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Ryan River Floodplain Study

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March 15, 2023
Final Report, Rev. R1

NHC Reference 3006954

Document Tracking

Date	Revision no.	Reviewer	Issued for
24 February 2023	Draft R0	Jane Bachman (Geomorphology Section)	Client Review
02 March 2023	Draft R0	Neil Peters (whole)	Client Review

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CREDITS AND ACKNOWLEDGEMENTS

The authors would like to thank Pemberton Valley Dyking District (PVDD) for initiating this study and for the support provided during the project, in particular:

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EXECUTIVE SUMMARY

To reduce flooding during the 1940s and 1950s in the Pemberton Valley, the Lillooet River and several tributaries, including the Ryan River, were straightened, bypassing natural bends in several locations. In addition, some dikes were constructed, and Lillooet Lake was lowered by modifying the lake outlet. Despite the alterations, the rivers in the valley continued to flood. The Pemberton Valley Dyking District (PVDD) was subsequently formed and became responsible for upgrading and expanding dikes along the Ryan River, Lillooet River and its main tributaries. Northwest Hydraulic Consultants Ltd. (NHC) previously completed floodplain maps for the Lillooet River (NHC, 2018) on behalf of PVDD and has been retained to update a portion of these maps to incorporate the design flood for the Ryan River.

With a drainage basin area of 416 km^2, the Ryan River is a steep tributary to the Lillooet River. The upper watershed is characterized by steep terrain with an east-west orientation, as well as numerous tributaries with glaciers, rock falls, debris flow and debris flood deposits, avalanche tracks, and forestry activity. The channel stability of the Ryan River is strongly influenced by these sediment and debris sources, and this is most evident immediately downstream of the fan apex where extensive deposition of sediment and debris has occurred. Channel avulsion and bank erosion are also evident near the upstream section of the dike. The orientation of the upper watershed valley and its steep terrain characteristics, mixed hydrologic regime, and runoff response to seasonal Pacific storms during the fall directly contribute to the hydrogeomorphic characteristics observed in and near the fan. The morphology of the Ryan River changes when it reaches the Lillooet River valley, and channel gradient changes abruptly. Sediment and woody debris deposition immediately downstream of the fan apex is a critical contributor to channel instability. Large woody debris jams and large hydrogeomorphic event deposits are present and strongly influence lateral stability.

While the record of flood history on the Ryan River is very short (a gauge was only installed recently), the Lillooet River has a flow record stretching back the last 100 years. The record shows an increase in flood peaks since about the late 1970s. Evidence of this increase is also found in the flow records for other watercourses in the region, including the Ryan River. The increase in peak flows has been accompanied by a shift in the timing of annual floods. Instead of floods being caused by snowmelt in the springtime, annual peak floods are now more consistently caused by heavy rains in the fall or early winter. The flood flows are the result of intense low-pressure weather systems or atmospheric rivers. This shift in timing of the annual flood peak may be permanent, and climate change impacts are foreseen to further increase flood flows in the future.

NHC undertook a detailed hydrological assessment to estimate flood flow quantiles for the Ryan River, ranging from 50-year to 500-year return periods. NHC considered several approaches when establishing the methodology for this project; ultimately, our team conducted a regional flow frequency assessment using historical flow data from 10 representative Water Survey of Canada hydrometric gauges. The hydrology assessment included consideration of potential end-of-century climate change impacts and incorporation of an appropriate increase to design flows. In view of observed regional changes in timing and magnitude of peak flows since the 1970s, namely on the Lillooet River, NHC has adopted a 20% increase for the 500-year design flow on the Ryan River to account for the potential future impacts of climate change.

To support the hydraulic modelling and development of mapping, NHC updated a digital elevation model (DEM) of the valley from the Lillooet flood study, extending up the Ryan River several kilometres.

The hydraulic model uses the DEM as input and then calculates water levels corresponding to certain inflows and boundary water levels – in this case, the Lillooet River. NHC calibrated the model to observed water levels and flows and then used it to simulate the 50, 100, 200, 500-year scenarios for the Ryan River, including climate change.

The designated floodplain maps were developed from several different simulated results due to the complexity of the floodplain. As recommended by EGBC (2018) NHC chose a 500-year event due to the presence of the alluvial fan and the river's susceptibility to debris floods. Since it was necessary to tie the Ryan River maps into the recent (2018) Lillooet maps, a composite of scenarios was used ranging across and down the valley. The Ryan River scenarios used included a 500-year flood with climate change and a bulking factor of 1.4 to account for debris, a 500-year flood with climate change (no bulking factor), and a 200-year flood. The Ryan River floods were coincident with a 200-year Lillooet River flood. Freeboard allowance ranged from 1.0 metre (m) on the Ryan River to 0.6 m on the Lillooet River.

The designated flood maps show the extents of flooding and include flood construction levels (FCLs) as the minimum level for construction. The Squamish Lillooet Regional District has the authority to designate the maps as official floodplain mapping for their areas. The flood extents are very similar to the 1990 and 2018 maps, but the FCLs are considerably higher than the 1990 maps due to the increased flood flow and the more accurate modelling methods applied. The increases over 2018 are smaller, ranging from 0.2-1.0 m across the shared floodplain between the Ryan and Lillooet River and are caused primarily by the increased flow from the Ryan River and the increased freeboard. However, the configuration of the floodplain plays a role, water becomes confined between the dikes on the Ryan and the Lillooet Rivers on the floodplain which raises the water level in the central part of the valley. The flood depth and hazard maps are primarily intended for emergency response planning. NHC produced flood depth and hazard maps for the 50, 100, and 200-year floods. Flood hazard ratings are based on flood depths and flow velocities combined.

The Pemberton Valley is now one of relatively few communities in British Columbia with up-to-date floodplain maps, providing valuable information for improving flood safety and emergency response in the valley. By sharing the results and educating key authorities, stake holders and the public, the PVDD will help reduce potential loss of life and flood damages during future extreme flood events. Planning new development away from high hazard areas and implementing the Ryan River updated FCLs is anticipated to lead to more flood-resilient development. Access and egress routes requiring improvement can readily be identified and the location of temporary evacuation areas determined. Substantial dike upgrades are likely to be costly, and a dialogue regarding tolerable flood risk should be initiated. Consideration should also be given to relocating or floodproofing existing housing and other development in extreme flood hazard areas.

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ABBREVIATIONS

Acronym / Abbreviation	Definition
BC	British Columbia
CSCM	Central South Coast Mountains
DEM	digital elevation model
EGBC	Engineers and Geoscientists British Columbia
ESCM	Eastern South Coast Mountains
FCL	flood construction level
FFA	flood frequency analysis
HEC	U.S. Army Corps of Engineers Hydrologic Engineering Center
HWM	high-water mark
LiDAR	light detection and ranging
LWD	large woody debris
NHC	Northwest Hydraulic Consultants Ltd.
PVDD	Pemberton Valley Dyking District
QPI	peak instantaneous flow
WSC	Water Survey of Canada

SYMBOLS AND UNITS OF MEASURE

Symbol / Unit of Measure	Definition
%	percent
km	kilometre
km^2	square kilometres
m	metre
m^3/s	cubic metres per second
mm	millimetre

1 INTRODUCTION

Located in the Coast Mountains roughly 160 kilometres (km) north of Vancouver, the Pemberton Valley extends from Lillooet Lake up to the confluence of Meager Creek and includes the Village of Pemberton, Mount Currie, and Pemberton Meadows. Pemberton Village currently has a population of approximately 2,600 people, with the local economy dependent on farming, logging, and tourism. The climate is warm and dry in the summer and generally wet in the winter.

The Prairie Farm Rehabilitation Administration initiated the straightening and diking of the Lillooet River and its tributaries, the Ryan River and Miller Creek, as well as the lowering of Lillooet Lake. The Pemberton Valley Dyking District (PVDD) was formed in 1947 to manage flood control and drainage in the Pemberton Valley. Over the next few decades, the Lillooet River, as well as the Ryan River and other tributaries underwent extensive anthropogenic change, which resulted in largely confining the Ryan River channel to the east valley wall.

1.1.1 Historical Flooding

Five significant floods have occurred over the past 78 years on the Lillooet River, four of them during the past 37 years, causing damage to the Pemberton area. The largest floods typically occur in the fall and are associated with rain-on-snow events. In the fall of 1984, Pemberton suffered another severe event, and residents had to be evacuated. This was the largest flood on record for the Lillooet River at the time. In addition, the dikes on the Ryan River were overtopped and failed. Peak flood levels were reached almost 26 hours after the dikes overtopped (KWL, 2002). The flood of 2003 was another fall flood, which occurred when a warm front caused prolonged rainfall in the area, setting rainfall records. The flood peaked during the night and set a new all-time high of 1,490 cubic metres per second (m^3/s) for the Lillooet River at the Water Survey of Canada (WSC) gauge near Pemberton, becoming yet another flood of record. The Ryan River breached its dike near the apex of the fan. In adjacent areas, the flood washed out Highway 99 at Rutherford Creek, cutting off Pemberton from Whistler and the Lower Mainland. Unprotected areas of the valley were inundated, and flood waters rose to the crest of several dikes near Pemberton (KWL, 2005).

The Ryan River only recently had a WSC hydrometric gauge installed, so flood history for this river is mostly unknown beyond large events when flooding was recorded in conjunction with the Lillooet River.

1.1.2 Previous Floodplain Mapping Studies

Several floodplain mapping and hydraulic modelling studies have been completed for the Pemberton Valley, which are focused on the Lillooet River. In 1973, the Water Management Division of the Ministry of Environment, Lands and Parks originally mapped the floodplain. The ministry revised the floodplain map in 1980 and again in 1990, following the 1984 flood. In 1995, the ministry once again updated the design profiles for the river following the 1991 flood, but deemed that actual floodplain mapping did not need to be updated at that time. In 2002, KWL further updated the design flood profiles, but did not produce mapping. The Ryan River has not been flood-mapped on its own.

In accordance with the Ministry of Forests guidelines, the PVDD is responsible for maintaining dikes on the Ryan River. In the Lillooet River Floodplain Mapping Final Report, Northwest Hydraulic Consultants Ltd. recommended additional mapping of the tributaries (NHC, 2018). PVDD therefore sought funding to complete flood mapping and design profiles for the Ryan River and retained NHC to carry out a floodplain mapping study of the approximately 16.5 km reach from the top of the Ryan River fan to the confluence with the Lillooet River.

1.2 Project Scope

This section provides a description of the project scope, which is summarized as follows:

1. Additional surveys
    a. Extend the bathymetric survey upstream by approximately 1.2 km to allow modelling of the Ryan River as it emerges from the hillside to help assess the potential for an avulsion at this location.
    b. Conduct additional bank surveys to improve the interpolation of the Ryan River's left and right banks in the strips between the bathymetric and LiDAR surveys.
    c. Survey of specified Ryan River dike sections where vulnerability identified.
    d. Resurvey selected sections to assess aggradation and degradation volumes since the previous survey in summer of 2017.
2. Hydrologic analysis
    a. Follow a regional approach. Since the Ryan River is ungauged, NHC has adopted a regional approach, similar to the one used for the previous work, to estimate the Ryan River's 20, 50, 100 and 200-year flood hydrographs. NHC's scope includes approximating the corresponding Lillooet River flows and flood levels at the Ryan River outlet based on previous modelling and estimating the impacts of climate change on the peak 200-year design conditions.
3. Channel stability analysis
    a. Conduct both an air photo desktop review and field observations to assess the lateral stability of the river.
4. Hydraulic modelling
    a. Update the digital elevation model (DEM) for the valley and extend the existing Lillooet River model further up the Ryan River.
    b. Calibrate and validate the model.
    c. Simulate design event for floodplain mapping.
5. Flood maps
    a. Develop a designated floodplain map depicting 200-year flood levels plus a freeboard allowance.
    b. Produce flood depth maps for the 50-, 100-, and 200-year floods.

c. Produce flood hazard maps showing a hazard rating based on flood depths and flow velocities.

6. Reporting

   a. Document the process of conducting additional surveys and analyses of hydrologic conditions and channel stability, modelling river hydraulics, and producing floodplain maps for the Ryan River.

2 HYDROLOGICAL ASSESSMENT

This section presents a description of NHC's hydrological assessment of the Ryan River and includes a watershed overview, flood flow estimates, climate change considerations, and flood hydrographs.

2.1 Watershed Overview

The Ryan River is a tributary to the Lillooet River, located in the Coast Mountains of southwestern British Columbia (BC). It drains into the Lillooet River from the west side of the Pemberton Valley, approximately 4 km upstream of the Village of Pemberton (Figure 2.1).

Key physical and hydrologic properties of the Ryan River watershed are summarized as follows:

- drainage area: 416 square kilometres (km^2)
- mean annual precipitation: 1,732 millimetres (mm) (NHC, 2021b) (UBC, 2021)
- glacier area: 16% (BC Freshwater Atlas, 2018)
- lake area: <1% (BC Freshwater Atlas, 2018)
- maximum watershed elevation: 2,603 m
- mean watershed elevation: 1,558 m
- minimum watershed elevation: 215 m
- aspect: west to east
- hydrologic zones: Eastern South Coast Mountains
Central South Coast Mountains (Government of British Columbia, 2022)
- ecozone and ecoprovince: Pacific Maritime
South Coastal Mountains (Marshall et al., 1999)

Figure 2.1 Ryan River watershed overview.

The region surrounding the Pemberton Valley is a transition zone between the very moist Coast Mountains and the dry Interior of BC. Within this transition zone, which connects the vastly different hydroclimates of BC's coastal and interior regions, there is considerable spatial and temporal variation in hydrology. Overall, the hydrologic regime in this area is snowmelt dominant; however, depending on the watershed, the hydrologic regimes may also be rainfall dominant, rain-snow hybrid, snow-glacier, and rain-snow-glacier hybrid (Eaton and Moore, 2010). In some places these regimes may also change over time based on medium- (e.g., El Niño 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 because of other processes such as heavy rainfall, rain-on-snow flooding, and rain-on-glacier flooding.

Although the WSC recently started gauging flows on the Ryan River in June 2021, several decades of data will be required before the river's flow regime can be defined. As a major tributary to the Lillooet River, the Ryan River may share a similar flow regime to the larger system, which is considered to have a rain-snow hybrid regime since around 1975 (NHC, 2018). Figure 2.2 compares average monthly hydrographs from WSC gauges 08MG028 Ryan River near Pemberton Meadows (WSC 08MG028) and 08MG005 Lillooet River near Pemberton (WSC 08MG005).

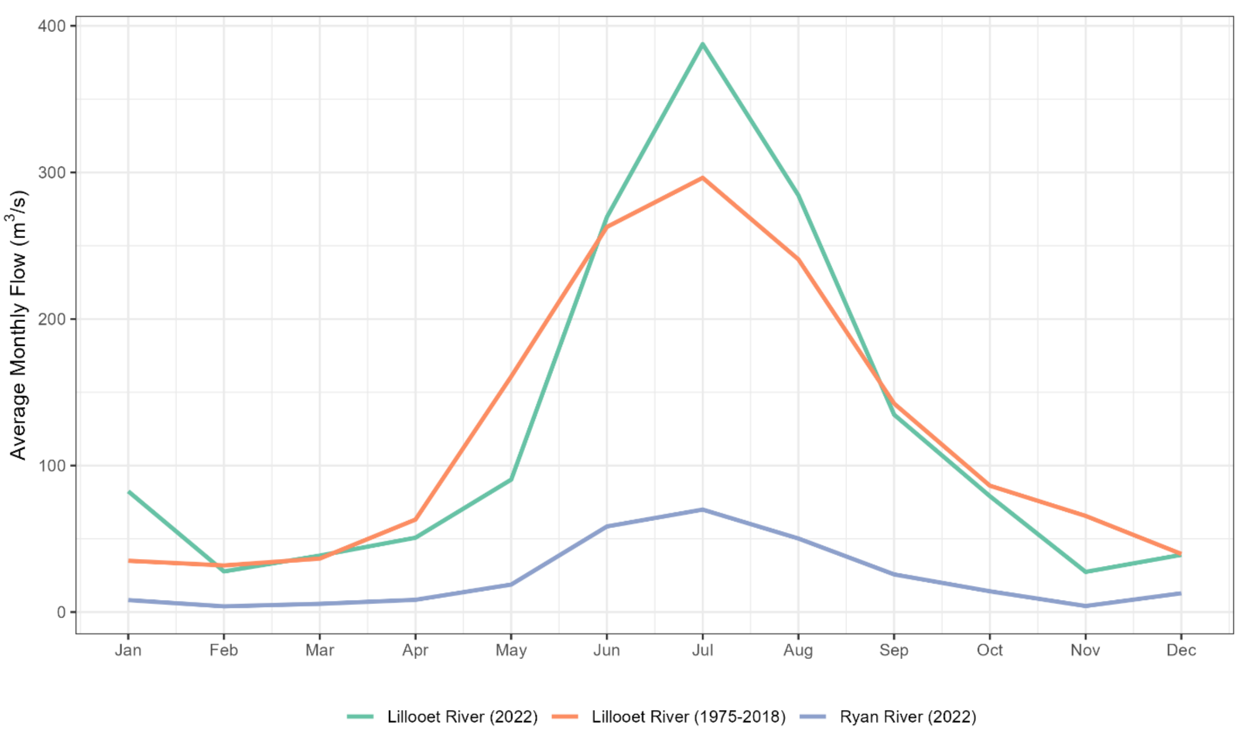

Figure 2.2 2022 monthly hydrographs for the Ryan River (WSC 08MG028) and Lillooet River (WSC 08MG005). The long-term monthly average for the Lillooet River was calculated from historical hydrometric data from 1975 to 2018.

2.2 Flood Flow Estimates

Flows on the Ryan River are currently recorded by WSC 08MG028, which was only established in June 2021, making the data record too short to perform a flood frequency analysis (FFA).

NHC explored several approaches to estimate flood quantiles for the Ryan River (see Section 2.1 for additional details). Ultimately, a regional hydrology assessment was deemed the most appropriate approach.

A regional hydrology assessment involves using flood quantiles from select gauged watersheds in the general region of a target watershed (i.e., the Ryan River). The selected gauged watersheds should capture a range of drainage areas but should otherwise be representative of probable hydrological and meteorological conditions in the target watershed. FFAs from the gauges are then used to establish a general regional relationship between peak flows and the drainage area for a given return period. This relationship can then be applied to estimate return-period peak flows for the target watershed based on its drainage area. The following sections summarize the process of the regional hydrology assessment to estimate flood quantiles for the Ryan River.

2.2.1 Selection of Regional Gauges

According to BC Hydrologic Zone classifications (Government of British Columbia, 2022), the Ryan River watershed overlaps two hydrologic zones: the Eastern South Coast Mountains (ESCM) and the Central South Coast Mountains (CSCM). NHC's assessment considered 48 watersheds gauged by WSC in the ESCM and CSCM hydrologic zones for inclusion as regional watersheds for the Ryan River's regional FFA, based on the following factors:

- suitability of gauge data records (duration and recency)
- drainage area
- proximity to the Ryan River watershed
- similar physical properties with the Ryan River watershed, such as:
    - mean annual precipitation
    - glacier area
    - lake area
    - median watershed elevation
    - WSC gauge elevation
    - watershed aspect
    - dominant ecozone/ecoprovince

Ultimately, NHC selected 10 WSC gauges for the regional assessment based on the above criteria, as summarized in Table 2.1.

Table 2.1 Regional gauges used for the Ryan River flood frequency analysis.

WSC Gauge	Record Period	Years Active	Distance from the Ryan River Watershed (km)	Drainage Area (km²)	Mean Annual Precipitation (mm)	Glacier Area (%)	Lake Area (%)	Median Watershed Elevation (m)	Dominant Flow Regime
Ryan River Watershed				416	1,732	16	0.3	1,558	
WSC 08GA071 *Elaho River near the Mouth*	1981 – 2018	38	29	1,200	2,566	22	0	1,547	Mixed
WSC 08GA072 *Cheakamus River above Millar Creek*	1982 – 2019	38	31	297	2,205	15	2	1,654	Mixed
WSC 08ME027 *Hurley River below Lone Goat Creek*	1996 – 2020	25	27	312	1,313	7	0	1,827	Mixed
WSC 08MG003 *Green River near Pemberton*	1913 – 1951	39	8	855	1,775	9	1	1,480	Mixed
WSC 08MG005 *Lillooet River near Pemberton*	1914 – 2017	99	3	2,100	1,456	18	0	1,656	Mixed
WSC 08MG006 *Rutherford Creek near Pemberton*	1914 – 1948	27	10	179	1,807	9	1	1,553	Mixed
WSC 08MG007 *Soo River near Pemberton*	1915 – 1948	26	15	283	1837	13	0	1,424	Mixed
WSC 08MG008 *Birkenhead River at Mount Currie*	1945 – 1971	27	8	596	1,159	1	1	1,568	Snowmelt
WSC 08MG025 *Pemberton Creek near Pemberton*	1987 – 2018	31	5	32.4	1,637	12	0	1,414	Rainfall
WSC 08MG026 *Fitzsimmons Creek below Blackcomb Creek*	1993 – 2017	24	27	89.7	1,755	6	0	1,696	Mixed

2.2.2 Flood Frequency Analysis

NHC completed FFAs for all selected regional gauges based on their peak instantaneous flow (QPI) data records from previous NHC studies, as summarized in Table 2.2. For each return period of interest, NHC plotted the QPI for each regional gauge against the gauge's drainage area and fit a power function through the dataset. NHC then determined fitted power law coefficients *a* and *b* for each return period based on equation 1:

$$Q = a \times A^b \qquad (1),$$

where Q is the flood flow (m^3/s) and A is the watershed area (km^2). Example fitting results for the 200-year return period are displayed in Figure 2.3. Fitted power law coefficients for each return period are summarized in Table 2.3.

Table 2.2 Peak instantaneous flow estimates for regional gauges.

WSC Gauge	QPI Estimate Based on Return Period (m^3/s)						
	2-year	5-year	10-year	20-year	50-year	100-year	200-year
WSC 08GA071 *Elaho River near the Mouth*[1]	684	904	1,064	1,228	1,459	1,646	1,846
WSC 08GA072 *Cheakamus River above Millar Creek*[1]	83	117	151	198	287	386	522
WSC 08ME027 *Hurley River below Lone Goat Creek*[1]	86	114	136	161	199	232	271
WSC 08MG003 *Green River near Pemberton*[2]	220	278	327	382	467	542	628
WSC 08MG005 *Lillooet River near Pemberton*[1]	620	849	1,031	1,233	1,540	1,810	2,118
WSC 08MG006 *Rutherford Creek near Pemberton*[3]	83	116	139	161	191	213	236
WSC 08MG007 *Soo River near Pemberton*[3]	116	150	172	192	217	236	255
WSC 08MG008 *Birkenhead River at Mount Currie*[2]	108	162	219	288	397	491	594
WSC 08MG025 *Pemberton Creek near Pemberton*[1]	17	23	27	31	35	38	40
WSC 08MG026 *Fitzsimmons Creek below Blackcomb Creek*[1]	19	25	29	35	43	52	62

Notes:

1. FFA results from *Lillooet River Floodplain Mapping* (NHC, 2018).
2. FFA results from *Birkenhead and Green River Floodplain Mapping and Risk Assessment* (NHC, 2021a).
3. FFA results determined from *British Columbia Extreme Flood Project* (NHC, 2021b). The WSC 08MG006 and WSC 08MG007 gauge records lack QPI data, so NHC converted the QPD (peak daily flow) FFAs to QPI FFAs using a regional QPI:QPD relationship, which was determined as the average from rank-to-rank linear relationships between QPD and QPI for WSC 08GA071, WSC 08GA072, WSC 08ME027, and WSC 08MG003.

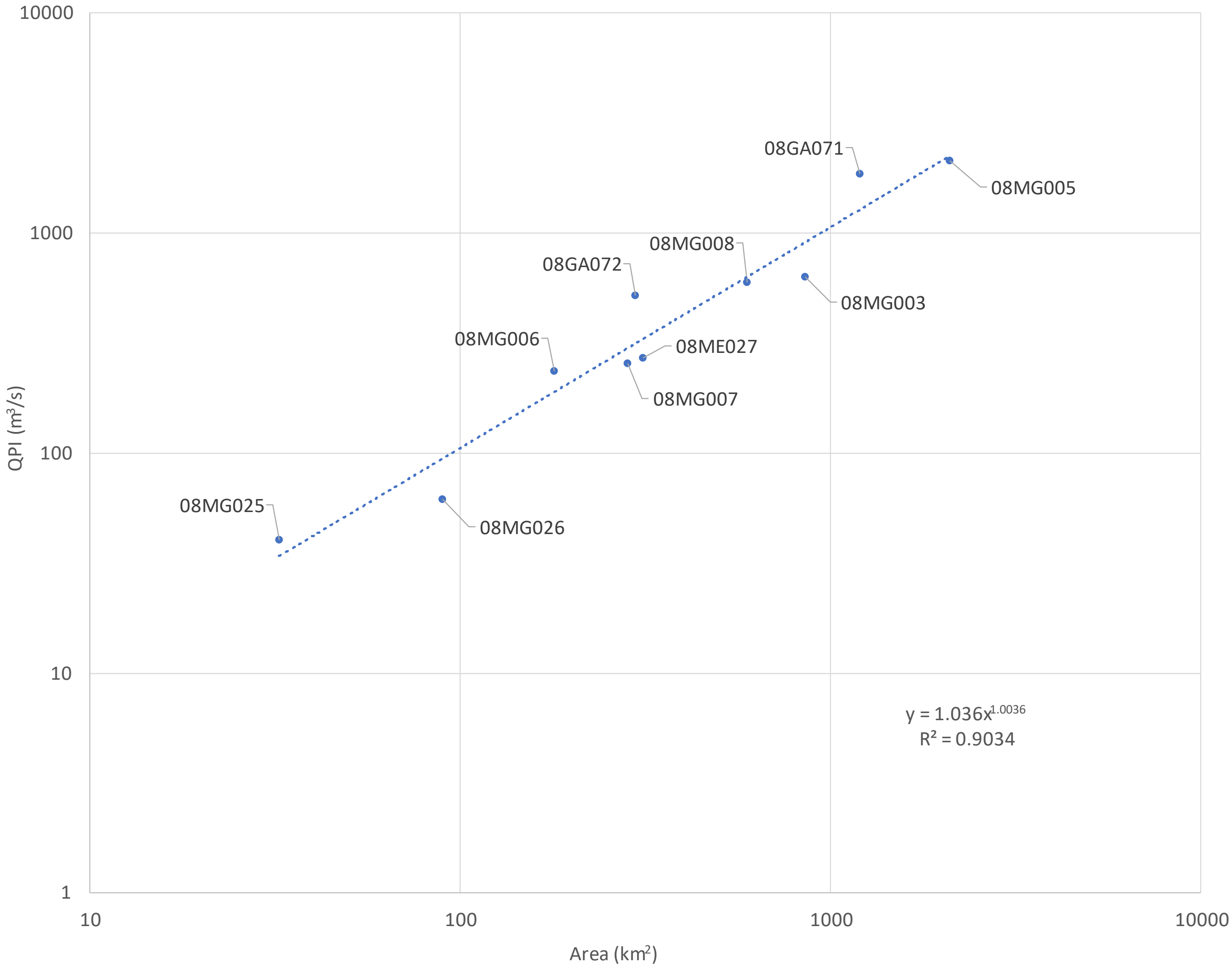

Figure 2.3 Regional hydrology relationship for the 200-year return period.

Table 2.3 Fitted power law coefficients for regional flood frequency analysis.

Return Period (years)	Coefficient *a*	Coefficient *b*
2	0.4735	0.9355
5	0.6198	0.9405
10	0.7031	0.9514
20	0.7796	0.9634
50	0.8782	0.9798
100	0.9553	0.9919
200	1.0360	1.0036

NHC used equation 1 in combination with the Ryan River watershed area and fitted power law coefficients in Table 2.3 to estimate return-period flood quantiles for the Ryan River. The study team tested the sensitivity of the regional assessment by removing one or two regional gauges at a time from the assessment and examining the resulting changes to the Ryan River flood quantiles. The flood quantiles were not found to be highly sensitive to variations in the selected regional gauges.

Since the pre-existing FFAs for the regional gauges that formed this assessment only provide a return period of 200 years, NHC extrapolated the FFA results for the Ryan River to a 500-year return period by fitting a Log Pearson III distribution to the flood quantile data. The final FFA results for the Ryan River are summarized in Table 2.4.

Table 2.4 Flood frequency analysis results for the Ryan River at its confluence with the Lillooet River.

Return Period (years)	QPI (m^3/s)	Lower 95% Prediction Interval (m^3/s)	Upper 95% Prediction Interval (m^3/s)
2	133	46	333
5	180	62	519
10	218	87	472
20	260	104	630
50	323	133	754
100	378	167	826
200	440	190	957
500	531	259	1,230

2.2.3 Comparison to Other Flood Frequency Analysis Approaches

In addition to the regional FFA detailed above, NHC explored area-based scaling to estimate the Ryan River flood quantiles from the flood quantiles of WSC proxy gauges, according to Equation 2:

$$Q_A = Q_B \cdot \left(\frac{A_A}{A_B}\right)^e \qquad (2),$$

where Q_A is the flow (m³/s) on the Ryan River for a selected return period; Q_B is the selected return-period peak flow at the given WSC proxy gauge; A_A is the Ryan River watershed area (416 km^2), and A_B is the drainage area of the WSC proxy gauge. The scaling exponent, *e* is intended to capture the effects of the flow desynchronizations within watersheds as they become larger. The *British Columbia Extreme Flood Project* (NHC, 2021b) provides recommended scaling exponents for watersheds across BC based on ecoprovince. While the Ryan River watershed is in ecoprovince 13.2 (with a recommended scaling exponent of 0.85), it is situated beside ecoprovince 14.3 (recommended scaling exponent 0.98). Assigning appropriate scaling exponents for a given watershed is a difficult practice, and in a transition region where the Ryan River watershed is located, considering a range of scaling exponents can be helpful.

NHC considered two WSC gauges as proxies for the Ryan River watershed: WSC 08MG005 and WSC 08MG003. The study team selected WSC 08MG005 because the Ryan River is a significant tributary to the Lillooet River and may share similar flow characteristics. WSC 08MG003 was selected because the Green River is a neighbouring watershed to the Ryan River, as well as a tributary to the Lillooet River. Both proxy gauge watersheds share similar physical properties with the Ryan River watershed (Table 2.1); WSC 08MG005 is more representative of the Ryan River watershed in terms of glacier coverage, while WSC 08MG003 is more representative of the Ryan River in terms of mean annual precipitation.

Table 2.5 summarizes the area-based scaling FFA results for the Ryan River scaling from WSC 08MG005 and WSC 08MG003, using scaling exponents 0.85 and 0.98.

Table 2.5 Area-based scaling approaches for determining the flood frequency analysis.

Return Period (years)	Scaling Exponent = 0.85		Scaling Exponent = 0.98	
	Scaled from WSC 08MG005	Scaled from WSC 08MG003	Scaled from WSC 08MG005	Scaled from WSC 08MG003
2	157	122	128	112
5	215	154	175	141
10	262	182	212	166
20	310	212	252	194
50	391	259	317	237
100	459	301	372	275
200	538	349	436	319

Return Period (years)	Scaling Exponent = 0.85		Scaling Exponent = 0.98	
	Scaled from WSC 08MG005	Scaled from WSC 08MG003	Scaled from WSC 08MG005	Scaled from WSC 08MG003
500	658		534	

Scaling from WSC 08MG005 using an exponent of 0.98 yields very comparable results to the regional FFA presented in Table 2.4. Regardless of scaling exponent, the scaled flood quantiles from WSC 08MG003 are much lower than those scaled from WSC 08MG005. This finding provides evidence of the hydrological variation within the Lillooet River watershed and shows that WSC 08MG005 cannot be assumed to represent hydrologic conditions of all Lillooet River sub-watersheds. The finding also indicates the Lillooet River sub-watersheds cannot be assumed to represent the hydrologic conditions of other sub-watersheds, which was a topic further explored in the *Birkenhead and Green River Floodplain Mapping and Risk Assessment* (NHC, 2021a). Considering these results, the regional hydrology assessment is still considered to be the most appropriate approach for estimating flood quantiles for the Ryan River.

2.3 Climate Change Considerations

In previous NHC studies (NHC, 2018, 2021a, 2021b), Mann-Kendall trend tests were performed on the peak flow records of the regional gauges selected for this assessment. Of the 10 regional gauges, only WSC 08MG005 Lillooet River Near Pemberton showed a statistically significant trend (95% confidence level) toward increasing peak flows.

NHC (2018) found that around 1975, the hydrologic regime of the Lillooet River shifted from snowmelt dominant to rain-snow hybrid; this shift was attributed to the Pacific Decadal Oscillation and long-term climate change. Although none of the other regional gauges in this study have shown increasing flow trends, the Ryan River is a major tributary to the Lillooet River, and it is possible that it may have similar sensitivity to climate change, potentially resulting in increased peak flows.

Year-round rising temperatures are expected to result in increased total precipitation, an increased rain-to-snowfall ratio, decreased winter snowpack accumulation, and glacier recession (Pike et al., 2010; Shrestha et al., 2012). 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, and this may apply to the Ryan River as well.

The Ryan River watershed hydrology may also be susceptible to land use changes. Given the landscape of the watershed, the most significant changes to the basin may occur due to the loss of glaciers and forest disturbances, from both human and natural causes. Glacier loss is not expected to cause increased peak flows; however, wildfires, infestations, logging, and urbanization can alter peak flows, depending on the severity and coverage of the impacts.

Engineers and Geoscientists BC (EGBC, 2018) recommends applying a 20% factor of safety to peak flow estimates where increased flows are expected due to climate change. NHC recommends applying this 20% increase to govern design flows for the Ryan River, as summarized in Table 2.6.

Table 2.6 Ryan River design flows for model input, accounting for climate change.

Return Period (years)	Present Day QPI (m^3/s)	Design QPI with 20% Increase for Climate Change (m^3/s)
2	133	160
5	180	216
10	218	262
20	260	312
50	323	388
100	378	454
200	440	528
500	531	637

2.4 Flood Hydrographs

NHC conducted 2-D flood modelling (Section 4.2) by converting the design flows in into unsteady flood hydrographs. The study team identified a strong correlation between the flow datasets for WSC 08MG005 and the new WSC 08MG028 on the Ryan River[1]. As such, the WSC 08MG005 gauge record is deemed appropriate for simulating flood hydrographs for the Ryan River. The study team selected the 2003 flood of record hydrograph to simulate extreme-flow conditions (Figure 2.4).

The WSC 08MG005 2003 flood hydrograph was converted to a unitless hydrograph with a peak value of 1 at the maximum value on the curve (Figure 2.5). The unitless hydrograph was then converted to inflow hydrographs for the Ryan River hydraulic model, where the peak value would equal the design QPI for the event of interest (i.e., 528 m^3/s for the 200-year design flow) (Figure 2.6).

[1] For the full WSC 08MG028 data record at the time of this assessment (June 2, 2021 to June 13, 2022), the flow correlation with WSC 08MG005 was R^2=0.983 for daily flow data and R^2=0.973 for 5-minute flow data.

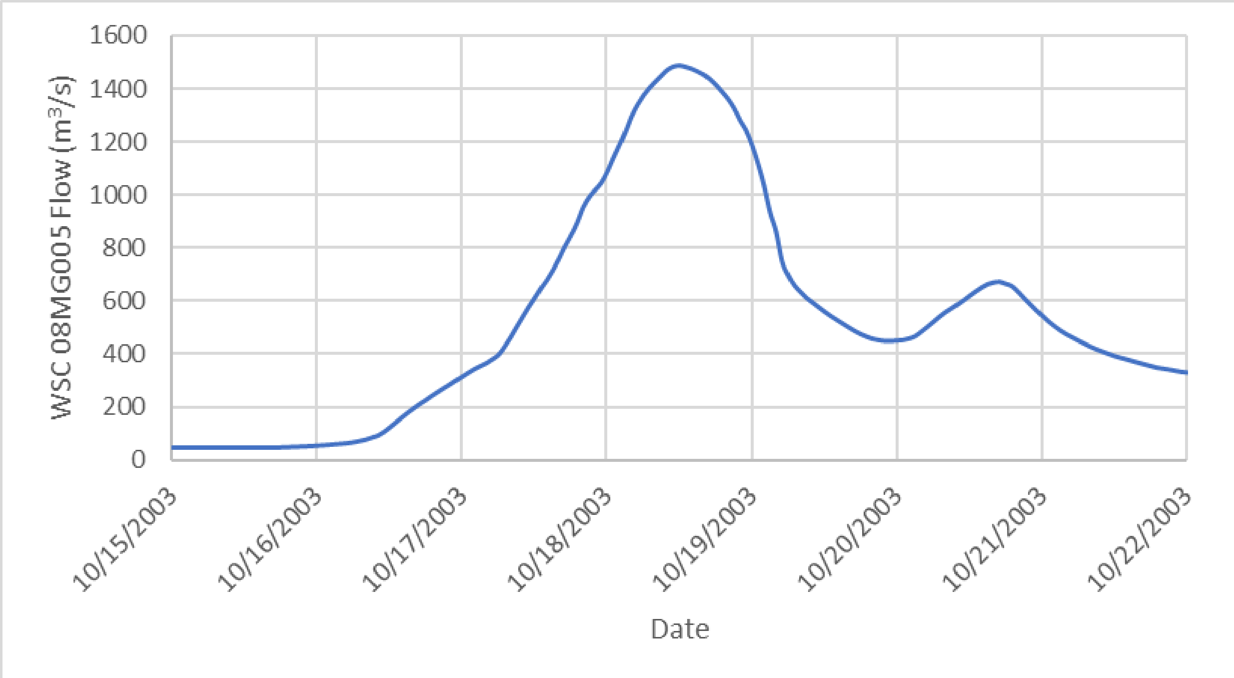

Figure 2.4 Hourly flow data for 2003 flood of record at WSC 08MG005.

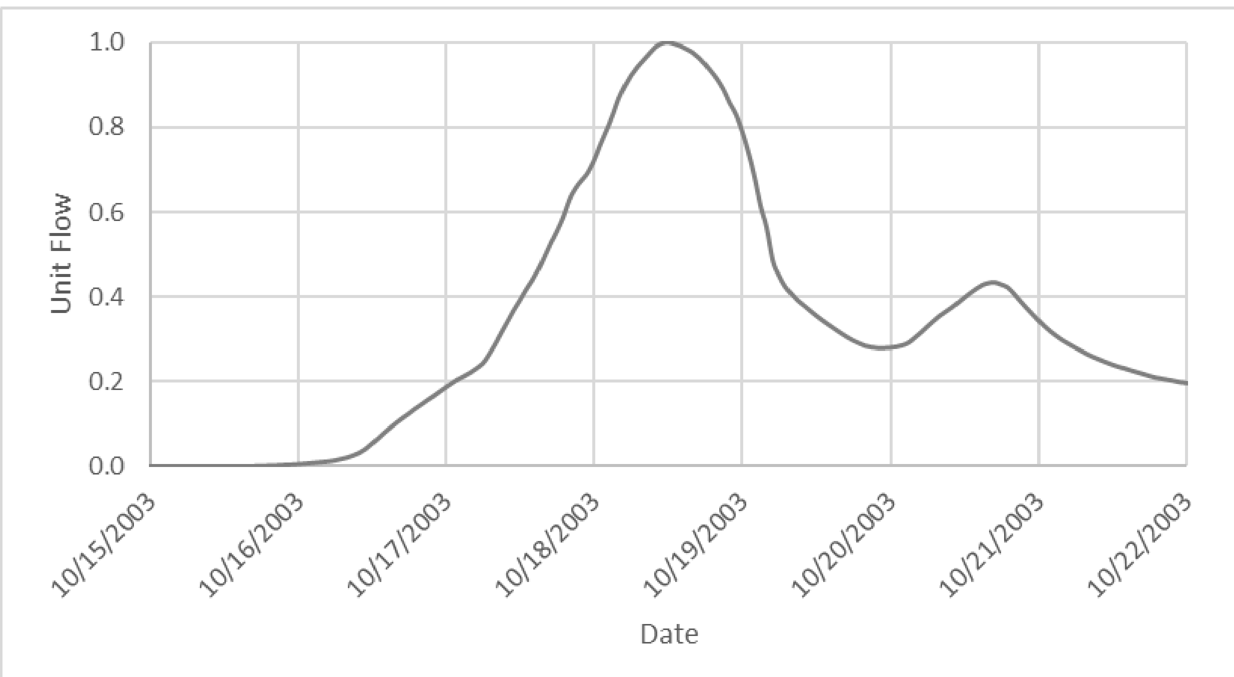

Figure 2.5 Unitless hydrograph developed from the 2003 flood of record at WSC 08MG005.

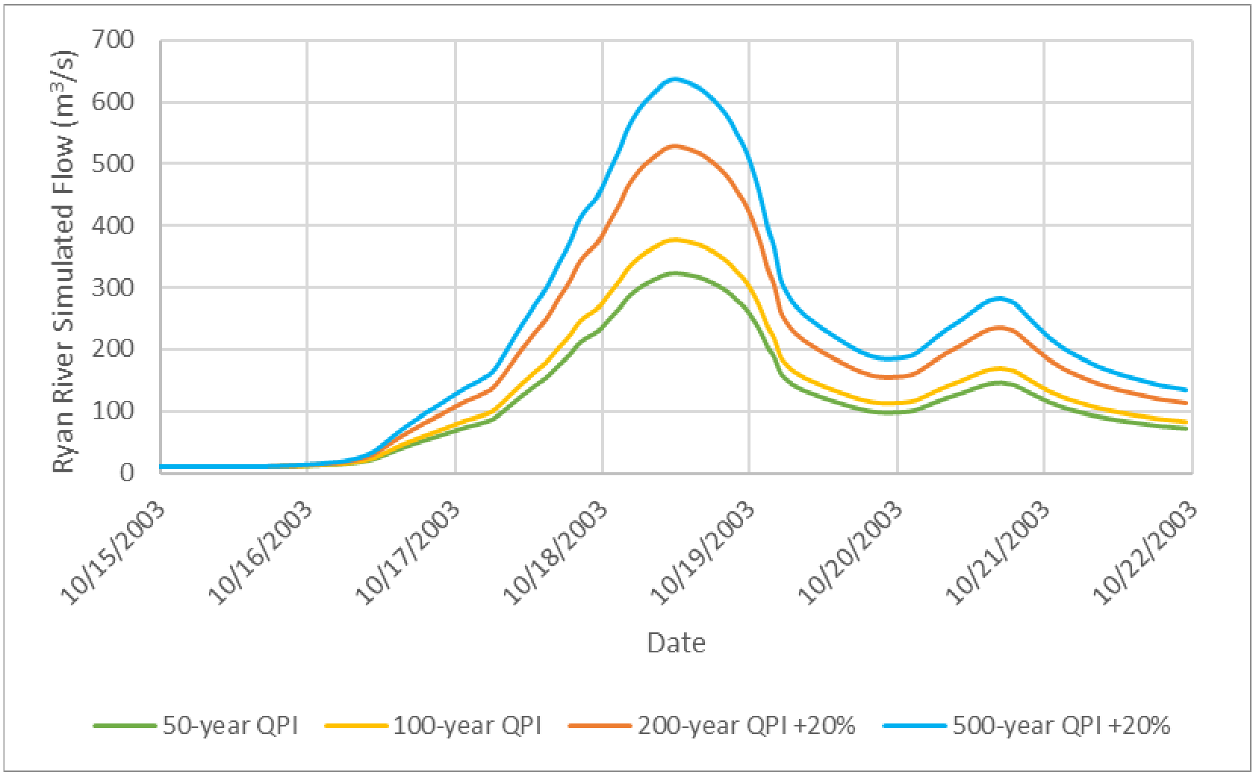

Figure 2.6 Simulated hydraulic model inflow hydrographs for the Ryan River.

3 GEOMORPHOLOGY

This section describes the geomorphic setting of the Ryan River watershed and summarizes the key findings from the channel stability assessment. More information is provided in Appendix A.

3.1 Geomorphic Setting

The Ryan River watershed has a complex and dynamic landscape that has been shaped by past periods of geologic and glacial activity. For the purposes of the channel stability assessment, NHC divided the Ryan River watershed into three distinct geomorphic regions: the upper watershed, the alluvial fan[2], and the lower watershed (Figure 3.1). The steep upper watershed is characterized by rugged, mountainous terrain with active sediment and woody debris sources from tributary channels, avalanche paths, and glaciers contributing materials to the channel. Channel morphology and planform are substantially different in the downstream lower gradient reaches. The confluence of the Ryan River with the Lillooet River valley marks a distinct geomorphic transition, where the Ryan River flows onto an alluvial fan. Downstream of the fan, the Ryan River flows along a more gradual channel gradient, forming a depositional reach in the lower watershed where past dike breaches and erosion have occurred. The following paragraphs describe the geomorphology of each of these regions in more detail.

Figure 3.1 Overview of the upper and lower Ryan River watersheds separated by the Ryan River fan. Crosses represent chainage markers, which are measured (in km) upstream of the mouth of the Ryan River.

Upstream of the confluence with the Lillooet River valley, the Ryan River drains a 376 km^2, highly glaciated (16 % by area) alpine basin, with elevations ranging from 235 m to 2,587 m and a mean elevation of 1,634 m above sea level. Glaciers in the upper watershed are actively receding, as

[2] The term *alluvial* technically applies to water-dominated processes (fluvial), whereas debris flows are classified as landslides and the term colluvial fan is used for the deposits. The term *alluvial fan* is often used in guidelines and literature without this distinction. For simplicity, the fans in this study were labelled as alluvial fans, include deposits from clearwater, debris flood and debris flows events, unless otherwise noted as colluvial fans.

evidenced by fresh moraines, which has led to de-buttressing of the confining bedrock; in some locations this has caused large rock falls (Holm et al., 2004). Several proglacial lakes intercept and attenuate sediment sourced from receding glaciers throughout the river headwaters; however, downstream reaches are relatively wide and dominated by large side- and mid-channel bars, indicating that sediment load remains high through the upper channel reaches.

The river generally flows east through the upper basin and is bounded by steep north- and south-aspect valley walls lined with debris-flow gullies and deforested avalanche paths. Avalanches reaching the main channel in the valley bottom appear to be the primary input of woody debris. Avalanches occurring in the winter and spring contribute very little sediment to the main channel as the alpine slopes are largely protected by snow; transfer of debris during snow avalanching may be higher when snow cover is reduced (Hart, 1979). The steep hillslopes in the upper watershed are prone to mass failures, and episodically deliver large volumes of sediment, ranging from 10^3 to 10^5 m^3 to the main channel through landslides and debris-flow events (Jordan and Slaymaker, 1991). These mass movements appear to be an important contributor to the basin's sediment yield. In the past, debris-flow or debris flood deposits appear to have reached the valley bottom temporarily dammed (or partially confined) the main channel. More detailed investigation in the upper watershed is required to determine the frequency of these events as this process can potentially lead to upstream aggradation and outburst flooding.

At the confluence with the Lillooet River floodplain, the Ryan River forms a large alluvial fan, as the channel gradient drops, and the river exits valley confinement. The Ryan dike has historically been susceptible to breaches at this location (KWL, 2002, 2009; NHC, 2018), in part due to the river's susceptibility to rapid lateral migration and channel avulsions produced during major floods. The position of the channel on the Ryan River fan is constrained to the south by the base of Mt. Ross, and to the north by the Ryan dike. The gullied hill slopes of Mt. Ross are prone to high-magnitude debris flows that occur on a decadal scale (Jordan and Slaymaker, 1991). Debris supplied from these events exerts a strong control on the stability and position of the main channel locally.

Flowing along the alluvial fan, the Ryan River forms a wandering-style morphology with one main channel and several side channels that cut through and flow around forested islands and bars. Here, the river forms a depositional zone whereby coarse sediment and large woody debris (LWD) tends to accumulate due to a decrease in the channel gradient from 5 – 6 % upstream of the fan to 0.1 % downstream of the fan. Logs floated downstream from the upper watershed tend to accumulate on bar surfaces, at the head of islands, and at the entrance to side channels. Over time, accumulation of LWD plugs channels and diverts flow into secondary channels, such that LWD jams form and maintain the multi-thread channel pattern, causing and mediating the frequency of channel avulsions and patterns of erosion and deposition (Collins et al., 2003). During periods between large floods, vegetation establishes and matures in the lee of these jams, stabilizing substrate and leading to island formation (Corenblit et al., 2007; Gurnell et al., 2001).

The lower 41 km^2 sub-basin of the Ryan River watershed includes most of the Lillooet River floodplain and the steep hillslopes of Mt. Ross and Sugarloaf Mountain (Figure 3.1). The river flattens from an average slope of approximately 5% at the Ryan River fan to approximately 0.05 % at the confluence with the Lillooet River, over a distance of 15 km. The lower 4 km of the Ryan River is underfit and flows through the historical channel of the Lillooet River, which was diverted to its current location as part of the Mackenzie Cut (Weatherly and Jakob, 2014). Through this reach, the river flows through a 30 – 40 m wide, single-thread, meandering channel along an average bed slope of 0.1%. The gentle gradient promotes deposition of the river's coarse sediment load, leading to the formation of an alternating bar sequence.

3.2 Channel Stability Assessment

The channel stability assessment focused on the Ryan River fan near a location of known previous dike susceptibility near the upstream of the Ryan River dike (River KM 15.5) however there was a second location at approximately where tension cracks were observed near River KM 9.1 (Figure 3.2). The objective of this assessment was to determine the lateral and vertical stability of the channel at upstream location and the relative controls on these reaches. NHC made this determination using a combined desktop and field-based approach. The study team reviewed air photos and satellite imagery to assess historical planform changes and sediment sources, while the field inspection documented current in-channel sediment deposits and bank materials and identified the potential influence of steep tributary gullies near the fan. NHC used the results from the channel stability assessment to determine appropriate bulking factor estimates to apply to design flow events used in floodplain mapping. These estimates were made based on identifying potential hydrogeomorphic processes operating within the watershed by following the debris flood classification scheme developed by Church and Jakob (2020), adding refinements described in Jakob et al. (2022).

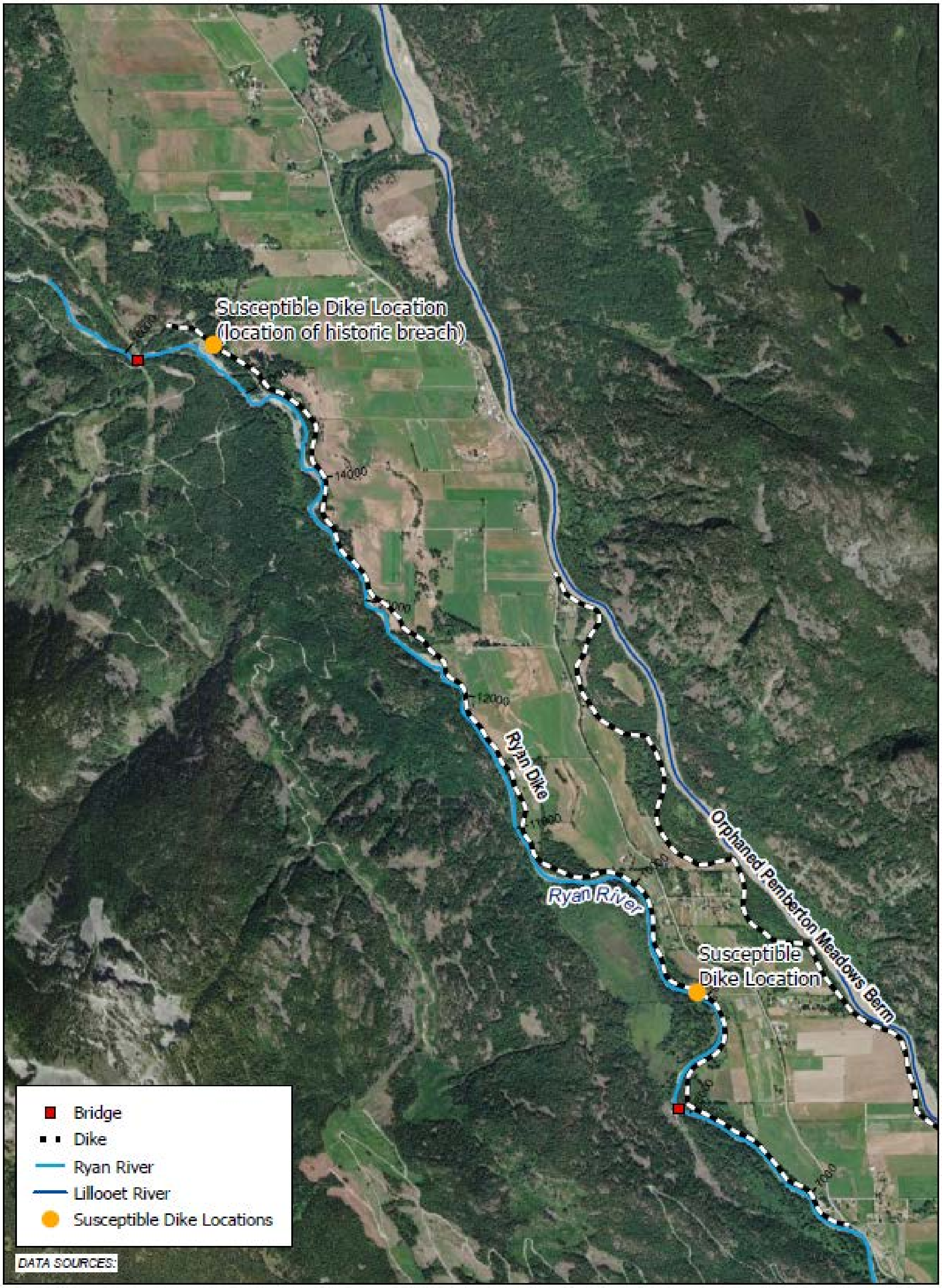

Figure 3.2 Susceptible dike locations and historic breach.

The air photo review revealed that the morphology of the channel at the Ryan River fan has changed substantially over the past 75 years. During this time, the river has transitioned from an irregularly meandering, predominantly single-thread channel to a wandering-type morphology characterized by periodic instabilities due to lateral migration and channel avulsions. Major changes to the channel appear to be driven by the timing and magnitude of peak flood events on the mainstem, with large floods occurring once per decade or more. Additionally, debris-flow events emanating from the gullied hill slopes of Mt. Ross and Sugarloaf Mountain deliver sediment directly to the main channel, causing channel instability and likely increasing the probability of a dike breach to occur. The potential for a channel blockage caused by one of these debris-flow events requires a detailed geotechnical assessment by a qualified professional, as per EGBC (2018) guidelines. The consequences of outburst flooding following a channel blockage has the potential to be catastrophic for nearby residences and infrastructure developed on the floodplain.

NHC compared topographic survey data collected during the field assessment with cross-section survey data collected by Kerr Wood Leidal from 2006 (KWL, 2006). The results of this comparison provide important information on channel bed stability over the past 17 years. Overall, no systematic trend of bed aggradation or degradation was observed across the assessed transects. Net changes on the order of 1 – 2 m have occurred, reflecting lateral migration of the main channel and deposition on bar surfaces. Given the high supply of sediment delivered from the upper watershed, the channel is likely to continue migrating across the available space on the valley bottom, with periodic channel avulsions relocating the position of the mainstem channel. Additional details of the survey comparisons are described in Appendix A.

NHC assessed bulking factors to apply to design flows used in floodplain mapping by identifying the hydrogeomorphic processes operating in the watershed, as well as determining the triggering mechanism of these events. The study team identified these processes by reviewing past reports, available air photos, satellite imagery, and field observations of channel deposits. For the Ryan River, the main channel is susceptible to both floods and debris floods, while the potential for debris flow exists in smaller tributary channels in both the upper and lower watersheds.

Following the classification scheme of Church and Jakob (2020), three types of debris floods are distinguished by their trigger mechanism. Type 1 debris floods are driven by meteorological events; Type 2 debris floods result from the dilution of debris flows as they translate through the channel system; and Type 3 debris floods are related to outbreak flooding following a channel blockage. Given the abundant sediment sources and debris-flow channels identified in the upper watershed, combined with observations of coarse channel deposits and woody debris accumulations at the fan, it appears that the Ryan River fan is susceptible to both Type 1 and Type 2 debris floods. Furthermore, the proximity of steep gullies on Mt. Ross that are capable of generating (and have previously) debris flows implies the possibility of Type 3 debris floods occurring on the main channel. This potential event warrants further investigation as Type 3 debris floods can have substantially higher bulking factors than other debris floods. Recommended bulking factors to design flows for the Ryan River watershed are summarized in Table 3.1. The bulking factor does not apply to entire length of the Ryan River in the valley because of the shallower gradient, the debris would have a chance to settle out before the confluence with the Lillooet. Based on the slope of the Ryan River and it comes down off its fan, we expect the debris to mostly settle out by river km 13 (measured from the confluence with the Lillooet) and for the river to transition to a clear water flood. Additional details describing the results of this hydrogeomorphic assessment are found in Appendix A.

Table 3.1 Recommended bulking factors to design flows for the Ryan River watershed.

Watershed	Hydrogeomorphic Process – Main Channel	Hydrogeomorphic Process – Tributary Channels Close to Fan Apex	Debris Flood Typology	Discharge Bulking Factor	Notes
Ryan River at the fan apex	Mixed floods and debris floods	Debris flood and debris-flow potential; avalanche tracks in the upper watershed appear to contribute substantial amounts of LWD to the channel.	Type 1	1.1 to 1.3	Extensive woody debris from avalanche tracks; several landslides in upper watershed.
			Type 2	1.2 to 1.4	
			Type 3	Unknown	Future investigation is required.

4 HYDRAULIC ANALYSIS

NHC developed a hydraulic model to simulate the Ryan River design floods and estimate corresponding flood levels and extents within the study area. This section describes the various tasks carried out and presents the subsequent results obtained. Key steps included: 1) updating the Lillooet DEM to represent the channel geometry; 2) extending the Lillooet hydraulic model; 3) calibrating validating the model; 4) performing model runs and reviewing results; 5) reviewing model limitations.

4.1 Digital Elevation Model Development

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 the most recent channel and dike surveys, as well as the 2016 LiDAR. The 2009 LiDAR was only used to fill any voids in the 2016 floodplain topography, which was typically limited to the outer edges of the DEM and the upper portion of the Ryan River (less than 30% of the final terrain). See NHC (2018) for details on the bathymetry data that were surveyed. In 2022, the Ryan River channel was extended upstream and updated near the top of the Ryan dike using drone survey data.

4.2 Model Extension

Ryan River flows are mostly confined by dikes, roads, and valley walls. Shallow bars and small islands in the upper reach are frequently overtopped during high-flow events, adding channel roughness and complexity to the hydraulics. The dike is expected to overtop during extreme-flow events and join the floodplain with the Lillooet River. Due to the complexity of the Lillooet River and the shared floodplain, NHC (2018) built a 2D model for the valley to provide a more accurate representation of hydraulic conditions. NHC used the HEC-RAS2D software developed by the U.S. Army Corps of Engineers Hydrologic Engineering Center (HEC), updating the hydraulic model for this study from version 5.0.7 to 6.2 (the current full version at the time of the study). The model extent, the hydraulic features and high water marks can be found in Figure 4.1.

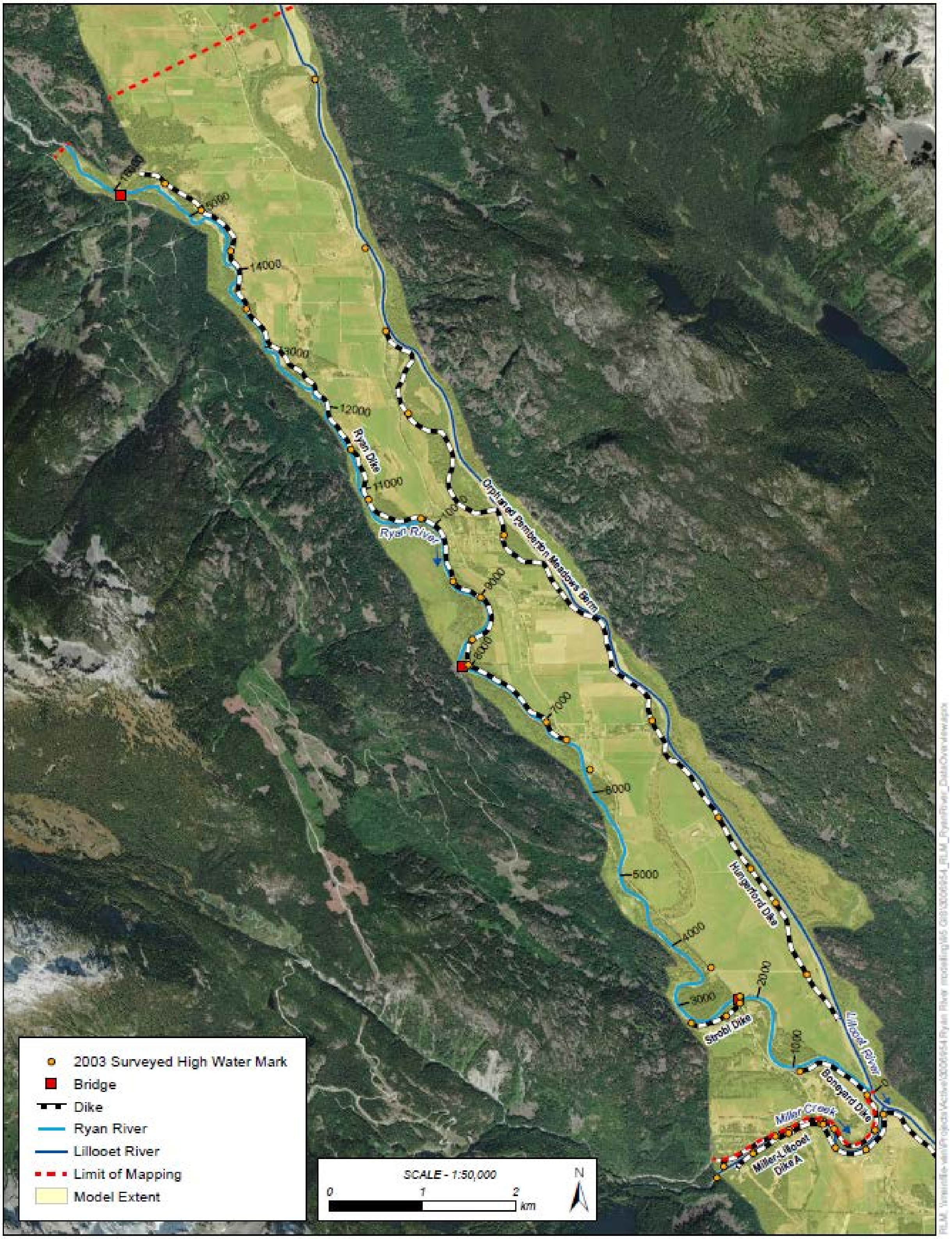

Figure 4.1 Hydraulic Model Extents

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 they 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 Ryan River, the model calibration and validation are somewhat limited by the amount, spatial extent, and accuracy of flow and water level data from past floods. NHC used the 2003 flood for primary model calibration and the 2022 data obtained during the river surveys 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 high-water marks (HWMs), 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 the channel shape and alignment) are accounted for in the momentum equation; consequently, Manning's n-values are generally lower.

NHC divided the Ryan River into reaches with similar channel bed material, sectional geometry, and plan form, then assigned each reach an initial roughness value for its in-channel portion. The team assigned these initial roughness values based on field observations of channel bed composition and verified them with values referenced in supporting literature (A Strickler, 1923; Bathurst, 1985; Brownlie, 1981; Engelund and Hansen, 1967; Jarrett, 1984; Limerinous, 1970; Maynord, 1991; van Rijn, 1984; Wong and Parker, 2006).

For the present study, NHC did not change the overbank portion of the model mesh developed for the Lillooet River study (NHC, 2018) and assigned roughness values to the overbank area using aerial imagery and professional judgement. Following the calibration process, NHC updated the Manning's n channel roughness coefficients for the Ryan River (Table 4.1).

Table 4.1 Channel roughness values used in hydraulic modelling of the Ryan River.

River	Reach	Manning's Coefficient (n)
Ryan River:	Lillooet River to km 8	0.040
	Km 8 to km 12	0.060
	Upstream of km 12	0.055

4.3.2 High-flow Calibration

For optimum calibration results, NHC recommends obtaining observed HWMs 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, numerous channel changes have taken place since the flood of record in 2003, including the Meager Slide in 2010. NHC deemed the 2003 event unsuitable for calibration on the Lillooet River, despite having extensive high-water information at a very high flow (1,490 m^3/s). Similarly on the Ryan River, the high flow caused the dike to breach and water to pour onto the floodplain. However, there has been no major sediment supply change on the Ryan River since that 2003 flood. So, while the data are old and there have likely been minor channel shifts, the floodplain on the whole has been fairly stable and is likely unchanged, so the 2003 flood was used for calibration based on the understanding that high uncertainty is associated with the calibration. There is also uncertainty regarding the vertical datum used for surveying the 2003 HWMs, so NHC converted the data to the current datum using best judgement. Unfortunately, since no HWMs were collected during the 2016 flood for the Ryan River, this more recent flood could not be used. The locations of the HWMs can be seen Figure 4.1.

The 2003 flood calibration results are included in Figure 4.2. Based on the calibration, the agreement between observed and simulated water levels has a mean absolute error of 0.4 m. Overall, the differences between the observed HWMs and the simulated water levels are likely due to the following factors:

- **Breach uncertainties:** The Ryan River dike breached in the 2003 event, although the exact geometry, location, and timing of the breach are unknown. Without knowing when the breach occurred and how (overtopping vs erosion vs, piping), NHC was required to develop simulations without a breach to identify where the water peaked and overtopped the dikes and how much water flowed to the lower river. The dike has been rebuilt since this event, so the dike crest elevations may be different, which would affect the results.
- **Bed level changes:** The 2003 flood occurred 20 years ago, and the channel has likely changed since then. Overall, there isn't a net aggradation or degradation but local variations are likely. 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 datum (KWL, 2005), where the benchmarks used were lost over time. As such, an assumed conversion (based on other nearby benchmarks and conversions) was applied and may results in inaccuracies.

- **Potential discrepancies in observed water levels:** The HWMs were surveyed after the flood receded; they vary for a particular location and may be affected by local features.

Despite the model under-predicting water levels in the upper Ryan and over-predicting water levels near the Lillooet confluence, NHC did not further adjust the channel roughness values for the following reasons:

- The roughness values selected are at the high end of plausible values for the channel form, bed texture, and channel slope based on referenced literature and past modelling experience. Also, further raising the roughness just spilled more water to the floodplain (due to the current dike heights and configuration) rather than improve the calibration.
- It is possible that the Ryan River was experiencing a debris flood or something close to it during the 2003 event, which would have also increased the water levels (given the amount of debris in the water). Further adjusting the roughness would make the model not well suited for clear-water floods.
- Under flood conditions, the lower portion of the Ryan River (roughly river km 5 to the confluence) is dictated by the Lillooet River. The calibration tended to over-predict the water level here likely because the timing of the floods for the two rivers is off. However, without gauge information from that time, there is limited information available to correct the timing of the flood.
- Some uncertainty remains regarding the accuracy of the 2003 HWMs.

Given the large amounts of uncertainty with the calibration event and the number of geometry changes since the flood, NHC deemed the model configuration acceptable and parameters were within a reasonable range of values.

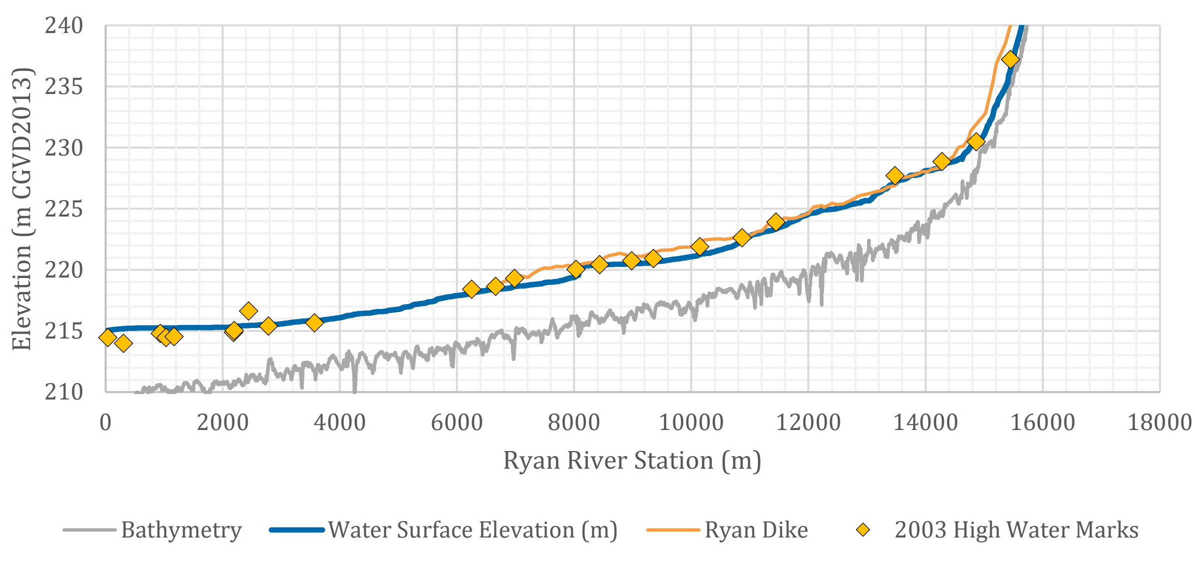

Figure 4.2 Ryan River 2003 calibration results.

4.3.3 Low-flow Calibration

In addition to calibrating high flows, NHC ran a low-flow scenario for the Ryan River calibration. The team determined the low flow to be approximately 5.8 m^3/s (at WSC 08MG028 on April 14, 2022), then modelled low flows using the calibrated Manning's n roughness values for the Ryan River. No surveyed water levels were available, other than the WSC gauge for the Ryan River and data from the drone imagery. The difference between the simulated and observed value was 0.5 m. The simulated values over-predicted the observed values, which was opposite to the calibration findings. Since this model will be used for flood purposes, NHC did not lower the roughness values to match the gauge more closely. Differences between the modelled and observed elevation can mostly likely be attributed to local variation in the channel geometry and proximity to the bridge. This portion of the Ryan River was surveyed in 2017, and there are some gravel bars and debris in the river, which can all cause the local water level to vary greatly from one side of the river to the other.

4.4 Model Results

NHC simulated several floods for the Ryan River, including the 50, 100, 200, 500, and 500-year plus climate change, then used the simulation results used to develop the floodplain maps, which are discussed in Section 5.

At lower flows, flooding is contained by the Ryan dike; however, the dike begins to overtop in several locations during higher flows. Overtopping begins to occur at around 250 m^3/s at the 11.1 km station, at 260 m^3/s at the 13.4 to 13.5 km station, and around 285 m^3/s at the 14.2 to 14.3 km station. The water moves across the floodplain toward the Lillooet River until it meet Pemberton Meadows Road. The water builds up behind Pemberton Meadows Road until it eventually overtops and flows into the Lillooet River. Water trapped on the west side of Pemberton Meadows Road flows south and joins the Ryan River again before its confluence with the Lillooet River.

If the Lillooet River and Ryan River are both flooding, the flood waters meet and combine on the floodplain, increasing the water surface elevation. Areas roughly on the west side of Pemberton Meadows Road are mainly supplied by the Ryan River, and the east-side areas are supplied by the Lillooet River. However, the Lillooet River typically experiences a bigger flood and eventually overwhelms the floodplain entirely. During a flood, the Lillooet River entirely dictates the water surface elevation in the lower Ryan River, from 0 km to 5 km upriver from the confluence with the Lillooet River.

4.5 Model Sensitivity

NHC carried out model sensitivity analyses to determine the effects of changing model parameters on water levels, flow depths, and inundation extents. The sensitivity analyses included an analysis of the impacts of varying the parameters of inflow, channel roughness values, and overbank roughness values within a credible range.

For the Ryan River, NHC tested the inflows with upper and lower limits of +/- 20%. When the inflows were increased and decreased by 20%, water surface elevations observed on the floodplain varied on average from +/- 0.05 m, with a maximum difference of up to +/-0.2 m.

The channel and overbank roughness conditions were also varied by +/- 20%. The water surface elevation, both in the channel and on the floodplain, varied up to +0.1 to -0.2 m. An isolated location near the upstream boundary where the water passes through a rapid showed higher sensitivity (up to 0.6 m), but this was likely due to the steepness of the creek and the fact that water here is likely close to supercritical flow.

4.6 Model Limitations and Uncertainties

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

4.6.1 Digital Elevation Model

The following limitations and assumptions are associated with the DEM:

- The 2016 LiDAR surveyed by Emergency Management BC did not cover the full extents of the Pemberton Valley, so NHC used the 2009 LiDAR 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.
- Due to the high-flow conditions during the bathymetric surveys, which made data collection quite challenging, the upper ends of the Lillooet River and tributaries had sparser survey data than the rest of the study reaches. NHC applied some interpolation to develop the channel geometry.
- For all the channels, NHC applied a smoothing algorithm and used professional judgement 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.
- NHC did not specifically model culverts, ditches, canals, and other drainage features.

4.6.2 HEC-RAS2D

For the 2D unsteady flow computations, the software used the full 2D Saint-Venant equations. NHC pre-processed the 2D computational cells to develop detailed hydraulic property tables based on the underlying terrain. This approach 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, despite bank erosion, scour, deposition, and potential avulsions taking place during high flows.

- The model assumes the absence of blockages, such as debris jams at bridge crossings and debris plugs at floodplain openings.
- The model is as accurate as its calibration. The 500-year design flood is larger than the calibration event, and the calibrated roughness coefficients may not be representative due to the age of the calibration event and data. NHC observed some under-prediction in the calibration but did not increase roughness coefficients as the values applied are considered to represent upper-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.
- Although NHC identified some limitations 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 and preparing up-to-date floodplain mapping and other required mapping products. NHC recommends using the flood profile developed herein, rather than the previous Ryan River flood mapping.

5 FLOOD MAPPING

This section presents details on NHC's flood mapping efforts and includes information on the flood mapping products used. In addition, this section describes the designated floodplain maps, including freeboard requirements, as well as flood depth maps and flood hazard maps.

5.1 Flood Map Products

NHC produced three types of map products:

- designated floodplain maps depicting the Ryan River 500-year flood levels, plus climate change, plus a freeboard allowance
- flood depth maps for the 50, 100, and 200-year flood events
- flood hazard maps showing a hazard rating based on flood depths and flow velocities for the 50, 100, and 200-year flood events.

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

5.2 Designated Floodplain Maps

The designated floodplain maps are comprised of 3 different flood scenarios that are mosaiced together and phased across the floodplain. The three flood scenarios are summarized in the table below.

Table 5.1 Flood scenarios used to develop designated floodplain maps

No.	Description and location where flood applies	Ryan River		Lillooet River		Freeboard (m)
		Return Period	Flow (m^3/s)	Return Period	Flow (m^3/s)	
1	Ryan River fan flood with x1.4 bulking factor for debris	500-year with Climate Change	892	200-year	2118[1]	1.0
2	Ryan River downstream of fan and shared Lillooet floodplain	500-year with Climate Change	637	200-year	2118[1]	1.0
3	Ryan River downstream of river km 5	200-year	422	200-year	2118[1]	0.6

1. The Lillooet River in the has several inflow points where it gains flows as it moved downstream. The flow provided is the flow at the WSC gauge (after the Ryan River confluence). The flow at the top of the model before the tributaries join is 1459 m^3/s.

Scenario 1 is applied across the Ryan River fan where debris is likely to affect the river. Further downstream (approximately river km 13 on the Ryan River) the flood transitions to the Scenario 2 where the bulking factor is removed as debris is likely to settle out due to the shallower gradient of the valley. Scenario 3 is applied at Ryan River KM 5 where the Lillooet River flood dominates the floodplain.

When developing a designated floodplain map for the Ryan River, NHC chose a 500-year event due to the presence of the alluvial fan and the river's susceptibility to debris floods as per EGBCs guidelines (2018). The team conducted a desktop study and primarily used these results to identify and delineate the Ryan River alluvial fan.

Alluvial fans can experience sizeable rapid changes in flow path as well as transport and deposit high loads of sediment and debris. Development of infrastructure on active alluvial fans is at risk of inundation, as well as high-velocity flow and physical impact or burial from sediment and debris. According to provincial guidelines, such areas must be treated uniquely from other flood hazard zones, and development permits should only be granted if no alternative land is available, and the area can be shown to be stable from hydraulic and geological processes (MFLNRORD, 2018).

Depending on the level of assessment and findings from the assessment, an alluvial fan can be classified as follows:

- active – an unconfined depositional zone that is susceptible to rapid aggradation, channel migration, and avulsion across the fan under the contemporary hydroclimatic conditions)
- inactive – the fan was developed under a different hydroclimatic regime (paraglacial fan)
- or unrated – it has not been determined if the entire fan or just the current channel area is susceptible to alluvial fan geomorphic hazards under current hydroclimatic conditions.

In this study, NHC classified several alluvial fan areas next to the Ryan River on Mt Ross as unrated. The Ryan River fan was classified as an active fan and showed historic use by Ryan River flows before construction of the Ryan River Dike. While much of the fan is currently cut off, a large clearwater or debris flood could occur and breach the dike on the fan and cause reoccupation of the fan. The unrated fans and gullies on Mt Ross could also create debris floods and possibly debris flows that could cross the Ryan River and blow out the dike or block the Ryan River which could cause it to breach the dike onto the fan. The classification of the Ryan River fan and nearby fans from Mt Ross are consistent with a Class 1 level of assessment as per EGBC Legislated Flood Hazard Assessment guidelines for rainfall and snowmelt-generated floods and Class 0 for debris flows, debris floods, and alluvial fans (EGBC, 2018). Anything above these would require a site-specific assessment. NHC did not map or assess any fans downstream of river KM 13 on the Ryan River. Delineation was based on available satellite imagery.

NHC mapped the designated flood event at a 1:10,000 scale on the 5 sheets (11”x17”) that are included in Appendix A of this report. NHC added freeboard (see Section 5.2.1) to the simulated water level surface then mapped the combined surface over the DEM and projected it across the floodplain to delineate the region’s flood extents. The maps show flood extents with and without freeboard allowance. With freeboard included, the maps indicate the FCL, the minimum level for construction at a certain point within the floodplain. Also included in the maps are isolines or lines corresponding to equal FCLs, generally in 0.5 m or 1 m increments.

5.2.1 Freeboard Requirements

Added to provide a safety factor, freeboard accounts for local variations in uncertainty in the flood level simulations, as well as account for water levels, such as standing waves, super-elevation at the outside of river bends, and local turbulence. Historically in BC, the minimum freeboard allowance applied has been the greater of 0.3 m above the instantaneous (or 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 accommodate 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[3], as suggested in recent provincial guidelines for sea dikes (BC MOE, 2011) and as discussed in the EGBC Professional Practice Guideline for floodplain mapping (APEGBC, 2017). The freeboard for the Lillooet River is 0.6 m due to the uncertainty of climate change on future flood flows and the impact of sedimentation on the river. NHC mapped the Ryan River with a freeboard of 1.0 m, choosing this higher freeboard for the Ryan River because of the uncertainty of debris in the Ryan River and its impact on flood events. Additionally, given the large uncertainty and range in differences observed in the calibration event, a larger freeboard was deemed more appropriate. See Table 5.1 for which scenarios

[3] A brief set of examples that use for a minimum of 0.6 m freeboard above the instantaneous flood flow within BC and includes a flood hazard study and mapping in Prince George, as well as the lower Fraser River, Maple Ridge, Squamish, and North Vancouver (KWL, 2014, 2017; MFLNRO and NHC, 2014; NHC, 2008, 2016, 2018, 2021a).

the freeboard is applied to). NHC recommends monitoring the Ryan River and the dike over time to assess for channel changes and potential impacts to flood levels.

5.3 Flood Depth Maps

NHC developed the flood depth maps using the water surfaces simulated in the model without a freeboard allowance and by subtracting the DEM surface 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 (Appendix B). The flood depth maps correspond to the 50, 100, and 200-year coincident floods on the Ryan and Lillooet River (for example, both rivers flooding at a 50-year flood at the same time). The colour shading references the criteria listed in Table 5.2, adapted from the national standard in Japan (EXCIMAP, 2007). NHC did not map inundation durations, which are highly sensitive to the flood hydrograph, dike breaching, and drainage patterns. In addition, NHC did not consider dike breaches for the depth mapping.

A comparison of the different return-period flood depth maps shows remarkably little increase in flood extents between the 50 and 200-year floods, but NHC noted significant increases in depth. This is to be expected, considering the valley is relatively flat and has steep valley walls. During floods with a return period that exceeds 50 years, most of the valley floor would be flooded.

Table 5.2 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 the ground floor in most houses; basements and underground parking areas are flooded, potentially causing evacuation; electricity has failed; vehicles are commonly carried off roadways.
1.0 to 2.0	The ground floor of most houses is flooded; residents are evacuated.
2.0 to 5.0	The first floor and often the roof of most houses are covered by water; residents are evacuated.
> 5.0	The first floor and often roof of most houses are covered by water; residents are evacuated.
Fan Hazard	Potential for dike breach and channel avulsion. Susceptible to debris, sedimentation, inundation, and high velocities.

5.4 Flood Hazard Maps

For the flood hazard maps, NHC extracted a velocity surface from the model and (as per the flood hazard rating equation shown in Table 5.3) and multiplied the velocity surface by the depth surface to create a hazard rating surface. The team then mapped this surface over the DEM, as shown on the three 11”x17” sheets at 1:20,000 scale in Appendix B. Similar to the depth mapping, NHC mapped the 50, 100, and 200-year return-period coincident floods for the Ryan and Lillooet River, allowing for dikes to overtop but not breach. Table 5.3 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 the 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 Ryan River floodplain near the confluence with the Lillooet River.

Table 5.3 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”
Fan Hazard	Fan Hazard	**Dangerous for all** “Potential for dike breach and channel avulsion. Susceptible to debris, sedimentation, inundation and high velocities.”

Source: UK DEFRA/Environmental Agency (2005)

6 CONCLUSIONS AND RECOMMENDATIONS

Based on the project findings, NHC has developed and offers the following conclusions and recommendations.

Conclusions:

1. Significant floods on the Lillooet and Ryan rivers have occurred in the past (1984, 1991, 2003, 2013, and 2016). Large-scale channel straightening and lowering of Lillooet Lake was carried out during the 1950s, and over time, a number of dikes and berms have been built, including the Ryan 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 on the Lillooet River, flood hazards are expected to increase with time.

2. Previous floodplain mapping for the valley used a range of survey datums. Although, it was possible for NHC to convert some previous results to the present datum (CGVD2013), some inaccuracies may exist.
3. Development of the Lillooet River floodplain has resulted in a much less complex network of river channels and has substantially reduced the active channel area of the Ryan River over the Lillooet River floodplain. Moderately frequent hydrogeomorphic flood events in the Ryan River will result in sediment and debris deposition in the reach immediately downstream of the fan apex where the alluvial fan is currently constrained by the dike. Increased sedimentation and debris jams in this area will result in increased potential for erosion, lateral channel migration and other channel instabilities, dike breaches, overtopping, and severity of flooding in the floodplain. With no other flood mitigation options, channel management (i.e. sediment and debris removal) will need to be part of the long-term flood management program for the Ryan River and surrounding area.
4. The NHC (2018) study suggests a change in the flow regime of the Lillooet River started roughly around 1975. Prior to 1975, the annual peak flow was typically generated by the freshet, 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 provides evidence of the sensitivity to climate modal shifts. Although the spatial analysis could not support applying these post-1975 changes to the Ryan River directly due to the absence of supporting data, it is still likely that the watershed is sensitive to climate change impacts because it is in the rain-snow transition zone. The current 500-year flood estimate for the Ryan River is 531 m^3/s. Based on EGBC guidelines and analyses of peak flow trends, NHC predicts that climate change may increase the flood peak estimate to 637 m^3/s by the end of the century.
5. The hydraulic model showed that the Ryan dike would be overtopped during the 50-year and greater floods. Overtopping is imminent at approximately 260 m^3/s. A dike breach would impact the floodplain with flood flows 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 many locations.
6. Although the hydraulic model has a number of limitations, it is a useful tool that has been developed by applying state-of-the-art modelling techniques. The simulated flood extents are similar to those developed for the 1990 and 2018 floodplain mapping; however, flood levels are generally much higher compared to the 1990 flood maps and FCL isoline patterns vary. The increase in water level from the 2018 to the 2023 maps varied from 0.2 – 1.0 m primarily caused by increased flows from the Ryan River and an increased freeboard. Some of the variation was caused by the configuration of the valley. The flood waters become confined on the floodplain between Ryan River Dike and Pemberton Meadows Berm and Hungerford Dike, increasing the water level, and therefore depth, through this area (up to 1.0 m).

Recommendations

1. Develop an up-to-date flood emergency response plan that considers the increased flood hazards. Coordinate the PVDD plan with the Village of Pemberton, Squamish Lillooet Regional

District, and Lílwat Nation. Depending on the location and nature of a dike breach, the response time after a breach, before hazardous flows block Pemberton Meadows Road and reach residences in Pemberton Meadows may be as little as 15 minutes.

2. Adopt the designated floodplain maps for the Ryan River and apply the FCLs shown on the mapping to future development.
3. Avoid major development or limit development 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. Make the provincial River Forecast Centre aware of flood hazards in the Lillooet Valley and emphasize with the importance of accurate and timely forecasts.
5. Improve protection measures in the area. NHC recommends the following measures:
   - Local authorities should review the depth and hazard rating maps and identify areas where flooding would have major impacts on existing development. Consider relocating or floodproofing housing and other development in critical areas.
   - Encourage the Ministry of Transportation and Infrastructure and other agencies to identify areas where road and egress can be improved to allow transport during high floods.
   - Ensure access to higher-elevation areas in the valley where residents and domestic animals can quickly be evacuated.
6. Update the hydraulic model over time. Typically, updates are recommended every 20 to 30 years but given the high uncertainty in the Pemberton Valley due to climate change and the significant aggradation taking place on the Lillooet River, NHC recommends reassessing the Ryan River every 10 years and updating the model as required. Include major changes within the floodplain 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. Over time, monitor apparent trends in observed peak flows and review potential changes in flows due to climate change. Installing a real time meteorological station in the upper watershed would support an assessment of meteorological triggers for flood and hydrogeomorphic events and compliment the hydrometric monitoring station currently active on the Ryan River to support forecasting of peak flow timing.
8. During large floods, collect HWMs and observe corresponding flood flows to accommodate future model calibration and validation updates.
9. Assess the dike susceptibility and avulsion hazard on the Ryan River fan in the context of hydrogeomorphic hazards originating in the upper watershed (i.e. debris flood, debris flow, outburst flood hazards).
10. A more detailed assessment is warranted of the hydrogeomorphic hazards (i.e. debris flood, debris flow, outburst flood hazards) in the upper watershed and the Ryan River alluvial fan.

7 REFERENCES

A Strickler (1923). Contributions to the Question of a Velocity Formula and Roughness Data for Streams, Channels and Closed Pipelines (Translation T-10).

APEGBC (2017). Flood Mapping in BC, APEGBC Professional Practice Guidelines, V1.0. The Association of Professional Engineers and Geoscientists of British Columbia, Burnaby, BC. 54 pp. [online] Available from: https://www.egbc.ca/app/Practice-Resources/Individual-Practice/Guidelines-Advisories/Document/01525AMW6CMLNYZOJFZ5AY4MD3UNNDZQWW/Flood%20Mapping%20in%20BC (Accessed 9 March 2021).

Bathurst, J. C. (1985). Flow resistance estimation in mountain rivers. Journal of Hydraulic Engineering, 111(4), 625–643.

BC Freshwater Atlas (2018). Hydrography datasets. [online] Available from: https://catalogue.data.gov.bc.ca/dataset/freshwater-atlas-watersheds.

BC MOE (2011). Climate Change Adaption Guidelines for Sea Dikes and Coastal Flood Hazard Land Use – Sea Dike Guidelines. Report prepared by Ausenco-Sandwell for BC Ministry of Environment (BC MOE). 59 pp.

Brownlie, W. R. (1981). Compilation of Alluvial Channel Data: Laboratory and Field. California Institute of Technology, Pasadena.

Church, M., and Jakob, M. (2020). What is a debris flood? Water Resources Research, 17. doi:10.1029/2020WR027144.

Collins, B. D., Montgomery, D. R., and Sheikh, A. J. (2003). Reconstructing the Historical Riverine Landscape of the Puget Lowland. Restoration of Puget Sound Rivers (pp. 79–128). University of Washington Press, Seattle, WA.

Corenblit, D., Tabacchi, E., Steiger, J., and Gurnell, A. M. (2007). Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: A review of complementary approaches. Earth-Science Reviews, 84, 56–86. doi:10.1016/j.earscirev.2007.05.004.

Eaton, B., and Moore, R. D. (2010). Regional Hydrology. Compendium of Forest Hydrology and Geomorphology in British Columbia (pp. 85–110). BC Ministry of Forests and Range, Forest Science Program.

EGBC (2018). Legislated Flood Assessments in a Changing Climate in BC, Version 2.1. Engineers & Geoscientists British Columbia, Burnaby, BC. 192 pp. [online] Available from: https://www.egbc.ca/getmedia/f5c2d7e9-26ad-4cb3-b528-940b3aaa9069/Legislated-Flood-Assessments-in-BC.pdf (Accessed 13 September 2018).

Engelund, F., and Hansen, E. (1967). A monograph on sediment transport in alluvial streams. Technical University of Denmark 0stervoldgade 10, Copenhagen K. [online] Available from:

http://resolver.tudelft.nl/uuid:81101b08-04b5-4082-9121-861949c336c9 (Accessed 26 June 2018).

EXCIMAP (2007). Flood mapping: a core component of flood risk management - Atlas of Flood Maps: Examples from 19 Countries, USA and Japan. European Commission - Environment. [online] Available from: http://ec.europa.eu/environment/water/flood_risk/flood_atlas/ (Accessed 13 August 2018).

Fleming, S. W., Whitfield, P. H., Moore, R. D., and Quilty, E. J. (2007). Regime-dependent streamflow sensitivities to Pacific climate modes cross the Georgia–Puget transboundary ecoregion. Hydrological Processes, 21(24), 3264–3287. doi:10.1002/hyp.6544.

Government of British Columbia (2022). B.C. Streamflow Inventory. British Columbia. [online] Available from: https://www2.gov.bc.ca/gov/content/environment/air-land-water/water/water-science-data/water-data-tools/provincial-hydrology-program/resources/streamflow-inventory.

Gurnell, A. M., Petts, G. E., Hannah, D. M., Smith, B. P. G., Edwards, P. J., Kollman, J., Ward, J. V., and Tockner, K. (2001). Riparian vegetation and island formation along the gravel-bed Fiume Tagliamento, Italy. Earth Surface Processes and Landforms, 26, 31–62.

Hart, J. S. (1979). Clastic sediment sources and suspended sediment yield in a coast mountain watershed, British Columbia (Master of Arts thesis). The University of British Columbia, Vancouver, British Columbia.

Holm, K., Bovis, M., and Jakob, M. (2004). The landslide response of alpine basins to post-Little Ice Age glacial thinning and retreat in southwestern British Columbia. Geomorphology, 57(3–4), 201–216. doi:10.1016/S0169-555X(03)00103-X.

Jakob, M., Davidson, S., Bullard, G., Busslinger, M., Collier-Pandya, B., Grover, P., and Lau, C. (2022). Debris-Flood Hazard Assessments in Steep Streams. Water Resources Research, 58, 31.

Jarrett, R. D. (1984). Hydraulics of high gradient streams. Journal of Hydraulic Engineering, 110(11), 1519–1539.

Jordan, P., and Slaymaker, O. (1991). Holocene sediment production in Lillooet River basin, British Columbia: a sediment budget approach. Geographie Physique et Quaternaire, 45(1), 45–57.

KWL (2002). Engineering Study for Lillooet River Corridor. Final Report. Report prepared by Kerr Wood Leidal Associates Ltd for B.C. Ministry of Water, Land and Air Protection. 204 pp.

KWL (2005). Lillooet River - October 2003 Flood: High Water Mark Survey. Technical Memorandum. Report prepared by Kerr Wood Leidal Associates Ltd for B.C. Ministry of Water, Land and Air Protection. 11 pp.

KWL (2006). PVDD Dyke Operation and Maintenance Manual: Appendix I Special Provisions for Specific Dykes; Tab I1 - Miller Creek. Pemberton Valley Dyking District.

KWL (2009). Ryan River Hydraulic Model and Dyking Assessment (713.029–300). Final Report. Prepared by Kerr Wood Leidal Associates Ltd. for the Pemberton Valley Dyking District. 43 pp.

KWL (2014). Creek Hydrology, Floodplain Mapping and Bridge Hydraulic Assessment - Floodplain Development Permit Area, Flood Construction Level Development and Use.

KWL (2017). District of Squamish Integrated Flood Hazard Management Plan - Final Report, October 2017. Prepared by Kerr Wood Leidal Associates Ltd. for District of Squamish. 251 pp. [online] Available from: https://squamish.ca/assets/IFHMP/1117/20171031-FINAL_IFHMP_FinalReport-compressed.pdf (Accessed 3 May 2018).

Limerinous, J. T. (1970). Determination of the Manning coefficient from measured bed roughness in natural channels.

Marshall, I. B., Schut, P. H., and Ballard, M. (1999). A National Ecological Framework for Canada: Attribute Data. Agriculture and Agri-Food Canada, Research Branch, Centre for Land and Biological Resources Research and Environment Canada, State of the Environment Directorate, Ecozone Analysis Branch, Ottawa/Hull. [online] Available from: http://sis.agr.gc.ca/cansis/nsdb/ecostrat/1999report/index.html.

Maynord, S. T. (1991). Flow resistance of riprap. Journal of Hydraulic Engineering, ASCE, 117(6), 687–696.

MFLNRO and NHC (2014). Simulating the Effects of Sea Level Rise and Climate Change on Fraser River Flood Scenarios. Report prepared jointly by Northwest Hydraulic Consultants Ltd. and BC Ministry of Forests, Lands and Natural Resource Operations. 202 pp. [online] Available from: http://www.env.gov.bc.ca/wsd/public_safety/flood/pdfs_word/Simulating_Effects_of_Sea_Level_Rise_and_Climate_Change_on_Fraser_Flood_Scenarios_Final_Report_May-2014.pdf.

MWLAP (2004). Flood Hazard Area Land Use Management Guidelines. Province of British Columbia, Ministry of Water, Land, and Air Protection. 72 pp.

NHC (2008). Flood Risk Evaluation and Flood Control Solutions, Phase 1. (34920). Report prepared by Northwest Hydraulic Consultants for City of Prince George.

NHC (2016). North Alouette and South Alouette Rivers Additional Floodplain Analysis: Phase 2 - Technical Investigations Completion Report. Report prepared by NHC for the City of Maple Ridge. 46 pp. [online] Available from: https://www.mapleridge.ca/DocumentCenter/View/8145/North-and-South-Alouette-Rivers-Floodplain-Study?bidId= (Accessed 6 December 2018).

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 (2021a). Birkenhead and Green River Floodplain Mapping and Risk Assessment. Lil̓wat Nation.

NHC (2021b). British Columbia Extreme Flood Project. Final Report Prepared for The Ministry of Forests, Lands, Natural Resource Operations and Rural Development by Northwest Hydraulic Consultants Ltd. 170 pp.

Pike, R. G., Bennet, K. E., Redding, T. E., Werner, A. T., Spittlehouse, D. L., Moore, R. D., Murdock, T. Q., Beckers, J., Smerdon, B. D., Bladon, K. D., Foord, V. N., Campbell, D. A., and Tschaplinski, P. J. (2010). Climate Change Effects on Watershed Processes in British Columbia. Compendium of Forest Hydrology and Geomorphology in British Columbia (pp. 699–747). BC Ministry of Forests and Range, Forest Science Program.

Radić, V., Cannon, A., Menounos, B., and Gi, N. (2015). Future changes in autumn atmospheric river events in British Columbia, Canada, as projected by CMIP5 global climate models. Journal of Geophysical Research: Atmospheres, 120(18), 9279–9302. doi:10.1002/2015JD023279.

van Rijn, L. C. (1984). Sediment transport, Part I: bed load transport. Journal of Hydraulic Engineering, 110(10), 1431–1456.

Shrestha, R. R., Schnorbus, M., Werner, A. T., and Berland, A. J. (2012). Modelling spatial and temporal variability of hydrologic impacts of climate change in the Fraser River basin, British Columbia, Canada. Hydrological Processes, (26), 1840–1860.

UBC (2021). ClimateNA_MAP. UBC Centre for Forest Conservation Genetics. [online] Available from: http://www.climatewna.com/.

UK DEFRA / Environmental Agency (2005). Flood Risk Assessment Guidance for New Development - Phase 2: Framework and Guidance for Assessing and Managing Flood Risk for New Development (R&D Techincal Report FD2320/TR2). Technical Report. Defra / Environment Agency, Food and Coastal Defence R&D Programme, London, UK. 384 pp. [online] Available from: http://evidence.environment-agency.gov.uk/FCERM/Libraries/FCERM_Project_Documents/FD2320_3364_TRP_pdf.sflb.ashx (Accessed 13 August 2018).

Weatherly, H., and Jakob, M. (2014). Geomorphic response of Lillooet River, British Columbia, to meander cutoffs and base level lowering. Geomorphology, 217, 48–60.

Wong, M., and Parker, G. (2006). Reanalysis and correction of bed-load relation of Meyer-Peter and Müller using their own database. Journal of Hydraulic Engineering, ASCE, 132(11), 1159–1168. doi:10.1061/(ASCE)0733-9429(2006)132:11(1159).

APPENDIX A

GEOMORPHOLOGY DOCUMENTATION

Photo source: NHC (2022)

Appendix A - Ryan River Geomorphology - Channel Stability Assessment

March 20, 2023
Appendix A, Final Report, Rev. R1

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1 INTRODUCTION

1.1 Background

NHC was retained by the Pemberton Valley Dyking District (PVDD) to complete floodplain mapping of the Ryan River. As a core component of mapping flood levels on the Ryan River, NHC completed a qualitative channel stability assessment to provide discharge bulking factors for hydrogeomorphic processes that have or may occur in the watershed. These hydrogeomorphic processes include debris floods and debris flows that could influence the conveyance capacity or contribute to erosion and avulsion in the lower reaches, downstream of the fan apex, where the Ryan River is on the west side of the Lillooet floodplain and is confined by dikes. The channel stability assessment investigated the channel of the river where the Ryan River is confined by dikes. The Ryan dike has both eroded and breached multiple times in the past but the processes leading to these events are not well known.

The stability of the lower Ryan River is influenced by hydrogeomorphic processes and channel instability occurring upstream of the fan apex. The steep upper watershed is characterized by rugged mountainous terrain with active sediment and woody debris sources from tributary channels, avalanche paths and glaciers contributing materials to the channel. Channel morphology and planform is substantially different in the downstream lower gradient reaches. The confluence with the Lillooet River valley marks a distinct geomorphic transition, downstream of which, the Ryan River flows along a more gradual channel gradient, forming a depositional reach in the lower watershed where past dike breaches and erosion has occurred.

In this report we present the findings of NHC's channel stability assessment. The assessment includes an inventory of landslide activity and channel characteristics in the upper watershed based on aerial photography and satellite imagery to identify sediment sources and mechanisms of delivery to the main channel. A ground-based inspection was conducted at and downstream of the fan apex to document the depositional environment and investigate the roles that two tributaries originating on Mt. Ross have on the channel near a known dike breach. The field inspection also included assessment of a downstream reach at a location on the dike were erosion and tension cracks were identified. These ground-based observations informed the understanding of channel stability and the processes shaping the contemporary channel form.

1.2 Study Objectives

The main objectives guiding this assessment are:

- To identify and describe the major sediment and woody debris sources and depositional zones within the Ryan River watershed.
- To identify the current and historical hydrogeomorphic events that are influencing the stability of the Ryan River.
- To estimate the potential discharge bulking factors associated with hydrogeomorphic events
- To qualitatively assess the relative controls on the stability of the Ryan River.

2 PHYSIOGRAPHY

The Ryan River, located within the southern Coastal Mountain Range of British Columbia, is a major tributary of the Lillooet River. The Ryan River watershed can be divided into three broad geomorphic regions (Figure 2.2):

1. Upstream of the confluence with the Lillooet River valley, the Ryan River conveys water, sediment and woody debris from a highly glaciated alpine basin that was partially deforested (clear cut) in the mid 20th century. Colluvial processes dominate in the river headwaters where the gradient is highest (Figure 2.1). Downstream, the river has a stepped pattern, characteristic of rivers flowing through glacially sculpted landscapes with lower gradient reaches (0.5 - 2 %) separated by short steeper steps (5 - 10 %). The downstream end of this watershed region is the fan apex.
2. Near RK 15, the river flows into the Lillooet River floodplain, forming an alluvial fan. The fan is partially confined by the Ryan River dike, which lies perpendicular to the natural channel flow direction and by colluvial deposits originating from Mt. Ross.
3. Downstream of the fan, the Ryan River flows parallel to the Lillooet River, confined to the west margin of the Lillooet River floodplain by the Ryan dike.

The channel morphology of the Ryan River in each of these regions are described in more detail in Sections 6.1.1, 6.2.1, and 6.3.1 to explain the factors influencing channel stability and the rationalization for discharge bulking factors.

Figure 2.1 Overview of the upper and lower Ryan River watersheds separated by the Ryan River fan.

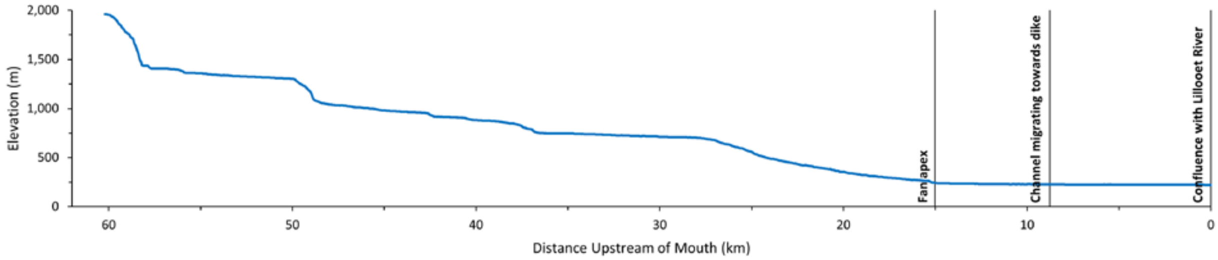


Figure 2.2 Long profile of the Ryan River.

3 GEOLOGY

The Ryan River watershed has a complex and dynamic landscape shaped by past periods of geologic and glacial activity. The bedrock geology of the Ryan River watershed is predominantly composed quartz dioritic intrusive rocks from the Late Jurassic to Early Cretaceous period with marine sedimentary and volcanic rocks of the Gambier Group (Lower Cretaceous period) present in the middle of the watershed (Bellefontaine et al., 1994).

The most recent glacial period in this area was the Fraser Glaciation, which began approximately 29,000 years ago and ended around 11,000 years ago (Clague, 1981). During this time, ice advanced and over-rode most of the peaks in the southern Coastal Mountain range (Ryder, 1972), causing substantial changes to the landscape in the upper Ryan River watershed. The glaciers scoured and widened upper valley areas and depositing a veneer of till over the bedrock throughout much of the upper watershed. Since deglaciation, alpine glaciers have occupied the upper slopes in the watershed, leaving morainal deposits in front of the retreating glaciers. Glacial retreat has debuttressed and oversteepened slopes in the upper valley resulting in increased susceptibility to rock falls (Holm et al., 2004). The high bedload sediment supply in the upper valley has formed braided meltwater channels downstream of the glaciers.

Mountain slopes throughout the upper watershed have been subjected to erosion by debris flows and colluvial deposits are now located at the base of hillslopes. In the valley bottom, the Ryan River and its tributaries have reworked glacial and post-glacial sediments through fluvial erosion. The low-gradient reaches, covered by fluvial deposits, are often separated by narrower reaches that are confined by frequent bedrock outcrops in the upper watershed. In the Lillooet River valley bottom, the Ryan River flows through post-glacial alluvial sediments.

4 SUMMARY OF HYDROLOGY

The Ryan River watershed lies within the BC Coast Mountain range. The review of the region's hydrology (Section 2) shows that watersheds in this region have various hydrologic regimes including rainfall dominated, rain-snow hybrid, snow-glacier, and rain-snow-glacier hybrid with changes over time based on medium to long-term climate trends and year to year weather variations. Peak flows within the Ryan River watershed are generally expected to occur during the spring freshet, though peak flows generated at different times of the year are possible due to heavy rainfall, rain-on-snow flooding, and rain-on-glacier flooding. Atmospheric river events can also produce heavy rainfall and warm temperatures across all elevations, with the potential to cause rain-on-snow flooding (NHC, 2018).

There is one hydrometric station located in the Ryan River watershed operated by the Water Survey of Canada (08MG028), The station was installed at RK 8 along the lower Ryan River and has been in operation since June 2021. The maximum discharge recorded at the WSC gauge over the past year was 163 $m^3 s^{-1}$ on June 27th, 2021 (provisional data, subject to review).

5 HYDROGEOMORPHIC PROCESSES

Hydrogeomorphic processes involve the transport of water and sediment, typically within steep mountain creeks. In the Ryan River watershed, mass movements and hydrogeomorphic processes occur on a range of spatial and temporal scales. The processes range from large rock, snow, and debris avalanches on steep mountain slopes; debris flows and floods initiated in tributaries that fundamentally alter the morphology of downstream channel reaches; and clearwater floods that re-distribute and re-organize sediment stored along the bars and bed of the river in the river channel and floodplain (Table 5.1).

Table 5.1 Hydrogeomorphic process descriptions.

Hydrogeomorphic process	Typical Slope Gradient[1]	Description
Debris avalanche	>45%	A gravitational mass movement whereby rock or debris falls from an oversteepened hillslope.
Debris flow	25-45%	A rapid, gravity-driven mass movement event that occurs in steep channels involving the transport of well-mixed water and debris.
Debris flood	10-25%	A heavily sediment-laden flood that occurs on relatively steep channels, capable of substantially higher morphologic change and destructive potential than clearwater floods.
Clearwater flood	<5%	A high discharge flow that transports a relatively low amount of sediment.

Notes:
1. Typical slope gradients referenced from Figure 4 in BGC (2020a)

Debris floods can be further classified by their triggering mechanisms (Church and Jakob, 2020). The triggers for these events are important to consider when developing bulking factor estimates as the impacts and return periods vary substantially (see Table 3 in (Church and Jakob, 2020)). For example, Type 1 debris floods are meteorologically generated (i.e., occur during high precipitation events) with a return period of over two years and a bulking factor of 1.05. Type 2 debris floods occur when debris flows transition into debris floods due to a reduction in channel gradient and increase in water concentration. Typical return periods for these events are more than 50 years, and the bulking factor is in the range of 2-5. Type 3 debris floods represent the most catastrophic events that occur due to outbreak flooding. This may arise when a channel is dammed by wood, debris, or sediment that fails rapidly releasing a high volume of water impounded upstream of the blockage. Return periods for these events are more than 100 years and the typical bulking factor may range from 2 to 100.

The following subsection provides a brief review of previous studies that have documented colluvial and hydrogeomorphic processes within the Ryan River watershed, while a more thorough description of the various hydrogeomorphic processes observed in NHC's review of historical imagery is presented in the Results section.

5.1 Previous Studies

In a study focused on landslide activity in alpine basins along the upper Lillooet River valley, Holm et al. (2004) mapped four major rock slope failures in the upper Ryan River watershed (defined as events that significantly altered basin topography or have significant (> 10^5 m^3) landslide deposits). In a cirque glacier located south of the Ryan River near RK 45, the authors documented a rock avalanche that travelled across the glacier, breached an end moraine, and deposited a large volume of debris that temporarily dammed the tributary creek. This caused substantial aggradation of the floodplain up valley of the deposit.

Hart (1979) investigated clastic sediment sources and suspended sediment yield in the Wasp Creek watershed, a tributary that joins the Ryan River near RK 29 in the upper watershed. In this study, the author describes several important transport processes in the Wasp Creek watershed including rockfalls on bedrock slopes, debris avalanches and debris flows, snow avalanches, as well as slow mass movements. The author also describes a large debris flow event on the Ryan River that was triggered during a rain-on-snow event in November 1975. The debris flow deposit temporarily dammed the river leading to “enormous erosional consequences to the downstream channel”. The exact location of this event was not specified.

As part of a study investigating the sources, storage, and yield of clastic sediment in the Lillooet River watershed, Jordan and Slaymaker (1991) inventoried major debris flow channels in upper watershed tributaries of the Ryan River using aerial photos (1:50,000 scale). Two large debris flows with an estimated volume of 10^5 m^3, were mapped at the confluence of the Ryan and Lillooet River valleys (Ryan River fan area), that were initiated on the northeast aspect slopes of Mt. Ross, as well as a third large debris flow initiated higher in the Ryan River watershed near RK 34 (Figure 5.1). Numerous small debris flows (with estimated volumes 10^3 to 10^4 m^3) were mapped along the steep hillslopes in the upper Ryan River and Petersen Creek watersheds. In the upper Ryan River watershed, the main channel and adjacent valley walls are highly coupled, such that many of these debris flow events delivered sediment directly to the river channel in the valley bottom, potentially causing partial or complete channel blockages.

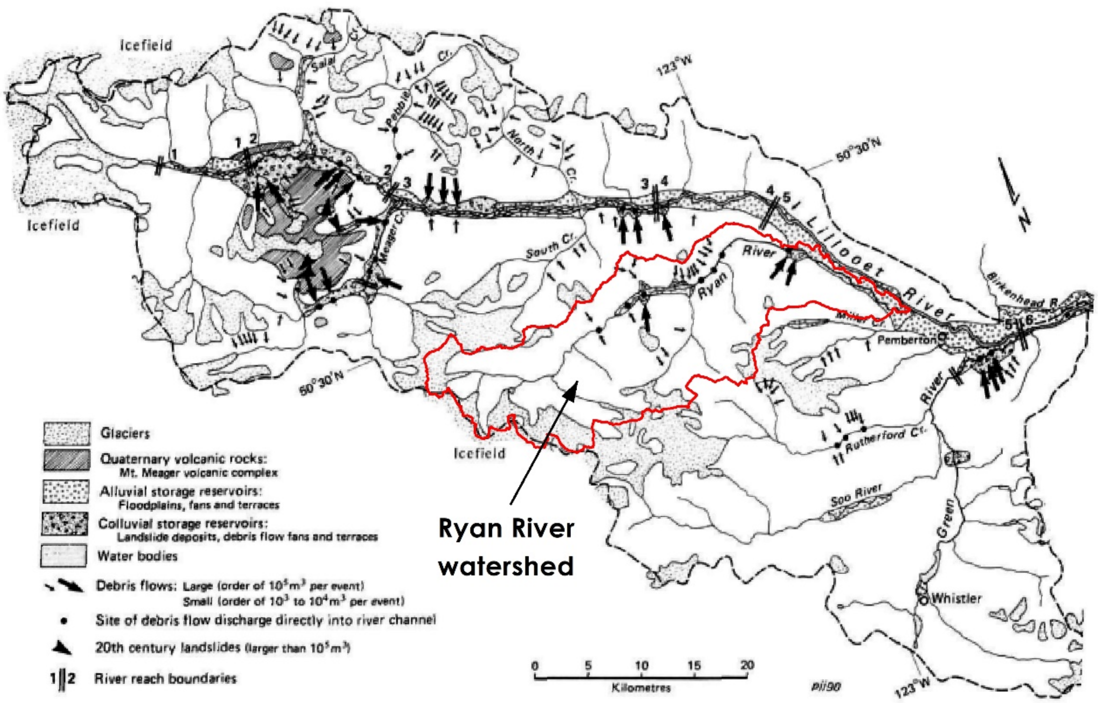


Figure 5.1 Historical debris flows in the Ryan River Watershed. Figure recreated from Jordan and Slaymaker (1991).

These studies are examples of some types of hydrogeomorphic processes documented in the Ryan River watershed and the alterations to the landscape, river channel, sediment sources and deposits that resulted. The upper watershed hillslopes are coupled (or partially coupled) with the river channel, therefore gravitational processes that occur in the upper watershed have direct consequences to downstream reaches, immediately in the case of landslide damming or over a longer time scale in the case of clearwater fan deposition. Building from these previous investigations, NHC identified and described hydrogeomorphic processes that occur in the Ryan River watershed to develop an understanding of the channel stability in the lower reaches where dike breaches or failures are a concern.

6 METHODS

6.1 Data Sources

In addition to field data collected during NHC's site inspection (Section 6.2), the following datasets were used to inform the channel stability assessment:

- Historical air photos from 1947, 1964/65, 1981, 1994, 2005, and 2016 (UBC Geographic Information Centre)
- Lidar DEM and orthophotos from 2006 (SLRD), 2009 (PVDD), and 2016 (EMBC)

- UAV orthophoto and DEM (2022, collected by NHC as part of this study)
- Topographic survey data from 2006 (KWL) and 2022 (NHC, this study)
- Publicly available imagery (e.g., Google Earth, Sentinel 2, ESRI)
- Publicly available datasets (e.g., CDEM, bedrock geology, etc.)
- Publicly available reports and peer-reviewed articles
- Regional precipitation data
- Regional hydrometric data and flood frequency analysis

6.2 Field Data Collection

Site inspections conducted to inform the channel stability assessment were completed by NHC on April 13th, 2022. At this time, the majority of the snow had melted in the valley bottom, and the river was low flow (discharge approximately < 7 m^3/s, provisional WSC data), facilitating observation of in-channel sediment deposits and bank materials that would be obscured or unsafe to document at higher flows. A Wolman pebble count was collected along a bar margin that paralleled the main channel flow within the Ryan River fan. The sediment deposit was estimated to be characteristic of the bed load transported by fluvial (clearwater) processes on an annual basis.

6.3 Assessment of Sediment Sources and Deposition

Sediment sources and depositional zones in the watershed were identified through a review of historical air photos, orthophotos, and satellite imagery. For the Ryan River fan, and the lower study site (RK 9), field observations also helped identify local sediment sources and patterns of deposition.

In addition, NHC assessed the Melton ratio and watershed length for gully sub-basins identified near the Ryan River fan (Jakob et al., 2022; Wilford et al., 2004). This was used as supporting evidence to identify tributary watersheds prone to debris flows, debris floods, and/or clearwater floods. Typically, watersheds prone to clearwater floods have a Melton ratio less than 0.3; debris-flood prone watersheds typically have a Melton ratio between 0.3 and 0.6, or greater than 0.6 with a watershed length exceeding 3 km; and debris flow prone watershed typically have a Melton ratio greater than 0.6 and a watershed length less than 3 km (Wilford et al., 2004). However, the boundaries between these process domains are not discrete, as many watersheds are susceptible to a mix of processes occurring at different frequencies and magnitudes (Church and Jakob, 2020). The analysis of steep creek processes presented in this report should be considered a preliminary step, that requires further follow up to better understand the magnitude and frequency of hydrogeomorphic processes operating in tributary channel watersheds, how they influence the main channel of the Ryan River and the potential hazards associated with these events (APEGBC, 2010).

6.4 Lateral Stability Assessment

In the upper watershed, the lateral stability of the Ryan River was assessed qualitatively through a review of historical and modern imagery. We defined reach breaks based on differences in channel morphology and slope, as well as evidence of channel migration and lateral instability. Stable reaches were defined as sections of channel that exhibited little to no lateral changes, while unstable reaches were defined as sections of channel that exhibited frequent and/or substantial changes in channel morphology through re-organization of bars and islands, channel widening, or channel avulsions.

At the Ryan River fan, lateral changes in channel planform were qualitatively assessed through a comparison of georeferenced historical air photos and orthophotos. A summary of major historical floods on the Ryan River was compiled to provide context for, and better interpret, temporal patterns in channel erosion and lateral migration.

Observations of lateral instability at the lower study site (near RK 9) were collected during NHC's site visit. Historical imagery was also reviewed to look for major changes in channel planform.

6.5 Vertical Stability Assessment

Vertical channel stability in the upper watershed was assessed qualitatively through inferences based on channel morphology and historical lateral stability.

For the Ryan River fan and the lower study site (RK 9), vertical stability was assessed by comparing topographic survey data collected in 2006 by KWL were compared with 2022 survey data collected by NHC. The 2006 survey data was collected using a variation of the CGVD28 vertical datum based on Water Resource Monuments in the area. This datum differs from the CGVD28 (HTv2.0) datum by approximately 20-30 cm. NHC's 2022 survey was collected using the CGVD2013 datum. Because there is no straightforward way to convert from CGVD (WRS monuments) to CGVD2013, we used NRCan's online software tool to convert the 2006 data from CGVD28 (HTv2.0) to GCGVD2013. This does not account for the global 20-30 cm offset between CGVD (WRS monuments) and CGVD28 (HTv2.0). Due to the datum issue with the 2006 data, the comparison of 2006 to 2022 elevations was limited to qualitative interpretations of change, and only approximate magnitudes of change. A further limitation of this analysis was that the orientation and position of the 2022 survey transects did not precisely overlap the KWL transects, and in places is offset from the historical transects by more than 30 m. Nonetheless, comparing the two surveys allowed us to make general observations of how the morphology of the bed has changed between 2006 and 2022, and provides further context to the planform changes described in Section 7.2.2.

7 RESULTS

The channel stability assessment focused on three geomorphic regions: the upper watershed, the Ryan River fan (near RK 15), and the lower Ryan River. These sites are discussed independently in the following sections.

7.1 Upper Watershed

7.1.1 Reach Description

Upstream of the confluence with the Lillooet River valley, the Ryan River drains a 376 km^2 highly glaciated (16 % by area) alpine basin, with elevations ranging from 235 m to 2,587 m and a mean elevation of 1,634 m above sea level (Figure 7.1). Glaciers in the upper watershed are actively receding, as evidenced by fresh moraines. This has led to de-buttressing of the confining bedrock, which in some locations has caused large rock falls (Holm et al., 2004). Several proglacial lakes intercept and attenuate sediment sourced from receding glaciers throughout the river headwaters, however, downstream reaches are relatively wide and dominated by large side- and mid-channel bars, indicating that sediment load remains high through the upper channel reaches (Panel A in Figure 7.1).

The river generally flows east through the upper basin and is bounded by steep north and south aspect valley walls lined with deforested avalanche paths (Panel B in Figure 6.1). Avalanches reaching the main channel in the valley bottom appear to be the primary input of woody debris, though there are very few log jams present throughout the channel. Avalanches occurring in the winter and spring contribute very little sediment to the main channel as the alpine slopes are largely protected by snow; transfer of debris during snow avalanching may be higher when snow cover is reduced (Hart, 1979).

The steep hillslopes in the upper watershed are prone to failure, and episodically deliver large volumes of sediment, ranging from 10^3 to 10^5 m^3, to the main channel through landslides and debris flow events (Jordan and Slaymaker, 1991). These mass movements appear to be an important contributor to the basin's sediment yield. In the past, debris flow deposits reaching the valley bottom appear to have temporarily dammed (or partially confined) the main channel. This process may have led to upstream aggradation and potentially dam outburst flooding. An example debris fan that likely blocked the channel and produced upstream deposition is shown in Panel C (Figure 7.1).

Petersen Creek is the largest tributary to the Ryan River by watershed area. The creek joins the main channel from the south near RK 28 and appears to be an important sediment source historically (Panel D, Figure 7.1). Numerous landslides and debris flows occur in the upper portions of the Petersen Creek watershed that likely transition to debris floods or clearwater floods prior to reaching the confluence with the Ryan River. Downstream of Petersen Creek, the main channel is confined by steep valley walls and colluvial cones. This confinement produces a transport-dominated reach, as the river is unable to migrate laterally. Sediment supplied by Petersen Creek and upstream on the mainstem is generally mobilized through this section of the river and deposited downstream of RK 20 where the channel gradient and valley confinement are reduced. This results in a wider channel with numerous bars and islands (Panel E, Figure 7.1). These in-channel storage sites provide an important source of sediment to the Ryan River fan and are likely eroded by annual peak floods.

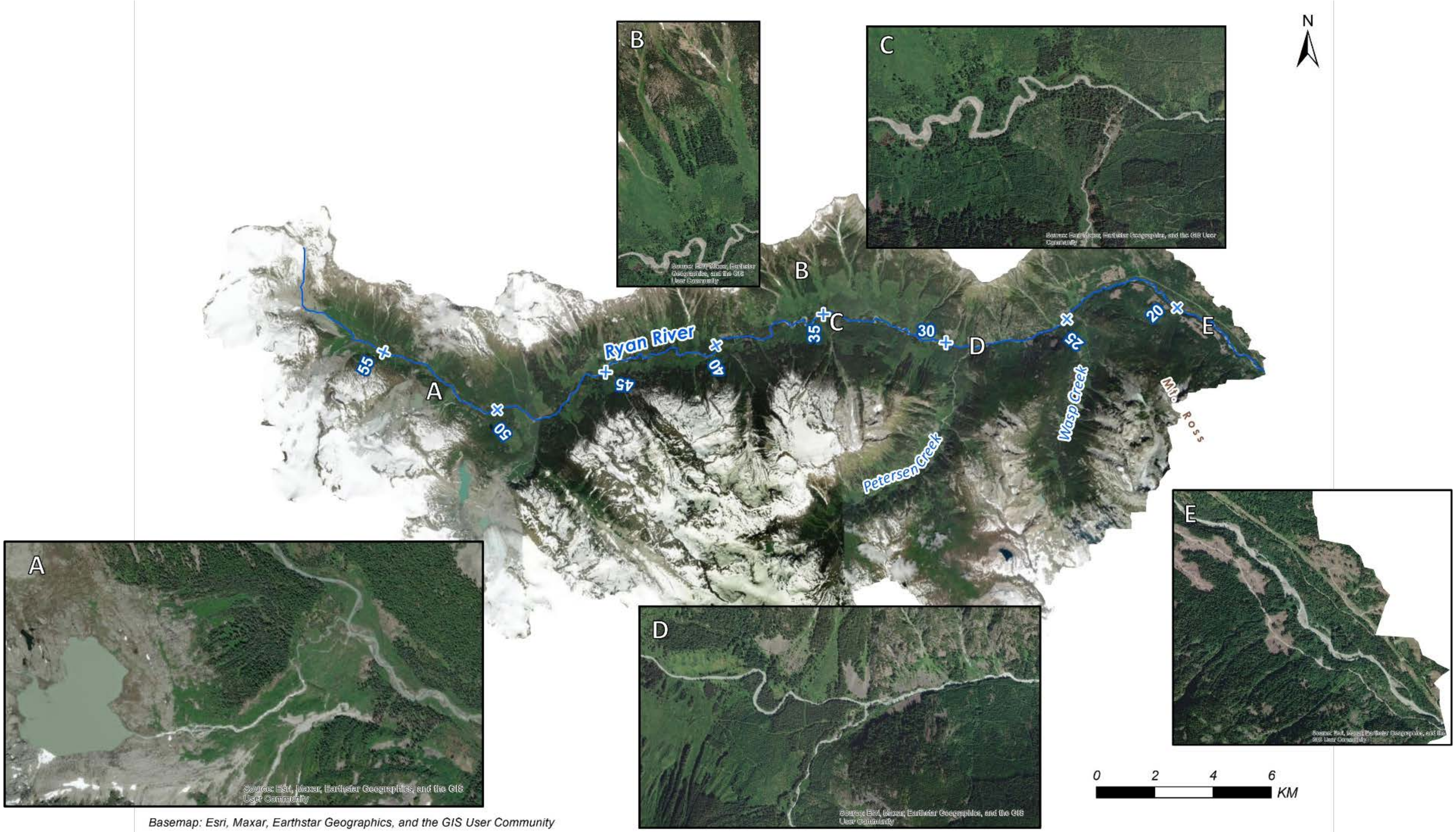


Figure 7.1 Geomorphic features and processes in the upper Ryan River watershed. Base map is a composite of imagery from 2014 to 2021.

7.1.2 Lateral Stability

The upper Ryan River watershed consists of a series of laterally stable and unstable channel reaches (Figure 7.2). The extent of these reaches was delineated approximately using ArcMap's satellite imagery base map, which for the Ryan River watershed includes imagery from 2014 to 2021. The position of unstable and stable reaches changes over time due to long-term sediment migration through the watershed, and the timing and location of high-magnitude sediment delivery events from the adjacent hillslopes. The purpose of this section is to describe the types of processes and geomorphic settings that create and maintain channel stability (and instability), rather than to focus on the exact position of unstable channel reaches at a specific point in time.

In the upper watershed, laterally stable reaches tend to occur where the valley gradient is high and adjacent hillslopes confine the position of the channel (e.g., Panel A in Figure 7.2). This produces a narrow and generally straight or low-sinuosity channel planform. The morphology of stable channel reaches is best described as a cascade or step-pool channel morphology (Montgomery and Buffington, 1993), where the flow of water is typically controlled by bedrock outcrops and/or large boulders. While sediment supply to these reaches is high because of the direct coupling to hillslopes, there is little room for sediment storage and thus these reaches act as sediment transport zones (Buffington et al., 2003). The most prominent laterally stable reach in the upper basin occurs from approximately RK 30 to RK 20, where the channel is either partly or fully confined and there are few in-channel storage sites. Sediment supplied from upstream and from adjacent hillslopes is conveyed through this reach and deposited downstream of RK 20, through to the Ryan River fan.

Laterally unstable channel reaches in the upper watershed were identified based on the presence of historical channel migration, bank erosion and channel avulsions. Laterally unstable reaches are characteristically wide and provide room to accommodate in-channel sediment storage, in the form of side bars, mid-channel bars and vegetated islands (Panel B in Figure 7.2). The bars in the river act as short-term sediment storage zones (< ~ 5 years) as they are frequently re-worked and re-organized by peak flood events. Relative to stable channel reaches, the unstable reaches form on lower gradients and are less confined by the valley walls. Where sediment supply is locally high, such as glacial outwash channels in the river headwaters, the river forms a multi-thread channel configuration to accommodate the high sediment load.

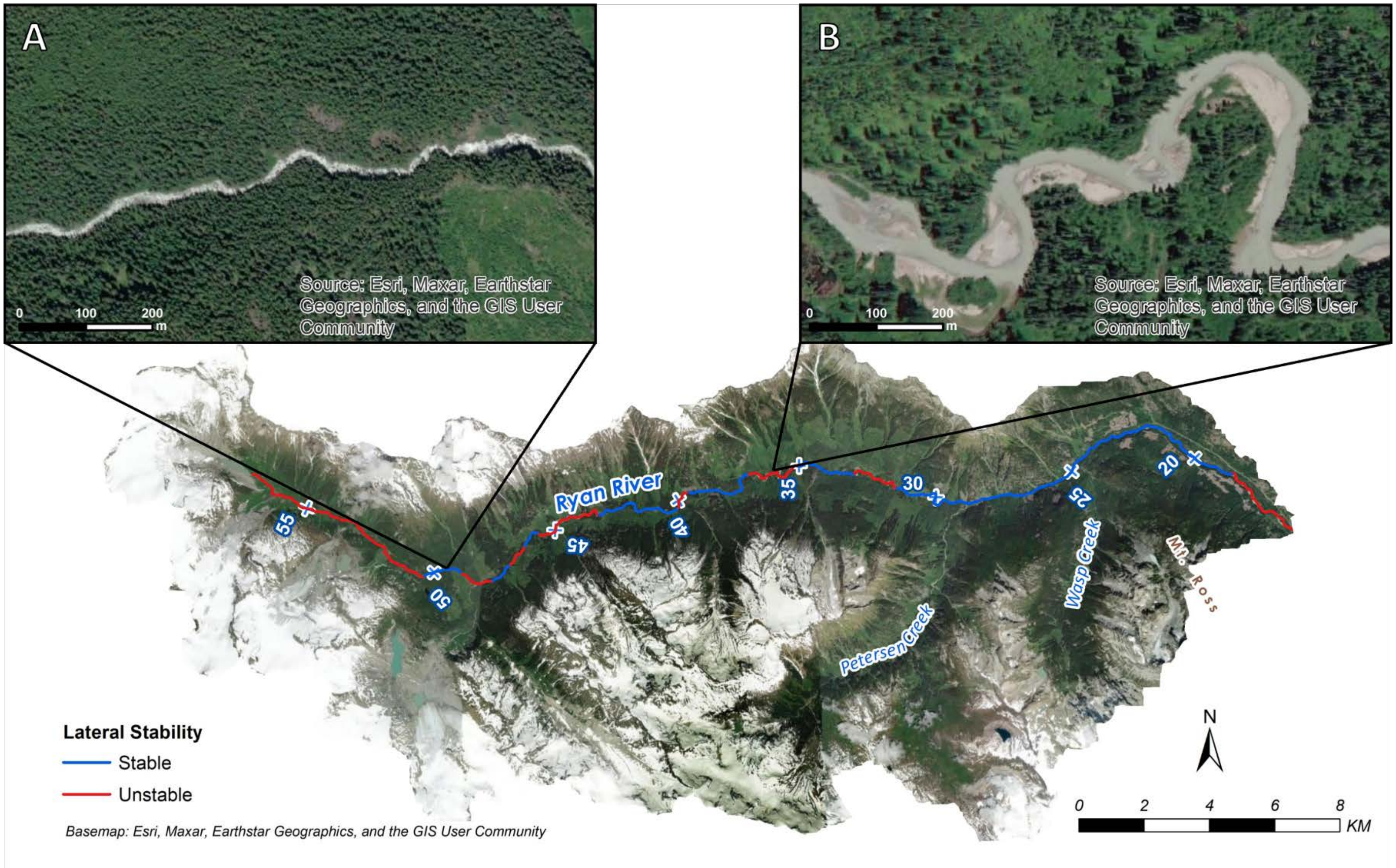


Figure 7.2 Upper Ryan River watershed channel reaches. Base map is a composite of imagery from 2014 to 2021.

7.1.3 Vertical Stability

While no direct measurements were made of vertical stability in the upper watershed, we can make some inferences based on the lateral stability and planform of the river.

In the narrow, confined reaches of the river, the erosive force of flowing water and sediment is likely to cause degradation of the channel bed as the river is unable to erode laterally. Over time this leads to a steep channel-gradient with shallow depth to bedrock (Buffington et al., 2003). Mass wasting events on the confining hillslopes play an important role on the long-term vertical stability of these reaches, as high-magnitude events that reach the valley bottom are capable of blocking the channel and causing upstream aggradation (Hart, 1979; Jordan and Slaymaker, 1991).

In the laterally unstable channel reaches (see Figure 7.2), the vertical stability of the channel is likely tied to the position of in-channel bars and islands. In these reaches, the river forms an alternating series of topographic highs (riffles) and lows (pools) due to flow constriction and expansion around bars and islands, whereby flow constriction leads to pool scour, and expansion leads to deposition of riffles and bars. This self-reinforcing process likely maintains the morphology of the river over the short to medium term (decadal scale) but is likely reset during extreme events capable of major morphologic change to bar and river morphology.

7.2 Ryan River Fan

7.2.1 Reach Description

At the confluence with the Lillooet River floodplain, the Ryan River forms a large alluvial fan, as the channel gradient drops, and the river exits valley confinement. The Ryan dike has historically been susceptible to breaches at this location (KWL, 2002, 2009; NHC, 2018), which is unsurprising given that alluvial fans are definitionally unstable environments, whereby changes in channel planform may occur rapidly due to lateral migration and channel avulsions.

In this reach, the channel forms a wandering-style morphology with one main channel and several side channels that cut through and flow around forested islands and bars (Figure 7.3). This section of the river forms a depositional zone whereby coarse sediment and LWD tends to accumulate due to a decrease in channel gradient from 5-6 % upstream of the fan to 0.1 % downstream of the fan. The position of the channel is constrained to the south by the base of Mt. Ross, and to the north by the Ryan dike. Channel width ranges from 60 to 100 m.

Surficial sediment on bars ranges in size from sand to boulders. A Wolman-style pebble count (Wolman, 1954) was collected along the bar margin shown in Figure 7.3. The median size of surficial sediment at this location is 97 mm and the 84th percentile material is 168 mm (Figure 7.4). This sample reflects sediment likely mobilized by annual floods, collected adjacent to the low-flow main channel.

Figure 7.3 Ryan River fan study area (2022 NHC UAV orthophoto).

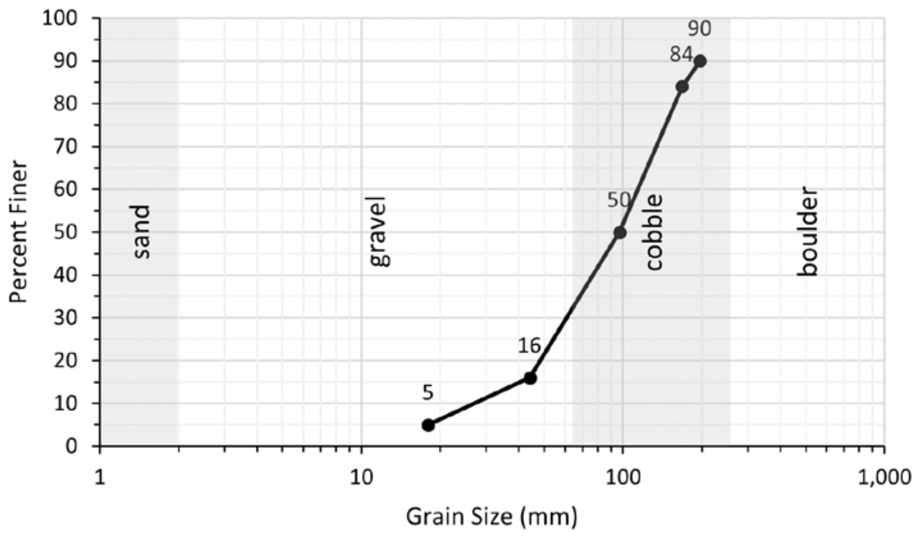


Figure 7.4 Wolman pebble count collected at a bar-channel margin on April 13th, 2022. Location of the pebble count labelled in Figure 7.3.

LWD and vegetation appears to be an important control on the morphology of the channel through this reach on an annual basis. Logs floated downstream from the upper watershed tend to accumulate on bar surfaces, at the head of islands, and at the entrance to side channels (Figure 7.5). These can plug channels and divert flow into secondary channels, such that over time the LWD jams form and maintain the multi-thread channel pattern, causing and mediating the frequency of channel avulsions and patterns of erosion and deposition (Collins et al., 2003). During periods between large floods, vegetation establishes and matures in the lee of these jams, stabilizing substrate and leading to island formation (Corenblit et al., 2007; Gurnell et al., 2001).

Figure 7.5 Example of the spatial distribution of LWD accumulations from 2009.

7.2.2 Lateral Stability

Air photos and UAV imagery covering the period from 1947 to 2021 were used to assess changes in the planform of the Ryan River as well as the surrounding area. To provide context to the observed changes on the Ryan River, a timeline of historical major hydrogeomorphic events (i.e., sediment delivery events) on the Ryan River and in the Pemberton Valley is provided in Figure 7.6, as changes in channel morphology are driven by sediment transport events (Church, 2006).

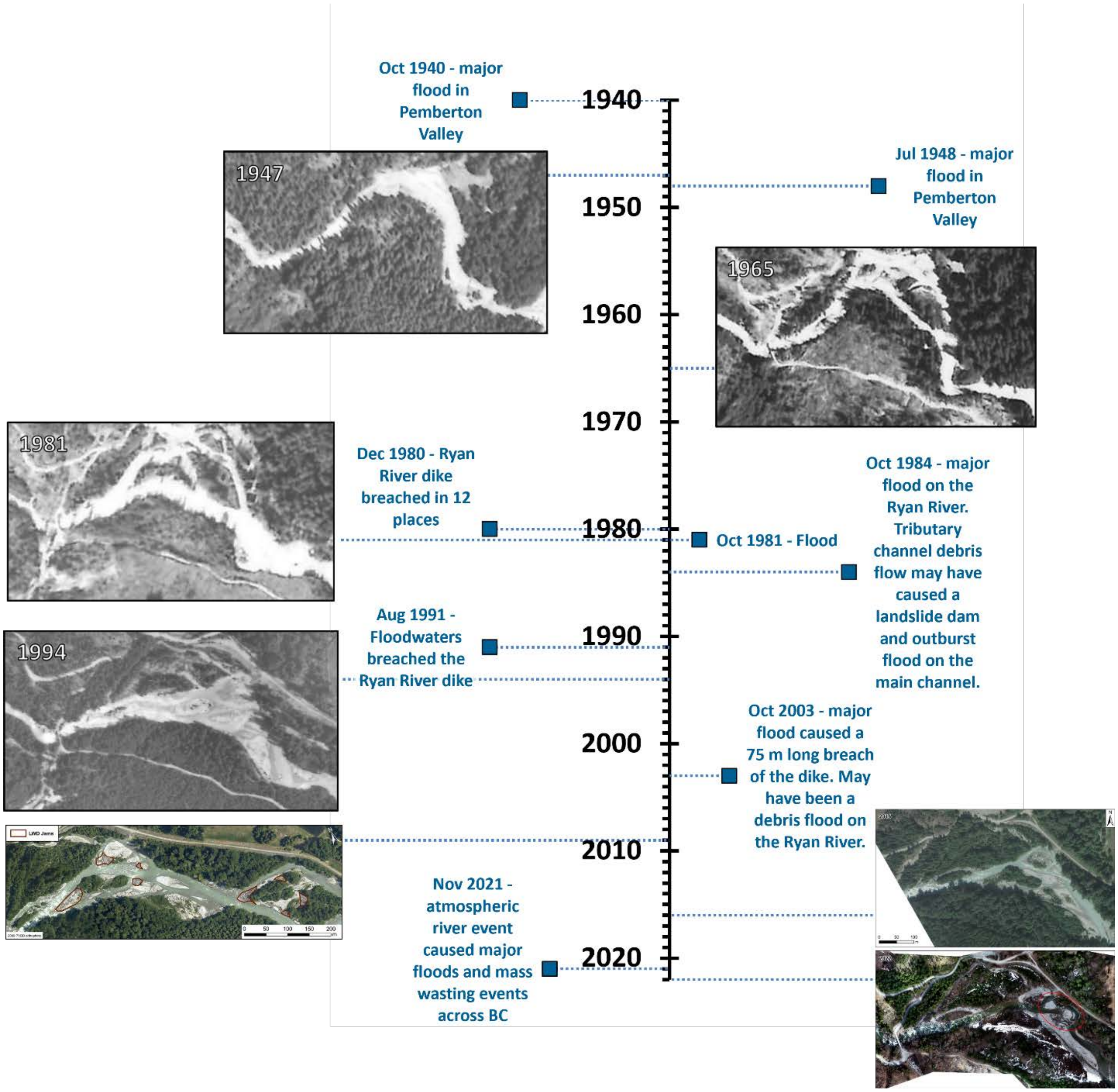


Figure 7.6 Ryan River flood history. Information sourced from BGC, 2020; Hart, 1979; KWL, 2002, 2009; NHC, 2018.

1947 – 2016

Air photos from the 1947 to 2016 period are presented in Figure 7.7. In 1947, the Ryan River fan exhibits an irregular, meandering channel morphology. A fresh chute cutoff of a high-amplitude meander bend is visible in 1947 (labelled A), which by 1965, is completely detached from the active channel. The 1965 channel exhibits a more braided morphology near the fan apex than in 1947, as the river cut two to three channels through the forested floodplain on the inside of the bend (labelled B). The transition from a single thread to multi-thread channel appears to coincide with the initiation of forest harvesting south of the river (labelled C).

Channel conditions in the 1981 air photo are likely reflective of changes produced by the December 1980 and possibly November 1975 floods. Between 1965 and 1981, the channel avulsed through the inside of the bend at the toe of the Mt. Ross fan, and splayed out onto the Lillooet River floodplain, breaching the Ryan dike near the rock quarry (red circle). The gully upslope of the red circled area appears recently active and may have contributed towards the instability of the main channel and dike breach downstream of the fan apex. Forestry activities extend farther upslope on the Mt. Ross fan south of the Ryan River by 1981 (labelled D).

Major floods in October 1981, October 1984, and August 1991 produced substantial changes to the morphology of the Ryan River fan. Channel width increased locally at point 'E' as the river avulsed onto the south floodplain margin, forming a mid-channel island and bar complex. Downstream of the fan apex, the main flow shifted from a northeast to east trajectory between 1981 and 1994 (red circle), focusing on a downstream section of the Ryan River dike – which was breached in both the 1984 and 1991 flood events (BGC, 2020b; KWL, 2002). The deforested hillslopes of Mt. Ross are mostly revegetated by 1994, though show evidence of active colluvial processes (gullying).

Between 1994 and 2004, a debris flow triggered in one of the Mt. Ross gullies, extending downslope of a resource road south of the Ryan River, but terminating shy of the main channel (labelled F). This event likely coincides with the major flooding that occurred in the Pemberton Valley in October 2003 due to a large rainstorm event.

Between 2005 and 2016, the extent and density of vegetation on mid-channel bars and islands increased, which suggests that this was likely a period of relative channel stability. However, the growth and stabilization of these islands may contribute to future erosion by re-directing flow towards the outer channel banks.

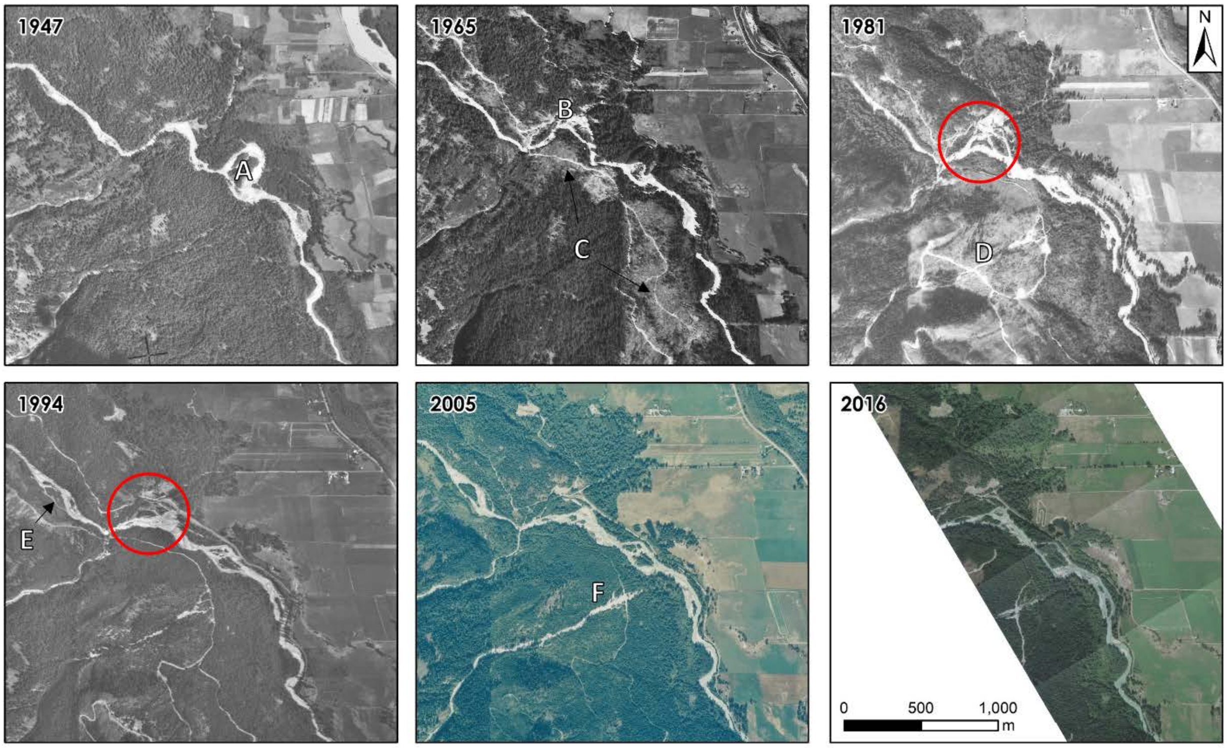


Figure 7.7 Comparison of historical air photos of the Ryan River fan (1947 – 2016).

2016 – 2022

Air photos from 2016 and NHC's 2022 UAV imagery are presented in Figure 7.8. Over this period, the channel eroded towards the Ryan dike (red circled area). The primary focus of erosion appears to have shifted 70-80 m downstream from where the dike was previously threatened by lateral migration. Sediment and LWD accumulation on the inside of the channel bend may be increasing the proportion of flow directed towards the dike in this area.

Summary of Lateral Stability

The Ryan River fan forms a depositional reach as the river exits confinement from the Ryan River valley and flows onto a more gradual gradient. Over the last 75 years, the morphology of the Ryan River fan has changed substantially. The river has transitioned from an irregular meandering channel to a wandering-type morphology defined by periodic instability due to lateral migration and channel avulsions.

Major changes to the morphology of the channel appear to be driven by the timing and magnitude of peak flood events on the mainstem, with large floods occurring once per decade or more. Additionally, debris flow events emanating from the gullied hillslopes of Mt. Ross and Sugarloaf Mountain deliver sediment directly to the main channel, causing channel instability and likely increasing the probability of a dike breach to occur.

During periods between large floods, vegetation establishes and matures on bar and floodplain surfaces, stabilizing sediment and increasing resistance to erosion. This leads to the focus of erosion varying over time according to the extent and distribution of vegetated islands. That is until the next extreme flood occurs, capable of resetting the fluvial landform dynamics (Gurnell et al., 2001).

The cyclical pattern between periods of relative channel stability and instability, produced by the mainstem flood regime and debris flows in tributary channels, is likely to continue in the future. However, as temperature rise, the timing and intensity of peak floods is likely to change, as well as the mechanism triggering these events. We can generally expect to see continued morphological development via lateral erosion and channel avulsions in response to these changes, which may affect the capacity of the Ryan dike to contain floodwaters during high magnitude events.

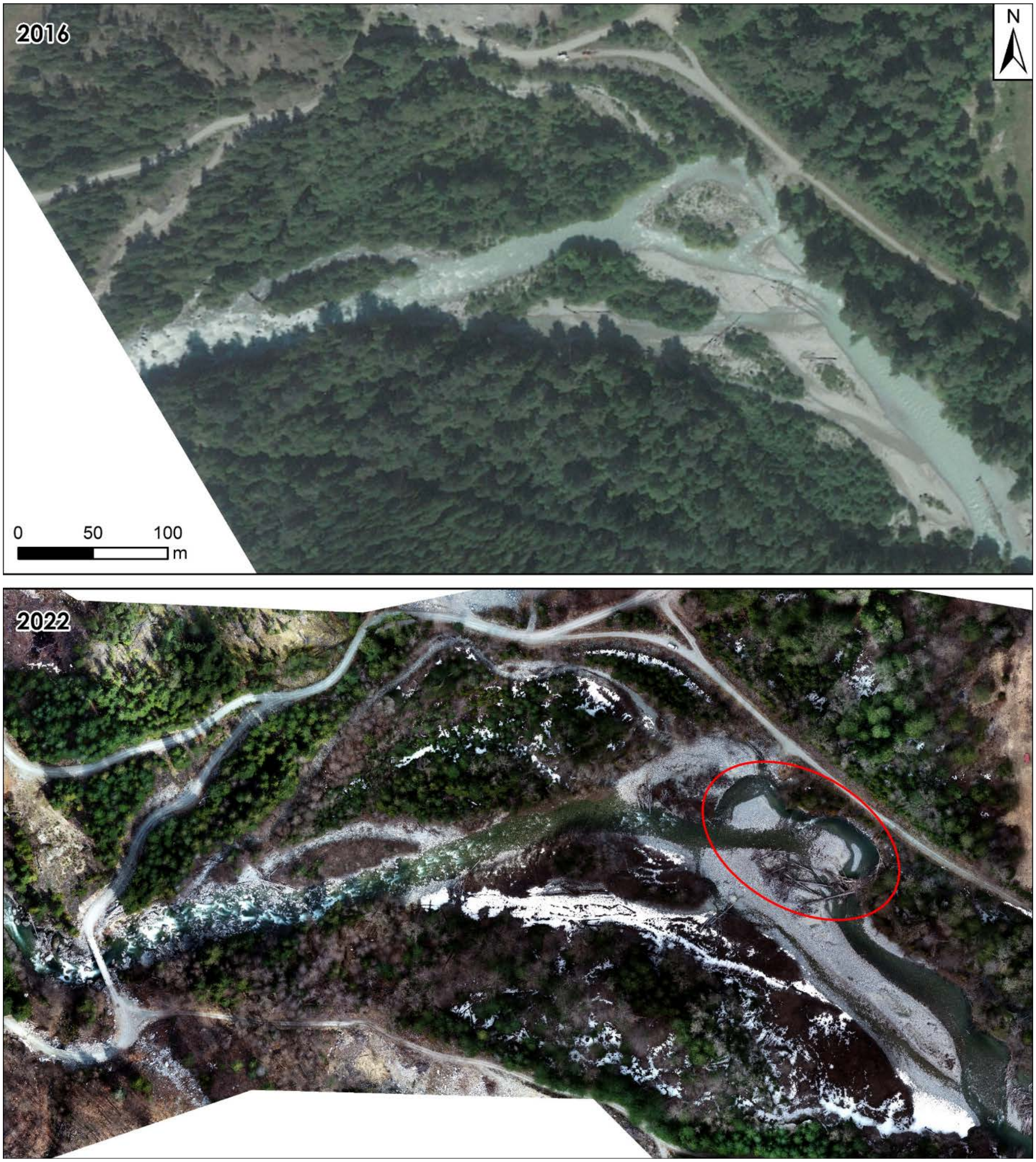


Figure 7.8 Comparison of the Ryan River fan in 2016 (UBC air photo) and 2022 (NHC UAV orthophoto).

7.2.3 Vertical Stability

Topographic survey data collected in 2006 by KWL were compared with 2022 survey data collected by NHC to assess changes in channel bed elevation over this period. Two transects were compared at the Ryan River fan, labelled XS 42 and 43 in Figure 7.3.

Cross-section 43 is presented in Figure 7.9. In 2006, the channel thalweg is located approximately 105 m across the cross-section, adjacent to the Ryan dike. A mid-channel bar is present between this channel and a second channel located roughly 180 m across the cross-section. In 2022, the mid-channel bar has expanded and aggraded, partially infilling the channel adjacent to the Ryan dike. Net aggradation on the bar appears to be in the range of 1-2 m between 2006 and 2022, reflecting an average annual rate of 6-12 cm per year. While changes along the right side of the cross-section are difficult to interpret due to differences in the position of the 2006 and 2022 survey points, it appears that the main channel to the right of the bar has deepened by 2022.

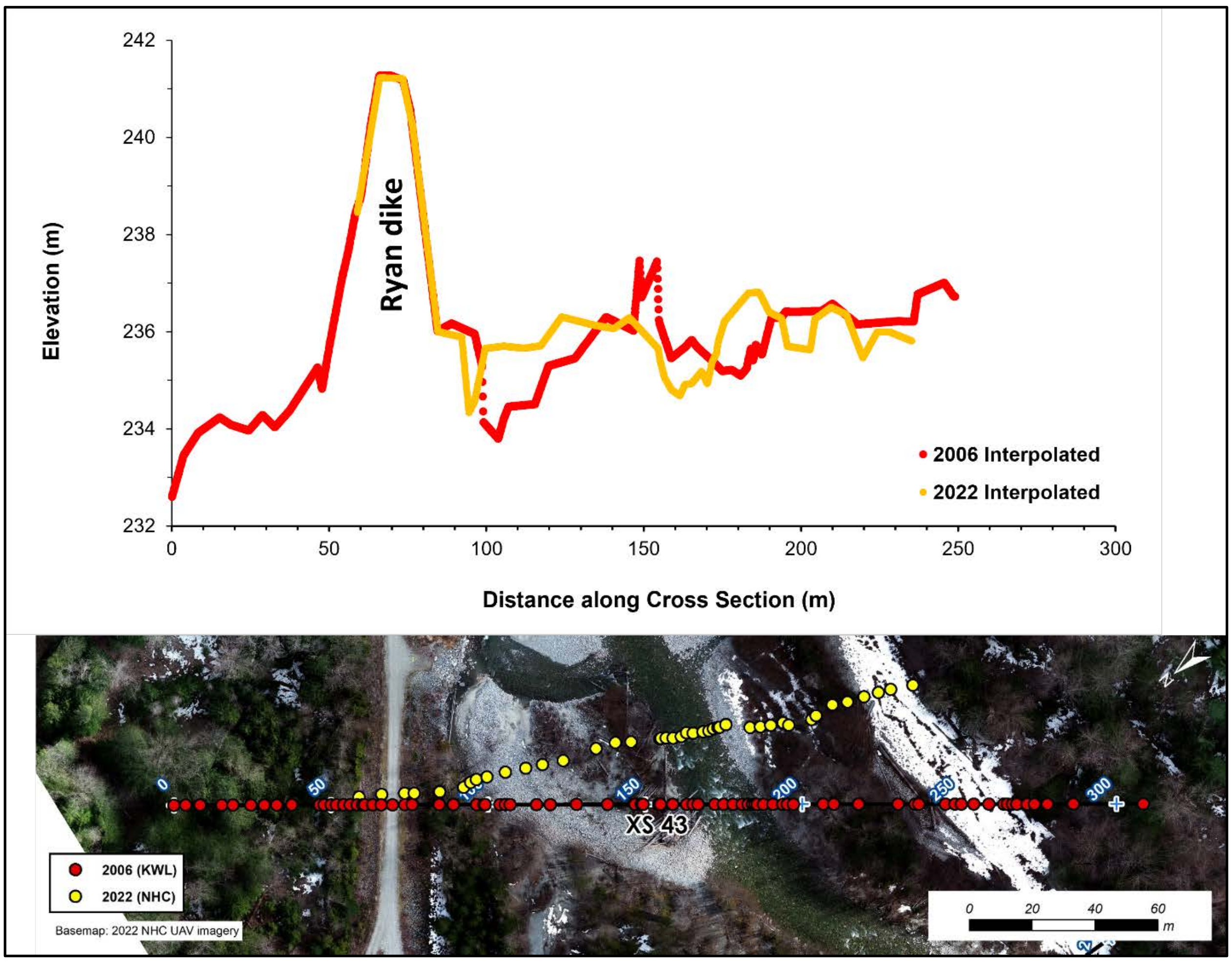


Figure 7.9 Cross-section 43 comparison.

Cross-section 42 is presented in Figure 6.10. The low-flow channel located approximately 140-150 m across the cross-section filled by roughly 0.5 m between 2006 and 2022. This was compensated for by 0.5 m of net scour where the river incised into a bar surface approximately 180 m across the cross-section. The bar-top channel was eroded to a similar elevation as the current main channel, indicating a potential for this to become the future main channel position. Overall, this cross-section appears to be in a state of quasi-equilibrium with no obvious trend of deposition or erosion dominating the transect.

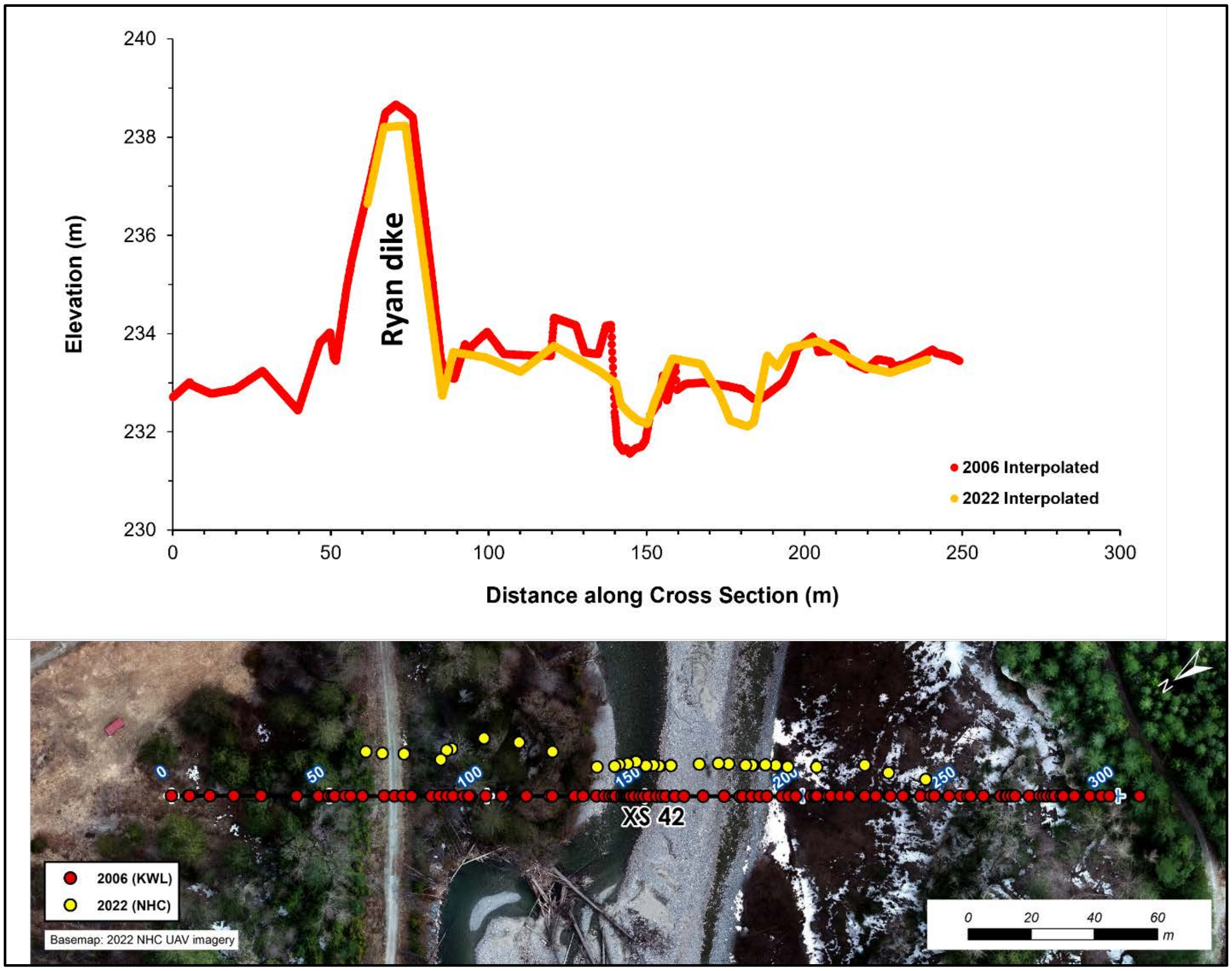


Figure 7.10 Cross-section 42 comparison.

7.2.4 Mt. Ross and Sugarloaf Mountain Debris Flow Hazards

As described in Section 7.2.2, NHC identified past debris flow activity in tributary gullies near the Ryan River fan. Specifically, three gullies, on the hillslopes of Mt Ross and Sugarloaf Mountain show evidence of past debris flow activity in historical air photos, field photos, and/or Google Earth imagery (Figure 7.11). Jordan and Slaymaker (1991) estimated debris flow deposits on the order of 100,000 m^3 per event in these channels, describing the frequency of debris flows in many of the channels in the Lillooet Watershed as “probably in the order of at least one per decade” (p. 50). The authors also noted that a large debris flow at the Ryan River fan was observed to be active in 1975 (Hart, 1979) and again in 1984. These high-magnitude events discharged debris directly into the Ryan River main channel and over the long term (decade scale) exert a strong control on the stability and position of the lower Ryan River channel. An exposure of the debris flow deposits from Mt Ross that the Ryan River now erodes into can be seen in Photo 7.1.

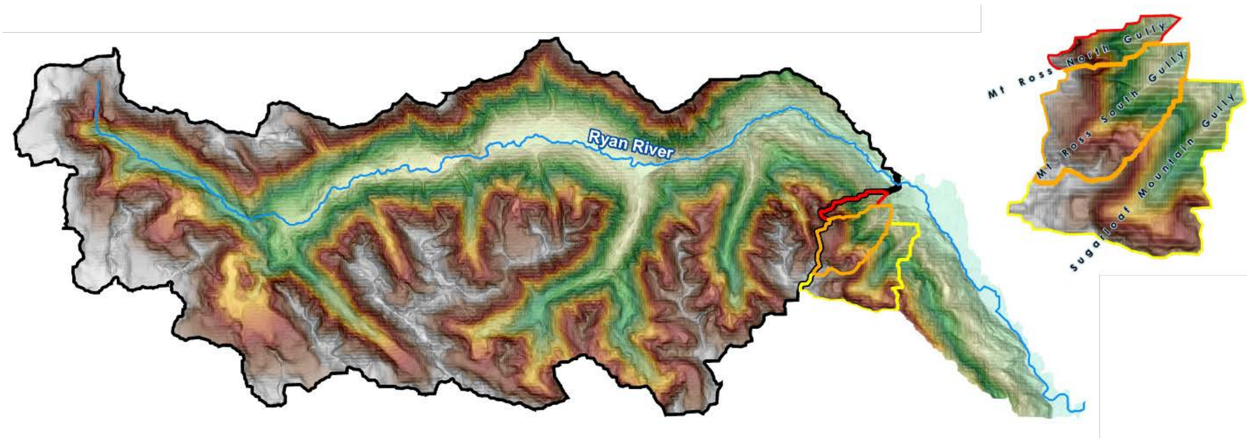


Figure 7.11 Three gully basins shown in red, orange, and yellow on the hillslopes of Mt. Ross and Sugarloaf Mountain. Black outline reflects the Ryan River watershed upstream of the confluence with the Lillooet River floodplain.

Photo 7.1 The Ryan River erodes into a poorly sorted mix of sediment consisting of angular coarse fragments in a fine-grained matrix, likely reflective of a debris flow deposit from Mt. Ross to the southwest.

In addition to the air photo evidence and field observations of past debris flow deposits near the Ryan River fan, NHC assessed the Melton ratio and watershed length for each of the gully sub-basins identified in Figure 6.11 to discriminate between the dominant watershed processes: clearwater floods, debris floods, or debris flows. In Figure 7.12, steep creek processes for watersheds in British Columbia and Alberta are plot as a function of watershed stream length and Melton ratio with the Mt. Ross and Sugarloaf Mountain gullies data plot overtop. Two of the three gullies fall within the ‘mixed debris floods and debris flows' domain, while the north-most gully is 'mostly prone to debris flows'. Although a larger watershed area, the area upstream of the Ryan River fan is mostly prone to clearwater floods (Figure 7.12).

Given the proximity of the Mt. Ross and Sugarloaf Mountain gullies to the lower Ryan River, the Ryan dike, and to farmland and residences behind the dike, we recommend that a formal landslide assessment be completed as per APEGBC (2010) guidelines. This should include recognition, characterization, and estimation of the hazards, and may include estimation of potential consequences.

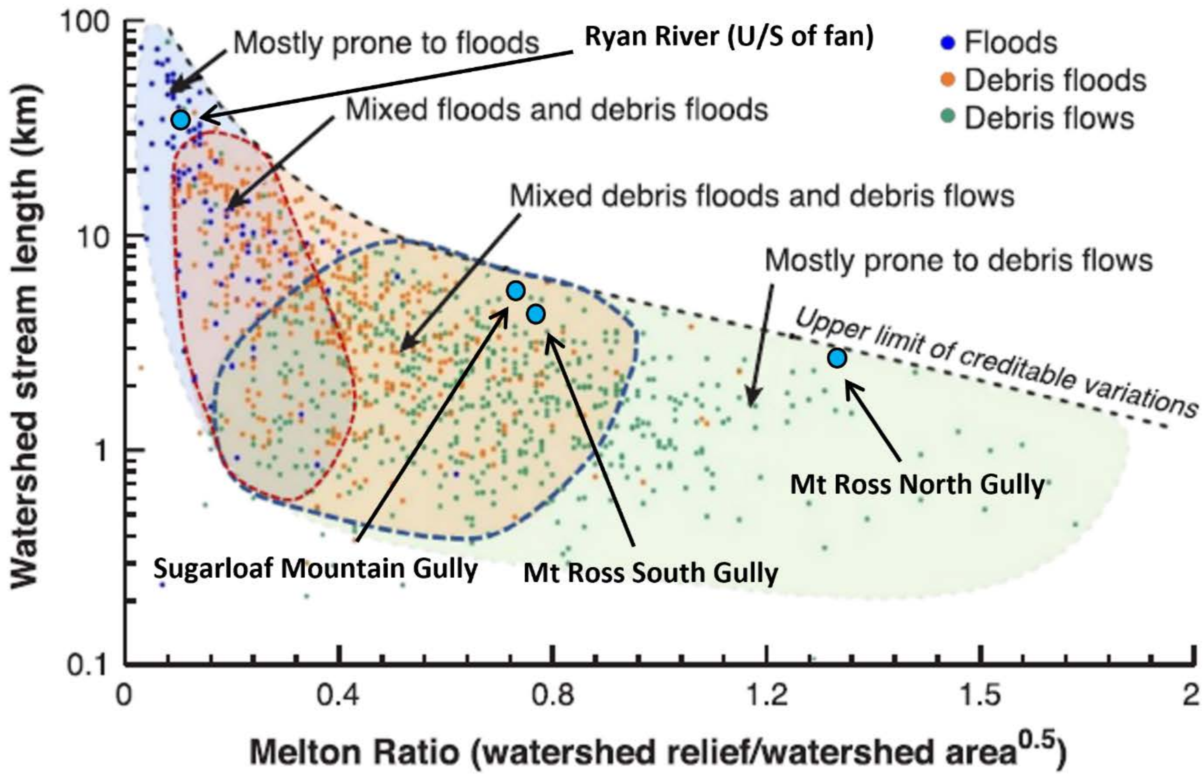


Figure 7.12 Steep creek processes as a function of Melton ratio and watershed stream length (adapted from Figure 4 in Church and Jakob, 2020).

7.3 Lower Watershed

7.3.1 Reach Description

The lower 41 km^2 sub-basin of the Ryan River watershed includes most of the Lillooet River floodplain and the steep hillslopes of Mt. Ross and Sugarloaf Mountain (Figure 7.13). The river flattens from an average slope of approximately 5 % at the Ryan River fan, to approximately 0.05 % at the confluence with the Lillooet River over a distance of 15 km. The lower 4 km of the Ryan River is underfit and flows through the historical channel of the Lillooet River, which was diverted to its current location as part of the Mackenzie Cut (Weatherly and Jakob, 2014).

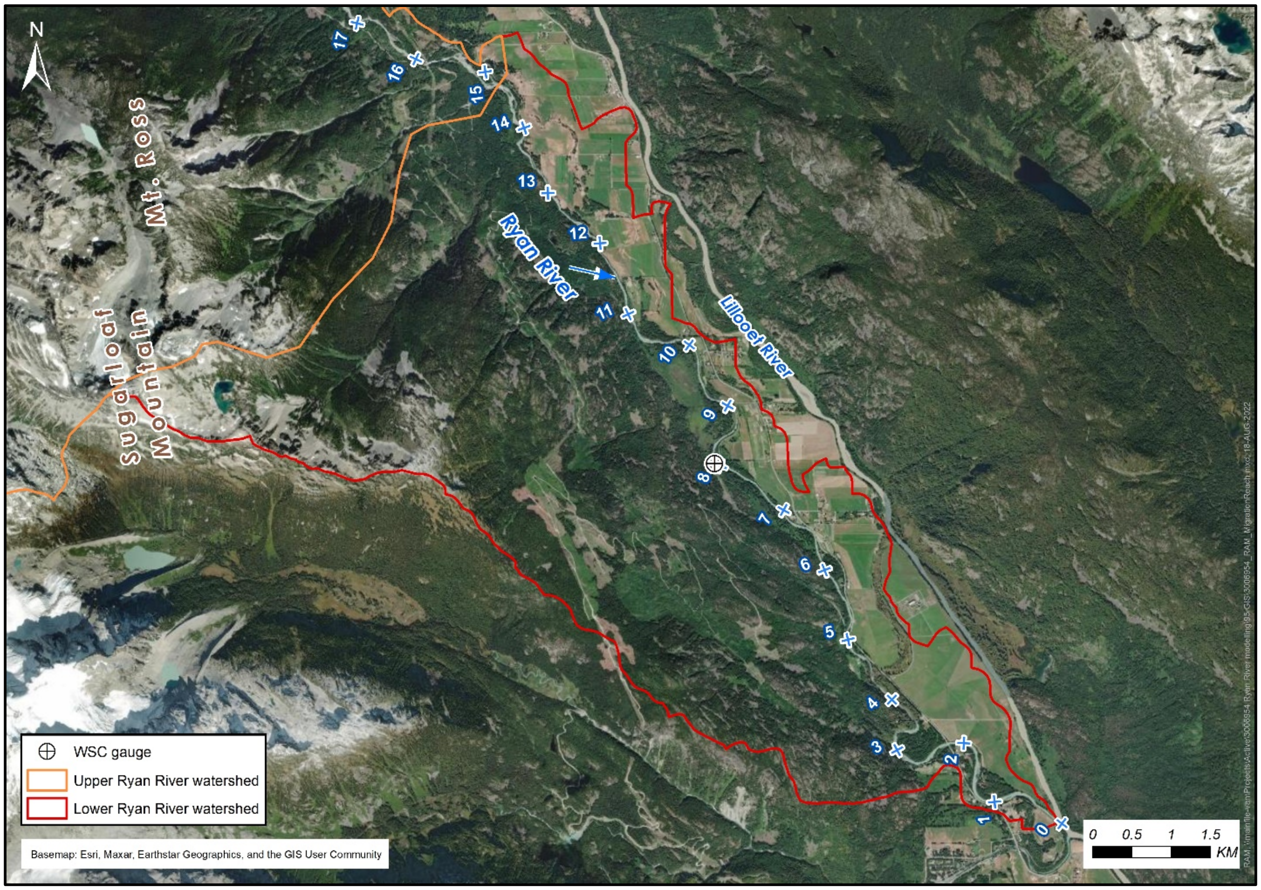


Figure 7.13 Lower Ryan River watershed.

The focus of our assessment in the lower watershed was the channel reach located at RK 9, where the PVDD identified lateral channel erosion (Figure 6.14). The river flows through a 30-40 m wide single-thread meandering channel through this reach along an average bed slope of 0.1 %. The gentle gradient promotes deposition of the river's coarse sediment load, leading to the formation of an alternating bar sequence (Photo 6.2).

Photo 7.2 Photo from 2017 of the Ryan River near RK 9 shows bar formation through the lower reach.

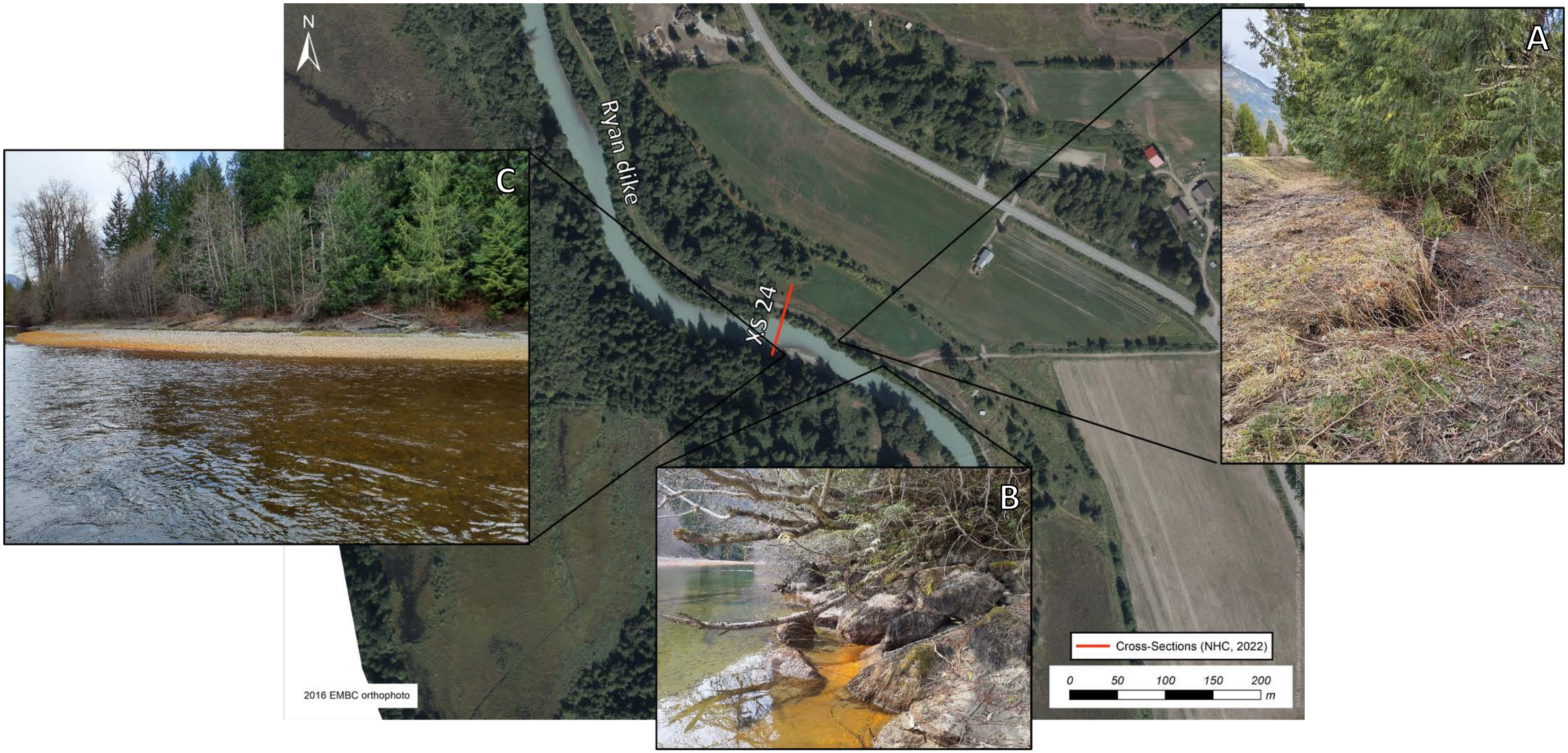


Figure 7.14 Lower Ryan River study site at RK 9. Inset photos collected during NHC's site visit on April 13th, 2022.

7.3.2 Lateral Stability

Relative to changes occurring in the upper watershed and at the fan, the lower reaches of the Ryan River are relatively stable and adjustments in channel form occur gradually over time. However, as cited by PVDD, the Ryan River is actively migrating towards the Ryan dike at RK 9. During NHC's site visit, tension cracks were noted adjacent to the top of the north channel bank, suggesting that bank stability is being compromised due to undercutting at the toe (Photo A in Figure 7.14). This material is likely to slough off into the river with continued fluvial erosion. The rock armouring lining this bank is not functioning as intended, with large openings between rocks where the river can erode into the sandy-silty bank material. Furthermore, some of the rocks appears to have been plucked from the bank onto the channel bed margin (Photo B in Figure 7.14). Without further maintenance, it is likely that the river will continue to encroach upon the Ryan dike due to lateral erosion during future flood events.

Across from the eroding bank, a gravel bar has formed on the inside of the channel bend (Photo C in Figure 7.14). This bar appears to consist of fine to coarse gravels. Sediment buildup in this area likely redirects flow north, increasing the erosive force focused on the outer bank causing the lateral migration towards the dike.

7.3.3 Vertical Stability

Topographic survey data collected in 2006 by KWL were compared with 2022 survey data collected by NHC to assess changes in channel bed elevation over this period. A single transect was compared near RK 9, labelled XS 24 in Figure 7.14.

Cross-section 24 is presented in Figure 7.15. The channel thalweg is located 50 m across the cross-section, adjacent to the north channel bank and Ryan dike. Between 2006 and 2022 the thalweg aggraded by roughly 0.5 m. An approximately equal magnitude of degradation occurred 70-80 m across the cross-section adjacent to the south channel bank. This reflects an average annual rate of change 3 cm per year.

Spatial trends in erosion and deposition at this site are likely to be strongly influenced by the gravel bar attached to the right (south) channel bank immediately downstream. The bar increases flow resistance locally, relative to other portions of the bed, causing the upstream scour observed at cross-section 24. Changes to the morphology of this bar, such as lateral or vertical accretion, or downstream migration, could affect the extent and location of undercutting and erosion focused on the opposing north bank. Given the abundant sources of sediment supplied from upstream channel reaches, we should expect to see deposition to continue through the lower channel reaches, which may continue or even increase the rate of lateral migration and erosion near the Ryan dike at RK 9.

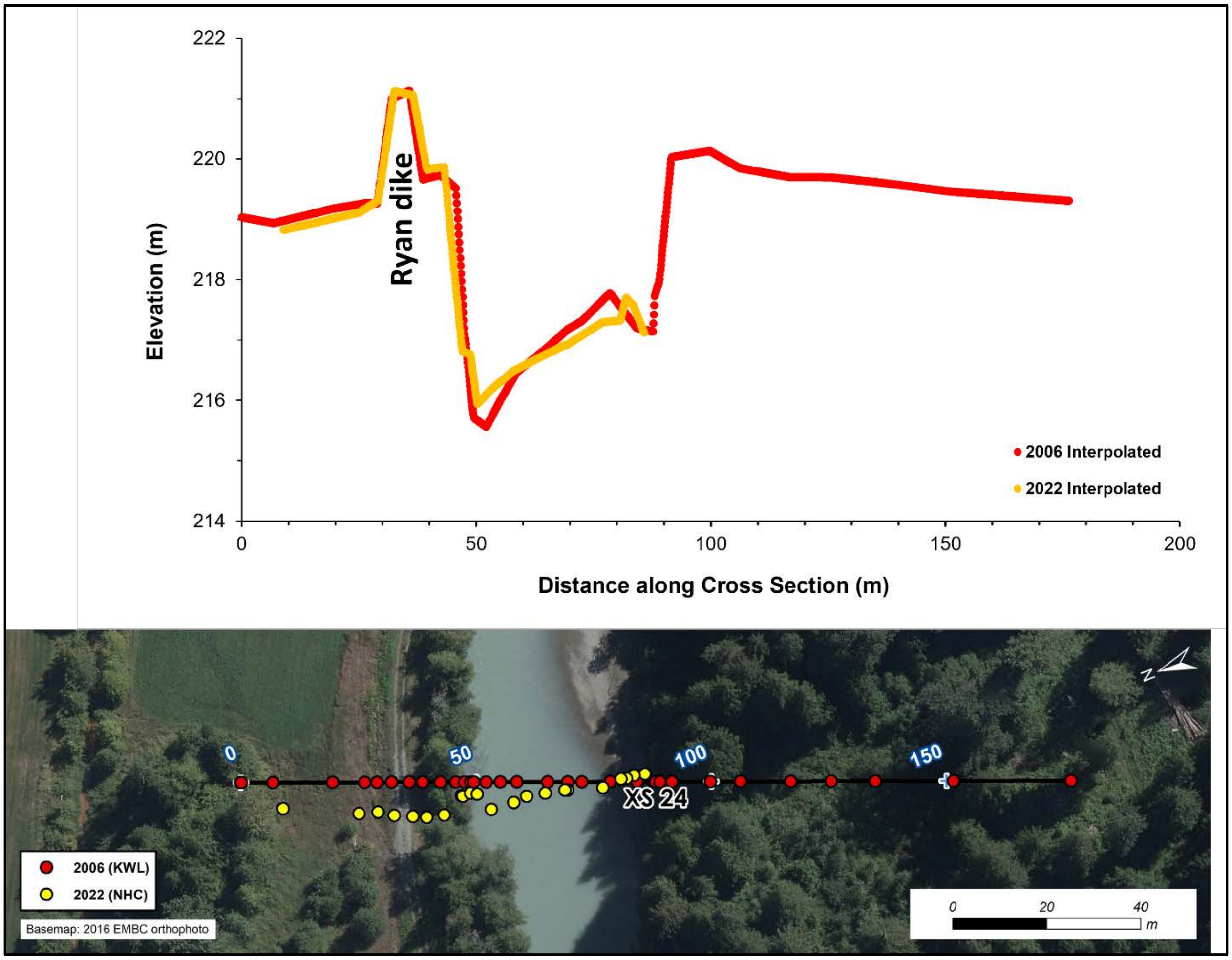


Figure 7.15 Cross-section 24 comparison.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

1. A range of hydrogeomorphic processes occur in the upper Ryan River watershed that either directly or indirectly supply sediment and LWD to the main channel in the valley bottom. This includes rockfalls, snow and debris avalanches, debris flows, debris floods, and clearwater floods.
2. The Ryan River fan has historically been an unstable channel environment. The channel is prone to avulsions and extensive erosion during peak flood events which has historically led to channel braiding and dike breaches associated with high flows.
3. Tributary gullies on the slopes of Mt. Ross and Sugarloaf Mountain are susceptible to debris flows and debris floods that may reach the Ryan River in the valley bottom. These processes may contribute sediment and debris to the river that will influence the channel stability.

4. Changes in the lower channel reaches of the river occur more gradually than upstream in the watershed. Currently, lateral erosion near RK9 may is causing the river to encroach upon the Ryan dike.

8.2 Recommendations

8.2.1 Debris Flood Discharge Bulking Factors for Flood Mapping

Bulking factor estimates for design flows on the Ryan River have been provided to account for potential debris flood events (Table 8.1). This assessment uses the debris flood classification scheme developed by Church and Jakob (2020) with refinements in Jakob et al. (2022). Bulking factor estimates are provided for Type 1 (meteorological debris floods) and Type 2 (debris flow dilution) based on the evidence of these events detailed in this report. No estimate is provided for Type 3 (outbreak debris flood) events, though there is a possibility of the events to occur, because this requires a detailed geotechnical assessment that is beyond the scope of this study.

Table 8.1 Recommended bulking factors to design flows for the Ryan River watershed.

Watershed	Hydrogeomorphic Process – Main Channel	Hydrogeomorphic Process – Tributary Channels (in close proximity to fan apex)	Debris Flood Typology	Discharge Bulking Factor Recommended	Notes
Ryan River at the fan apex	Mixed floods and debris floods	Debris flood and debris flow potential. Avalanche tracks in the upper watershed appear to contribute substantial amounts of large woody debris to the channel.	Type 1	1.1 to 1.3	Extensive woody debris from avalanche tracks. Several landslides in upper watershed.
			Type 2	1.2 to 1.4	
			Type 3	TBD	

8.2.2 Additional Recommendations

1. Further investigations should be conducted to better characterize the sediment sources and potential hazards in the upper watershed because this has a direct effect on the stability of downstream channel reaches. This could include a helicopter survey of the watershed to identify any slope failures that may have occurred during the November 2021 atmospheric river event.
2. A detailed landslide hazard assessment should be completed for the tributary gullies on the Mt. Ross and Sugarloaf Mountain hillslopes. These gullies pose a potential geotechnical hazard that may directly affect the Ryan dike and residences in the vicinity. The potential for debris flows to dam the Ryan River and generate an outbreak flood should be assessed due to the high risk this type of event would pose to nearby residents on the floodplain.

3. Rock armouring near RK 9 should be maintained and monitored to mitigate against continued lateral erosion at this location.

9 REFERENCES

APEGBC (2010). *Guidelines for Legislated Landslide Assessments for Proposed Residential Developments in BC*.

Bellefontaine, K., Alldrick, D., and Desjardins, P. J. (1994). *Mid Coast (all or parts of 92F, G, J, K, L, M, N; 93D; 102P; 103A)*. Ministry of Energy, Mines and Petroleum Resources.

BGC (2020a). *RDCK Floodplain and Steep Creek Study - Steep Creek Assessment Methodology*. Prepared by BGC Engineering Inc. for the Regional District of Central Kootenay, Vancouver, BC.

BGC (2020b). *Squamish-Lillooet Regional District Geohazard Risk Prioritization*. Final. Prepared by BGC Engineering Inc. for the Squamish Lillooet Regional District. 264 pp.

Buffington, J. M., Woodsmith, R. D., Booth, D. B., and Montgomery, D. R. (2003). Fluvial processes in Puget Sound Rivers and the Pacific Northwest. *Restoration of Puget Sound Rivers* (pp. 46–78). University of Washington Press, Seattle, WA.

Church, M. (2006). Bed material transport and the morphology of alluvial river channels. *Annual Review of Earth and Planetary Science*, 34, 325–254.

Church, M., and Jakob, M. (2020). What is a debris flood? *Water Resources Research*, 17. doi:10.1029/2020WR027144.

Clague, J. J. (1981). *Late Quaternary Geology and Geochronology of British Columbia. Part 2: Summary and Discussion of Radiocarbon-Dated Quaternary History.* Geological Survey of Canada, Ottawa, ON. Paper 80–35. 41 pp.

Collins, B. D., Montgomery, D. R., and Sheikh, A. J. (2003). Reconstructing the Historical Riverine Landscape of the Puget Lowland. *Restoration of Puget Sound Rivers* (pp. 79–128). University of Washington Press, Seattle, WA.

Corenblit, D., Tabacchi, E., Steiger, J., and Gurnell, A. M. (2007). Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: A review of complementary approaches. *Earth-Science Reviews*, 84, 56–86. doi:10.1016/j.earscirev.2007.05.004.

Gurnell, A. M., Petts, G. E., Hannah, D. M., Smith, B. P. G., Edwards, P. J., Kollman, J., Ward, J. V., and Tockner, K. (2001). Riparian vegetation and island formation along the gravel-bed Fiume Tagliamento, Italy. *Earth Surface Processes and Landforms*, 26, 31–62.

Hart, J. S. (1979). *Clastic sediment sources and suspended sediment yield in a coast mountain watershed, British Columbia* (Master of Arts thesis). The University of British Columbia, Vancouver, British Columbia.

Holm, K., Bovis, M., and Jakob, M. (2004). The landslide response of alpine basins to post-Little Ice Age glacial thinning and retreat in southwestern British Columbia. *Geomorphology*, 57(3–4), 201–216. doi:10.1016/S0169-555X(03)00103-X.

Jakob, M., Davidson, S., Bullard, G., Busslinger, M., Collier-Pandya, B., Grover, P., and Lau, C. (2022). Debris-Flood Hazard Assessments in Steep Streams. *Water Resources Research*, 58, 31.

Jordan, P., and Slaymaker, O. (1991). Holocene sediment production in Lillooet River basin, British Columbia: a sediment budget approach. *Geographie Physique et Quaternaire*, 45(1), 45–57.

KWL (2002). *Engineering Study for Lillooet River Corridor*. Final Report. Report prepared by Kerr Wood Leidal Associates Ltd for B.C. Ministry of Water, Land and Air Protection. 204 pp.

KWL (2009). *Ryan River Hydraulic Model and Dyking Assessment* (713.029–300). Final Report. Prepared by Kerr Wood Leidal Associates Ltd. for the Pemberton Valley Dyking District. 43 pp.

Montgomery, D. R., and Buffington, J. M. (1993). *Channel classification, prediction of channel response, and assessment of channel condition*. Timber Fish and Wildlife.

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.

Ryder, J. M. (1972). Pleistoncene chronology and glacial geomorphology: Studies in southwestern British Columbia. In O. Slaymaker and H.J. McPherson (Eds.), *Mountain Geomorphology* (pp. 63–72).

Weatherly, H., and Jakob, M. (2014). Geomorphic response of Lillooet River, British Columbia, to meander cutoffs and base level lowering. *Geomorphology*, 217, 48–60.

Wilford, D. J., Sakals, M. E., Innes, J. L., Sidle, R. C., and Bergerud, W. A. (2004). Recognition of debris flow, debris flood and flood hazard through watershed morphometrics. *Landslides*, 1(1), 61–66. doi:10.1007/s10346-003-0002-0.

Wolman, M. G. (1954). A method of sampling coarse river-bed materials. *Transactions of the American Geophysical Union*, 35(6), 951–956.

APPENDIX B

FLOODPLAIN MAPS

DRAFT General Notes

1. This map delineates the potential for flooding under conditions caused by a 500-year return period event plus climate change and a bulking factor (over a specific area) as described in NHC (2023). The 500-year event is only mapped on the main stem of the Ryan River. The Lillooet River is mapped at a 200-year. For more information on the conditions that generate a flood event please see NHC (2023).

2. A freeboard allowance (margin of safety) of 1.0 m for the Ryan River upstream of where the Lillooet River influences the flood levels (everything more than 5 km upstream of the confluence) and 0.6 m is used where the flood levels are dominated by the Lillooet River (everything downstream of 5 km on the Ryan River). It is added to account for various sources of uncertainty (such as debris and blockages) in the model inputs and parameters.

3. Unrated Alluvial fans and an active alluvial fan (Ryan River alluvial fan) are identified on the maps. Fans can be classified as **unrated** (i.e., it has not been determined if the entire fan or just the current channel area is susceptible to alluvial geomorphic hazards under current hydroclimatic conditions), **active** (i.e., unconfined depositional zone susceptible to rapid aggradation, channel migration, and avulsion across the fan under the contemporary hydroclimatic conditions), or **inactive** (i.e., the fan was developed under a different hydroclimatic regime, (paleofan)). While the Ryan River Fan is confined by the Ryan River dike, a breach of the dike and reoccupation of the fan is possible. Downstream of Ryan River 13 KM the alluvial fans were not mapped or assessed.

4. Lidar data surveyed in 2016 and 2009 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. The Ryan River survey was extended upstream to the study limit mapped in 2022 and included in the DEM. 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.

5. 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.

6. The flood levels are based on water surface elevations simulated using a two-dimensional hydraulic model developed by NHC (2018) and updated in NHC (2023) using RAS2D software. Model roughness values were initially assigned based on typical channel and overbank resistance values, then calibrated to a flood event in 2003 for the Ryan River and validated to low flow event in 2022.

7. 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. The area behind the dikes is considered part of the floodplain and is modeled and mapped as if the dikes are a non-erodible feature of the landscape. In an actual flood event, it is likely that some of the dikes would erode and breach, potentially resulting in flood level variations from those shown. For sites in the Ryan River Floodplain with partial protection from existing dikes, the FCL should be either the FCL provided in the following map OR 1.0 m above surrounding natural grade; whichever is higher.

8. 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.

9. 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.

10. 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 Pemberton Valley Dyking District (PVDD) do not assume any liability for such variations.

Data Sources:

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, and additional surveys as described in NHC (2018). The extent of flooding and displayed isolines are based on the Lidar DEM.

2. PVDD boundary and cadastral parcel boundaries supplied by Squamish Lillooet Regional District.

3. Municipal boundary downloaded from DataBC.

4. Orthophoto imagery acquired by EMBC in 2016.

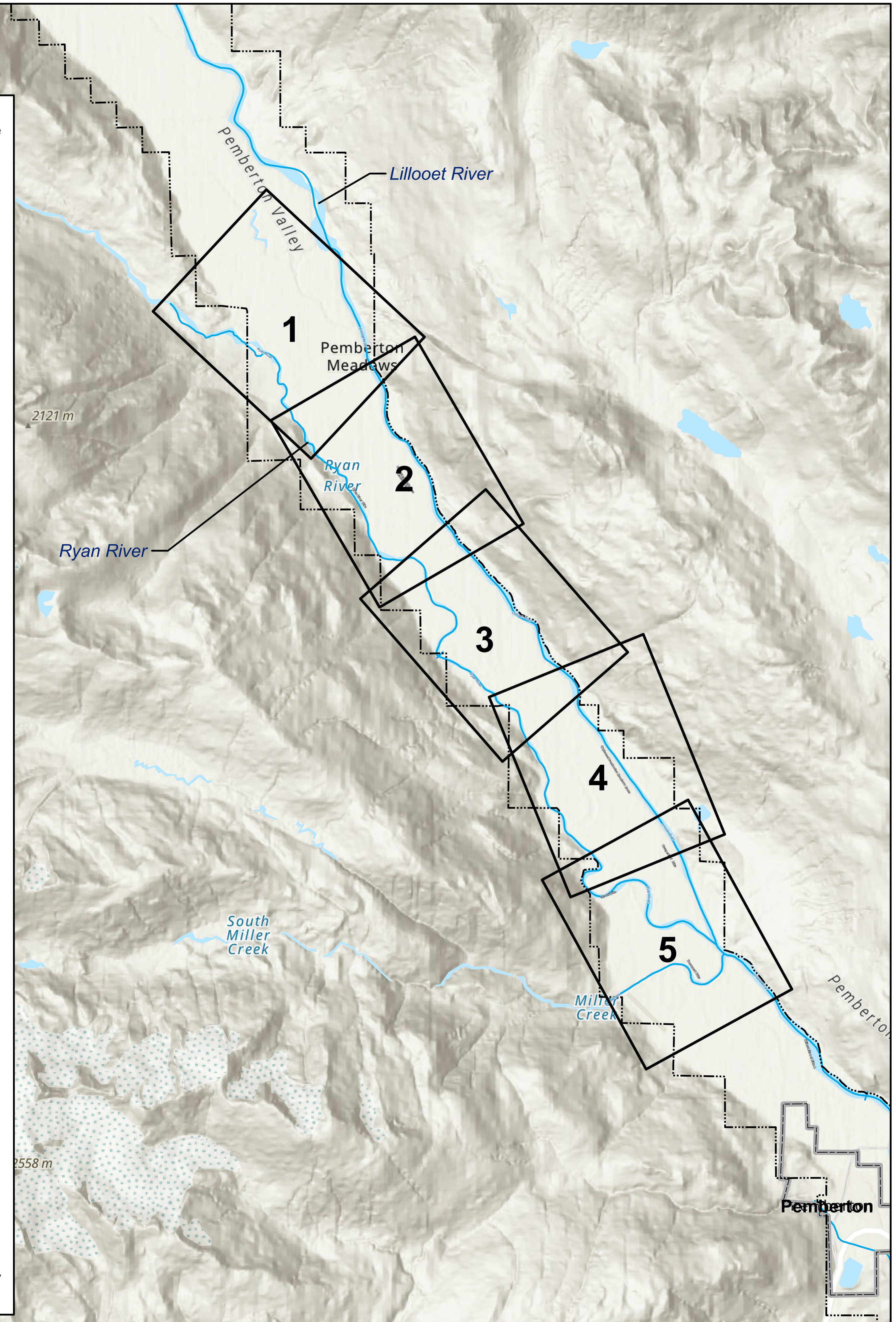
5. Additional base mapping and orthoimagery from Esri.

References:

NHC (2018). Lillooet River Floodplain Mapping. Final Report. Prepared for Pemberton Valley Dyking District.

NHC (2023). Ryan River Floodplain Mapping. Final Report. Prepared for Pemberton Valley Dyking District

Disclaimer



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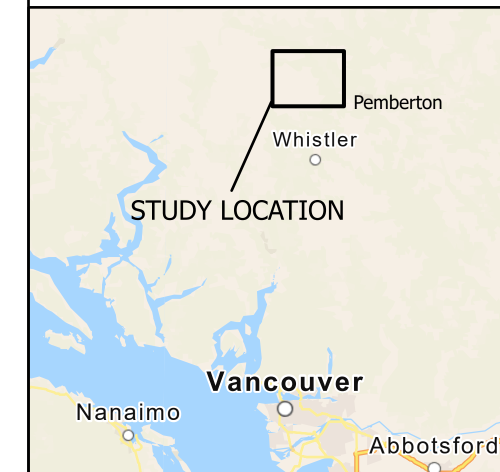

- Map Sheet Scale at 1 : 10,000
- Pemberton Valley Dyking District
- City of Pemberton
- Stream

SCALE - 1:80,000

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Units: METRES; Vertical Datum: CGVD2013

Job: 3006954	Date: 20-MAR-2023

RYAN RIVER FLOODPLAIN MAPPING

DESIGNATED FLOODPLAIN KEY PLAN

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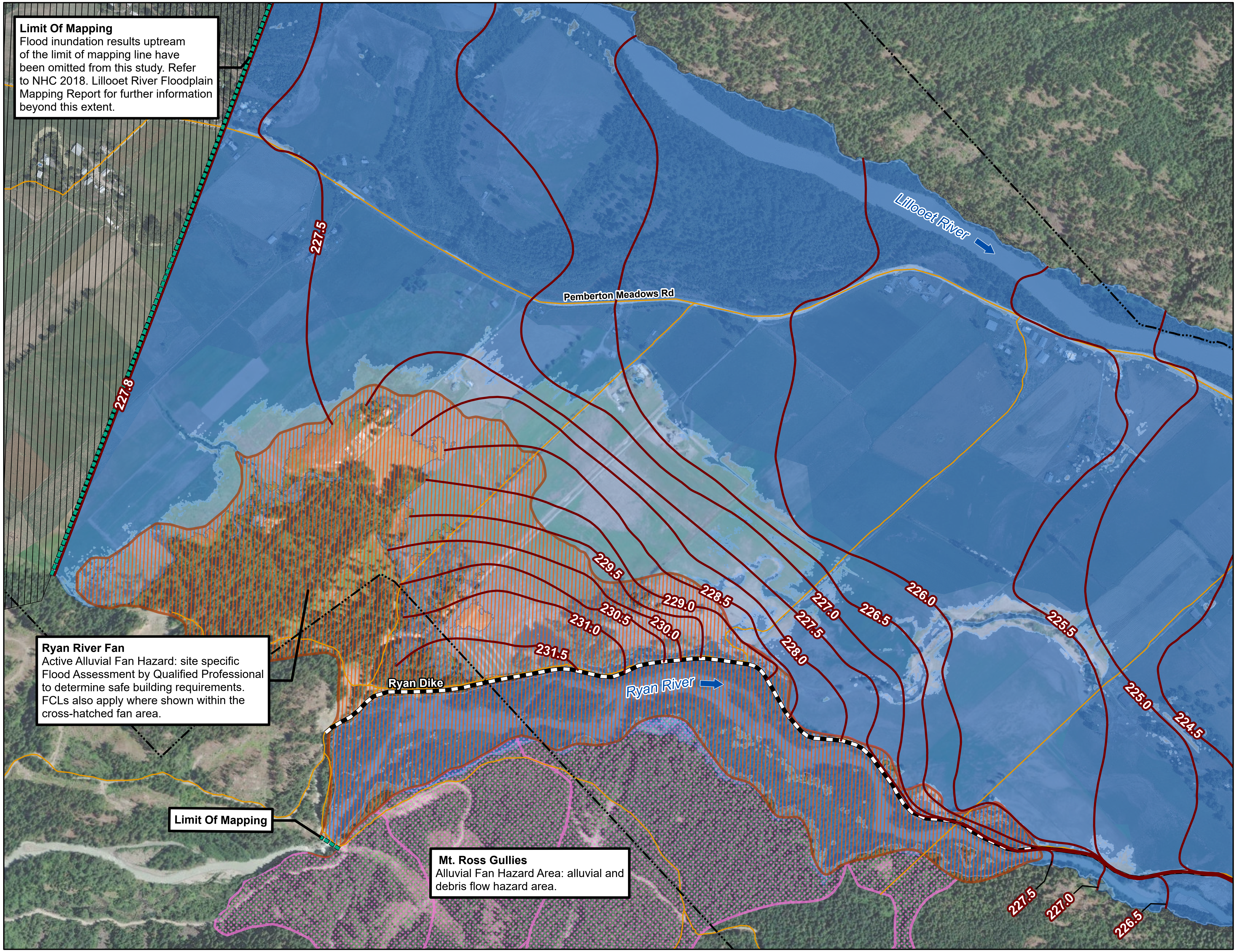

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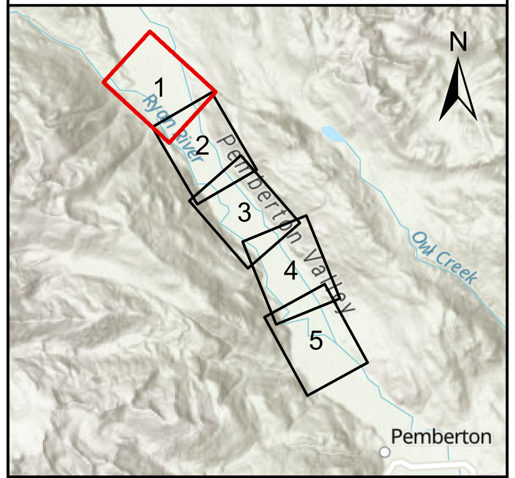


- Pemberton Valley Dyking District
- City of Pemberton
- Flow Direction
- Major Road
- Local Road
- Dike
- Limit of Mapping
- Flood Construction Level Isoline (FCL) *(Elevation in metres)*
- Flood Extent Including Freeboard
- Flood Extent

Fan Hazard

- Ryan River Fan
- Mt. Ross Gullies Fan

PLEASE REFER TO MAP NOTES ON INDEX SHEET

SCALE - 1:10,000

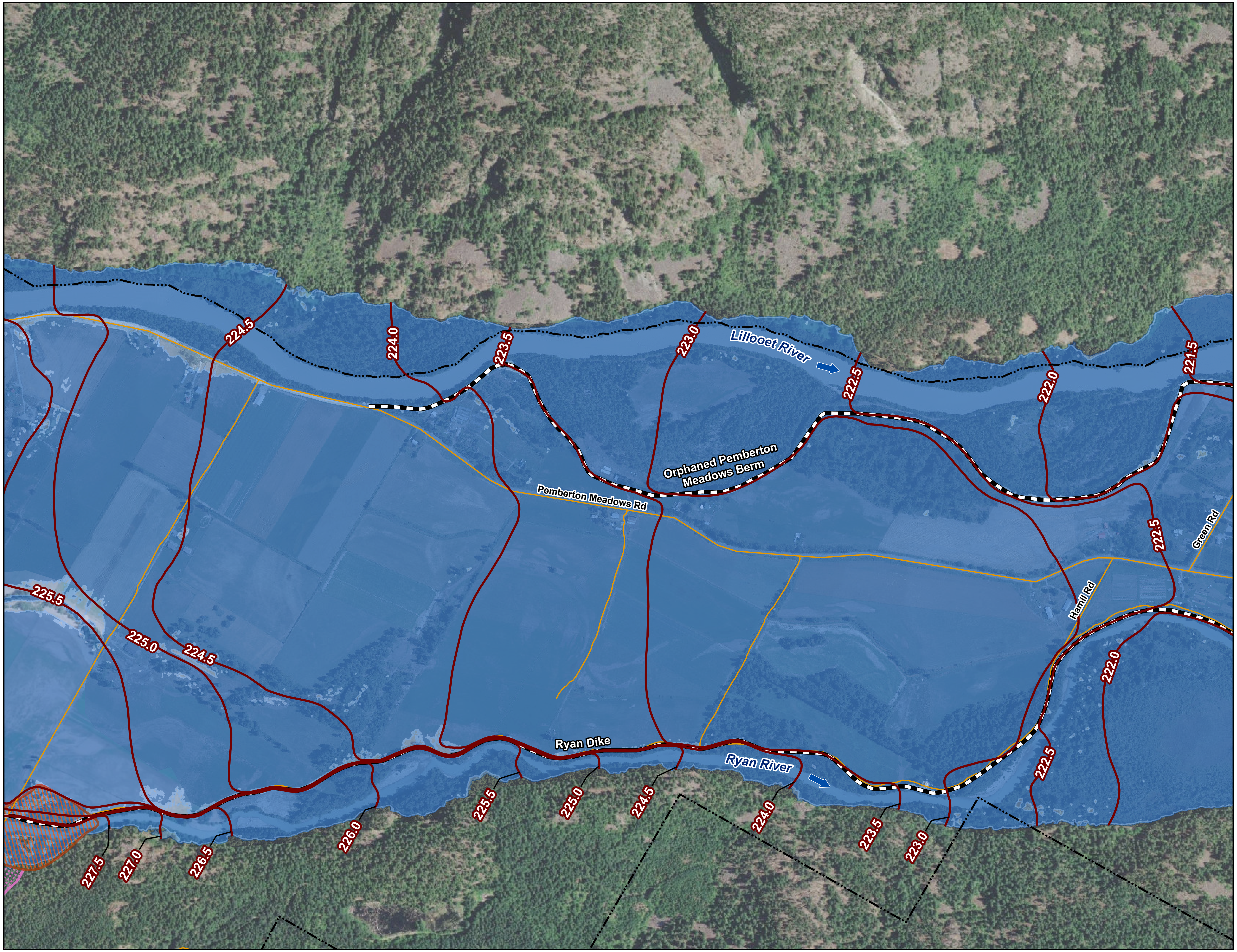
0 100 200 300 400 Meters

Coordinate System: NAD 1983 CSRS UTM ZONE 10N
Units: METRES; Vertical Datum: CGVD2013

Job: 3006954	*Date: 20-MAR-2023*

RYAN RIVER FLOODPLAIN MAPPING

DESIGNATED FLOODPLAIN MAP INCLUDING FREEBOARD



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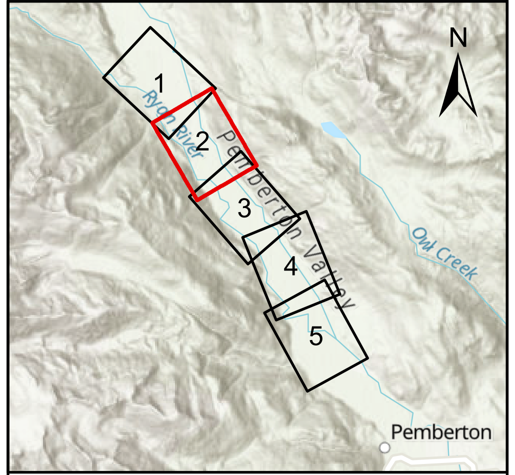

- Pemberton Valley Dyking District
- City of Pemberton
- Flow Direction
- Major Road
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- Limit of Mapping
- Flood Construction Level Isoline (FCL) *(Elevation in metres)*
- Flood Extent Including Freeboard
- Flood Extent

Fan Hazard

- Ryan River Fan
- Mt. Ross Gullies Fan

PLEASE REFER TO MAP NOTES ON INDEX SHEET

SCALE - 1:10,000

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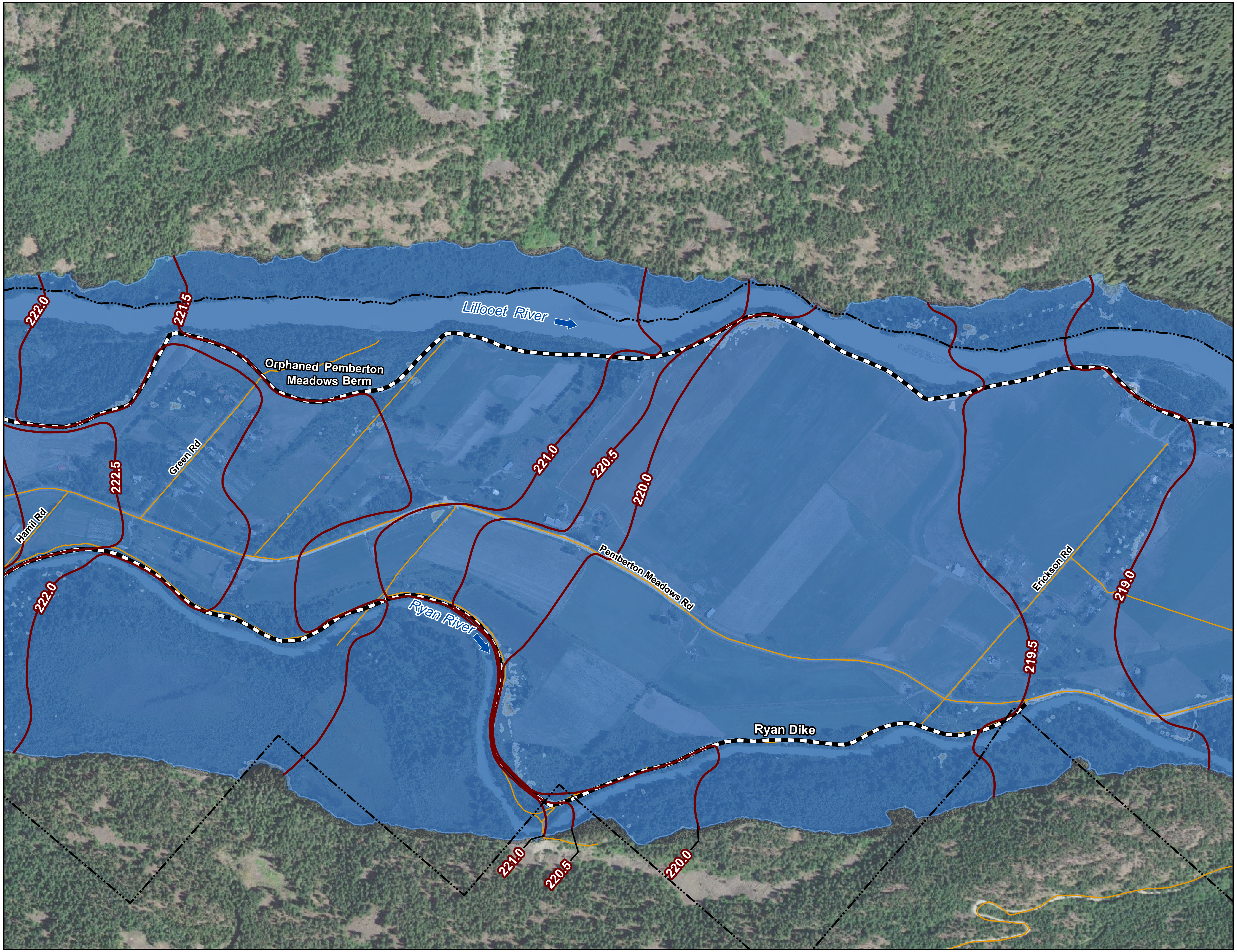
Coordinate System: NAD 1983 CSRS UTM ZONE 10N
Units: METRES; Vertical Datum: CGVD2013

Job: 3006954 | *Date: 20-MAR-2023*

RYAN RIVER FLOODPLAIN MAPPING

DESIGNATED FLOODPLAIN MAP INCLUDING FREEBOARD

SHEET 2 of 5



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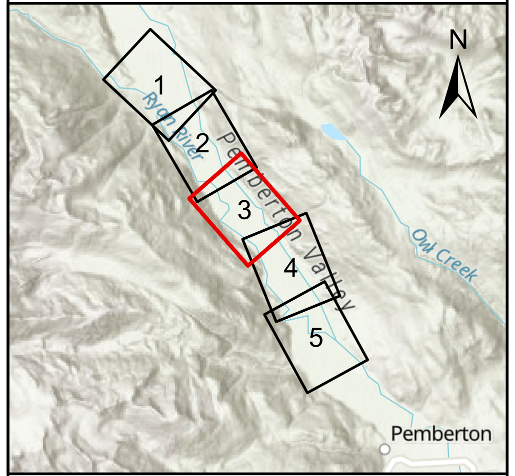

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Flow Direction
Major Road
Local Road
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Limit of Mapping
Flood Construction Level Isoline (FCL) *(Elevation in metres)*
Flood Extent Including Freeboard
Flood Extent

Fan Hazard

Ryan River Fan
Mt. Ross Gullies Fan

PLEASE REFER TO MAP NOTES ON INDEX SHEET

SCALE - 1:10,000

0 100 200 300 400 *Meters*

Coordinate System: NAD 1983 CSRS UTM ZONE 10N
Units: METRES; Vertical Datum: CGVD2013

Job: 3006954	Date: 20-MAR-2023

RYAN RIVER FLOODPLAIN MAPPING

DESIGNATED FLOODPLAIN MAP INCLUDING FREEBOARD

SHEET 3 of 5

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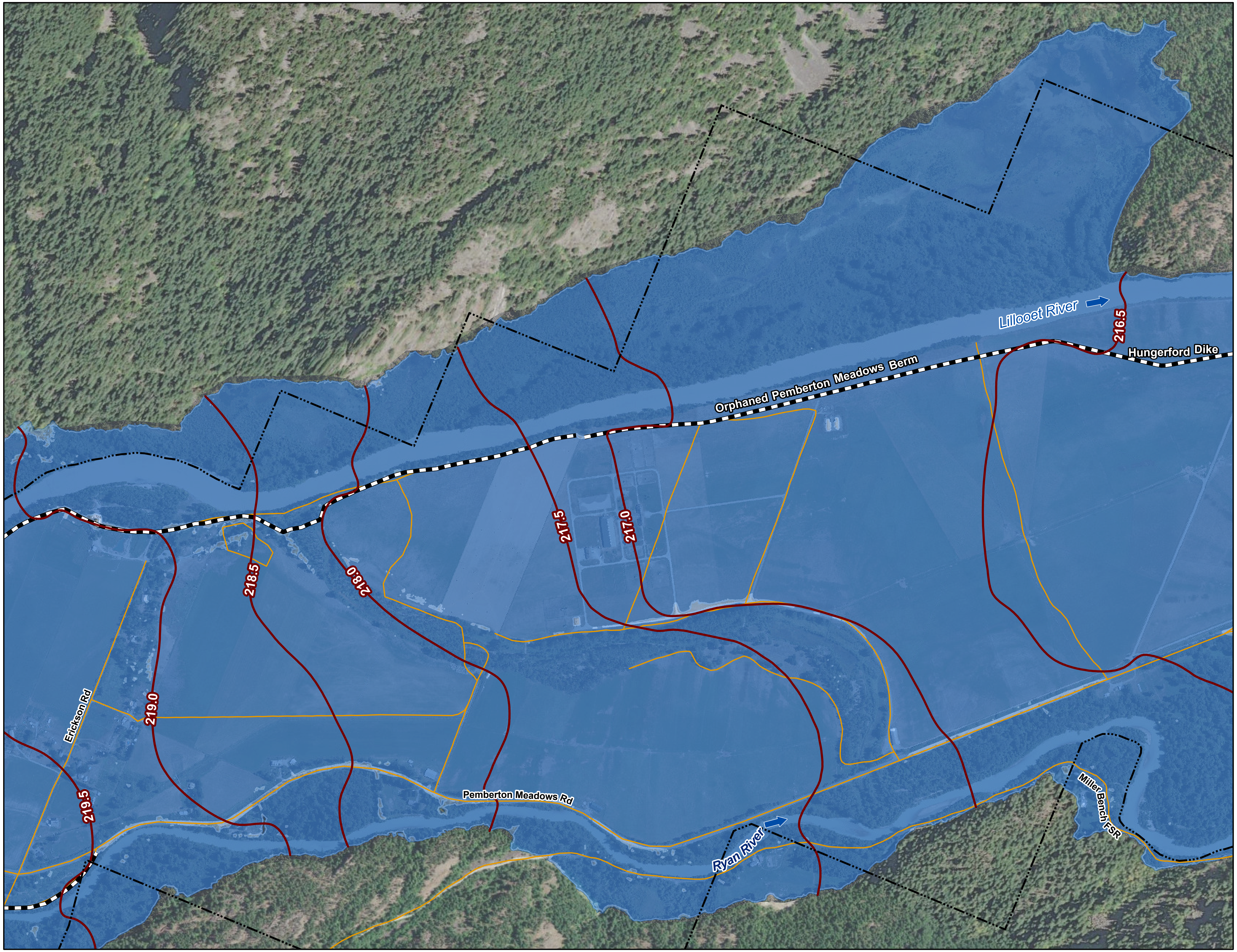

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PEMBERTON VALLEY DYKING DISTRICT

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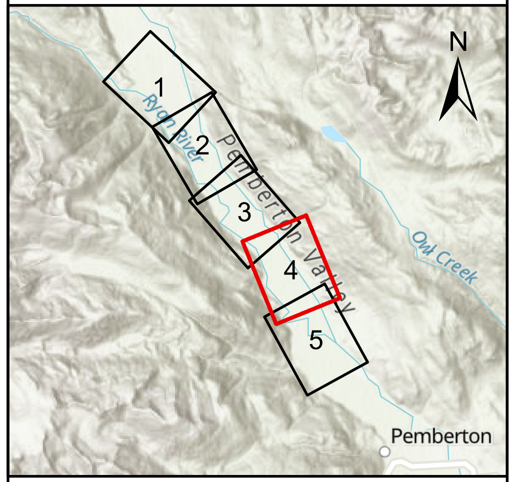

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- Limit of Mapping
- Flood Construction Level Isoline (FCL) *(Elevation in metres)*
- Flood Extent Including Freeboard
- Flood Extent

Fan Hazard

- Ryan River Fan
- Mt. Ross Gullies Fan

PLEASE REFER TO MAP NOTES ON INDEX SHEET

SCALE - 1:10,000

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Coordinate System: NAD 1983 CSRS UTM ZONE 10N
Units: METRES; Vertical Datum: CGVD2013

Job: 3006954	*Date: 20-MAR-2023*

RYAN RIVER FLOODPLAIN MAPPING

DESIGNATED FLOODPLAIN MAP INCLUDING FREEBOARD

SHEET 4 of 5

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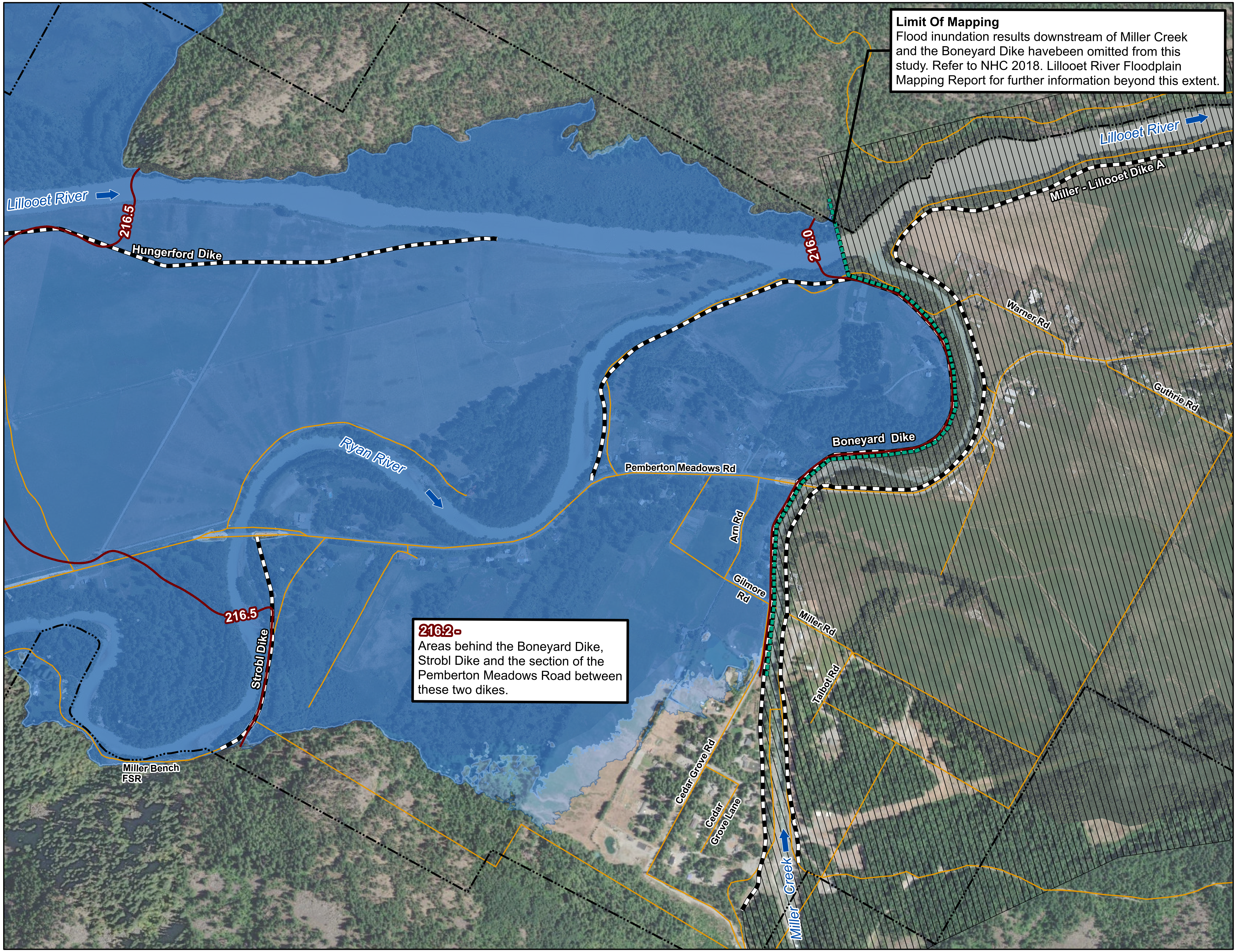

PEMBERTON VALLEY DYKING DISTRICT

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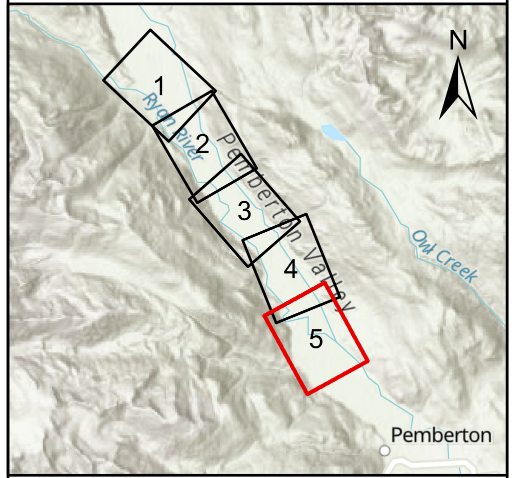

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- Flood Extent Including Freeboard
- Flood Extent

Fan Hazard

- Ryan River Fan
- Mt. Ross Gullies Fan

PLEASE REFER TO MAP NOTES ON INDEX SHEET

SCALE - 1:10,000

0 100 200 300 400 *Meters*

Coordinate System: NAD 1983 CSRS UTM ZONE 10N
Units: METRES; Vertical Datum: CGVD2013

Job: 3006954	*Date: 20-MAR-2023*

RYAN RIVER FLOODPLAIN MAPPING

DESIGNATED FLOODPLAIN MAP INCLUDING FREEBOARD

SHEET 5 of 5

RLM, \\vanfile-van\Projects\Active\3006954 Ryan River modelling\05 GIS\3006954_RLM_RyanRiver_DesignatedFloodplainMaps1.aprx

APPENDIX C

FLOOD DEPTH AND HAZARD MAPS

DRAFT General Notes

1. These maps delineate the potential for flood hazard under conditions caused by a 50-year, 100-year and 200-year return period coincident flood event on the Ryan River and Lillooet River as described in NHC (2023). These maps are not the designated floodplain map. Please see NHC (2023) for details on the designated floodplain mapping. The flood depths and hazard ratings are only shown for the floodplain of the Ryan River and Lillooet River.

2. Fan hazard has been identified based on the alluvial fans identified in NHC (2023). Fan hazards can include unconfined deposition of sediment, rapid aggradation, channel migration, and avulsion across the fan under the contemporary hydroclimatic conditions. Fan hazards can extend beyond the delineated edge of the fan or dike and run out into the floodplain (Extended Fan Hazard Area). Fan edges were based on available satellite imagery. Downstream of Ryan River 13 KM the alluvial fans were not mapped or assessed.

3. Lidar data surveyed in 2016 and 2009 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. The Ryan River survey was extended upstream to the study limit mapped in 2022 and included in the DEM. The maps depict flood levels based on ground conditions represented in this DEM. Any changes to ground/channel elevations, land use or buildings from those included in the model will affect the flood levels and render site-specific information obsolete.

4. 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.

5. The flood levels are based on water surface elevations simulated using a two-dimensional hydraulic model developed by NHC (2018) and updated in NHC (2023) using RAS2D software. Model roughness values were initially assigned based on typical channel and overbank resistance values, then calibrated to a flood event in 2003 for the Ryan River and validated to low flow event in 2022.

6. The Lillooet Valley Dikes cannot contain a 200-year flood in current conditions and will overtop at flows less than the 200-year flood. The area behind the dikes is considered part of the floodplain and the depths and hazard ratings have been mapped as if the dikes are a non-erodible feature of the landscape. In an actual flood, the dikes could erode and breach when overtopped. Depending on the dike breach locations, the depths and hazard ratings could vary significantly from those shown on the maps.

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 hazard extents.

8. 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 Pemberton Valley Dyking District (PVDD) do not assume any liability for such variations.

Data Sources:

1. 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, and additional surveys as described in NHC (2023). The extents of flooding are based on the Lidar DEM. A freeboard allowance is not included.

2. PVDD boundary and cadastral parcel boundaries supplied by Squamish Lillooet Regional District.

3. Municipal boundary downloaded from DataBC.

4. Orthophoto imagery acquired by EMBC in 2016.

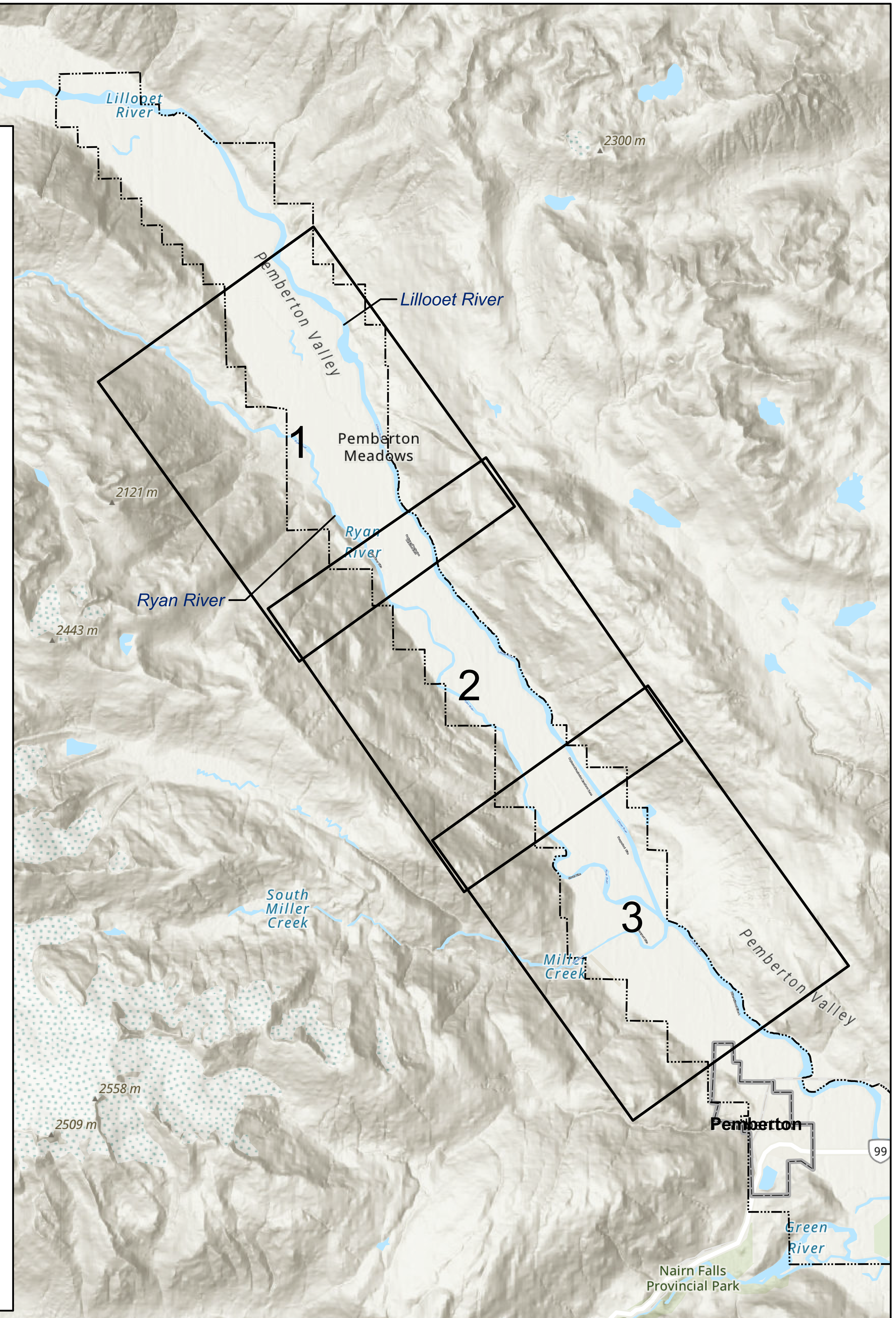
5. Additional base mapping and orthoimagery from Esri.

References:

NHC (2018). Lillooet River Floodplain Mapping. Final Report. Prepared for Pemberton Valley Dyking District.

NHC (2023). Ryan River Floodplain Mapping. Final Report. Prepared for Pemberton Valley Dyking District

Disclaimer



PEMBERTON VALLEY DYKING DISTRICT

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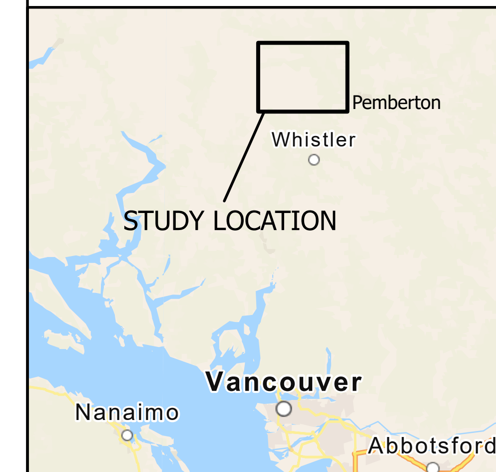


Map Sheet Scale at 1 : 20,000
Pemberton Valley Dyking District
City of Pemberton
Stream

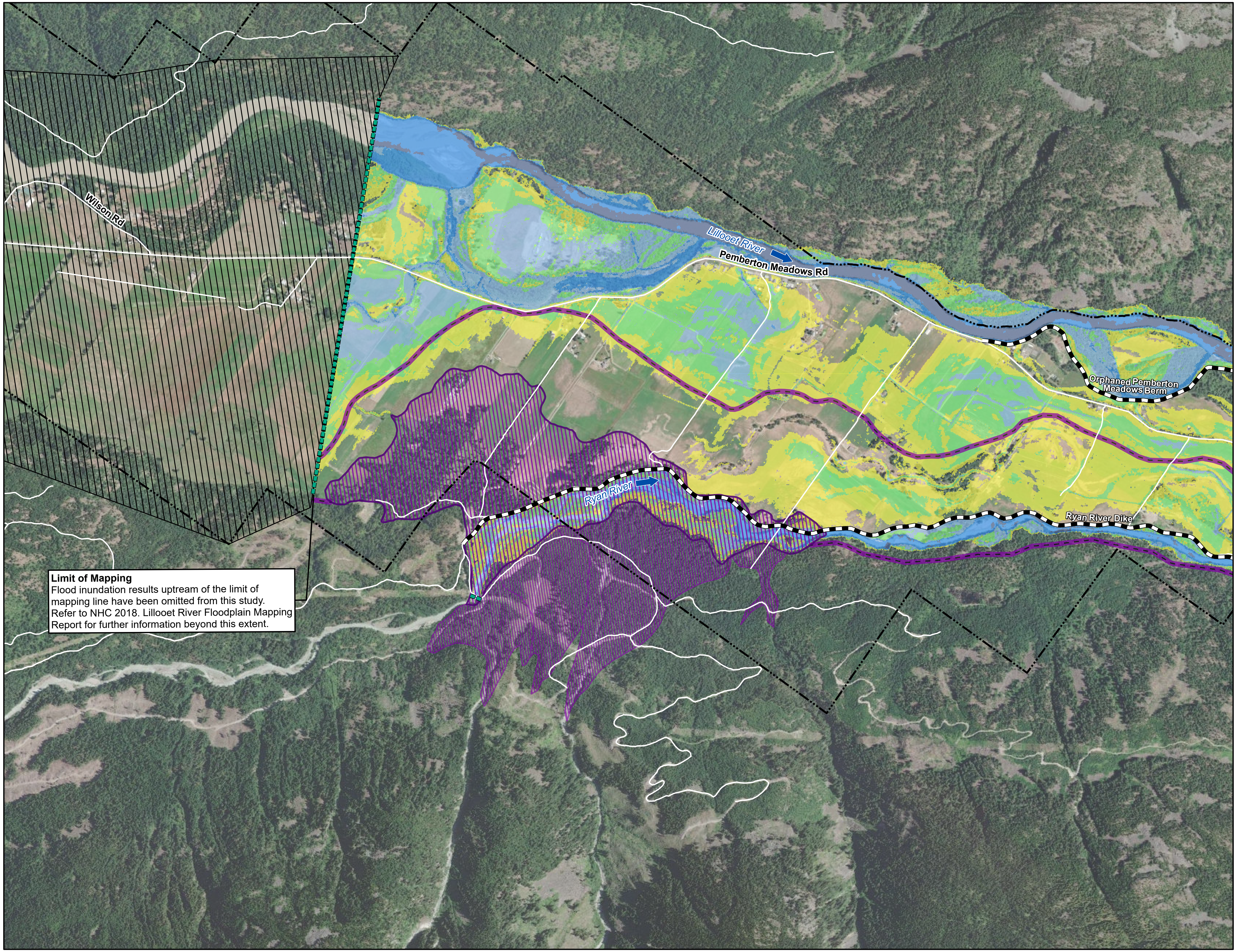
SCALE - 1:100,000
0 1,000 2,000 3,000 4,000 Meters
N

Coordinate System: NAD 1983 CSRS UTM ZONE 10N
Units: METRES; Vertical Datum: CGVD2013

Job: 3006954	Date: 20-MAR-2023

PEMBERTON VALLEY DYKING DISTRICT
RYAN RIVER MODELLING

FLOOD DEPTH AND HAZARD RATING MAPS - KEY PLAN



PEMBERTON VALLEY DYKING DISTRICT

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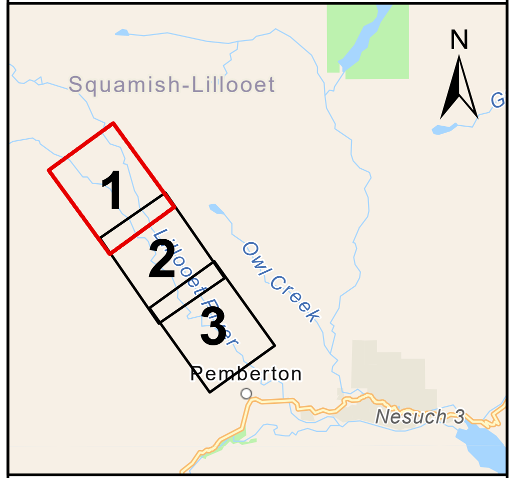

Pemberton Valley Dyking District
City of Pemberton
Flow Direction
Dike
Limit Of Mapping
Extended Fan Hazard Area

Depth (m)

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

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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Fan Hazard: Potential for Dike Breach and channel avulsion. Susceptible to debris, sedimentation, inundation and high velocities.

PLEASE REFER TO MAP NOTES ON INDEX SHEET

SCALE - 1:20,000
0 200 400 600 800 *Meters*

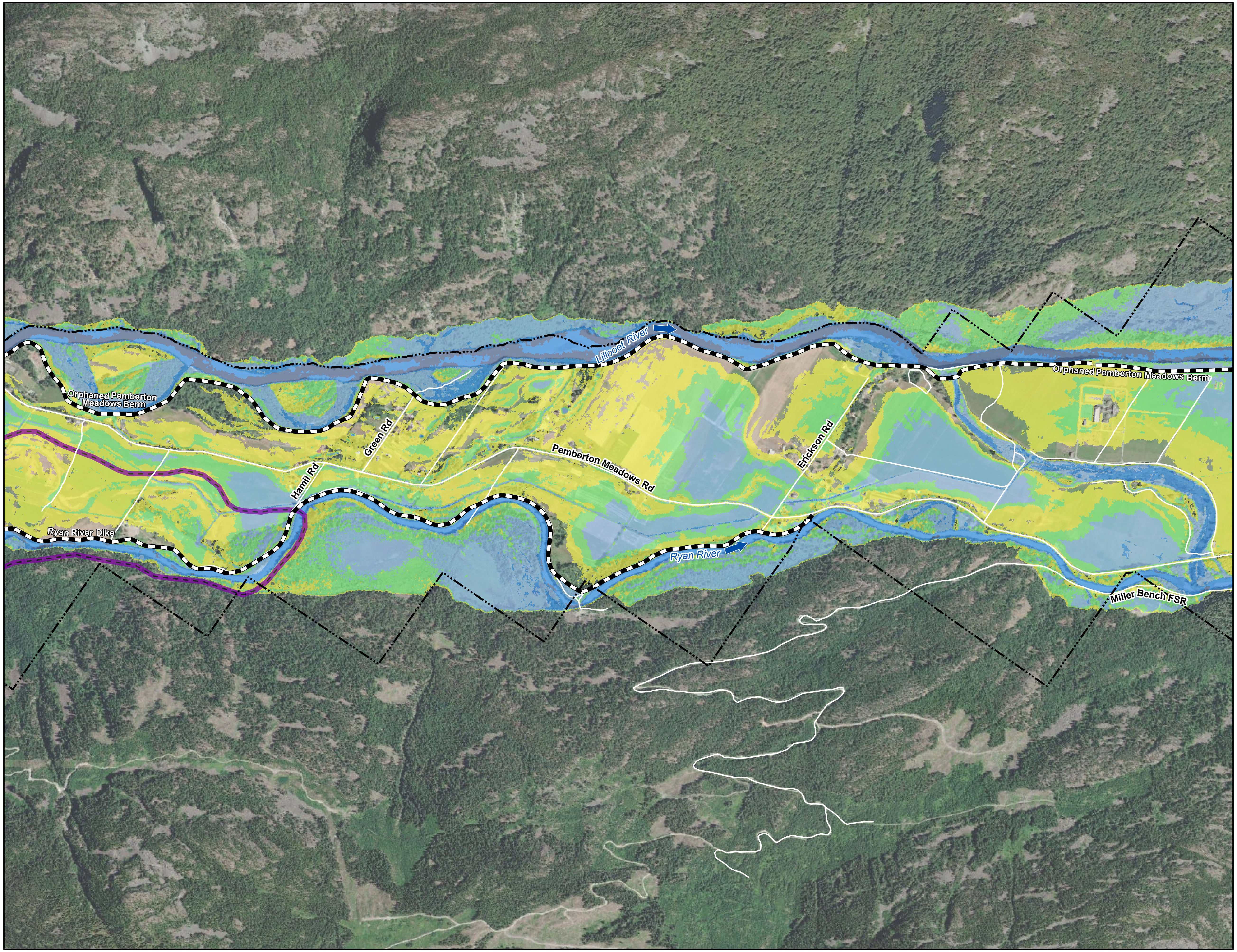
Coordinate System: NAD 1983 CSRS UTM ZONE 10N
Units: METRES; Vertical Datum: CGVD2013

Job: 3006954	*Date: 19-MAR-2023*

PEMBERTON VALLEY DYKING DISTRICT
RYAN RIVER MODELLING

FLOOD DEPTH
50 -YEAR RYAN RIVER EVENT

RLM, \\mainfile-van\Projects\Active\3006954 Ryan River modelling\95 GIS\3006954_RLM_RyanRiver_HazardandDepthMaps1.aprx



PEMBERTON VALLEY DYKING DISTRICT

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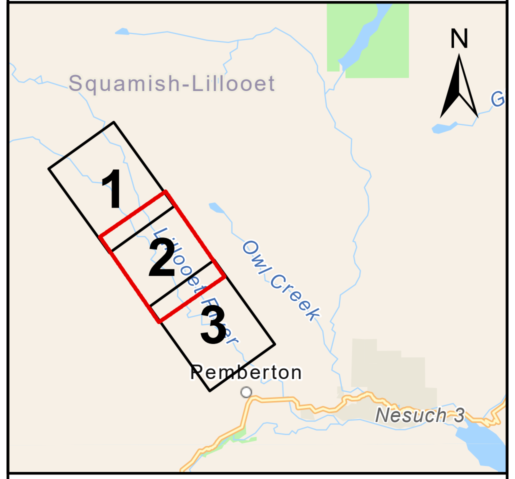

Pemberton Valley Dyking District
City of Pemberton
Flow Direction
Dike
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PLEASE REFER TO MAP NOTES ON INDEX SHEET

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0 200 400 600 800 Meters

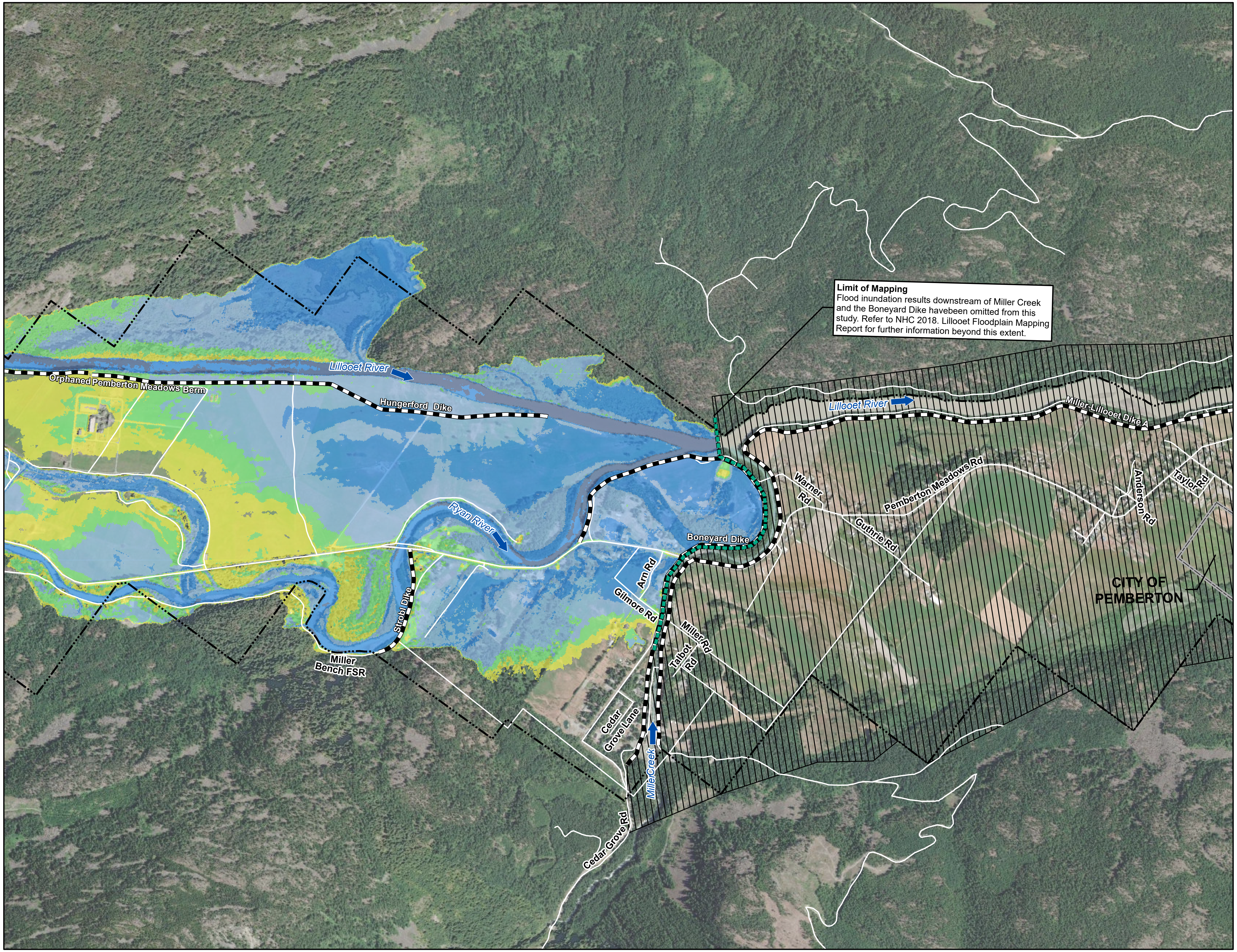
Coordinate System: NAD 1983 CSRS UTM ZONE 10N
Units: METRES; Vertical Datum: CGVD2013

Job: 3006954	Date: 19-MAR-2023

PEMBERTON VALLEY DYKING DISTRICT
RYAN RIVER MODELLING

FLOOD DEPTH
50 -YEAR RYAN RIVER EVENT

SHEET 2 of 3



PEMBERTON VALLEY DYKING DISTRICT

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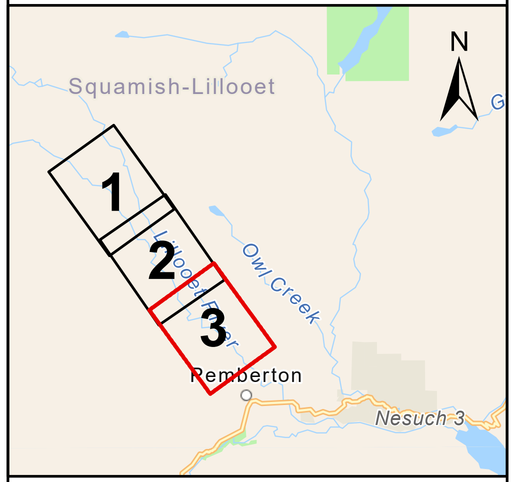

Pemberton Valley Dyking District
City of Pemberton
Flow Direction
Dike
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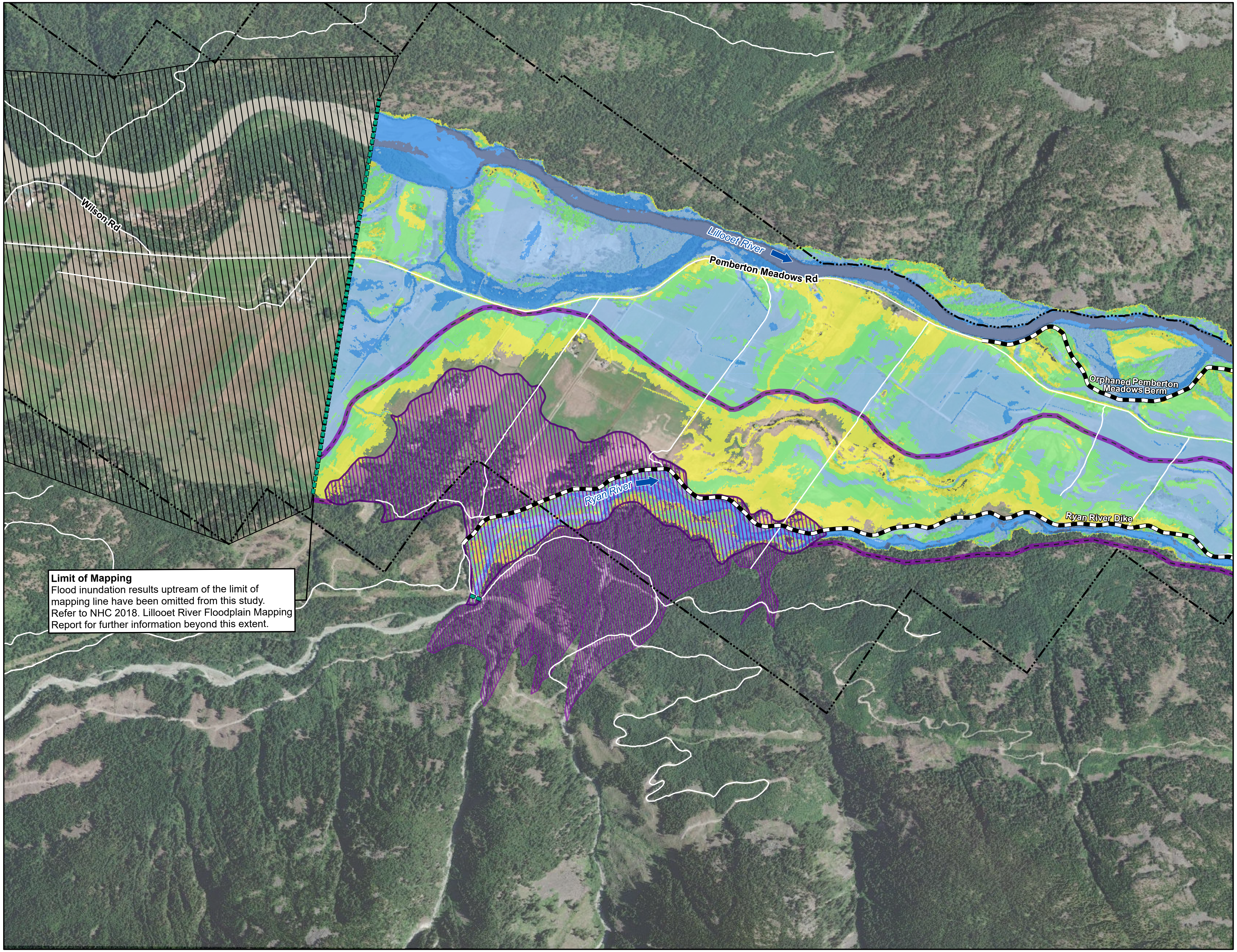
Units: METRES; Vertical Datum: CGVD2013

Job: 3006954 | *Date: 19-MAR-2023*

PEMBERTON VALLEY DYKING DISTRICT
RYAN RIVER MODELLING

FLOOD DEPTH
50 -YEAR RYAN RIVER EVENT

SHEET 3 of 3



PEMBERTON VALLEY DYKING DISTRICT

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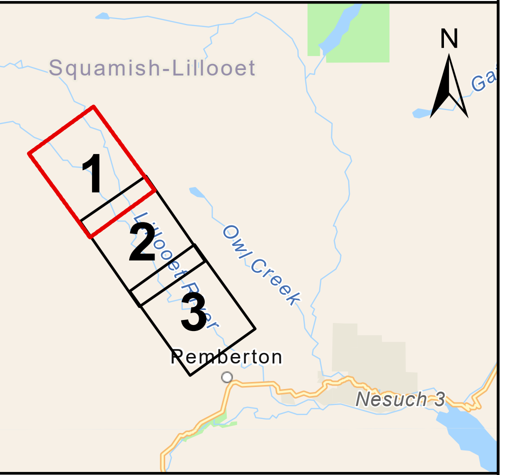

- Pemberton Valley Dyking District
- City of Pemberton
- Flow Direction
- Dike
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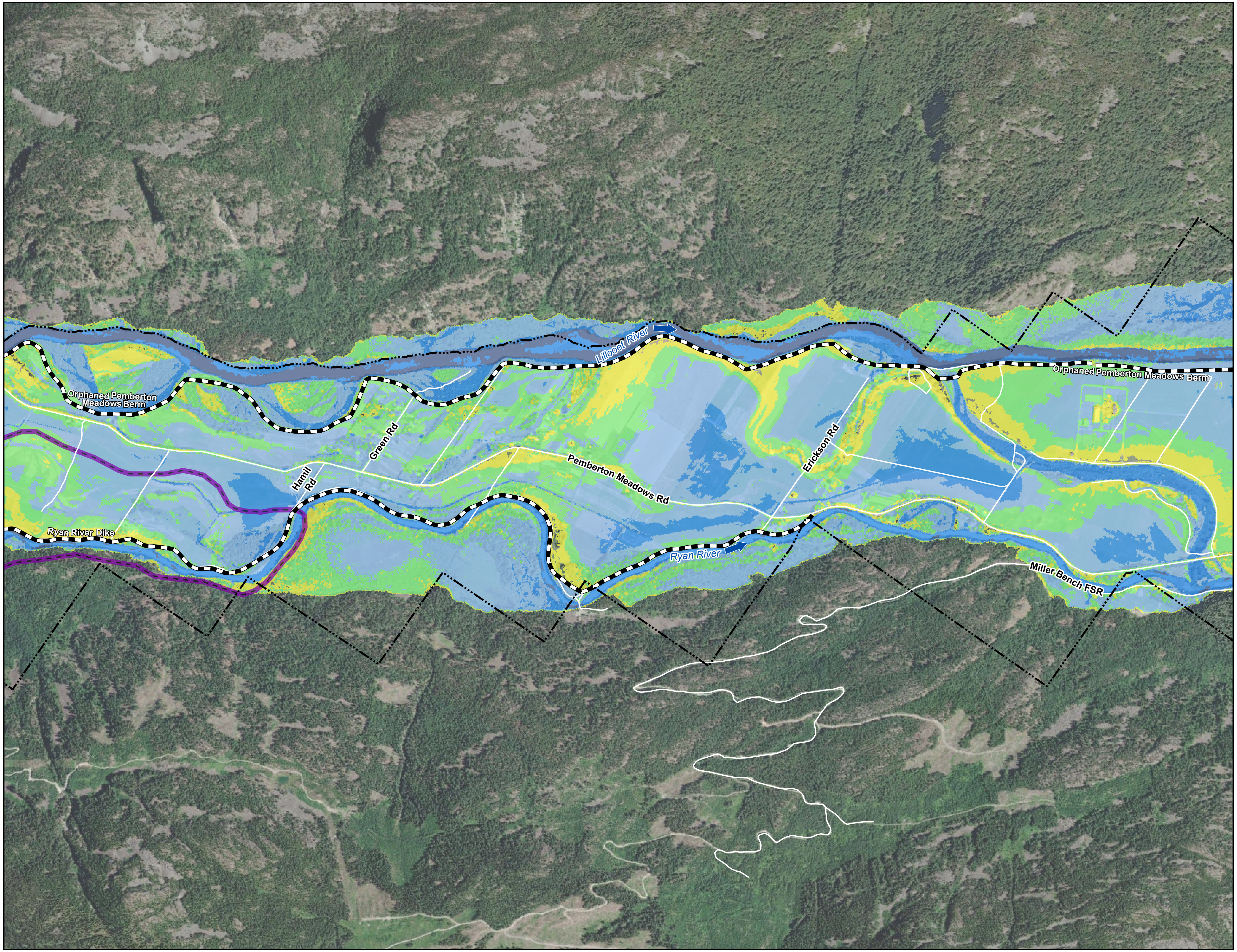
Units: METRES; Vertical Datum: CGVD2013

Job: 3006954	Date: 20-MAR-2023

PEMBERTON VALLEY DYKING DISTRICT
RYAN RIVER MODELLING

FLOOD DEPTH
100 -YEAR RYAN RIVER EVENT

SHEET 1 of 3



PEMBERTON VALLEY DYKING DISTRICT

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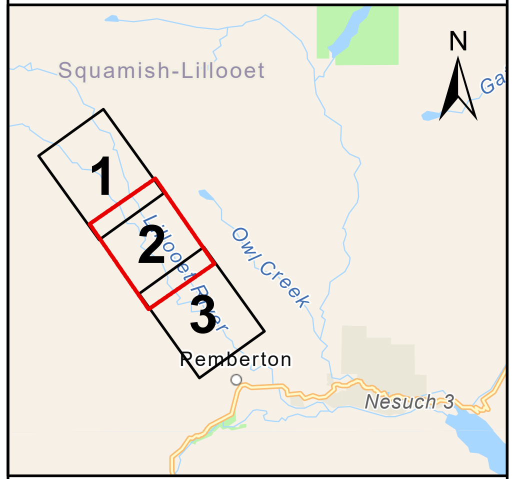

Pemberton Valley Dyking District
City of Pemberton
Flow Direction
Dike
Limit Of Mapping
Extended Fan Hazard Area

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Units: METRES; Vertical Datum: CGVD2013

Job: 3006954 | *Date: 20-MAR-2023*

PEMBERTON VALLEY DYKING DISTRICT
RYAN RIVER MODELLING

FLOOD DEPTH
100 -YEAR RYAN RIVER EVENT

SHEET 2 of 3

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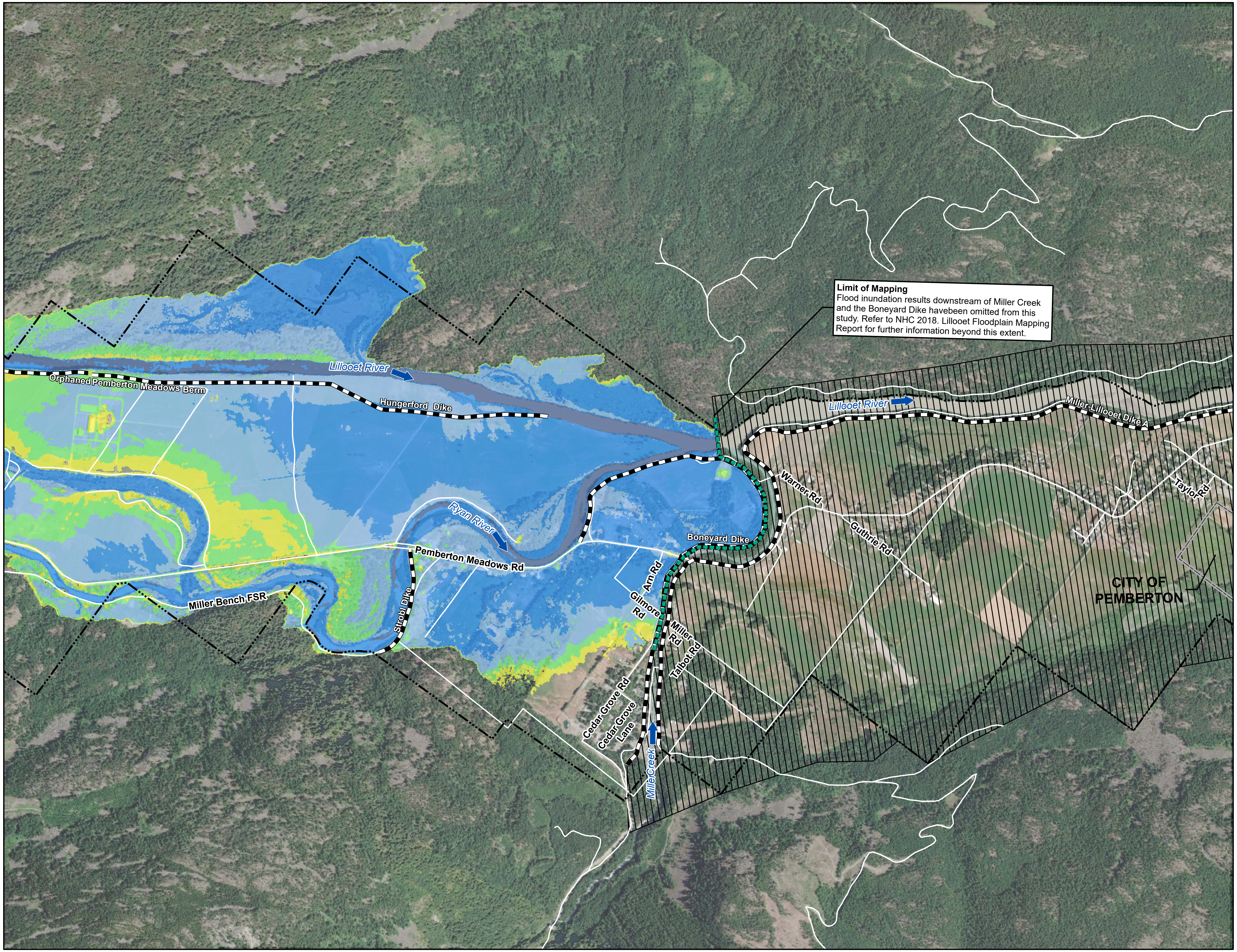

PEMBERTON VALLEY DYKING DISTRICT

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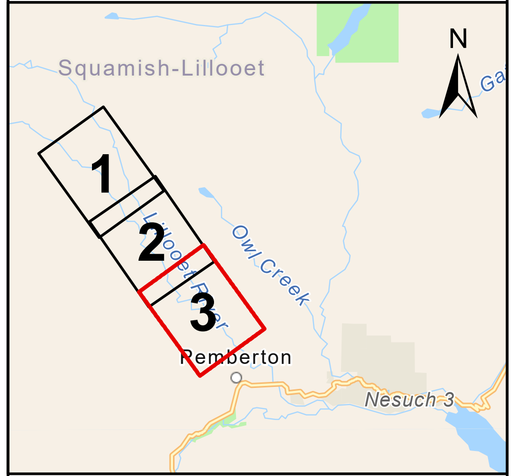

Pemberton Valley Dyking District
City of Pemberton
Flow Direction
Dike
Limit Of Mapping
Extended Fan Hazard Area

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SCALE - 1:20,000

0 200 400 600 800 Meters

N

Coordinate System: NAD 1983 CSRS UTM ZONE 10N
Units: METRES; Vertical Datum: CGVD2013

Job: 3006954	*Date: 20-MAR-2023*

PEMBERTON VALLEY DYKING DISTRICT
RYAN RIVER MODELLING

FLOOD DEPTH
100 -YEAR RYAN RIVER EVENT

SHEET 3 of 3

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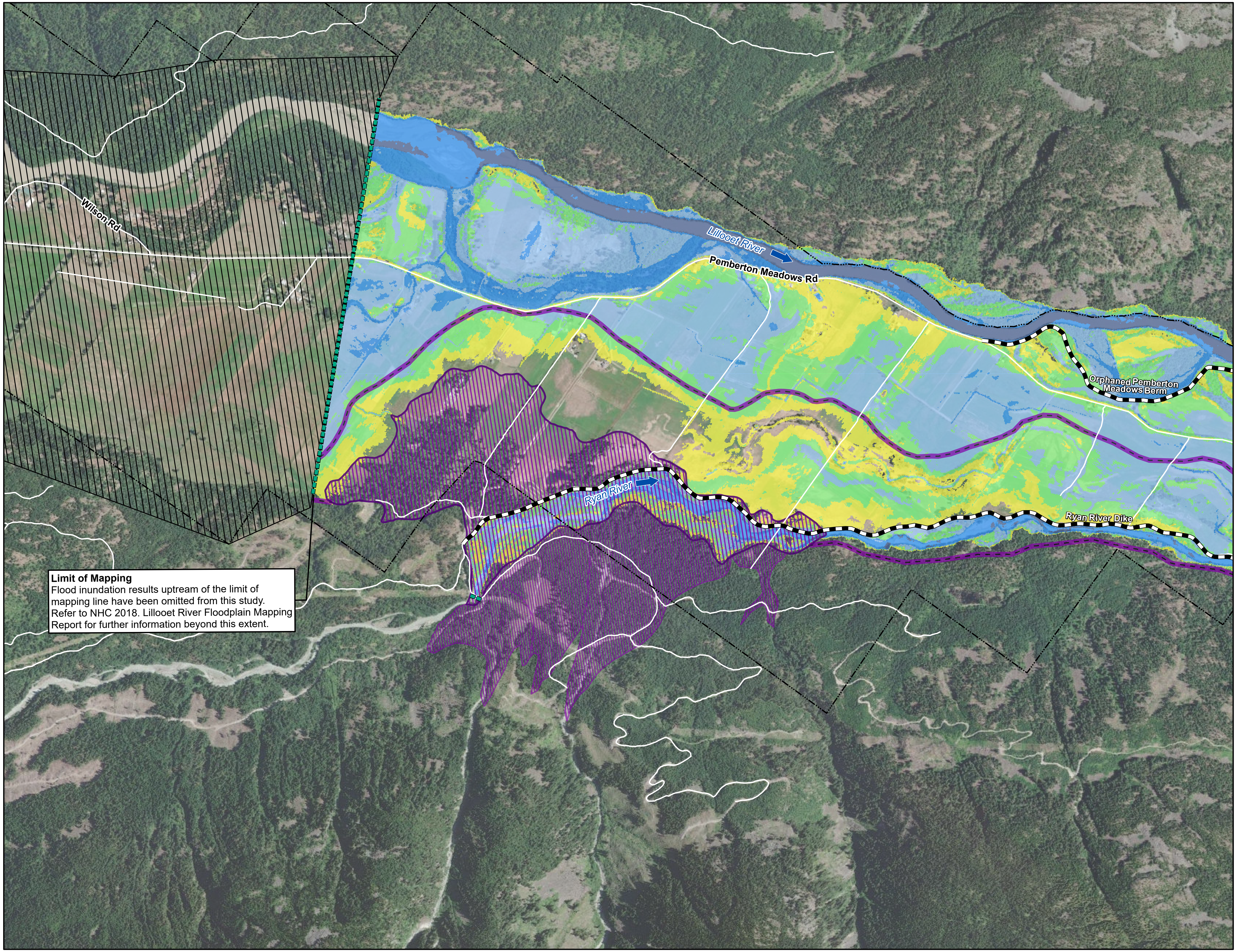

Limit of Mapping
Flood inundation results upstream of the limit of mapping line have been omitted from this study. Refer to NHC 2018. Lillooet River Floodplain Mapping Report for further information beyond this extent.

PEMBERTON VALLEY DYKING DISTRICT

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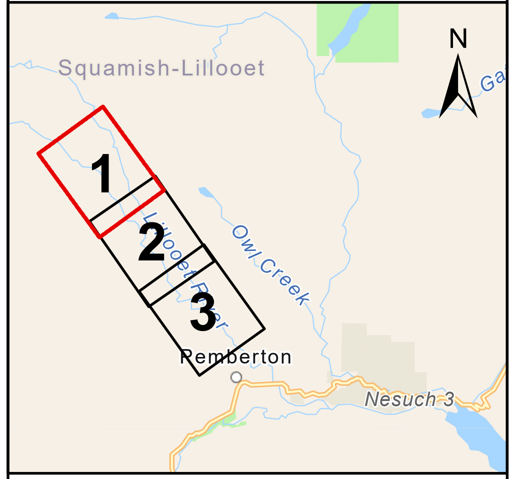

Pemberton Valley Dyking District
City of Pemberton
Flow Direction
Dike
Limit Of Mapping
Extended Fan Hazard Area

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SCALE - 1:20,000
0 200 400 600 800 *Meters*

Coordinate System: NAD 1983 CSRS UTM ZONE 10N
Units: METRES; Vertical Datum: CGVD2013

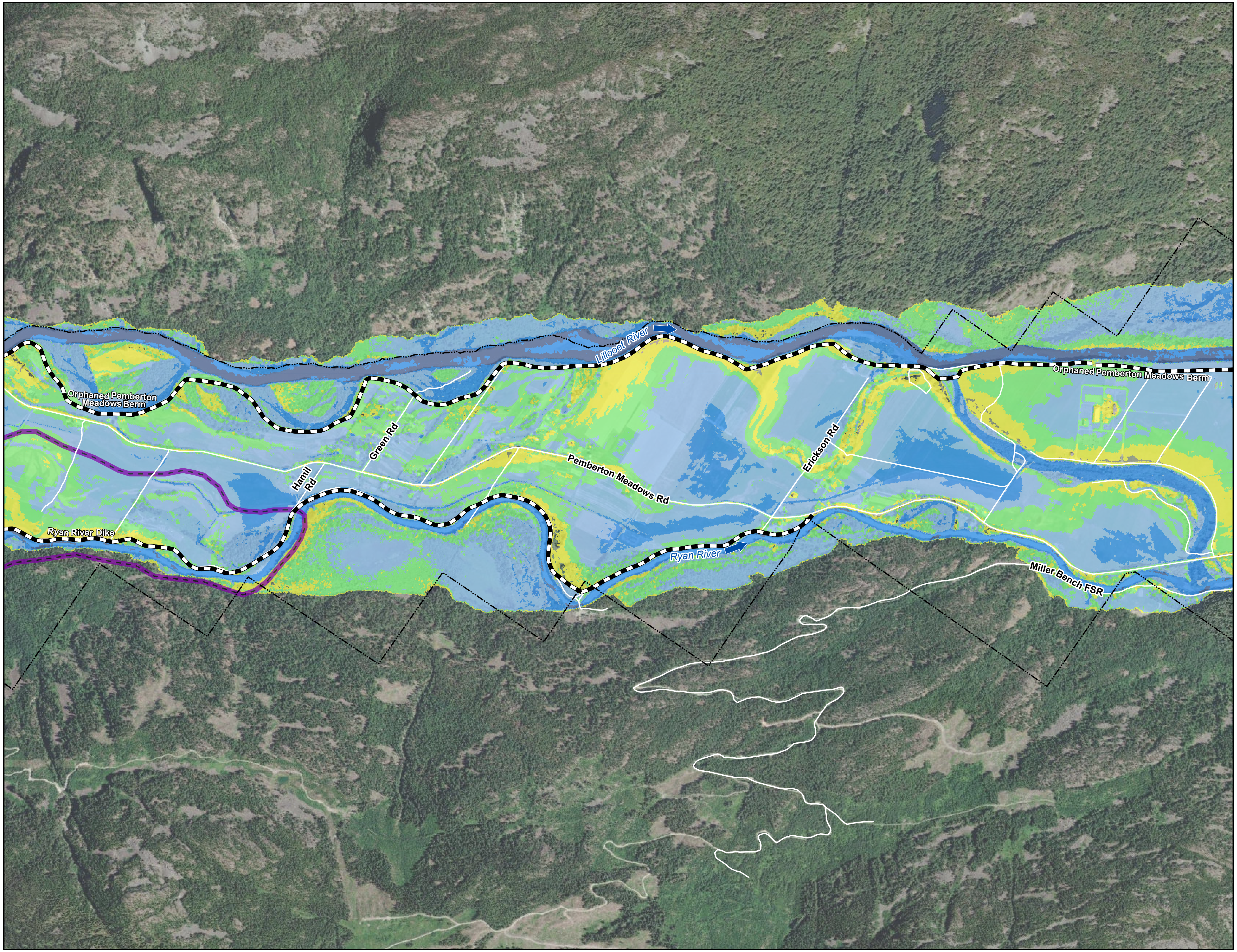
Job: 3006954	*Date: 20-MAR-2023*

PEMBERTON VALLEY DYKING DISTRICT
RYAN RIVER MODELLING

FLOOD DEPTH
200 -YEAR RYAN RIVER EVENT

SHEET 1 of 3

RLM, \\mainfile-van\Projects\Active\3006954 Ryan River modelling\95 GIS\3006954_RLM_RyanRiver_HazardandDepthMaps1.aprx



PEMBERTON VALLEY DYKING DISTRICT

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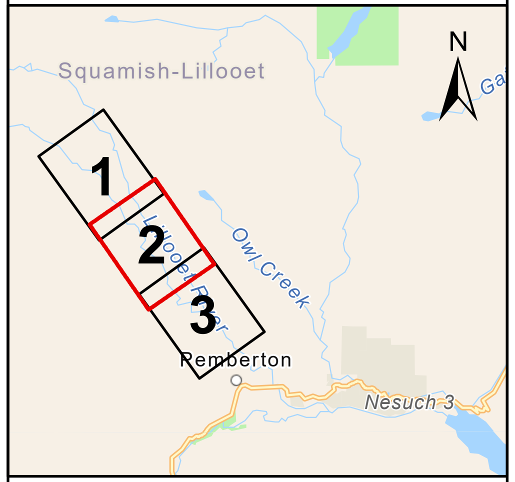

- Pemberton Valley Dyking District
- City of Pemberton
- Flow Direction
- Dike
- Limit Of Mapping
- Extended Fan Hazard Area

Depth (m)

- 0 to 0.5
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PLEASE REFER TO MAP NOTES ON INDEX SHEET

SCALE - 1:20,000

0 200 400 600 800 Meters

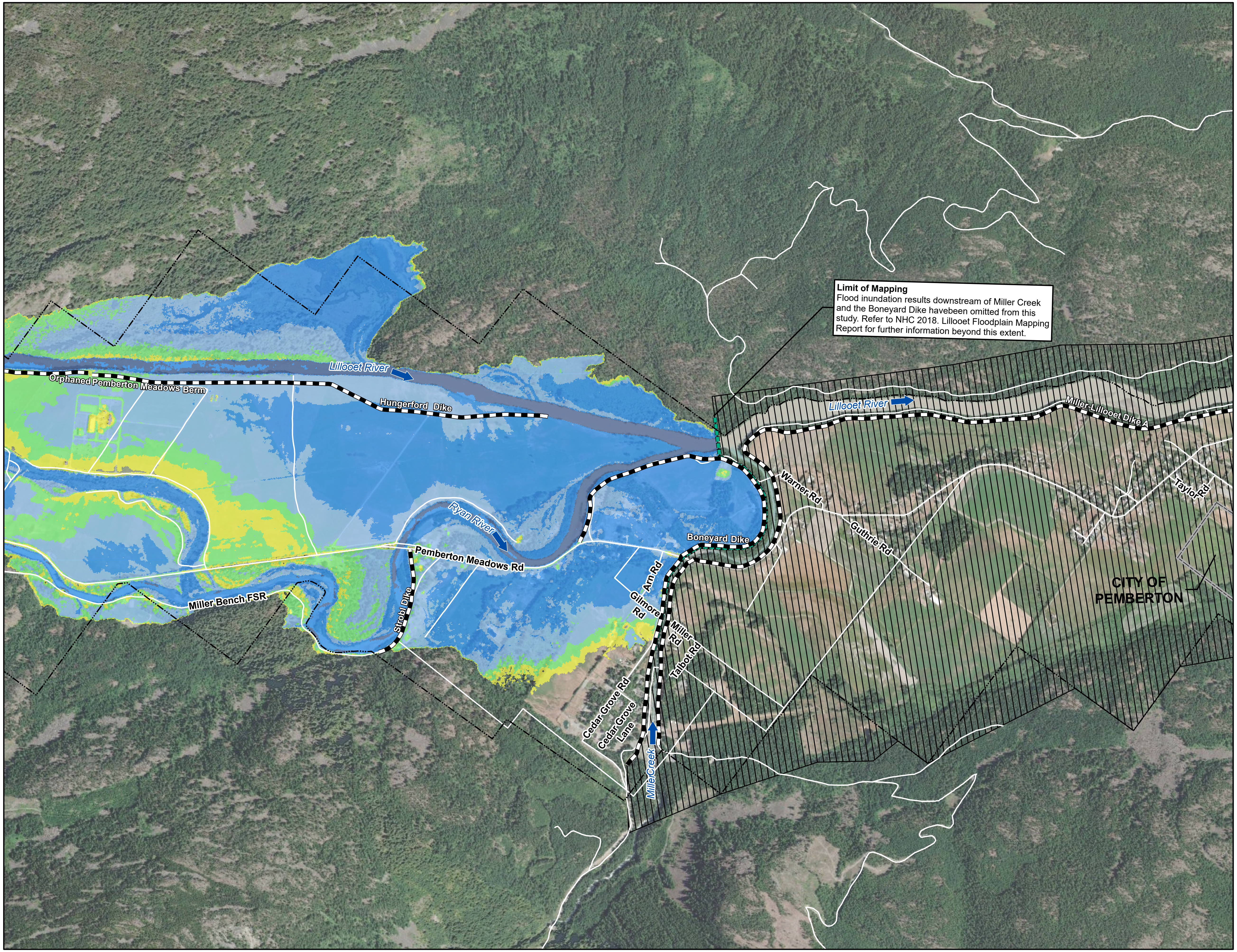
Coordinate System: NAD 1983 CSRS UTM ZONE 10N
Units: METRES; Vertical Datum: CGVD2013

Job: 3006954 | *Date: 20-MAR-2023*

PEMBERTON VALLEY DYKING DISTRICT
RYAN RIVER MODELLING

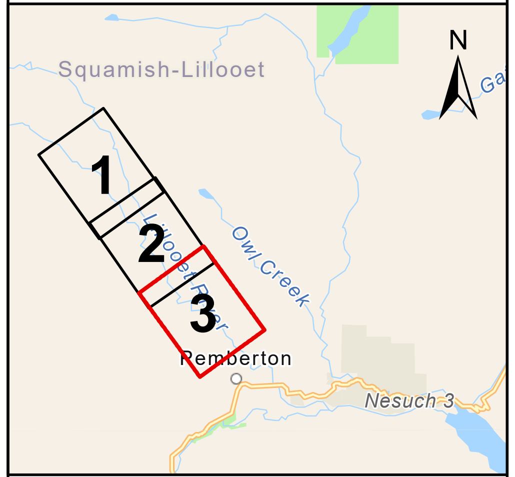
FLOOD DEPTH
200 -YEAR RYAN RIVER EVENT

SHEET 2 of 3



PEMBERTON VALLEY DYKING DISTRICT

nhc northwest hydraulic consultants



Pemberton Valley Dyking District
City of Pemberton
Flow Direction
Dike
Limit Of Mapping
Extended Fan Hazard Area

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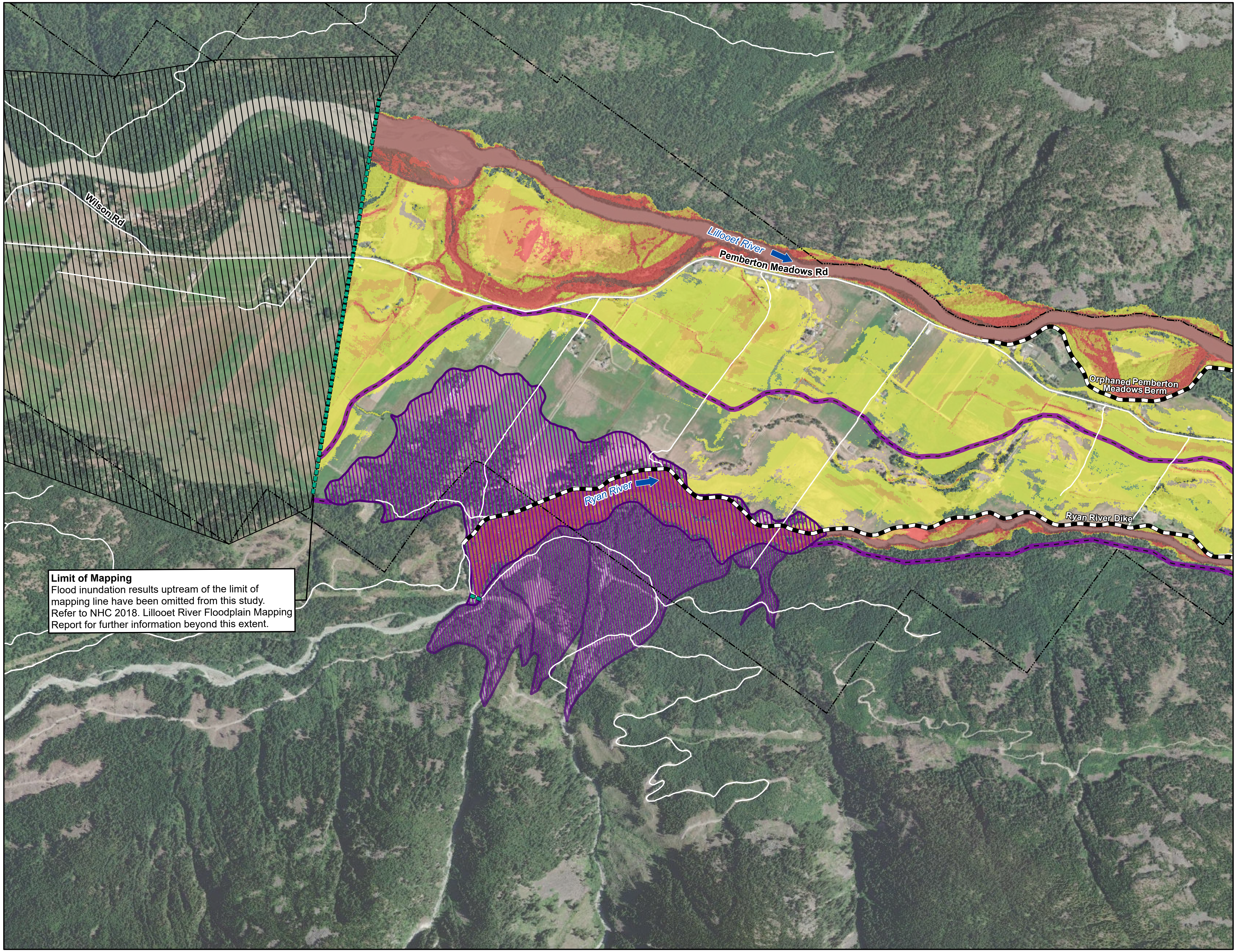
Units: METRES; Vertical Datum: CGVD2013

Job: 3006954 | *Date: 20-MAR-2023*

PEMBERTON VALLEY DYKING DISTRICT
RYAN RIVER MODELLING
FLOOD DEPTH
200 -YEAR RYAN RIVER EVENT

SHEET 3 of 3



PEMBERTON VALLEY DYKING DISTRICT

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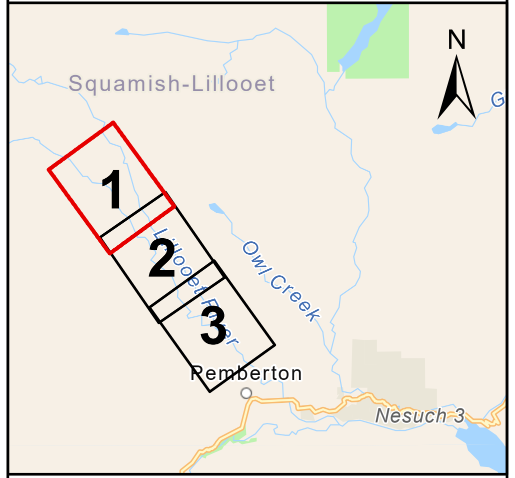

Pemberton Valley Dyking District
City of Pemberton
Flow Direction
Limit Of Mapping
Dike
Extended Fan Hazard Area

Hazard Rating (m*m/s)

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

Low: Caution - Flood zone with shallow flowing water or deep standing water.
Moderate: Dangerous for some (e.g. children) - Danger: flood zone with deep or fast flowing water.
Significant: Dangerous for most people - Danger: flood zone with deep fast flowing water.
Extreme: Dangerous for all - Extreme danger: flood zone with deep, fast flowing water.
Extreme Fan: Dangerous for all - Potential for Dike Breach and channel avulsion. Susceptible to debris, sedimentation, inundation and high velocities.

PLEASE REFER TO MAP NOTES ON INDEX SHEET

SCALE - 1:20,000
0 200 400 600 800 *Meters*

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Units: METRES; Vertical Datum: CGVD2013

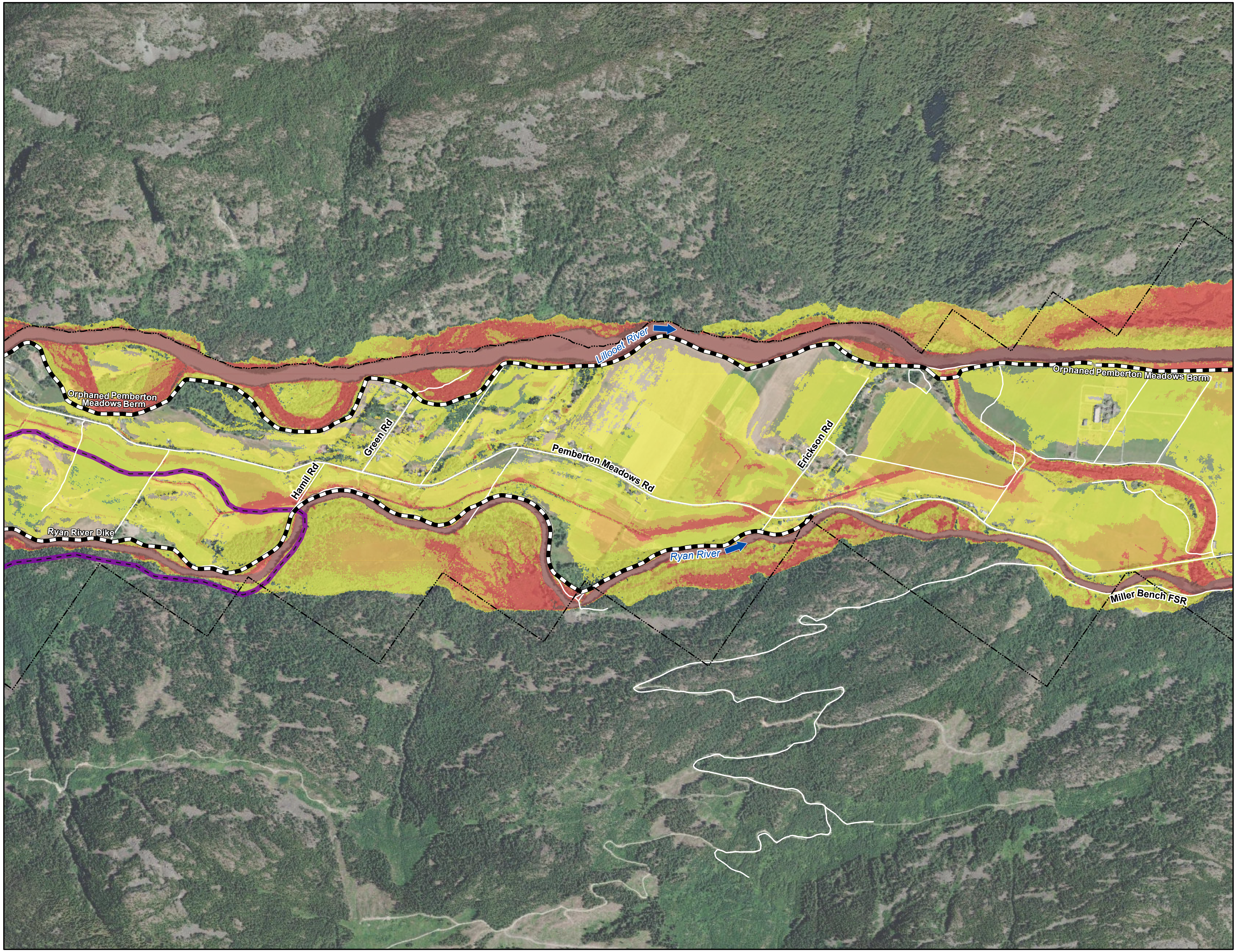
Job: 3006954 *Date: 20-MAR-2023*

PEMBERTON VALLEY DYKING DISTRICT
RYAN RIVER MODELLING

FLOOD HAZARD RATING
50 -YEAR RYAN RIVER
EVENT

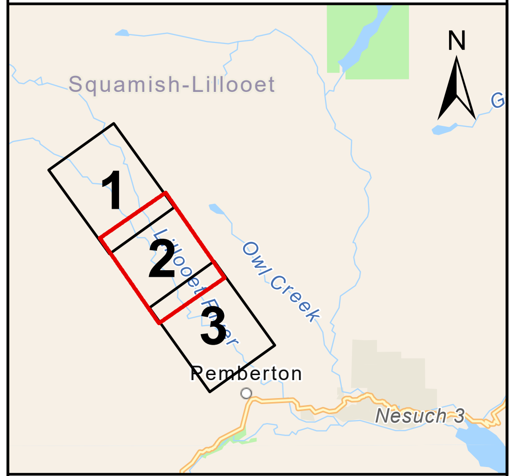
SHEET 1 of 3

RLM, \\mainfile-van\Projects\Active\3006954 Ryan River modelling\95 GIS\3006954_RLM_RyanRiver_HazardandDepthMaps1.aprx



PEMBERTON VALLEY DYKING DISTRICT

nhc northwest hydraulic consultants



- Pemberton Valley Dyking District
- City of Pemberton
- Flow Direction
- Limit Of Mapping
- Dike
- Extended Fan Hazard Area

Hazard Rating (m*m/s)

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

Low: Caution - Flood zone with shallow flowing water or deep standing water.
Moderate: Dangerous for some (e.g. children) - Danger: flood zone with deep or fast flowing water.
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Extreme Fan: Dangerous for all - Potential for Dike Breach and channel avulsion. Susceptible to debris, sedimentation, inundation and high velocities.

PLEASE REFER TO MAP NOTES ON INDEX SHEET

SCALE - 1:20,000

0 200 400 600 800 Meters

Coordinate System: NAD 1983 CSRS UTM ZONE 10N
Units: METRES; Vertical Datum: CGVD2013

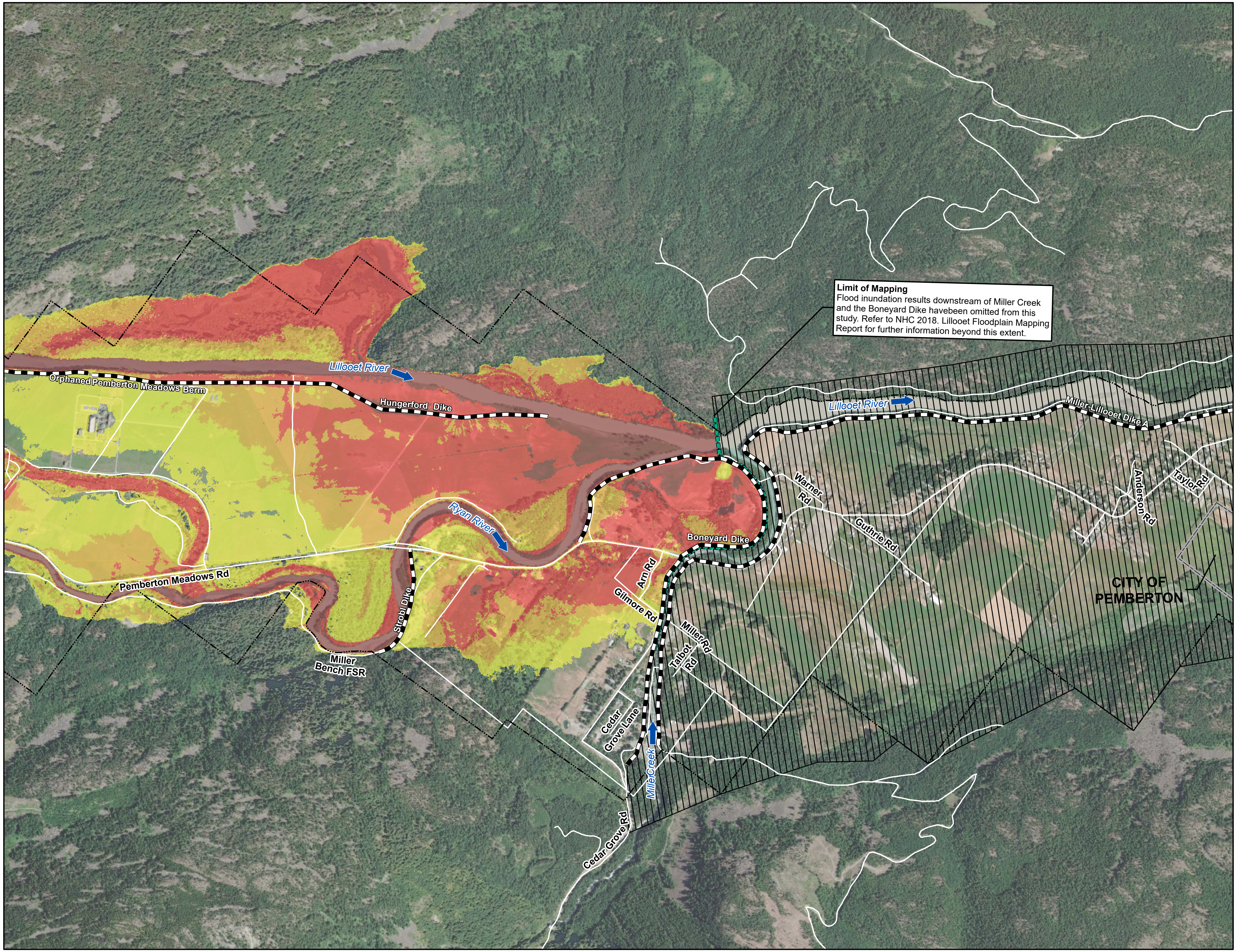
Job: 3006954	Date: 20-MAR-2023

PEMBERTON VALLEY DYKING DISTRICT
RYAN RIVER MODELLING

FLOOD HAZARD RATING
50 -YEAR RYAN RIVER
EVENT

SHEET 2 of 3

RLM, \\nhcfile-van\Projects\Active\3006954 Ryan River modelling\95 GIS\3006954_RLM_RyanRiver_HazardandDepthMaps1.aprx



PEMBERTON VALLEY DYKING DISTRICT

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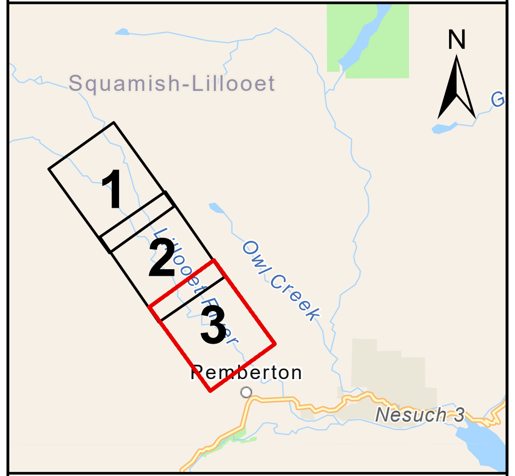

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0 200 400 600 800 Meters
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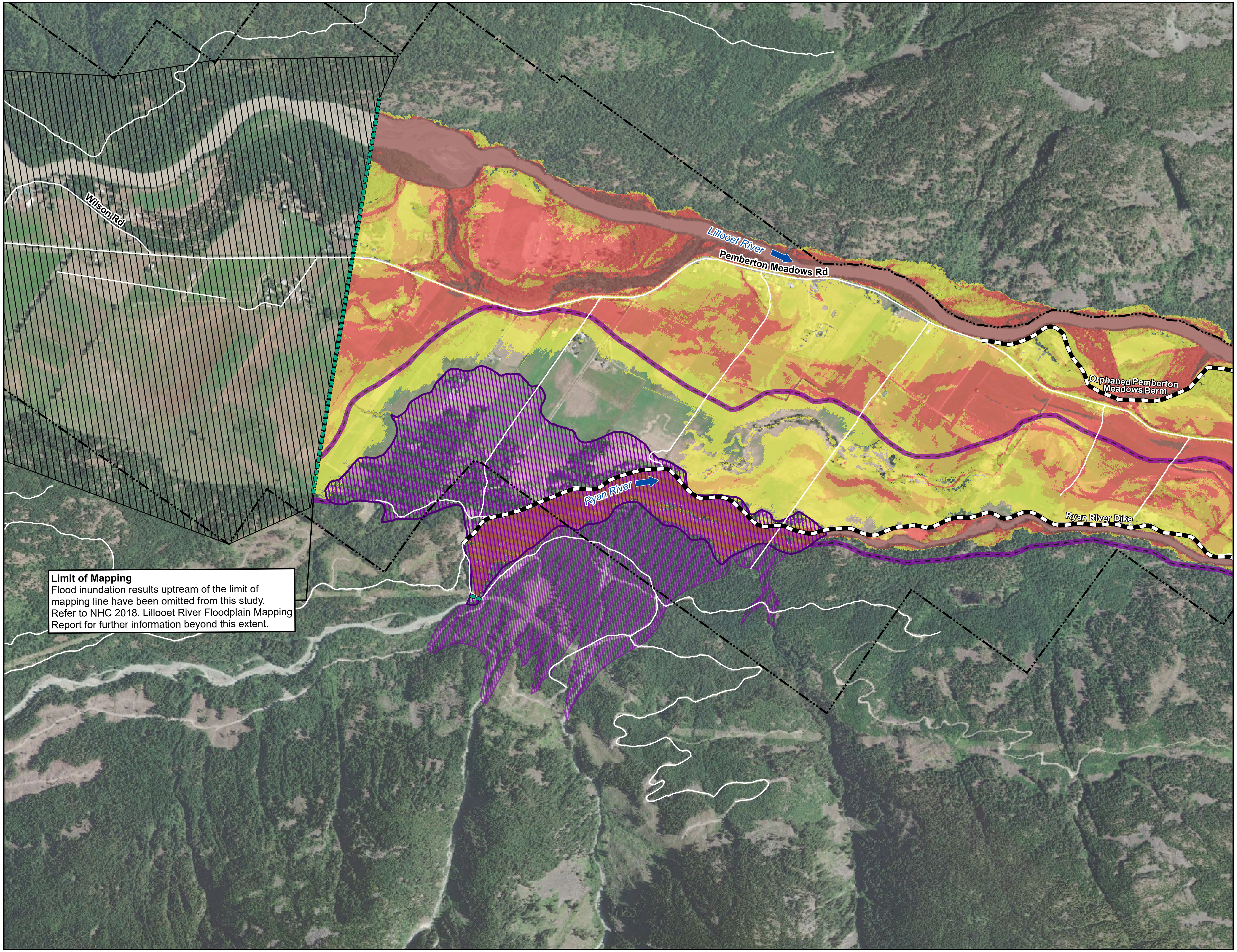
Coordinate System: NAD 1983 CSRS UTM ZONE 10N
Units: METRES; Vertical Datum: CGVD2013

Job: 3006954 | *Date: 20-MAR-2023*

PEMBERTON VALLEY DYKING DISTRICT
RYAN RIVER MODELLING

FLOOD HAZARD RATING
50 -YEAR RYAN RIVER EVENT

SHEET 3 of 3



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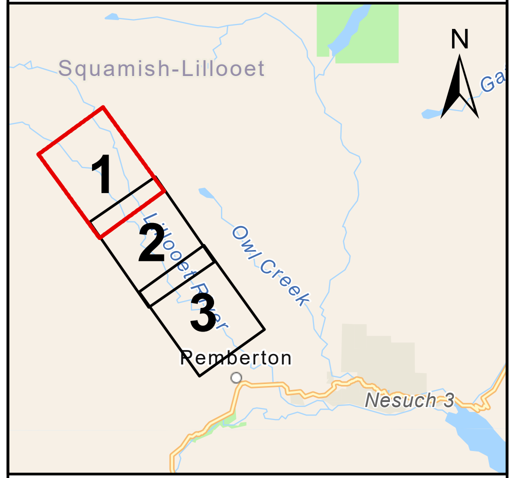

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0 200 400 600 800 *Meters*

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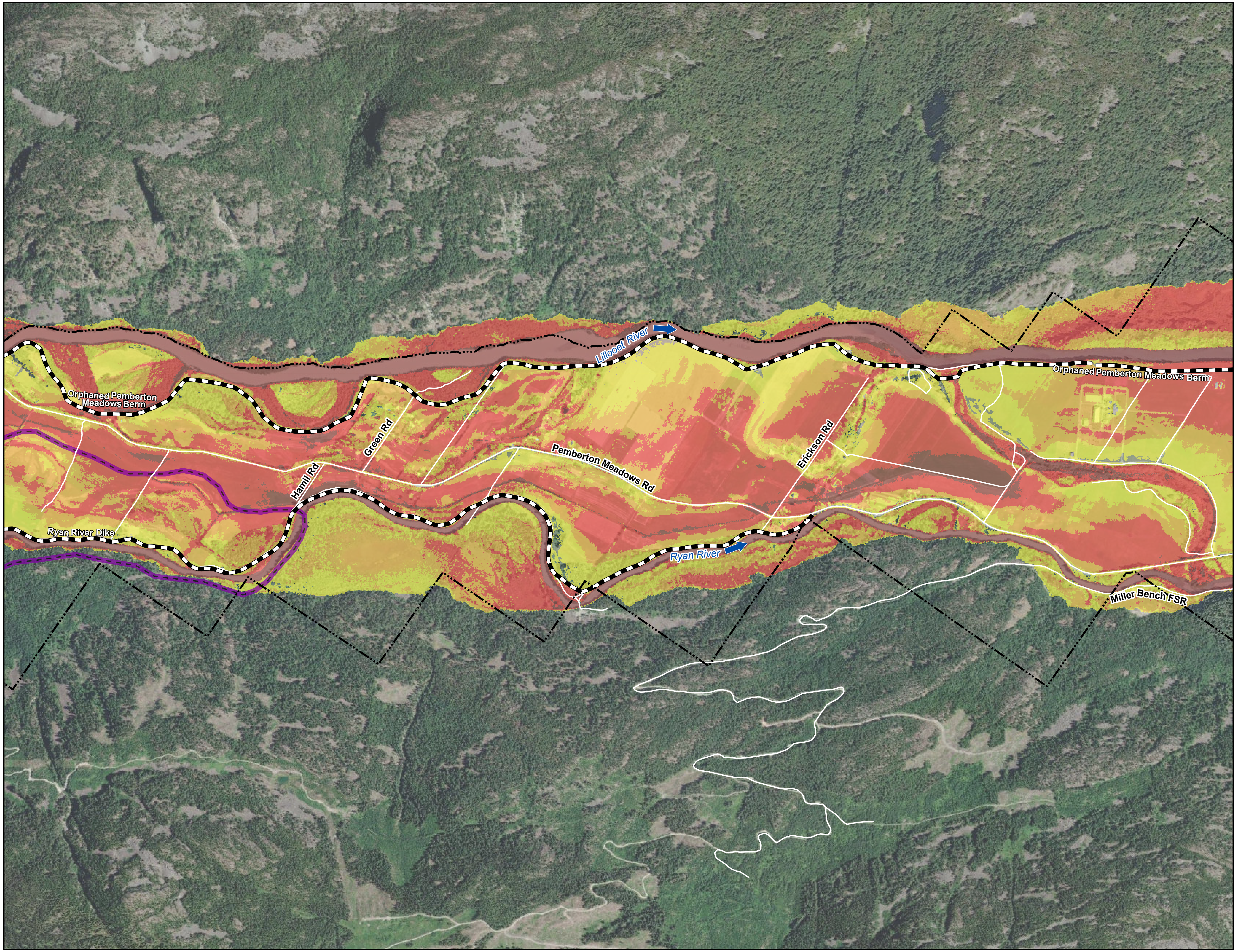
Units: METRES; Vertical Datum: CGVD2013

Job: 3006954	Date: 20-MAR-2023

PEMBERTON VALLEY DYKING DISTRICT
RYAN RIVER MODELLING

FLOOD HAZARD RATING 100 -YEAR RYAN RIVER EVENT

SHEET 1 of 3



PEMBERTON VALLEY DYKING DISTRICT

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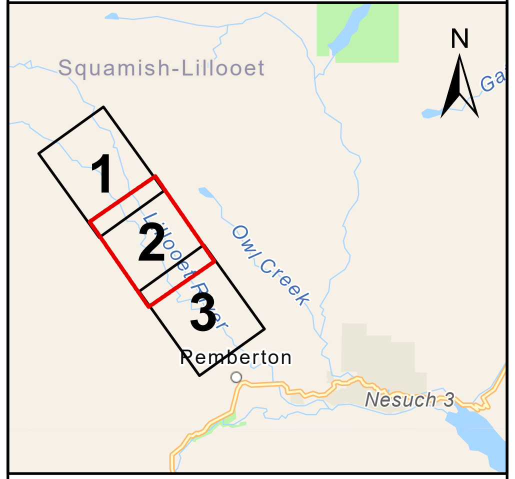

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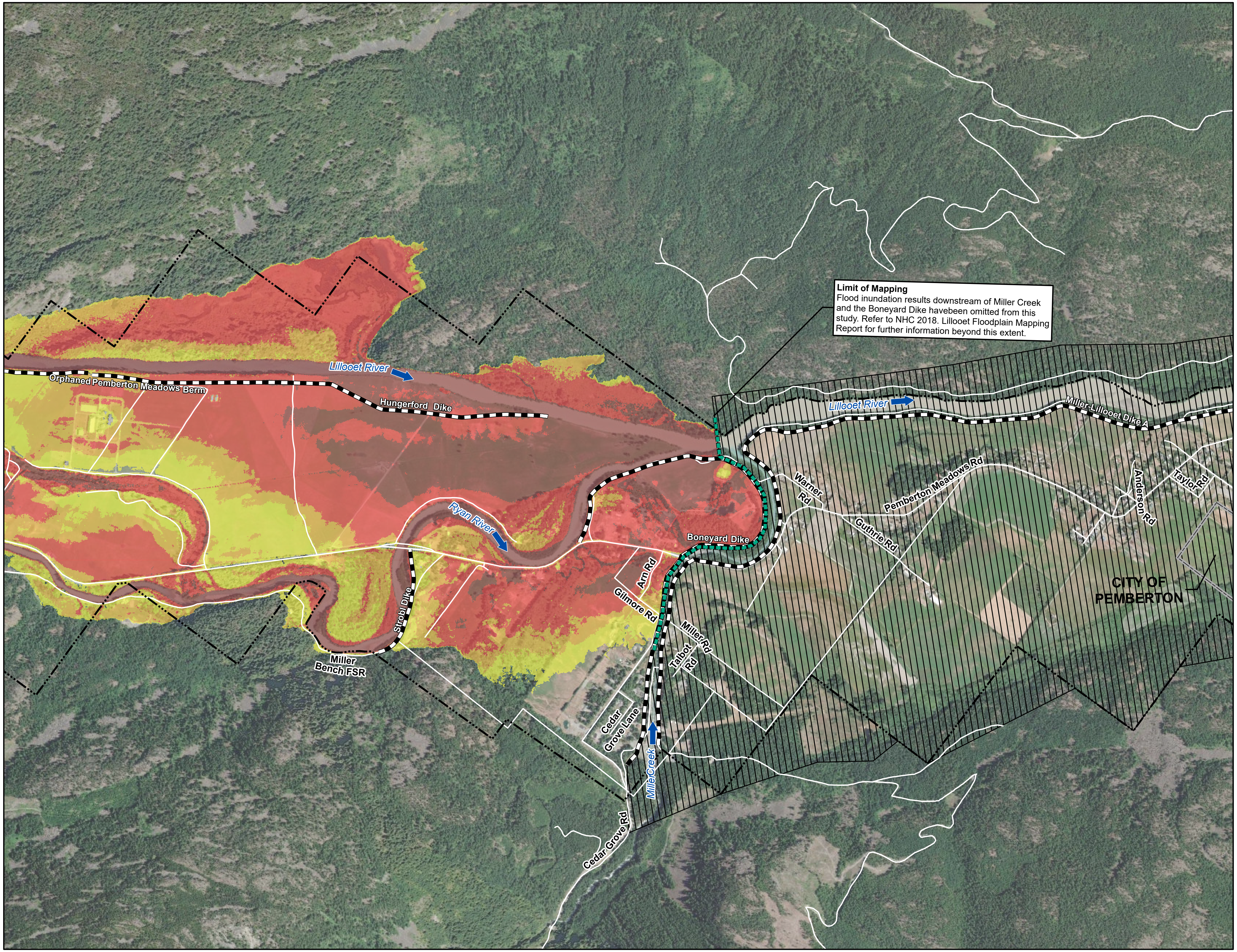
PEMBERTON VALLEY DYKING DISTRICT
RYAN RIVER MODELLING

FLOOD HAZARD RATING
100 -YEAR RYAN RIVER EVENT

SHEET 2 of 3

RLM, \\mainfile-van\Projects\Active\3006954 Ryan River modelling\95 GIS\3006954_RLM_RyanRiver_HazardandDepthMaps1.aprx



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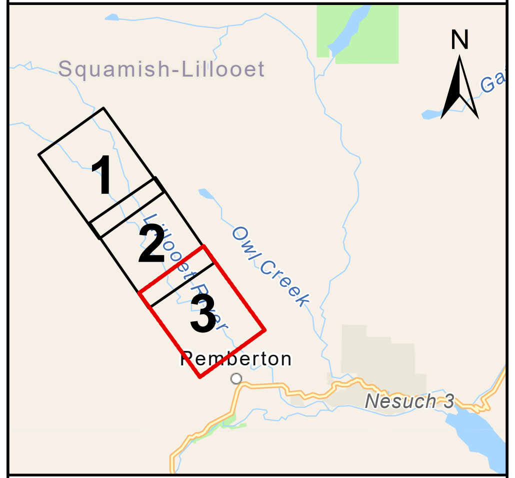

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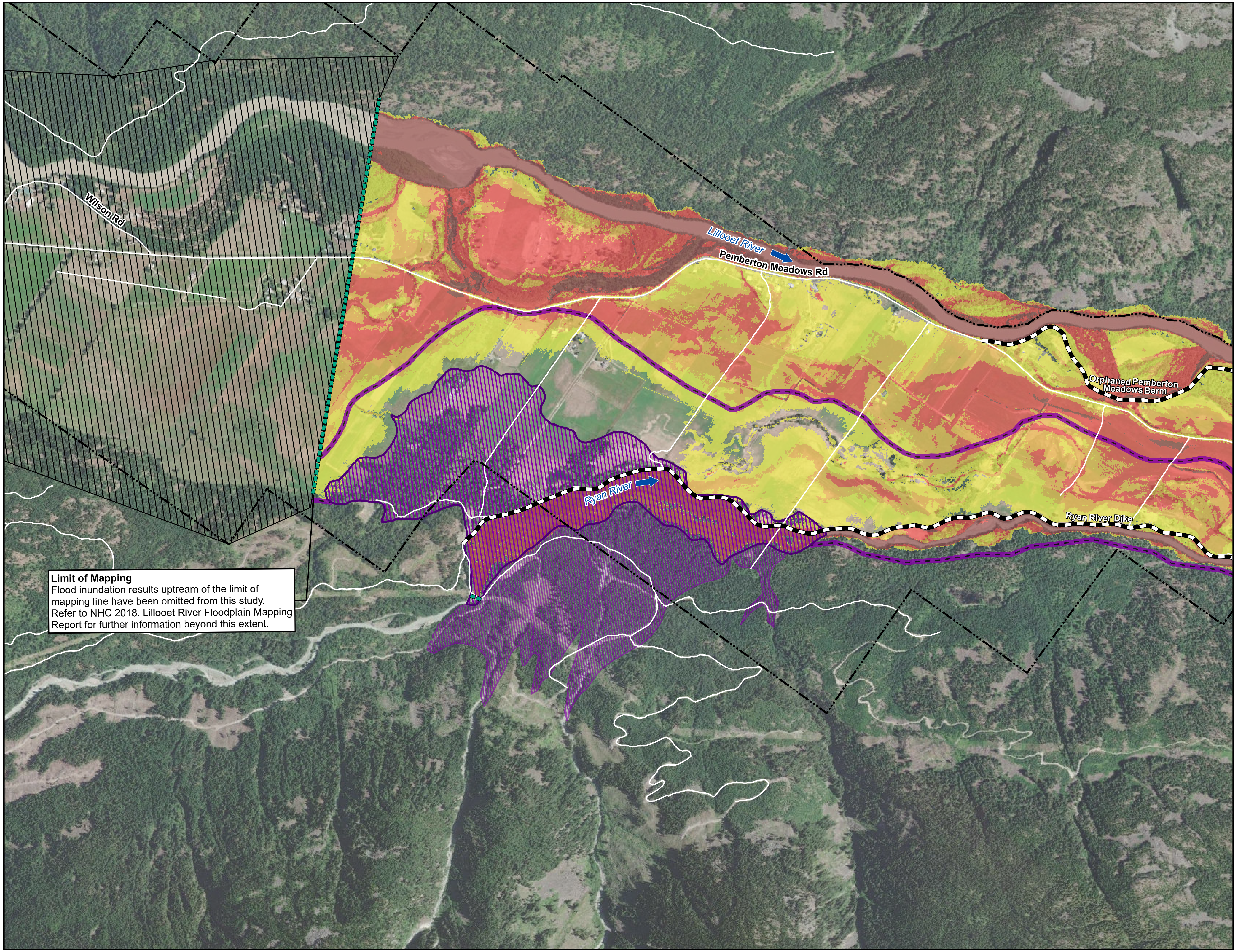
PEMBERTON VALLEY DYKING DISTRICT
RYAN RIVER MODELLING

FLOOD HAZARD RATING
100 -YEAR RYAN RIVER EVENT

SHEET 3 of 3



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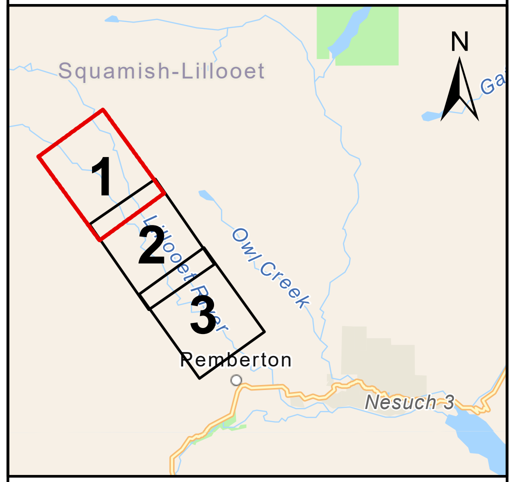

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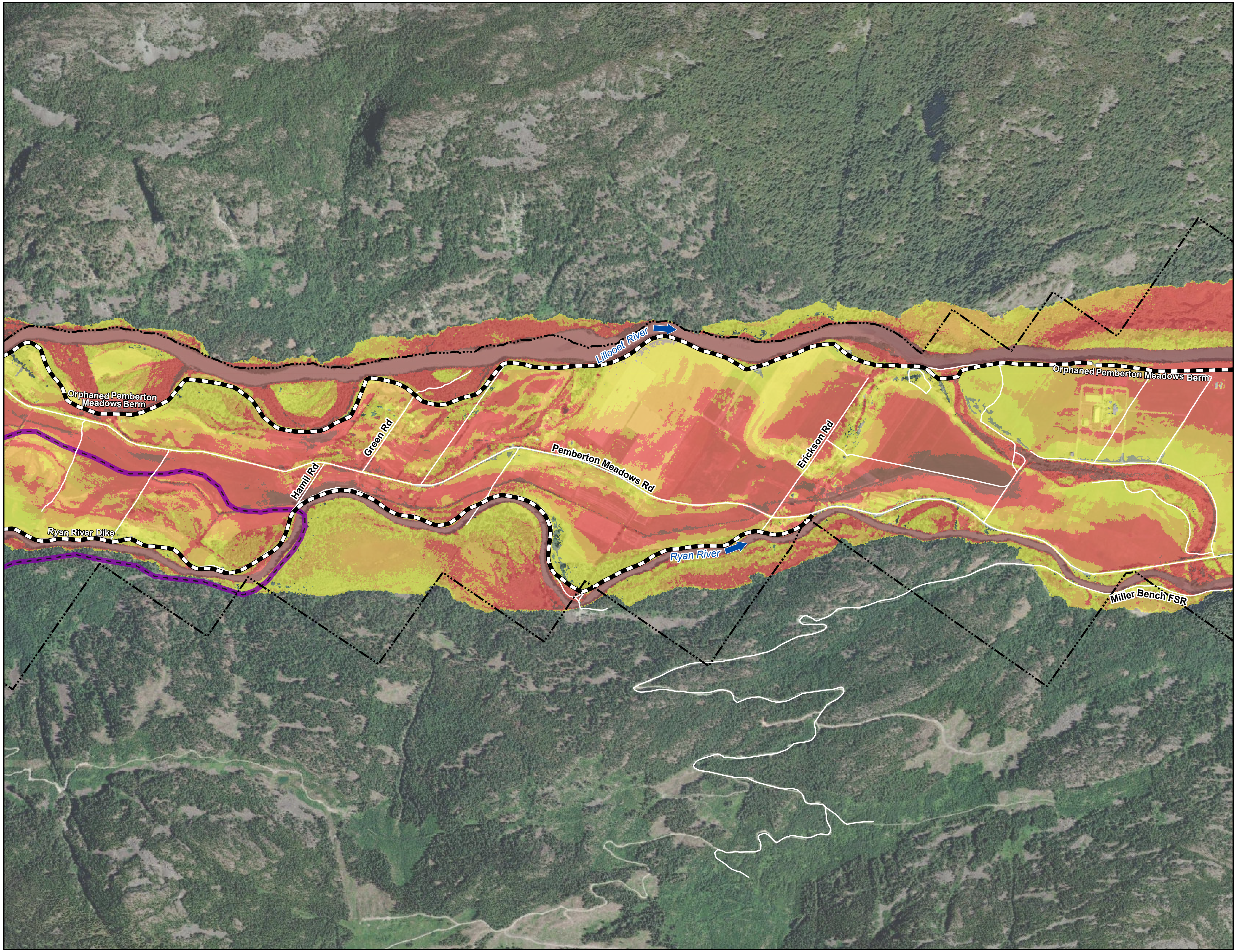
PEMBERTON VALLEY DYKING DISTRICT
RYAN RIVER MODELLING

FLOOD HAZARD RATING
200 -YEAR RYAN RIVER EVENT

SHEET 1 of 3



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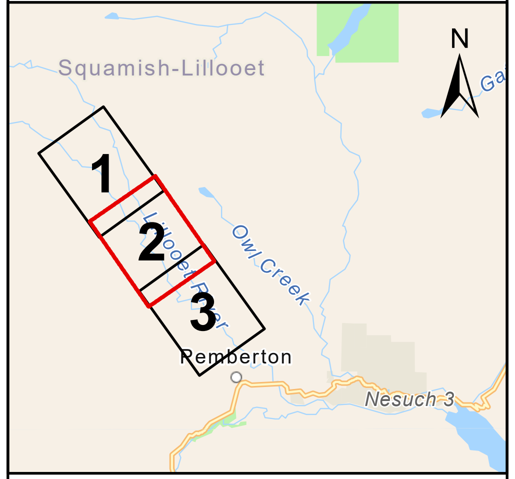

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FLOOD HAZARD RATING
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SHEET 2 of 3

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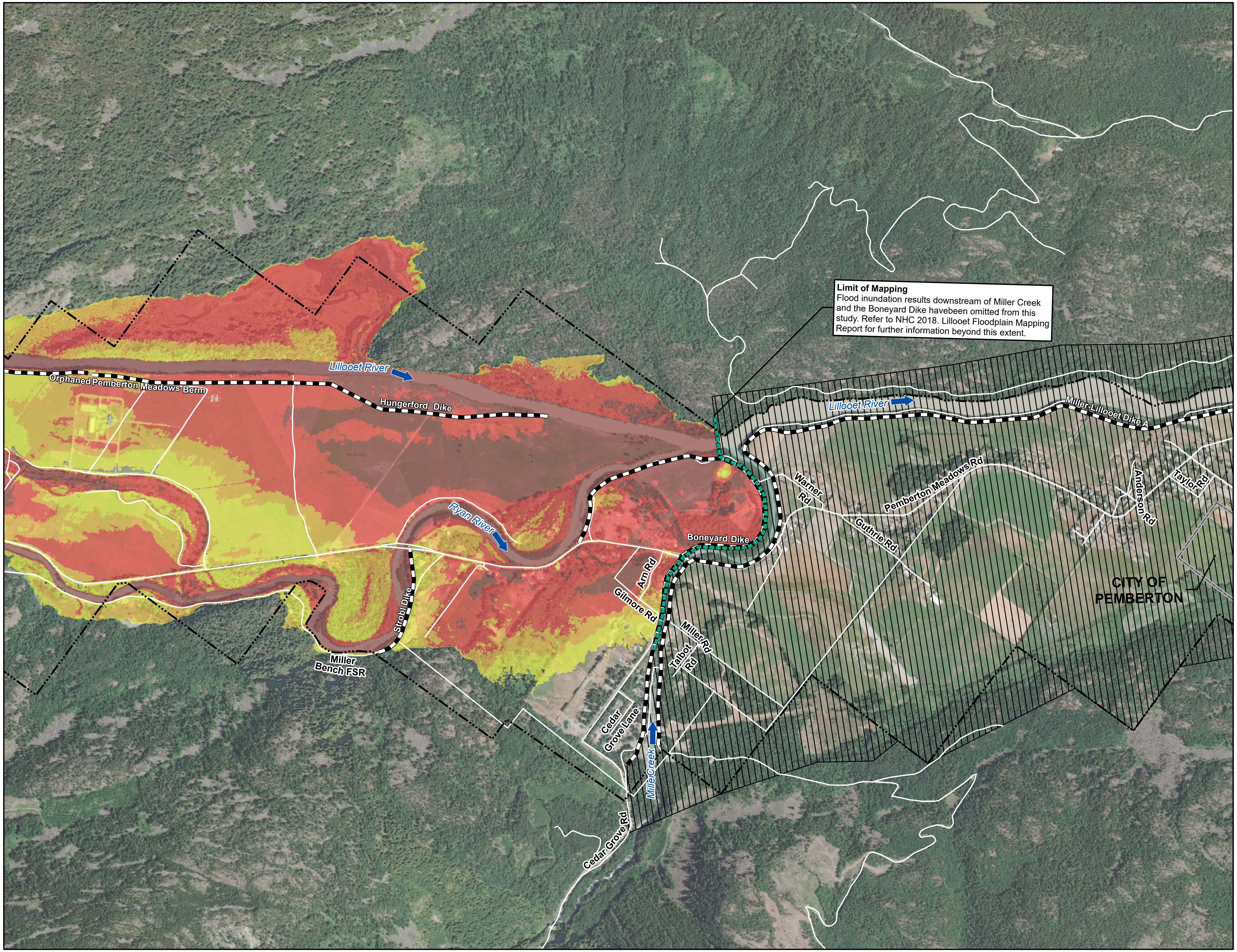

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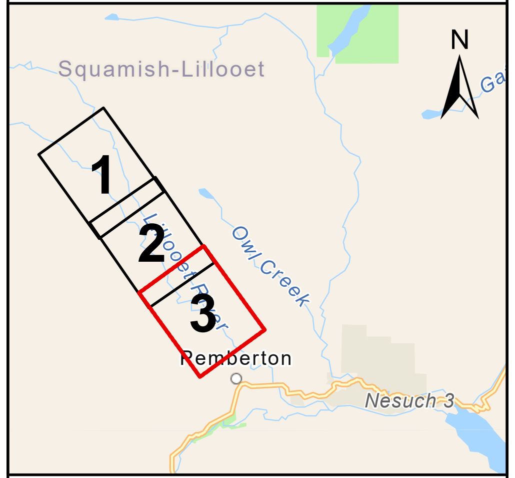

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