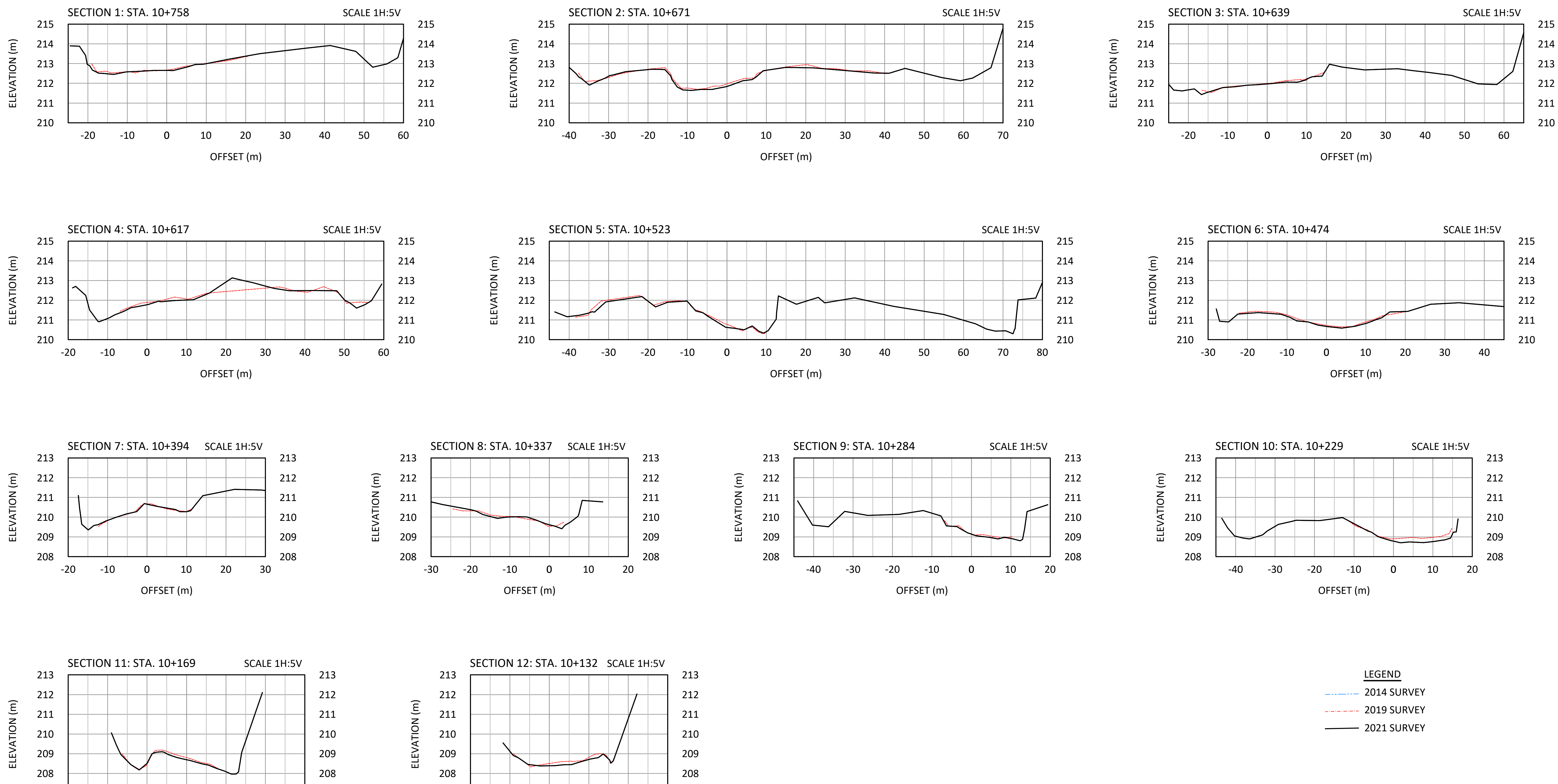
DRAWING INFORMATION	
DATE	24 MAR 2021
DESIGNED BY	N/A
DRAWN BY	CSM
CHECKED BY	WPH
SHEET SIZE	B (11" x 17")

LIL'WAT NATION
FLOOD PLAIN MAPPING

PLAN

PROJECT NUMBER	3004698
DRAWING NUMBER	3004698-05-1
SHEET NUMBER	1
REVISION	0

Filename: \\mainfile-van\Projects\Active\3004698 Lil'wat Nation FPM\96 CAD\3004698-05-SET-XSComp-r0a.dwg, 24-Mar-21 9:40:25 AM



NOTES:
- 2014 SURVEY BY DOUG BUSH (CGVD28 CONVERTED TO CGVD 2013)
- 2019 SURVEY BY NHC, 4 SEPTEMBER (CGVD 2013)
- 2021 SURVEY BY NHC, 1 AND 2 MARCH (CGVD 2013)

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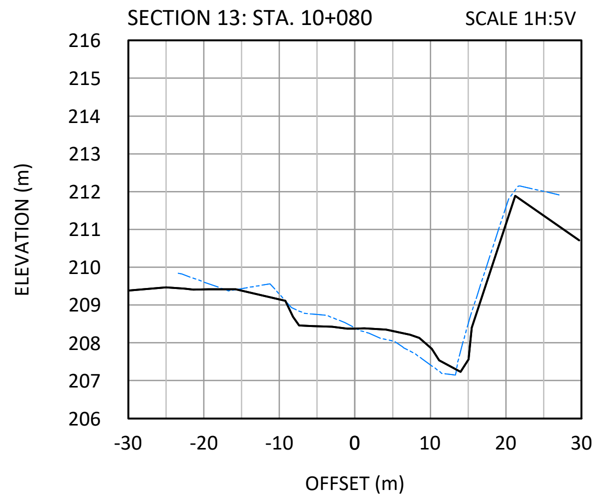
REVISIONS		

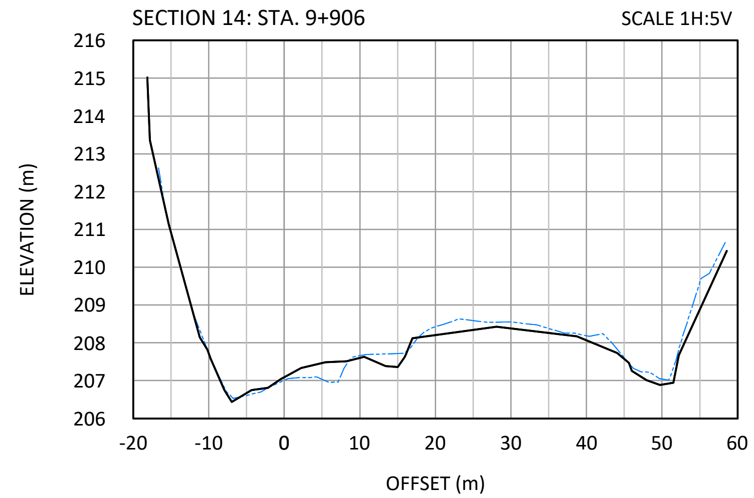
DRAWING INFORMATION	
DATE	24 MAR 2021
DESIGNED BY	N/A
DRAWN BY	CSM
CHECKED BY	WPH
SHEET SIZE	B (11" x 17")

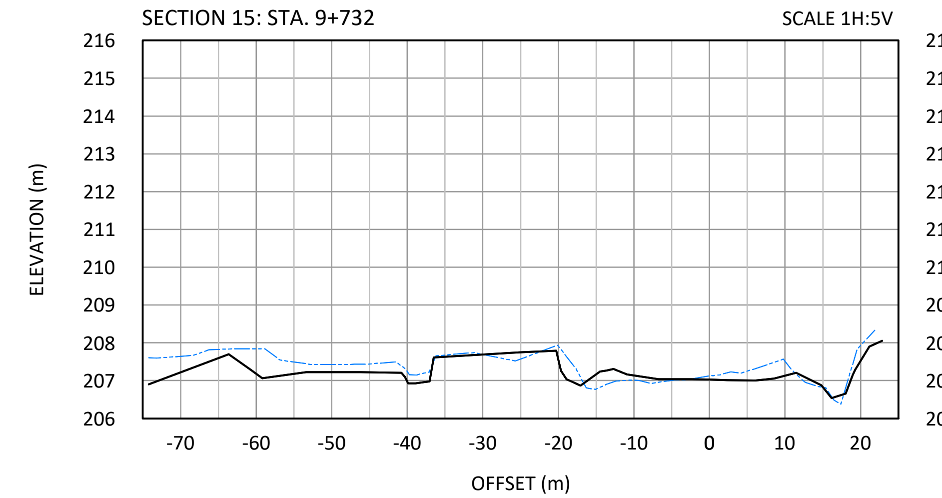
LIL'WAT NATION
FLOOD PLAIN MAPPING

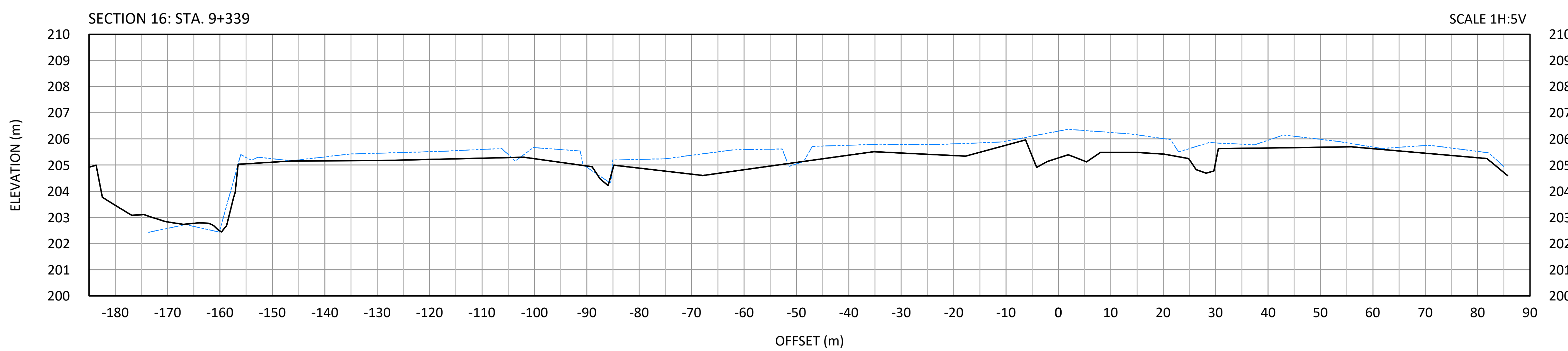
CROSS SECTION COMPARISON
SECTIONS 1 THROUGH 12

PROJECT NUMBER	3004698
DRAWING NUMBER	3004698-05-2
SHEET NUMBER	2
REVISION	0









LEGEND
- 2014 SURVEY
- 2019 SURVEY
- 2021 SURVEY

NOTES:
- 2014 SURVEY BY DOUG BUSH (CGVD28 CONVERTED TO CGVD 2013)
- 2019 SURVEY BY NHC, 4 SEPTEMBER (CGVD 2013)
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REVISIONS

DRAWING INFORMATION	
DATE	24 MAR 2021
DESIGNED BY	N/A
DRAWN BY	CSM
CHECKED BY	WPH
SHEET SIZE	B (11" x 17")

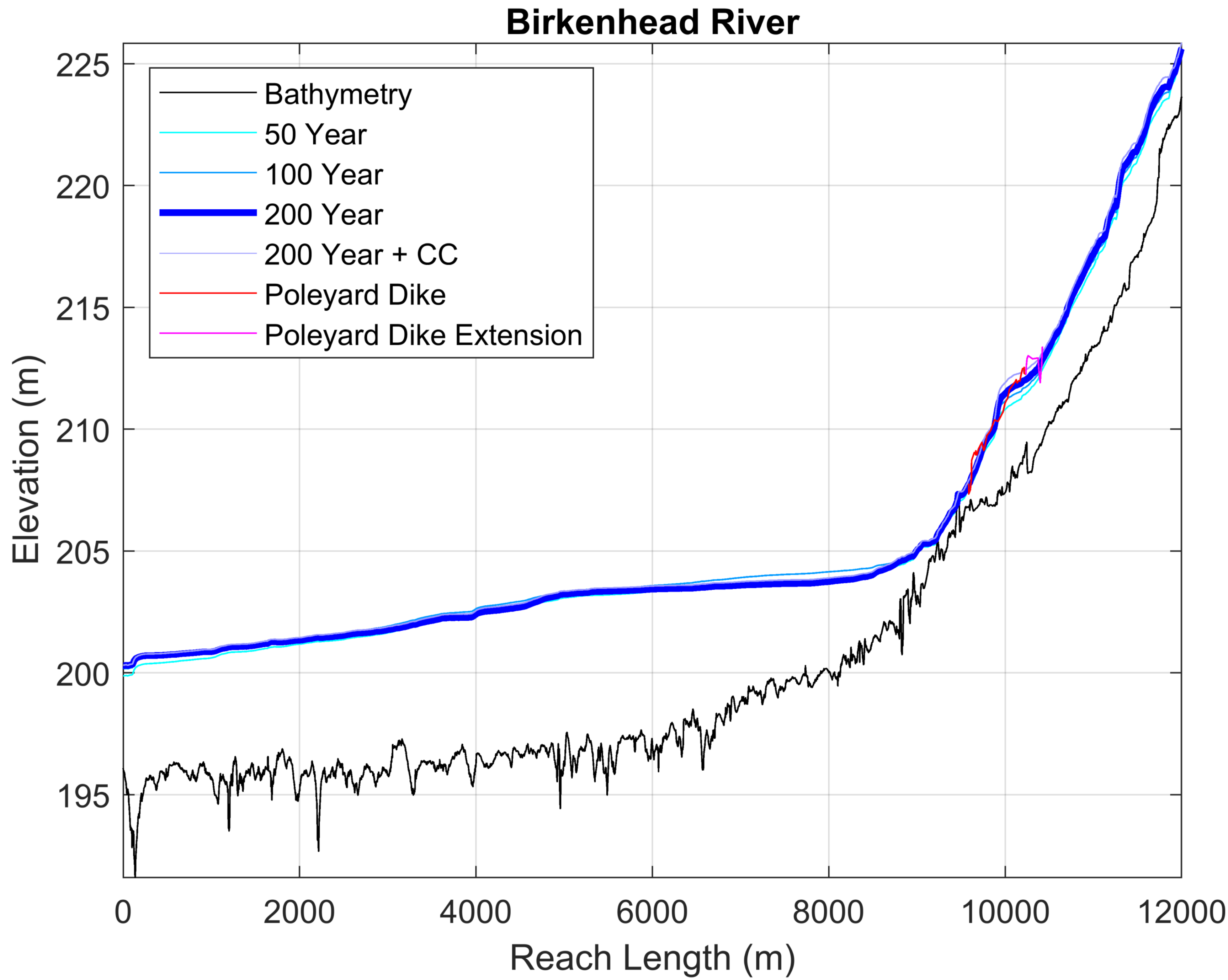
LIL'WAT NATION
FLOOD PLAIN MAPPING

CROSS SECTION COMPARISON
SECTIONS 13 THROUGH 16

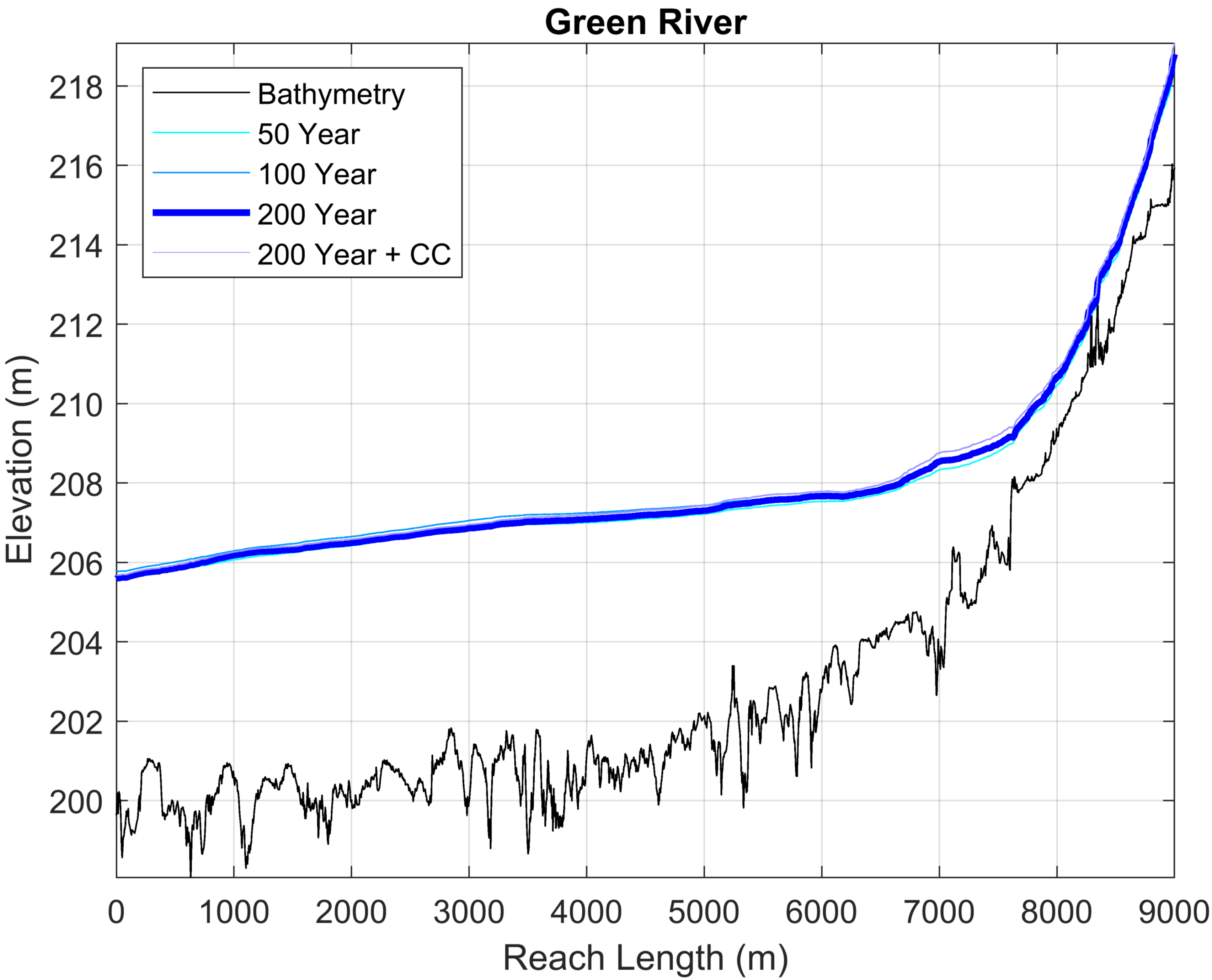
PROJECT NUMBER	3004698
DRAWING NUMBER	3004698-05-3
SHEET NUMBER	3
REVISION	0

APPENDIX B

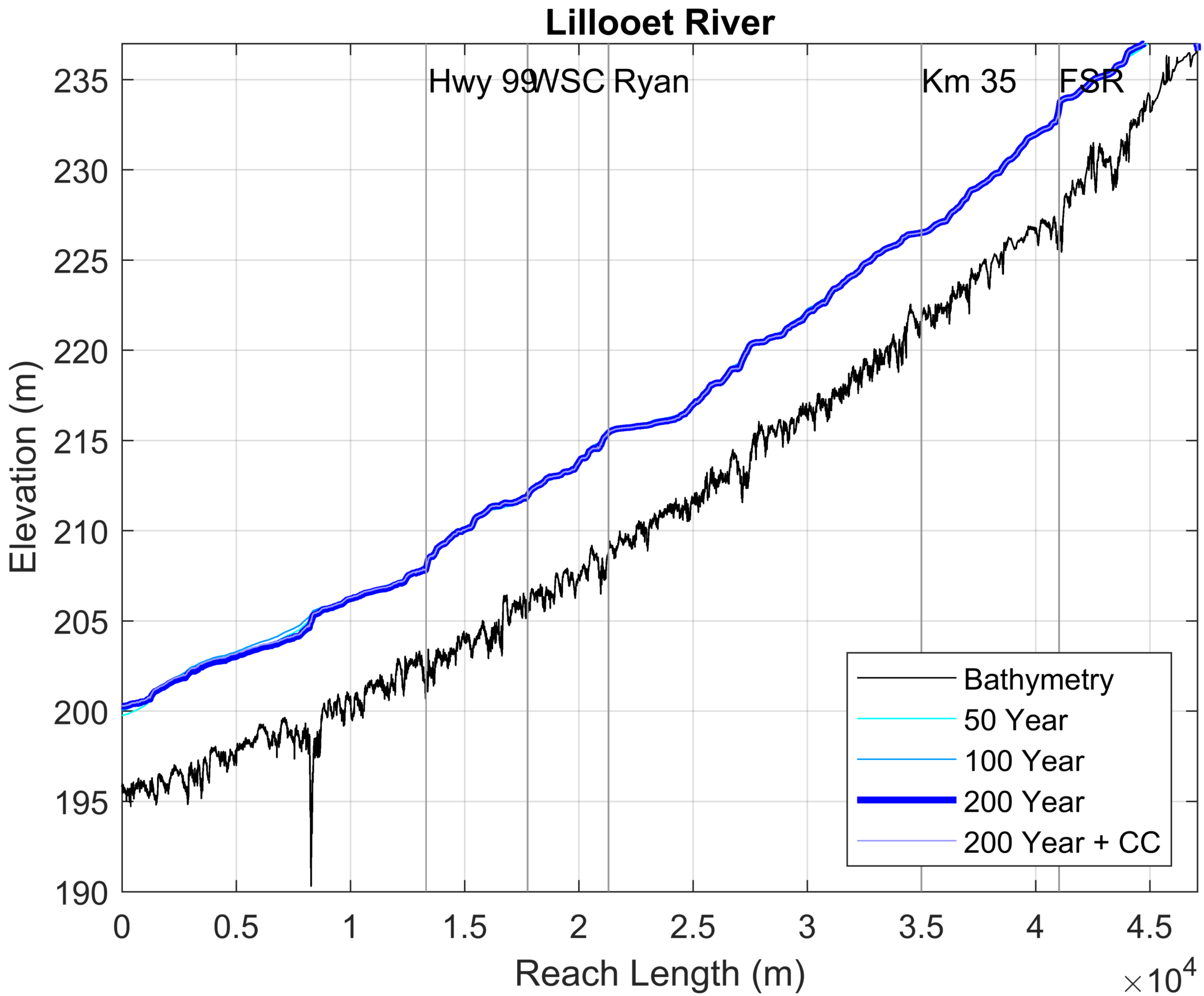
MODELLED DESIGN PROFILES



Birkenhead River
Bathymetry
50 Year
100 Year
200 Year
200 Year + CC
Poleyard Dike
Poleyard Dike Extension
Elevation (m)
225
220
215
210
205
200
195
0
2000
4000
6000
8000
10000
12000
Reach Length (m)

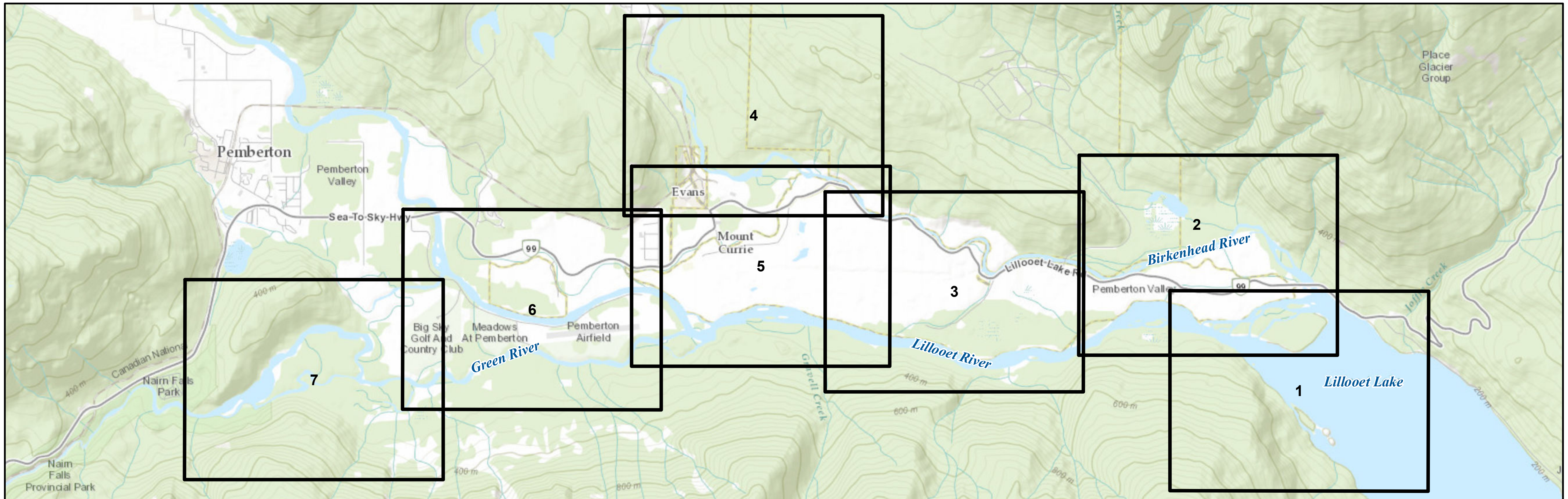


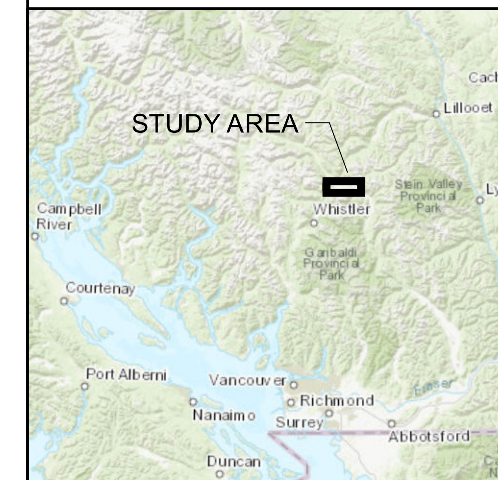
Green River
Bathymetry
50 Year
100 Year
200 Year
200 Year + CC
Elevation (m)
218
216
214
212
210
208
206
204
202
200
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
Reach Length (m)



Lillooet River
Hwy 99
WSC
Ryan
Km 35
FSR
Bathymetry
50 Year
100 Year
200 Year
200 Year + CC
Elevation (m)
Reach Length (m)
×10^4
190
195
200
205
210
215
220
225
230
235
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5

APPENDIX C
FLOODPLAIN MAPS





Designated Floodplain Map General Notes

1. These maps delineate the potential for flooding under conditions caused by a 200-year return period event as described in NHC (2020). The estimated flood flows for the Birkenhead and Green Rivers include a climate change flow increase allowance of 25% (end-of-century estimate) in combination with a present day 200-year event on the main stem of the Lillooet River. This flood scenario was selected in consultation with Lil'wat First Nation and is applicable to only Indigenous Lands in the area. For more information on the conditions that correspond to a 200-year event, please see NHC (2020).

2. A freeboard allowance (margin of safety) of 0.6 m is included in the flood levels on the Birkenhead, Green and Lillooet Rivers. It accounts for various sources of uncertainty in the model inputs and parameters.

3. Lidar data surveyed in 2016 was used to create a Digital Elevation Model (DEM) for the study area. The DEM surface was modified to include ground survey data for all dikes specified in NHC (2018) and to include surveyed channel bathymetry for the study reaches (NHC, 2020). The maps depict flood levels based on ground conditions represented in this DEM. Any changes to ground and channel elevations (including fills, bridges, dikes, roads and railway embankments) land use or buildings from those included in the model may significantly affect the flood levels and render site-specific flood level information obsolete.

4. The model geometry was kept fixed although variations (channel erosion, degradation or aggradation) may occur during a flood event and/or over time. The maps do not provide information on site-specific hazards such as land erosion or sudden shifts in the water courses. Channel obstructions such as log-jams, local storm water inflows, groundwater or other land drainage can cause flood levels to exceed those indicated on the map. Lands adjacent to a floodplain may be subject to flooding from tributary streams that are not indicated on the maps.

5. The flood levels are based on water surface elevations simulated using a two-dimensional hydraulic model developed by NHC (2018) using RAS2D software and updated by NHC (2020). Model roughness values for Birkenhead and Green Rivers were initially assigned based on typical channel and overbank resistance values, then calibrated to a flood event in 2003, more recent high flow data being unavailable.

6. None of the existing dikes in the Lillooet Valley can currently contain a 200-year flood and will overtop at some flow less than the 200-year flood. Generally, dikes within the floodplain are considered part of the floodplain and are modelled and mapped as if the dikes are a non-erodible feature of the landscape. Some of these dikes may erode and breach, potentially resulting in flood level variations from those shown. For sites in the Lillooet River Floodplain with partial protection from existing dikes, the FCL should be either the FCL OR 1.0 m above surrounding natural grade; whichever is higher. As the Poleyard Dike, on the south side of the Birkenhead River, directly impacts Mount Currie and will overtop in a 100-year flood event, the dike was breached for the mapping. The breach was assumed to be 100 m wide, with 2:1 side slopes and located about 325 m from the upstream end of the dike.

7. The accuracy of simulated flood levels is limited by the reliability and extent of the water level data and flow magnitude used for calibrating the model. The accuracy of the location of the floodplain boundary is limited by the accuracy of the DEM, model boundary conditions and model parameters. Locally raised areas have not been mapped in the floodplain extents.

8. Floodplain maps are an administrative tool that indicates flood elevations and floodplain boundaries for a designated flood. A Qualified Professional must be consulted for site-specific engineering analysis.

9. Industry best practices were followed to generate the flood extent maps. However, actual flood levels and extents may vary from those shown and Northwest Hydraulic Consultants Ltd. (NHC) and Lil̓wat Nation do not assume any liability for such variations.

Flood Depth and Hazard Rating Map General Notes

1. These maps delineate potential flood depths and hazards under conditions caused by the 50-, 100- and 200-year return period events as described in NHC (2018 and 2020). The estimated flood flows for the Birkenhead and Green Rivers include a climate change flow increase allowance of 25% (end-of-century estimate) in combination with a present day 200-year event on the main stem of the Lillooet River. This flood scenario was selected in consultation with Lil'wat First Nation and is applicable to only Indigenous Lands in the area. The flood depths and hazard ratings are only shown for the floodplain of the Birkenhead River, Green River and lower reach of the Lillooet River where the Birkenhead and Green Rivers influence the Lillooet River flood event. For more information on the conditions that correspond to a 200-year event, please see NHC (2020). These maps are not the designated floodplain map.

2. Lidar data surveyed in 2016 was used to create a Digital Elevation Model (DEM) for the study area. The DEM surface was modified to include ground survey data for all dikes specified in NHC (2018) and to include surveyed channel bathymetry for the study reach (NHC, 2020). The maps depict flood levels based on ground conditions represented in this DEM. Any changes to ground and channel elevations (including fills, bridges, dikes, roads and railway embankments) land use or buildings from those included in the model may significantly affect the flood levels and render site-specific flood level information obsolete.

3. The model geometry was kept fixed although variations (erosion, degradation or aggradation) may occur during a flood event and/or over time. The maps do not provide information on site-specific hazards such as land erosion or sudden shifts in the water courses. Channel obstructions such as log-jams, local storm water inflows, groundwater or other land drainage can cause flood levels to exceed those indicated on the map. Lands adjacent to a floodplain may be subject to flooding from tributary streams that are not indicated on the maps.

4. The flood levels are based on water surface elevations simulated using a two-dimensional hydraulic model developed by NHC (2018) using RAS2D software and updated by NHC (2020). Model roughness values for Birkenhead and Green rivers were initially assigned based on typical channel and overbank resistance values, then calibrated to a flood event in 2003, more recent high flow data being unavailable.

5. None of the existing dikes in the Lillooet Valley can currently contain a 200-year flood and will overtop at some flow less than the 200-year flood. Generally, dikes within the floodplain are considered part of the floodplain and are modelled and mapped as if the dikes are a non-erodible feature of the landscape. Some of these dikes may erode and breach, potentially resulting in flood level variations from those shown. As the Poleyard Dike, on the south side of the Birkenhead River, directly impacts Mount Currie and will overtop in a 100-year flood event, the dike was breached for the 100- and 200-year flood mapping. The breach was assumed to be 100 m wide, with 2:1 side slopes and located about 325 m from the upstream end of the dike.

6. The accuracy of simulated flood levels is limited by the reliability and extent of the water level data and flow magnitude used for calibrating the model. The accuracy of the location of the floodplain boundary is limited by the accuracy of the DEM, model boundary conditions and model parameters. Locally raised areas have not been mapped in the floodplain hazard extents.

7. A Qualified Professional must be consulted for site-specific engineering analysis. Industry best practices were followed to generate the flood depth and hazard maps. However, actual flood levels and extents may vary from those shown and Northwest Hydraulic Consultants Ltd. (NHC) and Lil̓wat Nation do not assume any liability for such variations.

Data Sources and References:

1. Flood level is based on hydraulic modelling conducted by NHC. The model is based on a 2016 Lidar DEM provided by Emergency Management BC (EMBC), surveys conducted by NHC in 2017, 2019, and additional surveys as described in NHC (2018, 2020). The extents of flooding are based on the Lidar DEM. A freeboard allowance is not included in the depth and hazard maps.

2. Cadastral parcel boundaries supplied by Squamish Lillooet Regional District.

3. Municipal boundary downloaded from DataBC.

4. Orthophoto imagery acquired by EMBC in 2016.

5. Additional base mapping and orthoimagery from Esri.

Reference:

NHC (2018). Lillooet River Floodplain Mapping Final Report (NHC PN3002903). Report prepared by Northwest Hydraulic Consultants for Pemberton Valley Dyking District. [online] Available from: https://www.pvdd.ca/assets/pdf/resources/LillooetRiverFloodMapping_FinalReport.pdf.

NHC (2020). Birkenhead and Green River Floodplain Mapping and Risk Assessment. Report. Draft Report Prepared by Northwest Hydraulic Consultants for the Lil̓wat Nation, North Vancouver, BC.

Disclaimer

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Legend

Map Panel Layout (1:10,000)

Scale:1 cm = 600 m

0 500 1,000 2,000 Meters

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES Vertical Datum: CGVD(2013)

Engineer	GIS	Reviewer
VCCB	MAO	MCM

Job Number	Date
3004698	02-SEPT-2020

BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

200-YEAR + CC DESIGNATED FLOODPLAIN MAP INDEX

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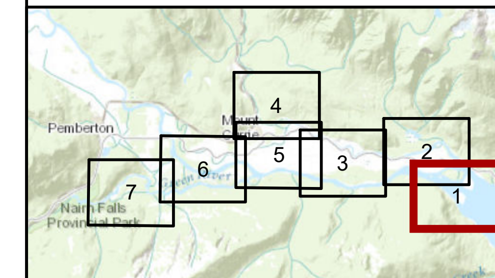

Legend

- Breach Location
- Flow Direction
- Dike
- Major Road
- Local Road
- Railway
- FCL including 0.6m Freeboard
- Pemberton Valley Dyking District
- Nation Land
- Flood Extents
- Flood Extents with 0.6m Freeboard

Note: Nation Land boundaries provided by Lil'wat Nation

Scale - 1:10,000

0 100 200 400 Meters

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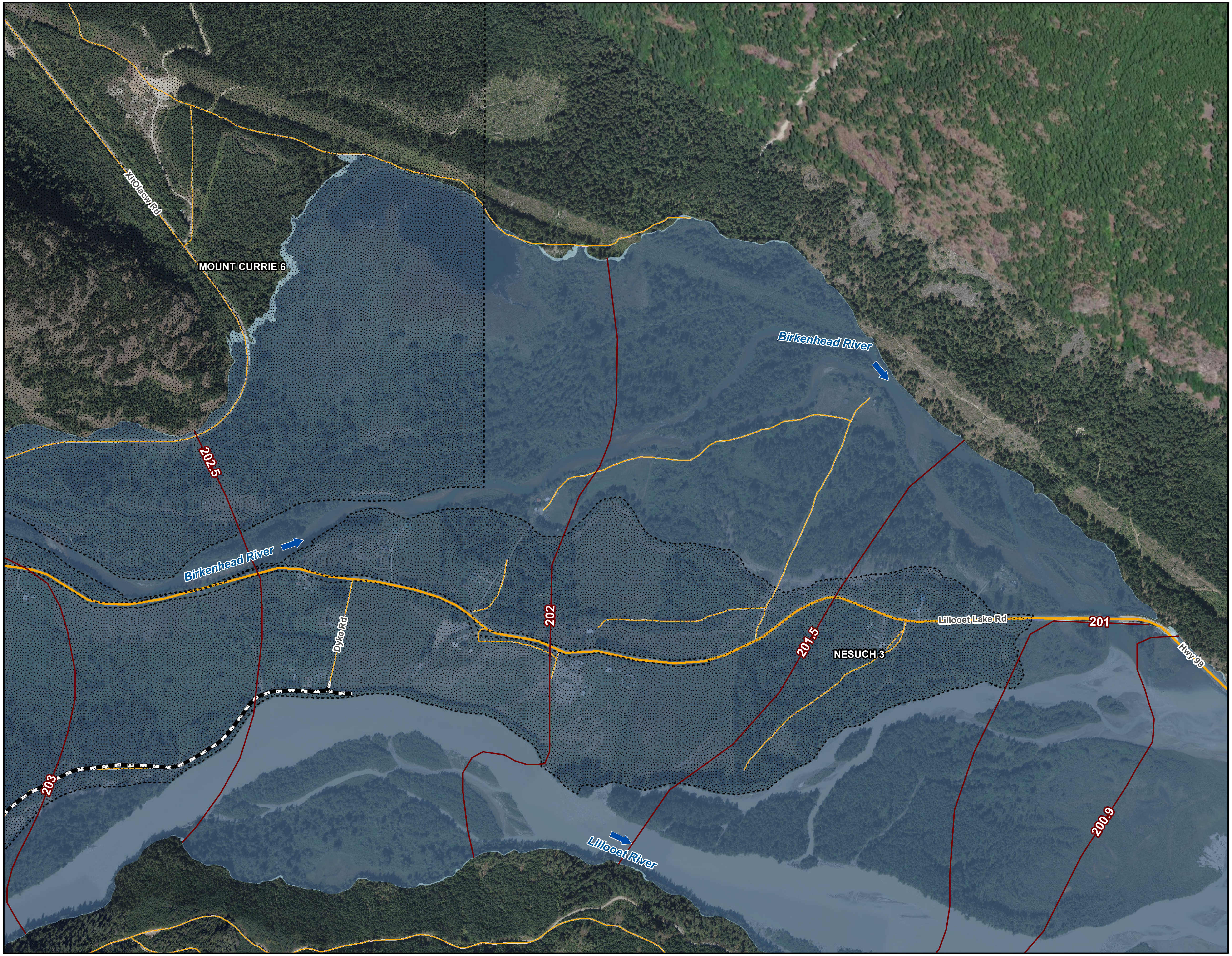
Engineer	GIS	Reviewer
VCCB	MAO	MCM

Job Number	Date
3004698	22-SEPT-2020

BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

200-YR FLOODPLAIN MAPS INCLUDING FREEBOARD, BIRKENHEAD/GREEN CLIMATE CHANGE (TO YEAR 2100)

SHEET 1 OF 7



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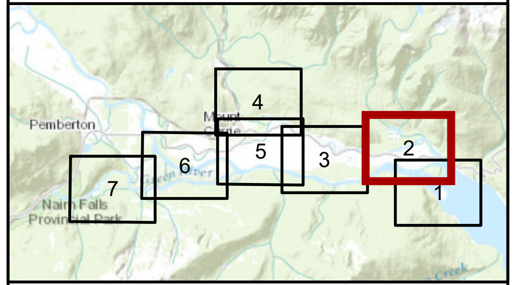

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Engineer	GIS	Reviewer
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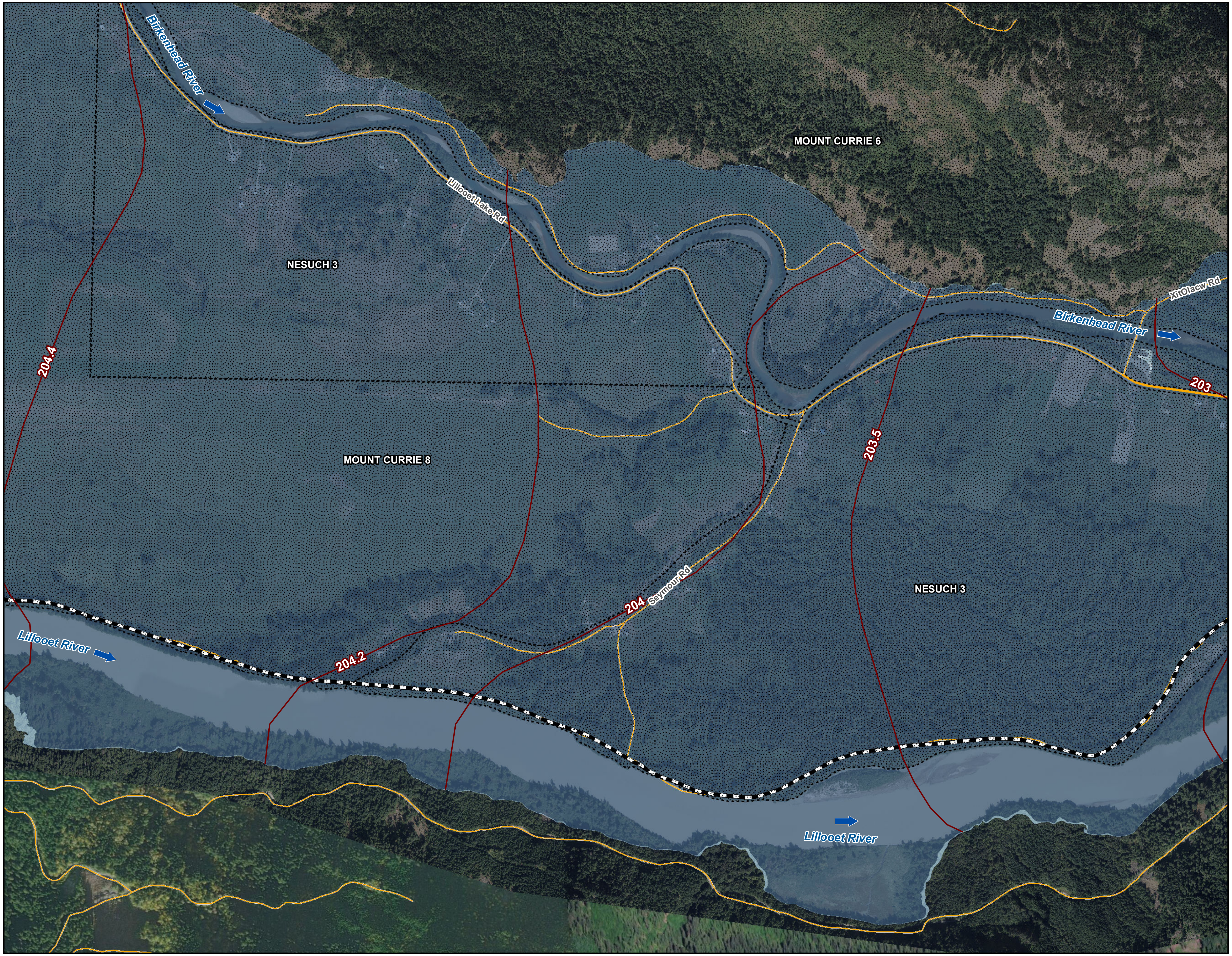
Job Number	Date
3004698	22-SEPT-2020

BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

200-YR FLOODPLAIN MAPS INCLUDING FREEBOARD, BIRKENHEAD/GREEN CLIMATE CHANGE (TO YEAR 2100)

SHEET 2 OF 7



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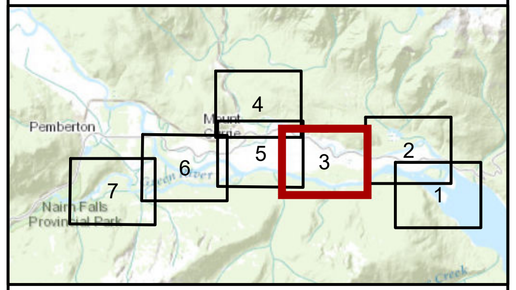

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Units: METRES *Vertical Datum: CGVD(2013)*

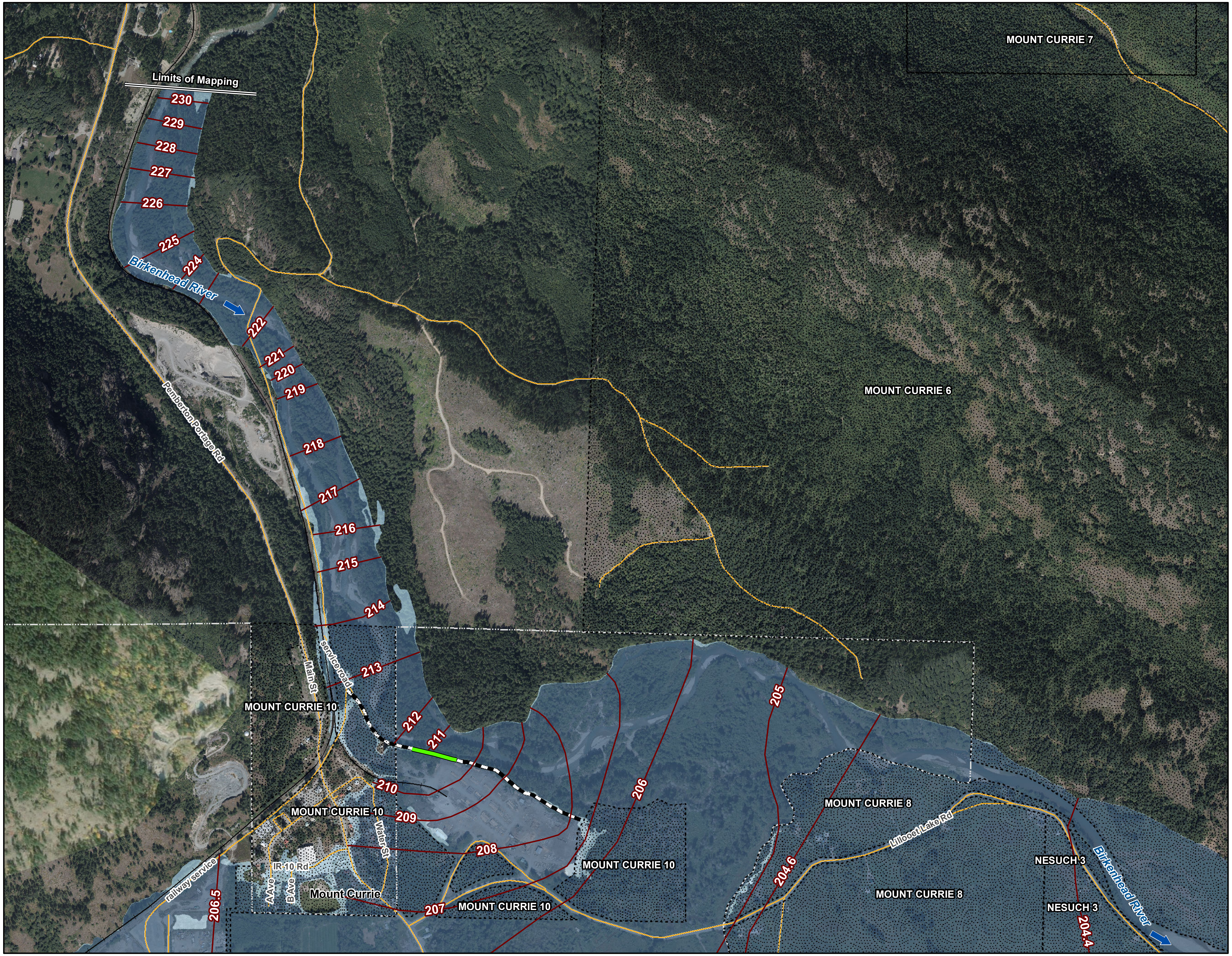
Engineer	GIS	Reviewer
VCCB	MAO	MCM

Job Number	Date
3004698	22-SEPT-2020

BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

200-YR FLOODPLAIN MAPS INCLUDING FREEBOARD, BIRKENHEAD/GREEN CLIMATE CHANGE (TO YEAR 2100)

SHEET 3 OF 7



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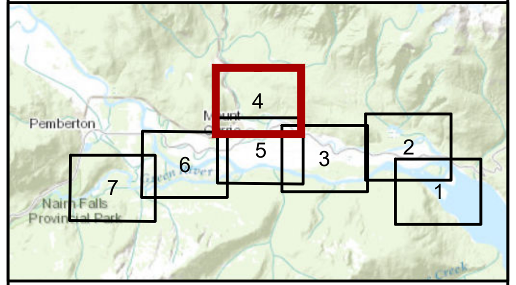

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Units: METRES Vertical Datum: CGVD(2013)

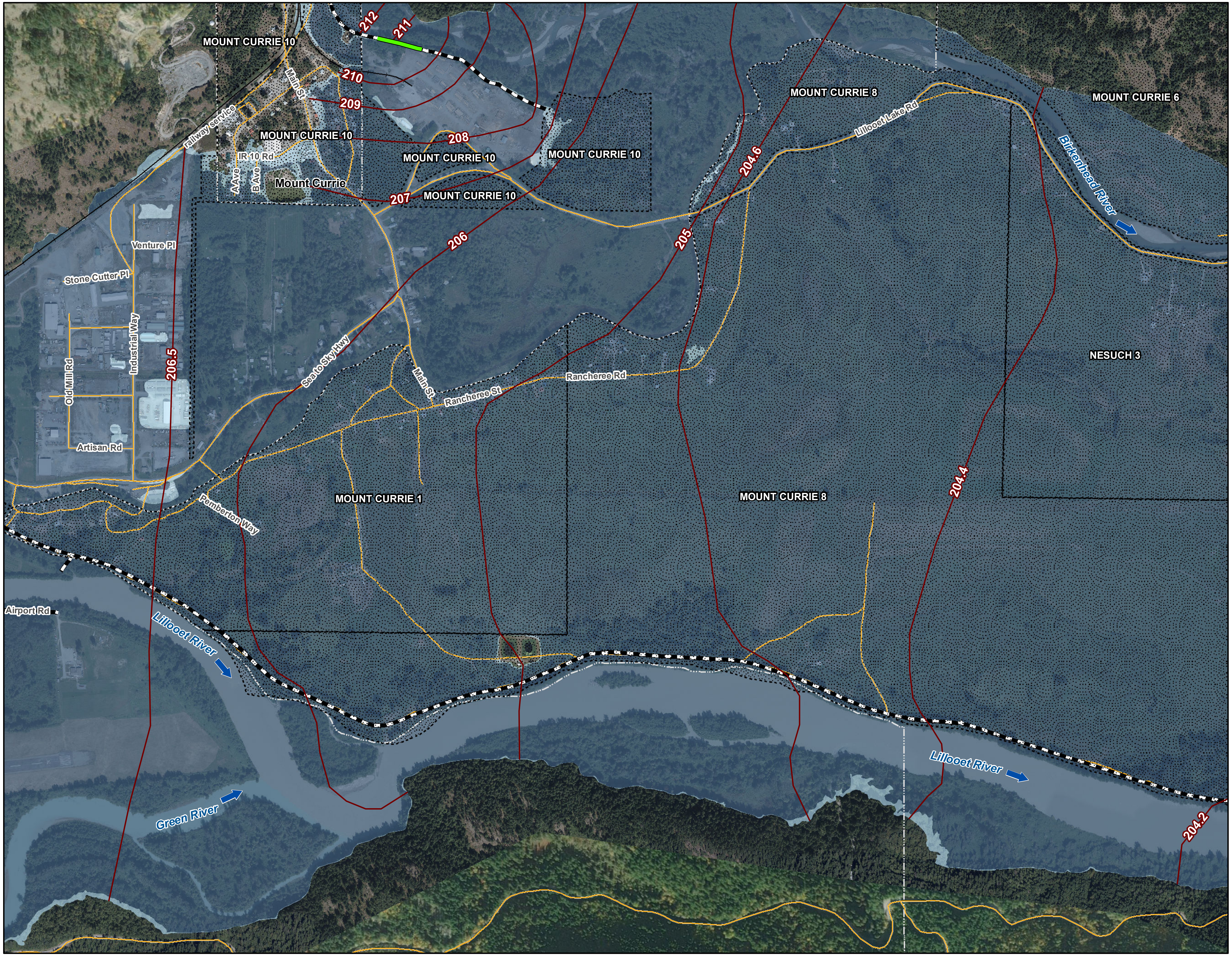
Engineer	*GIS*	*Reviewer*
VCCB	*MAO*	*MCM*

Job Number	*Date*
3004698	*22-SEPT-2020*

BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

200-YR FLOODPLAIN MAPS INCLUDING FREEBOARD, BIRKENHEAD/GREEN CLIMATE CHANGE (TO YEAR 2100)

SHEET 4 OF 7



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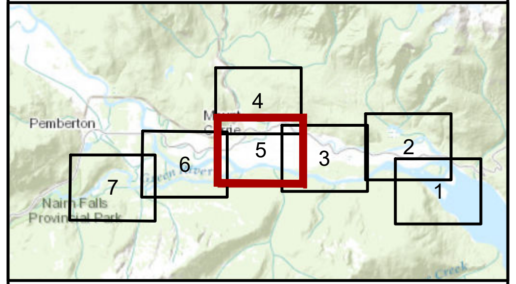

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0 100 200 400 Meters

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Units: METRES Vertical Datum: CGVD(2013)

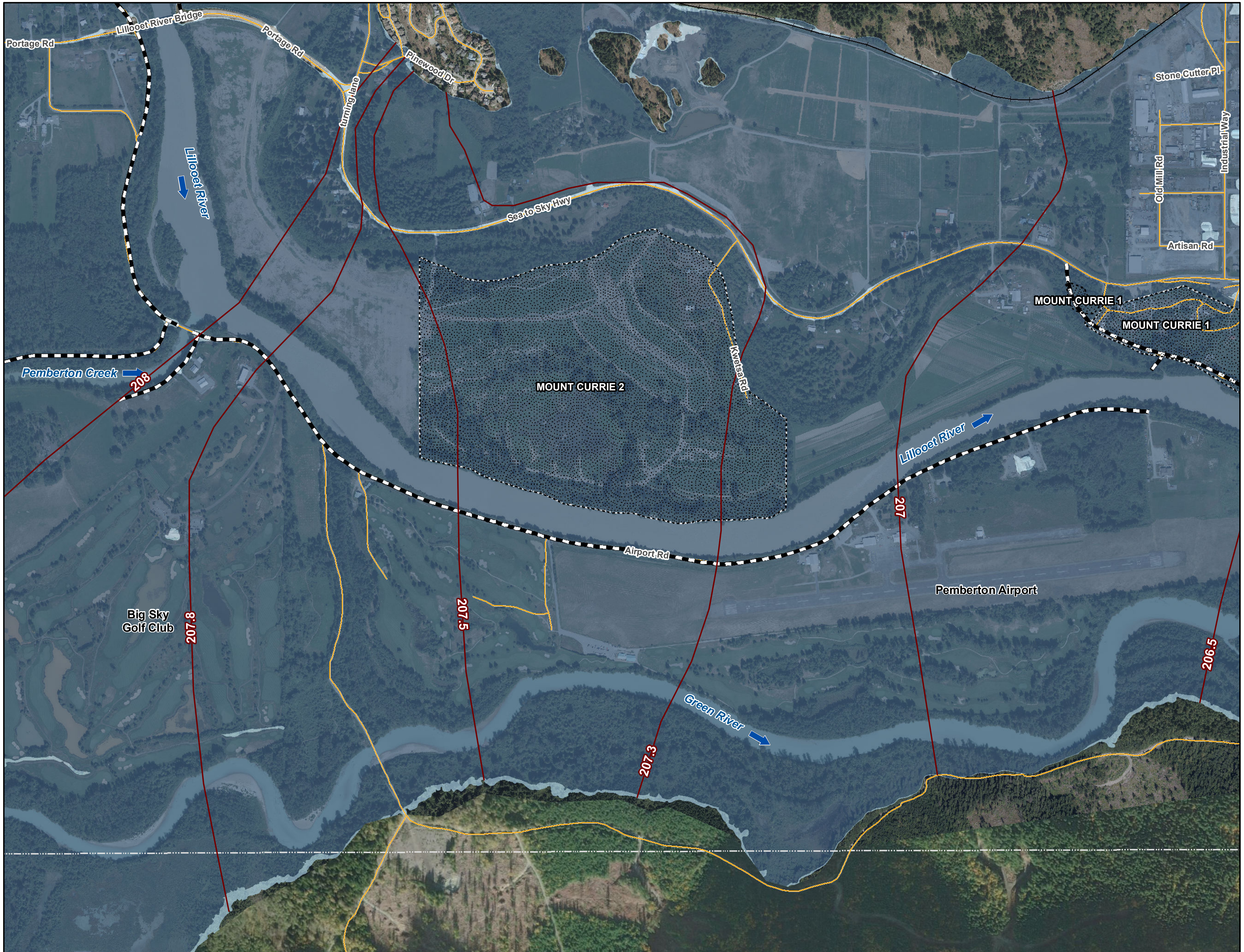
Engineer	GIS	Reviewer
VCCB	MAO	MCM

Job Number	Date
3004698	22-SEPT-2020

BIRKENHEAD AND GREEN RIVER
FLOODPLAIN MAPPING

200-YR FLOODPLAIN MAPS INCLUDING FREEBOARD, BIRKENHEAD/GREEN CLIMATE CHANGE (TO YEAR 2100)

SHEET 5 OF 7



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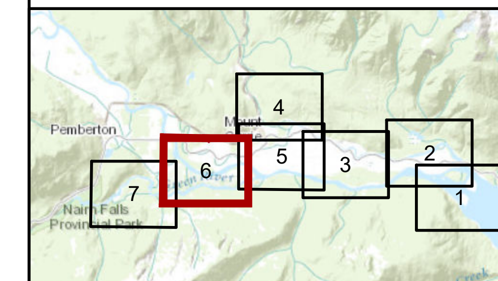

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Note: Nation Land boundaries provided by Lil'wat Nation

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0 100 200 400 Meters

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Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES Vertical Datum: CGVD(2013)

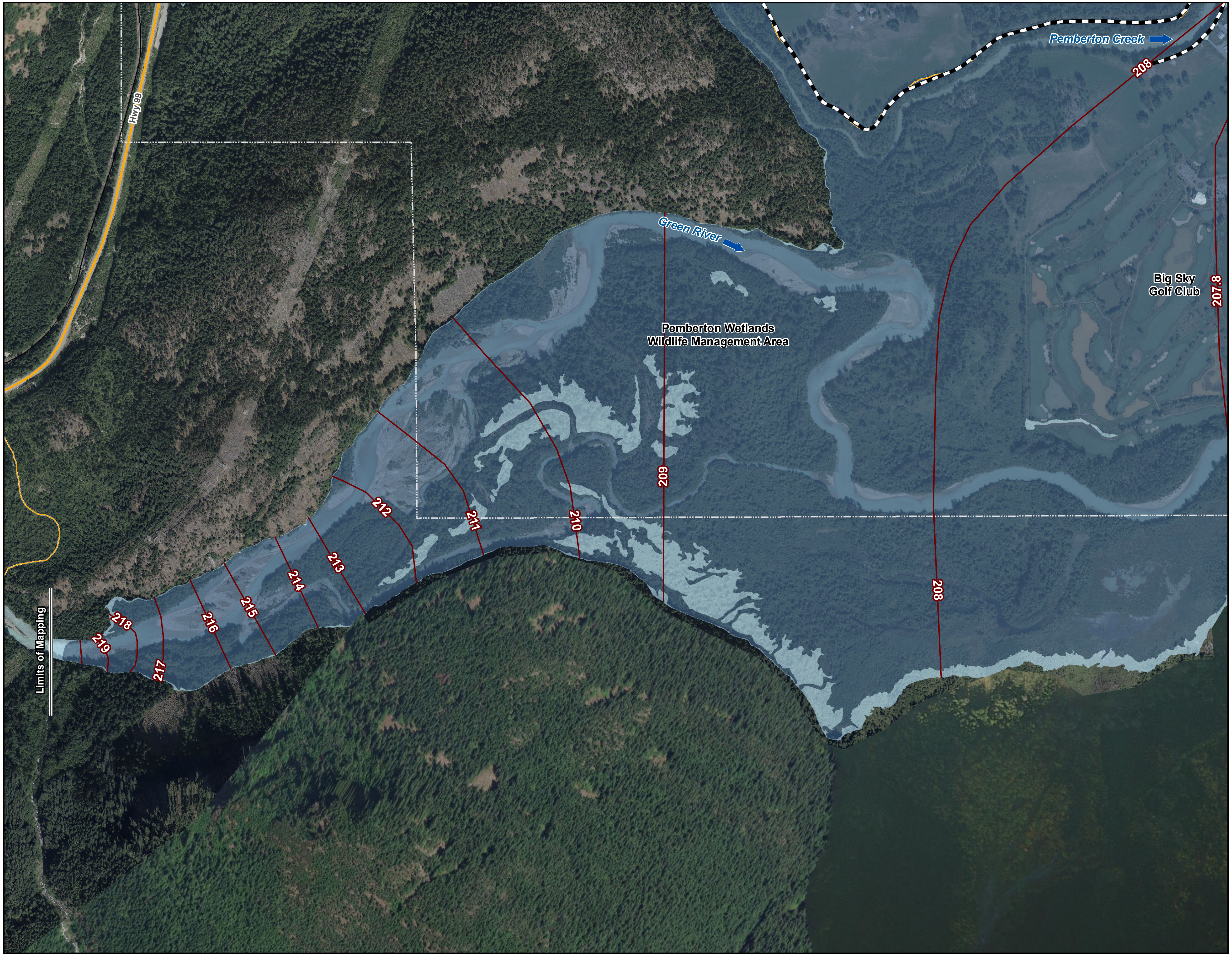
Engineer	GIS	Reviewer
VCCB	MAO	MCM

Job Number	Date
3004698	22-SEPT-2020

BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

200-YR FLOODPLAIN MAPS INCLUDING FREEBOARD, BIRKENHEAD/GREEN CLIMATE CHANGE (TO YEAR 2100)

SHEET 6 OF 7



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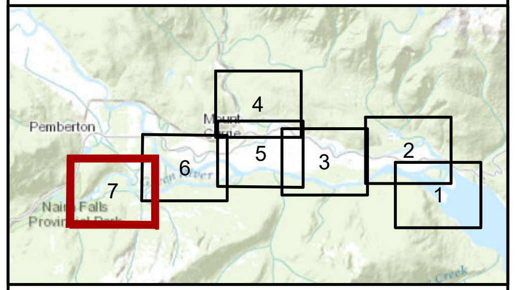

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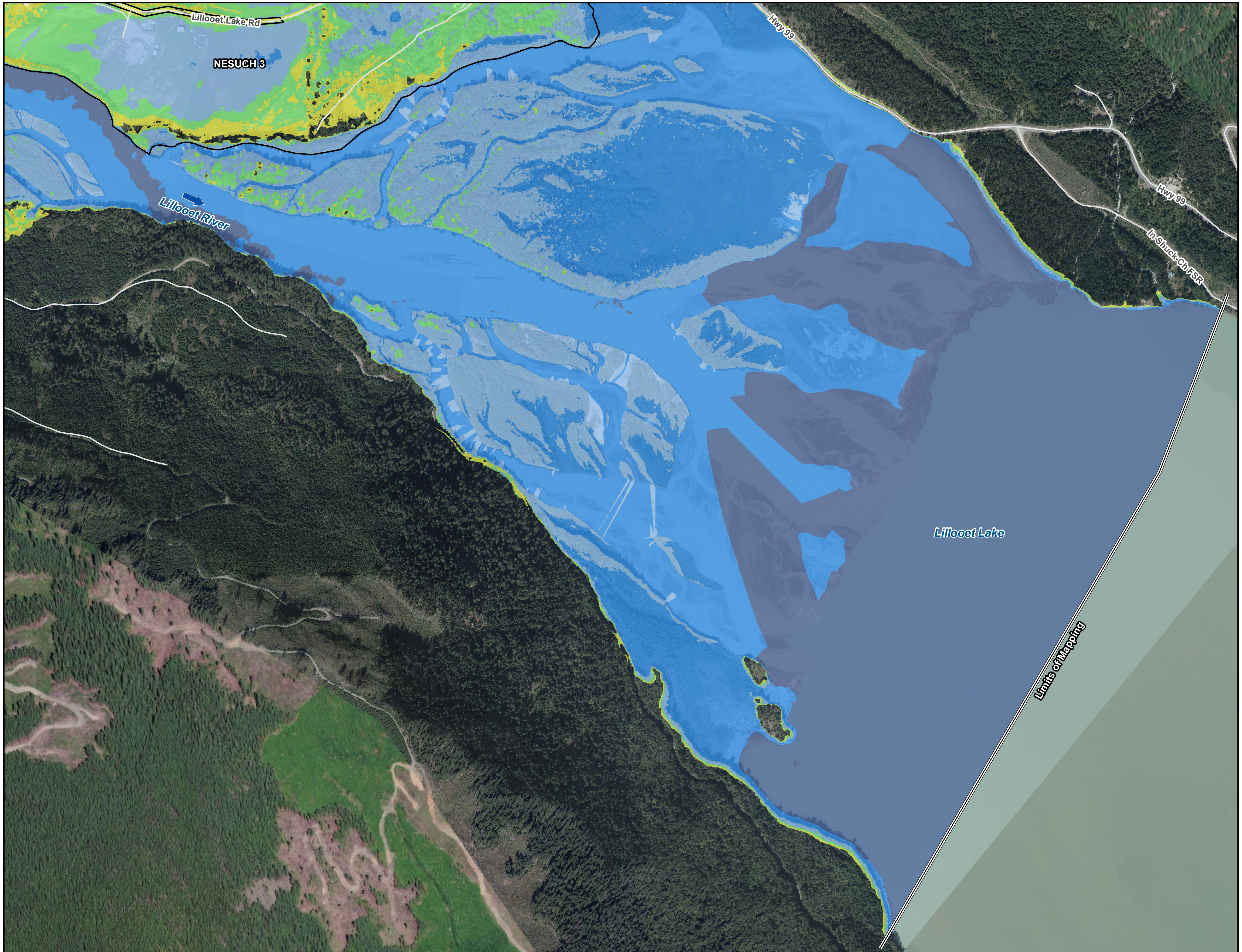
Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES Vertical Datum: CGVD(2013)

Engineer VCCB	*GIS* MAO	*Reviewer* MCM
Job Number 3004698	*Date* 22-SEPT-2020	

BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

200-YR FLOODPLAIN MAPS INCLUDING FREEBOARD, BIRKENHEAD/GREEN CLIMATE CHANGE (TO YEAR 2100)

SHEET 7 OF 7



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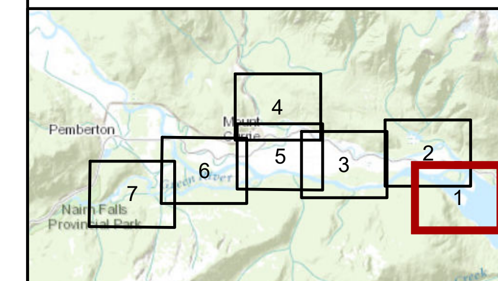

Legend

- Flow Direction
- Dike
- Pemberton Valley Dyking District
- Nation Land (provided by Lil'Wat Nation)

Depth (m)

- 0 to 0.5
- 0.5 to 1.0
- 1.0 to 2.0
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- > 5.0; River

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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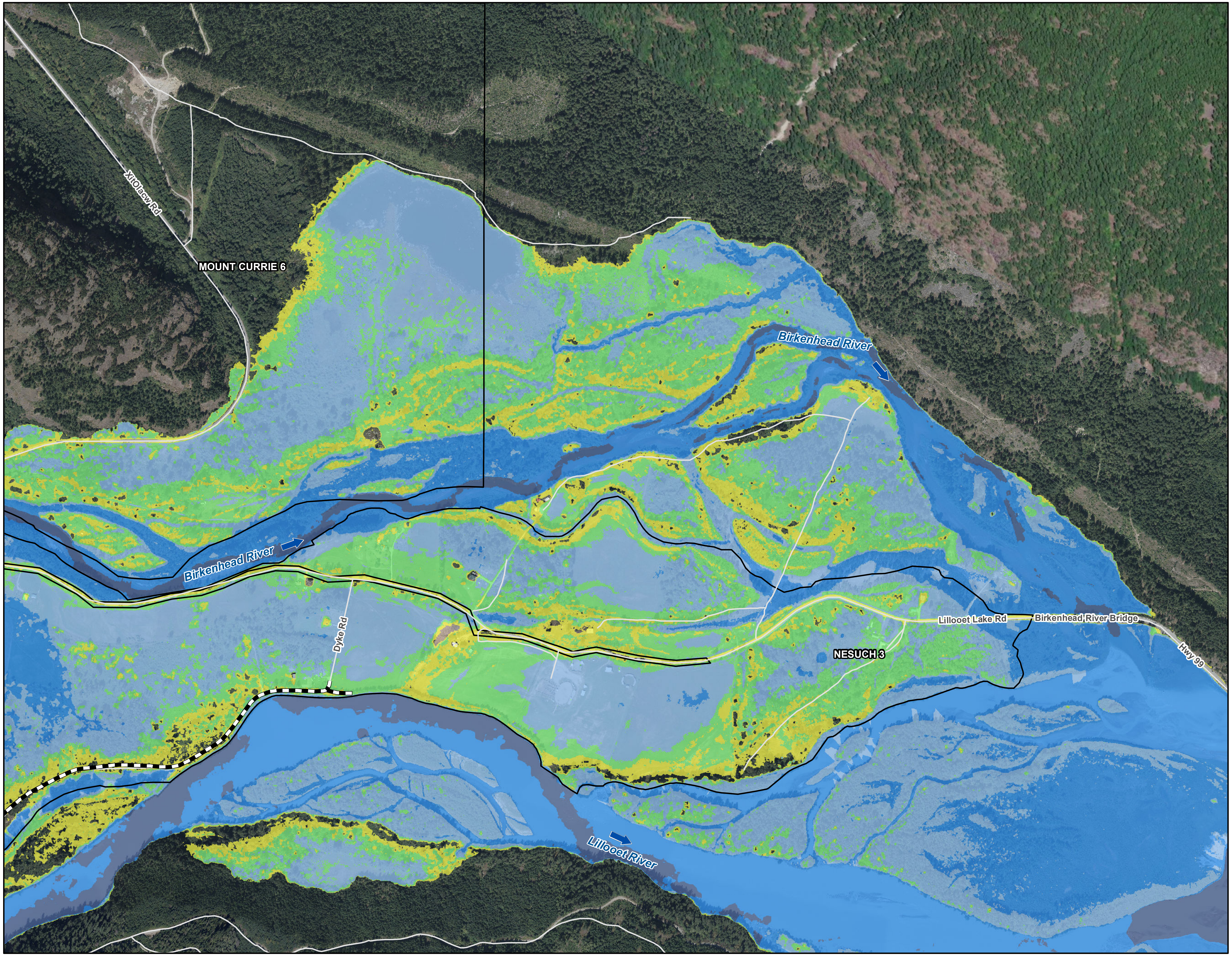
Engineer	GIS	Reviewer
VCCB	MAO	MCM

Job Number	Date
3004698	22-SEPT-2020

BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

FLOOD DEPTH 50-YR EVENT FOR BIRKENHEAD, GREEN & LILLOOET, INCLUDING CLIMATE CHANGE ON BIRKENHEAD & GREEN

SHEET 1 OF 7



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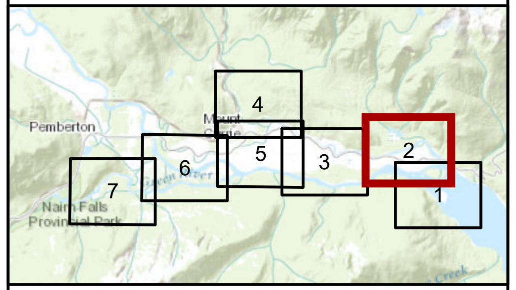

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Units: METRES Vertical Datum: CGVD(2013)

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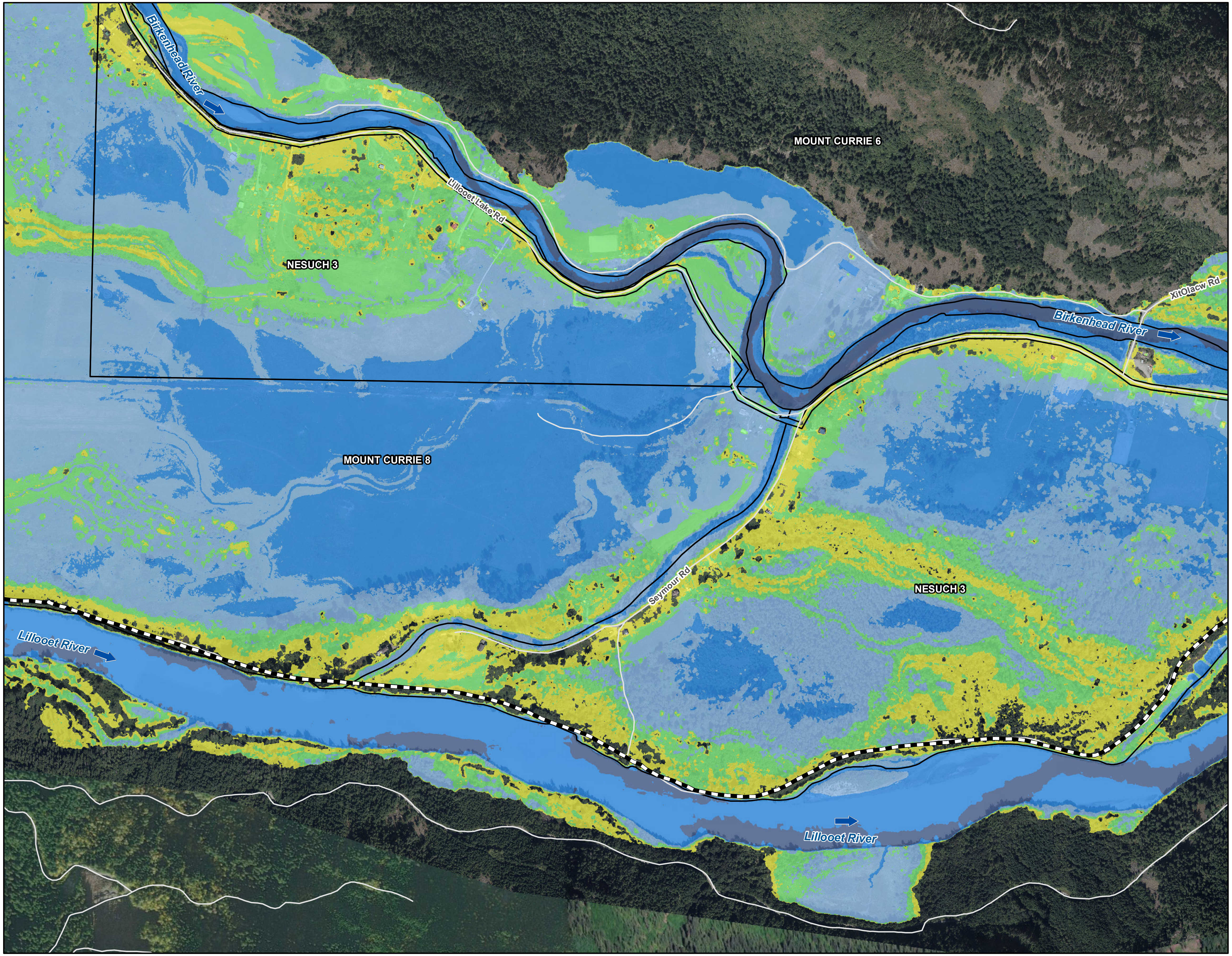
Job Number	Date
3004698	22-SEPT-2020

BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

FLOOD DEPTH 50-YR EVENT FOR BIRKENHEAD, GREEN & LILLOOET, INCLUDING CLIMATE CHANGE ON BIRKENHEAD & GREEN

SHEET 2 OF 7



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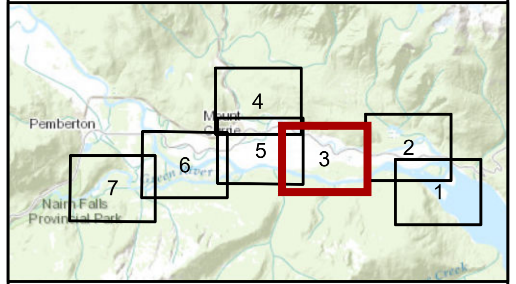

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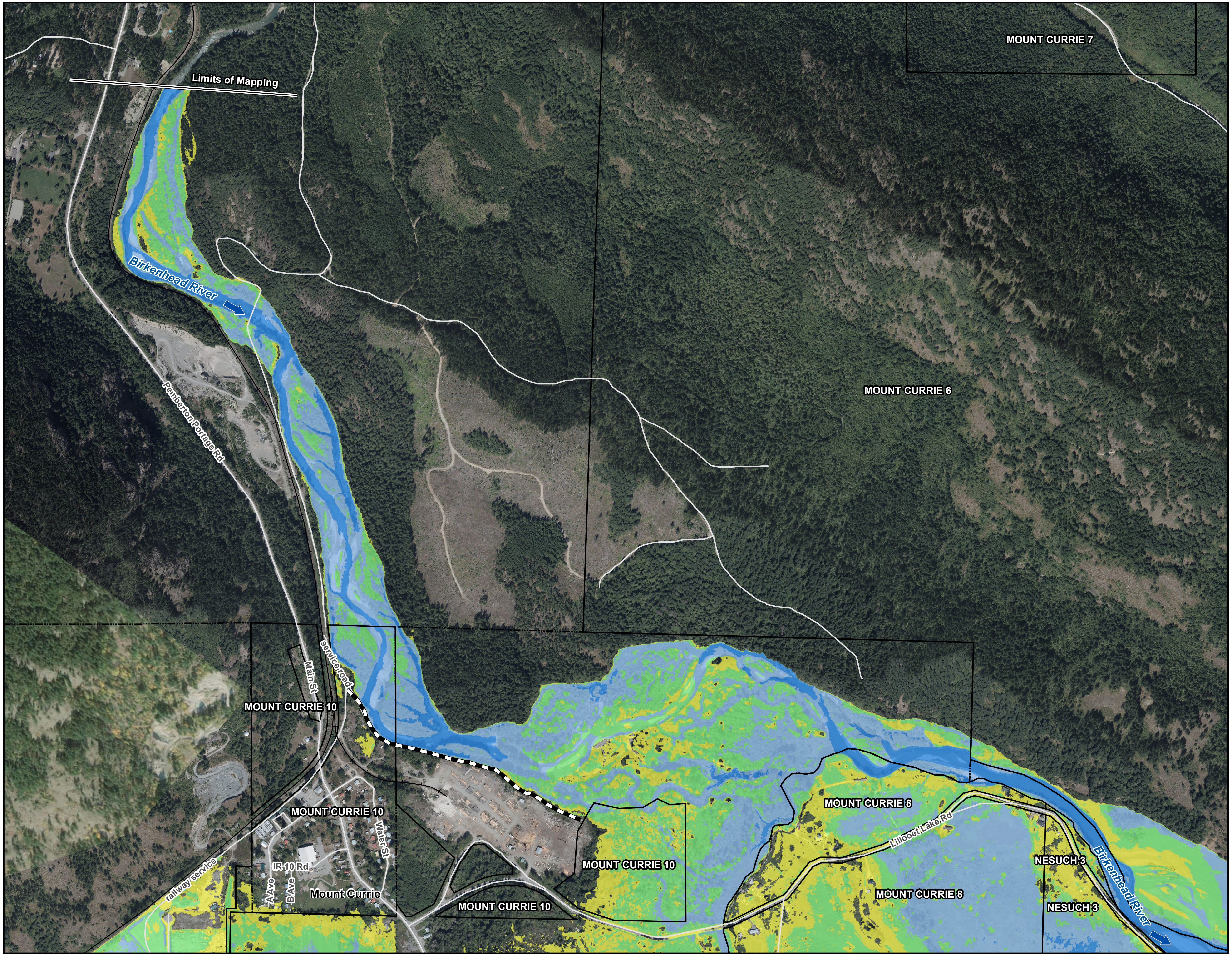
Engineer	GIS	Reviewer
VCCB	*MAO*	*MCM*

Job Number	Date
3004698	*22-SEPT-2020*

BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

FLOOD DEPTH 50-YR EVENT FOR BIRKENHEAD, GREEN & LILLOOET, INCLUDING CLIMATE CHANGE ON BIRKENHEAD & GREEN

SHEET 3 OF 7



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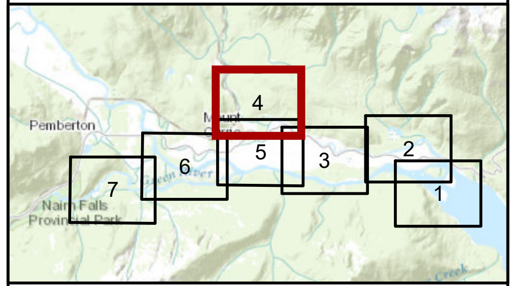

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BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

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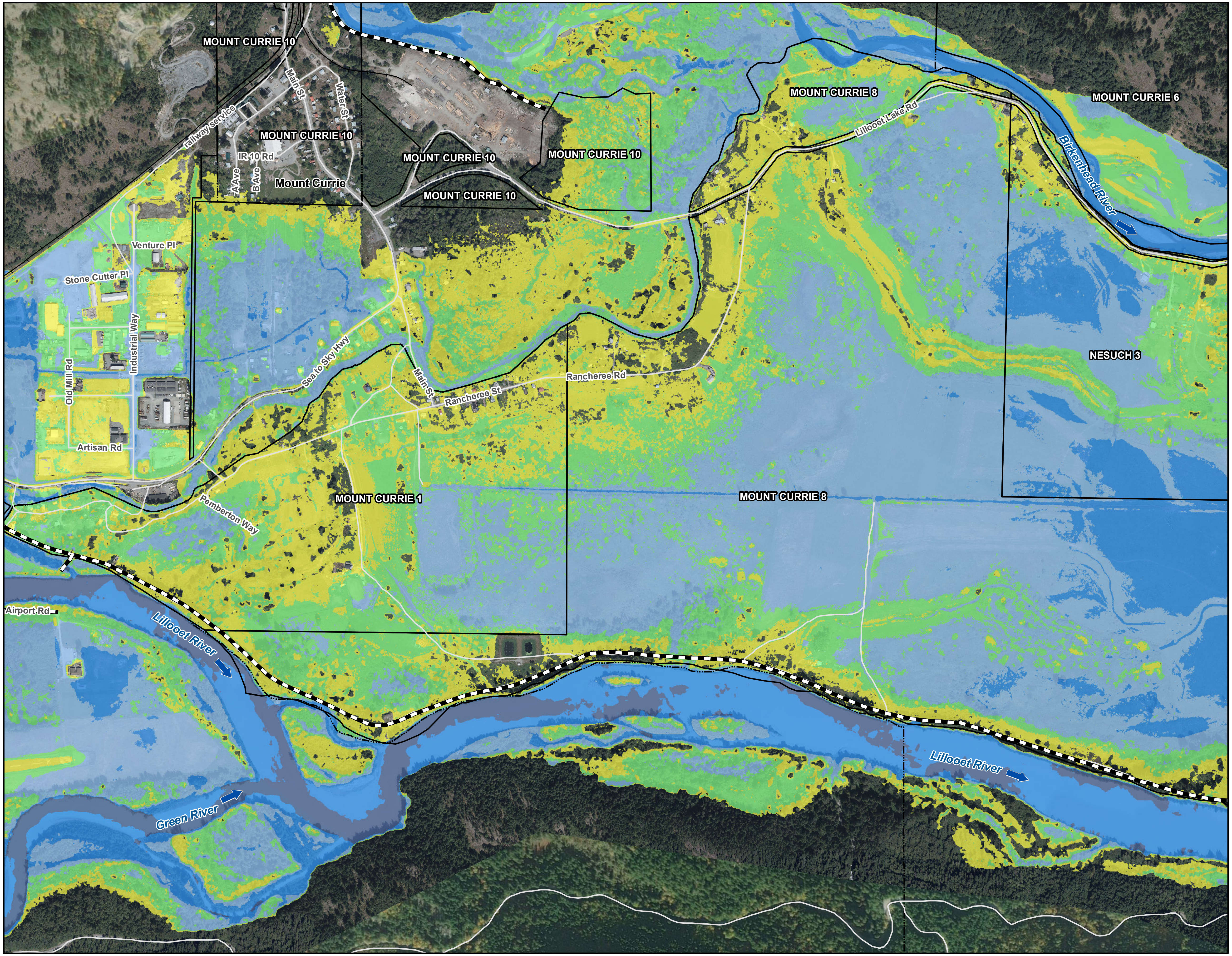

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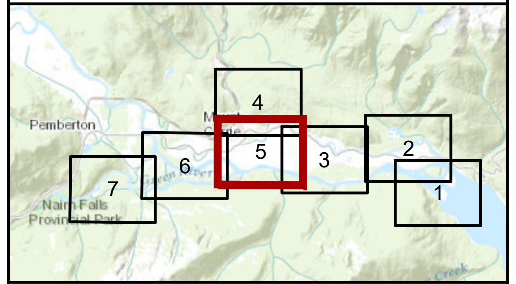

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BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

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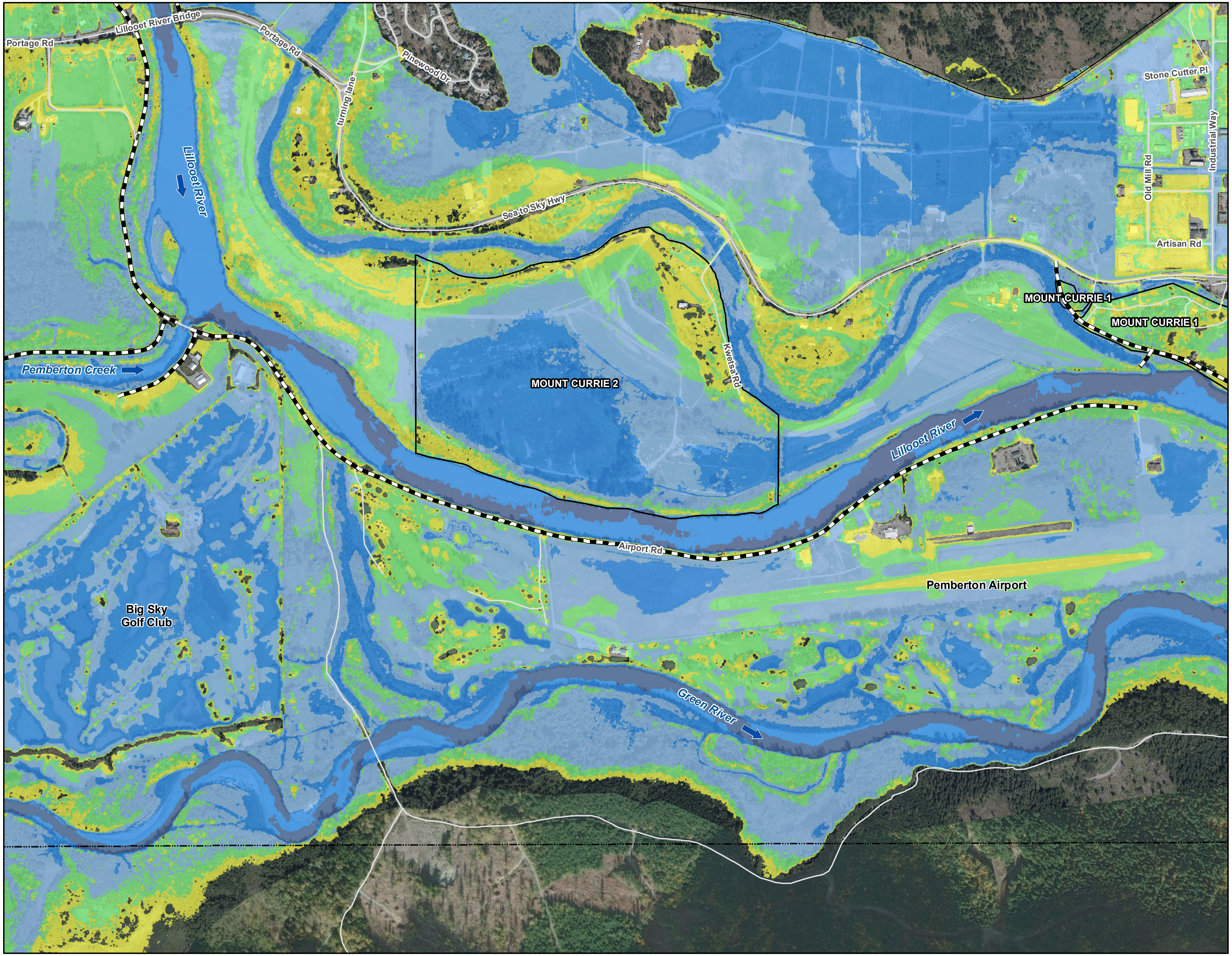

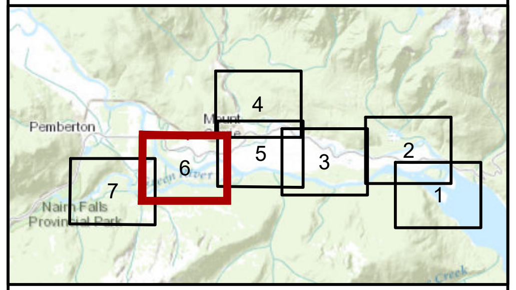

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BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

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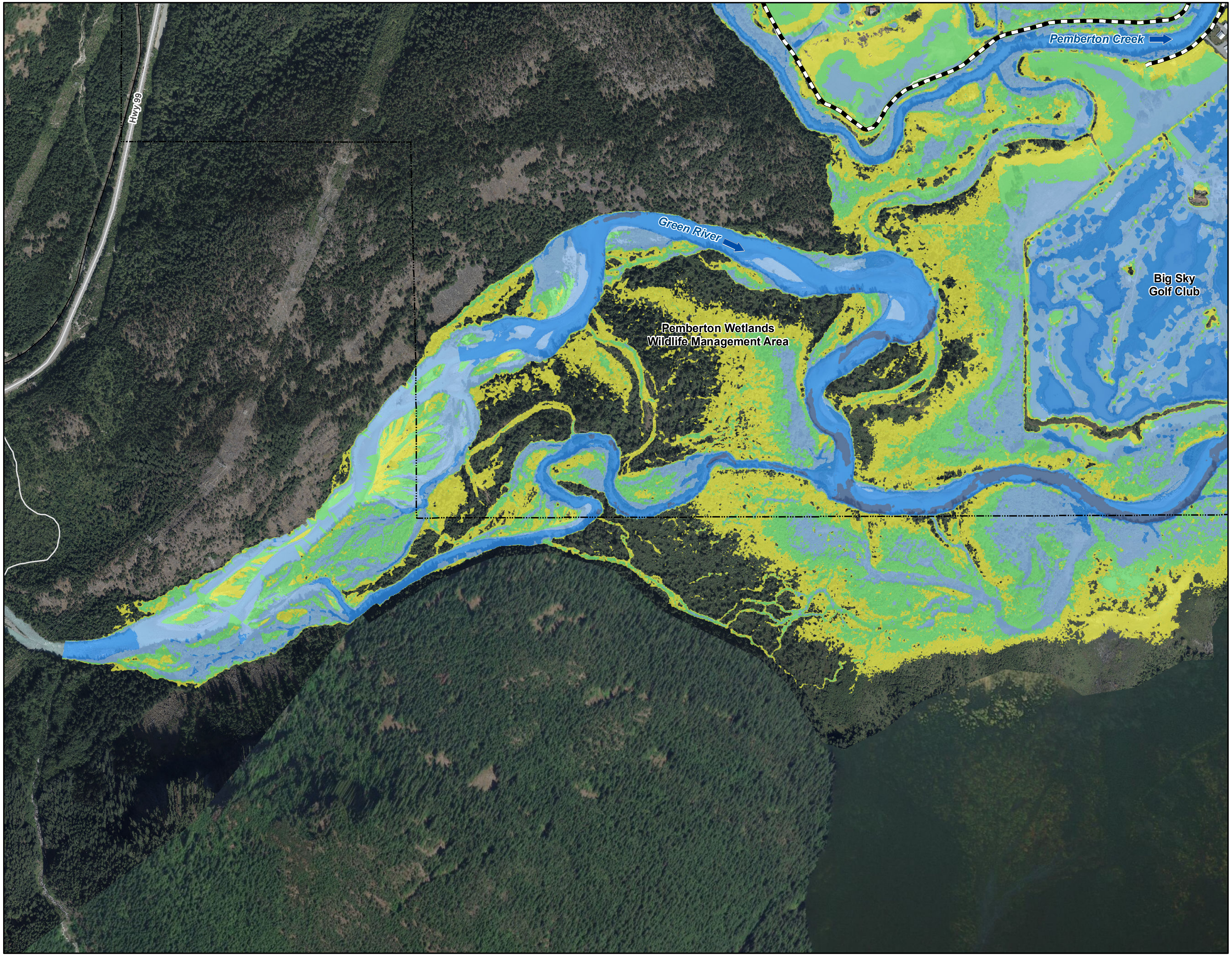
SHEET 6 OF 7



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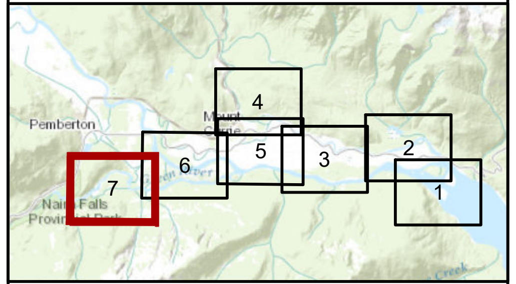

Legend

- Flow Direction
- Dike
- Pemberton Valley Dyking District
- Nation Land (provided by Lil'Wat Nation)

Depth (m)

- 0 to 0.5
- 0.5 to 1.0
- 1.0 to 2.0
- 2.0 to 5.0
- > 5.0; River

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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Scale - 1:10,000

0 100 200 400 Meters

N

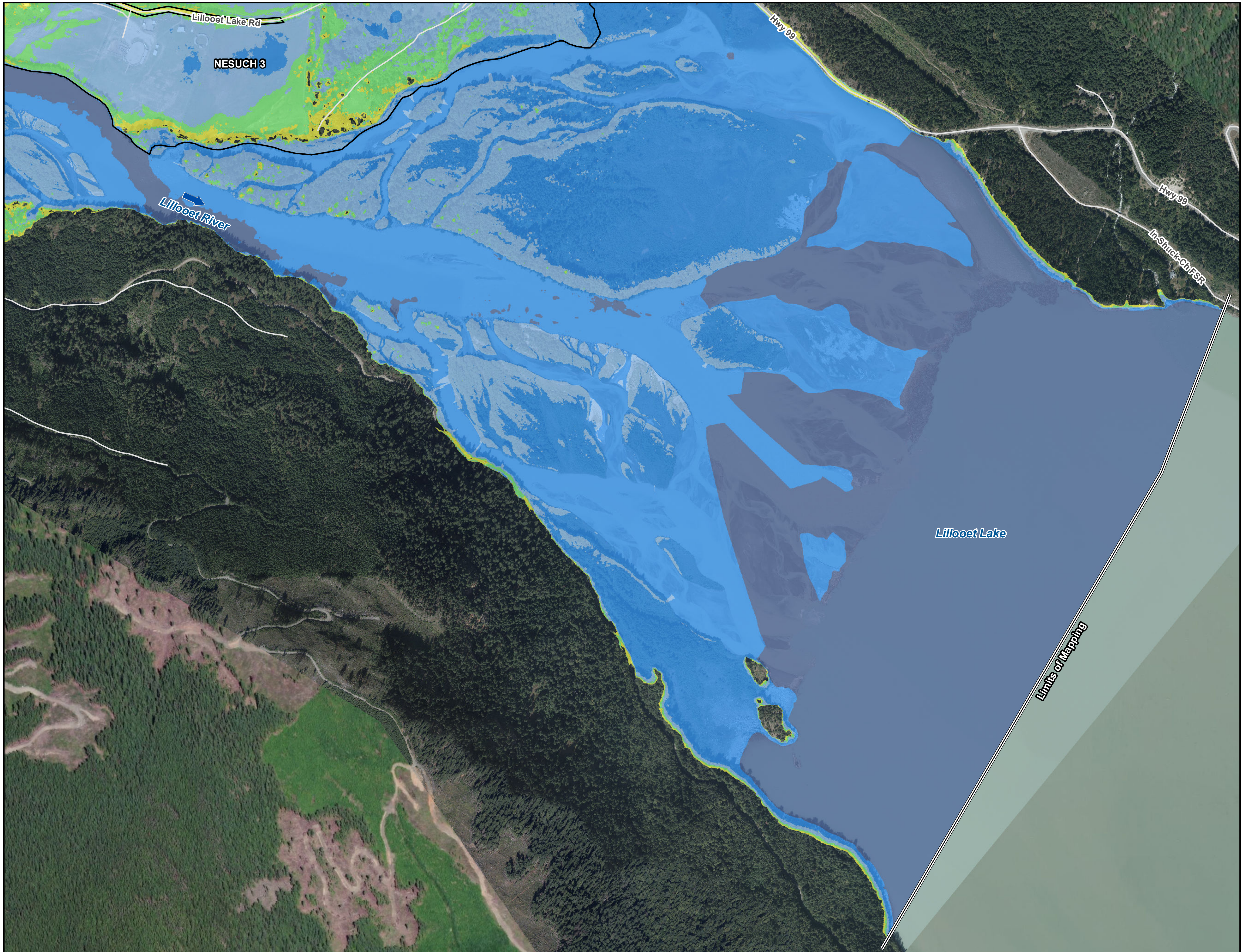
Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES Vertical Datum: CGVD(2013)

Engineer	GIS	Reviewer
VCCB	MAO	MCM

Job Number	Date
3004698	22-SEPT-2020

BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

FLOOD DEPTH 50-YR EVENT FOR BIRKENHEAD, GREEN & LILLOOET, INCLUDING CLIMATE CHANGE ON BIRKENHEAD & GREEN



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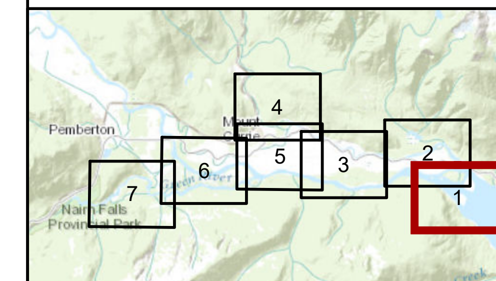

Legend

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- Flow Direction
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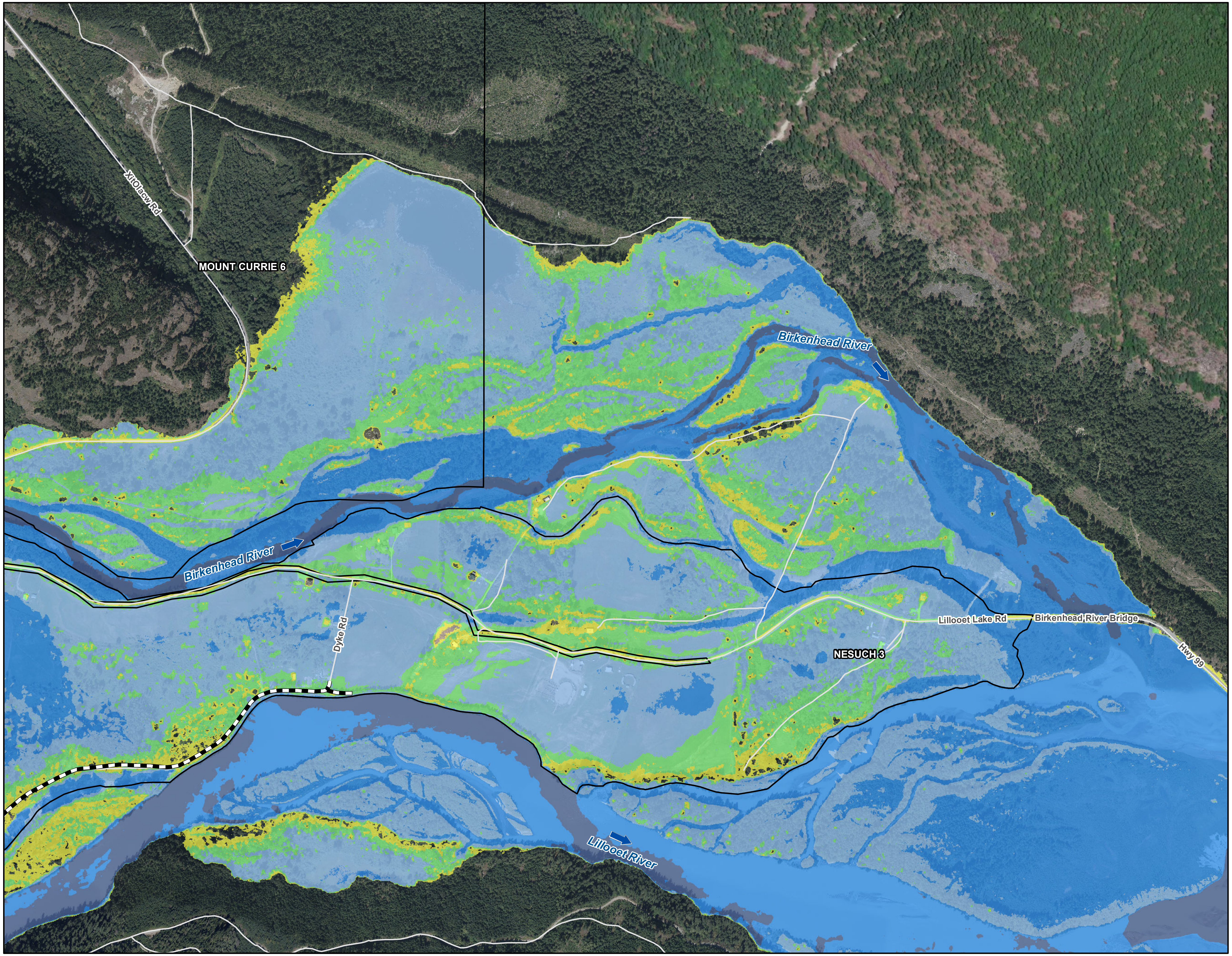
BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

FLOOD DEPTH 100-YR BREACH EVENT FOR BIRKENHEAD, GREEN & LILLOOET, INCLUDING CLIMATE CHANGE ON BIRKENHEAD & GREEN

SHEET 1 OF 7



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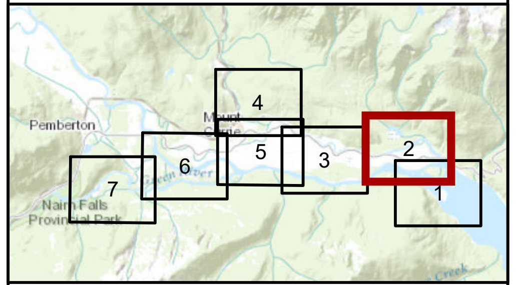

Legend

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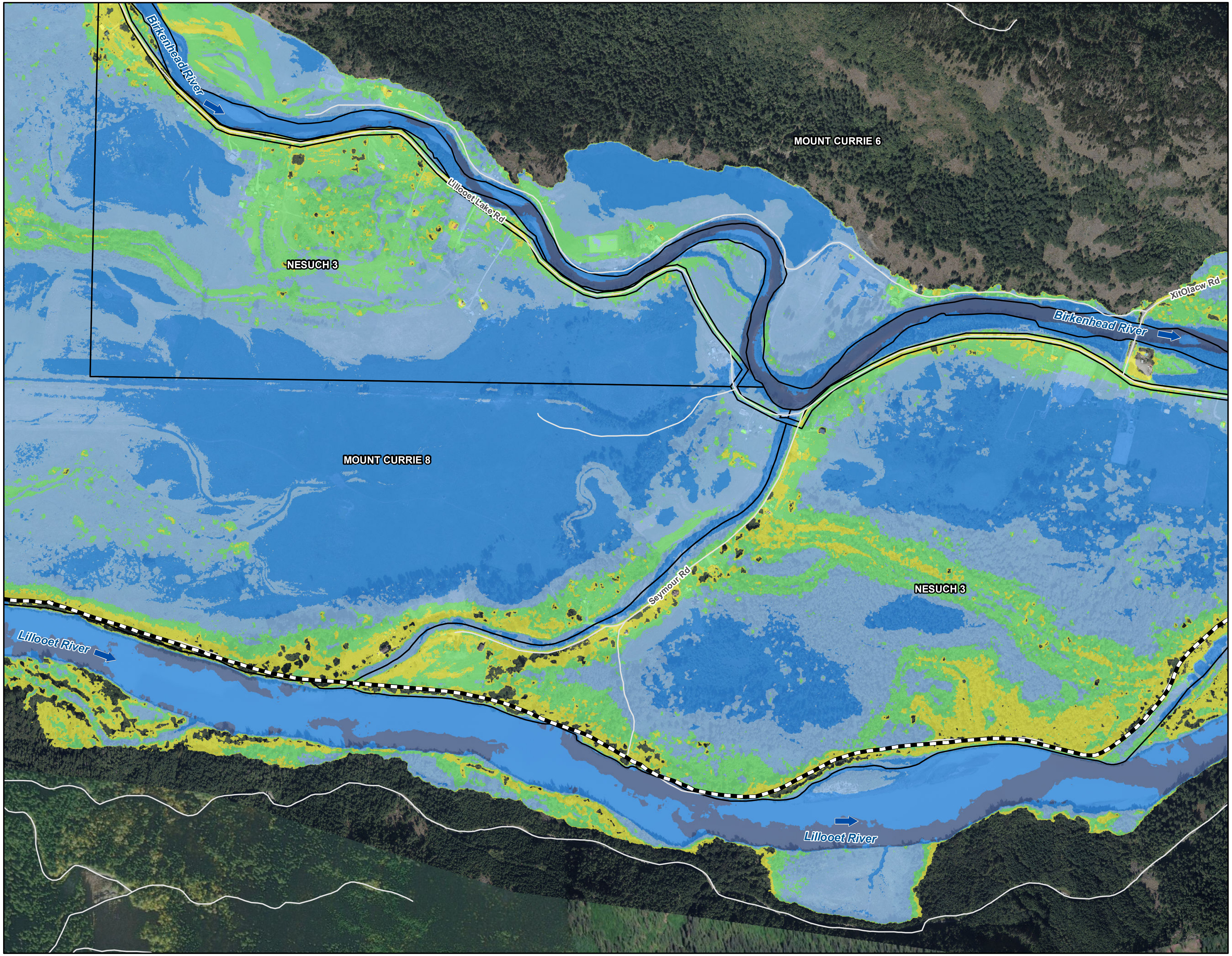

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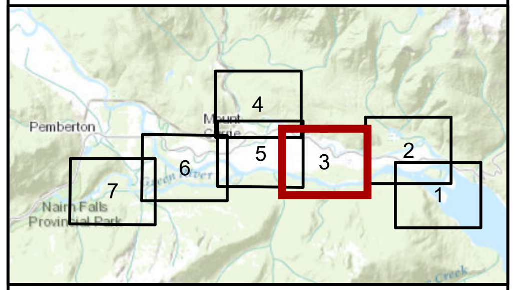

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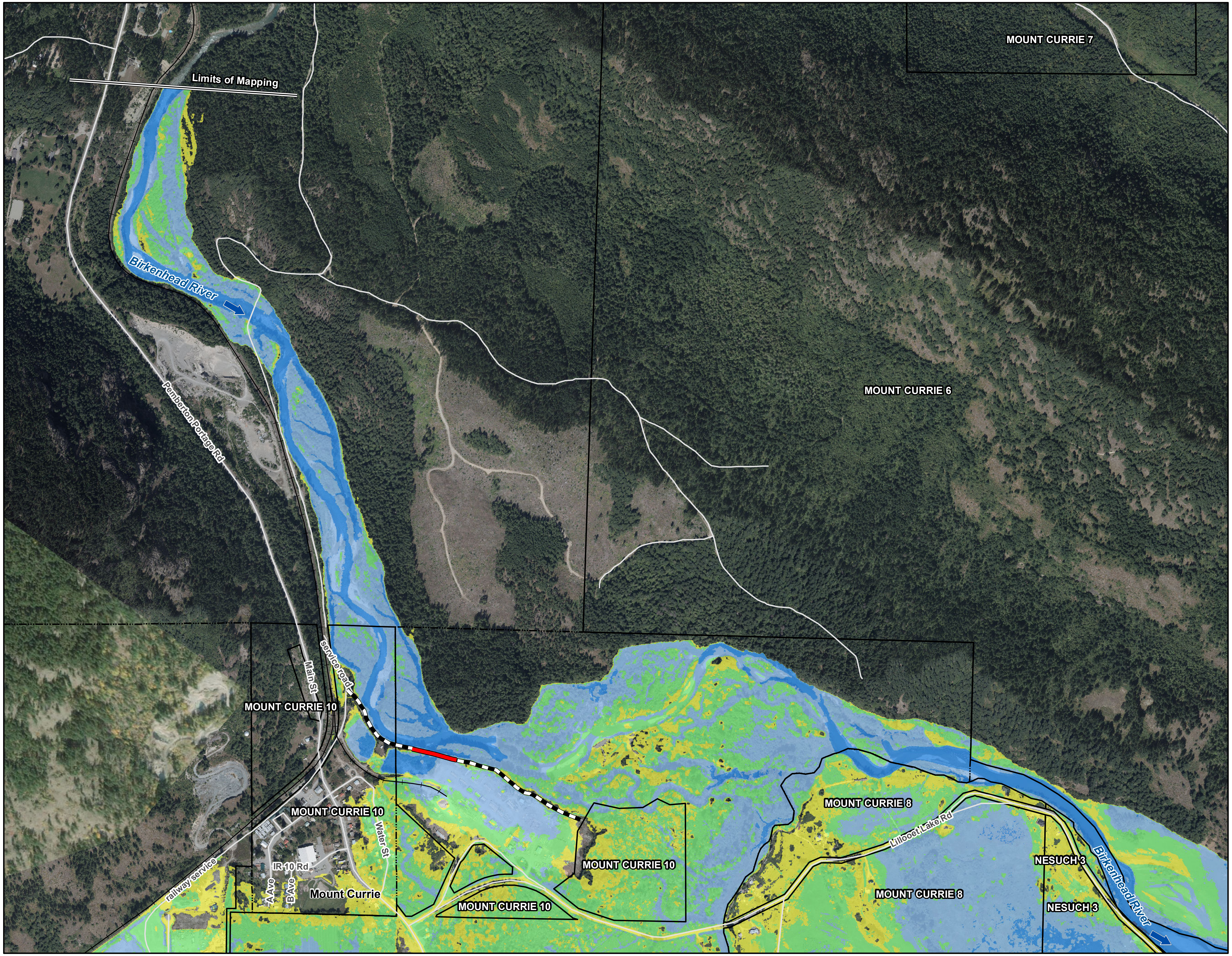

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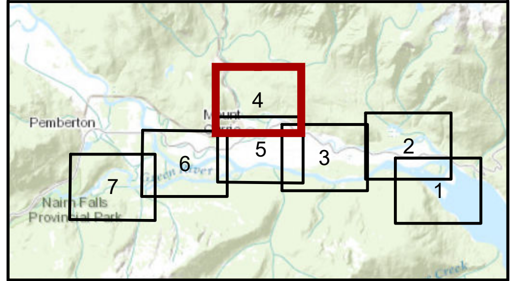

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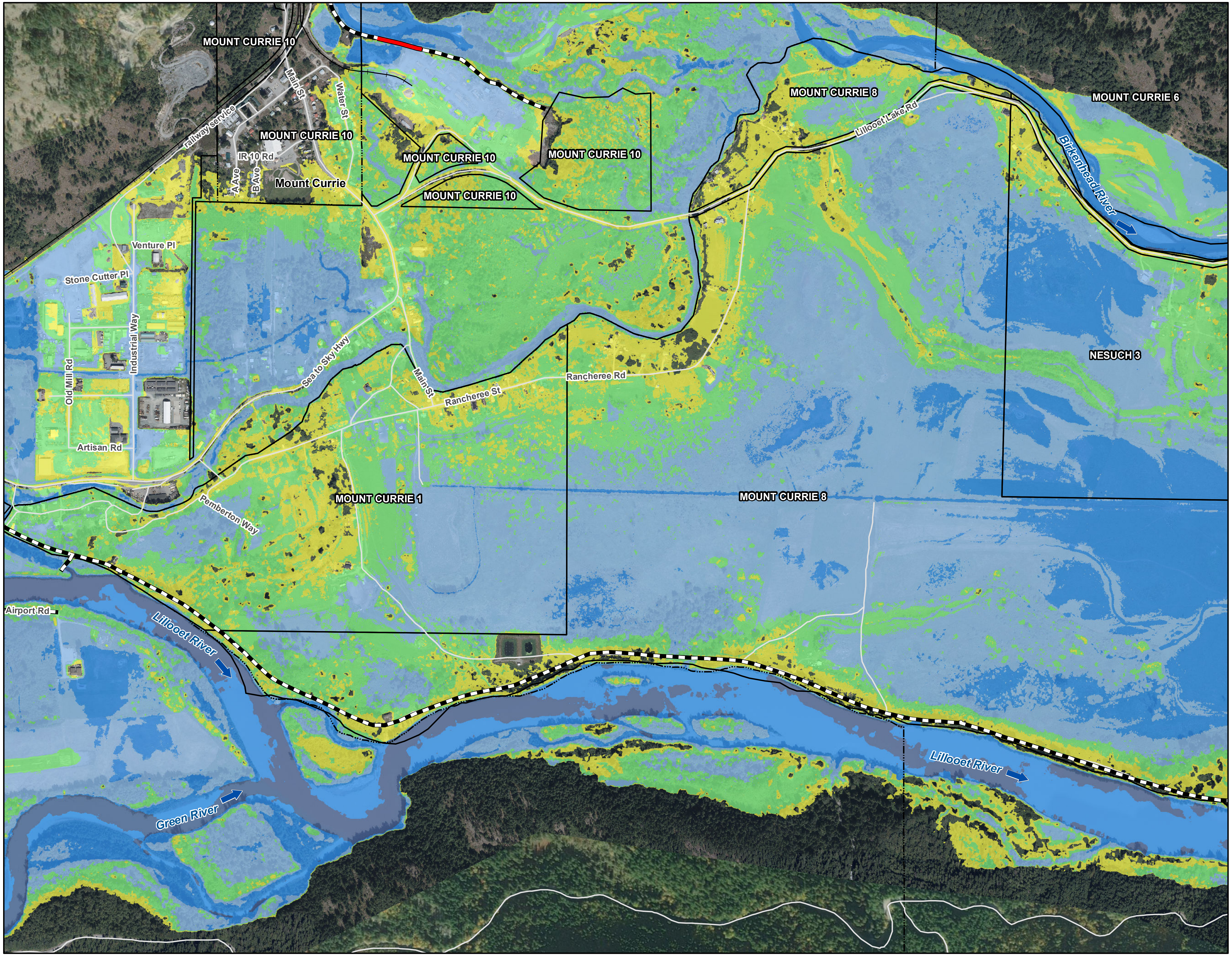

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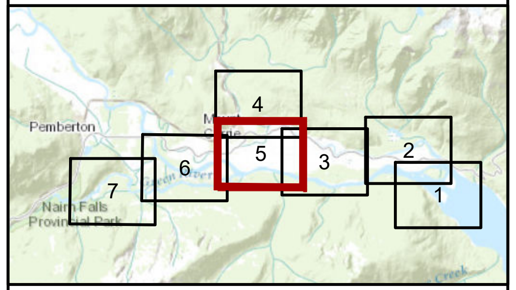

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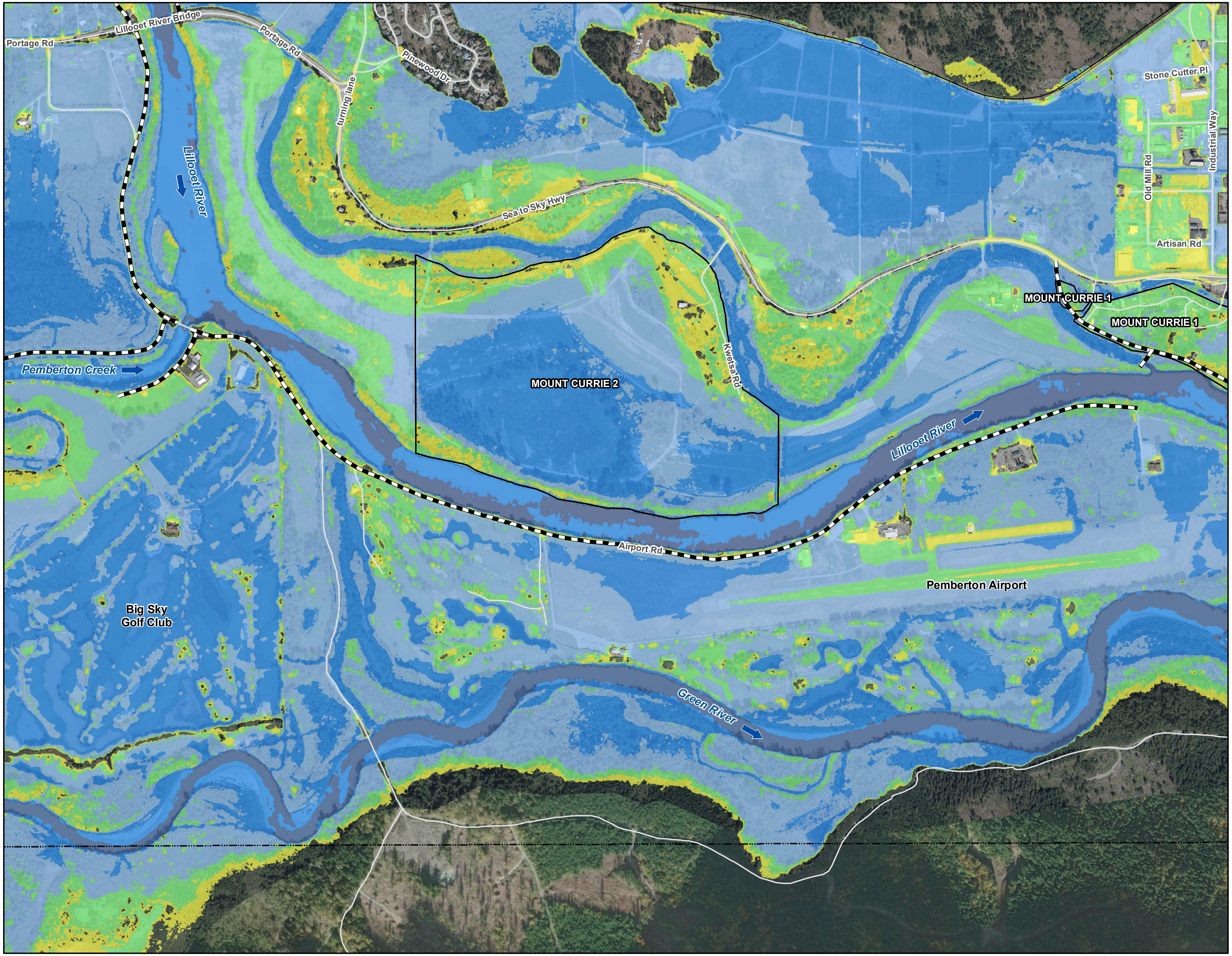
BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

FLOOD DEPTH 100-YR BREACH EVENT FOR BIRKENHEAD, GREEN & LILLOOET, INCLUDING CLIMATE CHANGE ON BIRKENHEAD & GREEN

SHEET 5 OF 7



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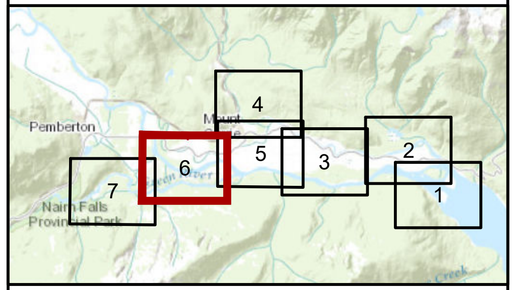

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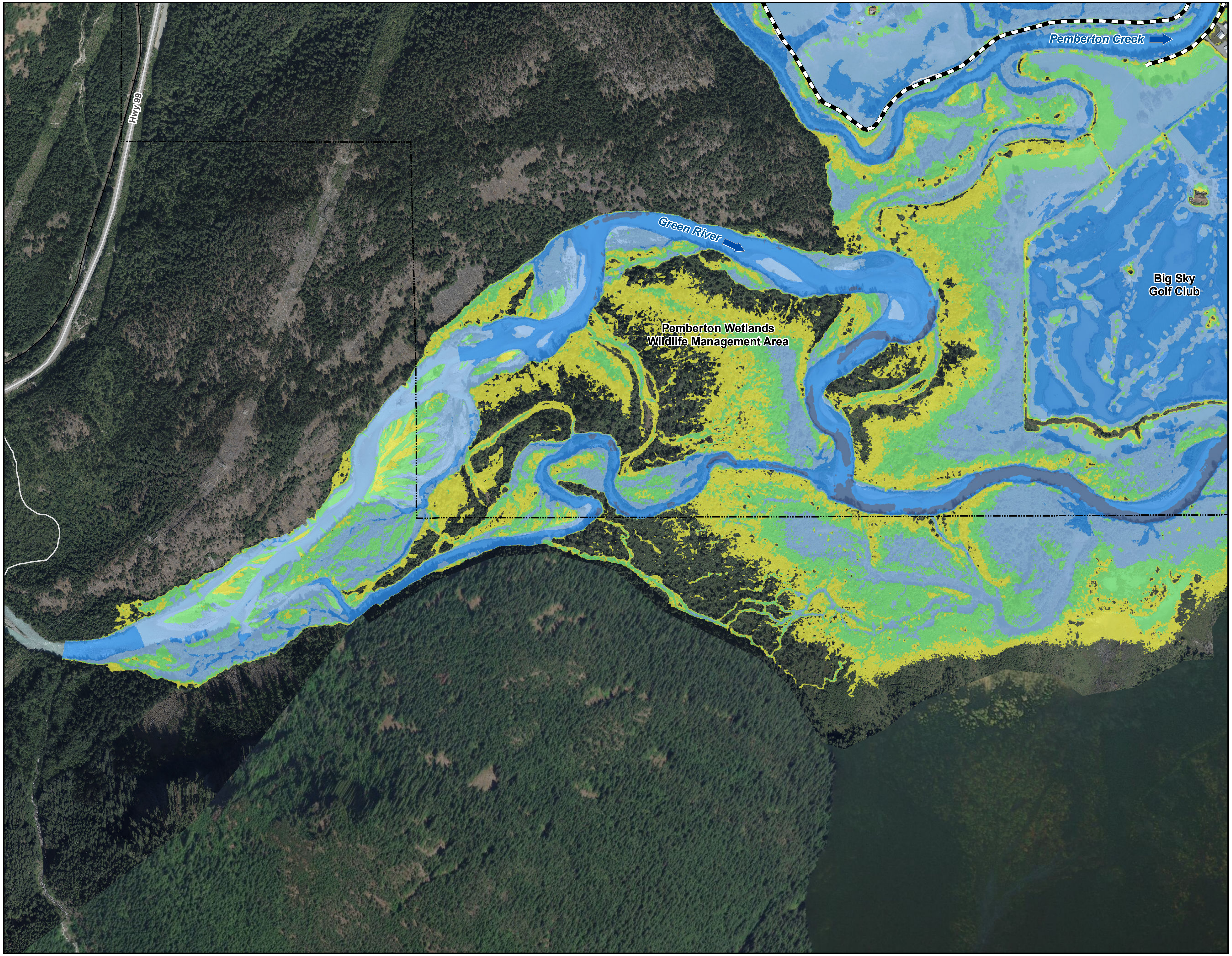
BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

FLOOD DEPTH 100-YR BREACH EVENT FOR BIRKENHEAD, GREEN & LILLOOET, INCLUDING CLIMATE CHANGE ON BIRKENHEAD & GREEN

SHEET 6 OF 7



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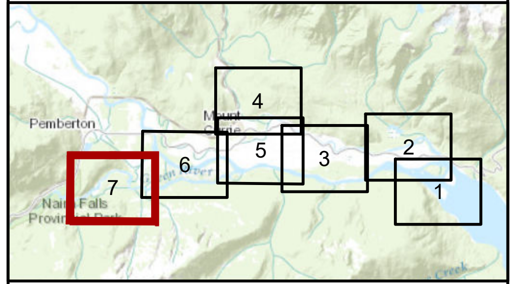

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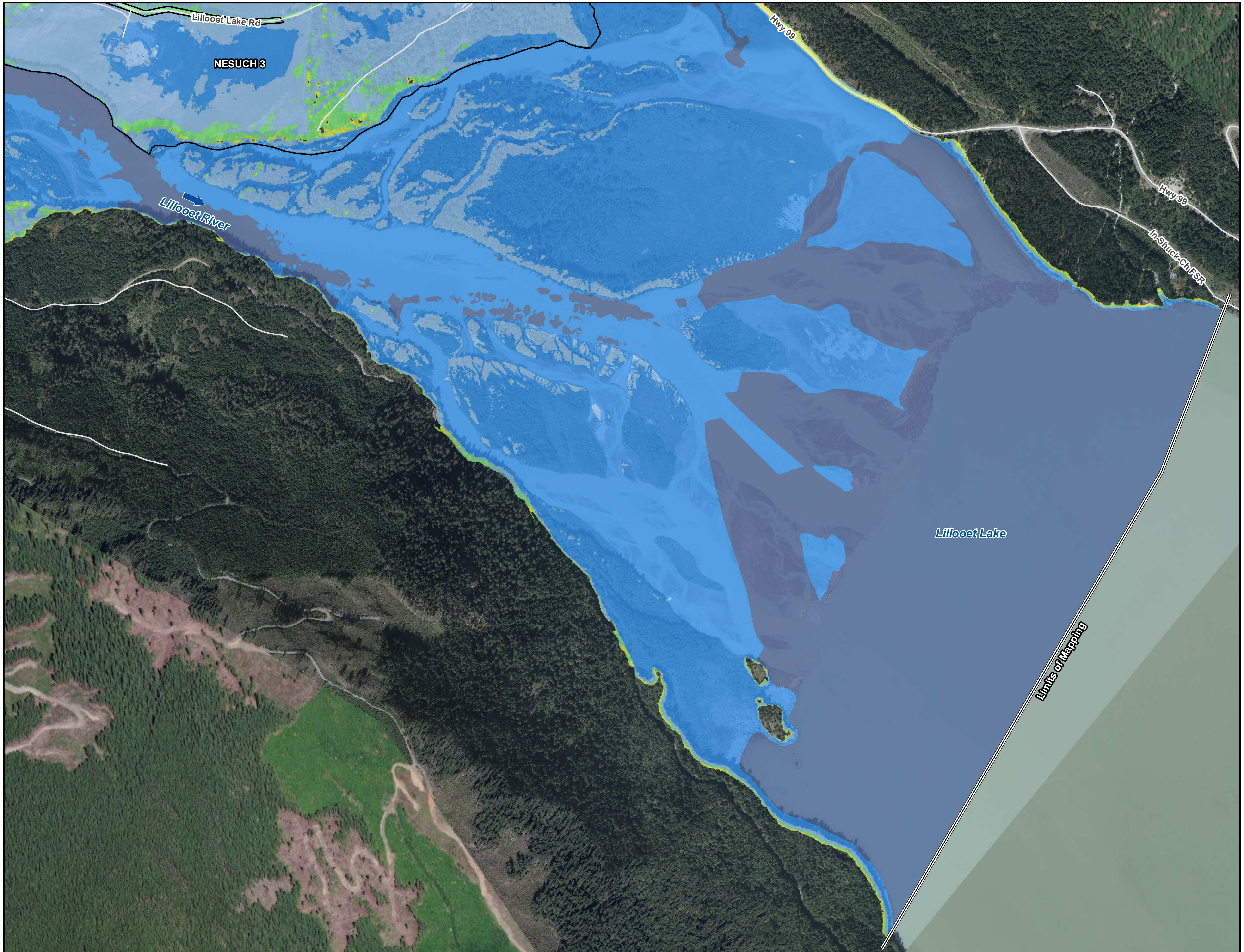
BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

FLOOD DEPTH 100-YR BREACH EVENT FOR BIRKENHEAD, GREEN & LILLOOET, INCLUDING CLIMATE CHANGE ON BIRKENHEAD & GREEN

SHEET 7 OF 7



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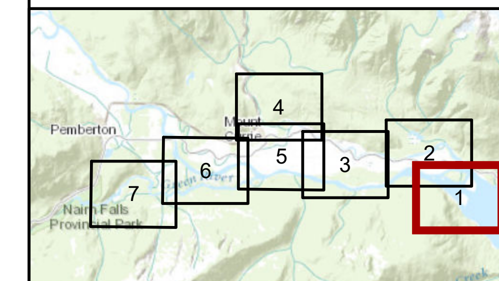

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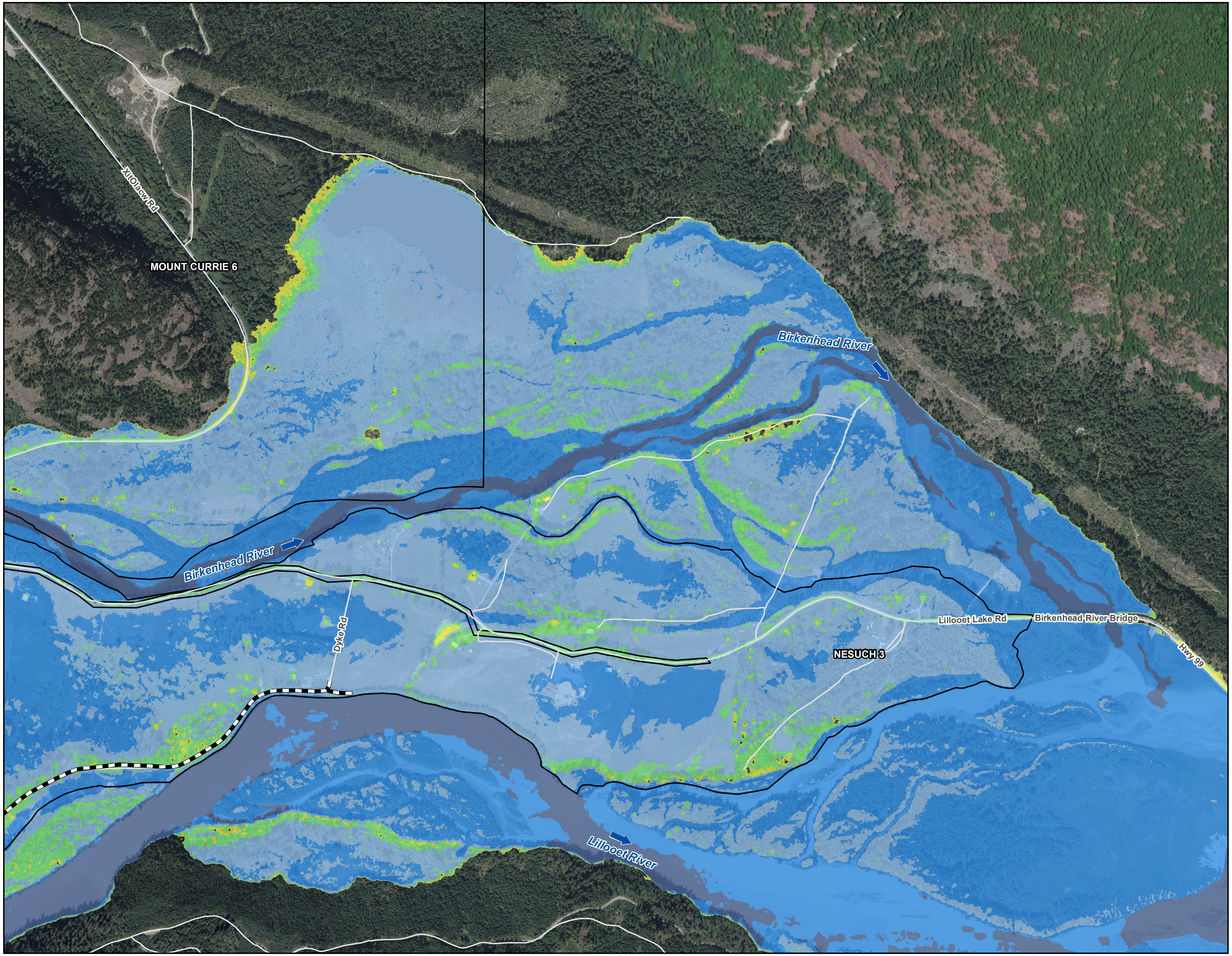
BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

FLOOD DEPTH 200-YR BREACH EVENT FOR BIRKENHEAD, GREEN & LILLOOET, INCLUDING CLIMATE CHANGE ON BIRKENHEAD & GREEN

SHEET 1 OF 7



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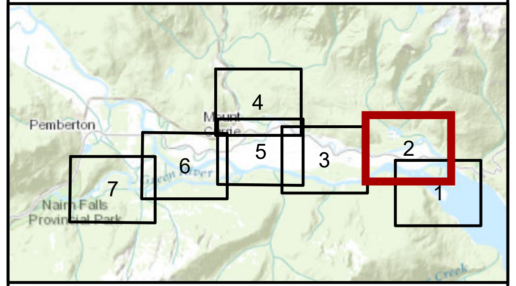

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BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

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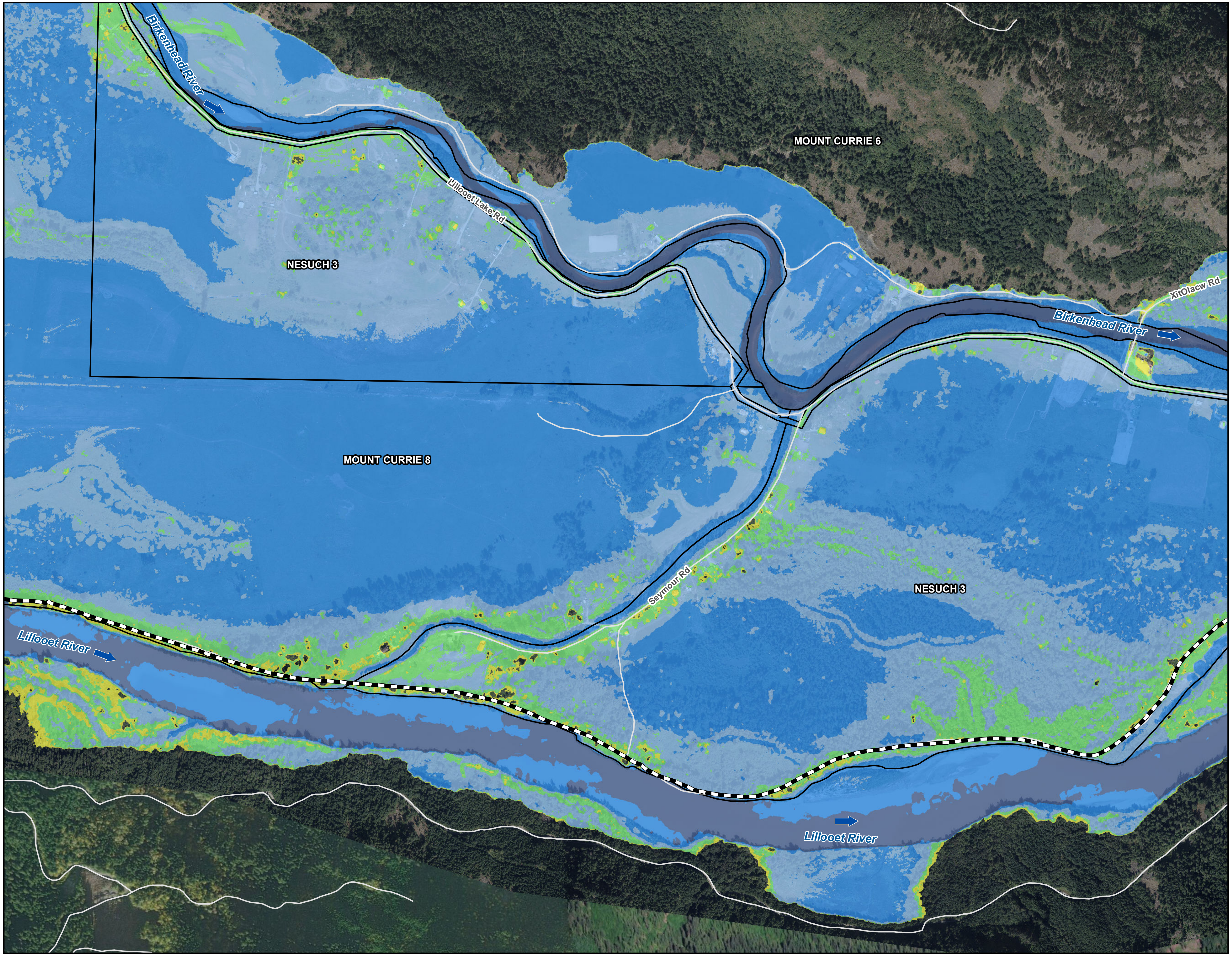

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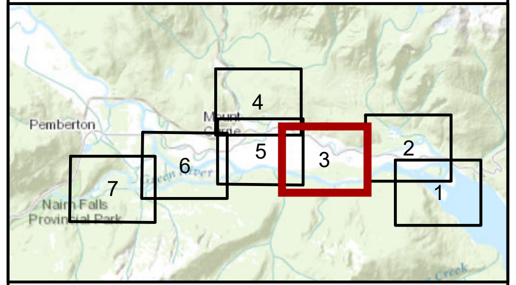

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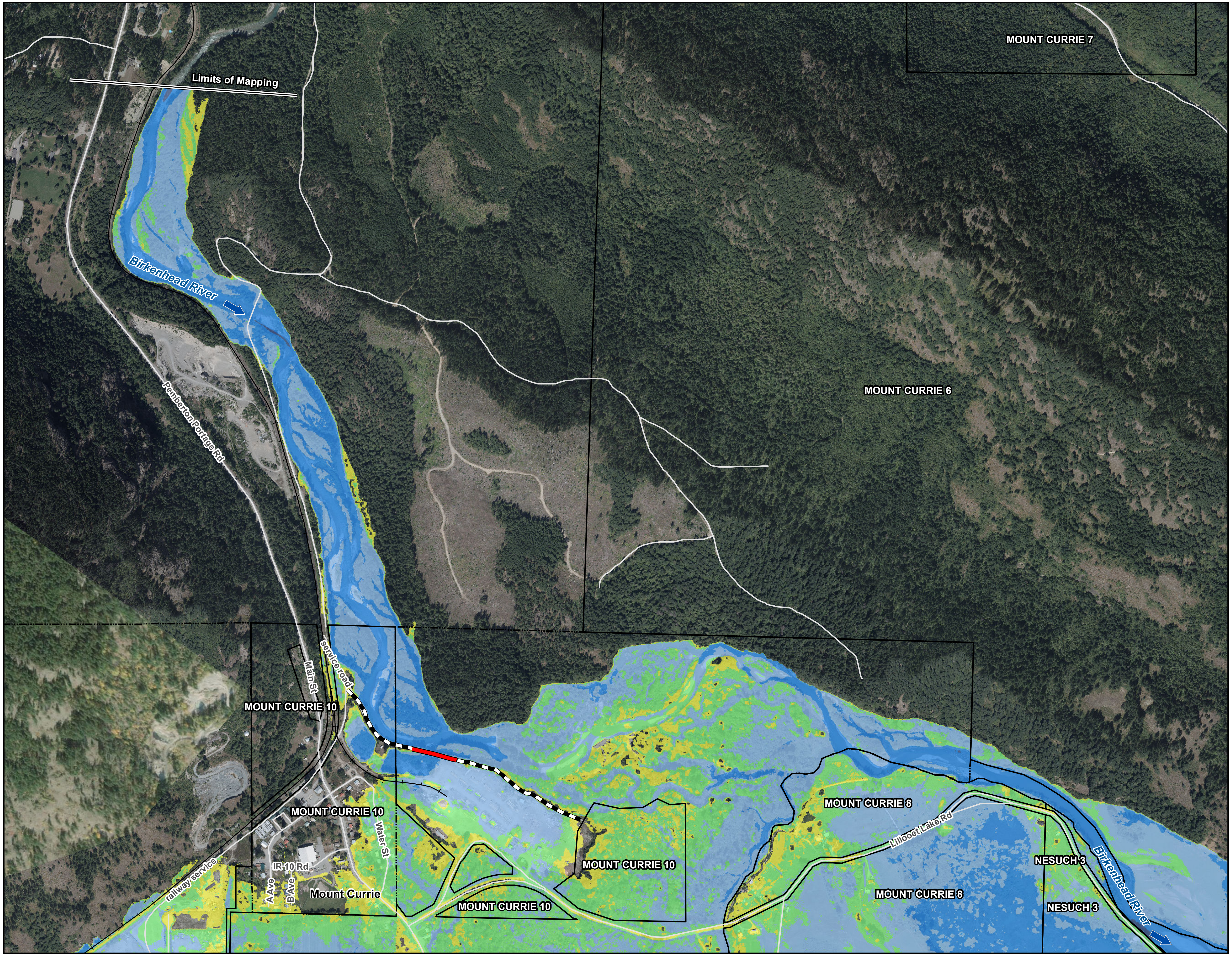
BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

FLOOD DEPTH 200-YR BREACH EVENT FOR BIRKENHEAD, GREEN & LILLOOET, INCLUDING CLIMATE CHANGE ON BIRKENHEAD & GREEN

SHEET 3 OF 7



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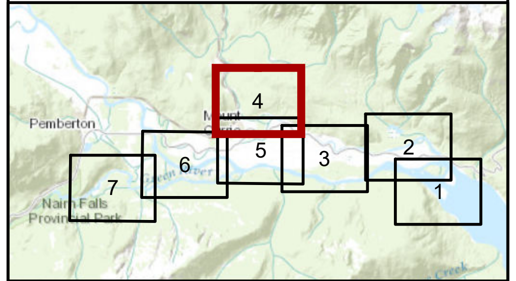

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BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

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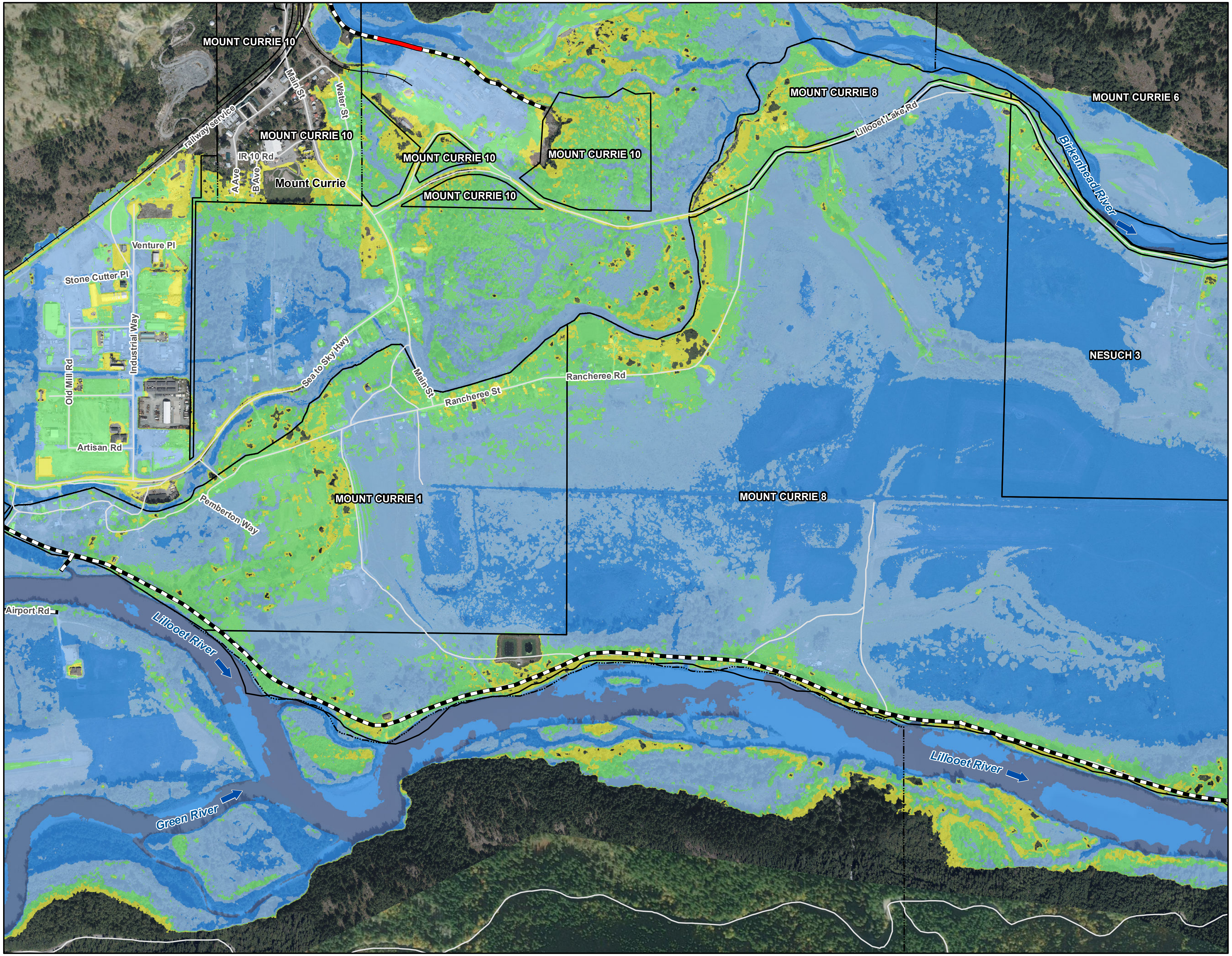

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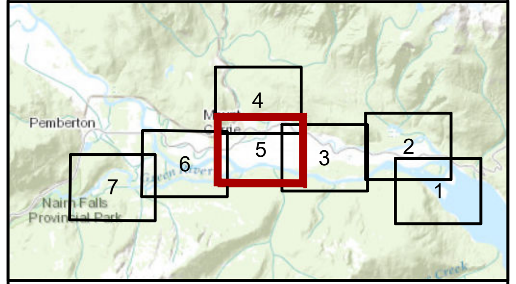

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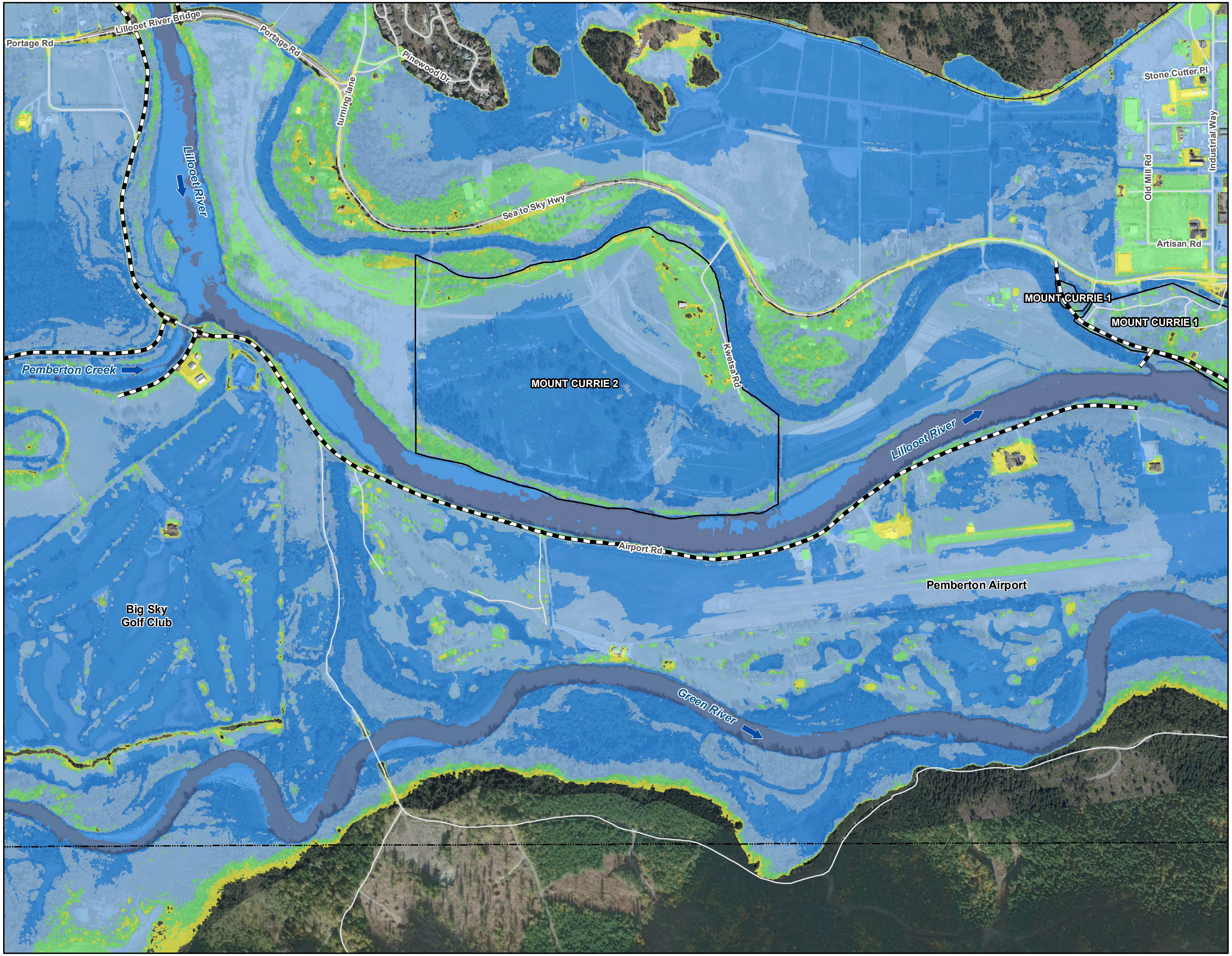

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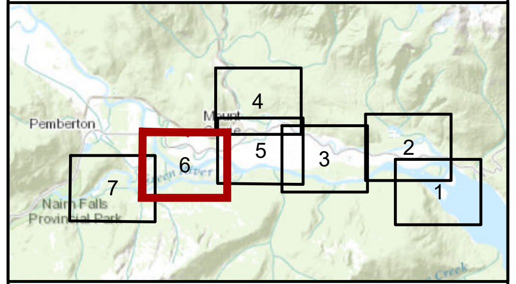

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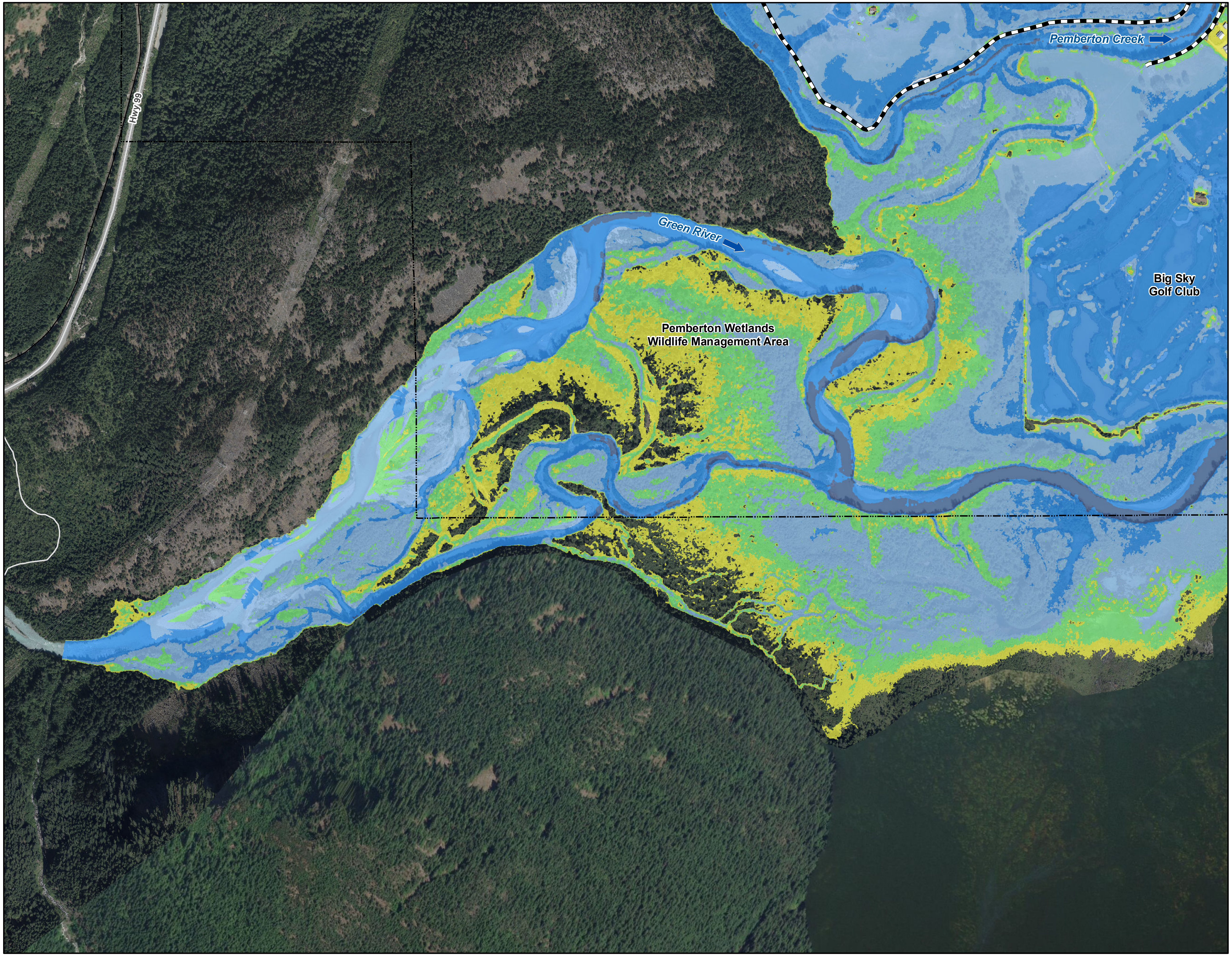
BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

FLOOD DEPTH 200-YR BREACH EVENT FOR BIRKENHEAD, GREEN & LILLOOET, INCLUDING CLIMATE CHANGE ON BIRKENHEAD & GREEN

SHEET 6 OF 7



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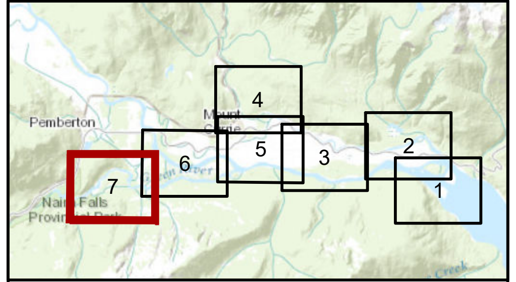


Legend

- Breach Location
- Flow Direction
- Dike
- Pemberton Valley Dyking District
- Nation Land (provided by Lil'Wat Nation)

Depth (m)

- 0 to 0.5
- 0.5 to 1.0
- 1.0 to 2.0
- 2.0 to 5.0
- > 5.0; River

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.
0.5-1.0m: Water on ground floor; basements and underground parking flooded, potentially causing evacuation; electricity failed; vehicles are commonly carried off roadways.
1.0-2.0m: Ground floor flooded; residents evacuate.
2.0-5.0m: First floor and often roof covered by water; residents evacuate.

Scale - 1:10,000

0 100 200 400 Meters

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES Vertical Datum: CGVD(2013)

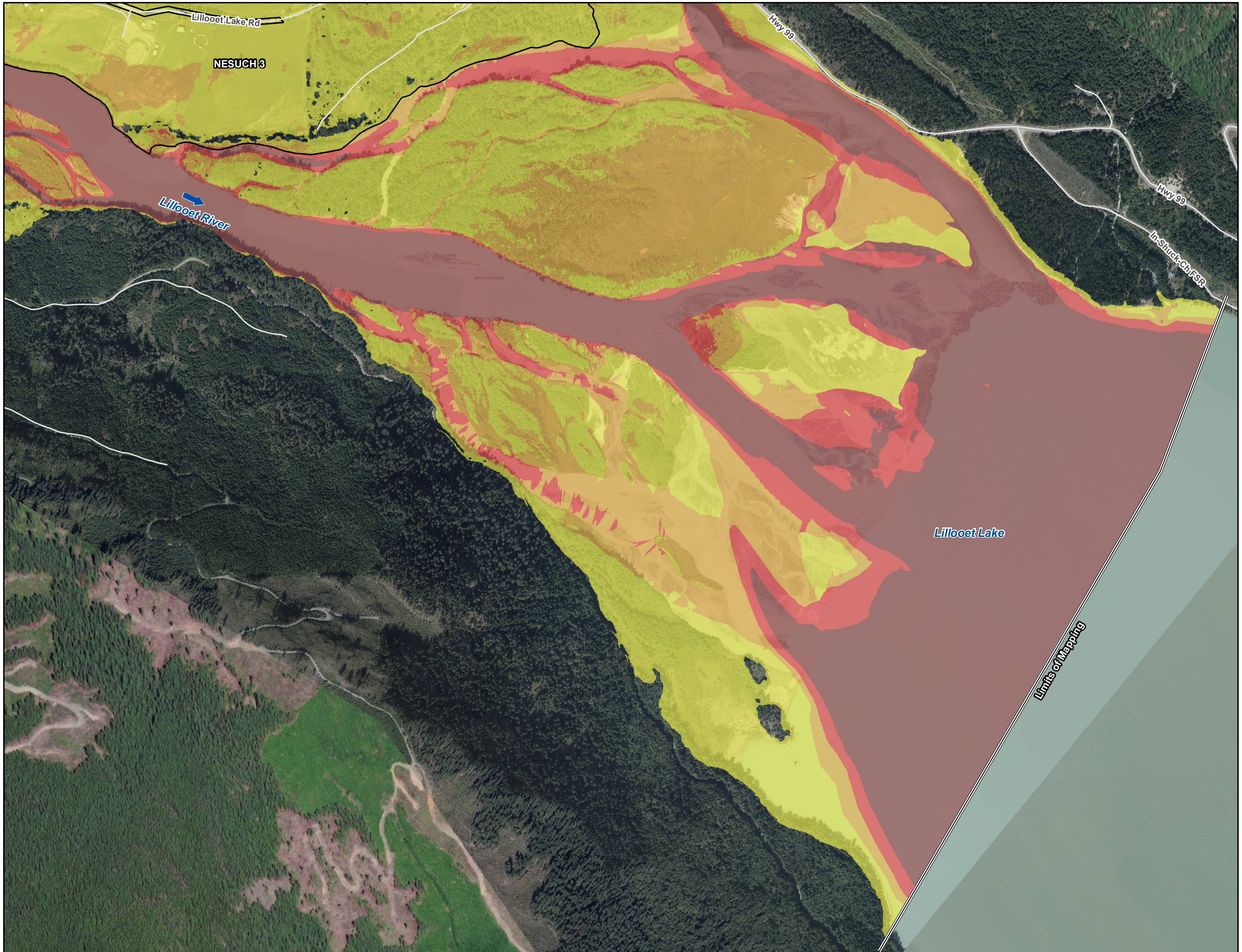
Engineer	GIS	Reviewer
VCCB	MAO	MCM

Job Number	Date
3004698	22-SEPT-2020

BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

FLOOD DEPTH 200-YR BREACH EVENT FOR BIRKENHEAD, GREEN & LILLOOET, INCLUDING CLIMATE CHANGE ON BIRKENHEAD & GREEN

SHEET 7 OF 7



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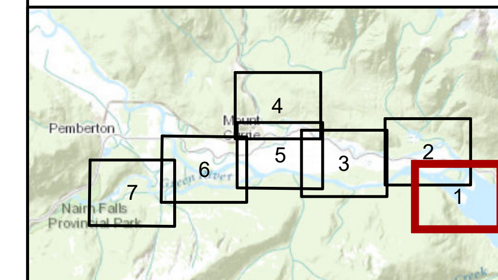

Legend

- Flow Direction
- Dike
- Pemberton Valley Dyking District
- Nation Land (provided by Lil'Wat Nation)

Hazard Rating (m*m/s)

Hazard Rating = Depth x (Velocity + 0.5)

- Low: < 0.75
- Moderate: 0.75 - 1.25
- Significant: 1.25 - 2.5
- Extreme: > 2.5

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

Please refer to General Notes on Map Index Sheet.

Scale - 1:10,000

0 100 200 400 Meters

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Engineer	GIS	Reviewer
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Job Number	Date
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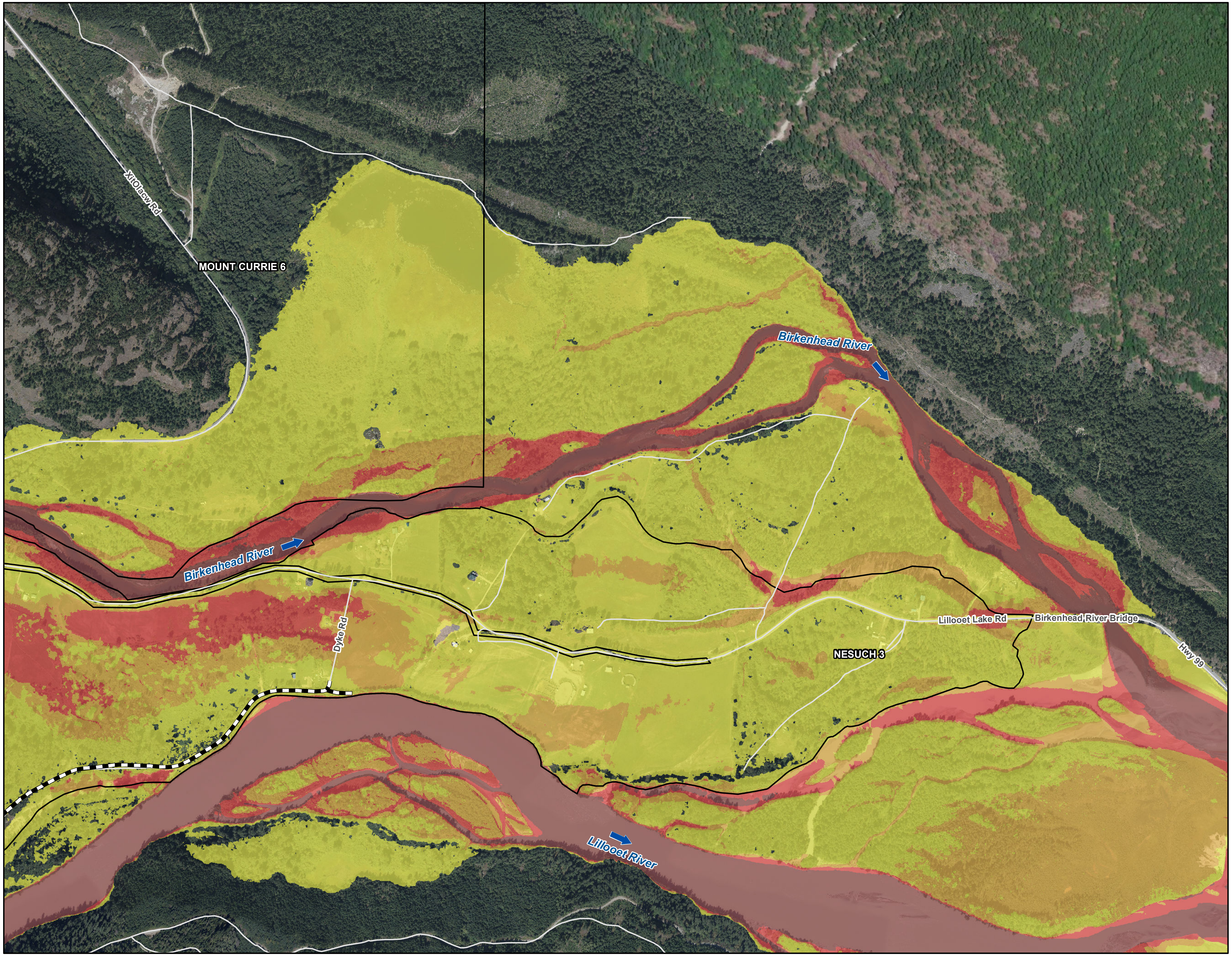
BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

FLOOD HAZARD 50-YR EVENT FOR BIRKENHEAD, GREEN & LILLOOET, INCLUDING CLIMATE CHANGE ON BIRKENHEAD & GREEN



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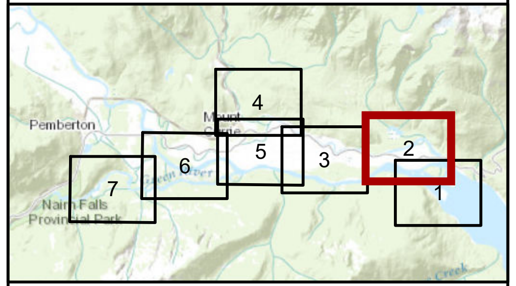

Legend

Flow Direction

Dike

Pemberton Valley Dyking District

Nation Land (provided by Lil'Wat Nation)

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Engineer	GIS	Reviewer
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Job Number	Date
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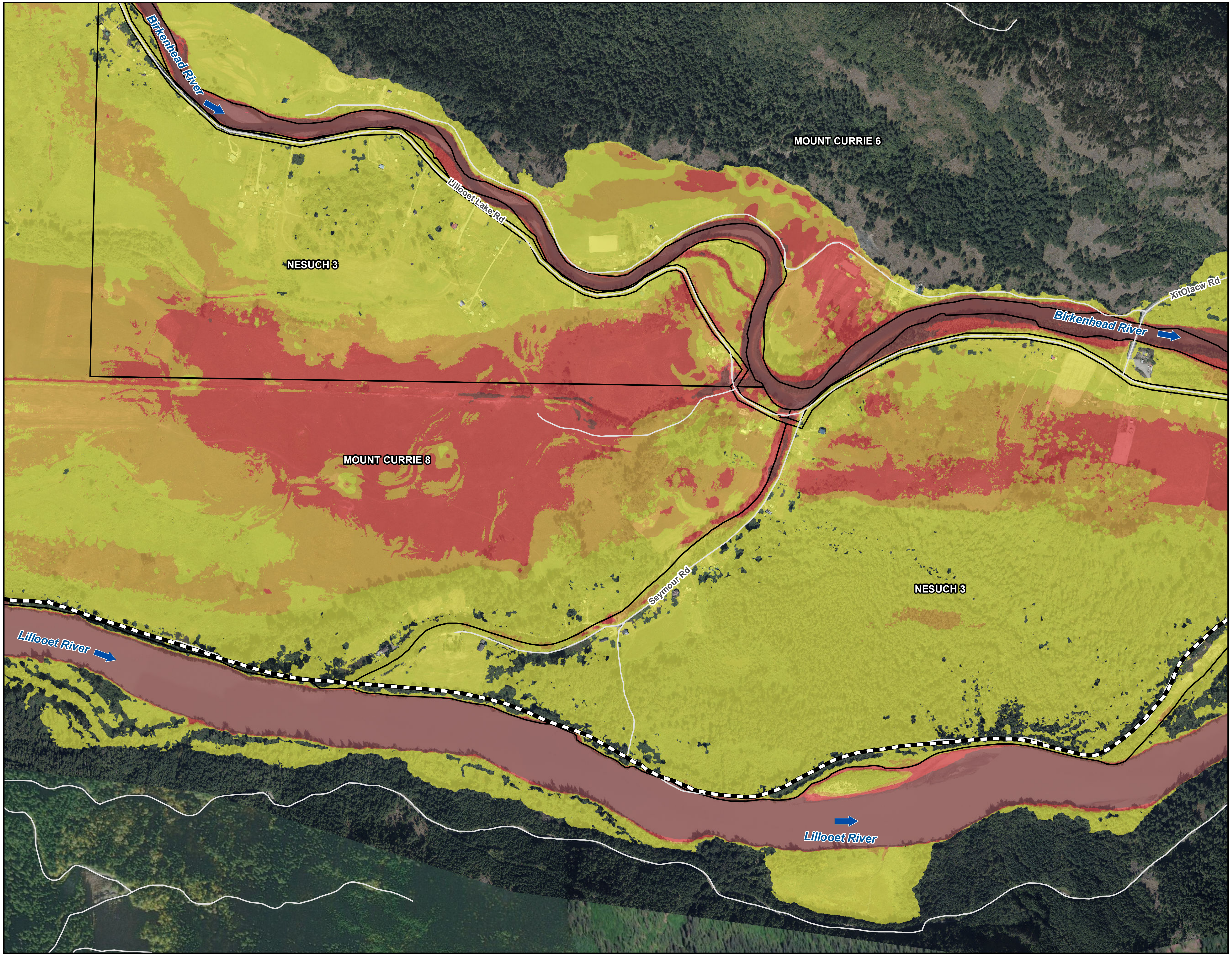
BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

FLOOD HAZARD 50-YR EVENT FOR BIRKENHEAD, GREEN & LILLOOET, INCLUDING CLIMATE CHANGE ON BIRKENHEAD & GREEN

SHEET 2 OF 7



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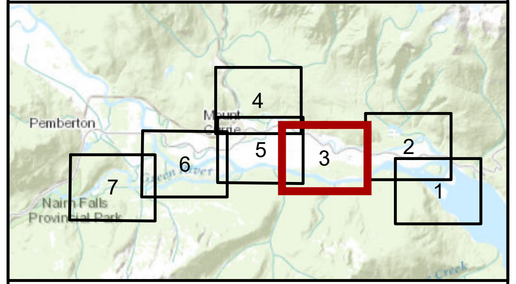

Legend

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Job Number	Date
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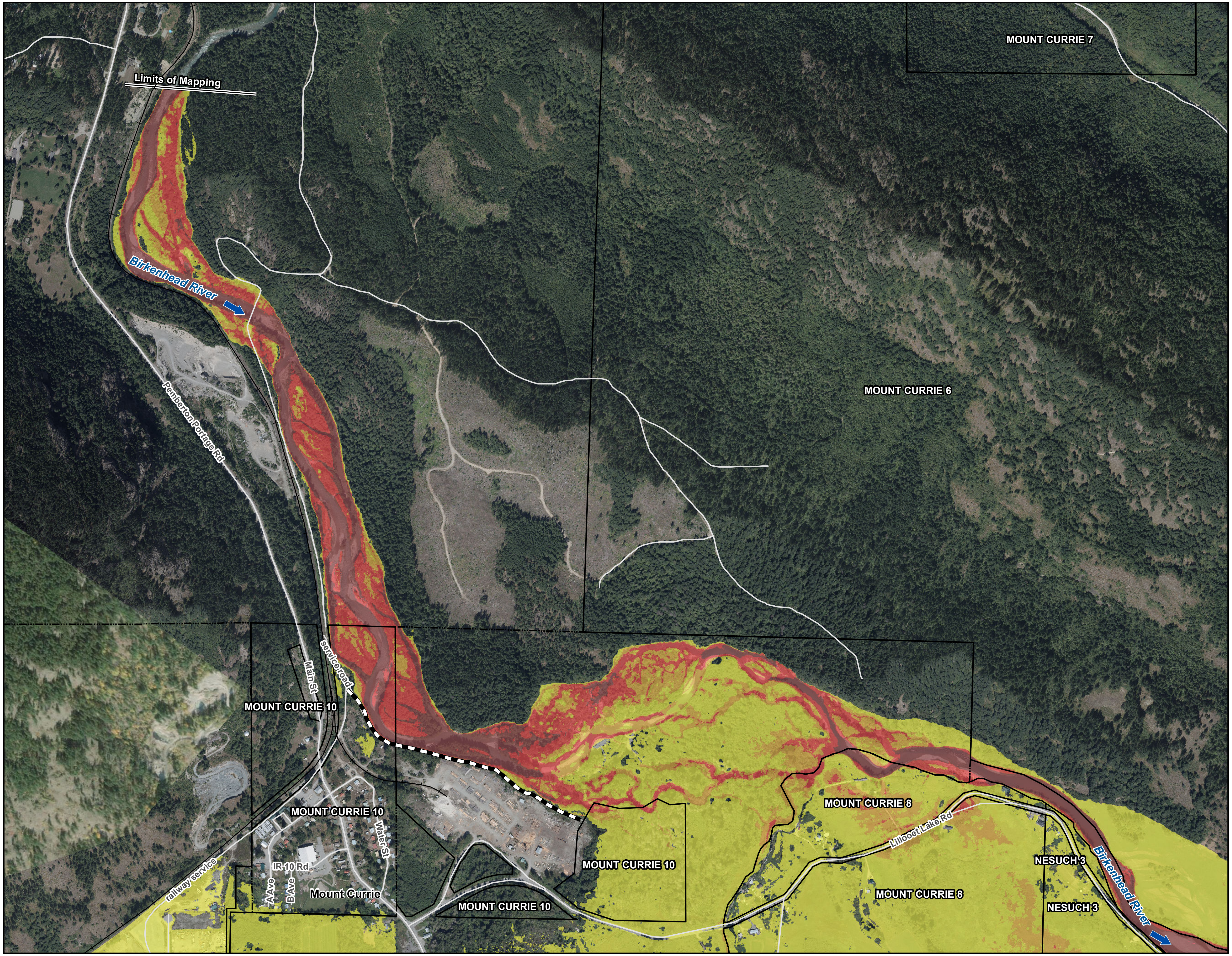
BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

FLOOD HAZARD 50-YR EVENT FOR BIRKENHEAD, GREEN & LILLOOET, INCLUDING CLIMATE CHANGE ON BIRKENHEAD & GREEN

SHEET 3 OF 7



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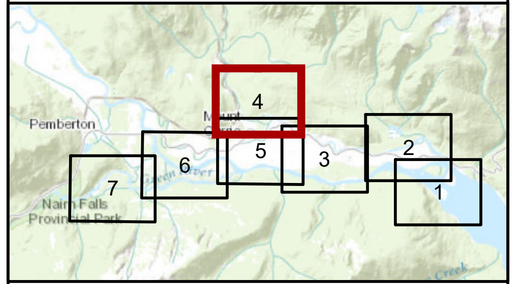

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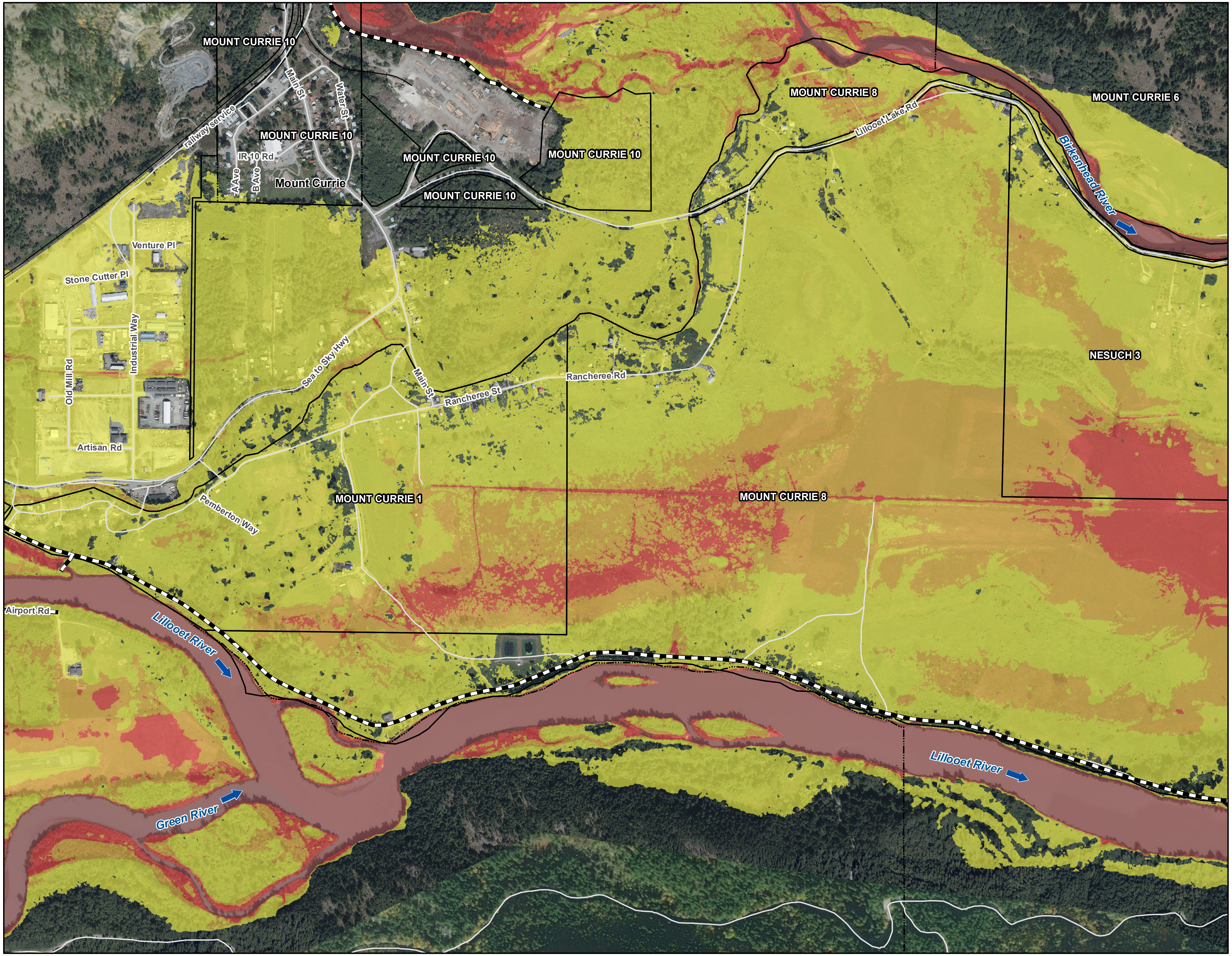
BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

FLOOD HAZARD 50-YR EVENT FOR BIRKENHEAD, GREEN & LILLOOET, INCLUDING CLIMATE CHANGE ON BIRKENHEAD & GREEN

SHEET 4 OF 7



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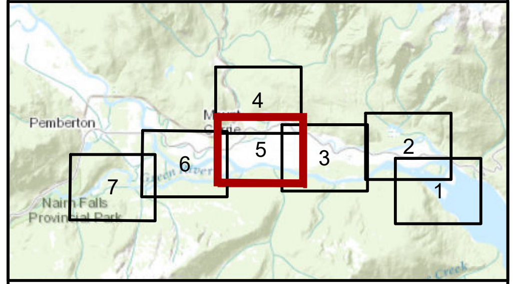

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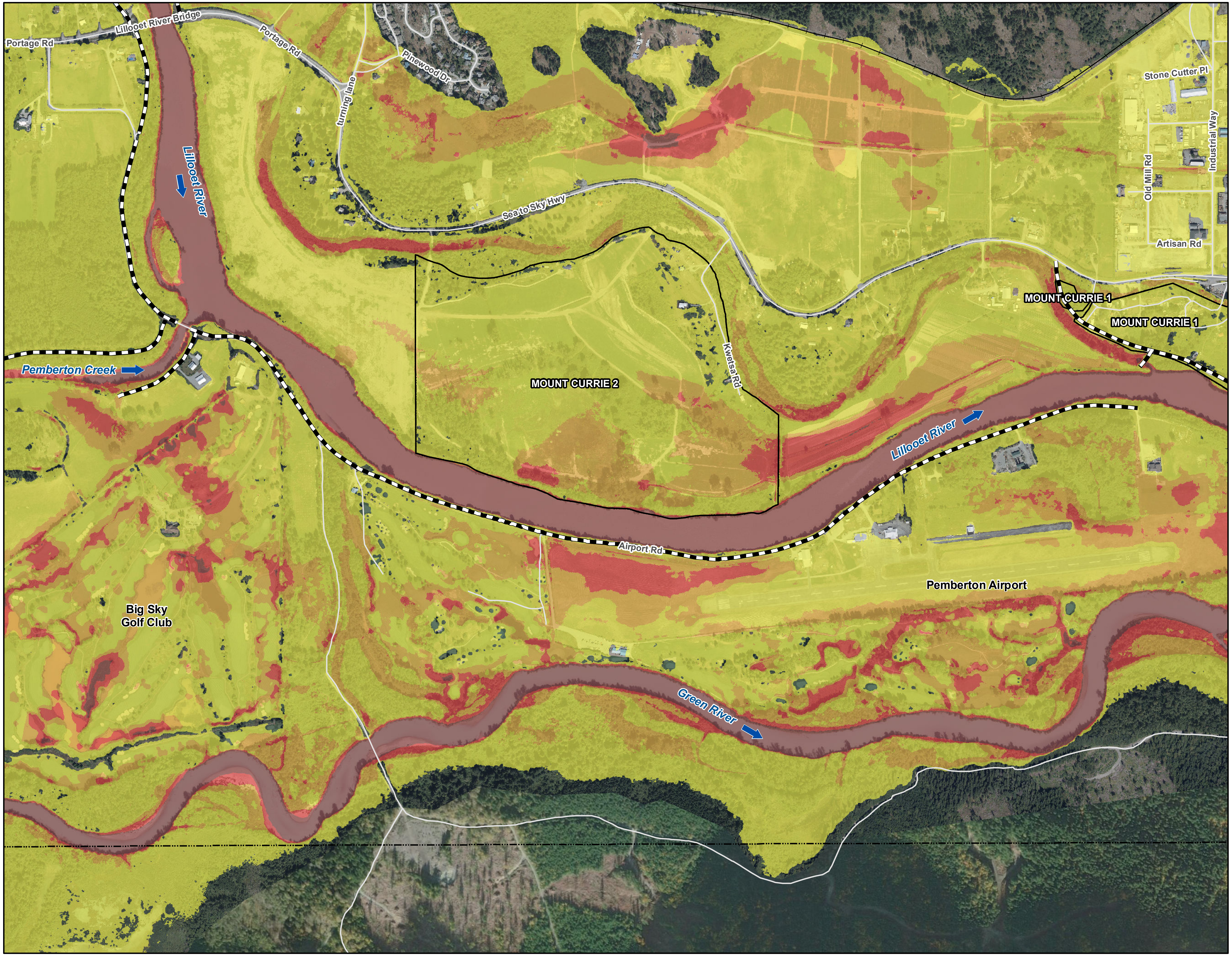
BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

FLOOD HAZARD 50-YR EVENT FOR BIRKENHEAD, GREEN & LILLOOET, INCLUDING CLIMATE CHANGE ON BIRKENHEAD & GREEN



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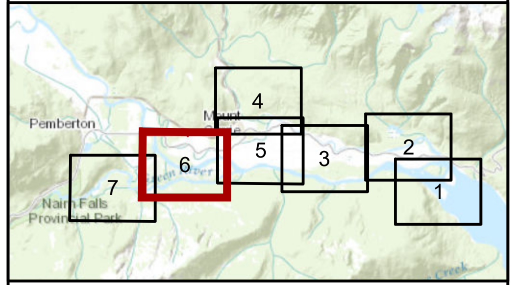

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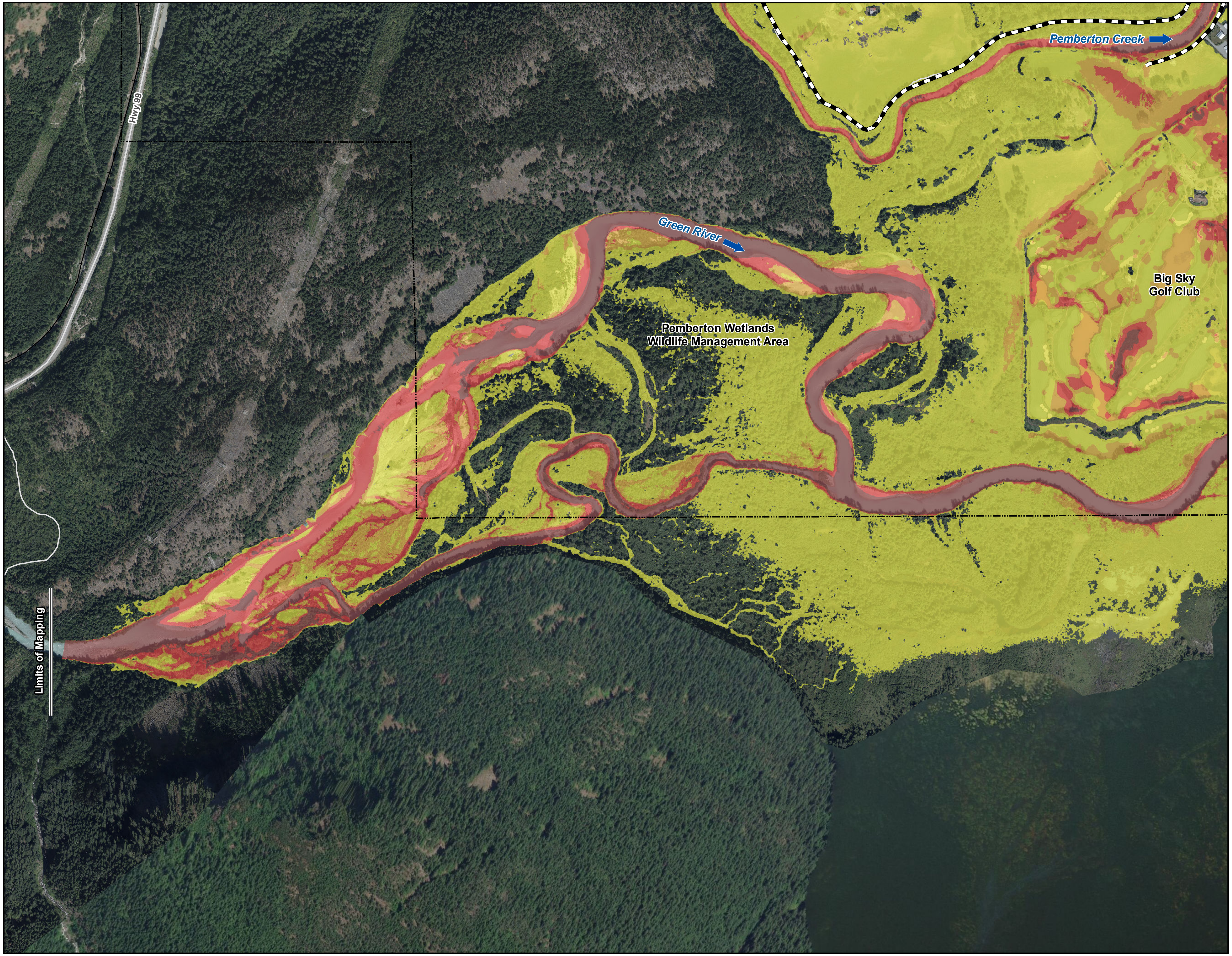
BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

FLOOD HAZARD 50-YR EVENT FOR BIRKENHEAD, GREEN & LILLOOET, INCLUDING CLIMATE CHANGE ON BIRKENHEAD & GREEN

SHEET 6 OF 7



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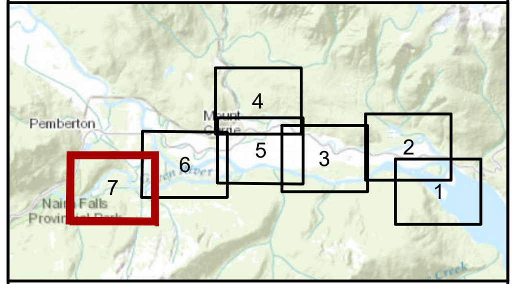

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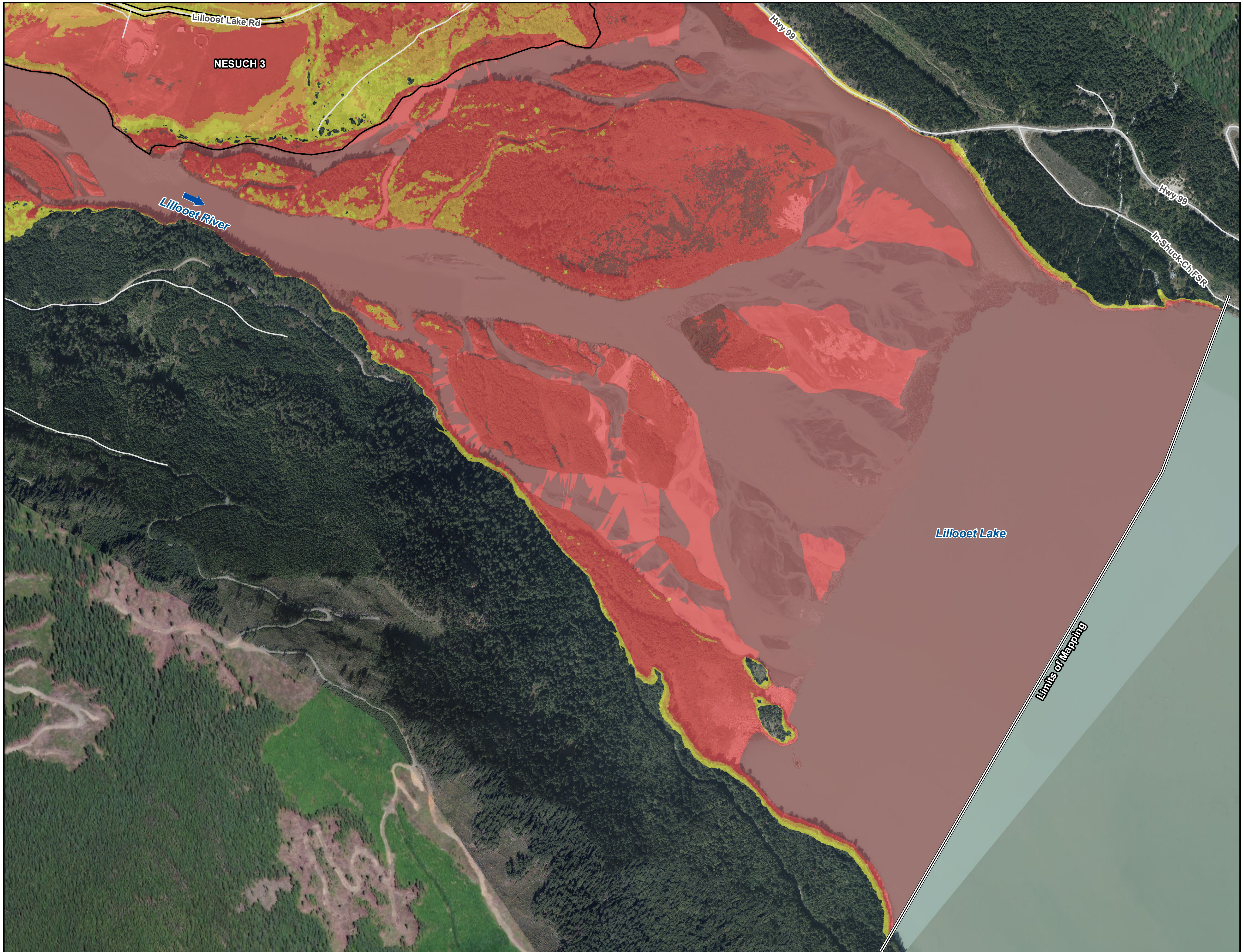
BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

FLOOD HAZARD 50-YR EVENT FOR BIRKENHEAD, GREEN & LILLOOET, INCLUDING CLIMATE CHANGE ON BIRKENHEAD & GREEN



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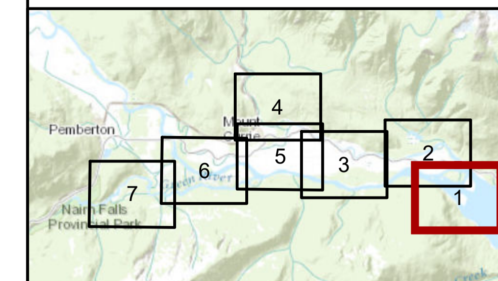

Legend

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Please refer to General Notes on Map Index Sheet.

Scale - 1:10,000
0 100 200 400 Meters
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Coordinate System: NAD 1983 UTM ZONE 10N
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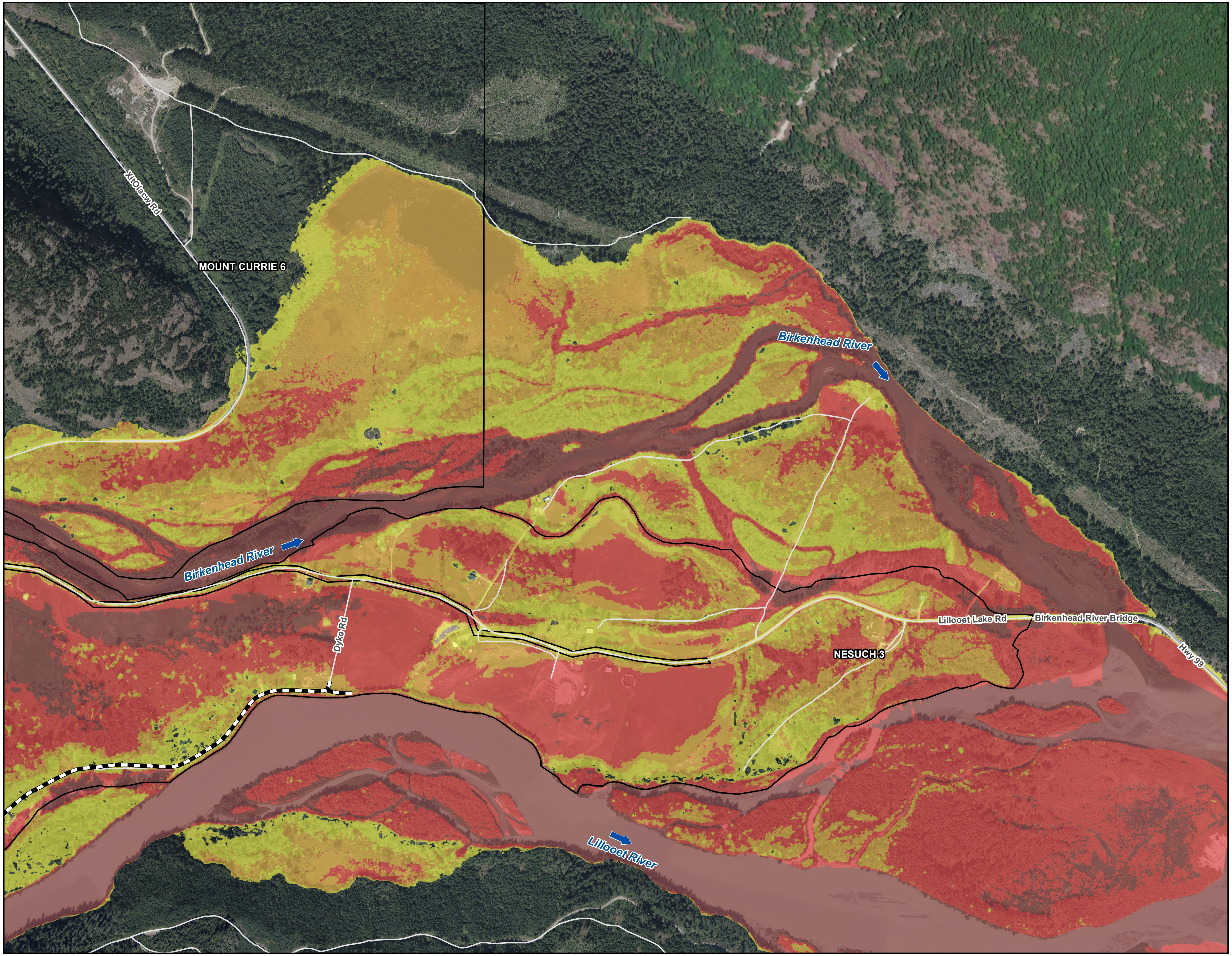
Engineer	GIS	Reviewer
VCCB	*MAO*	*MCM*

Job Number	Date
3004698	*22-SEPT-2020*

BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

FLOOD DEPTH 100-YR BREACH EVENT FOR BIRKENHEAD, GREEN & LILLOOET, INCLUDING CLIMATE CHANGE ON BIRKENHEAD & GREEN

SHEET 1 OF 7



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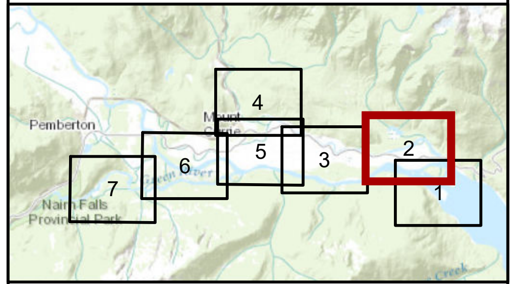

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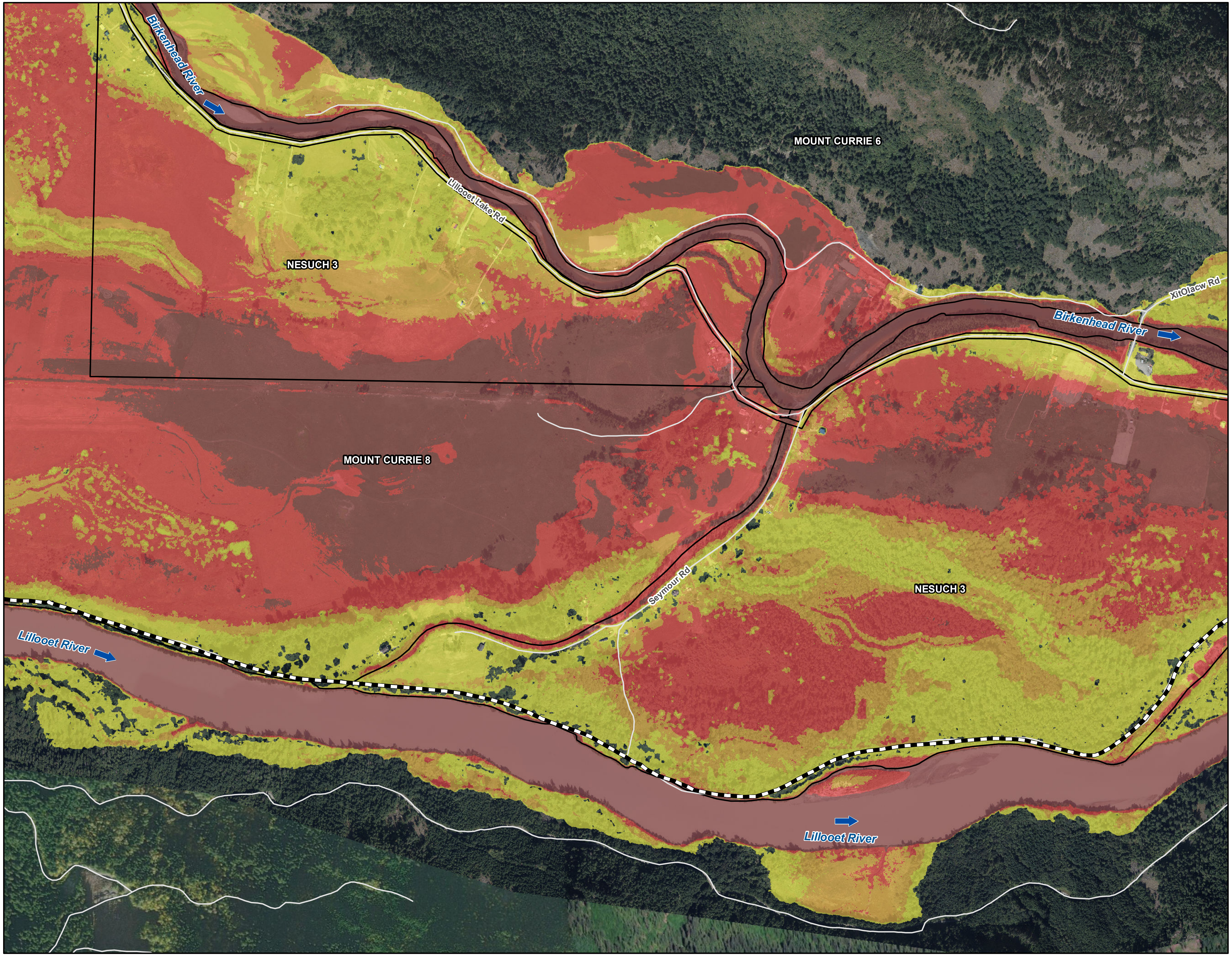
BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

FLOOD DEPTH 100-YR BREACH EVENT FOR BIRKENHEAD, GREEN & LILLOOET, INCLUDING CLIMATE CHANGE ON BIRKENHEAD & GREEN



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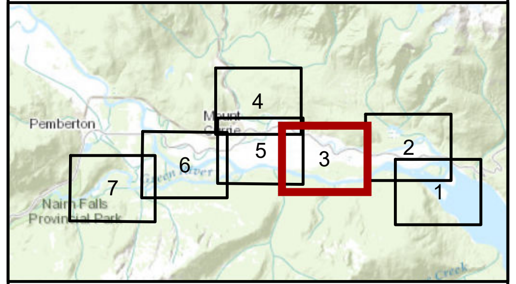

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Units: METRES *Vertical Datum: CGVD(2013)*

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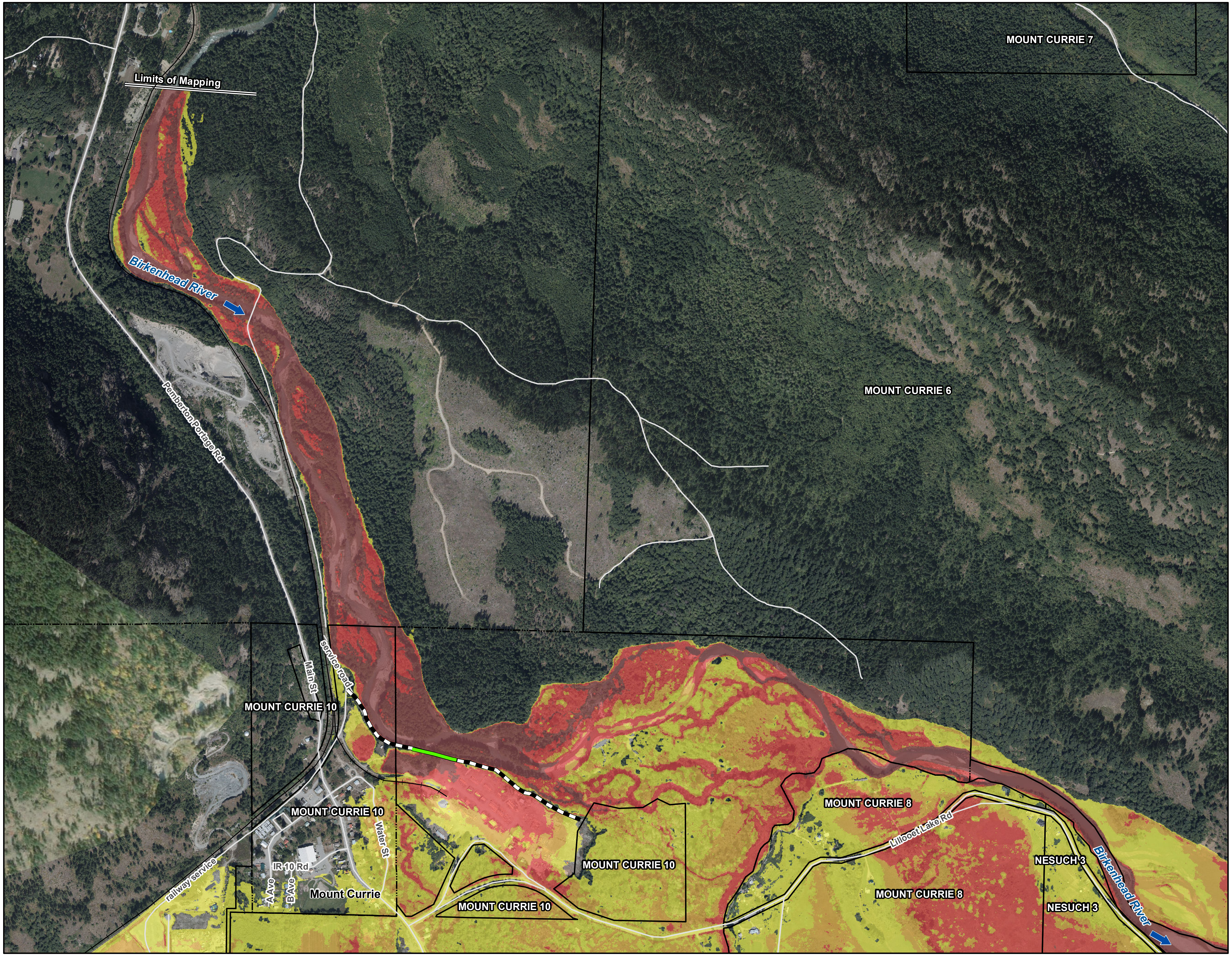
BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

FLOOD DEPTH 100-YR BREACH EVENT FOR BIRKENHEAD, GREEN & LILLOOET, INCLUDING CLIMATE CHANGE ON BIRKENHEAD & GREEN

SHEET 3 OF 7



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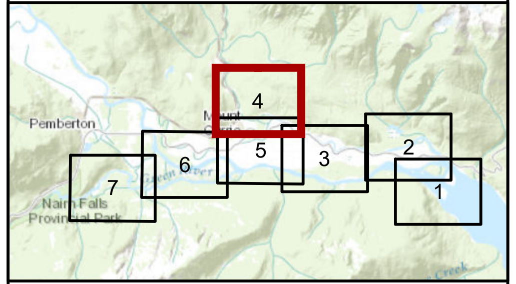

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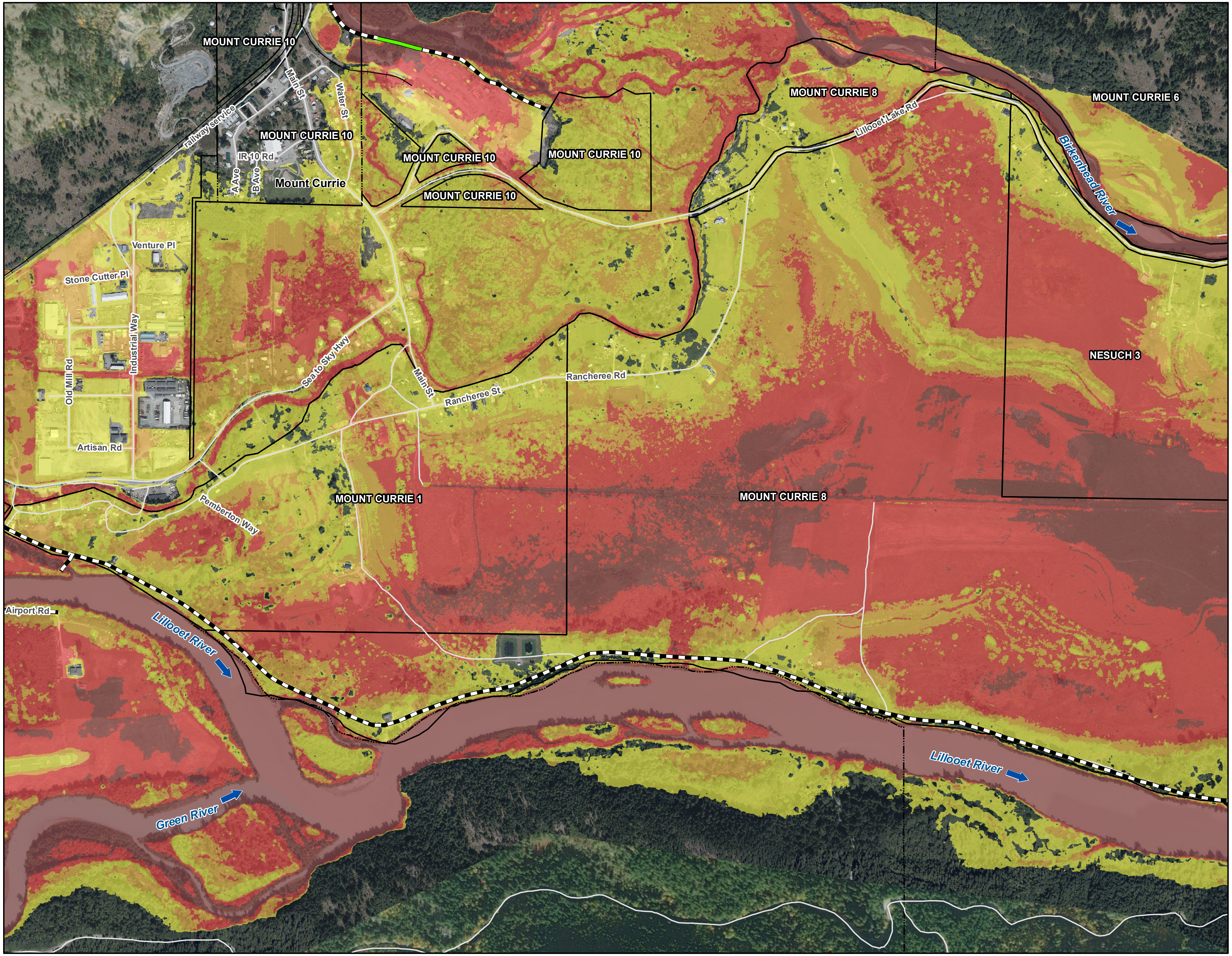
BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

FLOOD DEPTH 100-YR BREACH EVENT FOR BIRKENHEAD, GREEN & LILLOOET, INCLUDING CLIMATE CHANGE ON BIRKENHEAD & GREEN

SHEET 4 OF 7



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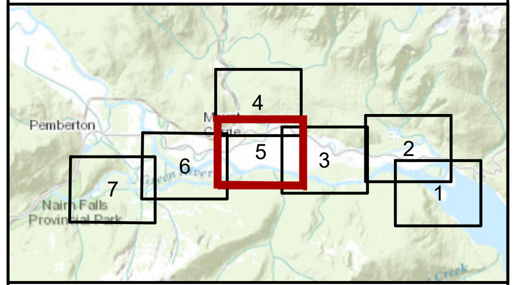

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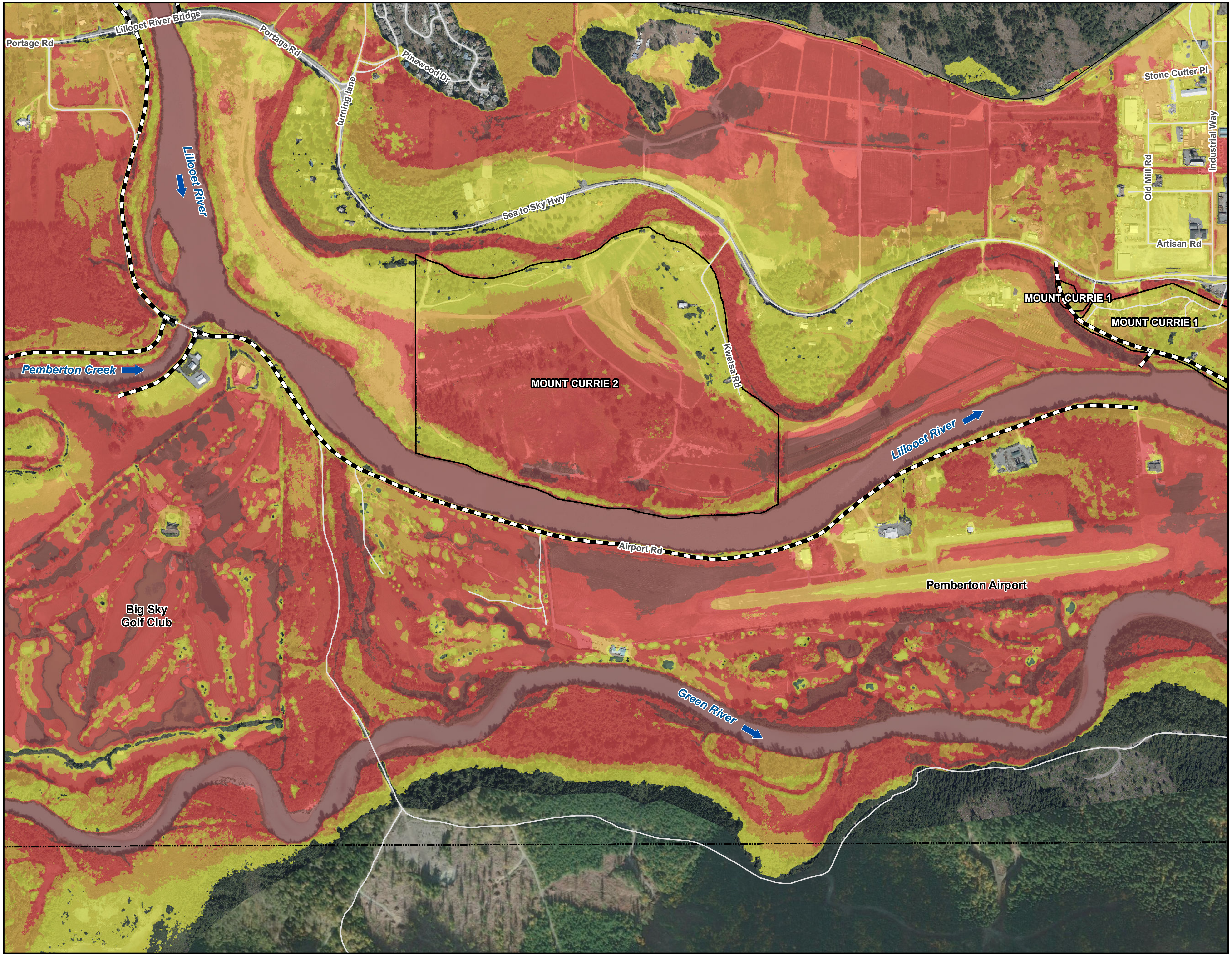
BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

FLOOD DEPTH 100-YR BREACH EVENT FOR BIRKENHEAD, GREEN & LILLOOET, INCLUDING CLIMATE CHANGE ON BIRKENHEAD & GREEN

SHEET 5 OF 7



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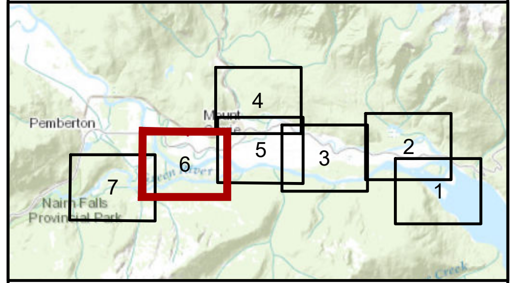

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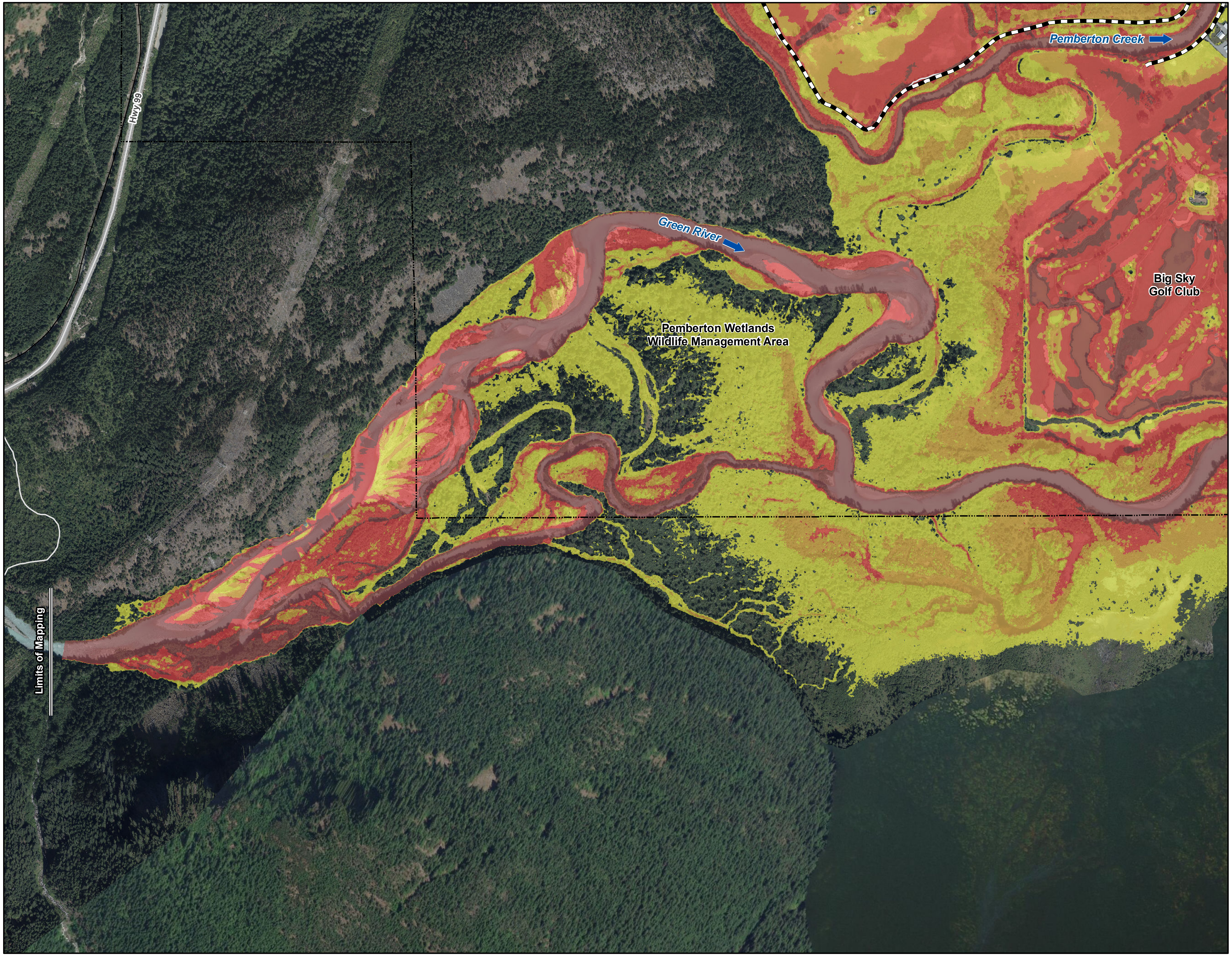
BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

FLOOD DEPTH 100-YR BREACH EVENT FOR BIRKENHEAD, GREEN & LILLOOET, INCLUDING CLIMATE CHANGE ON BIRKENHEAD & GREEN

SHEET 6 OF 7



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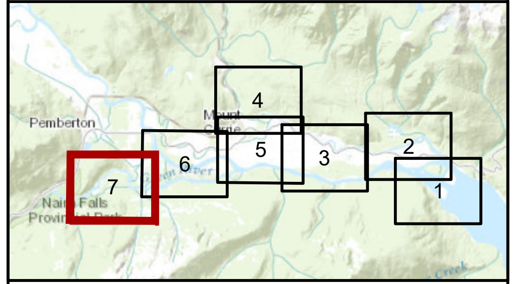


Legend

- Breach Location
- Flow Direction
- Dike
- Pemberton Valley Dyking District
- Nation Land (provided by Lil'Wat Nation)

Hazard Rating (m*m/s)

Hazard Rating = Depth x (Velocity + 0.5)

- Low: < 0.75
- Moderate: 0.75 - 1.25
- Significant: 1.25 - 2.5
- Extreme: > 2.5

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

Please refer to General Notes on Map Index Sheet.

Scale - 1:10,000

0 100 200 400 Meters

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES Vertical Datum: CGVD(2013)

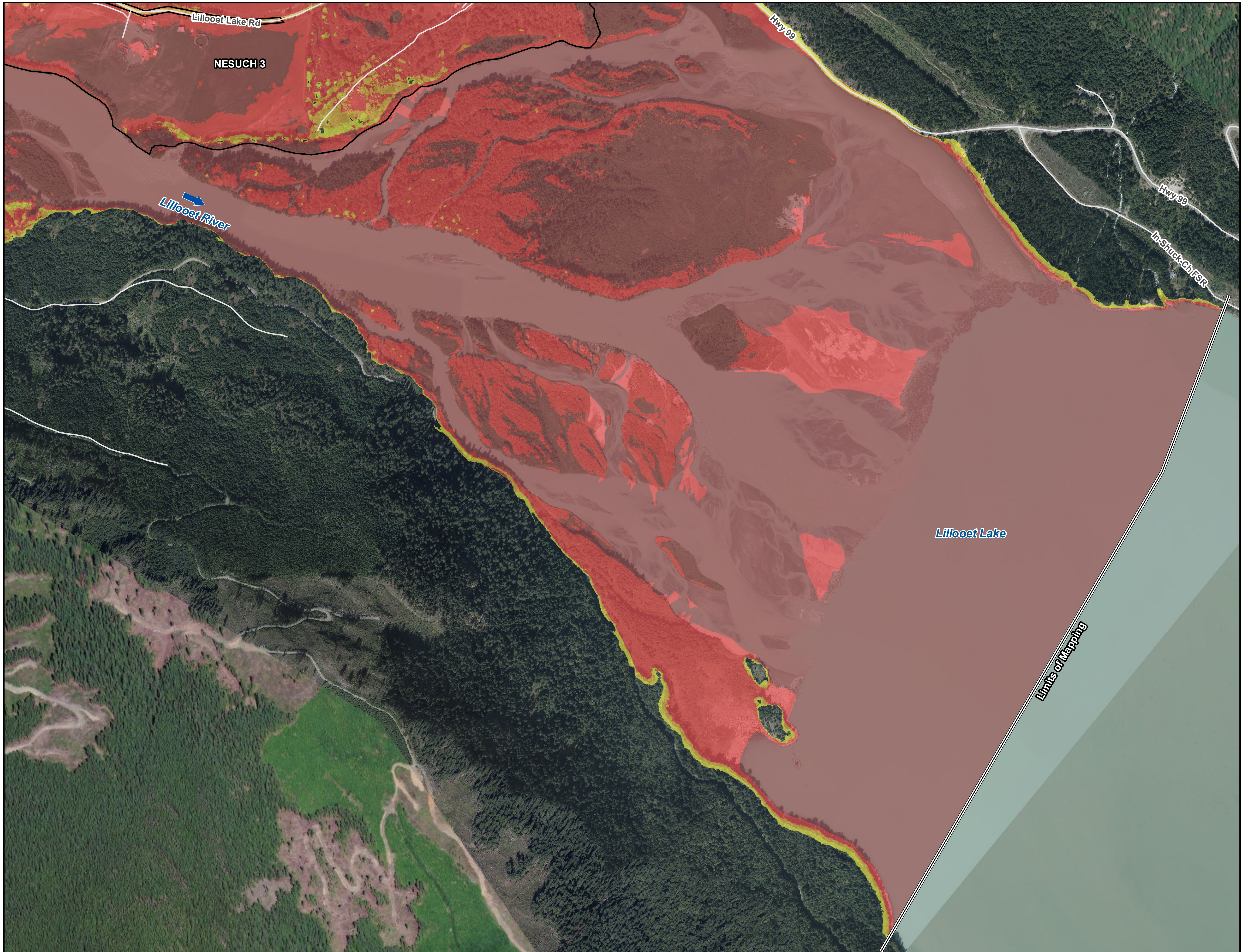
Engineer	GIS	Reviewer
VCCB	MAO	MCM

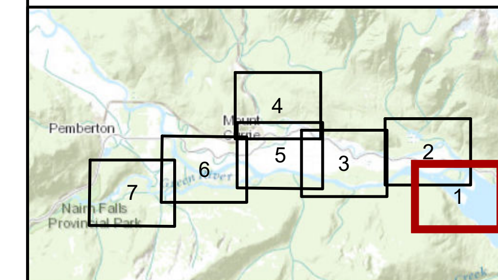
Job Number	Date
3004698	22-SEPT-2020

BIRKENHEAD AND GREEN RIVER
FLOODPLAIN MAPPING

FLOOD DEPTH 100-YR BREACH EVENT FOR BIRKENHEAD, GREEN & LILLOOET, INCLUDING CLIMATE CHANGE ON BIRKENHEAD & GREEN

SHEET 7 OF 7





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Legend

- Breach Location
- Flow Direction
- Dike
- Pemberton Valley Dyking District
- Nation Land (provided by Lil'Wat Nation)

Hazard Rating (m*m/s)

Hazard Rating = Depth x (Velocity + 0.5)

- Low: < 0.75
- Moderate: 0.75 - 1.25
- Significant: 1.25 - 2.5
- Extreme: > 2.5

Low: Caution - Flood zone with shallow flowing water or deep standing water.
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Please refer to General Notes on Map Index Sheet.

Scale - 1:10,000

0 100 200 400 Meters

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES Vertical Datum: CGVD(2013)

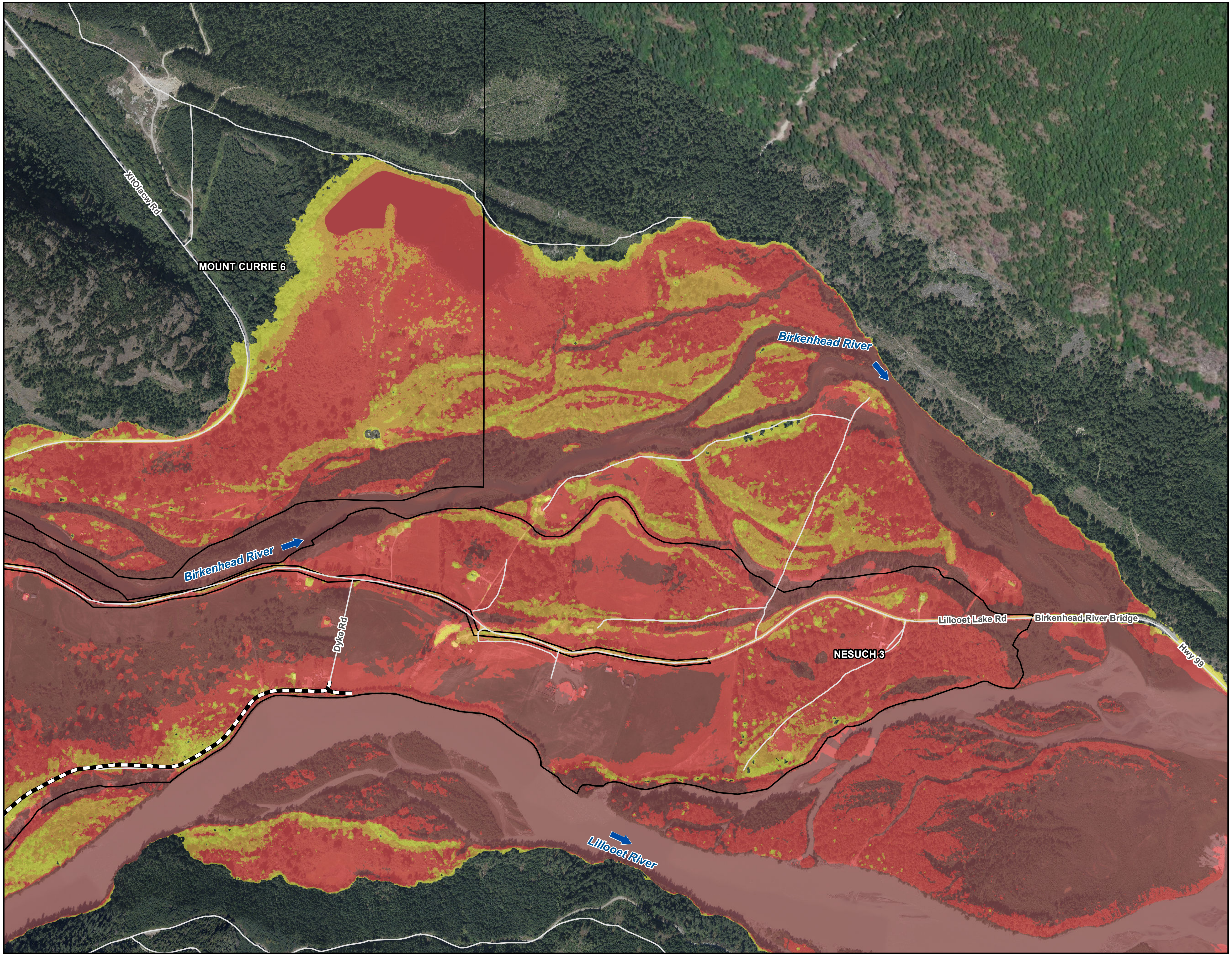
Engineer	GIS	Reviewer
VCCB	MAO	MCM

Job Number	Date
3004698	22-SEPT-2020

BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

FLOOD HAZARD 200-YR BREACH EVENT FOR BIRKENHEAD, GREEN & LILLOOET, INCLUDING CLIMATE CHANGE ON BIRKENHEAD & GREEN

SHEET 1 OF 7



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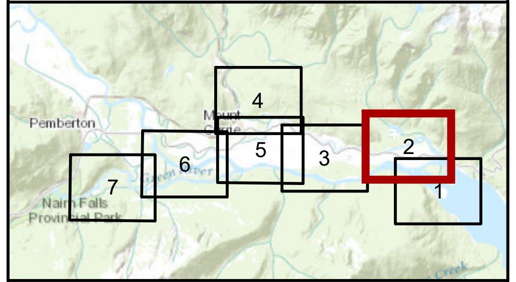

Legend

- Breach Location
- Flow Direction
- Dike
- Pemberton Valley Dyking District
- Nation Land (provided by Lil'Wat Nation)

Hazard Rating (m*m/s)

Hazard Rating = Depth x (Velocity + 0.5)

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Please refer to General Notes on Map Index Sheet.

Scale - 1:10,000

0 100 200 400 Meters

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES Vertical Datum: CGVD(2013)

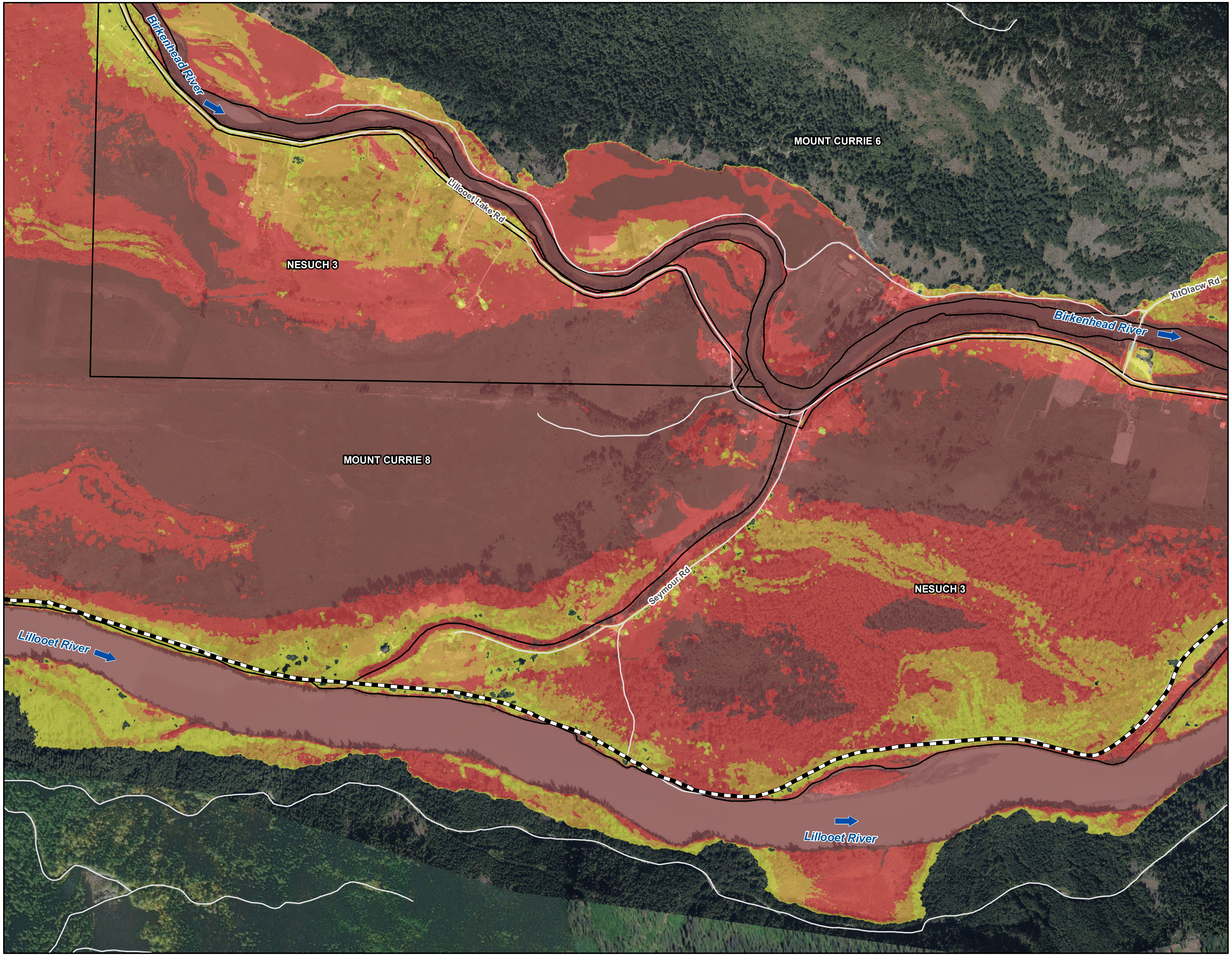
Engineer	*GIS*	*Reviewer*
VCCB	*MAO*	*MCM*

Job Number	*Date*
3004698	*22-SEPT-2020*

BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

FLOOD HAZARD 200-YR BREACH EVENT FOR BIRKENHEAD, GREEN & LILLOOET, INCLUDING CLIMATE CHANGE ON BIRKENHEAD & GREEN

SHEET 2 OF 7



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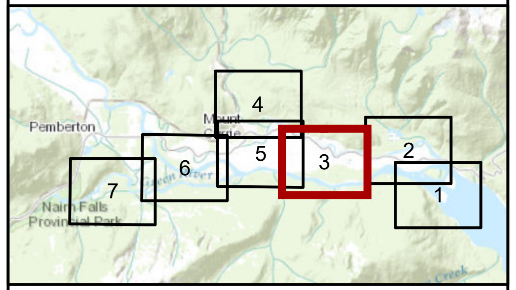

Legend

Breach Location
Flow Direction
Dike
Pemberton Valley Dyking District
Nation Land (provided by Lil'Wat Nation)

Hazard Rating (m*m/s)

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Scale - 1:10,000
0 100 200 400 Meters
N

Coordinate System: NAD 1983 UTM ZONE 10N
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Engineer	GIS	Reviewer
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Job Number	Date
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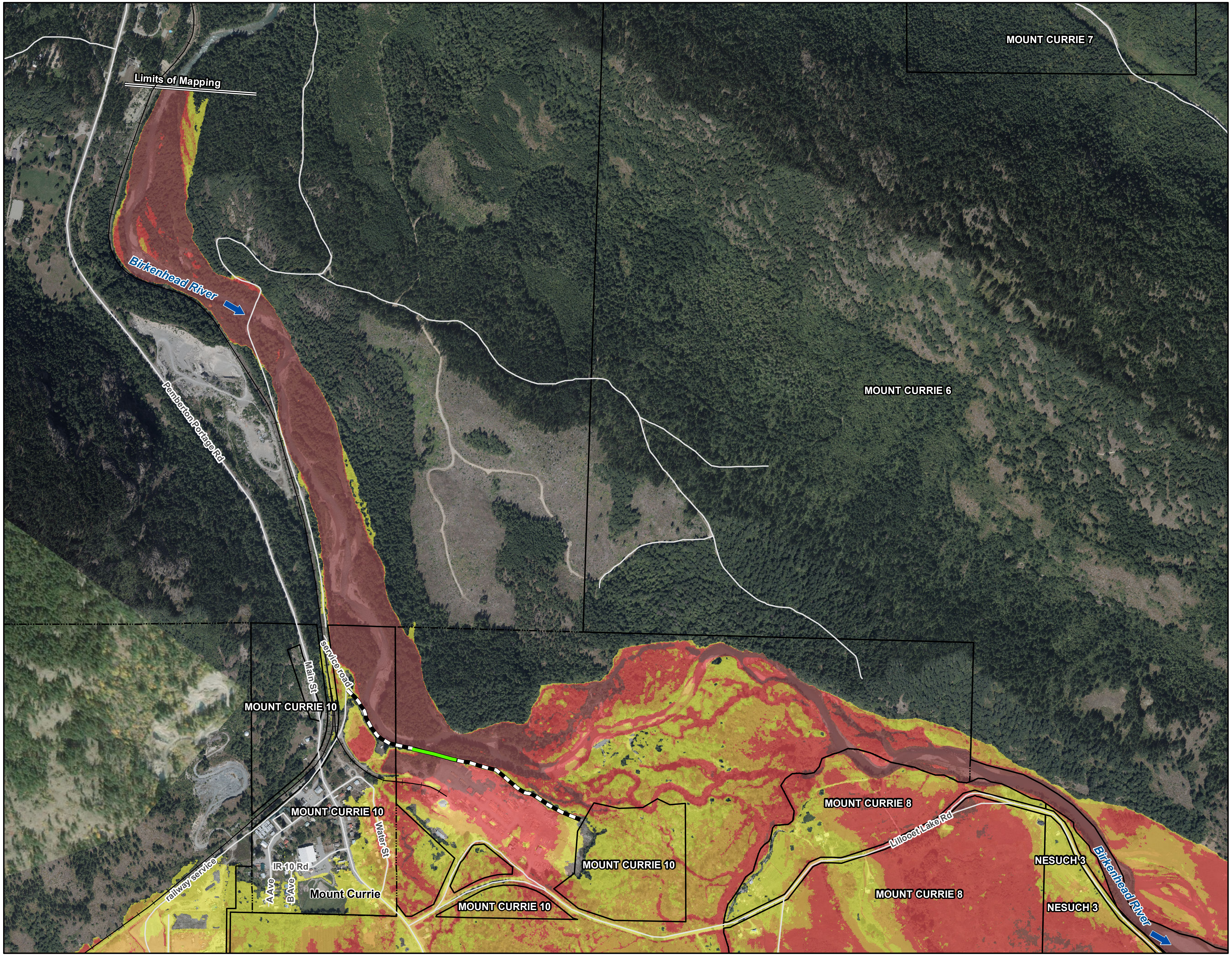
BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

FLOOD HAZARD 200-YR BREACH EVENT FOR BIRKENHEAD, GREEN & LILLOOET, INCLUDING CLIMATE CHANGE ON BIRKENHEAD & GREEN

SHEET 3 OF 7



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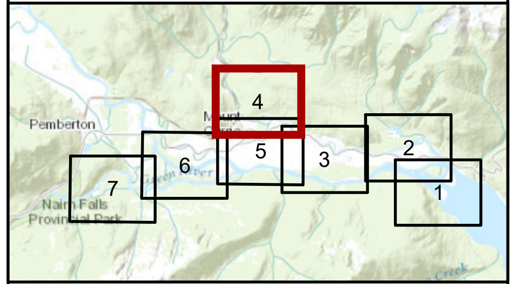

Legend

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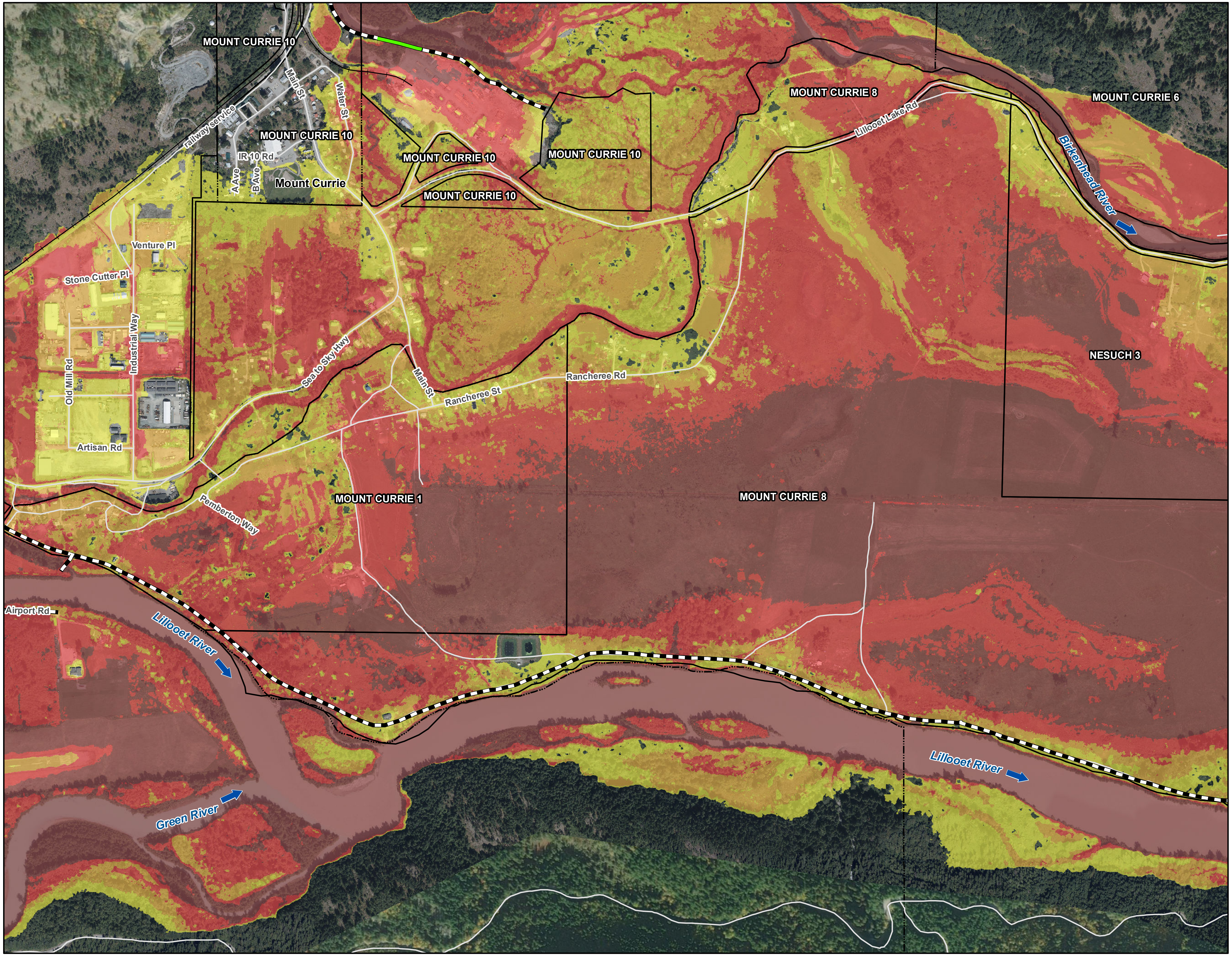
BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

FLOOD HAZARD 200-YR BREACH EVENT FOR BIRKENHEAD, GREEN & LILLOOET, INCLUDING CLIMATE CHANGE ON BIRKENHEAD & GREEN

SHEET 4 OF 7



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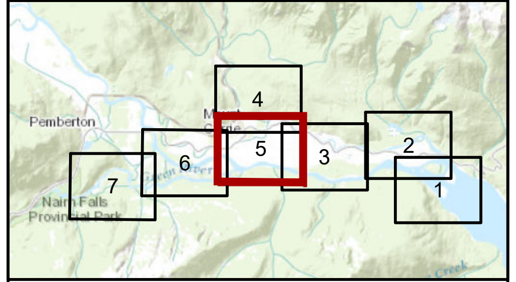

Legend

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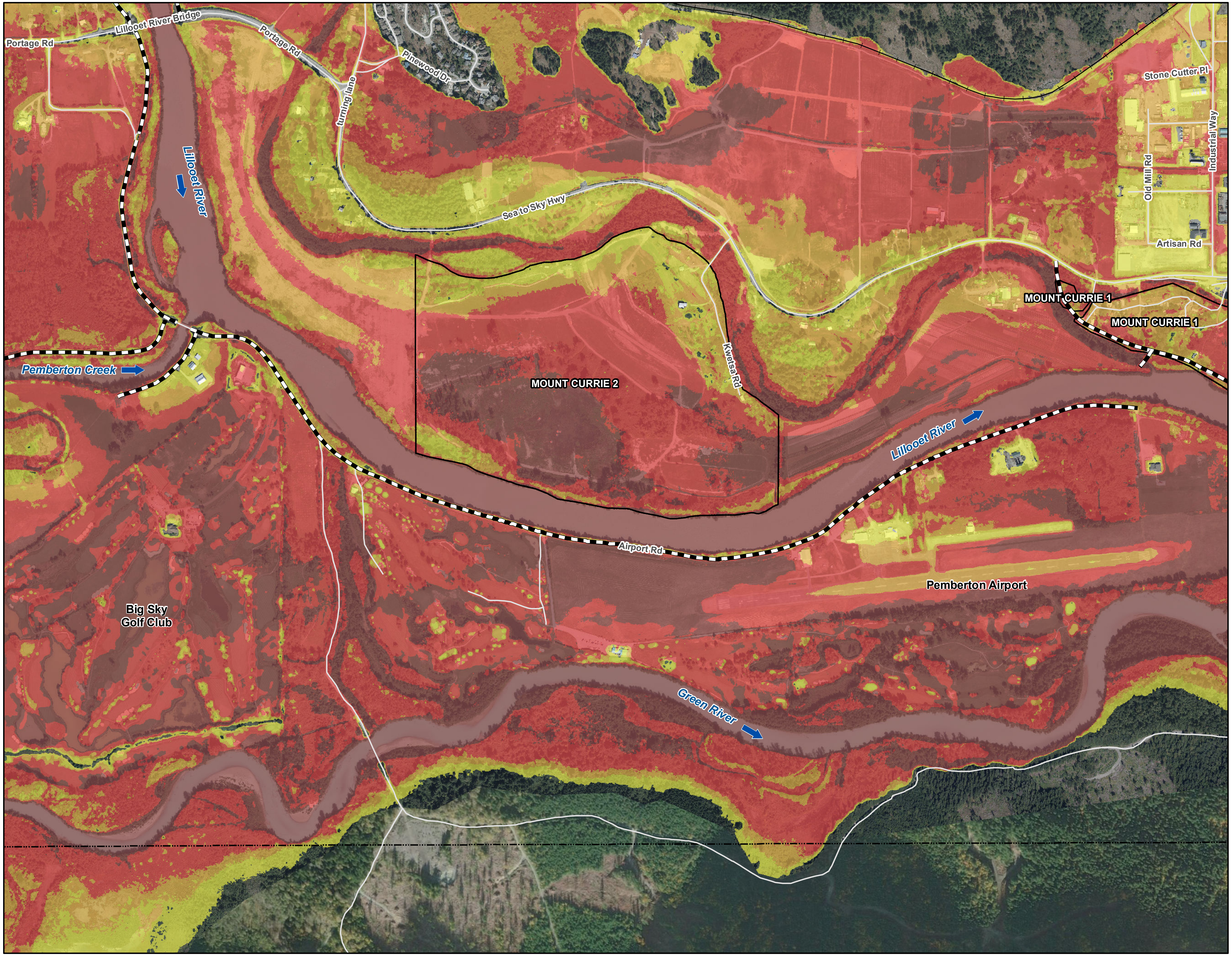
BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

FLOOD HAZARD 200-YR BREACH EVENT FOR BIRKENHEAD, GREEN & LILLOOET, INCLUDING CLIMATE CHANGE ON BIRKENHEAD & GREEN



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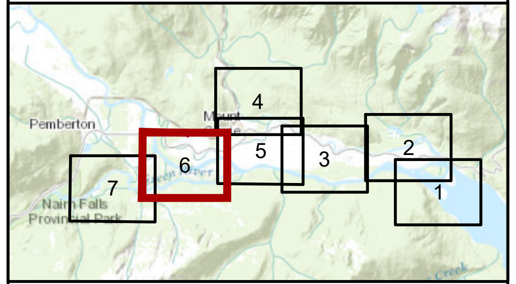

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BIRKENHEAD AND GREEN RIVER FLOODPLAIN MAPPING

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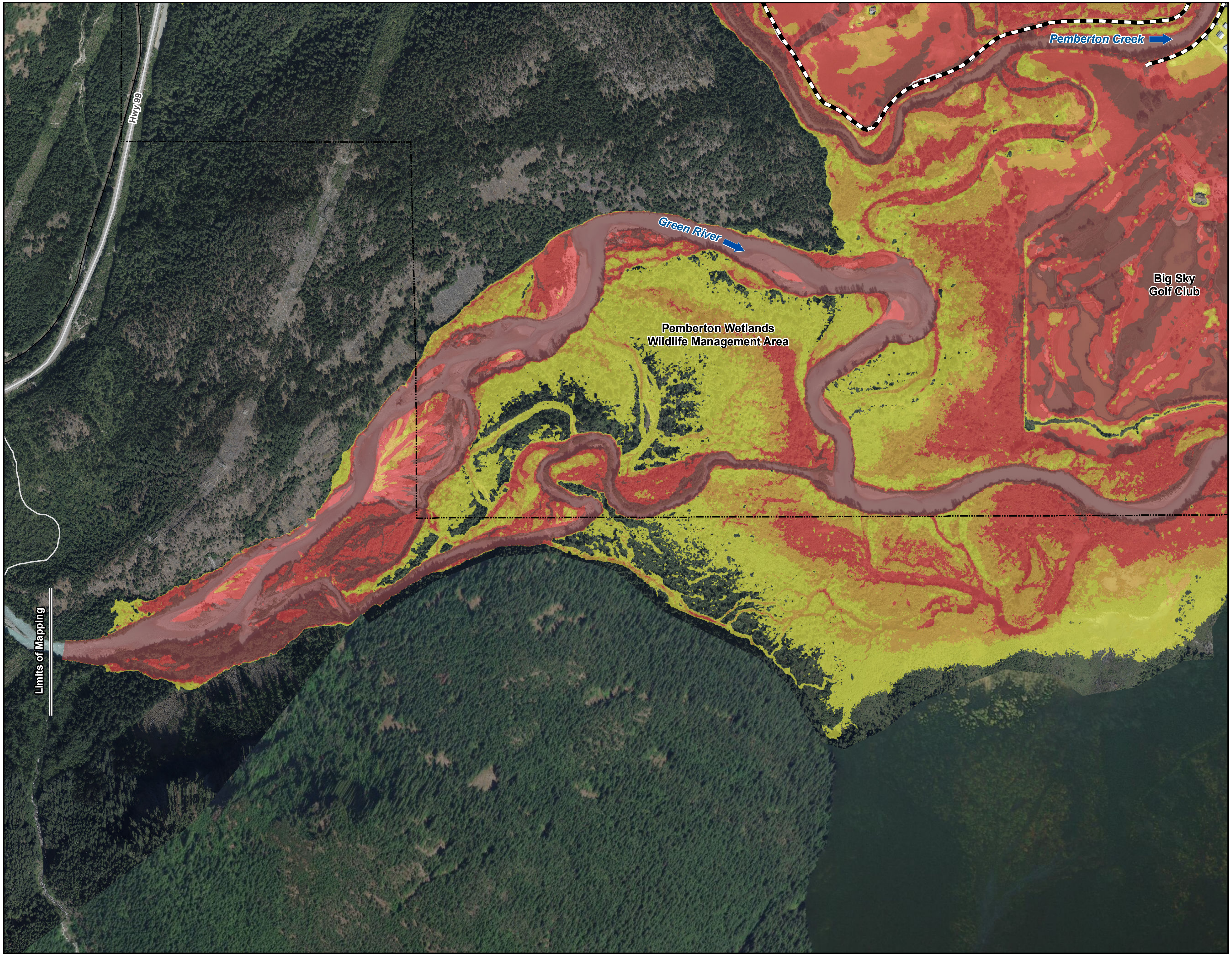

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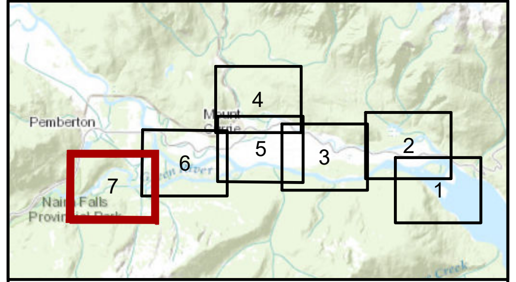

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BIRKENHEAD AND GREEN RIVER
FLOODPLAIN MAPPING

FLOOD HAZARD 200-YR BREACH EVENT FOR BIRKENHEAD, GREEN & LILLOOET, INCLUDING CLIMATE CHANGE ON BIRKENHEAD & GREEN

SHEET 7 OF 7