FORT MACLEOD
FLOOD HAZARD STUDY

FINAL REPORT

Prepared for:

Alberta Environment and Parks
River Engineering and Technical Services
Edmonton Alberta

20 December 2022

NHC Ref. No. 3004660

northwest hydraulic consultants
water resource specialists

Classification: Public

FORT MACLEOD FLOOD HAZARD STUDY

FINAL REPORT

Prepared for:

Alberta Environment and Parks
River Engineering and Technical Services
Edmonton, Alberta

Prepared by:

Northwest Hydraulic Consultants Ltd.
North Vancouver, British Columbia

20 December 2022

NHC Ref No. 3004660

Report prepared by:

Vanessa Bennett, MASc. P.Eng. (BC)
Hydrotechnical Engineer

Report reviewed by:

Robyn Andrishak, M.Sc., P.Eng.
Principal

DISCLAIMER

This report has been prepared by Northwest Hydraulic Consultants Ltd. for the benefit of Alberta Environment and Parks for specific application to the Fort Macleod Flood Hazard Study (Oldman River and Willow Creek). The information and data contained herein represent Northwest Hydraulic Consultants Ltd. best professional judgment in light of the knowledge and information available to Northwest Hydraulic Consultants Ltd. at the time of preparation and was prepared in accordance with generally accepted engineering practices.

Except as required by law, this report and the information and data contained herein are to be treated as confidential and may be used and relied upon only by Alberta Environment and Parks, its officers and employees. Northwest Hydraulic Consultants Ltd. denies any liability whatsoever to other parties who may obtain access to this report for any injury, loss or damage suffered by such parties arising from their use of, or reliance upon, this report or any of its contents.

CREDITS AND ACKNOWLEDGEMENTS

Northwest Hydraulic Consultants Ltd. (NHC) would like to express appreciation to:

River Engineering and Technical Services Section
Environmental Knowledge and Data Integration Branch
Alberta Environment and Parks (AEP)

for initiating this project, making available background information and providing advice and support throughout the project. The key AEP representative that supported the project is:

- James (Jim) Choles, M.Sc. P.Eng., CFM   River Hydraulics Engineer

The following NHC personnel were part of the study team and participated in the survey, creation and calibration of the hydraulic model, and mapping components of the study.

- Dale Muir, M.Eng. P.Eng.   Project management and technical support
- Robyn Andrishak, M.Sc., P.Eng.   Technical support and review
- Vanessa O'Connor, M.Eng., P.Eng.   Technical support and review
- Vanessa Bennett, MASc, P.Eng.   Project engineering and modelling
- Dr. Can Hua (Ken) Zhao, PhD., P.Eng.   Hydrology review
- Makamum Mahmood, M.Eng., P.Eng.   Hydrology
- Sarah North, GISP   Spatial data and mapping lead
- Jerry Yan, EIT   GIS support
- Ken Roy   Survey lead
- Jordan Morgenstern   Survey

EXECUTIVE SUMMARY

Fort Macleod is located in southeastern Alberta along the banks of the Oldman River and near the confluence of Willow Creek and the Oldman River. The Oldman River has experienced large floods in the recent past, including 1975, 1986, 1991, 1995 and 2013. Through a competitive tender, Alberta Environment and Parks (AEP) retained Northwest Hydraulic Consultants Ltd. (NHC) to assess and identify flood hazards along the Oldman River and Willow Creek through the Town of Fort Macleod and the adjacent areas of the Municipal District of Willow Creek.

The study was done according to Flood Hazard Identification Program Guidelines, incorporating technical changes implemented in 2021 regarding how floodways are mapped in Alberta. The overall objectives of the study are to enhance public safety and to reduce potential future flood damages and disaster assistance costs.

The Oldman River Flood Hazard Study was divided into six components. This report summarizes the work of i) survey and base data collection, ii) open water hydrology, iii) open water hydraulic modelling, iv) open water flood inundation mapping, and v) design flood hazard mapping; the final component being documentation.

NHC surveyed the channels and then used this data in combination with LiDAR and digital terrain model (DTM) provided by AEP. Based on this data, NHC developed a numerical hydraulic model using HEC-RAS. The model was developed as a one-dimensional (1D) flow model. Willow Creek and Oldman River channel have complex overbank flow. This multidirectional flow is challenging to representatively simulate with a 1D model. Therefore, a 2D hydraulic model was developed and calibrated prior to the 1D model to inform the development and calibration of the 1D model. Model results were calibrated using the largest of recently observed floods (1995) and validated against other observed floods. Results from the calibrated and validated model were then used as the basis for floodplain map generation. As is standard for AEP, floodway and flood fringe zones were delineated on the mapping.

Both the Oldman River and Willow Creek are regulated with numerous dams and diversions located upstream of the study. An *open water hydrology assessment* was conducted to determine the naturalized flows, that is the flow as if the channels were not regulated. This assessment used a diverse range of regional gauges, as data from local gauges was limited in record length and confidence in the flow data; primarily due to variable channel morphology and the resulting stage-discharge relationship. The assessment concluded with a frequency analysis to derive steady state daily and instantaneous maximum flows for a range of average return periods.

Using the model and the determined flows, water surface profiles were prepared for the 2-, 5-, 10-, 20-, 35-, 50-, 75-, 100-, 200-, 350-, 500-, 750-, and 1000-year open water flood frequency return period discharges. These profiles showed that the road and rail deck elevations for bridges crossing the Oldman River are above the 1000-year flood level, but the Highway 2 bridge and the rail bridge lower chords are under water for flows that exceed the 75-year. The approach roads for these two bridges and the Highway 811 crossing are inundated at lower return periods (20-year). On Willow Creek, the Highway 811 bridge is not overtopped but the low chord of the bridge is under water for events in excess of the 100-year flow and the approach road from the north is inundated at flows greater than the 50-year.

Based on the available data, calibration results, and sensitivity analysis, the open water HEC-RAS hydraulic model produces reliable water levels throughout the study reach for a wide range of discharges up to the 1000-year return period event. The model includes all pertinent physical features and the most up-to-date bathymetry and terrain data available as at the time of writing of this report. As such, the calibrated hydraulic model is considered appropriate for open water flood inundation map production.

The open water flood inundation maps and flood hazard maps provide information that can be used by provincial and local authorities to assist in emergency preparedness planning for future flood events. The flood hazard maps delineate the flood fringe, high hazard flood fringe, and the floodway which helps identify the properties most affected by deep water or high velocity. There are no flood control structures in the study reach for this project. However, some residential and non-residential structures may be impacted by the Oldman River floods that have return periods of 10-years and greater.

This entire document should be read and understood prior to applying the resulting model or simulation results. Residual risk exists beyond the presented results; more extreme (less frequent) events can occur and channel, watershed, and climatic conditions can change with time.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PHOTOGRAPHS

LIST OF ACRONYMS

ADCP	acoustic Doppler current profiler
ADV	acoustic Doppler velocimeter
AENV	Alberta Environment (currently part of AEP)
AEP	Alberta Environment and Parks
ASCM	Alberta Survey Control Monuments
CGVD28	Canadian Geodetic Vertical Datum of 1928
CP	control point
CSRS-PPP	Canadian Spatial Reference System Precise Point Positioning
DFO	Fisheries and Oceans Canada (Department of Fisheries and Oceans)
DTM	digital terrain model
ECCC	Environment and Climate Change Canada
FHIP	Flood Hazard Identification Program
LNID	Lethbridge Northern Irrigation District
MAE	mean absolute error
NAD83	North American Datum1983
NHC	Northwest Hydraulic Consultants Ltd.
RCP	Representative Concentration Pathway
SPBM	semi-permanent benchmarks
SSR	South Saskatchewan River
TIN	triangular irregular network
WSC	Water Survey of Canada
WSE	water surface elevation
3TM	three-degree Transverse Mercator

1 INTRODUCTION

1.1 Study Background

Fort Macleod is a town located in southern Alberta 40 km west of Lethbridge. The community is located along the banks of the Oldman River, immediately upstream of the confluence of Willow Creek and the Oldman River. This study, the Fort Macleod Flood Hazard Study, provides an assessment of the flood hazards along the Oldman River and Willow Creek within the Town of Fort Macleod and the surrounding area of the Municipal District of Willow Creek.

A provincial flood hazard study for Fort Macleod was completed in 1991 by AEP, formerly known as Alberta Environment (AENV). The present study provides an update of this work to account for records of flow since the previous study, current channel and floodplain geometry, and contemporary methods of data collection and analysis. The current study also incorporates a larger study area, most notably the inclusion of Willow Creek.

1.2 Study Objectives

This study was completed under the provincial Flood Hazard Identification Program (FHIP) guidelines, incorporating technical changes implemented in 2021 regarding how floodways are mapped in Alberta. This study and its results directly support the program purpose of enhancement of public safety and reduction of future flood damages through the identification of flood hazards.

The specific objective of the study is the production of a calibrated hydraulic model, flood inundation maps, floodway criteria maps, flood hazard maps, and a report describing the development and limitations of these deliverables. The scope of the work, or tasks to complete the work, includes:

1. Survey and base data collection;
2. Open water hydrology assessment;
3. Open water hydraulic modelling;
4. Open water flood inundation mapping;
5. Design flood hazard mapping;
6. Reporting and documentation; and
7. Project management.

The reference to open water, explicitly excludes the study of winter conditions in which the channel is substantially covered by ice.

1.3 Study Area & Reach

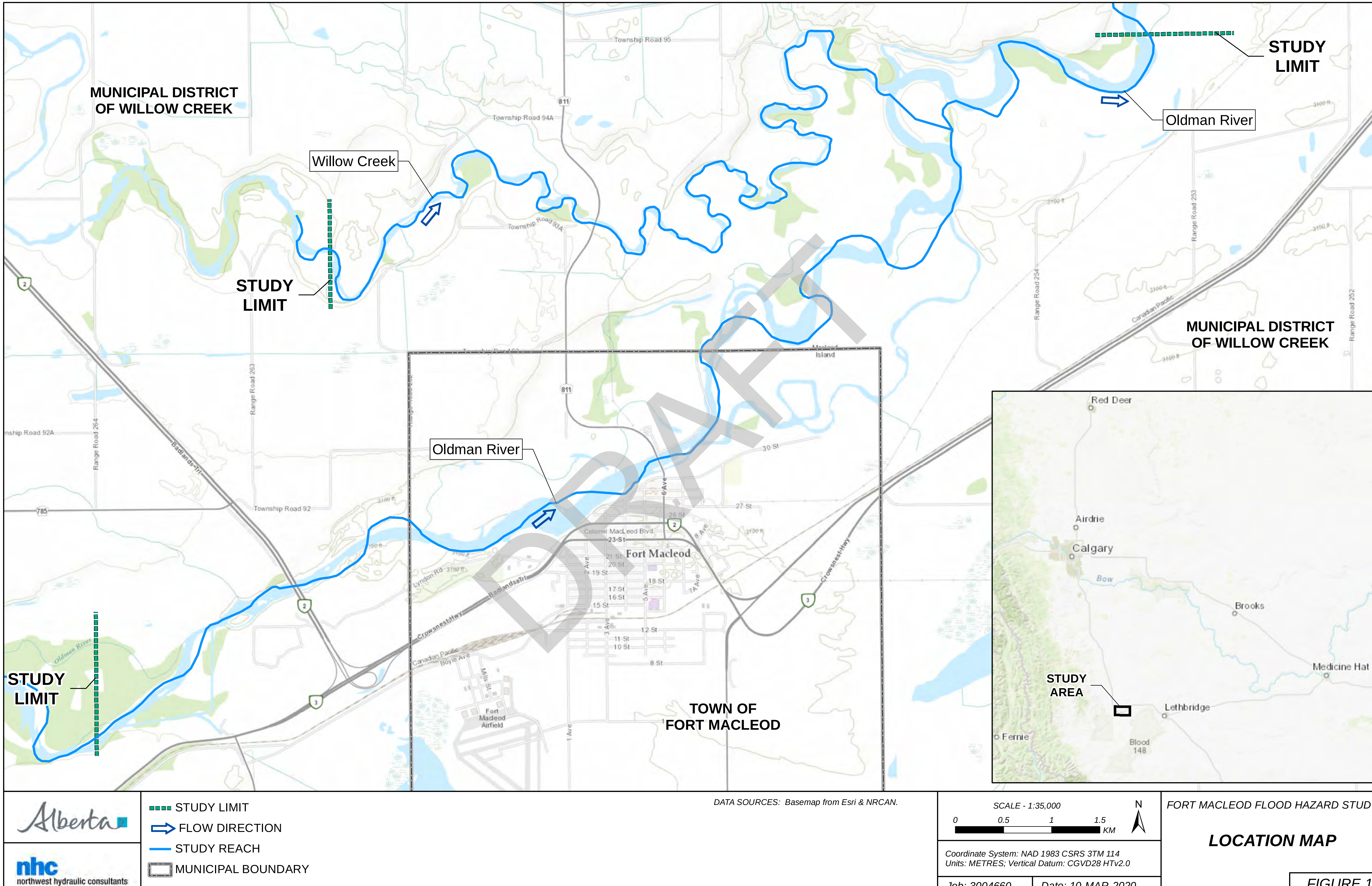
The Oldman River originates in the Rocky Mountains of southwestern Alberta, flowing easterly for approximately 360 km through the Foothills and Grassland Natural Regions where it confluences with the Bow river to form the South Saskatchewan River east of Lethbridge. The contributing drainage area near the mouth is approximately 27,500 km^2 according to the Water Survey of Canada (WSC). This river flood hazard study covers an 18.6 km long reach of the Oldman River near the Town of Fort Macleod, beginning from about 7 km upstream of the town and extending downstream approximately 11 km. The lower 15 km of Willow Creek, which confluences with the Oldman river in the lower portion of the study reach (**Figure 1**).

Willow Creek originates further north in the Rocky Mountains, draining an area of approximately 2,530 km^2, and flows in a southeasterly direction to join the Oldman River about eight kilometers downstream of Fort McLeod. Willow Creek flows are affected by the Chain Lakes project on its main stem and, to a lesser extent, by the Pine Coulee project located near Stavely. These two projects are located approximately 170 km and 130 km upstream of the mouth of Willow Creek.

The Oldman River is regulated by the Oldman Dam, completed in 1991 and located approximately 70 km upstream of Fort Macleod. Flow in the river is also modified by the Lethbridge Northern Irrigation District (LNID) diversion, which was constructed between 1919 and 1924 to divert water from the Oldman River roughly 40 km downstream of the dam for irrigation purposes. Flooding in Oldman River and Willow Creek usually occurs in late May or June as a result of snowmelt augmented by intense rainfall.

WSC monitors flows in the Oldman River downstream of the Oldman Dam at Brocket (WSC Station 05AA024). Between this station and Fort Macleod, there are two major tributaries contributing to the Oldman River: Beaver Creek and Pincher Creek. The LNID diversion is located downstream of these two tributaries and upstream of Fort Macleod.

Further description and discussion of the contributing watershed and naturalized hydrology is presented in **Appendix E**.



Classification: Public

2 SURVEY & BASE DATA COLLECTION

Geometric data used for this study was collected primarily through ground survey and aerial LiDAR collection. LiDAR was provided by AEP and is described later in this document under **Section 4.1 Hydraulic Modelling, Available Data**. This section of the report is limited to data collected by NHC as part of the current project.

2.1 Procedures and Methodology

The objective of the ground survey program was to survey channel cross sections along the study reach to support development of the hydraulic model. Before commencement of the work, a survey plan was submitted to and approved by AEP. A site inspection was conducted 24 April 2019 by AEP and NHC to inspect the study reach, identify specific locations that would require ground survey, discus approach for representing various flow paths in the model, and to gain an understanding of the local terrain and how it is expected to be affected by flood flows. The survey plan was revised following the site inspection and ground survey initiated. The ground survey program was predominantly conducted between 29 April and 10 May. Flow was low during the inspection and the survey; with much of the upstream flow diverted by LNID. In attempt to capture higher flows, additional survey data was collected 05 to 06 June 2019.

Ground positioning for the survey was measured using Real Time Kinetic (RTK) Global Navigation Satellite Systems (GNSS). A combination of Trimble, Topcon, and Sokkia GNSS receivers were used for the duration of the survey. Surveys were conducted from the boat using a Sonarmite M8 Single frequency echo sounder that measured the water depth from the bottom of the transducer (in areas generally deeper than 0.3 m). The position and elevation of the transducer was measured using the GNSS receiver that was mounted directly above the transducer. The elevation of the riverbed was derived from depth soundings by subtracting depth from the elevation of the transducer. A GNSS receiver was also attached to a survey rod to collect data located along the channel banks, dry bars, and in wet portions of the channel where the depth was too shallow to operate the echo sounder. The channel banks and a portion of the overbanks were surveyed to ensure sufficient overlap with the digital terrain model (DTM) generated from and provided with the LiDAR.

2.1.1 Coordinate System and Datum

Horizontal positions were referenced to the three-degree Transverse Mercator (3TM) projection with a central meridian of 114°W. The 3TM projection is part of the Canadian Spatial Reference System (CSRS) North American Datum of 1983 (NAD83) which is a three-dimensional grid on which the position of an object or feature can be precisely defined. Orthometric elevations are based on the Canadian Geodetic Vertical Datum of 1928 (CGVD28) and HT2.0 hybrid geoid model.

2.1.2 Control Network

A control point (CP) network was established based on long-term GNSS observations and the Canadian Spatial Reference System Precise Point Positioning (CSRS-PPP) service provided by Natural Resources Canada (2020). Two Alberta Survey Control Monuments (ASCM) were used in the CP network along with three semi-permanent benchmarks (SPBM) established by NHC for the survey program. The SPBM's consisted of 0.9 m long rebar with an aluminum cap. A list of CP coordinates is provided in **Table 1**.

CP coordinates were determined by simultaneously logging static GNSS positions for at least one hour at two to four CPs. Static baselines were post-processed and control network adjustments were performed using Trimble Business Center software. One CP having the smallest reported CSRS-PPP coordinate error estimates was used to constrain and minimize the errors in the network adjustment (refer to **Appendix A**). CSRS-PPP and ASCM coordinates for CPs that are included within the NAD83 CSRS subset data published by AEP (2019), were used to validate the adjusted CP coordinates. The baseline processing, network adjustment, and CSRS-PPP reports are provided in **Appendix A**.

Table 1 Control point summary

Point Name	Type	Easting (m)	Northing (m)	Elevation (m)
ASCM 79343	ASCM	42325.303	5511961.984	957.291
ASCM 293795	ASCM	45807.627	5510492.167	935.488
NHC1	SPBM	39984.198	5510008.909	955.171
NHC2	SPBM	43936.49	5511344.022	935.967
NHC3	SPBM	47993.993	5513630.303	947.577

Easting, northing, and elevation error estimates were computed in Trimble Business Center for each of the CPs in the control network. The CPs were adjusted to maintain a confidence level of 95% across the survey. The adjusted values are provided in **Table 2**. The coordinates for ASCM 79343 were constrained (i.e. fixed) to their reported CSRS-PPP values. The largest horizontal and vertical errors resulting from network adjustment were +0.024 m and +0.048 m, respectively.

1. After post processing using both CSRS-PPP Coordinates and a network adjustment; the horizontal and vertical residuals of the surveyed control network coordinates were calculated and are provided in **Table 3.**

A comparison between the surveyed CP coordinates and published ASCM coordinates is provided in **Table 4.** The mean of the elevation offsets is -0.006 m, which indicates good vertical agreement between the control network and local ASCMs.

Table 2 Control point summary, positions adjusted for network error confidence of 95%

Point Name	Easting (m)	Northing (m)	Elevation (m)
ASCM79343	42325.302	5511961.984	957.309
ASCM293795	45807.626	5510492.167	935.506
NHC1	39984.197	5510008.909	955.189
NHC2	43936.489	5511344.022	935.985
NHC3	47993.992	5513630.303	947.595

Notes

2. ASCM 293795 Coordinate was constrained in the network adjustment.

Table 3 Comparison between surveyed control point coordinates and reported CSRS-PPP values

Point Name	Residuals (Surveyed Minus CSRS-PPP)		
	Easting (m)	Northing (m)	Elevation (m)
ASCM79343	0	0	0
ASCM293795	-0.001	0	0.018
NHC1	-0.012	0.024	0.008
NHC2	0.009	0.013	0.048
NHC3	-0.005	0.008	-0.013

Table 4 Alberta Survey Control Monument coordinate offsets

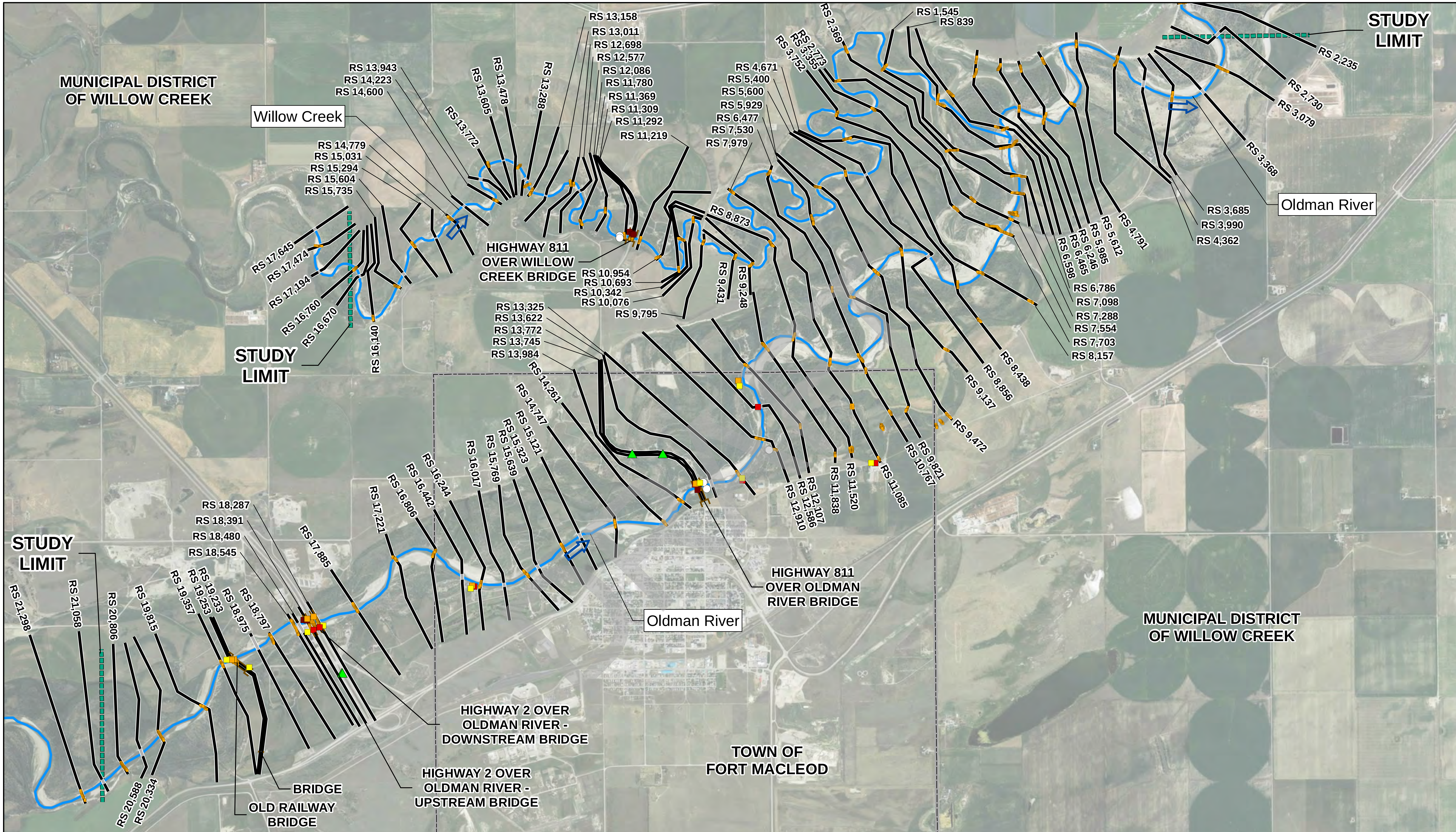
ASCM Number	GPS Measurement Mode	Offset (Surveyed Minus Published)		
		Easting (m)	Northing (m)	Elevation (m)
ASCM79343	Static	-0.116	-0.009	-0.001
ASCM293795	Static	0.014	0.057	0.041

2.2 Cross Sections

River cross section locations were selected to ensure accurate representation of the channel hydraulics in the hydraulic model. That is, sections for survey were located to provide representative geometry and adequately capture changes in channel width and slope. The cross section survey was divided into reaches corresponding to the channel being surveyed. During the planning process for the survey, each cross section was assigned a number in an effort to organize the cross sections sequentially on each channel. A total of 89 cross sections were surveyed. A summary of the surveyed cross sections is listed in **Table 5** and graphically presented in **Figure 2**. Further information is provided in **Appendix B**.

Table 5 Summary of surveyed cross sections

Reach	Reach Length (km)	No. of Cross Sections	Average Spacing (m)	Minimum Spacing (m)	Maximum Spacing (m)
Oldman River - KM 000	6,711	13	526	132	879
Oldman River - KM 006	16,798	39	382	20	946
Willow Creek - KM 000	17,658	37	462	17	1,052



STUDY LIMIT
FLOW DIRECTION
STUDY REACH
MUNICIPAL BOUNDARY
CROSS SECTION SURVEY POINT
SURVEYED CROSS SECTION
INTERPOLATED CROSS SECTION
MODELLED CULVERT
BRIDGE
SURVEY DISCHARGE MEASUREMENT LOCATION
HIGHWATER MARK LOCATION BY YEAR
1986 1991 1995 2013

DATA SOURCES: Basemap from Esri World

SCALE - 1:35,000
0 0.5 1 1.5 KM
N

Coordinate System: NAD 1983 CSRS 3TM 114
Units: METRES; Vertical Datum: CGVD28 HTv2.0

Job: 3004660
Date: 16-APR-2020

FORT MACLEOD FLOOD HAZARD STUDY

CROSS SECTION AND HYDRAULIC STRUCTURE LOCATIONS

FIGURE 2

Alberta
nhc northwest hydraulic consultants

MSN_\\manfile-van\Projects\Active\3004660 Fort Macleod FHS\95 GIS\3004660_MSN_Fig_T6_SectionsAndStructures3.mxd

Classification: Public

2.3 Hydraulic Structures

The hydraulic structures measured as part of the survey program consist of 4 bridges and 4 culverts. The locations of the hydraulic structures are shown in **Figure 2**. During the survey, the following data were collected at each bridge:

- span length;
- deck width;
- deck elevation;
- top of curb or solid guardrail elevation;
- low chord elevation;
- abutment shape, elevation, and description
- pier: number, width, type, shape, and location; and
- photographs of the bridge, banks.

Culvert information collected included:

- culvert type;
- shape;
- dimensions (diameter or span and height);
- length;
- entrance and exit condition;
- invert elevation (upstream and downstream);
- embankment slope and crest elevation (upstream and downstream); and
- photographs of the culvert.

Survey data for these structures have been assembled and provided as a digital study file.

Where available the collected survey data was expanded on using bridge drawings provided by Alberta Transportation. **Table 6** provides a list of the hydraulic structures included in this study and which drawings were available, further details are provided in **Appendix C**. River stationing in the table refers to the stationing applied in the hydraulic model, with 0 m being the downstream most station.

Table 6 Hydraulic structure survey summary

River Station (m)	Structure Type	Bridge File Number	Description	Drawings Provided
Oldman River				
13,756	Bridge	01097	Highway 811 bridge	Yes
18,362	Bridge	00756N and 00756S	Highway 2 bridge	Yes
19,248	Bridge	-	Abandoned railway bridge (main river)	No
19,248	Bridge	-	Abandoned railway bridge (side channel)	No
13,756	Culvert	02062	Highway 811 culvert	No
13,756	Culvert	02063	Highway 811 culvert	No
18,362	Culvert	00509	Highway 2 culvert	No
18,362	Culvert	00509	Highway 2 culvert	No
Willow Creek				
11,301	Bridge	00992	Highway 811 bridge	Yes

2.4 Flood Control Structures

FHIP guidelines describe flood control structures, such as dikes, as "walls constructed to prevent water from rivers or lakes from flooding surrounding lands. Often [flood control structures] are earth berms but can also be constructed of concrete and other materials." Dedicated flood control structures typically require regulatory approval prior to construction, receive routine inspection and maintenance, and are officially recognized by AEP and local authorities as flood control infrastructure. Based on site inspection and communications with AEP, the Town of Fort Macleod, the Municipal District of Willow Creek, and Alberta Transportation, no flood control structures exist within the study area.

Road and railway embankments or berms may perform as flood barriers and affect flood inundation but may not be classified as dedicated flood control structures. These structures are classified as non-dedicated flood control structures. The following were identified as non-dedicated flood control structures:

- Girl Guide Camp Road (left bank of Oldman River);
- Daisy May Campground berm (right bank of Oldman River);
- Water treatment and new intake site road (right bank of Oldman River);
- Highway 2 embankment.

2.5 Other Features

2.5.1 Discharge Measurements

Discharge measurements, often referred to as flow measurements, were collected for use in development and verifying the hydraulic model. Specific application for the measurements include correlating flow with surveyed water levels and to determining flow distribution at flow confluence and splits, such as the irrigation channel that initiates 700 m downstream of the Highway 811 bridge on the right bank of the Oldman River.

Locations of the discharge measurements are shown in **Figure 2**. The measurements were collected 21 June 2019 between 8:00 am and 12:30 pm. Discharge was measured using a boat-mounted Sontek M9 RiverSurveyor acoustic Doppler current profiler (ADCP) which has an accuracy of ±0.25% of measured velocity and can provide measurements in depths ranging from 0.06 m to 40 m. Discharges on Willow Creek and the irrigation channel were measured with a FlowTracker Handheld acoustic Doppler velocimeter (ADV) which has an accuracy of ±1%. Discharges were measured using WSC standard procedures. The measured discharges are summarized in **Table 7**.

Table 7 Discharge measurement summary

River	Location	River Station (m)	Discharge (m^3/s)	Water Elevation (m)
Oldman R.	Hwy 811 Bridge	13,755.91	25.3	935.07
Oldman R.	Irrigation Channel	12,988.79	1.9	933.37
Oldman R.	Confluence with Willow Cr.	2,049.25	26.3	918.76
Willow Cr.	Hwy 811 Bridge	11,300.75	2.5	933.00

The preliminary discharge for the Oldman River at Fort Macleod gauge reported by the Government of Alberta for 21 June 2019 between 11:00 am and 12:00 pm fluctuated around 24 m^3/s. The measured discharge at Highway 811 bridge was within 1.0 m^3/s of this record (within 5%). Similarly, a difference of 0.2 m^3/s (within 8%) exists between the discharge measured on Willow Creek and the corresponding reported value for the gauge on Willow Creek at Highway 811 (observed at 2.7 m^3/s).

2.5.2 Site Photographs

Appendix D provides annotated reach representative photographs obtained during the site inspection and survey program. The time and other metadata information are imbedded in the electronic images.

2.5.3 Aerial Imagery

Aerial imagery was acquired for AEP by OGL Engineering Ltd. on 26 July 2019 (OGL Engineering, 2019). Fully processed orthophoto mosaics were provided to NHC by AEP on 04 February 2020. This data was used in preparation of the mapping products.

2015 orthophoto imagery was obtained from the Alberta Municipal Data Sharing Partnership. This data was used to define flow roughness and other features in the development of the hydraulic model, since the 2019 data was not available earlier.

2.5.4 Base Mapping Features

The following data sets were obtained or created to support modelling and mapping during the study:

- Administrative –town and municipal district boundaries from AltaLIS Base Features;
- Transportation – road and rail networks from Alberta Municipal Data Sharing Partnership, AltaLIS Base Features, National Road Network, and National Railway Network;
- Key places – place points with names from Alberta Municipal Data Sharing Partnership;
- Land cover – digitized by NHC based on 2015 orthophotography;
- Hydrography – stream networks from AltaLIS Base Features;
- Historic flood reports and mapping – from Alberta Flood Hazard Mapping GIS Data Archive.

2.5.5 Survey and DTM Comparison

There were 9 locations chosen within the DTM boundaries that were expected to be clear and accurate readings from the LiDAR (street crossings, parking lots, and open areas with little obstruction or vegetation). These locations were surveyed during the ground survey and the data compared to the DTM. A summary of the comparison can be seen in **Table 8**. The root meet square (RMS) of the difference is 0.047 m.

Table 8 Survey and DTM comparison

Surveyed Elevation (m)	DTM Elevation (m)	Observed Difference (m)
957.67	957.71	0.04
939.08	939.12	0.05
937.98	938.03	0.06
959.41	959.48	0.07
936.47	936.52	0.04
951.53	951.60	0.07
952.97	953.01	0.04
971.79	971.81	0.02
964.24	964.25	0.01

3 FLOOD HYDROLOGY

3.1 Flooding History

3.1.1 General information

A description of local past floods has been prepared to provide context for this study and hydraulic model calibration and validation. This documentation includes observations and records for both open water and ice jam related flooding.

3.1.2 Open Water Floods

Historic floods, with respect to hydrology in this report, refer to major floods that occurred prior to the period of hydrometric data collection and systematic recording of water level and discharge. The magnitude of historic floods can be estimated based on observations or even anecdotal information.

Fort Macleod has experienced numerous floods over the century and half since it was established. The town was established around 1874 on a peninsula of the Oldman River and was promptly flooded within a few years. It was relocated to higher ground shortly after in 1884 leaving only the Old Fort Archaeological Site (Provincial Archives of Alberta, 1876). There are several records of early flooding in Fort Macleod; previous studies identified the occurrence of historic floods along the Oldman River in 1897, 1899, 1902, and 1908 (AENV, 1991). Unfortunately, no records or information recording magnitude of the events have been found. Several pictures of the flood from 1902 in the Glenbow Museum Archive show extensive flood waters from the Oldman River (Glenbow Museum Archive, 1902). There is a picture of the Highway 811 bridge over the Oldman River washed downstream as well as the Canadian Pacific Railway tracks wiped out and only held together by the welded rails. The Galt Museum and Archives also has several images that appear to be from the same event showing extensive damage caused by the flood.

In 1883, the main channel of Oldman River bisected around an area which is still called Macleod Island (right side of channel 800 m downstream of Highway 811 bridge). By 1912 the river channel reformed as a single channel, leaving the side channel abandoned except for limited ponding and conveyance of overflows. The abandoned channel, located south of Macleod Island, has been turned into an irrigation channel. These channel changes likely occurred during a series of floods that occurred during those years (AENV, 1991). Further supporting occurrence of floods during this period, is reports of a major flood (estimated as a 150-year flood) occurrence, in 1908, at Lethbridge. Records were not kept at Fort Macleod at this time.

One of the largest floods on the Oldman River at For Macleod occurred in 1923. It had an estimated mean daily discharge of 1990 m^3/s (AENV, 1991). No highwater mark records are available. Subsequent floods occurred in 1942, 1948, 1953, and 1964. In 1975 a flood caused one death at Fort Macleod (Calgary Herald, 2013). Aerial imagery collected during the flood shows overland flooding from the Oldman River with water overtopping the north approach road of the Highway 811 bridge. Based on the photographs, relic overbank channels near the Willow Creek confluence were inundated with water passing over several farm fields. Additional floods in 1986 and 1991 were smaller, and few high-water marks were recorded.

The largest recorded flood on the Oldman River occurred in 1995. Most of the Oldman River valley was inundated with various residences in the floodplain flooded. Aerial imagery flown near the peak of the event shows extensive flooding with nearly the entire Willow Creek confluence inundated (AENV, 1995b). Water overtopped Highway 2 and Highway 811. There was significant erosion along the banks of the Oldman River and specifically around south abutment of the Highway 2 bridge (**Photo 1**) (Alberta Transportation, 1995).

The most recent floods, occurring 2005 and 2013, were also sizable flood events that caused erosion and local flooding near Fort Macleod. Neither was as high nor caused as much damage as the flood of 1995. Recent floods at Fort Macleod along the Oldman River are listed in **Table 9** along with associated daily flow, instantaneous peak flow, and approximate average return period (see **Appendix E** for more details).

There was no recorded flood history found for Willow Creek during this study.

Table 9 Estimated flow and return period of recent flood events, Oldman River at Fort Macleod

Year	Date	Max Daily Flow (m^3/s)	Peak Flow (m^3/s)	Approximate Return Period (year)
2013	6/21/2013	1,000[1]	1,180[2]	20
2005	6/8/2005	1,020[1]	1,204[2]	20
1995	6/7/1995	N/A	2,950[3]	200
1991	6/22/1991	363[4]	428[2]	2 – 5
1986	5/29/1986	329[4]	388[2]	2
1975	6/20/1975	1,230[4]	1,451[2]	35

Notes:
1. Data obtained from Oldman River at Highway 811 (05AB917) gauge.
2. Peak flow has been estimated based on instantaneous to daily peak discharge ratio of 1.18. See Open Water Hydrology Assessment for details (NHC, 2019).
3. From 1995 Flood Frequency Analysis for South Saskatchewan River Basin – Draft Report from AENV (1995a)
4. Estimated by routing the daily flows from Oldman River near Brocket (05AA024) to Fort Macleod with available tributaries and considering the irrigation diversions; no gauge correction was done.

Photo 1 Highway 2 erosion of right abutment, 1995 flood, north facing view (Alberta Transportation, 1995)

3.1.3 Ice Jam Floods

A number of flood events occurred within Fort Macleod as a result of ice jams during breakup. Information from these events are presented in the following paragraphs.

In 1972 there was an ice jam within Fort MacLeod's town limits (AENV, 1991). During this event, 365 m of Highway 811 was flooded to a depth as deep as 0.45 m. Overland flooding was extensive on the north side of the river including portions of the Girl Guide camp. In 1978, ice jam related flooding occurred during spring break-up and caused Highway 811 to close for a short time before the ice broke up.

February 1986, high atmospheric temperatures led to a rapid snowmelt and subsequent ice jam flooding along the Oldman River. Highway 811 was flooded but no residences were affected. The flood resulted in significant erosion along the banks of the Oldman River downstream of Highway 2. No ice jams floods have been reported in recent times.

3.2 Flood Frequency Analysis

3.2.1 Flood Frequency Flow Estimates

The regulated and naturalized flood frequency discharges for a range of return periods up to 1000 years was determined during the open water hydrology assessment. This assessment was documented and is attached as (**Appendix E**). The flood frequency flow estimates are provided in **Table 10, Table 11,** and **Table 12** for the Oldman River at Fort Macleod, Oldman River downstream of the confluence with Willow Creek, and for Willow Creek at Highway 811.

Table 10 Flood frequency estimates of natural/naturalized flows for Oldman River at Fort Macleod

Return Period (Years)	Annual Probability of Exceedance (%)	Peak Instantaneous Discharge (m^3/s)	
		Value	95% Confidence Limit
1000	0.1	4,850	3,660 - 6,880
750	0.13	4,450	3,380 - 6,240
500	0.2	3,920	3,010 - 5,410
350	0.29	3,500	2,720 - 4,770
200	0.5	2,910	2,300 - 3,880
100	1	2,300	1,860 - 2,980
75	1.3	2,080	1,690 - 2,660
50	2	1,790	1,480 - 2,250
35	2.9	1,560	1,300 - 1,940
20	5	1,250	1,060 - 1,510
10	10	920	800 - 1,080
5	20	649	576 - 743
2	50	353	316 - 394

Table 11 Flood frequency estimates of naturalized flows for Oldman River below Willow Creek

Return Period (Years)	Annual Probability of Exceedance (%)	Peak Instantaneous Discharge (m^3/s)	
		Value	95% Confidence Limit
1000	0.1	6,180	4,580 - 8,950
750	0.13	5,630	4,210 - 8,070
500	0.2	4,920	3,730 - 6,940
350	0.29	4,370	3,350 - 6,070
200	0.5	3,600	2,810 - 4,880
100	1	2,800	2,240 - 3,690
75	1.3	2,520	2,030 - 3,280
50	2	2,150	1,760 - 2,750
35	2.9	1,860	1,540 - 2,350
20	5	1,470	1,240 - 1,810
10	10	1,070	921 - 1,270
5	20	740	652 - 854
2	50	391	348 - 439

Table 12 Flood frequency estimates of naturalized flows for Willow Creek at Highway 811

Return Period (Years)	Annual Probability of Exceedance (%)	Peak Instantaneous Discharge (m^3/s)	
		Value	95% Confidence Limit
1000	0.1	1,950	1,340 - 3,110
750	0.13	1,780	1,230 - 2,810
500	0.2	1,560	1,090 - 2,420
350	0.29	1,380	974 - 2,110
200	0.5	1,130	812 - 1,690
100	1	864	637 - 1,250
75	1.3	769	572 - 1,100
50	2	646	487 - 907
35	2.9	549	420 - 758
20	5	417	325 - 559
10	10	282	226 - 364
5	20	175	145 - 218
2	50	70	59 - 84

3.2.2 Comparison to Previous Studies

Previous flood frequency estimates for the Oldman River at Fort Macleod are presented in the following studies:

- Flood Frequency Analysis of Oldman River at Town of Fort Macleod, AENV (1985);
- 1995 Flood Frequency Analysis for South Saskatchewan River Basin – Draft, AENV (1995a).

These reports have been reviewed and results compared in the preparation of the open water hydrology assessment for this study (**Appendix E**).

4 HYDRAULIC MODELLING

4.1 Available Data

Key data used to develop and calibrate the hydraulic model includes the survey data, flow measurements, and site observations documented in **Section 2 Data Collection**, high-resolution terrain data (LiDAR DTM and aerial images), as well as the design flows, flow record, and high water marks. Additional information such as past studies and historical flood photographs also informed model development and calibration. The data available for this study, not otherwise presented in this document, are summarized below.

4.1.1 Digital Terrain Model

A digital terrain model (DTM) based on airborne LiDAR data was supplied by AEP for this study. The DTM was based on data collected for the study area by Airborne Imaging on 26 October 2018 (Airborne Imaging, 2020). The LiDAR-derived DTM is reported to have a vertical accuracy of ±0.031 m at 95% on hard, flat, open surfaces, based on a set of independently collected verification points (Airborne Imaging, 2020).

NHC compared a selection of 2019 survey points to the LiDAR-derived DTM. The location for comparison data points were selected for hard, flat, open surfaces. The comparison included nine points and suggested a vertical accuracy of ±0.047 m.

A preliminary version of the LiDAR was provided at the start of the project and was used for the hydraulic modelling described below. The final hydro-flattened LiDAR was received 22 November 2019 and was compared to the preliminary LiDAR to ensure the data was consistent and no changes or adjustments to the model were required.

4.1.2 Existing Models

No existing hydraulic models were available for this reach, but the results of the previous 1991 study and modelling parameters were obtained and considered in the model development and calibration.

4.1.3 High Water Marks

High water mark observations provide documentation of the peak water levels that occurred at a given location. A record of high water marks ideally includes numerous water level points along a channel reach, surveyed during the peak of a flood or marked by debris, staining, or staking and surveyed days or even years following the flood. Alternatively, or in addition, the high water mark record may include ground or air photos from the flood that illustrates the level or extent of inundation. These data provide observations to compare simulated results useful for hydraulic model calibration and validation.

For this study, high water marks were provided by AEP and include surveyed water levels along the Oldman River for the 1986, 1991, 1995, and 2013 floods and along Willow Creek for the 2013 flood. All of these events were open water floods. The available high water mark data are listed in **Table 13** and mapped in **Figure 2**.

Table 13 Summary of reported high water marks

High Water Mark ID	River Station (m)	Elevation (m) [CVD28]	Event Date	Location
Oldman River				
2013-OLD-3-a	13,770	938.21	21-Jun-13	Hwy 811 bridge
2013-OLD-3-b	13,754	938.88	21-Jun-13	Hwy 811 bridge (*Suspect Point*)
2013-OLD-4-a	18,427	948.34	21-Jun-13	Hwy 2 bridge (*Suspect Point*)
95-OM-2	18,281	947.41	7-Jun-95	Hwy 2 bridge
95-OM-4-a	13,749	938.97	7-Jun-95	Hwy 811 bridge
95-OM-4-b	13,777	939.27	7-Jun-95	Hwy 811 bridge
95-OM-3	16,293	943.72	7-Jun-95	Pumphouse - Fish and Game Park
95-OM-5	13,352	938.12	7-Jun-95	Sewage treatment plant
95-OM-6	12,260	935.02	7-Jun-95	Girl Guide camp (*Suspect Point*)
95-OM-6A	12,582	937.16	7-Jun-95	Water intake downstream of Hwy 811
95-OM-7	11,126	934.08	7-Jun-95	Farm downstream of Fort McLeod
91-OM-1A	19,232	945.91	22-Jun-91	Railway Trestle
91-OM-1B	19,254	945.78	22-Jun-91	Railway Trestle
91-OM-2A	18,325	944.50	22-Jun-91	Hwy 2 bridge
91-OM-2B	18,389	944.47	22-Jun-91	Hwy 2 bridge
91-OM-3	16,317	941.36	22-Jun-91	Pumphouse - Fish and Game Park
91-OM-4A	13,753	937.25	22-Jun-91	Hwy 811 bridge
91-OM-4B	13,768	937.11	22-Jun-91	Hwy 811 bridge
91-OM-6	12,260	935.20	22-Jun-91	Girl Guide Camp
86-OM-1.1	19,125	945.31	29-May-86	Right bank of CPR bridge
86-OM-1A.1	19,301	945.90	29-May-86	Left bank of CPR bridge
86-OM-2.1	18,402	944.23	29-May-86	Hwy 2 bridge
86-OM-2.2	18,246	943.97	29-May-86	Hwy 2 bridge
86-OM-3.1	16,320	940.99	29-May-86	Pumphouse - Fish and Game Park
86-OM-5.1	13,333	936.31	29-May-86	Water treatment plant
86-OM-4.1	13,728	937.00	29-May-86	Hwy 811 bridge
86-OM-6.1	12,299	934.82	29-May-86	Girl Guide camp
86-OM-7.1	-	931.96	29-May-86	MacLeod Island
Willow Creek				
2013-WL-13-a	11,332	936.45	21-Jun-13	Hwy 811 bridge
2013-WL-13-b	11,305	936.27	21-Jun-13	Hwy 811 bridge
2013-WL-13-c	11,290	936.31	21-Jun-13	Hwy 811 bridge

4.1.4 Gauge Data & Rating Curves

Gauge data and rating curves are used for model validation. The WSC maintained a gauge on the Oldman River at Fort MacLeod (05AB007) from 1910 to 1948. This gauge was abandoned due to channel instability and resulting challenges in developing and applying a stage-discharge rating curve. AEP re-established a gauge at this location, Oldman River at Highway 811 (05AB917) which has been in operation since 2001. A rating curve wasn't provided but the observation data (both elevation and discharge) and the physical discharge measurements from the gauge were obtained to support model creation and calibration.

The Willow Creek at Highway 811 gauge (05AB046) was established in 1999 by WSC and has continued to be maintained. AEP took over this gauge in 2011 and has been maintaining the rating curve since. Rating curves and station description for the Willow Creek gauge were obtained to support the creation and validation of the hydraulic model. However, the physical discharge measurements and confidence rating of the rating curve was not available.

Table 14 lists the gauging station for which data were examined and the respective periods of record. The gauges used for hydrologic analysis in determination of past and design events is presented in **Appendix E**.

Table 14 List of hydrometric gauges supporting model creation and calibration

Station No.	Station Name	Watershed Area (km^2)	Period of Record
05AA024	Oldman River near Brocket	4,400	1966-2016, 2017-2018
05AB007	Oldman River near Fort Macleod	5,760	1910-1948
05AB917	Oldman River at Highway 811	5,760	2001-2015, 2017-2018
05AB002	Willow Creek near Nolan	2,290	1909-1924, 1942-1999
05AB046	Willow Creek at Highway No. 811	2,510	1999-2018

4.1.5 Flood Photography

AEP provided photographs of the Oldman River at Fort Macleod taken during 1975, 1995, and 2005 floods and photographs of lower Willow Creek taken during the 1995 and 2005 flood. Flood photographs included ground taken photos and air photos that showing either water level or flood extents.

No flood imagery was provided for the 2013 flood. No orthoimagery was collected for the Oldman River or Willow Creek near Fort Macleod during the 2013 flood peak or post peak; despite such imagery was collected for other major rivers in the province during that time.

4.2 Channel and Floodplain

4.2.1 General Description

The Oldman River occupies an approximately 1 km wide river valley that is incised up to 30 m below the surrounding landscape. The channel planform is characteristic of many rivers in the region that occupy floodways that were formed during the post-glacial period under a much higher flow and sediment discharge regime. The present channel meanders within the constraints of the valley, with frequent meander cutoffs and interactions with the valley sidewalls. Downstream of the study reach, the river becomes increasingly incised to the point that it occupies a narrow valley and reverts to a single-thread, generally straight planform. The river valley contains several continuous terrace levels extending anywhere from a couple of meters high to 10-20 m high at the sides of the valley.

4.2.2 Channel Characteristics

The Oldman River is sinuous with occasional islands. It has a pool and riffle sequences as well as a diagonal transverse pattern with side bars. It is not obviously aggrading or degrading and it is occasionally confined. The channel thalweg is moderately unstable and predominantly made up of gravel and sand (Kellerhals et al., 1972). The overall reach-average channel slope is 0.0015 m/m. Based on 2-year flow conditions, the average top width of Oldman River through the study reach is about 256 m and the mean cross section depth was about 1.1 m.

Willow Creek has a reach-average channel slope of 0.001 m/m. Based on 2-year flow conditions, the average top width of Willow Creek through the study area is about 163 m and the mean cross section depth was about 1.2 m.

4.2.3 Floodplain Characteristics

The floodplain near Fort Macleod is mainly cultivated land and some urbanized plains with a river cut valley that is sparsely forested and lined with shrub or grass (Kellerhals et al., 1972). The land use within the Oldman River floodplain study area is primarily agricultural and parkland; this includes the occasional residence, campgrounds, and a golf course. Land use along Willow Creek within the study area is predominantly agricultural and undeveloped shrub and grasslands. The confluence is made up almost entirely of sparse forest with shrubs and grasslands.

The floodplain vegetation consists mainly of undeveloped sparse forests mixed with interspersed areas of dense tree stands and heavy bush as well as shrubs and grasslands. There are some agricultural fields and a few pockets of urban development near Fort Macleod and Highway 811 on the Oldman River and Willow Creek.

4.2.4 Anthropogenic Features

A total of 10 hydraulic structures (bridges and culverts) have been documented along the channel or floodplain within the study area and are included in the model and accounted for in the analysis. Details on these hydraulic structures are provided in **Appendix C**.

Along the Oldman River there is also guidebank armouring at the upstream left bank of the Highway 2 bridge, eight rock spurs on the right bank upstream of Highway 811 bridge, four rock spurs on the left bank upstream of the Highway 811 bridge, and 12 rock spurs on the right bank downstream of Highway 811 bridge. Various parks, playgrounds, campgrounds, a golf course, and some residential developments are also located on or near the floodplain of the study reach. There is a local water intake downstream of the Highway 811 bridge near the Girl Guide Camp for the Town of Fort Macleod. There is a diversion / irrigation channel on the right bank near the water intake. The diversion / irrigation channel is operated by culverts with gates. There is also a larger diversion / irrigation canal just below the upstream study boundary that diverts flow for irrigation on the plains several kilometres from the study reach.

4.3 Model Construction

4.3.1 Methodology

The U.S. Army Corps of Engineers *Hydrologic Engineering Center-River Analysis System* (HEC-RAS) computer program (Version 5.0.7, March 2019) was used to calculate the flood levels along the study reach. HEC-RAS can perform one-dimensional (1D), two-dimensional (2D), or combined 1D and 2D hydraulic calculations for a network of channels and hydraulic structures. For this study, a 1D model was constructed, and used as the basis to calculate water surface profiles for steady state gradually varied flow. Due to the complex overbank flow paths along Willow Creek and near the confluence, as well as complex in channel flow at the spurs, a 2D model was also generated. The 2D model was used to inform the development and calibration of the 1D model.

The basic inputs required by HEC-RAS are a series of cross sections with known distances between sections (channel and overbank flow distances), roughness coefficients along each cross section, inflow along the reach (typically the same between confluences), and a prescribed water level at the downstream boundary of the model.

The computational procedure for steady flow calculations are based on the solution of the 1D energy equation. Energy losses between river sections are calculated as friction losses (using Manning's equation) and expansion/contraction losses. The momentum equation is used by the model where rapidly varied flow conditions arise; such as, bridges and stream junctions. The analytical approach employed by HEC-RAS has the following assumptions and potential limitations:

- Flow is gradually varied and boundary friction losses between cross sections are estimated by Manning's equation using section-average parameters.
- Changes in the channel and floodplain geometry resulting from erosion or mobile bed processes that might arise during a flood are not accounted for or modelled.
- Each model cross section is apportioned into three separate conveyance components representing the main channel, left overbank, and right overbank; the water level is assumed to be constant across all three conveyance components.
- The flow is one-dimensional, therefore only velocity components in the principal direction of flow are accounted for in the equations and calculations.

The following sections outline the model construction and parameter selection process for this study.

4.3.2 Geometric Database

The geometric database provides the components of the HEC-RAS model geometry, including cross sections, internal hydraulic structures, and boundary conditions. Each component is described below. Additional information and data are provided as part of the electronic deliverables of the study.

Cross Section Data

Cross section alignments were established in GIS to be perpendicular to flood flow and follow the general path of surveyed cross sections (refer to **Section 2.2**). The overbank portions were aligned perpendicular to the anticipated path of the majority of overbank flow. The 2D model was used to help visualize the direction and contribution of flow.

Each cross section extends through the left and right overbanks up the valley wall to an elevation beyond the anticipated 1,000-year flood level. Cross section elevations were derived from a combination of the DTM data (overbank) and ground survey data (channel). Cross section alignments were defined to pass through the surveyed point data and extended overbank (DTM) above the anticipated 1000-year flood level. The cross-section data based from the channel survey and DTM were combined in HEC-RAS using the *graphical cross section editor*. The number of elevation points in the combined cross sections were reduced to below the maximum allowable (500) using the *minimize area change* point filter option.

Distances between each cross section along the channel centerline and along the central flow path of the left and right overbank areas were measured in GIS and exported with other cross section data to the HEC-RAS model. These lengths are used by the model to estimate the energy loss between cross sections. Cross section details based on NHC's surveys are provided in **Appendix B**.

The location of the left and right banks (denoted as bank stations) were determined by inspecting the cross-section geometry and comparing with aerial and ground photographs of the channel. These points denote the location where flow transitions from in-channel to overbank.

Bridges, Culverts, and Weirs

The modelled reach includes four bridge crossings, and four culverts. **Table 6** provides a summary of bridges and culverts included in the analysis. Further information of these structures incorporated into the model are tabulated in **Appendix F**. Any culverts and bridges in the study area that do not contribute to the conveyance of the flood, are not relevant to the hydraulic computations and therefore were not modelled (i.e. culverts and bridges that service local drainage only or are located in areas of zero velocity).

The alignment and location of each bridge structure was established in GIS between the upstream and downstream surveyed cross sections adjacent to the bridge. The bridge cross sections include the approach roadway, the abutments, high and low chord profiles (defining the bridge deck), and the any bridge piers. The approach roadway profile was based on elevation data sampled from the DTM. Geometry of the bridge abutments, high and low chords, and piers were determined from the surveyed data and where available and relevant, the AT drawings. The modeled bridge geometry was checked against the bridge photographs, full feature LiDAR points, and where available details from AT bridge file records and as-built (or design) drawings.

Bridge hydraulics for all Oldman River and Willow Creek crossings were modelled using the energy (standard step) equation for all flows.

Boundary Conditions

Boundary conditions are required at the inflow and outflow boundaries of the model as well as at the internal boundaries located at the junctions within the model domain. HEC-RAS defines junctions as locations where two or more streams converge together or split apart. Within the Fort Macleod study reach, the only junction occurs where Willow Creek and the Oldman River converge. Junctions divide the streams in the model domain into sub-reaches:

- The *Oldman River KM 000* reach and *KM 006* reach represent the model reaches downstream and upstream of the confluence with Willow Creek, respectively.
- *Willow Creek KM 000* reach represent the entire segment of this tributary within the study area.

Discharge is required as the boundary condition at the upstream end of each sub-reach. The junction within the model domain represents an internal boundary through which the discharge of the upstream sub-reaches pass into the downstream sub-reach.

A normal depth water level approximation was assigned as the boundary condition at the downstream boundary of the Oldman River. The normal depth slope was 0.001 m/m which was calculated based on the reach-averaged energy grade line slope near the downstream limit of the study reach. The model sections extend downstream adequately to ensure any reasonable change in the downstream boundary condition does not influence results in the study reach (for the range of studied flows).

Internal Flow Changes

Due to the complex nature and open valley of the confluence of Oldman River and Willow Creek, additional flow change locations were required above the modelled confluence. At higher flow events, water starts spilling from Willow Creek to Oldman River (*transfer 1*) across the valley. Some of this water returns back to Willow Creek (*transfer 2*) as overbank flow upstream of the modelled junction. The volume of flow transfers are presented in **Table 15** with XS referring to the station within the hydraulic model that the transfer occurs.

Table 15 Flow balance at confluence of Willow Creek and Oldman River

Return Period (years)	Oldman River Inflow (m^3/s)	Willow Creek Inflow (m^3/s)	Discharge (m^3/s)					
			Transfer 1			Transfer 2		
			Flow Transfer 1 (*to Oldman River*)	Oldman River Flow @ XS 9,472	Willow Creek Flow @ XS 5,929	Flow Transfer 2 (*to Willow Creek*)	Oldman River Flow @ XS 8,157	Willow Creek Flow @ XS 3,752
1000	4850	1950	390	5240	1560	585	4655	2145
750	4450	1780	356	4806	1424	534	4272	1958
500	3920	1560	312	4232	1248	312	3920	1560
350	3500	1380	276	3776	1104	138	3638	1242
200	2910	1130	283	3193	848	0	3193	848
100	2300	864	285	2585	579	0	2585	579
75	2080	769	246	2326	523	0	2326	523
50	1790	646	194	1984	452	0	1984	452
35	1560	549	154	1714	395	0	1714	395
20	1250	417	104	1354	313	0	1354	313
10	920	282	0	920	282	0	920	282
5	649	175	0	649	175	0	649	175
2	353	70	0	353	70	0	353	70

4.3.3 Model Calibration

Model calibration involved the selection or modification of modelling parameters to ensure simulated water levels adequately represent observed water levels along the study reach for both high and low flow conditions (modelling parameters are presented in the following subsection). Calibration parameters include:

- Manning's roughness coefficient for the channel and floodplain;
- Ineffective flow areas at each model cross section;
- Expansion and contraction loss coefficients; and
- Discharge coefficient for flow overtopping roadway crossings and embankments.

Of the above, the primary calibration parameter is typically Manning's roughness for the river channel. Values for each cross section are selected by comparing the simulated water surface profile to observed water levels and high water marks. Typical challenges or limitations include:

- The availability and accuracy of the high water mark data.
- Proper identification of high water mark locations.
- Uncertainties in estimates of the flood peak discharge during calibration events.

The hydraulic model was calibrated for both low and high flow conditions using available data. Calibration priority was placed on high flow conditions as parameters are to be kept constant for the full range of simulated flow. These data included surveyed water levels, high water marks provided by AEP, as well as WSC hydrometric gauge data and rating curves. Post calibration, values were reviewed with those considered physically reasonable (boundary conditions, roughness, obstructions, etc.) and comparable with past studies (particularly the previous Fort Macleod flood hazard study (AENV, 1991)).

High Flow Calibration and Validation

High water marks are available for calibration and validation from several flood events including 2013, 1995, 1991, and 1986. The 1995 flood was used for model calibration as it is the largest recent flood and has the greatest number of high water marks available. The floods of 2013, 1991, and 1986 were used as validation events. High water observations for these floods extended over about half of the study reach, centered around Town of Fort Macleod. The number and location of high water marks are described in **Section 4.1.3** and shown in **Figure 2**.

Comparison between simulated water surface profiles and observed water levels for both calibration and validation events are shown for Oldman River on **Figure 3** and for Willow Creek on **Figure 4**. A tabular summary of the high flow calibration is provided in **Table 16**. Comparison of simulated water levels to the 1995 observations have a mean absolute error (MAE) of 0.22 m. The simulated water level and inundation extents for the 1995 flood visually appear similar to photographs from this flood and results from the 2D model.

Figure 3 and **Figure 4** also includes the comparison between simulated water surface profiles and surveyed water levels for each validation event. Comparison of simulated water levels to high water mark observations have a MAE of 0.04 m for 2013 flood, a MAE of 0.27 m for the 1991 flood, a MAE of 0.39 m for the 1986 flood. The model tended to underpredict the 2013 event and overpredict the 1991 and 1986 validation events.

From the hydrometric gauges within the study reach, reported water levels from flood events were used for calibration similar to the high water marks and rating curves from the gauges were compared with similar curved developed from the model. The rating curve from the Oldman River at Highway 811 gauge has been identified by WSC and AEP as being unstable due to frequent channel changes, and the rating curve for the Willow Creek at Highway 811 gauge was lacking the underlying flow measurements or confidence rating; making it difficult to ascertain what range of flows the curve can be relied on. Therefore, comparisons with the gauge data were reviewed, but not directly used for model calibration or validation. **Figure 5** illustrates such a comparison with the rating curve from Willow Creek, which illustrates its reasonable comparison for moderate flows, but divergence for the more extreme flows (i.e. greater than the 10-year flood), which are likely to have less physical flow measurements used for curve development. However, **Figure 6** illustrates a good comparison for low and high flows which gives more weight to the current calibration.

Low Flow Validation

Despite attempting to target high flows, the flow measurements and corresponding water elevations surveyed by NHC June 2019 represent low flow conditions. These corresponding measured water levels and discharges were used to validate the assigned channel Manning's roughness coefficients. **Table 7** in **Section 2.5.1** summarizes the measured discharges for Oldman River and Willow Creek used in the low flow model validation.

The low flow profile for Oldman River was established in the model based on the measured flow data on 21 June 2019 at Highway 811 Bridge on Oldman River. No profile was surveyed for Willow Creek as the flows were too low to operate a boat. Channel and overbank roughness values were assigned based on the survey photographs, aerial imagery and land cover types (Table 17).

The low flow validation profile points aren't tabulated (over 700 points), but the result is shown in **Figure 3,** and the statistical results calculate a mean absolute error (MAE) of 0.36 m. Majority of the points were below observed water levels, which is not unexpected due to the presence of several braids and side channels along the study reach. Minimal emphasis was placed on the low flow validation because flow conditions at the time of the survey were less than one-tenth of the 2-year flood discharge estimate, and the model was calibrated with a focus on higher flow events.

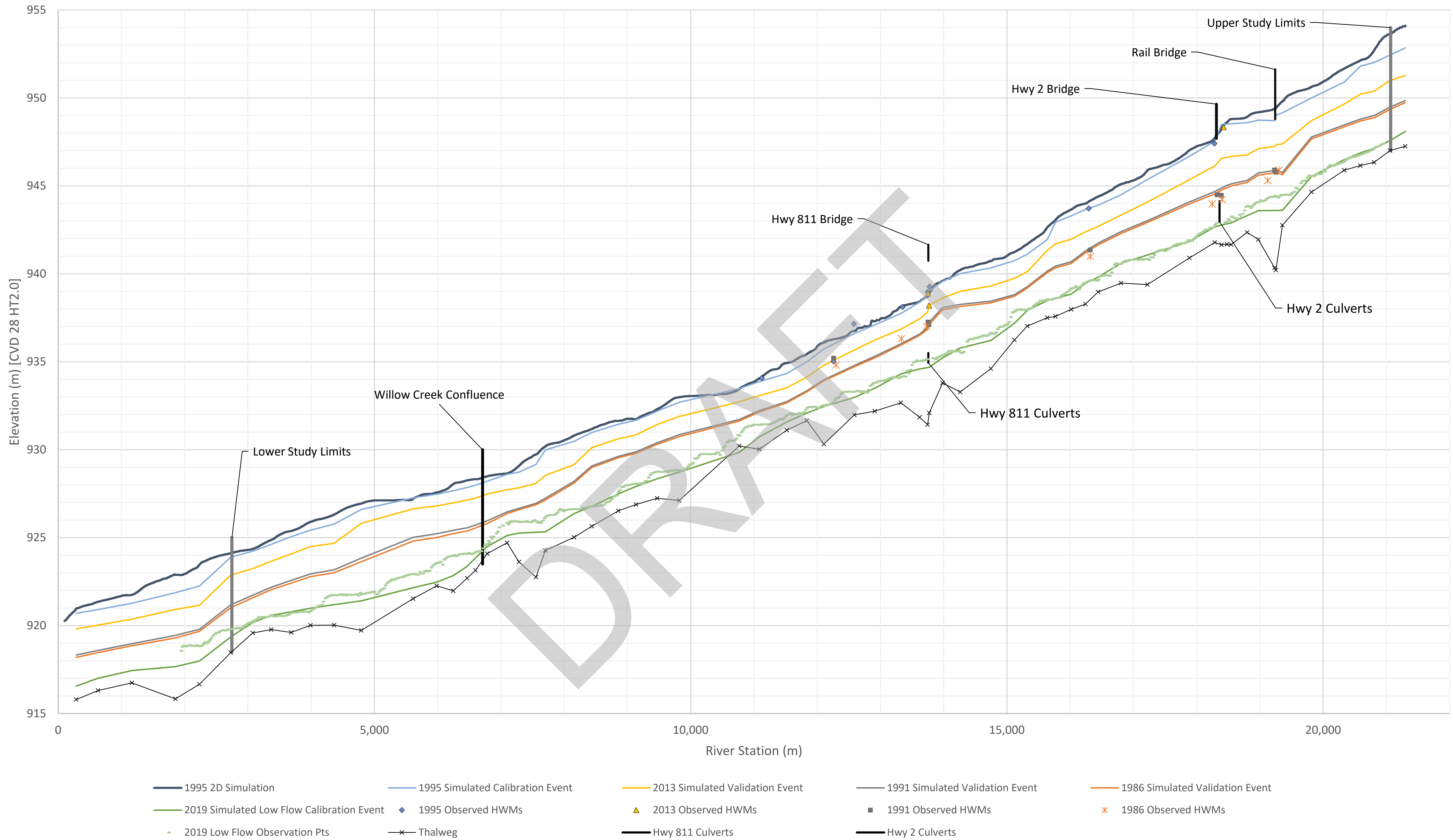


Figure 3 Calibration and validation profile, Oldman River

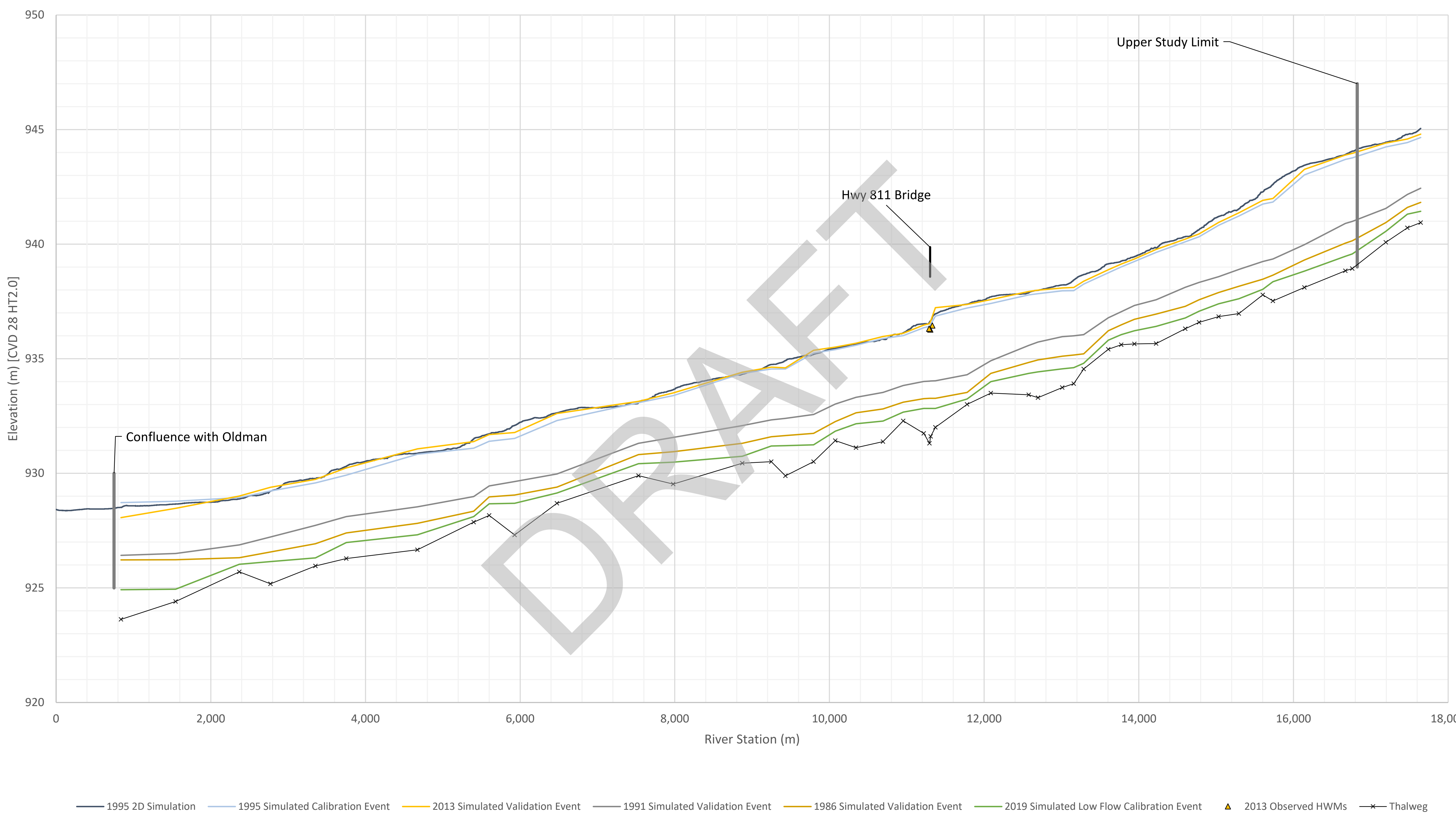


Figure 4 Calibration and validation profile, Willow Creek

Table 16 Calibration and validation results for high flow conditions

High water Mark ID	River Station (m)	Event Date	Discharge (m^3/s)	Observed High water Mark (m)	Simulated Water Level (m)	Simulated Minus Observed
Oldman River						
95-OM-2	18,281	7-Jun-95	2,950[1]	947.41	947.54	0.13
95-OM-3	16,293	7-Jun-95	2,950[1]	943.72	943.72	0.00
95-OM-4-b	13,777	7-Jun-95	2,950[1]	939.27	939.04	-0.23
95-OM-4-a	13,749	7-Jun-95	2,950[1]	938.97	938.83	-0.14
95-OM-5	13,352	7-Jun-95	2,950[1]	938.12	937.81	-0.31
95-OM-6A	12,582	7-Jun-95	2,950[1]	937.16	936.59	-0.57
95-OM-7	11,126	7-Jun-95	2,950[1]	934.08	936.01	0.99
2013-OLD-3-a	13,770	21-Jun-13	1,180[2]	938.21	938.17	-0.04
91-OM-1A	19,254	22-Jun-91	428[3]	945.91	945.88	-0.03
91-OM-1B	18,325	22-Jun-91	428[3]	945.78	945.90	0.12
91-OM-2A	18,389	22-Jun-91	428[3]	944.50	944.75	0.25
91-OM-2B	16,317	22-Jun-91	428[3]	944.47	944.88	0.41
91-OM-3	13,753	22-Jun-91	428[3]	941.36	941.47	0.11
91-OM-4A	13,768	22-Jun-91	428[3]	937.25	937.04	-0.21
91-OM-4B	12,260	22-Jun-91	428[3]	937.11	937.21	0.10
91-OM-6	19,254	22-Jun-91	428[3]	935.20	934.24	-0.96
86-OM-1.1	19,125	29-May-86	388[3]	945.31	945.69	0.38
86-OM-1A.1	19,301	29-May-86	388[3]	945.90	945.70	-0.20
86-OM-2.1	18,402	29-May-86	388[3]	944.23	944.78	0.55
86-OM-2.2	18,246	29-May-86	388[3]	943.97	944.49	0.52
86-OM-3.1	16,320	29-May-86	388[3]	940.99	941.38	0.39
86-OM-5.1	13,333	29-May-86	388[3]	936.31	935.97	-0.34
86-OM-4.1	13,728	29-May-86	388[3]	937.00	936.81	-0.19
86-OM-6.1	12,299	29-May-86	388[3]	934.82	934.24	-0.58
Willow Creek						
2013-WL-13-a	11332	21-Jun-13	527[4]	936.45	936.87	0.42
2013-WL-13-b	11305	21-Jun-13	527[4]	936.27	936.62	0.35
2013-WL-13-c	11290	21-Jun-13	527[4]	936.31	936.53	0.22
Willow Creek Gauge	11300	21-Jun-13	527[4]	936.70	936.58	-0.12

Notes:

1. From 1995 Flood Frequency Analysis for South Saskatchewan River Basin – Draft Report from AENV (1995a)
2. Data obtained from Oldman River at Highway 811 (05AB917) gauge.
3. Peak flow has been estimated based on instantaneous to daily peak discharge ratio of 1.18. See Open Water Hydrology Assessment for details (NHC, 2019).
4. Data obtained from Willow Creek at Highway 811 (05AB046) gauge.

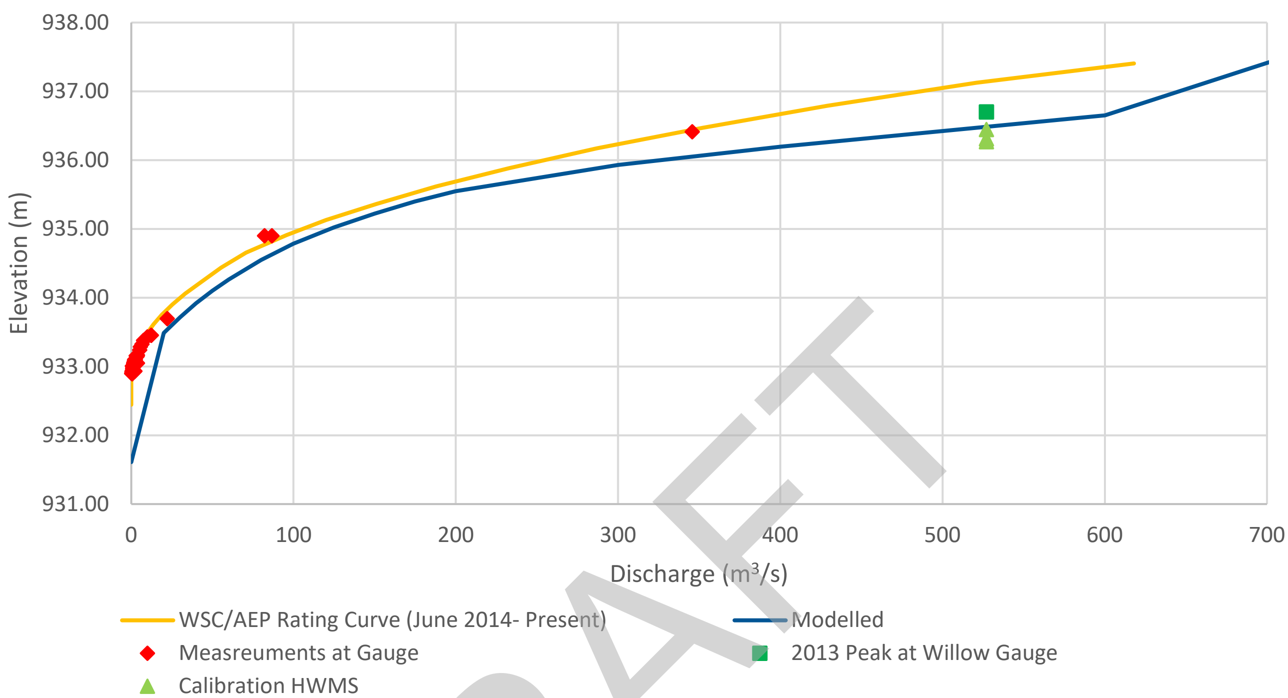


Figure 5 Rating curve used in model validation, Willow Creek at Highway 811 (05AB046)

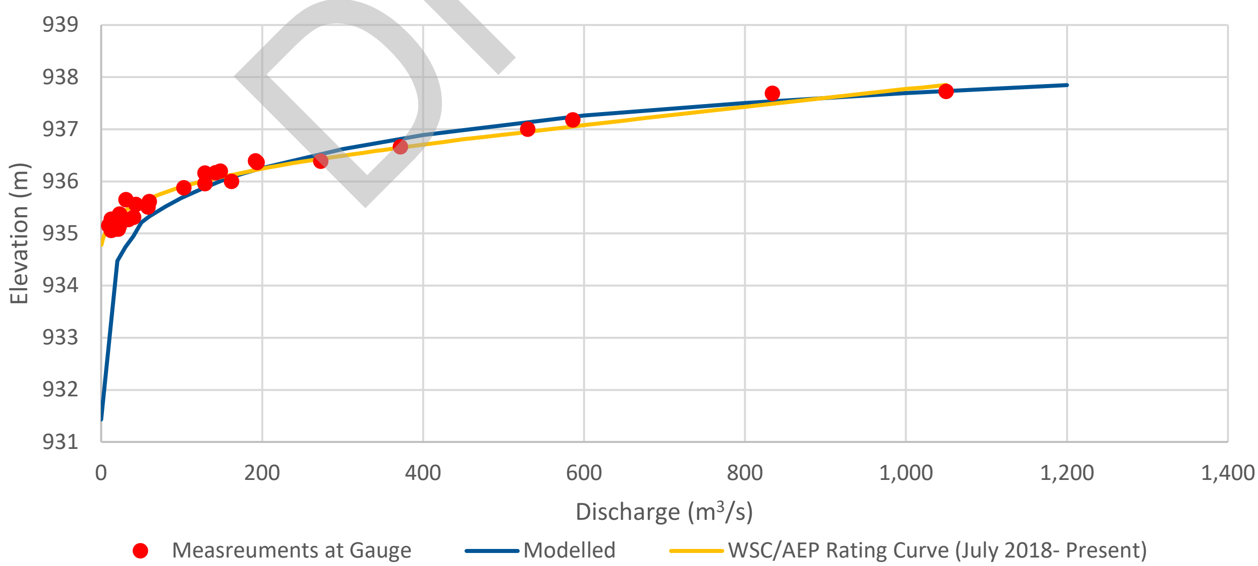


Figure 6 Rating curve use in model validation, Oldman River at Fort Macleod (05AB917)

4.3.4 Model Parameters & Options

The following subsections describe the model parameters and options adopted in the HEC-RAS model. These include parameters for flow resistance or roughness for the channel and overbank (Manning's coefficients), contraction and expansion loss coefficient, roadway weir coefficient, and ineffective areas.

Channel and Overbank Roughness Values

Computations in HEC-RAS are based solving the energy equation between successive cross sections. The energy loss is the sum of friction loss and expansion/contraction loss. Friction loss is calculated using the Manning's equation (Brunner, 2016). The Manning's n (also referred to as roughness coefficient or value) represents the channel's resistance to flow between the successive cross sections. As stated in Chow (1959) for a 1D model it must therefore account for

- Surface roughness, the size and shape of grains of material forming the wetted perimeter
- Vegetation, similar to surface roughness potentially more notably reduces the capacity of the channel and impedes flow
- Channel irregularity, comprising of irregularity in wetted perimeter and variations in cross section, size, and shape; such as bed forms, and abrupt variations in the channel, and any channel form that induces flow patterns such as the development of sinuous flow across a channel.
- Channel alignment, that is the consideration of channel form either as large radius meanders versus sharp, server changes in channel direction.
- Obstructions, such as log jams and bridge piers

In addition, the conditions for the time of assessment must be considered, in that the flow resistance can be further influenced by the following:

- Stage and discharge, as flow and depth increase, the resistance to flow typically decreases.
- Geomorphic processes, as flows increase sediment and debris mobilization can influence the bed forms as well as channel shape; consideration of erosion, scour, channel migration, and bar and dune migration may be required.

Despite the potential change in roughness with flow and over time, roughness values were set based on review of photographs, aerial imagery, the DTM, and the site inspection. The selected roughness values were compared to those used in the previous flood hazard study (AENV, 1991) to identify and substantial differences and assess if any differences were warranted.

For the overbank areas, 6 distinct land cover types were identified based on the orthophotos; these are described in Table 17. Each land cover type was assigned a constant roughness coefficient based on values provided in reference literature (Chow, 1959).

Table 17 Roughness coefficients selected based on surface cover, overbank areas

Land cover type	Description	Roughness Coefficient
Islands	Alluvial substrate with light vegetation and debris.	0.042
Ponded water	Open water area where flow of water is deep and low velocity.	0.024
Light vegetation	Agricultural crops or pastureland with grasses, light brushes, and trees.	0.045
Dense vegetation	Medium to dense brushes and trees.	0.10
Grass	Covered with grasses and some manmade features (for example trails and pathways).	0.036
Urban	Developed with buildings, transportation corridors, and sporadic trees, shrubs, and other obstructions.	0.07

Channel roughness was initially estimated based on channel substrate and form. The roughness coefficient chosen to represent the channel through the spur section was selected based on a review of Cowan (1956) and Chow (1959). Cowan's (1956) procedure involves reviewing different characteristics of the river and estimating the effects of these factors to determine the value Manning's roughness coefficient for the channel. The value may be computed by

$$n = (nb + n_1 + n_2 + n_3 + n_4)m$$

where

n_b = a base value of n for a straight, uniform, smooth channel in natural materials,

n_1=a correction factor for the effect of surface irregularities,

n_2 =a value for variations in shape and size of the channel cross section,

n_3 =a value for obstructions,

n_4 =a value for vegetation and flow conditions, and

m =a correction factor for meandering of the channel.

Based on the range of values for each n_x in Cowan's (1956) procedure, the following n values were chosen.

Table 18 Cowan's (1956) procedure values

Parameter	Description	Willow Cr. Roughness	Oldman R. Roughness	Roughness at Spur
Nb	Material involved	0.022	0.024	0.024
n1	Degree of irregularity	0.003	0.003	0.005
n2	Variation across Channel	0.003	0.005	0.005
n3	Relative effect of obstructions	0.003	0.001	0.026
n4	Vegetation	0.002	0.000	0.005
m	Degree of meandering	1.0	1.0	1.0
	Result:	0.033	0.033	0.065

When reviewing Chow's (1959) roughness coefficients, the Oldman River was determined to be a major stream with irregular and rough sections. The range of roughness coefficients suitable is 0.035 to 0.100 with no normal value listed. This range supports the choice of 0.033 for typical section and 0.065 for the spurs as suitable roughness coefficients.

Simulation results from the 1D model were than compared to identify any unexplained changes in water level as well as to assess conformance with results from the 2D model and observed water levels (i.e. calibration and validation steps). During the development of the model and the initial calibration effort, it was determined that a single roughness value was generally acceptable for the in-channel roughness. Exception to this, was the reaches with rock spurs along the Oldman River near Highway 811 bridge. The spurs substantially alter the local hydraulics, increasing the roughness.

Expansion and Contraction Coefficients

To account for the effect of flow contraction or expansion on the energy balance between successive cross sections, HEC-RAS multiplies the absolute difference in velocity head by a coefficient. The coefficients range from 0.10 for gradual transitions to 0.80 for abrupt transitions (Brunner, 2016). The default values of 0.1 and 0.3 (for expansion and contraction coefficients) were utilized throughout the majority of the hydraulic model. Expansion and contraction coefficients were increased to 0.3 and 0.5, respectively for cross sections located near bridges where flow through the bridge opening results in rapid contraction of the flow.

Obstruction and Ineffective Flow Areas

Blocked obstructions in the floodplain, such as buildings, walls, storage tanks, or elevated foundations were not specified in the HEC-RAS model. A blocked obstruction was used to artificially block passage of flow through one cross section in the confluence. This was necessary because the cross section included a high-water channel in the floodplain that cut back on itself compared to the main channel and would have therefore flowed opposite to the direction of flow in the main channel. This violates the assumptions of HEC-RAS 1D. Obstructions associated with bridge piers and structural members were modelled using the standard bridge editor specifications in HEC-RAS.

Ineffective flow areas were specified at cross sections in the HEC-RAS model, based on a review of the local terrain and floodplain features both at and between cross sections. Ineffective flow areas can be specified within portions of cross sections where water is expected to pond, but where the velocity of that water, in the downstream direction, is also expected to be close to or equal to zero (Brunner, 2016). The downstream direction is taken relative to the cross section lines defined in the model, so the orientation of cross sections was considered when specifying ineffective flow areas.

Ineffective flow areas in the model may be specified as either permanent or non-permanent. Permanent ineffective flow areas apply regardless of the water surface elevation, whereas non-permanent ineffective flow areas become effective above a defined elevation. Non-permanent conditions often produce the undesirable result of water level profiles for high magnitude floods crossing below water level profiles computed for lower flood magnitudes.

Permanent ineffective flow areas were also used to account for flow patterns influenced by nearby bridge abutments and roadway embankments crossing the floodplain. These types of obstructions tend to direct flow towards the bridge opening. Several site-specific factors were taken into account when configuring ineffective flow areas at bridges and culverts in the study area, including distance from the cross section to the bridge, terrain features, and bridge geometry.

Flow Splits, Islands, and Diversions

The study reaches were adequately represented without flow splits around islands. Where a cross section intersected an island, the HEC-RAS model assumed equal water level on both sides of the island based on the composite channel conveyance properties and computed energy losses. This assumption is increasingly valid once flood magnitudes increase and islands becomes inundated.

Diversions may include avulsion channels or flow paths that reduce the total discharge carried by the main channel along a portion of the study reach. There were no such diversions encountered within the study area, and all flood flows were confined to the cross sections modelled along the study reaches.

4.3.5 Flood Frequency Profiles

The hydraulic model was used to generate flood frequency profiles for the thirteen open water floods of varying magnitude ranging from 2-year to 1000-year. The computed flood frequency water levels at each surveyed cross section on Oldman River and Willow Creek are provided in **Appendix F**. These results are plotted graphically in **Figure 7** for Oldman River and **Figure 8** for Willow Creek.

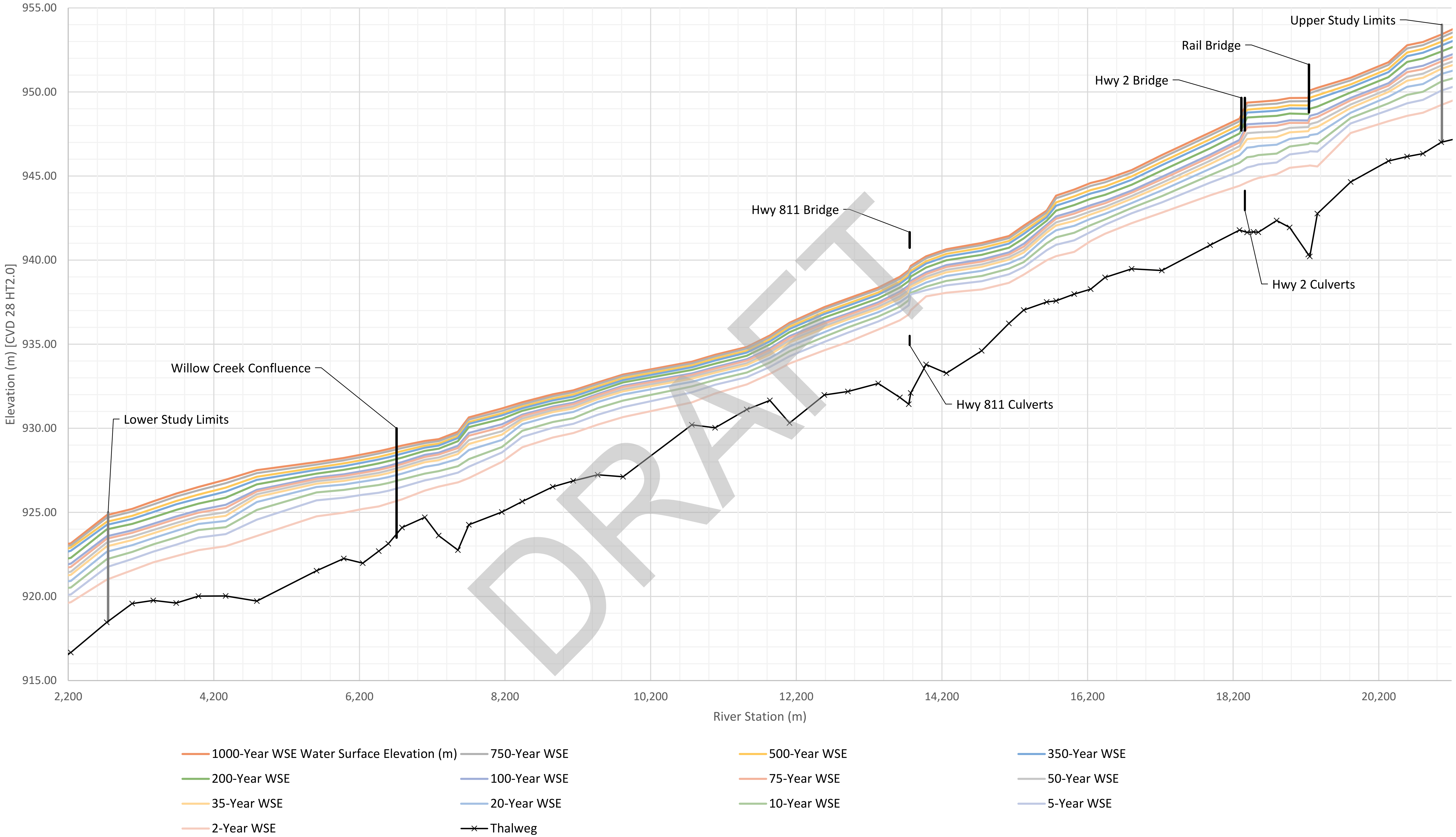


Figure 7 Flood profile for range of flood flows, Oldman River

nhc

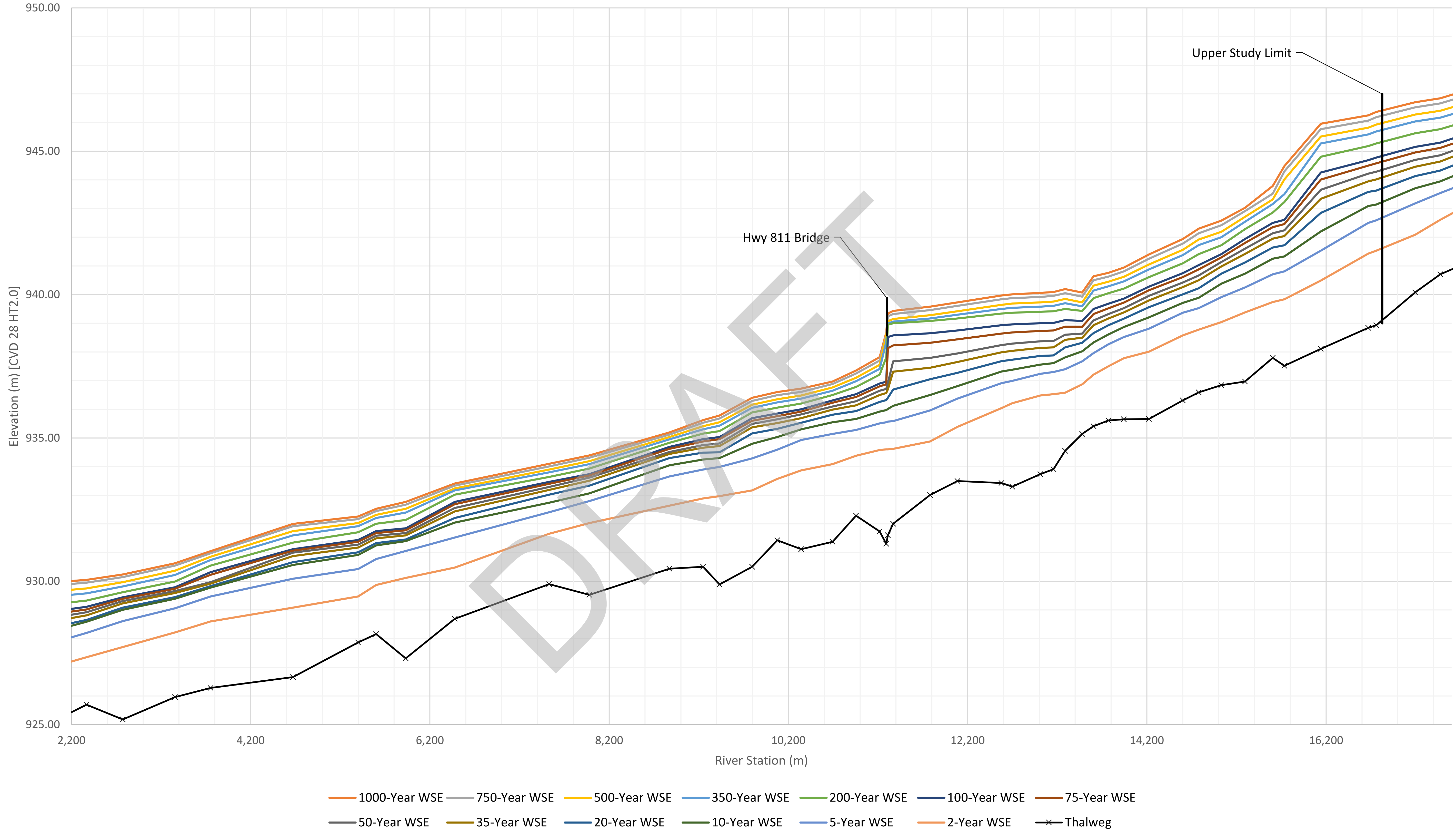


Figure 8 Flood profile for range of flood flows, Willow Creek

Classification: Public

4.3.6 Model Sensitivity

The sensitivity of the open water hydraulic model to adjustments in boundary conditions, and Manning's roughness values were evaluated. These parameters affect the computed water surface profiles, and by direct result, predicted flood depths and inundation limits. The sensitivity analysis provides an indication of the plausible range of error in the model results and identifies the relative importance of each parameter to the overall error. When selecting the range of plausible parameters to test during the model sensitivity analyses, consideration was given to the variability of the factors with season and discharge. The 100-year flood was used as the baseline for the sensitivity analyses.

A summary of the sensitivity analysis results is provided below. All the sensitivity analysis profiles are tabulated in **Appendix G**.

Results from the model validation and sensitivity analysis should be reviewed and understood prior to using the model and simulation results.

Boundary Conditions – Upstream

Since the flow is subcritical the upstream boundary condition is the inflow. The lower and upper limits of the 95% confidence interval for the 100-year instantaneous peak discharges (as shown in **Table 10** and **Table 12**) were examined in the sensitivity analysis. **Table 19** provides a summary of the deviation from the 100-year flood levels for the lower 95% limit discharge and the upper 95% limit discharge of the Oldman River and Willow Creek. Water surface elevations are presented in **Appendix G (Table G1)** and profiles are illustrated in **Figure 9** and **Figure 10.**

Table 19 Sensitivity analysis results for variation in 100-year flood magnitude

River	Difference from Baseline Profile (m)			
	Lower Flood Frequency Estimates		Higher Flood Frequency Estimates	
	Maximum	Average	Maximum	Average
Oldman River	-0.4	-0.3	0.5	0.3
Willow Creek	-1.6	-0.4	1.3	0.4

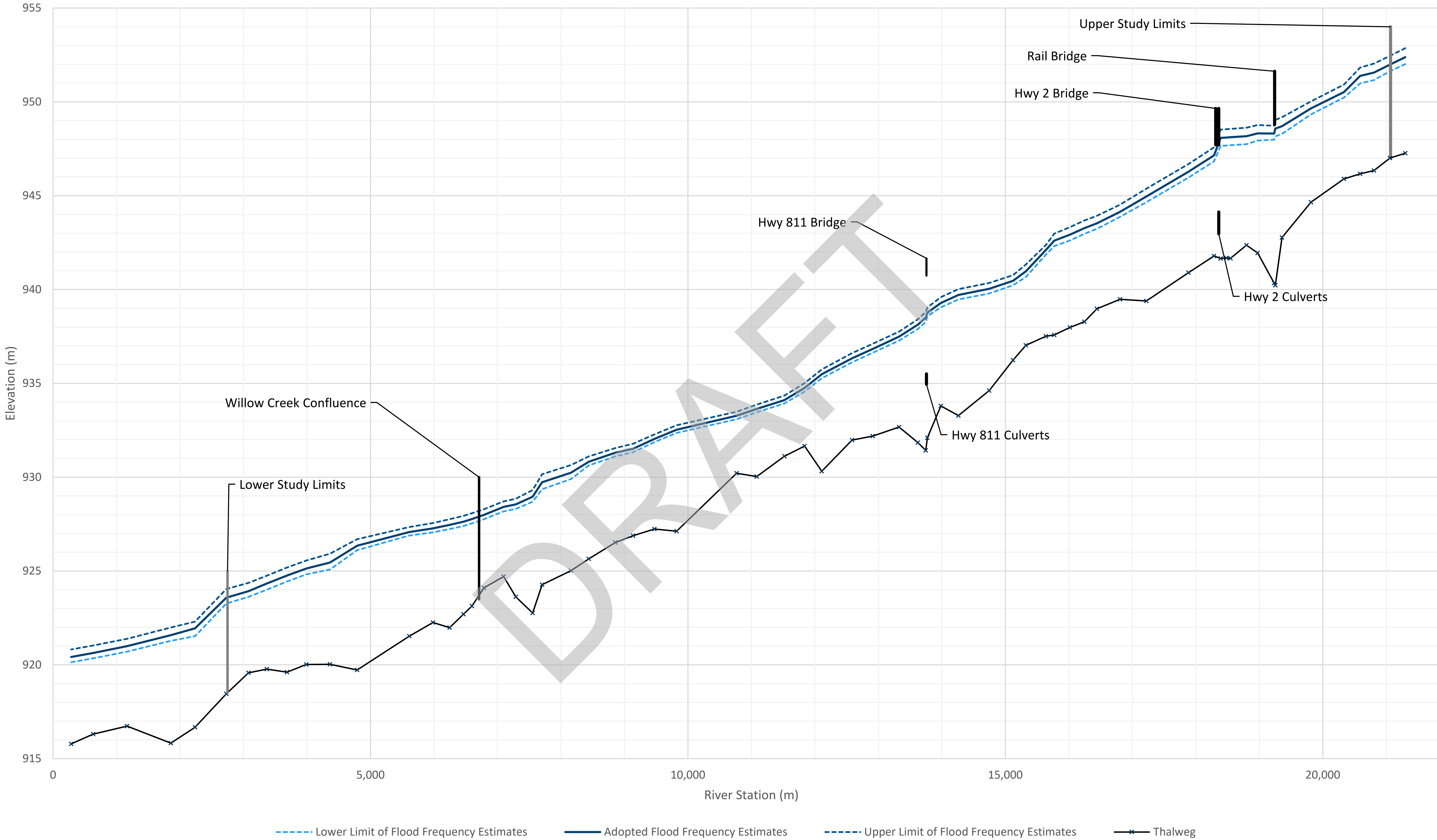


Figure 9 Simulated 100-year water surface profile sensitivity to flood magnitude, Oldman River

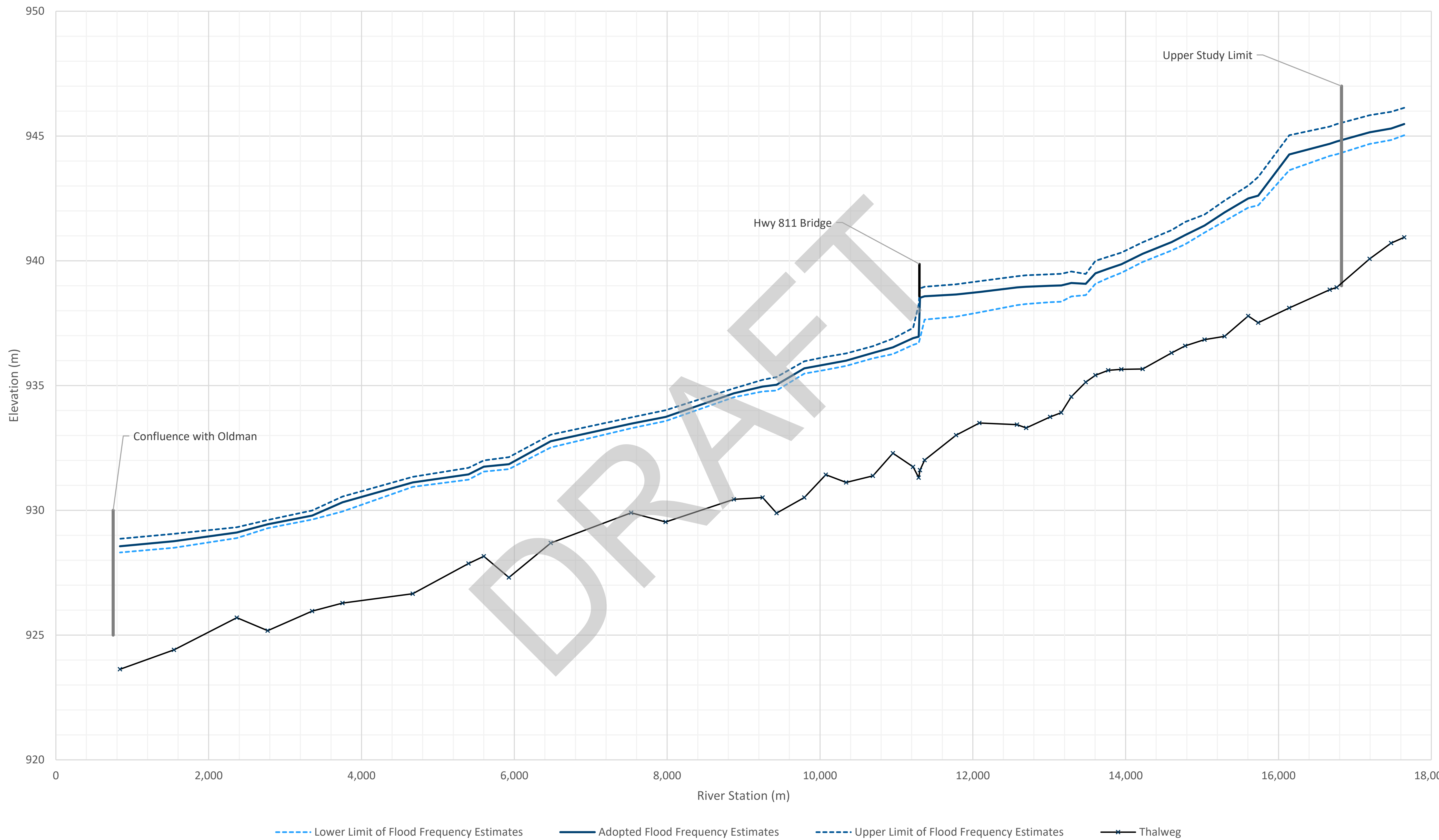


Figure 10 Simulated 100-year water surface profile sensitivity to flood magnitude, Willow Creek

Willow Creek is the most sensitive to changes in flood estimation with average deviations from the baseline 100-year profile reaching 0.4 m and maximum deviations reaching 1.6 m. The average and maximum deviations from the baseline profile on Oldman River reaches 0.4 m and 0.5 m, respectively.

Boundary Conditions - Downstream

The downstream boundary condition is the downstream water level, either implicitly provided or input as a slope. In the base model, the downstream boundary condition was set to a normal depth (slope) of 0.001 m/m based on the energy grade slope at the downstream end of the model (based on initial simulations). At the 100-year flood frequency discharge, the full range of plausible energy grade slopes for the entire model was taken and applied to the downstream boundary. The results are presented in **Appendix G** (**Table G2**).

The water surface elevation profiles for the selected slope, a low slope (high water level), and greater slope (lower water level) are plotted for Oldman River on **Figure 11**. The deviation from the calibrated profile has impact up to river station 1,855 m for both the high and low energy grade slopes (stationing is measured from the downstream end of the model). This is below the study boundary limits, and therefore the boundary conditions are not expected to influence the model results.

The downstream boundary for Willow Creek is the water level within Oldman River and hence is dependent solely on the simulation results.

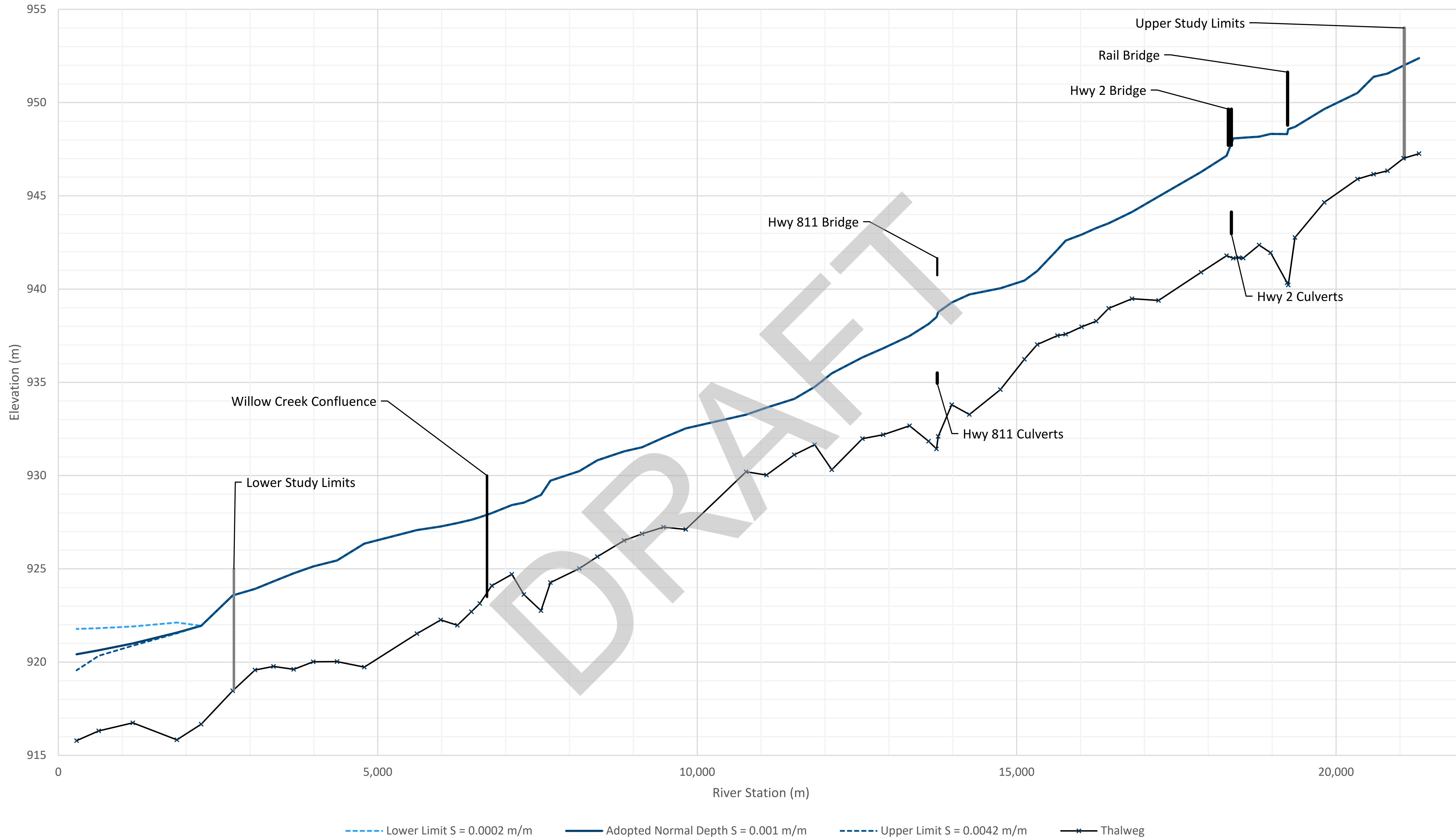


Figure 11 Simulated 100-year water surface profile sensitivity to downstream boundary condition, Oldman River

Manning's Roughness

The sensitivity of the model to Manning's roughness was evaluated. Channel roughness was examined independently of overbank roughness. The sensitivity of a lower and higher Manning's roughness was examined for all the modelled reaches. The results of the sensitivity analysis are discussed below.

The sensitivity of computed 100-year flood levels to overbank roughness was evaluated by selecting low and high roughness coefficients for each of the modelled river reaches. These plausible values were generally within 20% of the overbank roughness values adopted for the base model considering seasonal variations in vegetation growth and density. For the low and high roughness sensitivity runs, the overbank roughness values were adjusted by ± 20% to reflect this range (**Table 20**). The sensitivity analysis was run concurrently Oldman River and Willow Creek.

Table 20 Overbank roughness values used in sensitivity analysis

Land Cover Type	Overbank Roughness		
	Base	Low (-20%)	High (+20%)
Islands / Bars	0.042	0.034	0.050
Lakes or ponded water	0.024	0.019	0.029
Light vegetation	0.045	0.036	0.054
Dense vegetation	0.1	0.080	0.120
Grass	0.036	0.029	0.043
Urban	0.07	0.056	0.084

Table 21 presents a summary of the results of the 100-year computed flood level sensitivity analysis for varying overbank roughness values. Water surface elevations for each case are presented in **Table G3** in **Appendix G** and profiles are plotted on **Figure 12** and **Figure 13**.

Table 21 Sensitivity analysis results for variation in overbank roughness

River	Difference from Baseline Profile (m)			
	Low Roughness (-20%)		High Roughness (+20%)	
	Maximum	Average	Maximum	Average
Oldman River	-0.28	-0.13	0.22	0.12
Willow Creek	-2.23	-0.18	0.17	0.09

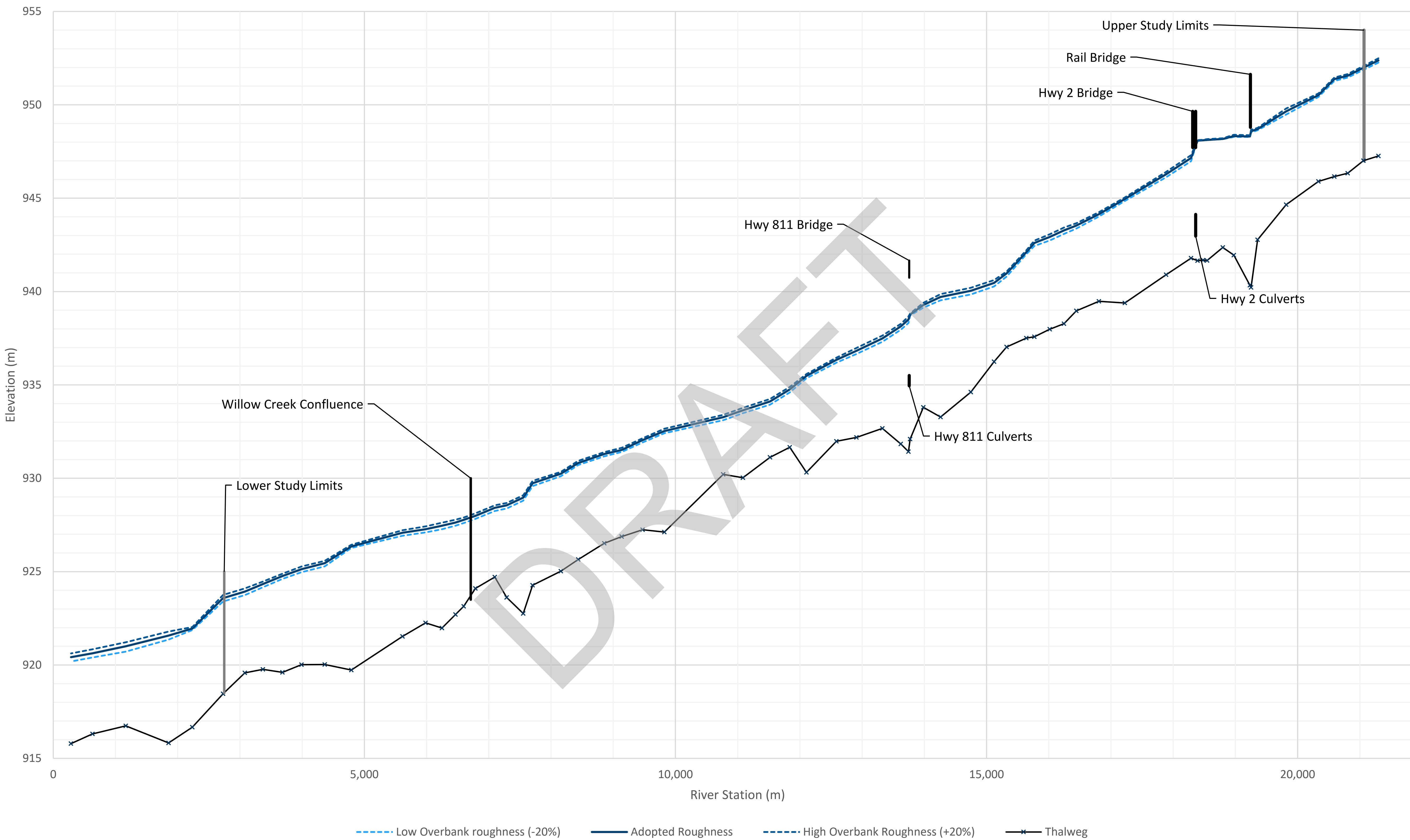


Figure 12 Simulated 100-year water surface profile sensitivity to overbank roughness, Oldman River

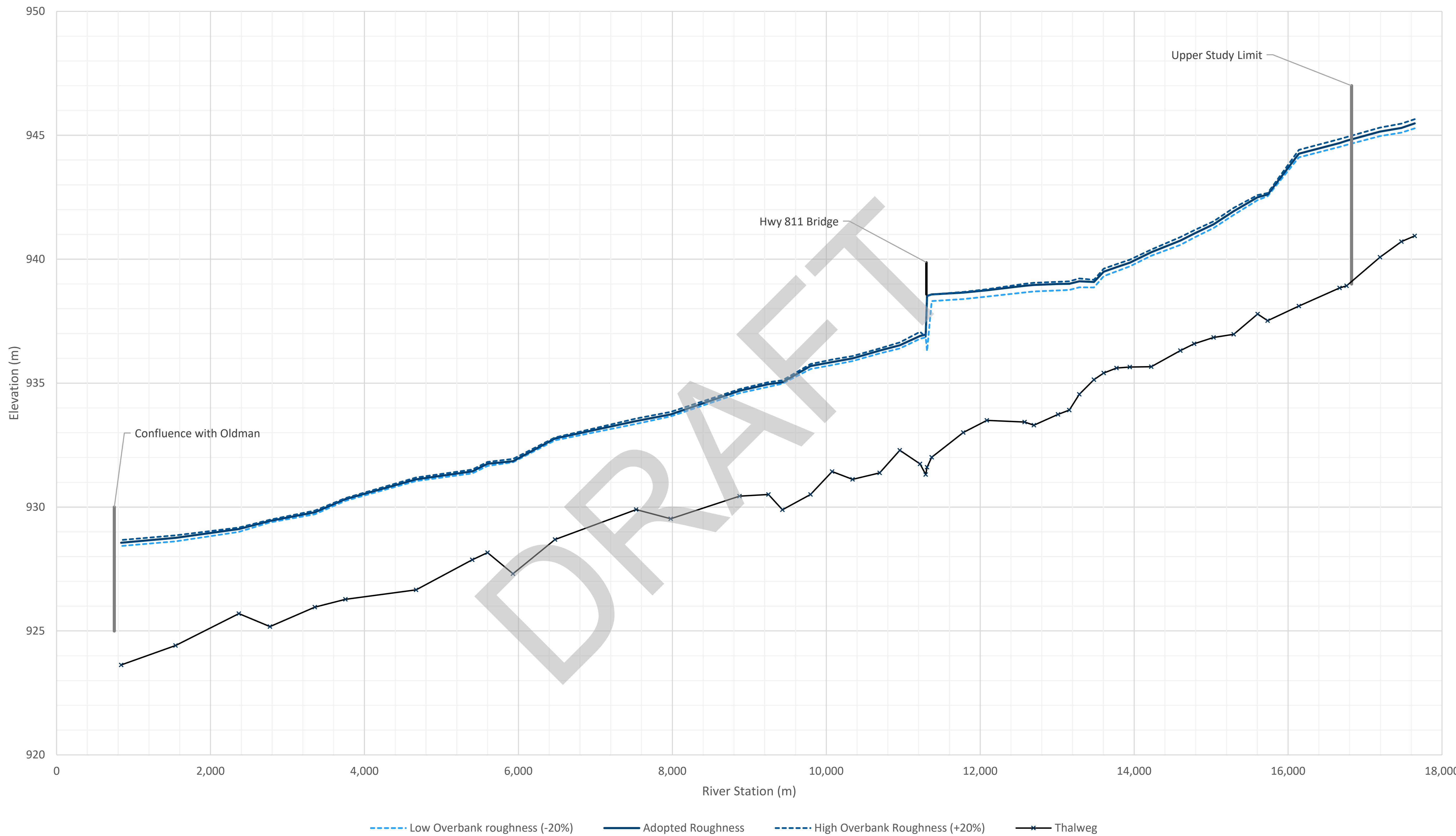


Figure 13 Simulated 100-year water surface profile sensitivity to overbank roughness, Willow Creek

On average, flood levels were 0 to 0.13 m below base values for low overbank roughness. For high overbank roughness, computed flood levels were on average between 0 and 0.12 m above base values.

The channel roughness on Oldman River and Willow Creek was 0.033 except for where the spurs exist near Highway 811 crossing. A plausible range of channel roughness for the modelled length of Oldman River and Willow Creek is considered to be approximately 0.028 to 0.038 (15% of the calibrated roughness). For the low and high roughness sensitivity runs, the channel roughness value was adjusted by ±15% to reflect this range. The sensitivity analysis was run concurrently for Oldman River and Willow Creek using the values summarized in **Table 22.**

Table 22 Channel roughness values used in sensitivity analysis

River	Reach	Channel Roughness		
		Base	Low (-15%)	High (+15%)
Oldman River	KM 000	0.026	0.022	0.030
Oldman River	KM 006	0.026	0.022	0.030
Oldman River	Spurs	0.065	0.075	0.055
Willow Creek	All	0.026	0.022	0.030

Table 23 provides a summary of the deviation from the 100-year flood levels for low and high channel roughness for reaches of Oldman River and Willow Creek. Water surface elevations for each creek are presented in **Table G4 in Appendix G** and profiles are illustrated in **Figure 14** and **Figure 15.**

Table 23 Sensitivity analysis results for variation in main channel roughness

River	Difference from Baseline Profile (m)			
	Low Roughness (-15%)		High Roughness (+15%)	
	Maximum	Average	Maximum	Average
Oldman River	-0.27	-0.07	0.20	0.06
Willow Creek	-0.18	-0.05	0.30	0.06

Both Oldman River and Willow Creek have average deviations from the baseline 100-year profile reaching 0.06 m and maximum deviations reaching 0.27 m and 0.18 m, respectively.

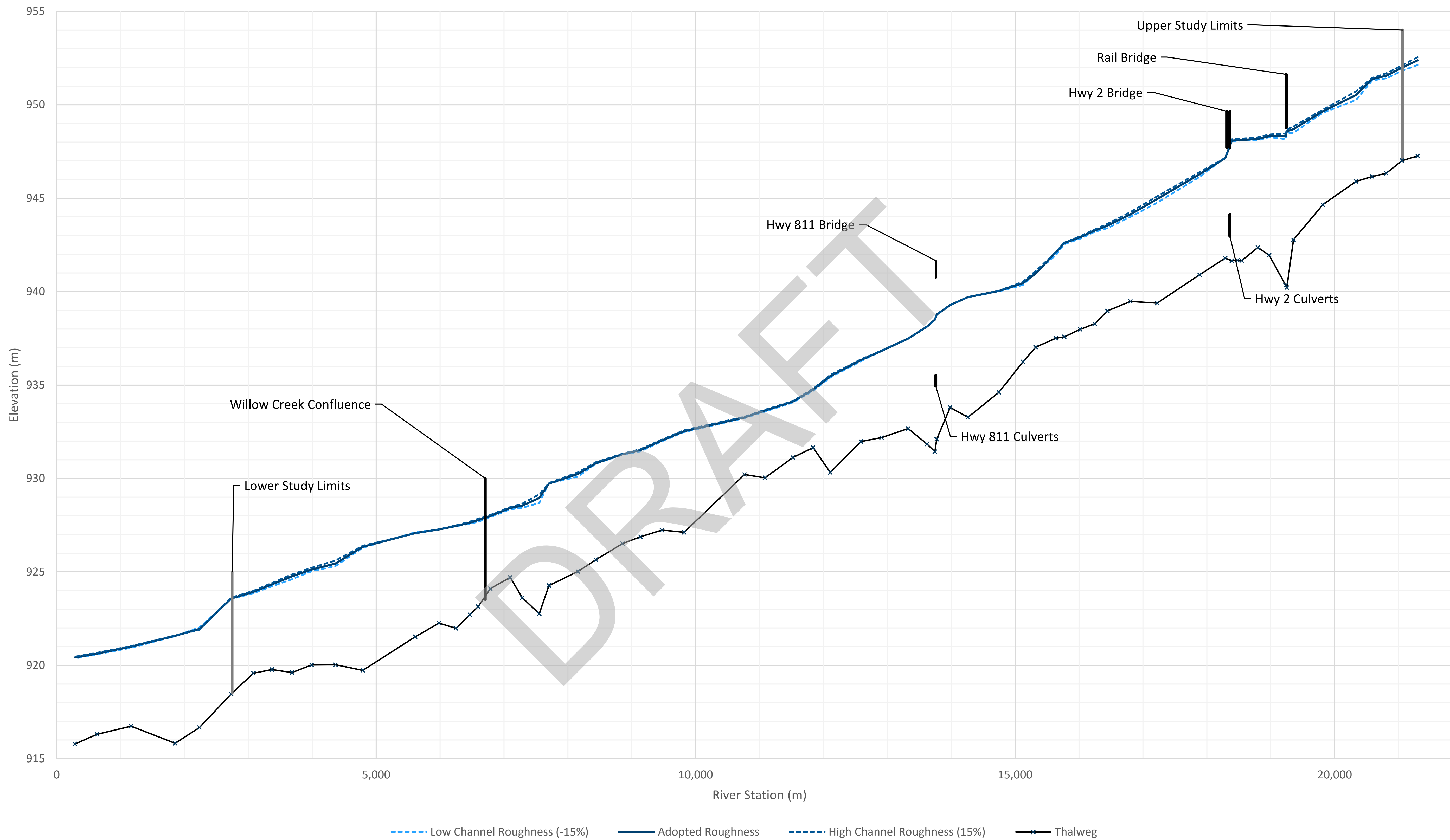


Figure 14 Simulated 100-year water surface profile sensitivity to channel roughness, Oldman River

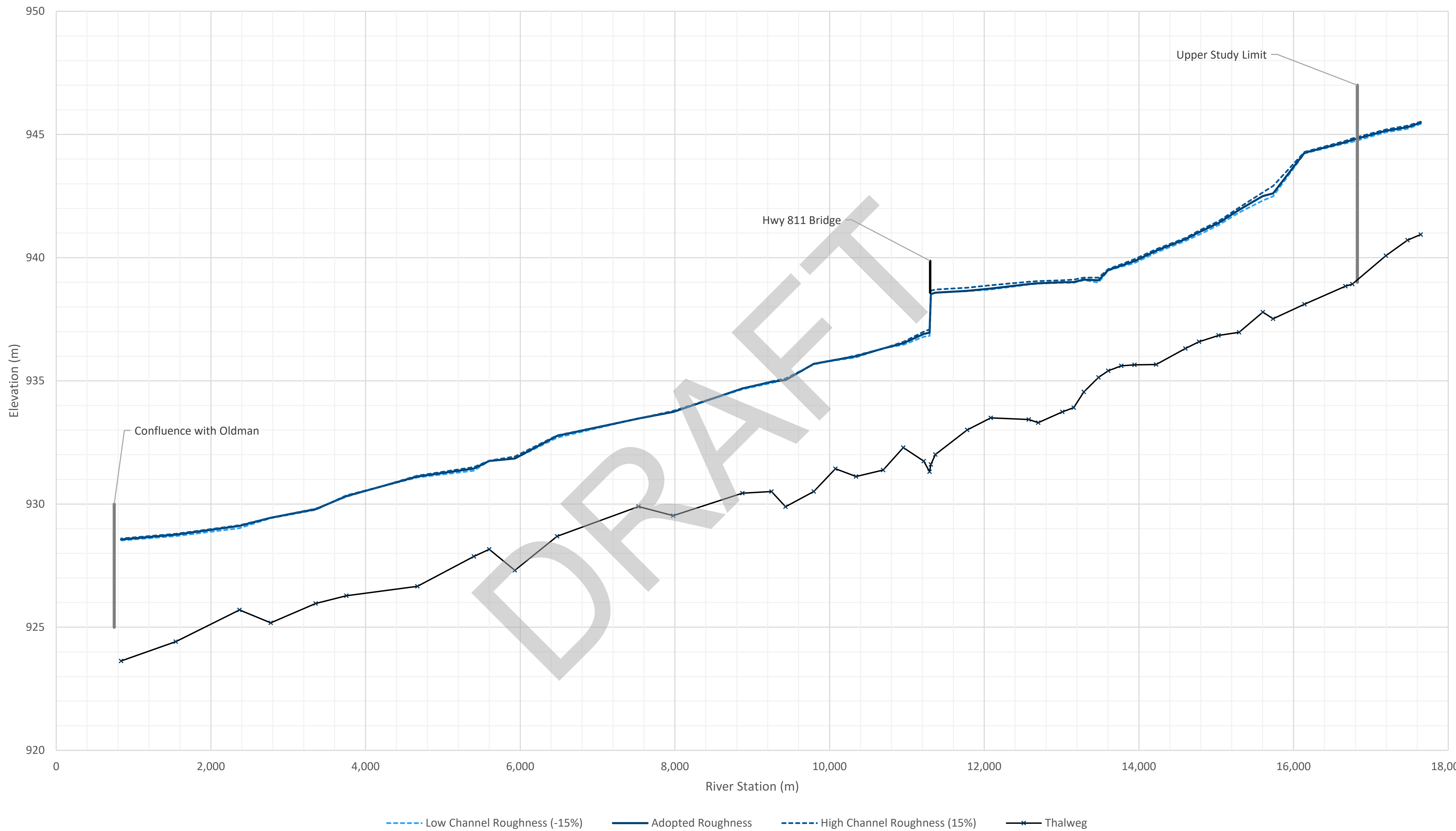


Figure 15 Simulated 100-year water surface profile sensitivity to channel roughness, Willow Creek

5 FLOOD INUNDATION MAPS

Flood inundation mapping shows areas of ground that could be covered by water under one or more flood scenarios for existing conditions. For this study, one flood inundation map series was created for each of the 13 flood frequency return periods from the 2-year through 1000-year scenarios. Additional information concerning the flood inundation map production is provided below.

5.1 Methodology

The methodology used to create the flood inundation maps followed four basic steps.

- Create a water surface elevation (WSE) triangular irregular network (TIN) representing a contiguous flood level profile along the modelled river reaches.
- Generate a WSE grid with the same grid geometry as the underlying DTM. Assign elevation values to each grid cell based on the corresponding value taken from the WSE TIN.
- Generate a depth grid (with the same grid geometry as the WSE grid) by subtracting elevation values from the underlying DTM from the corresponding WSE grid value. Negative depth values represent dry cells and were assigned a value of *NoData*.
- Generate inundation polygons based on the depth grids by converting depths greater than 0 m into inundation polygons.

The inundation polygons were further processed by smoothing, filtering out wetted areas that were not directly inundated (“isolated” areas), and removing very small dry areas, with the following additional steps:

- Some apparently isolated areas were retained as they were connected to direct inundation via culverts. There are no railway embankments in the study area that impact the delineation of inundation polygons.
- Very small dry areas (“holes”) with areas less than 100 m^2 were mapped as if inundated.
- A PAEK smoothing algorithm was applied with a 20 m tolerance. Inundation extent boundary locations were maintained at each cross section during the automated smoothing process.
- Following smoothing, polygons were reviewed and edited to ensure that extents for smaller flood frequency scenarios were not greater than extents for higher scenarios.

The inundation polygons were then used to clip the WSE grids and depth grids to the final inundation extents. Since the LiDAR-derived DTM indicates the approximate water surface elevation at the time of the LiDAR survey for submerged portions of riverbeds and other ground covered by water, depth values in those areas should not be considered accurate.

All the WSE TINs, WSE grids, depth grids and inundation polygons are in standard Esri file format and were created using standard ArcGIS tool sets.

5.2 Water Surface Elevation TIN Modifications

During preliminary mapping, major areas of backwater that have non-trivial consequences to residents and landowners were identified. Areas connected to the channel at one distinct location (overtopping point) were adjusted such that the water surface elevation across that area was set equal to the water surface elevation at the overtopping point. This generally reduced the size of the inundated area extending upstream of an overtopping point and increased the size of the inundated area extending downstream of the overtopping point, in comparison to using the water surface elevation projected from the adjacent channel. In a few instances, these adjustments resulted in a new reconnection point forming downstream. In these cases, the water surface elevations in the backwater area were re-adjusted such that they were interpolated linearly between the upstream overtopping point and the ground elevation at the new downstream reconnection point. Where necessary, water surface adjustments took into account the configuration of extents for higher and lower flood frequency scenarios to ensure consistency between inundation extents for different return periods.

5.3 Flood Inundation Areas

Flood inundation areas were identified as either being part of the actively-flowing river channel or flooded overbank areas connected to the actively-flowing river channel. At the 5-year through 50-year return periods, culverts on the right bank of Oldman River in the vicinity of Highway 2 connect apparently isolated areas to the direct inundation extent. There are no railway embankments or flood control structures in the study area that would impact the delineation of inundation areas.

All adjustments were made to the water surface tins so that inundation polygons could be re-generated from the data using the procedure described in **Section 5.1** above.

6 FLOODWAY DETERMINATION

Flood hazard identification involves the delineation of floodway and flood fringe zones for a specified design flood. A description of key terms from the FHIP Guidelines (Alberta Environment, 2011), incorporating technical changes implemented in 2021 regarding how floodways are mapped in Alberta, is provided in Sections 6.1 and 6.2 below.

6.1 Design Flood Selection

The design flood for open water flood hazard identification in Alberta is typically associated with a natural (non-regulated) peak instantaneous discharge that has a one percent chance of being equaled or exceeded in any given year. This is a flood with a statistical 100-year return period, also commonly referred to as the "one in one hundred year flood".

The 100-year flood was selected as the open water naturalized design flood for the Oldman River and Willow Creek. The discharge values used for the open water design flood correspond to the 100-year return period discharges listed in **Table 10** and **Table 12.**

6.2 Floodway & Flood Fringe Terminology

Flood Hazard Mapping

Flood hazard mapping identifies the area flooded for the design flood and is typically divided into floodway and flood fringe zones. Flood hazard maps can also show additional flood hazard information, including areas of high hazard within the flood fringe and incremental areas at risk for more severe floods, like the 200-year and 500-year floods. Flood hazard mapping is typically used for long-term flood hazard area management and land-use planning.

Flood hazard area

The flood hazard area is the area of land that will be flooded during the design flood. It is composed of the floodway and the flood fringe zones, which are defined below.

Floodway

When a floodway is first defined on a flood hazard map, it typically represents the area of highest flood hazard where flows are deepest, fastest, and most destructive during the design flood. The floodway generally includes the main channel of a stream and a portion of the adjacent overbank area. Previously mapped floodways do not typically become larger when a flood hazard map is updated, even if the flood hazard area gets larger or design flood levels get higher.

Flood Fringe

The flood fringe is the portion of the flood hazard area outside of the floodway. The flood fringe typically represents areas with shallower, slower, and less destructive flooding during the design flood. However, areas with deep or fast-moving water may also be identified as high hazard flood fringe within the flood fringe. Areas at risk behind flood berms may also be mapped as protected flood fringe areas.

Design Flood Levels

Design flood levels are the computed water levels associated with the design flood.

6.3 Flood Hazard Identification

6.3.1 Floodway Determination Criteria

In areas being mapped for the first time, the floodway typically represents the area of highest hazard where flows are deepest, fastest, and most destructive during the design flood. The following criteria, based on those described in current FHIP guidelines, are used to delineate the floodway in such cases:

- Areas in which the depth of water exceeds 1 m or the flow velocities are greater than 1 m/s shall be part of the floodway.
- Exceptions may be made for small backwater areas, ineffective flow areas, and to support creation of a hydraulically smooth floodway.
- In no case should the floodway boundary extend into the main river channel area.
- For reaches of supercritical flow, the floodway boundary should correspond to the edge of inundation or the main channel, whichever is larger.

When a flood hazard map is updated, an existing floodway will not change in most circumstances. Exceptions to this would be: (1) a floodway could get larger if a main channel shifts outside of a previously defined floodway or (2) a floodway could get smaller if an area of previously defined floodway is no longer flooded by the design flood.

Areas of deeper or faster moving water outside of the floodway are identified as high hazard flood fringe. These high hazard flood fringe zones are identified in all areas, whether they are newly mapped or have an existing floodway.

The selected floodway limiting stations and limiting criteria for each cross section are listed in **Table I1** in **Appendix I**. The limits of the floodway (also denoted as the floodway boundary) intersect cross sections at the floodway limiting stations. The exception occurs when the floodway limits are coincident with the inundation limits. This condition typically occurs when a floodway limiting station (defined by the usual criteria) is very close to the extent of inundation and there is no practical width of flood fringe – along steep valley walls or high slopes, for example. In these cases, the floodway limiting station corresponds to the station of the water edge and an inundation limit condition is noted in the table.

The floodway limit lines extending between cross sections were delineated based on the adjacent limiting criteria and drawn such that the resulting lines followed a *hydraulically smooth* path. For previously mapped reaches, an existing floodway from the 1991 flood study was adopted with adjustments for the aforementioned exceptions and direction provided by AEP. For newly mapped reaches, the lines mostly followed along the 1 m depth contour. In some instances, the floodway limits extended into depths less than 1 m where velocities were high. When the width of the flood fringe was impractically small, the floodway was drawn coincident with the water's edge.

6.3.2 Design Flood Profile

The design flood profile levels were those calculated for the 100-year open water flood condition. The resulting design flood level values are listed in **Appendix I**. **Figure 16** and **Figure 17** depict the open water design flood level profile for Oldman River and Willow Creek.

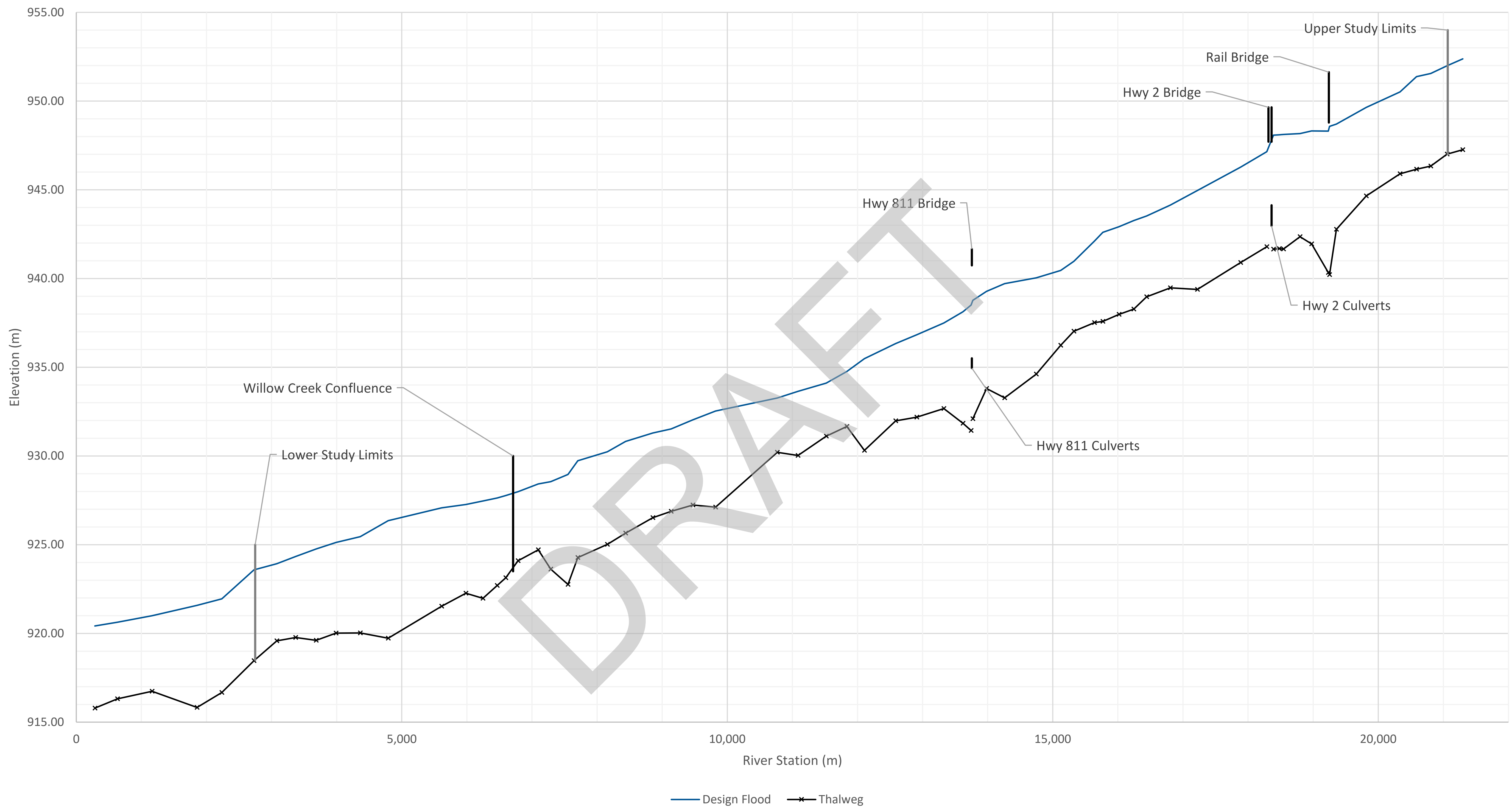


Figure 16 Open water design flood profiles – Oldman River

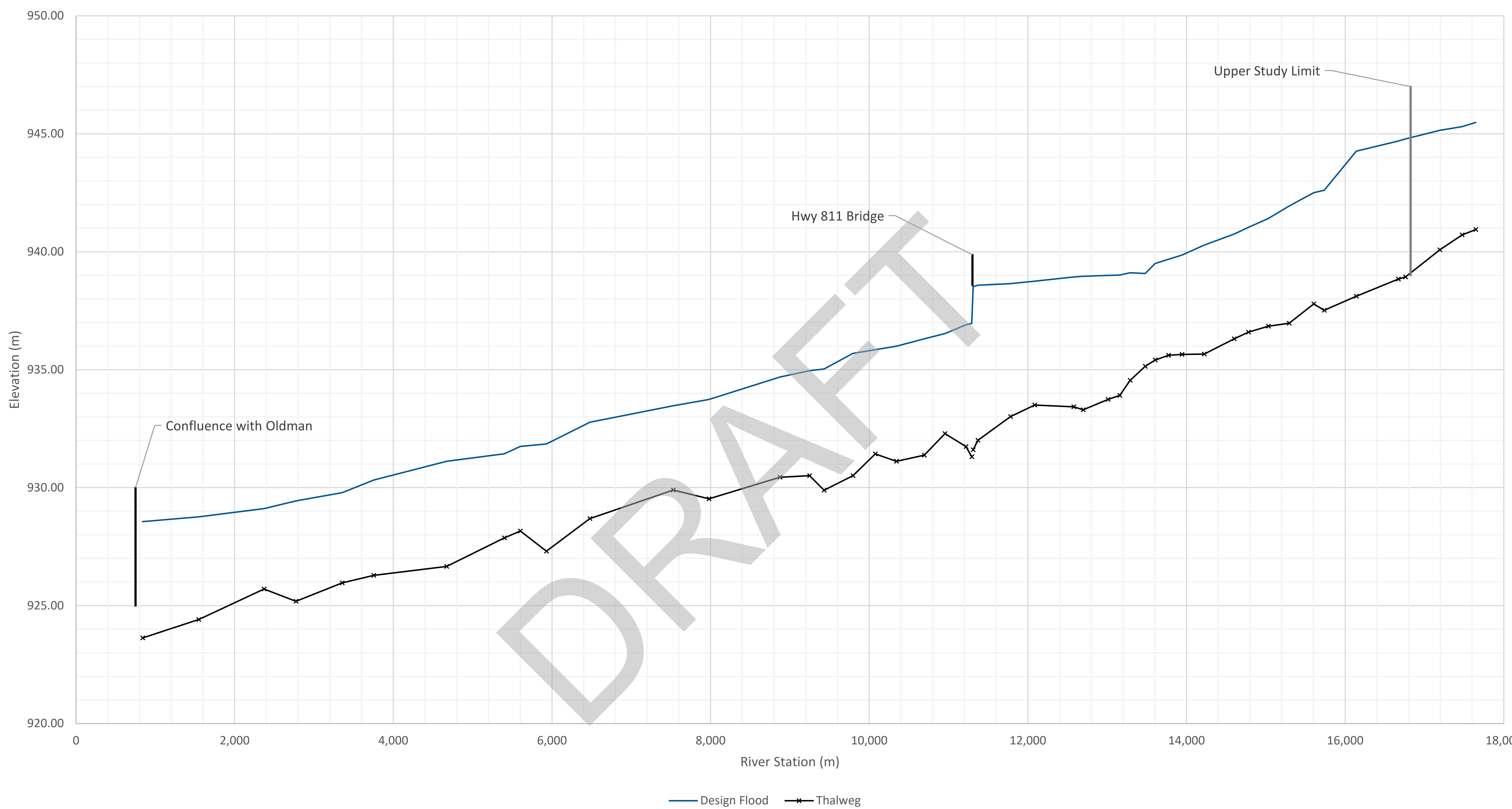


Figure 17 Open water design flood profiles – Willow Creek

6.3.3 Floodway Criteria Maps

The floodway criteria maps are a tool for determining floodway and flood fringe extents for the design flood, including boundaries of high hazard flood fringe and protected flood fringe areas. The mapping exercise began with the computed water surface elevations and flow velocities for the open water design flood. The extent of inundation was then mapped using the general procedure described in **Section 5.1**. This procedure included generation of the corresponding water surface elevation (WSE) triangular irregular network (TIN), WSE grid, and flood depth grid.

Inundated areas where the depth of water is 1 m or greater and the 1 m depth contours were derived from the flood depth grid. The depth contours were then filtered and smoothed using the same parameters and procedures as those applied to the inundation extents.

Since a one-dimensional computational modelling approach was used for this study, flow velocities were only available at the cross section locations. Channel and overbank discharge were discretized into up to 45 sub-sections along each cross section based on the computed water level and a weighted flow area approach. This provides a means to estimate the variation in velocity across a section. For this study, the maximum number of velocity subsections were specified in the overbanks. The velocity values for each segment along the cross sections were symbolized on the floodway criteria maps to visualize the transverse variation in velocity along each cross section.

The open water floodway criteria maps are provided in **Appendix J**. The information documented on the maps includes:

- inundation extents for the open water design flood;
- areas where the depth of water is 1 m or greater and the corresponding 1 m depth contour;
- the portions of each cross section where the computed velocity is 1 m/s or faster;
- the floodway limiting stations s and the floodway boundaries associated with the floodway limiting criteria;
- the previous-mapped floodway boundary (where it exists);
- stranded areas of dry ground within the flood hazard area; and
- the location and extent of all cross sections used in the HEC-RAS model.

6.3.4 Flood Hazard Maps

The flood hazard maps divide the design flood extents into floodway and flood fringe zones, including boundaries of high hazard flood fringe. The information used to create the flood hazard maps was based on the open water floodway criteria mapping information detailed in the **Section 6.3.3** above.

The limits of the flood fringe followed the extent of direct inundation of the open water design flood. Areas of high ground within the extent of direct inundation (and outside of the floodway) were preserved and were not indicated as flood fringe in the flood hazard map.

The resulting governing flood hazard maps are provided as **Appendix K**. All metadata for GIS Layers used in analysis are provided in **Appendix L**.

Areas in the Floodway

Notable overbank areas in the floodway include:

- The eastern part of Daisy May Campground;
- Properties south of Hwy 811 on the left bank of the Oldman River;
- McNab pit near Hwy 811; and
- Residences on the right bank of Willow Creek west of Hwy 811 bridge.

Areas in the High Hazard Flood Fringe

The high hazard flood fringe includes all inundated areas outside the floodway but within the deeper or faster moving water. Notable inundated areas within the high hazard flood fringe include:

- Park area and campground on south side of Hwy 2 bridge;
- Properties and residences south west of Hwy 2 bridge;
- Properties south of Hwy 811 on the left bank of Oldman River; and
- Properties on the left bank of Willow Creek west of Hwy 811 bridge.

Areas in the Flood Fringe

The flood fringe includes all inundated areas outside the limits of the floodway and high hazard flood fringe. Inundated areas of note within the flood fringe include:

- Residences near the Highway 811 bridge over Oldman River;
- The western park of Daisy May Campground; and
- Residences near Hwy 2 bridge on the south side.

7 POTENTIAL CLIMATE CHANGE IMPACTS

This section provides a summary of a qualitative interpretation of climate and hydrologic projections obtained from the scientific literature that would be pertinent to evaluating future changes in flood hazards in the study area.

Current global climate models indicate that temperature will increase in the upper South Saskatchewan River (SSR) basin due to projected increases in CO_2 concentrations in the atmosphere. In fact, by applying a linear trend to seasonal mean temperatures for the period from 1948 to 2016, it has been found that across the Canadian prairies mean temperature has increased 3.1°C in winter, 2.0°C in spring, and 1.8°C in summer (Bush and Lemmen, 2019). The same Environment and Climate Change Canada (ECCC) study predicts mean temperature across the prairies to increase an additional 1.9 (RCP 2.6) to 6.5°C (RCP 8.5) by the end of this century.

Similarly, (Bush and Lemmen, 2019) suggests that seasonal precipitation from 1948 to 2012 has changed by -5.9% in winter, 13.6% in spring, and 8.4% in summer; and is projected to increase annually by 5.9% (RCP 2.6) to 15.3% (RCP 8.5) by the end of this century. More concerning with respect to flood events, is that extreme precipitation is projected to increase across the prairies. The projected changes in annual maximum 24-hour precipitation for the Canadian prairie provinces to the end of this century, based on RCP 2.6 and RCP 8.5 is 5.1 to 17.5% for the 10-year, 6.0 to 19.1% for the 20-year, and 6.5 to 21.3% for the 50-year return period event (Bush and Lemmen, 2019). This may suggest that the 50-year event has a magnitude closer to the current 200-year event by the end of the century. However, the Oldman River and Willow Creek watersheds are relatively large withs floods resulting from a combination of rainfall and snowmelt. Despite the projected sizable increasing in precipitation over the next 80 years, the snowpack may also be substantially reduced as winter temperatures are projected to increase and spring snowpack is likely to be less.

A previous study conducted by NHC on the Elk River; a similarly sized channel located on the other side of the Rocky Mountain Divide, suggested that climate changes to the year 2100 is expected to impact the 200-year and 500-year flood flows with an increase of less than 10%. This relatively small increase in extreme flood flow in comparison to the project increase in precipitation is a result of the accompanying reduction in spring snowpack (NHC, 2019).

- Additional studies, more specific to the SSR, suggest the following impacts of climate change to the end of the current century; peak flows in the SSR is projected to increase by as much as 20% (Poitras et al., 2011) ;
- mean spring flows on the Oldman River are projected to increase by 29% (Islam and Gan, 2015)
- summer flows (July through August) could decrease by as much as 50% (DFO, 2013)
- variable projections for annual mean flow in the Oldman River and SSR ranging from -18% to +12% (Martz et al., 2007; Poitras et al., 2011);

In general, temperature and precipitation are projected to increase with climate change. However, the complexity of potential changes in snowpack and timing of events (intense rain during period of snowmelt) results in high uncertainty in the projected change in peak flows. The level of uncertainty if further increased when considering potential changes in land cover and resulting impacts to snowpack and runoff; such as loss of tree cover and soil changes associated with beetle infestation, wildfires, and changing land use. What is evident from review of the previous studies is that consideration of flood flows should account for increasing uncertainty when being projected to the future.

8 CONCLUSIONS

The objectives of this study were to assess river flood-related hazards along 19 km of Oldman River reach, and 15 km of Willow Creek reach that includes the Town of Fort Macleod and District of Willow Creek. The Oldman River Flood Hazard Study was divided into six components. This report summarizes the work of survey and base data collection, open water hydraulic modelling, open water flood inundation mapping, and design flood hazard mapping. The numerical model has been developed using the HEC-RAS computer program from the U.S. Army Corps of Engineers. River bathymetry and digital terrain data as well as flood frequency estimates from the ***Open Water Hydrology Assessment*** (NHC, 2019) component have been used to develop, calibrate, and apply the open water hydraulic model as described throughout this report. The report for the ***Open Water Hydrology Assessment*** mentioned above should also be read in conjunction with this report, as it provides additional pertinent background information.

Historically, a number of open water floods have occurred on the Oldman River. The largest recorded flood event on Oldman River was the June 1995 flood (peak discharge 3,230 m^3/s). The 1995 event was adopted for model calibration of the Oldman River reach with the 2013, 1991, and 1986 event as validation. The simulated water surface profiles agreed well with the measured high water marks with an average difference of 0.22 m below the 1995 flood event, 0.04 m below the 2013 flood event, 0.27 m above the 1991 flood event, and 0.39 m above the 1986 flood event. Willow Creek was calibrated to the 2013 flood event as it was the only event with measured HWMs. The simulated water surface profiles agreed well with the measured high water marks with an average difference of 0.27 m.

Water surface profiles were prepared for the 2-, 5-, 10-, 20-, 35-, 50-, 75-, 100-, 200-, 350-, 500-, 750-, and 1000-year open water flood frequency return period discharges. These profiles show that the road and rail deck elevations for bridges crossing the Oldman River are expected to be above the 1000-year flood level, but Hwy 2 bridge and the rail bridge lower chord is are expected to be under water at flows larger than the 75-year. The approach roads for Hwy 811 on the Oldman River is inundated in floods greater than the 5-year and Hwy 2 approach road expected to be inundated at flows greater than the 20-year. On Willow Creek, the bridge is not overtopped but the low chord of the bridge is under water in flows greater than the 100-year and the approach road from the north is inundated at flows greater than the 50-year.

Sensitivity of simulated water levels to various model parameters was investigated. Channel roughness in Oldman River and Willow Creek were shown to have greater effect on predicted 100-year flood levels than downstream boundary condition or overbank roughness within the range of plausible values. Based on the available data, calibration results, and sensitivity analysis, the open water HEC-RAS hydraulic model produces reliable water levels throughout the study reach for a wide range of discharges up to the 1000-year return period event. The model includes all pertinent physical features and the most up-to-date bathymetry and terrain data available as at the time of writing of this report. As such, the calibrated HEC-RAS model is considered appropriate for open water flood inundation map production.

The open water flood inundation maps and flood hazard maps provide information that can be used by provincial and local authorities to assist in emergency preparedness planning for future flood events. The flood hazard maps delineate the flood fringe, high hazard flood fringe, and the floodway which helps identify the properties most affected by deep water or high velocity. There are no flood control structures in the study reach for this project. However, some residential and non-residential structures may be impacted by Oldman River floods that have return periods of 10 years and greater.

REFERENCES

AENV (1985). *Flood Frequency Analysis of Oldman River at Town of Fort Macleod*. Alberta Environment.

AENV (1991). *Oldman River at Fort Macleod Flood Risk Mapping Study*. Alberta Department of the Environment - Water Resrouce Management Service: Technical Services Division.

AENV (1995a). *1995 Flood Frequency Analysis for South Saskatchewan River Basin – Draft Report*. (an internal document from Alberta Environment). Alberta Environment.

AENV (1995b). *Oldman River Flood at Fort Macleod - Aerial Imagery*.

Airborne Imaging (2020). *AEP 8 Sites - LiDAR Acquisition and Processing - 2018* (15152). 52 pp.

Alberta Environment and Parks (AEP) (2019). Geodetic control unit. [online] Available from: https://www.alberta.ca/geodetic-control-unit.aspx (Accessed 13 March 2020).

Alberta Government (2014). Flood Hazard Identification Program. [online] Available from: https://open.alberta.ca/publications/flood-hazard-identification-program-fact-sheet (Accessed 16 March 2020).

Alberta Transportation (1995). *Oldman R. - Hwy 2:08, 2km West of Fort Macleod - Flood of June 7, 1995*.

Brunner, G. W. (2016). *HEC-RAS River Analysis System. Hydraulic Reference Manual. Version 5.0*. Davis, CA.

Bush, E., and Lemmen, D. S. (2019). *Canada's Changing Climate Report, Government of Canada, ON, 444p*.

Calgary Herald (2013, 21 June). A history of southern Alberta flooding from 1897 to the present. *Calgary Herald*.

Chow, V. T. (1959). *Open Channel Hydraulics*. McGraw-Hill Book Company, New York.

Cowan, W.L. (1956). Estimating hydraulic "roughness coefficients." *Agricultural Engineering*, 37(7), 473–475.

DFO (2013). *Risk-based Assessment of Climate Change Impacts and Risks on the Biological Systems and Infrastructure within Fisheries and Ocean Canada's mandate – Freshwater Large Aquatic Basin*. Science Response 2013/011. Fisheries and Oceans Canada. 43 pp.

Glenbow Museum Archive (1902). Glenbow Western Research Center - Fort Macleod Flood History.

Islam, Z., and Gan, T. Y. (2015). Potential combined hydrologic impacts of climate change and El Niño Southern Oscillation to South Saskatchewan River Basin. *JOURNAL OF HYDROLOGY - AMSTERDAM-*, 523, 34–48.

Kellerhals, R., Neill, C. R., and Bray, D. I. (1972). *Hydraulic and Geomorphic Characteristics of Rivers in Alberta* (72–1). River Engineering and Surface Hydrology Report. Research Council of Alberta. 54 pp.

Martz, L., Bruneau, J., and J.T. Rolfe (2007). *Climate Change and Water*. SSRB Final Technical Report.

Natural Resources Canada (2020). CSRS-PPP, Tools and Applications. [online] Available from: https://www.nrcan.gc.ca/maps-tools-publications/tools/geodetic-reference-systems-tools/tools-applications/10925#ppp (Accessed 13 March 2020).

NHC (2019). *Fort Macleod Flood Hazard Study: Open Water Hydrology Report* (3004660). Prepared by Northwest Hydraulic Consultants for Alberta Environment and Parks, North Vancouver, BC. 58 pp.

OGL Engineering (2019). *Fort Macleod River Hazard Aerial Imagery Memo*.

Poitras, V., Sushama, L., Seglenieks, F., Khaliq, M. N., and Soulis, E. (2011). Projected Changes to Streamflow Characteristics over Western Canada as Simulated by the Canadian RCM. *Journal of Hydrometeorology*, 12(6), 1395–1413. doi:10.1175/JHM-D-10-05002.1.

Provincial Archives of Alberta (1876). Heritage Resources Management Information System (HeRMIS) - Fort Macleod, Alberta. Heritage Resources Management Information System (HeRMIS) - Fort

Macleod, Alberta. [online] Available from:
https://hermis.alberta.ca/paa/PhotoGalleryDetails.aspx?st=Fort+Macleod+Flood&ReturnUrl=%2fpaa%2fSearch.aspx%3fst%3dFort%2bMacleod%2bFlood&dv=True&DeptID=1&ObjectID=A5460.

Appendix A: Survey Baseline Information

Baseline Processing Report

Project file data		Coordinate System	
Name:	\\mainfile-van\Projects\Active\3004660 Fort Macleod FHS\94 Field Data\00 Survey\2_Data Reduction\2019-04-29_ControlSurvey.vce	Name:	Canada/NAD 1983
Size:	66 KB	Datum:	NAD 1983 (Canada)
Modified:	2019-04-30 5:26:06 PM (UTC:-6)	Zone:	CM114W
Time zone:	Mountain Standard Time	Geoid:	Canada Geoid Model HT2_0
Reference number:		Vertical datum:	
Description:		Calibrated site:	
Comment 1:			
Comment 2:			
Comment 3:			

Processing Summary

Observation	From	To	Solution Type	H. Prec. (Meter)	V. Prec. (Meter)	Geodetic Az.	Ellipsoid Dist. (Meter)	ΔHeight (Meter)
ASCM79343 --- ASCM293795 (B1)	ASCM79343	ASCM293795	Fixed	0.003	0.009	113°19'54"	3780.095	-21.832
ASCM79343 --- NHC2 (B2)	ASCM79343	NHC2	Fixed	0.003	0.008	111°25'56"	1725.763	-21.344
ASCM293795 --- NHC2 (B3)	NHC2	ASCM293795	Fixed	0.004	0.009	114°56'35"	2056.077	-0.493
NHC2 --- NHC1 (B4)	NHC2	NHC1	Fixed	0.004	0.009	251°47'59"	4172.035	19.266
ASCM79343 --- NHC1 (B5)	ASCM79343	NHC1	Fixed	0.004	0.008	230°36'41"	3049.057	-2.070
ASCM293795 --- NHC1 (B6)	ASCM293795	NHC1	Fixed	0.004	0.011	265°44'28"	5843.897	19.769
NHC2 --- NHC3 (B7)	NHC2	NHC3	Fixed	0.003	0.010	61°03'55"	4657.641	11.526
ASCM79343 --- NHC3 (B8)	ASCM79343	NHC3	Fixed	0.004	0.013	74°02'56"	5909.532	-9.810
ASCM293795 --- NHC3 (B9)	ASCM293795	NHC3	Fixed	0.003	0.011	35°21'01"	3824.948	12.020

Acceptance Summary

Processed	Passed	Flag	Fail
9	9	0	0

Project File Data		**Coordinate System**	
Name:	\\mainfile-van\Projects\Active\3004660 Fort Macleod FHS\94 Field Data\00 Survey\2_Data Reduction\2019-04-29_ControlSurvey.vce	Name:	Canada/NAD 1983
Size:	66 KB	Datum:	NAD 1983 (Canada)
Modified:	2019-04-30 5:26:06 PM (UTC:-6)	Zone:	CM114W
Time zone:	Mountain Standard Time	Geoid:	Canada Geoid Model HT2_0
Reference number:		Vertical datum:	
Description:		Calibrated site:	
Comment 1:			
Comment 2:			
Comment 3:			

Network Adjustment Report

Adjustment Settings

Set-Up Errors

GNSS

Error in Height of Antenna:	0.000 m
Centering Error:	0.000 m

Covariance Display

Horizontal:

Propagated Linear Error [E]:	U.S.
Constant Term [C]:	0.000 m
Scale on Linear Error [S]:	1.960

Three-Dimensional

Propagated Linear Error [E]:	U.S.
Constant Term [C]:	0.000 m
Scale on Linear Error [S]:	1.960

Adjustment Statistics

Number of Iterations for Successful Adjustment:	2
Network Reference Factor:	0.78
Chi Square Test (95%):	Passed
Precision Confidence Level:	95%
Degrees of Freedom:	15

Post Processed Vector Statistics

Reference Factor:	0.78
Redundancy Number:	15.00
A Priori Scalar:	1.00

Control Coordinate Comparisons

Values shown are control coordinates minus adjusted coordinates.

Point ID	ΔEasting (Meter)	ΔNorthing (Meter)	ΔElevation (Meter)	ΔHeight (Meter)
ASCM293795	-0.001	0.000	0.018	?
NHC1	-0.012	0.024	0.008	?
NHC2	0.009	0.013	0.048	?
NHC3	-0.005	0.008	-0.013	?

Control Point Constraints

Point ID	Type	East σ (Meter)	North σ (Meter)	Height σ (Meter)	Elevation σ (Meter)
ASCM79343	Grid	Fixed	Fixed		Fixed
Fixed = 0.000001(Meter)					

Adjusted Grid Coordinates

Point ID	Easting (Meter)	Easting Error (Meter)	Northing (Meter)	Northing Error (Meter)	Elevation (Meter)	Elevation Error (Meter)	Constraint
ASCM293795	45807.627	0.001	5510492.167	0.001	935.488	0.005	
ASCM79343	42325.303	?	5511961.984	?	957.291	?	ENe
NHC1	39984.198	0.001	5510008.909	0.002	955.171	0.005	
NHC2	43936.490	0.001	5511344.022	0.001	935.967	0.004	
NHC3	47993.993	0.001	5513630.303	0.001	947.577	0.006	

Adjusted Geodetic Coordinates

Point ID	Latitude	Longitude	Height (Meter)	Height Error (Meter)	Constraint
ASCM293795	N49°43'49.08548"	W113°21'52.43289"	919.682	0.005	
ASCM79343	N49°44'37.57908"	W113°24'45.75102"	941.515	?	ENe
NHC1	N49°43'34.93671"	W113°26'43.40940"	939.445	0.005	
NHC2	N49°44'17.16086"	W113°23'25.52377"	920.175	0.004	
NHC3	N49°45'30.04790"	W113°20'01.86606"	931.702	0.006	

Adjusted ECEF Coordinates

Point ID	X (Meter)	X Error (Meter)	Y (Meter)	Y Error (Meter)	Z (Meter)	Z Error (Meter)	3D Error (Meter)	Constraint
ASCM293795	-1638428.575	0.002	-3792618.698	0.003	4844154.661	0.004	0.005	
ASCM79343	-1641166.075	?	-3790204.279	?	4845139.769	?	?	ENe
NHC1	-1643914.971	0.002	-3790621.360	0.003	4843887.131	0.004	0.005	
NHC2	-1639877.410	0.002	-3791271.581	0.003	4844715.752	0.003	0.005	
NHC3	-1635455.366	0.002	-3791317.388	0.004	4846179.814	0.004	0.006	

Error Ellipse Components

Point ID	Semi-major axis (Meter)	Semi-minor axis (Meter)	Azimuth
ASCM293795	0.002	0.001	169°
NHC1	0.002	0.002	8°
NHC2	0.002	0.002	173°
NHC3	0.002	0.002	162°

Adjusted GNSS Observations

Observation ID		Observation	A-posteriori Error	Residual	Standardized Residual
NHC2 --> NHC1 (PV4)	**Az.**	251°47'59"	0.077 sec	-0.008 sec	-0.184
	ΔHt.	19.270 m	0.005 m	0.004 m	1.436
	Ellip Dist.	4172.034 m	0.001 m	-0.002 m	-1.932
ASCM293795 --> NHC1 (PV6)	**Az.**	265°44'28"	0.057 sec	-0.041 sec	-1.149
	ΔHt.	19.764 m	0.005 m	-0.005 m	-1.516
	Ellip Dist.	5843.899 m	0.001 m	0.001 m	1.704
ASCM79343 --> NHC2 (PV2)	**Az.**	111°25'56"	0.157 sec	-0.078 sec	-0.835
	ΔHt.	-21.340 m	0.004 m	0.003 m	1.504
	Ellip Dist.	1725.763 m	0.001 m	0.000 m	0.551
ASCM79343 --> NHC3 (PV8)	**Az.**	74°02'56"	0.051 sec	0.040 sec	1.306
	ΔHt.	-9.813 m	0.006 m	-0.003 m	-0.671
	Ellip Dist.	5909.532 m	0.001 m	0.000 m	-0.541
NHC2 --> ASCM293795 (PV3)	**Az.**	114°56'35"	0.135 sec	0.094 sec	1.081
	ΔHt.	-0.494 m	0.005 m	0.000 m	-0.171
	Ellip Dist.	2056.076 m	0.001 m	-0.001 m	-1.282
NHC2 --> NHC3 (PV7)	**Az.**	61°03'55"	0.062 sec	-0.014 sec	-0.466
	ΔHt.	11.527 m	0.006 m	0.001 m	0.505
	Ellip Dist.	4657.642 m	0.001 m	0.001 m	0.988
ASCM79343 --> NHC1 (PV5)	**Az.**	230°36'41"	0.097 sec	0.049 sec	0.983
	ΔHt.	-2.070 m	0.005 m	0.000 m	-0.106
	Ellip Dist.	3049.057 m	0.001 m	0.000 m	-0.187
ASCM79343 --> ASCM293795 (PV1)	**Az.**	113°19'54"	0.071 sec	-0.005 sec	-0.123
	ΔHt.	-21.834 m	0.005 m	-0.002 m	-0.913
	Ellip Dist.	3780.095 m	0.001 m	0.000 m	0.023
ASCM293795 --> NHC3 (PV9)	**Az.**	35°21'01"	0.076 sec	-0.026 sec	-0.624
	ΔHt.	12.021 m	0.006 m	0.000 m	0.099
	Ellip Dist.	3824.948 m	0.001 m	0.000 m	0.231

Covariance Terms

From Point	To Point		Components	A-posteriori Error	Horiz. Precision (Ratio)	3D Precision (Ratio)
ASCM293795	ASCM79343	**Az.**	293°22'07"	0.071 sec	1 : 3036588	1 : 3030552
		ΔHt.	21.834 m	0.005 m		
		ΔElev.	21.803 m	0.005 m		
		Ellip Dist.	3780.095 m	0.001 m		
ASCM293795	NHC1	**Az.**	265°44'28"	0.057 sec	1 : 4237394	1 : 4238749
		ΔHt.	19.764 m	0.005 m		
		ΔElev.	19.683 m	0.005 m		
		Ellip Dist.	5843.899 m	0.001 m		
ASCM293795	NHC2	**Az.**	294°57'46"	0.135 sec	1 : 1619236	1 : 1617754
		ΔHt.	0.494 m	0.005 m		
		ΔElev.	0.479 m	0.005 m		
		Ellip Dist.	2056.076 m	0.001 m		
ASCM293795	NHC3	**Az.**	35°21'01"	0.075 sec	1 : 2803389	1 : 2813018
		ΔHt.	12.021 m	0.006 m		
		ΔElev.	12.089 m	0.006 m		
		Ellip Dist.	3824.948 m	0.001 m		
ASCM79343	NHC1	**Az.**	230°36'41"	0.097 sec	1 : 2093179	1 : 2095871
		ΔHt.	-2.070 m	0.005 m		
		ΔElev.	-2.120 m	0.005 m		
		Ellip Dist.	3049.057 m	0.001 m		
ASCM79343	NHC2	**Az.**	111°25'56"	0.157 sec	1 : 1399550	1 : 1394550
		ΔHt.	-21.340 m	0.004 m		
		ΔElev.	-21.324 m	0.004 m		
		Ellip Dist.	1725.763 m	0.001 m		
ASCM79343	NHC3	**Az.**	74°02'56"	0.051 sec	1 : 4503902	1 : 4495793
		ΔHt.	-9.813 m	0.006 m		
		ΔElev.	-9.714 m	0.006 m		
		Ellip Dist.	5909.532 m	0.001 m		
NHC2	NHC1	**Az.**	251°47'59"	0.077 sec	1 : 2935217	1 : 2936671
		ΔHt.	19.270 m	0.005 m		
		ΔElev.	19.204 m	0.005 m		
		Ellip Dist.	4172.034 m	0.001 m		
NHC2	NHC3	**Az.**	61°03'55"	0.062 sec	1 : 3613616	1 : 3623943
		ΔHt.	11.527 m	0.006 m		

		ΔElev.	11.610 m	0.006 m	
		Ellip Dist.	4657.642 m	0.001 m	

Date: 2020-03-31 9:57:48 PM	Project: \\mainfile-van\Projects\Active\3004660 Fort Macleod FHS\94 Field Data\00 Survey\2_Data Reduction\2019-04-29_ControlSurvey.vce	Trimble Business Center

CSRS-PPP 2.26.0 (2019-02-25)

base11900.19o
BASE_1

Data Start	Data End	Duration of Observations
2019-04-29 22:14:42.00	2019-04-29 23:09:40.00	0:54:58
Processing Time		**Product Type**
14:25:42 UTC 2019/04/30		NRCan Rapid
Observations	**Frequency**	**Mode**
Phase and Code	Double	Static
Elevation Cut-Off	**Rejected Epochs**	**Estimation Steps**
7.5 degrees	0.00 %	2.00 sec
Antenna Model	**APC to ARP**	**ARP to Marker**
TPSGR3	L1 = 0.216 m L2 = 0.218 m	H:2.000m / E:0.000m / N:0.000m

(APC = antenna phase center; ARP = antenna reference point)

Estimated Position for base11900.19o

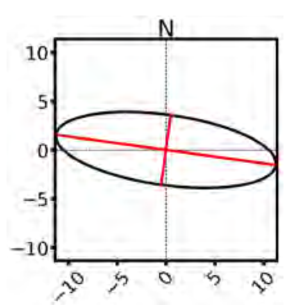
	Latitude (+n)	Longitude (+e)	Ell. Height
NAD83(CSRS) (2002)†	49° 45' 30.04816"	-113° 20' 1.86632"	931.681 m
Sigmas(95%)	0.032 m	0.090 m	0.089 m
A priori*	49° 45' 30.06811"	-113° 20' 1.94302"	930.359 m
Estimated − A priori	-0.616 m	1.535 m	1.322 m

Orthometric Height CGVD28 (HTv2.0)

947.564 m

(click for height reference information)

95% Error Ellipse (cm)
semi-major: 11.363 cm
semi-minor: 3.601 cm
semi-major azimuth: 97° 51' 52.05"



UTM (North) Zone 12

5514377.009 m (N)
331910.436 m (E)

Scale Factors
0.999947 (point)
0.999801 (combined)

*(Coordinates from RINEX header used as a priori position)

†(Epoch transformation using velocity grid NAD83v70VG)

CSRS-PPP 2.26.0 (2019-02-25)

base1190.19o
BASE_1

Data Start	Data End	Duration of Observations
2019-04-29 20:12:30.00	2019-04-29 21:48:44.00	1:36:14
Processing Time		**Product Type**
14:25:50 UTC 2019/04/30		NRCan Rapid
Observations	**Frequency**	**Mode**
Phase and Code	Double	Static
Elevation Cut-Off	**Rejected Epochs**	**Estimation Steps**
7.5 degrees	0.00 %	2.00 sec
Antenna Model	**APC to ARP**	**ARP to Marker**
TPSGR3	L1 = 0.216 m L2 = 0.218 m	H:2.000m / E:0.000m / N:0.000m

(APC = antenna phase center; ARP = antenna reference point)

Estimated Position for base1190.19o

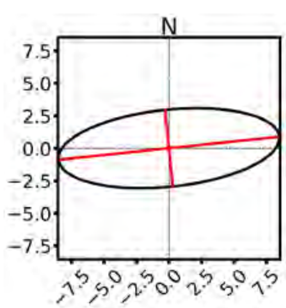
	Latitude (+n)	Longitude (+e)	Ell. Height
NAD83(CSRS) (2002)†	49° 43' 34.93751"	-113° 26' 43.40997"	939.445 m
Sigmas(95%)	0.025 m	0.068 m	0.045 m
A priori*	49° 43' 34.95713"	-113° 26' 43.48163"	941.274 m
Estimated − A priori	-0.606 m	1.435 m	-1.829 m

Orthometric Height CGVD28 (HTv2.0)

955.179 m

(click for height reference information)

95% Error Ellipse (cm)
semi-major: 8.533 cm
semi-minor: 2.959 cm
semi-major azimuth: 84° 3' 14.77"



UTM (North) Zone 12

5511078.425 m (N)
323762.008 m (E)

Scale Factors
0.999982 (point)
0.999834 (combined)

*(Coordinates from RINEX header used as a priori position)

†(Epoch transformation using velocity grid NAD83v70VG)

CSRS-PPP 2.26.0 (2019-02-25)

base1190.19o
BASE_1

Data Start	Data End	Duration of Observations
2019-04-29 20:46:04.00	2019-04-29 23:29:26.00	2:43:22
Processing Time		**Product Type**
14:26:38 UTC 2019/04/30		NRCan Rapid
Observations	**Frequency**	**Mode**
Phase and Code	Double	Static
Elevation Cut-Off	**Rejected Epochs**	**Estimation Steps**
7.5 degrees	0.00 %	2.00 sec
Antenna Model	**APC to ARP**	**ARP to Marker**
TPSGR3	L1 = 0.216 m L2 = 0.218 m	H:1.492m / E:0.000m / N:0.000m

(APC = antenna phase center; ARP = antenna reference point)

Estimated Position for base1190.19o

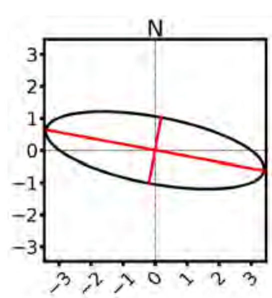
	Latitude (+n)	Longitude (+e)	Ell. Height
NAD83(CSRS) (2002)†	49° 44' 17.16130"	-113° 23' 25.52329"	920.216 m
Sigmas(95%)	0.010 m	0.027 m	0.029 m
A priori*	49° 44' 17.13230"	-113° 23' 25.59509"	919.109 m
Estimated − A priori	0.896 m	1.438 m	1.107 m

Orthometric Height CGVD28 (HTv2.0)

936.015 m

(click for height reference information)

95% Error Ellipse (cm)
semi-major: 3.467 cm
semi-minor: 1.040 cm
semi-major azimuth: 100° 32' 53.27"



UTM (North) Zone 12

5512254.628 m (N)
327764.708 m (E)

Scale Factors
0.999964 (point)
0.999820 (combined)

*(Coordinates from RINEX header used as a priori position)

†(Epoch transformation using velocity grid NAD83v70VG)

CSRS-PPP 2.26.0 (2019-02-25)

50961190.19o
2

Data Start	Data End	Duration of Observations
2019-04-29 19:46:31.00	2019-04-29 23:18:45.00	3:32:14
Processing Time		**Product Type**
16:42:57 UTC 2019/04/30		NRCan Rapid
Observations	**Frequency**	**Mode**
Phase and Code	Double	Static
Elevation Cut-Off	**Rejected Epochs**	**Estimation Steps**
7.5 degrees	0.00 %	1.00 sec
Antenna Model	**APC to ARP**	**ARP to Marker**
TRM60158.00	L1 = 0.085 m L2 = 0.081 m	H:1.831m / E:0.000m / N:0.000m

(APC = antenna phase center; ARP = antenna reference point)

Estimated Position for 50961190.19o

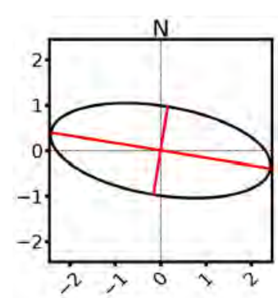
	Latitude (+n)	Longitude (+e)	Ell. Height
NAD83(CSRS) (2002)†	49° 43' 49.08549"	-113° 21' 52.43295"	919.691 m
Sigmas(95%)	0.009 m	0.019 m	0.022 m
A priori*	49° 43' 49.09796"	-113° 21' 52.56050"	922.348 m
Estimated − A priori	-0.385 m	2.554 m	-2.657 m

Orthometric Height CGVD28 (HTv2.0)

935.506 m

(click for height reference information)

95% Error Ellipse (cm)
semi-major: 2.451 cm
semi-minor: 0.978 cm
semi-major azimuth: 99° 14' 28.09"



UTM (North) Zone 12

5511328.654 m (N)
329600.374 m (E)

Scale Factors
0.999957 (point)
0.999812 (combined)

*(Coordinates from RINEX header used as a priori position)

†(Epoch transformation using velocity grid NAD83v70VG)

Classification: Public

CSRS-PPP 2.26.0 (2019-02-25)

50661191.19o
1

Data Start	Data End	Duration of Observations
2019-04-29 19:25:09.00	2019-04-29 23:39:44.00	4:14:35
Processing Time		**Product Type**
16:43:40 UTC 2019/04/30		NRCan Rapid
Observations	**Frequency**	**Mode**
Phase and Code	Double	Static
Elevation Cut-Off	**Rejected Epochs**	**Estimation Steps**
7.5 degrees	0.06 %	1.00 sec
Antenna Model	**APC to ARP**	**ARP to Marker**
TRM60158.00	L1 = 0.085 m L2 = 0.081 m	H:1.549m / E:0.000m / N:0.000m

(APC = antenna phase center; ARP = antenna reference point)

Estimated Position for 50661191.19o

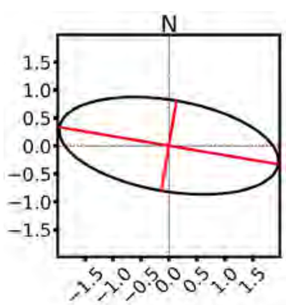
	Latitude (+n)	Longitude (+e)	Ell. Height
NAD83(CSRS) (2002)†	49° 44' 37.57912"	-113° 24' 45.75101"	941.508 m
Sigmas(95%)	0.007 m	0.016 m	0.020 m
A priori*	49° 44' 37.55836"	-113° 24' 45.87007"	943.010 m
Estimated − A priori	0.641 m	2.384 m	-1.502 m

Orthometric Height CGVD28 (HTv2.0)

957.291 m

(click for height reference information)

95% Error Ellipse (cm)
semi-major: 1.984 cm
semi-minor: 0.816 cm
semi-major azimuth: 99° 37' 18.99"



UTM (North) Zone 12

5512936.489 m (N)
326179.417 m (E)

Scale Factors
0.999971 (point)
0.999823 (combined)

*(Coordinates from RINEX header used as a priori position)

†(Epoch transformation using velocity grid NAD83v70VG)

Appendix B: Cross Section Details

Table B1 Cross Section Details – Oldman River and Willow Creek

River	Reach	River Station (m)	Survey Date	Thalweg Elevation (m)	TOB Channel Width (m)
Oldman River	KM 000	286	09-May-2019	915.79	86.16
Oldman River	KM 000	1,165	09-May-2019	916.74	86.91
Oldman River	KM 000	1,855	09-May-2019	915.83	89.45
Oldman River	KM 000	2,235	09-May-2019	916.67	84.70
Oldman River	KM 000	3,079	09-May-2019	919.58	131.99
Oldman River	KM 000	3,685	09-May-2019	919.61	116.41
Oldman River	KM 000	4,362	09-May-2019	920.03	110.43
Oldman River	KM 000	4,791	09-May-2019	919.73	82.46
Oldman River	KM 000	5,612	05, 09-May-2019	921.53	94.89
Oldman River	KM 000	5,985	05, 09-May-2019	922.26	144.84
Oldman River	KM 000	6,246	05, 09-May-2019	921.98	178.55
Oldman River	KM 000	6,465	09-May-2019	922.70	146.98
Oldman River	KM 000	6,598	04, 09-May-2019	923.14	148.70
Oldman River	KM 006	6,786	04, 09-May-2019	924.10	107.03
Oldman River	KM 006	7,098	04, 09-May-2019	924.71	145.39
Oldman River	KM 006	7,288	04, 09-May-2019	923.62	101.32
Oldman River	KM 006	7,554	04, 09-May-2019	922.76	101.48
Oldman River	KM 006	7,703	04, 09-May-2019	924.27	280.46
Oldman River	KM 006	8,157	04, 09-May-2019	925.02	105.42
Oldman River	KM 006	8,438	04, 09-May-2019	925.65	135.10
Oldman River	KM 006	9,137	04, 09-May-2019	926.88	125.46
Oldman River	KM 006	9,472	04, 09-May-2019	927.24	87.44
Oldman River	KM 006	9,821	04, 09-May-2019	927.12	135.91
Oldman River	KM 006	10,767	04, 09-May-2019	930.21	180.13
Oldman River	KM 006	11,085	03, 04, and 09-May-2019	930.03	76.90
Oldman River	KM 006	11,520	03, 04, and 09-May-2019	931.12	113.96
Oldman River	KM 006	11,838	04, 09-May-2019	931.66	148.87
Oldman River	KM 006	12,107	04, 08-May-2019	930.32	191.77
Oldman River	KM 006	12,910	04, 08-May-2019	932.19	90.41
Oldman River	KM 006	13,325	08-May-2019	932.67	142.83
Oldman River	KM 006	13,745	08-May-2019	931.43	47.45
Oldman River	KM 006	13,772	08-May-2019	932.10	57.95
Oldman River	KM 006	13,984	08-May-2019	933.80	129.31
Oldman River	KM 006	14,261	08-May-2019	933.28	91.68
Oldman River	KM 006	14,747	08-May-2019	934.61	71.43
Oldman River	KM 006	15,323	08-May-2019	937.03	96.98
Oldman River	KM 006	15,769	08-May-2019	937.58	81.95
Oldman River	KM 006	16,244	08-May-2019	938.28	195.14

River	Reach	River Station (m)	Survey Date	Thalweg Elevation (m)	TOB Channel Width (m)
Oldman River	KM 006	16,806	08-May-2019	939.48	165.91
Oldman River	KM 006	17,221	08-May-2019	939.39	87.97
Oldman River	KM 006	17,885	08-May-2019	940.90	80.99
Oldman River	KM 006	18,287	08-May-2019	941.79	118.98
Oldman River	KM 006	18,391	08-May-2019	941.65	116.45
Oldman River	KM 006	18,545	08-May-2019	941.66	160.49
Oldman River	KM 006	18,797	08-May-2019	942.36	89.47
Oldman River	KM 006	19,233	08-May-2019	940.34	78.58
Oldman River	KM 006	19,253	08-May-2019	940.22	85.48
Oldman River	KM 006	19,357	08-May-2019	942.77	68.94
Oldman River	KM 006	19,815	07-May-2019	944.65	141.46
Oldman River	KM 006	20,334	07-May-2019	945.90	103.25
Oldman River	KM 006	20,806	07-May-2019	946.34	102.28
Oldman River	KM 006	21,298	07-May-2019	947.26	95.39
Willow Creek	KM 000	839	05-May-2019	923.63	43.90
Willow Creek	KM 000	1,545	05-May-2019	924.41	60.93
Willow Creek	KM 000	2,369	05-May-2019	925.70	52.50
Willow Creek	KM 000	2,773	05-May-2019	925.18	38.44
Willow Creek	KM 000	3,355	05-May-2019	925.96	49.97
Willow Creek	KM 000	3,752	05-May-2019	926.28	38.43
Willow Creek	KM 000	4,671	05-May-2019	926.66	58.88
Willow Creek	KM 000	5,600	05-May-2019	928.16	52.94
Willow Creek	KM 000	5,929	05-May-2019	927.31	39.96
Willow Creek	KM 000	6,477	05-May-2019	928.69	55.96
Willow Creek	KM 000	7,530	05-May-2019	929.90	43.45
Willow Creek	KM 000	7,979	05-May-2019	929.53	38.40
Willow Creek	KM 000	8,873	05-May-2019	930.44	41.45
Willow Creek	KM 000	9,248	05-May-2019	930.51	52.41
Willow Creek	KM 000	9,431	05-May-2019	929.89	38.92
Willow Creek	KM 000	9,795	06-May-2019	930.51	28.91
Willow Creek	KM 000	10,076	06-May-2019	931.43	42.68
Willow Creek	KM 000	10,342	06-May-2019	931.12	39.88
Willow Creek	KM 000	10,693	06-May-2019	931.38	29.42
Willow Creek	KM 000	10,954	06-May-2019	932.29	35.92
Willow Creek	KM 000	11,219	06-May-2019	931.74	44.89
Willow Creek	KM 000	11,292	08-May-2019	931.31	39.82
Willow Creek	KM 000	11,309	08-May-2019	931.61	46.48
Willow Creek	KM 000	11,369	06-May-2019	932.01	36.40
Willow Creek	KM 000	11,780	06-May-2019	933.01	43.40

River	Reach	River Station (m)	Survey Date	Thalweg Elevation (m)	TOB Channel Width (m)
Willow Creek	KM 000	12,086	06-May-2019	933.50	38.41
Willow Creek	KM 000	12,698	06-May-2019	933.30	46.99
Willow Creek	KM 000	13,158	06-May-2019	933.91	44.47
Willow Creek	KM 000	13,478	06-May-2019	935.14	50.97
Willow Creek	KM 000	13,772	06-May-2019	935.61	59.42
Willow Creek	KM 000	14,223	06-May-2019	935.66	35.00
Willow Creek	KM 000	14,779	06-May-2019	936.59	38.92
Willow Creek	KM 000	15,294	06-May-2019	936.97	47.22
Willow Creek	KM 000	15,735	06-May-2019	937.52	32.95
Willow Creek	KM 000	16,140	06-May-2019	938.11	26.46
Willow Creek	KM 000	16,760	06-May-2019	938.93	41.09
Willow Creek	KM 000	17,474	06-May-2019	940.71	48.91

Appendix C: Hydraulic Structures Summary

Bridge Description

Name:	Hwy 811 (MacKenzie Bridge)	**AT Bridge File No.:**	01097
Watercourse:	Oldman River	**River Station (m):**	13,755.91

Geometry

Length of Span (m):	168.4	**Top of Curb/Solid Rail Elev. (m):**	941.66
Deck Width (m):	5.0	**Low Chord Elev. (m):**	939.87
Pier Type:	Concrete	**No. of Piers:**	3
Pier Shape:	triangular	**Pier Width (m):**	5.0

Photo(s)

Upstream Side of Bridge

Downstream Side of Bridge

Bridge Description

Name:	Hwy 811	**AT Bridge File No.:**	00992
Watercourse:	Willow Creek	**River Station (m):**	11,300.75

Geometry

Length of Span (m):	71.2	**Top of Curb/Solid Rail Elev. (m):**	939.87
Deck Width (m):	7.3	**Low Chord Elev. (m):**	938.58
Pier Type:	Concrete	**No. of Piers:**	2
Pier Shape:	Triangular	**Pier Width (m):**	0.62

Photo(s)

Upstream Side of Bridge

Downstream Side of Bridge

Bridge Description

Name: Hgihway 2 Bridge
AT Bridge File No.: 00756 N&S
Watercourse: Oldman River
River Station (m): 18,361.61

Geometry

Length of Span (m): 134.0
Top of Curb/Solid Rail Elev. (m): 951.07
Deck Width (m): 12.2
Low Chord Elev. (m): 949.13
Pier Type: Concrete with Steel
No. of Piers: 3
Pier Shape: Circular with Slope
Pier Width (m): 0.92

Photo(s)

Upstream Side of Bridge

Downstrea m Side of Bridge

Bridge Description

Name: Abandoned Railway Bridge
AT Bridge File No.: N/A
Watercourse: Oldman River
River Station (m): 19,248.49

Geometry

Length of Span (m): 183.1
Top of Curb/Solid Rail Elev. (m): 950.32
Deck Width (m): 4.5
Low Chord Elev. (m): 948.77
Pier Type: Concrete
No. of Piers: 5
Pier Shape: Triangular
Pier Width (m): 2.5

Photo(s)

Upstream Side of Bridge

Downstream Side of Bridge

Bridge Description

Name:	Abandoned Railway Bridge	**AT Bridge File No.:**	N/A
Watercourse:	Oldman River	**River Station (m):**	19,248.49

Geometry

Length of Span (m):	10.4	**Top of Curb/Solid Rail Elev. (m):**	952.32
Deck Width (m):	4.5	**Low Chord Elev. (m):**	951.50
Pier Type:	N/A	**No. of Piers:**	N/A
Pier Shape:	N/A	**Pier Width (m):**	N/A

Photo(s)

Upstream Side of Bridge

Downstream Side of Bridge

Culvert Description

Name:	Hwy 2 over Oldman River relic channel	**AT Bridge File No.:**	00509_1
Watercourse:	Oldman River	**River Station (m):**	18,361.61

Geometry

Length (m):	81.9	**Upstream Invert Elev. (m):**	944.13
Diameter (m):	0.9	**Downstream Invert Elev. (m):**	944.01
Culvert Material:	CSP	**Entrance Type:**	Mitered to slope
Culvert Shape:	Circular	**Entrance Condition:**	Some Vegetation

Photo(s)

Upstream Side of Bridge

Downstream Side of Bridge

Bridge Description

Name:	Hwy 2 over Oldman River relic channel	**AT Bridge File No.:**	00509_2
Watercourse:	Oldman River	**River Station (m):**	18,361.61

Geometry

Length (m):	94.3	**Upstream Invert Elev. (m):**	943.15
Diameter (m):	0.9	**Downstream Invert Elev. (m):**	942.97
Culvert Material:	CSP	**Entrance Type:**	Mitered to slope
Culvert Shape:	Circular	**Entrance Condition:**	Some Vegetation

Photo(s)

Upstream Side of Bridge

Downstream Side of Bridge

Bridge Description

Name:	Hwy 811 over Oldman River relic channel	**AT Bridge File No.:**	02062
Watercourse:	Oldman River	**River Station (m):**	13,755.91

Geometry

Length (m):	25.2	**Upstream Invert Elev. (m):**	935.03
Diameter (m):	0.9	**Downstream Invert Elev. (m):**	934.95
Culvert Material:	CSP	**Entrance Type:**	Projecting from fill
Culvert Shape:	Circular	**Entrance Condition:**	Good

Photo(s)

Upstream Side of Bridge

Downstream Side of Bridge

Bridge Description

Name:	Hwy 811 over Oldman River relic channel	**AT Bridge File No.:**	02063
Watercourse:	Oldman River	**River Station (m):**	13,755.91

Geometry

Length (m):	24.7	**Upstream Invert Elev. (m):**	935.405
Diameter (m):	0.9	**Downstream Invert Elev. (m):**	935.504
Culvert Material:	CSP	**Entrance Type:**	Projecting from fill
Culvert Shape:	Circular	**Entrance Condition:**	Good

Photo(s)

Upstream Side of Bridge

Downstream Side of Bridge

Appendix D: Reach Representative Photos

Oldman River

Oldman River (downstream view) at cross section 006_20805.94. (objId898)

Oldman River (upstream view) at cross section 006_20805.94 (obidj901)

Oldman River (upstream view) at cross section 006_19356.58(objid911)

Oldman River (downstream view) at cross section 006_19356.58 (objid913)

Oldman River (downstream view) at planned cross section 006_15768.81. (objid 449)

Oldman River (upstream view) near planned cross section 006_15638.86. (objid 458)

Oldman Rive Side Channelr (downstream view) at planned cross section 006_11085.27. (objid 827)

Oldman River Side Channel (upstream view) between planned cross section 006_11085.27 and 006_10766.55 (objid 387)

Oldman River (upstream view) near planned cross section 006_9820.63.(objid 996)

Oldman River (downstream view) at planned cross section 006_10766.55.(objid 992)

Oldman River (upstream view) at planned cross section 000_4790.93. (objid 973)

Oldman River (downstream view) at planned cross section 000_3078.91. (objid 975)

Willow Creek

Willow Creek (upstream view) between planned cross section 000_2369.10 and 000_2773.04. (objid 663)

Willow Creek (downstream view) between planned cross section 000_2369.10 and 000_2773.04 (objid 636).

Willow Creek (downstream view) at planned cross section 000_14778.88. (objid 893)

Willow Creek (upstream view) at planned cross section 000_14778.88 (objid 895).

Appendix E: Open Water Hydrology Assessment

FORT MACLEOD FLOOD HAZARD STUDY
19TDRSTR824

OPEN WATER HYDROLOGY
FINAL REPORT

Prepared for:

Alberta Environment and Parks
River Engineering and Technical Services
Edmonton, Alberta

Prepared by:

Northwest Hydraulic Consultants Ltd.
North Vancouver, British Columbia

11 October 2019

NHC Ref. No. P3004660

Prepared by:

Can Hua (Ken) Zhao, PhD, PEng
Principal

Md Makamum Mahmood, MEng, PEng
Engineer

Reviewed by:

Dale Muir, MEng, PEng
Principal

DISCLAIMER

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

1.1 Background

The Fort Macleod Flood Hazard Study was initiated by Alberta Environment and Parks (AEP) to identify and assess flood hazards along the Oldman River and Willow Creek through the town of Fort Macleod and adjacent areas of the Municipal District of Willow Creek. This study was facilitated under the Flood Hazard Identification Program (FHIP) with the intent to enhance public safety and reduce future flood damages within the Province of Alberta. Results from this study are intended to inform local land use planning decisions, flood mitigation projects, and emergency response planning.

A flood mapping study for Fort Macleod was completed in 1991 by AEP, formerly known as Alberta Environment (AENV). The present study provides an update of this work to account for additional flow data, current survey data, and contemporary methods of data collection and analysis. Further, the current study incorporates a larger study area, most notably the inclusion of Willow Creek. The current study is comprised of the following major study components:

1. Survey and Base Data Collection
2. Open Water Hydrology Assessment
3. Open Water Hydraulic Modelling
4. Open Water Flood Inundation Mapping
5. Design Flood Hazard Mapping

This report summarizes the work of the second component – ***Open Water Hydrology Assessment***.

1.2 Study Objectives

The objective of this component of the overall flood hazard study is to provide open water flood frequency estimates for the 2-, 5-, 10-, 20-, 35-, 50-, 75-, 100-, 200-, 350-, 500-, 750-, and 1000-year floods along all modelled streams under naturalized conditions. According to the terms of reference for the Fort Macleod Flood Hazard Study, the flood frequency estimates are required above and below major tributaries and at all locations where flow changes are substantial in comparison to the flood flow and hence necessary to be accounted for in the hydraulic modelling. Based on this criterion, the following locations have been selected for flood frequency estimates (location names are as per Water Survey of Canada gauge sites, where gauge sites do or did exist):

- Oldman River near Fort Macleod (WSC Station 05AB007)
- Oldman River below Willow Creek
- Willow Creek at Highway No. 811 (WSC Station 05AB046)

These locations are shown in **Figure 1**. The flood frequency estimates, which are supported by a brief description of the hydrologic characteristics of the Oldman River basin, are meant to provide a framework for the hydraulic analysis that will ultimately identify flood hazards within the study area.

1.3 Scope of Report

Flows in the Oldman River are regulated upstream of Fort Macleod by the Oldman Dam and Lethbridge Northern Irrigation District (LNID) diversion projects. Flows in Willow Creek are regulated upstream of Fort Macleod by the Chain Lakes and Pine Coulee projects. As the flow regulations could have effects on flood peaks at Fort Macleod, the flood hazard study requires flow naturalization to remove effects of the flow regulations, and subsequent flood frequency analysis under the naturalized conditions.

In presenting the development of the flood frequency estimates, this report contains the following:

- a description of the hydrologic characteristics of the study area and the prevailing flood generating mechanisms;
- routing of naturalized flows from Oldman Reservoir and Chain Lakes to Fort Macleod and the creation of naturalized annual maximum flow series at the flood frequency estimate sites listed in **Section 1.2**;
- statistical descriptions of the naturalized flood peaks, and corresponding frequency curves, at the flood frequency estimate sites; and
- a brief discussion of the effects of climate change on the flood regime.

1.4 Study Area and Reach

1.4.1 Oldman River

The Oldman River originates in the Rocky Mountains in southwestern Alberta. It generally flows in an easterly direction through the Foothills and Grassland Natural Regions and enters the South Saskatchewan River. The total length of the Oldman River is approximately 360 km. Its drainage area near the mouth is approximately 27,500 km^2 according to the Water Survey of Canada (WSC). While the river hazard study area is limited to an approximately 18.6 km long sub-reach of the Oldman River near Fort Macleod (**Figure 1**), the open water hydrologic assessment covers the entire contributing watershed upstream of Fort Macleod: an area of approximately 5,760 km^2 (the drainage area for WSC Station 05AB007), including the 4,380 km^2 drainage area upstream of Oldman Reservoir (WSC Station 05AA032). A basin map is shown in **Figure 2.**

The Oldman River is regulated by the Oldman Dam located approximately 70 km upstream of Fort Macleod. Construction of the dam was completed in 1991. About 40 km downstream of the dam, flow is withdrawn via the LNID diversion. The diversion was constructed between 1919 and 1924.

WSC monitors flows in the Oldman River downstream of the dam at Brocket (WSC Station 05AA024). Between this station and Fort Macleod, there are two major tributaries contributing to the Oldman River: Beaver Creek and Pincher Creek, which are gauged by WSC Stations 05AA004 and 05AB013. The LNID diversion is located downstream of these two tributaries and upstream of Fort Macleod. Diverted flows are recorded by WSC Stations 05AB032, 05AB018, 05AB019, 05AB020 and 05AB016.

Of the most interest for this study are annual peak events. These events usually occur in late May or June during snowmelt augmented by rainfall storms.

1.4.2 Willow Creek

Willow Creek joins the Oldman River about eight kilometers downstream of Fort Macleod. It also originates in the Rocky Mountains and generally flows in a southeasterly direction. The total drainage area of the creek is approximately 2,530 km^2. A basin map is shown in **Figure 3.** Willow Creek flows are affected by the Chain Lakes project on its main stem and, to a lesser extent, by the Pine Coulee project. These two projects are located approximately 170 km and 130 km upstream of the mouth of Willow Creek, respectively.

Chain Lakes Reservoir is located about 35 km west of Nanton, Alberta. This reservoir was formed in 1966 by constructing two earthfill dams to the north and south of a chain of three small lakes draining south to Willow Creek. The drainage area upstream of the reservoir is about 213 km^2, which represents less than 10% of the Willow Creek basin area. The north dam has a low-level outlet discharging a riparian flow to Meinsinger Creek, which flows north to the Highwood River. This outlet has a capacity of 1.8 m^3/s at Full Supply Level (FSL) of El. 1297.1 m. The south dam discharges to Willow Creek via a low-level outlet with a capacity of about 9.8 m^3/s and an uncontrolled service spillway with its crest elevation at FSL.

The Pine Coulee project is located approximately 40 km downstream of the Chain Lakes south dam. The project came into service in 1999. It diverts flows from Willow Creek through a head gate structure to Pine Coulee Reservoir on Pine Creek, which was a small intermittent tributary of Willow Creek. The diversion usually occurs between April and August. According to the flow record for Pine Coulee Diversion Canal below Head Gates (WSC Station 05AB042), the diverted daily discharges are always smaller than 10 m^3/s and representative of a relatively small percent of the Willow Creek discharges. Flow returns to Willow Creek from the reservoir via a gated low-level outlet in the main dam. According to the flow data for Pine Coulee Outflow below Reservoir (WSC Station 05AB045), the annual maximum daily discharges from Pine Coulee Dam were smaller than 8 m^3/s except in 2005. The 2005 maximum daily discharge is 19.2 m^3/s, which is the largest of the record but negligible in comparison with the Willow Creek discharge for the same event: 510 m^3/s as recorded by WSC Station 05AB041 at Oxly Ranch. **Figure 4** shows differences between daily diverted flows to Pine Coulee Reservoir and the reservoir outflows to Willow Creek from 1999 to 2014. The differences represent net changes in the Willow Creek flow due to the Pine Coulee project, with positive and negative values for decrease and increase respectively. For 98% of the time, the net changes were with ±5 m^3/s. The maximum decrease and increase were 8.4 m^3/s in 2001 and 19.2 m^3/s in 2005, respectively. These changes are negligible when compared with the magnitude of Willow Creek flows. Therefore, effects of flow regulation due to the Pine Coulee project were neglected in this study.

2 DATA COLLECTION

2.1 Available Data

Flow naturalization for the Oldman River was completed by NHC (2019) as part of the Medicine Hat River Hazard Study, based on WSC published streamflow and water level data up to 2016. The current open water hydrology assessment is based on the previous study, while the analysis is extended to include years 2017 and 2018 using additional hydrometric data obtained from WSC and AEP. The stations providing the hydrometric data used in this study are listed in **Table 1**. Their locations are shown in **Figure 2** and **Figure 3**.

Table 1: Key hydrometric stations describing Oldman River and Willow Creek flows

Type	Station No.	Station Name	Drainage Area (km^2) [1]	Period of Record
Flow	05AA024	Oldman River near Brocket	4,400	1966-2016, 2017-2018[2]
	05AB007	Oldman River near Fort Macleod	5,760	1910-1948
	05AB917	Oldman River at Highway 811		2001-2015[2], 2017-2018[2]
	05AD019	Oldman River near Monarch	8,880	1948-1969
	05AB041	Willow Creek at Oxly Ranch	833	1997-2018
	05AB021	Willow Creek near Claresholm	1,180	1908, 1944-2016, 2017-2018[2]
	05AB015	Willow Creek near Granum	2,000	1924-1931, 1935-1941
	05AB002	Willow Creek near Nolan	2,290	1909-1924, 1942-1999
	05AB046	Willow Creek at Highway No. 811	2,510	1999-2018
	05AA004	Pincher Creek at Pincher Creek	158	1910-1931, 1936, 1965-2016, 2017-2018[2]
	05AB013	Beaver Creek near Brocket	256	1921-1925, 1966-2018
	05AB032	Lethbridge Northern Irrigation District Canal at Headgates	N/A	1925-1928, 1977, 1979-1980
	05AB018	Lethbridge Northern Irrigation District Canal at Syphon Spillway	N/A	1924, 1926-1930, 1932
	05AB019	Lethbridge Northern Irrigation District Canal above Oldman Flume	N/A	1930, 1979-1980, 1986-2018
	05AB020	Lethbridge Northern Irrigation District Canal below Oldman Flume	N/A	1925-1930, 1932
	05AB016	Lethbridge Northern Irrigation District Canal at Menzaghies Bridge	N/A	1925-1930, 1932-1985
	05AB042	Pine Coulee Diversion Canal below Headgates	N/A	1999-2018
	05AB045	Pine Coulee Outflow below Reservoir	86	1999-2018
Water Level	05AA032	Oldman Reservoir near Pincher Creek	4,380	1992-2018
	05AB037	Chain Lakes Reservoir near Nanton	213	1972-2018

Notes:

1. Drainage area based on information from WSC
2. Preliminary data provided by AEP

2.2 Historic Flood Data

For the current context, historic floods refer to major floods that occurred prior the start of systematic hydrometric data collection. If the magnitude of a historic flood can be estimated based on available historic information, the estimate could be used to improve flood frequency estimates. Previous studies identified the occurrence of historic floods along the in Oldman River in 1897, 1899, 1902 and 1908 (AENV, 1991); unfortunately, no records or information suggesting magnitude of the events have been found.

2.3 Previous Flood Frequency Analysis

Previous flood frequency estimates for the Oldman River at Fort Macleod are presented in the following studies:

- Flood Frequency Analysis of Oldman River at Town of Fort Macleod by AENV (1985)
- 1995 Flood Frequency Analysis for South Saskatchewan River Basin – Draft Report from AENV (1995)

These reports have been reviewed in the preparation of this work.

3 FLOW NATURALIZATION

3.1 General Approach

Flow naturalization is a process by which anthropogenic effects, such as regulation due to storage or diversion of flow, are removed to re-create the natural flow that would have occurred in the absence of these interventions.

Flow naturalization to remove effects of the Oldman Dam, LNID diversion, and Chain Lakes projects was completed as part of the Medicine Hat River Hazard Study by NHC (2019). The study developed naturalized daily flow timeseries for the 1911 – 2016 period at various locations along the Oldman River from the dam to the South Saskatchewan River, including Oldman River near Brocket (WSC Station 05AA024), at the LNID diversion, at the Willow Creek confluence and other downstream locations. The study also provided naturalized daily flow timeseries for the 1930-2016 period at various locations along Willow Creek from Chain Lakes to the Oldman River confluence. These estimates were developed following the Project Depletion approach. In this approach, natural inflows to the Oldman and Chain Lakes reservoirs were estimated from water balance analyses and/or upstream gauge data, and flows downstream of the dams were then naturalized by routing both gauged and naturalized outflows from the dams to the study sites with gauge correction being applied. In the routing process, the gauged flows were routed first reach by reach along the main stems, together with gauged or estimated tributary inflows wherever available; the differences between the routed and recorded flows at the downstream gauge were then used to adjust the routed naturalized flows (gauge correction); and the adjusted flows were taken as the naturalized flow estimates for this downstream gauge site. The flow naturalization task also included routing of gauged, pre-regulation natural flows to estimate pre-regulation flows at downstream ungauged sites. All routing analyses were performed using a HEC-ResSim model at a daily time step. Details of the process are described in NHC (2019).

For the present study, the HEC-ResSim flow routing model from the Medicine Hat River Hazard Study (NHC, 2019) was refined to output naturalized flow estimates for Oldman River near Fort Macleod (WSC Station 05AB007), with the period of the analysis being extended to include 2017 and 2018. The structure of the updated model is illustrated in **Figure 5**. Note that the downstream reaches that were included in the original model have been removed as they are not required for the present study. The present study also provides natural flow estimates for Willow Creek at Highway No. 811 from 1910 to 1930.

The flow naturalization process and results for the present study are summarized in the following sections. Readers are encouraged to review the Medicine Hat River Hazard Study – Open Water Hydrology Assessment Report (NHC, 2019) for additional details related to the analysis described in the following sections.

Note that the flow naturalization process uses available gauge data for flow correction to reduce uncertainty in the results due to errors in routing and tributary inflow estimates. At locations where gauge data are not available (i.e. gauge correction cannot be performed), uncertainty in the naturalized flow estimates is expected to be higher and is subject to tributary inflow estimation. Different methods were used for different sites and for different periods to account for tributary inflows.

3.2 Flow Naturalization for Oldman River near Fort Macleod

Naturalized flows for Oldman River at Fort Macleod (WSC Station 05AB007) were estimated as follows:

- 1911-1922: the gauge data for Oldman River near Fort Macleod (WSC Station 05AB007) were used directly as they represent the pre-regulation natural condition.
- 1923-1930 and 1936: the natural flows for Oldman River near Brocket (WSC Station 05AA024) were routed to Fort Macleod, together with tributary inflows estimated from the available gauge data for Pincher Creek (WSC Station 05AA004) and/or Beaver Creek (WSC Station 05AB013), and gauge correction was performed based on the flow data for Oldman River near Fort Macleod (WSC Station 05AB007).
- 1933-1935 and 1937-1948: the natural flows for Oldman River near Brocket (WSC Station 05AA024) were routed to Fort Macleod without tributary inflows due to missing flow data, while gauge correction was performed based on the flow data for Oldman River near Fort Macleod (WSC Station 05AB007).
- 1949-1964: the natural flows for Oldman River near Fort Macleod were estimated by subtracting Willow Creek flows from the natural flows estimated for Oldman River near Monarch (WSC Station 05AD019); and additional details are provided later.
- 1965-2000 and 2016: the natural/naturalized flows for Oldman River near Brocket (WSC Station 05AA024) were routed to Fort Macleod, together with tributary inflows estimated from the available gauge data for Pincher Creek (WSC Station 05AA004) and/or Beaver Creek (WSC Station 05AB013); but gauge correction was not performed because of missing gauge data at the Fort Macleod site.
- 2001-2015 and 2017-2018: the naturalized flows for Oldman River near Brocket were routed to Fort Macleod, together with tributary inflows estimated from the available gauge data for Pincher Creek (WSC Station 05AA004) and Beaver Creek (WSC Station 05AB013), and flow correction was performed based on the gauge data for AEP Station 05AB917.

As described above, the Project Depletion approach uses available gauge data for flow correction to reduce uncertainty in results due to errors in routing and tributary inflow estimation. The gauge correction for the current analysis was based on the gauge data for WSC Station 05AB007 (1911-1948, missing 1931 and 1932) and AEP Station 05AB917 (2001-2018, missing 2016) at Fort Macleod. It should be noted that the discharge versus gauge height relationships for WSC Station 05AB007 and AEP Station 05AB917 are highly unstable given the frequent channel adjustments in this active braided channel in this area, and the flow data for these gauge stations may not be as accurate as for other WSC stations. Therefore, the naturalized flows for Oldman River at Fort Macleod may bear greater uncertainty than estimates for other gauged sites, such as Oldman River near Brocket. Local gauge data are not available at Fort Macleod to perform gauge correction for the 1965-2000 period and 2016; and hence estimates for those years may have slightly higher uncertainty. Nevertheless, the flow naturalization for all these periods (1911-1930, 1933-1948 and 1965-2018) accounts for tributary inflows between Brocket and Fort Macleod, which could be estimated reasonably well based on the gauge data for Pincher Creek (WSC Station 05AA004) and/or Beaver Creek (WSC Station 05AB013). Therefore, the results represent the best estimate from the available data. Annual maximum daily discharges from those estimates appear to be reasonable based on comparisons with data for upstream and downstream sites.

Although the naturalized flow routing (from the Brocket station to Fort Macleod) was also performed for 1931-1932 and 1949-1964, the results cannot be used to represent naturalized flows for Oldman River near Fort Macleod, because neither tributary inflows nor gauge correction could be estimated due to the gauge data gaps. As such, an alternative approach was undertaken. Natural flow estimates for Oldman River near Monarch (WSC Station 05AD019) are available from the HEC-ResSim model for the previous study (NHC, 2019). This discontinued gauge station was located approximately 38 km downstream of the Willow Creek confluence and about 9 km upstream of the Belly River confluence. It provides flow data for the 1948-1969 period. So, gauge correction has been included in the natural flow estimates for this station for this period. The flow travel time from the Willow Creek confluence to this station is much shorter than one day (i.e. negligible in the analysis with a daily time step). The drainage area for this station (8,880 km^2) is about 7% greater than that for the Oldman River at the Willow Creek confluence. There is no major tributary joining within this sub-reach. While local runoff could slightly increase Oldman River flows at near Monarch, attenuation through this sub-reach would tend to offset the flow increase. As such, it is reasonable to assume that the daily flows for Oldman River below Willow Creek are equal to flows near Monarch. Therefore, the 1949-1964 natural flow estimates for the Monarch station were transferred to Oldman River below Willow Creek with no adjustments. Subsequently, the differences between these estimates and naturalized Willow Creek flows were taken as the naturalized flows for Oldman River near Fort Macleod for this same period. Note that estimation for naturalized Willow Creek flows is described in **Section 3.4**.

The complete data series of natural and naturalized flows for Oldman River near Fort Macleod is shown in **Figure 6**, which covers the periods of 1911-1930 and 1933-2018. Annual peak discharges were extracted from this data series and were used to develop flood frequency estimates in **Section 4.2**.

3.3 Flow Naturalization for Oldman River below Willow Creek

The Willow Creek and Oldman River confluence is located approximately 8 km downstream of Fort Macleod. Willow Creek is the only major tributary within this Oldman River sub-reach. Its drainage area accounts for approximately 30% of the total drainage area for Oldman River below the confluence (8,350 km^2). Estimation for naturalized Willow Creek flows is described in **Section 3.4**. The naturalized daily flows for Oldman River below Willow Creek were estimated from addition of estimates for Oldman River near Fort Macleod and for Willow Creek at Highway No. 811 (WSC Station 05AB046). The resulting naturalized daily flow series covers the periods of 1911-1930 and 1935-2018 and is shown in **Figure 7**.

3.4 Flow Naturalization for Willow Creek at Highway No. 811

As described above, the NHC (2019) study provided naturalized daily flow timeseries at various locations along Willow Creek between Chain Lakes Reservoir and its confluence with the Oldman River, for the period that spans from 1930 to 2016.

For Willow Creek at Highway No. 811 (WSC Station 05AB046), the gauge correction was limited to the period of record from 2000 to 2018. Naturalized flows at this location for earlier years were estimated by prorating natural (measured) and naturalized flows for upstream gauges by drainage area ratios, for pre- and post-regulation periods respectively. The upstream gauges used include:

- Willow Creek near Nolan (WSC Station 05AB002), where measured natural flows are available for 1910-1923 and 1942-1965 (within the pre-regulation period), and naturalized flow estimates with gauge correction are available for 1966-1999 (within the post-regulation period); and
- Willow Creek near Granum (WSC Station 05AB015), which provides gauged natural flows for 1924-1930 and 1935-1941 (within the pre-regulation period).

These two stations are located approximately 32 km and 50 km upstream of the Highway 811 station (05AB046) respectively (**Figure 3**). The flow travel times to the Highway 811 station are shorter than one day (i.e. negligible in the analysis with a daily time step). The drainage areas for WSC Stations 05AB002 and 05AB015 are 2,290 km^2 and 2,000 km^2 respectively, which are only 9% and 20% smaller than that for Willow Creek at Highway No. 811 (2,510 km^2). Tributary inflows between these stations consist primarily of runoff from Porcupine Hills, which is expected to be hydrologically similar to the upper portion of the Willow Creek watershed. It is believed to be conservative while reasonable to transpose the daily flow data or estimates from these two stations to the Highway 811 station based on drainage area ratios.

The complete data series of naturalized daily flows for Willow Creek at Highway No. 811 is shown in **Figure 8**, which covers the periods of 1910-1930 and 1935-2018. Annual peak discharges were derived from this data series and were used to develop flood frequency estimates in **Section 4.3**.

4 FLOOD FREQUENCY ANALYSIS

4.1 General Approach

Frequency analysis was performed for natural/naturalized annual maximum instantaneous discharges for the sites of interest listed in **Section 1.2**. The analysis was conducted using the USACE HEC-SSP (version 2.1) flood frequency program and a spreadsheet model developed by NHC. In accordance with the Hydrologic and Hydraulic Guidelines for Flood Hazard Area Delineation by AENV (2008) and Guidelines on Flood Frequency Analysis by Alberta Transportation (AT, 2001), various theoretical probability distributions were tested, including the normal (N), log-normal (LN), three-parameter log-normal (LN3), Pearson type III (P3), log-Pearson type III (LP3), Gumbel (G), generalized extreme value (GEV), and Weibull (W) distributions. In accordance with AT (2001), the method of moments was used in the calculation of means, variances, and skew coefficients with theoretical limits being considered. The Cunnane positioning formula was used to plot data points for visualization purposes, while the Weibull plotting formula, which is another method commonly used in North America, was also used for a sensitivity test when needed.

The goodness of fit of each of the distributions, as applied to a flood series, was compared through the Kolmogorov–Smirnov test (K-S test) and a least squares method.

The K-S test can be used to compare a sample with a reference probability distribution. It quantifies a distance between the empirical probability of the sample and the cumulative distribution function of the reference distribution. The maximum distance (referenced to as D-statistic value, D_n) can be used to describe the goodness of fit: a smaller D_n value would indicate a better fit between the empirical distribution and the theoretical one.

The least squares method (Kite, 1977) is based on the sum of squared errors (*SSE*) calculated by

$$SSE = \sqrt{\frac{1}{n-m}\sum_{i=1}^{n}(x_i - y_i)^2} \qquad \textbf{(Equation 1)}$$

where n is the number of recorded events, m is the number of parameters used by a frequency distribution, x_i is the i^{th} recorded peak discharge, and y_i is the discharge computed from the frequency distribution at the probability equal to the empirical probability of discharge x_i.

The *SSE* values of the tested probability distributions were then normalized by the mean peak discharge (Q_{pm}) to provide a dimensionless *SSE*. In this approach a lower dimensionless *SSE* would indicate a better fit between the empirical distribution and the theoretical one.

Each of these methods has their own advantages and disadvantages. The D_n value from the K-S test is defined as the maximum discrepancy between the predicted probabilities (for given flood peaks) by the frequency curve and empirical probabilities from the data sample, which would usually occur in the middle part of the frequency curve. On the other hand, the *SSE* value represents the average deviation of predicted flood peaks from the measured or estimated discharges.

In this study, the applied frequency distributions were ranked first by D_n and *SSE* values separately and the sums of the rankings were then compared to derive the final combined ranking. Note, however, that using these statistical methods tends not to provide a foolproof assessment of the goodness of fit along the tails of the distributions, which are especially important in defining the return periods of severe floods. Therefore, the selection of the best representative distribution is based as much on judgement, visual assessment and Bayesian concept as it is on the statistical ranking result.

The United States Geological Survey (USGS) "Guidelines for Determining Flood Frequency" Bulletin 17B and Bulletin 17C were also reviewed and considered for the present study. The USGS Guidelines provide a framework primarily intended to standardize the methods to account for historic flood information, zero flows or low outliers, and high outliers, and methods to estimate population parameters. They use the LP3 as the base distribution for flood frequencies and recommend use of a weighted average of station skew and a regional skew. Bulletin 17C (USGS, 2018) updates Bulletin 17B (USGS, 1982), addressing known major limitations by recommending some new and ostensibly improved methods. For example, Bulletin 17C (1) improves on the approach for identification of low outliers by using a Multiple Grubbs-Beck Test to replace the Grubbs-Beck Test used in Bulletin 17B; (2) uses regional skew estimates based on the Bayesian Weighted Least Squares/Bayesian Generalized Least Squares method to replace the regional skew coefficient map in Bulletin 17B; and (3) uses the new Expected Moments Algorithm (EMA) to extend the method of moments to better handle lower outlier adjustments, regional skew information and historical information. The primary difficulty with the application of Bulletin 17C guidelines is that regional skew estimates are not available in Alberta. As a result, only the station skewness was used in the present study. Note that, when the station skewness is used and no outliers are detected in the population, the resulting Bulletin 17C curve is often identical to a standard LP3 curve based on the method of moments.

4.2 Oldman River

4.2.1 Flood Characteristics

Based on the available WSC flow records for the Oldman River, more than 90% of the annual peaks occurred in late May and June, due to snowmelt augmented by rainfall. At Fort McLeod, Oldman River flows are affected by operations of Oldman Dam (since 1991) and LNID diversion (since 1923).

Figure 9 illustrates the relationship between annual instantaneous peak (Q_i) and maximum daily (Q_d) discharges for the Oldman River near Fort Macleod. The line of best fit shown was based on the pre-regulation flow data published by WSC for Oldman River near Brocket (Stations 05AA024) and near Fort Macleod (Station 05AB007). As such, it represents the natural flow condition. It results in an instantaneous-to-daily peak discharge ratio (Q_i/Q_d ratio) of 1.18. The figure also includes regulated flow data for Oldman River near Brocket and both pre- and post-regulation flow data for WSC Station 05AD007 (Oldman River near Lethbridge), which is located approximately 100 km downstream of Fort Macleod. The linear relationship, which is based on the natural flow data recorded upstream of Fort Macleod, appears to provide a good representation for all the data points shown. As discussed later, however, this relationship is unlikely valid for the 1995 flood event near Fort Macleod.

4.2.2 Flood Frequency Analysis for Oldman River near Fort Macleod

Figure 10 and **Table 2** show the natural/naturalized annual peak flow series for Oldman River near Fort Macleod. Data for the 1911-1922 (pre-regulation) period were from the gauge record for WSC Station 05AB007. For more recent years, the annual maximum daily discharges were derived from the naturalized flow estimates presented in **Section 3.2**. Instantaneous peak discharges for naturalized flows or missing in the pre-reregulation gauge record were calculated based on the Q_i/Q_d ratio (1.18) from the relationship shown in **Figure 9**, with exception for the 1995 event.

The gauge data for the Oldman Dam outflows were missing during the 1995 flood event. An hourly inflow hydrograph was synthesized by Alberta Public Works for this event. Based on a review of available gauge data on the headwaters feeding Oldman Reservoir, NHC (2019) indicates that the synthetic inflow hydrograph is reasonable and has adopted it for the Oldman River flow naturalization. As a result, the estimated 1995 maximum daily discharge for Fort Macleod is 1,900 m^3/s (**Table 2**). The synthetic hydrograph (which represents the naturalized flow at the dam) indicates a Q_i/Q_d ratio of 1.7, which is greater than the ratio adopted from **Figure 9**. Applying this ratio (1.7) to the naturalized maximum daily discharge for Fort Macleod results in an instantaneous peak estimate of 3,230 m^3/s for the 1995 event. AENV (1995) estimated the 1995 naturalized instantaneous peak discharge for Oldman River near Fort Macleod as 3,700 m^3/s, which is about 15% greater than the current estimate. The flow estimating approach undertaken by AENV (1995) is generally consistent with the current study, except that it does not include flow routing from Oldman Dam to Fort Macleod, which might be one reason for their result being greater. The current estimate of 3,230 m^3/s has been adopted in this study as it accounts for flow attenuation through routing from the dam to Fort Macleod. The Q_i/Q_d ratio 1.7 was also used to estimate the 1995 instantaneous peak discharge for Oldman River below Willow Creek.

Table 2: Annual peak discharges of natural/naturalized flows for Oldman River near Fort Macleod

Year	Maximum Instantaneous Discharge (m^3/s)	Date	Maximum Daily Discharge (m^3/s)	Date
1911	**551**		467	May-16
1912	**361**		306	Jun-16
1913	**454**		385	May-29
1914	**197**		167	Jun-5
1915	**345**		292	Jun-26
1916	**719**		609	Jun-21
1917	340	Jun-10	331	Jun-10
1918	**280**		237	Jun-12
1919	**308**		261	May-28
1920	283	Jun-18	276	Jun-18
1921	**297**		252	May-26
1922	282	Jun-6	271	Jun-6
1923	**2,350**		*1,990*	*Jun-1*
1924	**246**		*209*	*Jun-9*
1925	**335**		*284*	*May-22*

Year	Maximum Instantaneous Discharge (m³/s)	Date	Maximum Daily Discharge (m³/s)	Date
1926	**142**		*120*	*Jun-23*
1927	**584**		*495*	*Jun-12*
1928	**468**		*397*	*Jul-1*
1929	**795**		*674*	*Jun-4*
1930	**231**		*196*	*May-31*
1933	**170**		*144*	*Jun-23*
1934	**650**		*551*	*Jun-8*
1935	**223**		*189*	*May-24*
1936	**172**		*146*	*Jun-2*
1937	**477**		*404*	*Jun-13*
1938	**537**		*455*	*May-27*
1939	**289**		*245*	*Jun-17*
1940	**209**		*177*	*May-12*
1941	**93**		*78*	*Jun-3*
1942	**1,260**		*1,070*	*May-12*
1943	**246**		*208*	*Jun-18*
1944	**80**		*68*	*Jun-28*
1945	**488**		*414*	*Jun-7*
1946	**300**		*254*	*May-29*
1947	**358**		*303*	*May-11*
1948	**1,300**		*1,100*	*Jun-18*
1949	**208**		*177*	*May-27*
1950	**317**		*269*	*Jun-16*
1951	**553**		*468*	*Jun-25*
1952	**236**		*200*	*Apr-28*
1953	**1,560**		*1,320*	*Jun-10*
1954	**528**		*448*	*May-20*
1955	**373**		*317*	*May-21*
1956	**490**		*415*	*May-22*
1957	**293**		*248*	*May-22*
1958	**303**		*257*	*May-13*
1959	**345**		*292*	*Jun-6*
1960	**314**		*266*	*May-14*
1961	**547**		*463*	*May-28*
1962	**252**		*214*	*Jun-15*
1963	**654**		*554*	*Jul-1*
1964	**742**		*629*	*Jun-9*
1965	**658**		*558*	*Jun-19*
1966	**324**		*274*	*Jun-6*
1967	**752**		*637*	*Jun-1*

Year	Maximum Instantaneous Discharge (m^3/s)	Date	Maximum Daily Discharge (m^3/s)	Date
1968	**319**		*270*	*May-24*
1969	**561**		*476*	*Jun-26*
1970	**396**		*336*	*Jun-14*
1971	**375**		*318*	*May-28*
1972	**763**		*647*	*Jun-1*
1973	**242**		*205*	*May-19*
1974	**464**		*393*	*Jun-18*
1975	**1,460**		*1,240*	*Jun-20*
1976	**297**		*252*	*May-11*
1977	**81**		*68*	*May-12*
1978	**290**		*246*	*Jun-6*
1979	**329**		*279*	*May-27*
1980	**319**		*271*	*May-27*
1981	**651**		*552*	*May-22*
1982	**218**		*185*	*Jun-16*
1983	**212**		*180*	*May-27*
1984	**144**		*122*	*Jun-1*
1985	**177**		*150*	*May-26*
1986	**402**		*341*	*May-29*
1987	**214**		*181*	*May-2*
1988	**148**		*125*	*Jun-9*
1989	**223**		*189*	*Jun-11*
1990	**490**		*415*	*May-26*
1991	**589**		*499*	*Jun-21*
1992	**197**		*167*	*Jul-11*
1993	**494**		*419*	*Jul-13*
1994	**232**		*196*	*May-20*
1995	3,230 (4)		*1,900*	*Jun-7*
1996	**364**		*308*	*Jun-5*
1997	**470**		*399*	*Jun-2*
1998	**645**		*547*	*May-29*
1999	**246**		*209*	*May-27*
2000	**134**		*114*	*May-24*
2001	**209**		*177*	*Jun-6*
2002	**827**		*701*	*Jun-10*
2003	**259**		*220*	*May-27*
2004	**130**		*110*	*May-29*
2005	**1,350**		*1,140*	*Jun-8*
2006	**327**		*278*	*Jun-16*
2007	**211**		*179*	*Jun-6*

Year	Maximum Instantaneous Discharge (m^3/s)	Date	Maximum Daily Discharge (m^3/s)	Date
2008	**924**		*783*	*May-25*
2009	**148**		*125*	*Jun-1*
2010	**818**		*693*	*Jun-18*
2011	**776**		*658*	*Jun-9*
2012	**382**		*324*	*Jun-25*
2013	**1,130**		*961*	*Jun-21*
2014	**1,220**		*1,030*	*Jun-19*
2015	**308**		*261*	*Jun-3*
2016	**118**		*100*	*May-25*
2017	**420**		*356*	*May-25*
2018	**339**		*288*	*May-9*

Notes:

1. The 1911-1922 data are from the pre-regulation record for Oldman River at Fort Macleod (WSC Station 05AB007).
2. The 1923-1930 and 1933-2018 peak daily discharges (shown in italic) are from the results of flow naturalization.
3. The bolded and underlined values are based on Q_i=1.18Q_d.
4. The 1995 instantaneous peak is based on Q_i=1.7Q_d.

The 1995 event with the estimated instantaneous peak discharge of 3,230 m^3/s is the largest event, which is followed by the 1923 event peaking at 2,350 m^3/s. The other major events are noticeably smaller with peak discharges under 1,600 m^3/s. **Table 3** summarizes the statistical parameters of the natural/naturalized instantaneous peak flow data set.

Table 3: Summary of statistical parameters of natural/naturalized annual instantaneous peak flow series for Oldman River near Fort Macleod

Parameter	Natural/Naturalized Flood Series 1911-2018
Years of record	106
Mean (m^3/s)	482
Median (m^3/s)	337
Standard deviation (m^3/s)	447
Coefficient of variation	0.926
Skew coefficient (minimum, maximum, actual)	1.85, 2.22, 3.38

Each of the frequency distributions in the adopted suite were fitted to the instantaneous flood peaks shown in **Table 2**. The goodness of fit analysis (K-S test and least squares method) was undertaken for each distribution and the results are summarized in **Table 4**.

Table 4: Goodness-of-fit comparison for probability distributions applied to natural/naturalized annual peaks for Oldman River near Fort Macleod

Distribution	D_n	Normalized *SSE* ($Q_{pm} = 482\ m^3/s$)	Rank by D_n	Rank by *SSE*	Combined Ranking
Normal (N)	0.188	0.571	9	9	9
Log-normal (LN)	0.072	0.288	3	6	4
Three parameter log-normal (LN3)	0.115	0.186	4	3	3
Pearson III (P3)	0.177	0.241	7	5	6
Log-Pearson III (LP3)	0.061	0.134	1	1	1
Gumbel (G)	0.176	0.384	6	8	7
Generalized extreme value (GEV)	0.118	0.223	5	4	4
Weibull (W)	0.185	0.293	8	7	8
Bulletin 17C	0.061	0.134	1	1	1

The LP3 distribution and Bulletin 17C are identical (as expected). They produce the smallest D_n and *SSE* values and are ranked the best, followed by the LN3 distribution. The GEV distribution is nearly identical to the LN3 except that its lower tail does not fit the data as well. The combined ranking for LN is the same as for GEV. Its lower and middle parts fit the data better; however, it tends to underpredict peak discharges for longer return periods. The other three distributions (P3, Weibull and Gumbel) do not fit the data well. **Figure 11** shows a comparison of the LP3, LN3 and LN, while the other evaluated distributions are shown graphically in **Appendix A**.

From a visual inspection of **Figure 11**, the LP3 curve represents the data better than the other two and, therefore, is recommended. The adopted LP3 curve with 95% confidence limits is shown in **Figure 12**.

4.2.3 Flood Frequency Analysis for Oldman River below Willow Creek

Figure 13 and **Table 5** show the naturalized annual peak flow series for Oldman River below Willow Creek. The annual maximum daily discharges were derived from the naturalized flow estimates presented in **Section 3.3**. The naturalized instantaneous peak discharges were calculated based on the Q_i/Q_d ratio 1.18 from the relationship shown in **Figure 9**, except the 1995 peak, which was based on the Q_i/Q_d ratio 1.7 as discussed above.

Table 5: Annual peak discharges of naturalized flows for Oldman River below Willow Creek

Year	Maximum Instantaneous Discharge (m^3/s)	Maximum Daily Discharge (m^3/s)	Date
1911	**556**	471	May-16
1912	**411**	348	Jun-16
1913	**472**	400	May-29
1914	**201**	170	Jun-5
1915	**489**	415	Jun-26
1916	**761**	645	Jun-21
1917	**480**	406	Jun-10

Year	Maximum Instantaneous Discharge (m^3/s)	Maximum Daily Discharge (m^3/s)	Date
1918	**284**	241	Jun-12
1919	**313**	265	May-28
1920	**352**	298	May-18
1921	**304**	258	May-26
1922	**327**	277	Jun-6
1923	**2,530**	*2,150*	*Jun-1*
1924	**297**	*252*	*Jun-9*
1925	**350**	*297*	*May-22*
1926	**198**	*168*	*Jun-22*
1927	**683**	*579*	*Jun-12*
1928	**549**	*465*	*Jul-2*
1929	**985**	*835*	*Jun-4*
1930	**242**	*205*	*May-31*
1935	**230**	*195*	*Dec-24*
1936	**174**	*147*	*Dec-2*
1937	**536**	*454*	*Dec-14*
1938	**585**	*496*	*Dec-26*
1939	**392**	*332*	*Dec-17*
1940	**219**	*186*	*Dec-12*
1941	**105**	*89*	*Dec-3*
1942	**1,670**	*1,410*	*Dec-12*
1943	**259**	*219*	*Dec-25*
1944	**82**	*70*	*Dec-28*
1945	**537**	*455*	*Dec-7*
1946	**320**	*271*	*Dec-7*
1947	**392**	*332*	*Dec-11*
1948	**1,430**	*1,210*	*Dec-18*
1949	**219**	*186*	*May-23*
1950	**323**	*273*	*Jun-16*
1951	**626**	*530*	*Jun-25*
1952	**255**	*216*	*Apr-28*
1953	**1,830**	*1,550*	*Jun-10*
1954	**554**	*470*	*May-20*
1955	**470**	*399*	*May-21*
1956	**502**	*425*	*May-22*
1957	**305**	*258*	*May-22*
1958	**332**	*282*	*May-13*
1959	**365**	*309*	*May-27*
1960	**333**	*283*	*May-14*
1961	**556**	*471*	*May-28*
1962	**259**	*220*	*Jun-15*

Year	Maximum Instantaneous Discharge (m^3/s)	Maximum Daily Discharge (m^3/s)	Date
1963	**860**	*729*	*Jul-1*
1964	**752**	*638*	*Jun-9*
1965	**707**	*599*	*Jun-19*
1966	**355**	*301*	*Jun-6*
1967	**898**	*761*	*Jun-1*
1968	**325**	*276*	*May-24*
1969	**691**	*586*	*Jun-26*
1970	**439**	*372*	*Jun-14*
1971	**383**	*324*	*May-28*
1972	**769**	*652*	*Jun-1*
1973	**252**	*213*	*May-19*
1974	**477**	*404*	*Jun-18*
1975	**1,500**	*1,270*	*Jun-20*
1976	**314**	*266*	*Aug-9*
1977	**83**	*70*	*May-12*
1978	**316**	*268*	*Jun-6*
1979	**349**	*296*	*May-27*
1980	**334**	*283*	*May-27*
1981	**742**	*629*	*May-22*
1982	**223**	*189*	*Jun-15*
1983	**217**	*184*	*May-27*
1984	**145**	*123*	*Jun-1*
1985	**179**	*151*	*May-26*
1986	**409**	*347*	*May-29*
1987	**216**	*183*	*May-2*
1988	**151**	*128*	*Jun-9*
1989	**228**	*193*	*Jun-11*
1990	**548**	*464*	*May-30*
1991	**595**	*504*	*Jun-21*
1992	**240**	*203*	*Jul-11*
1993	**566**	*480*	*Jul-13*
1994	**268**	*227*	*May-21*
1995	3,740 (2)	*2,200*	*Jun-7*
1996	**397**	*336*	*Jun-5*
1997	**537**	*455*	*May-27*
1998	**763**	*647*	*May-29*
1999	**267**	*226*	*Jun-5*
2000	**139**	*117*	*May-24*
2001	**229**	*194*	*Jun-6*
2002	**984**	*834*	*Jun-10*
2003	**323**	*274*	*Mar-14*

Year	Maximum Instantaneous Discharge (m^3/s)	Maximum Daily Discharge (m^3/s)	Date
2004	**141**	*119*	*May-29*
2005	**1,910**	*1,610*	*Jun-8*
2006	**452**	*383*	*Jun-16*
2007	**231**	*195*	*Jun-6*
2008	**1,010**	*857*	*May-25*
2009	**155**	*131*	*Jun-1*
2010	**882**	*747*	*Jun-18*
2011	**957**	*811*	*May-28*
2012	**494**	*419*	*Jun-25*
2013	**1,570**	*1,330*	*Jun-21*
2014	**1,630**	*1,380*	*Jun-19*
2015	**327**	*277*	*Jun-3*
2016	**131**	*111*	*May-25*
2017	**431**	*365*	*May-25*
2018	**354**	*300*	*May-9*

Notes:

1. The bolded and underlined values are based on Q_i=1.18Q_d.
2. The 1995 instantaneous peak is based on Q_i=1.7Q_d.

The 1995 event with an instantaneous peak discharge of 3,740 m^3/s is the largest event, which is followed by the 1923 event peaking at 2,530 m^3/s. The other major events are noticeably smaller with peak discharges under 2,000 m^3/s. **Table 6** summarizes the statistical parameters of the naturalized instantaneous peak flow data set.

Table 6: Summary of statistical parameters of naturalized annual instantaneous peak flow series for Oldman River below Willow Creek

Parameter	Naturalized Flood Series 1911-2018
Years of record	104
Mean (m^3/s)	550
Median (m^3/s)	374
Standard deviation (m^3/s)	533
Coefficient of variation	0.968
Skew coefficient (minimum, maximum, actual)	1.94, 2.28, 3.21

Each of the frequency distributions in the adopted suite were fitted to the instantaneous flood peaks shown in **Table 5**. The goodness of fit analysis (K-S test and least squares method) was undertaken for each distribution and the results are summarized in **Table 7**.

Table 7: Goodness-of-fit comparison for probability distributions applied to naturalized annual peaks for Oldman River below Willow Creek

Distribution	D_n	Normalized *SSE* (Q_{pm} = 550 m^3/s)	Rank by D_n	Rank by *SSE*	Combined Ranking
Normal(N)	0.219	0.595	9	9	9
Log-normal (LN)	0.065	0.285	3	7	5
Three parameter log-normal (LN3)	0.126	0.195	4	3	3
Pearson III (P3)	0.182	0.231	6	4	5
Log-Pearson III (LP3)	0.060	0.121	1	1	1
Gumbel (G)	0.185	0.397	7	8	8
Generalized extreme value (GEV)	0.126	0.235	4	5	4
Weibull (W)	0.188	0.277	8	6	7
Bulletin 17C	0.060	0.121	1	1	1

The LP3 distribution and Bulletin 17C are identical. They produce the smallest D_n and *SSE* values and are ranked the best, followed by LN3 and GEV. The other distributions do not fit the data well and generally predict noticeably lower discharges for longer return periods. **Figure 14** shows a comparison of the LP3, LN3 and GEV curves for the naturalized flood peaks of Oldman River below Willow Creek, while the other evaluated curves are shown graphically in **Appendix A**.

From a visual inspection of **Figure 14**, the LP3 curve provides the best fit for the data and, therefore, is recommended. The adopted LP3 curve with 95% confidence limits is shown in **Figure 15**.

4.3 Willow Creek

4.3.1 Flood Characteristics

Based on the WSC flow records, more than 65% of the annual peaks at Willow Creek study reach occurred in May and June, due to snowmelt runoff with or without rainfall. **Figure 16** illustrates the relationship between annual instantaneous peak and maximum daily discharges for the lower reach of Willow Creek. The line of best fit shown is based on the flow data published by WSC for Stations 05AB002 (Willow Creek near Nolan), for the 1942-1965 period (the pre-regulation period). It results in a Q_i/Q_d ratio of 1.56. While the line is a good fit for the data points with daily discharges smaller than 100 m^3/s, the data points at higher discharges are scattered. The upper and lower 95% confidence limits for the line of best fit were also estimated as shown in **Figure 16**, from which the upper and lower limits of the ratio would be 1.69 and 1.43, respectively.

Figure 16 also includes available post-regulation peak discharge data for Willow Creek near Nolan (WSC Station 05AB002, 1966-1999) and Willow Creek at Highway No. 811 (WSC Station 05AB046, 2000-2018). In the range of daily discharges smaller than 100 m^3/s, those data points appear to support a Q_i/Q_d ratio slightly smaller than that from the line of best fit for the pre-regulation natural flow data (1.56). The data points with higher discharges also become scattered; however, they tend to fall on the upper 95% confidence limit line, which is based on the historical natural flow data recorded at Nolan. Note that, for large events, the Chain Lakes project (which has an ungated spillway) is expected to have smaller effects on downstream flows in Willow Creek. Based on the flow data for the post-regulation period shown in **Figure 16** (which includes the record high 2005 event), it appears more appropriate to use the upper 95% confidence limit to predict instantaneous peak discharges. Therefore, the upper limit of the Q_i/Q_d ratio, 1.69, has been adopted to estimate naturalized instantaneous peak discharges for Willow Creek at Highway No. 811.

4.3.2 Flood Frequency Analysis for Willow Creek at Highway No. 811

Figure 17 and **Table 8** show the annual naturalized peak flow series for Willow Creek at Highway No. 811. The annual maximum daily discharges were derived from the naturalized flow estimates presented in **Section 3.4**. The naturalized instantaneous peak discharges were calculated using the Q_i/Q_d ratio 1.69 as discussed above.

Table 8: Annual peak discharges of naturalized flows for Willow Creek at Highway No. 811

Year	Maximum Instantaneous Discharge (m^3/s)	Maximum Daily Discharge (m^3/s)	Date
1910	**4**	3	Sep-21
1911	**78**	46	Sep-5
1912	**71**	42	Jun-16
1913	**40**	24	Apr-12
1914	**24**	14	Apr-6
1915	**208**	123	Jun-26
1916	**107**	64	Jun-10
1917	**153**	90	May-28
1918	**21**	13	Mar-26
1919	**22**	13	Apr-1
1920	**162**	96	May-9
1921	**42**	25	Apr-3
1922	**46**	27	Apr-22
1923	**376**	223	Jun-2
1924	**73**	43	Jun-9
1925	**51**	30	Jun-15
1926	**109**	65	Jun-20
1927	**221**	131	May-30
1928	**128**	76	Jul-3
1929	**271**	161	Jun-4
1930	**48**	28	Feb-18
1935	**131**	78	Apr-13
1936	**82**	48	Apr-9
1937	**94**	56	Jun-14
1938	**86**	51	May-24
1939	**148**	88	Jun-17
1940	**25**	15	Apr-13
1941	**18**	11	Jun-3

Year	Maximum Instantaneous Discharge (m^3/s)	Maximum Daily Discharge (m^3/s)	Date
1942	**587**	348	May-12
1943	**144**	85	Apr-3
1944	**18**	10	Apr-5
1945	**70**	42	Jun-7
1946	**107**	64	Jun-8
1947	**51**	30	Jun-12
1948	**187**	111	May-23
1949	**31**	18	May-22
1950	**17**	10	May-28
1951	**168**	99	Jun-24
1952	**113**	67	Apr-7
1953	**771**	456	Jun-9
1954	**64**	38	May-12
1955	**187**	111	May-20
1956	**59**	35	Jul-5
1957	**28**	17	May-9
1958	**97**	57	Apr-14
1959	**52**	31	Jun-28
1960	**54**	32	Mar-19
1961	**18**	11	May-17
1962	**69**	41	Apr-5
1963	**370**	219	Jun-30
1964	**69**	41	May-7
1965	**70**	41	Jun-19
1966	**53**	*31*	*Jun-8*
1967	**236**	*140*	*Jun-2*
1968	**23**	*13*	*Jun-12*
1969	**190**	*113*	*Jun-27*
1970	**72**	*42*	*Jun-15*
1971	**50**	*30*	*Jun-8*
1972	**79**	*47*	*Apr-7*
1973	**61**	*36*	*May-27*
1974	**63**	*37*	*May-2*
1975	**151**	*89*	*Jun-21*
1976	**64**	*38*	*Aug-9*
1977	**18**	*11*	*Apr-6*
1978	**58**	*34*	*Jun-1*
1979	**36**	*21*	*May-18*
1980	**37**	*22*	*May-28*
1981	**135**	*80*	*May-23*
1982	**29**	*17*	*Jun-7*

Year	Maximum Instantaneous Discharge (m^3/s)	Maximum Daily Discharge (m^3/s)	Date
1983	**16**	*9*	*Apr-27*
1984	**5**	*3*	*Jun-12*
1985	**16**	*9*	*Sep-14*
1986	**60**	*35*	*Feb-26*
1987	**15**	*9*	*Apr-2*
1988	**5**	*3*	*Jun-12*
1989	**11**	*6*	*May-10*
1990	**103**	*61*	*May-27*
1991	**40**	*24*	*Jun-22*
1992	**62**	*37*	*Jul-11*
1993	**147**	*87*	*Jun-17*
1994	**53**	*32*	*May-21*
1995	**525**	*311*	*Jun-8*
1996	**77**	*45*	*Apr-6*
1997	**169**	*100*	*May-27*
1998	**314**	*186*	*Jun-17*
1999	**41**	*24*	*Jun-5*
2000	**20**	*12*	*Jun-20*
2001	**44**	*26*	*Jun-7*
2002	**290**	*172*	*Jun-11*
2003	**185**	*109*	*Mar-14*
2004	**34**	*20*	*Aug-25*
2005	**798**	*472*	*Jun-8*
2006	**178**	*105*	*Jun-16*
2007	**35**	*21*	*Jun-19*
2008	**220**	*130*	*May-26*
2009	**25**	*15*	*Jun-7*
2010	**103**	*61*	*Jun-19*
2011	**351**	*208*	*May-28*
2012	**160**	*95*	*Jun-25*
2013	**629**	*372*	*Jun-21*
2014	**585**	*346*	*Jun-19*
2015	**37**	*22*	*May-18*
2016	**19**	*11*	*Jun-26*
2017	**31**	*18*	*Jun-16*
2018	**35**	*21*	*Apr-16*

Notes:

1. The bolded and underlined values are based on Q_i=1.69Q_d.

The 2005 event with an instantaneous peak discharge of 798 m^3/s is the largest event. The 1953 event is slightly smaller and has a peak discharge of 771 m^3/s, which is followed by four other events with similar magnitudes: 2013 (629 m³/s), 1942 (587 m³/s), 2014 (585 m³/s) and 1995 (525 m³/s). **Table 9** summarizes the statistical parameters of the naturalized instantaneous peak flow data set.

Table 9: Summary of statistical parameters of naturalized annual instantaneous peak flow series for Willow Creek at Highway No. 811

Parameter	Naturalized Flood Series 1910-2018
Years of record	105
Mean (m^3/s)	124
Median (m^3/s)	69
Standard deviation (m^3/s)	155
Coefficient of variation	1.25
Skew coefficient (minimum, maximum, actual)	2.50, 2.59, 2.59

Each of the frequency distributions in the adopted suite were fitted to the instantaneous flood peaks shown in **Table 8**. The goodness of fit analysis (K-S test and least squares method) was undertaken for each distribution and the results are summarized in **Table 10**.

Table 10: Goodness-of-fit comparison for probability distributions applied to naturalized annual peaks for Willow Creek at Highway No. 811

Distribution	D_n	Normalized *SSE* (Q_{pm} = 115 m^3/s)	Rank by D_n	Rank by *SSE*	Combined Ranking
Normal(N)	0.205	0.652	9	9	9
Log-normal (LN)	0.038	0.292	1	5	4
Three parameter log-normal (LN3)	0.166	0.295	7	6	6
Pearson III (P3)	0.144	0.227	5	2	5
Log-Pearson III (LP3)	0.040	0.284	2	3	1
Gumbel (G)	0.196	0.442	8	8	8
Generalized extreme value (GEV)	0.165	0.325	6	7	6
Weibull (W)	0.133	0.226	4	1	1
Bulletin 17C	0.040	0.284	2	3	1

The LN distribution produces the smallest D_n value; however, its *SSE* value is relatively high. The Weibull distribution is in an opposite situation: it has the lowest *SSE* but a relatively high D_n value. The LP3 and Bulletin 17C are identical with a D_n value close to the smallest and very small *SSE* value. So, in the combined ranking, they are ranked the same as the Weibull distribution, as the best. The P3 and GEV results are very similar to the Weibull, while the GEV curve is poorer in fitting the data at the lower tail. The LN3, Gumbel and normal distributions do not fit the data well.

Figure 18 shows a comparison of the LP3, LN and Weibull curves for the naturalized flood peaks of Willow Creek at Highway No. 811 (WSC Station 05AB046), while the other evaluated curves are shown graphically in **Appendix A**. From a visual inspection of **Figure 18**, the Weibull distribution does not fit the data points at the lower tail, while the LP3 and LN curves appear to provide a better fit for all data points except the 2005 event (the largest event). It should be noted that the estimated peak discharge for the 2005 event is only 12% higher than that for the second largest event (1953), and when the 2005 peak is plotted using the Weibull plotting formula (another method commonly used in North America), the data point becomes more closer to the LP3 and LN curves. While the LP3 and LN curves are nearly identical, it is recommended that the LP3 be adopted for naturalized flood peaks for Willow Creek at Highway No. 811 (WSC Station 05AB046), to be consistent with the analysis for the Oldman River study sites. The adopted LP3 curve with 95% confidence limits is shown in **Figure 19**.

4.4 Uncertainty and Confidence

There are three main contributions to the uncertainty that is inherent in the frequency curves defined above – errors in reported flood flow, errors in the flow naturalization, and errors associated with the application of standard statistical procedures to imperfect samples of populations.

With respect to flood peaks reported by WSC, most errors are typically expected during the highest flow events, which also are of the most interest. For the most part, these types of errors, unless they are systematic in one direction, tend to balance out statistically and do not necessarily contribute to unreliable estimates of the ensemble mean and variance. However, if errors are more pronounced in estimating the high flood peaks, the ensemble skewness may not be calculated properly and those statistical distributions that rely on the skewness may not properly represent the real parameters of the population. It is beyond the scope of this study to assess the reliability of each of the flood peaks reported by WSC, so the default position is to assume that all data reported by WSC are correct.

Errors in estimating flood peaks can also occur in the application of the flow naturalization procedure. Most of these errors are related to the lack of regional data and the calculation of differences between large flows that clearly contain uncertainties. In this study, the flow naturalization procedure was carried out using multiple approaches to check the simulation outcomes. While other methodologies may produce different results, it is unlikely that they would be any more defensible than those produced herein. Again, while there may be errors in individual numbers, the ensemble means, and variances would still be representative of the general population.

Finally, the statistical procedures are imperfect. The number of data points in each of the flood series are quite large from a hydrologic perspective, and the mean and variance are estimated reasonably well. However, estimates of the sample skewness are necessary to properly extrapolate the frequency to longer return periods. Sample skewness at one station is usually thought to be an insufficient metric by which to define the skewness of the population, and the literature recommends that a blended skewness that reflects regional skewness values is adopted. However, the flow data series used in the present study include the longest records in the region; as such, introducing regional skewness would not improve the results. Moreover, there are no guidelines in Alberta for developing regional skew values.

The application of statistical procedures that demand year to year randomness, independence, and stationarity in the flood peaks may also be somewhat problematical. While stationarity appears not to be a problem, one could argue that no flood peaks are independent from each other due to year to year storage-related memory in large river basins. The difficulty is that no statistical method is sufficiently discrete to be able to differentiate statistically amenable data sets from those that are not, because of short record lengths. Therefore, while it may be difficult to demonstrate absolute year to year randomness, there is confidence that the data are sufficiently well behaved to apply the necessary statistical procedures.

The analysis presented in this report follows industry standards and is based on the best available information. The results are reasonable and adequate for the river flood hazard study. For return periods longer than 200 years, the estimates could be in considerable error as shown by the confidence limits on each of the frequency plots.

5 SUMMARY OF ADOPTED FLOOD FREQUENCIES

5.1 Oldman River at Fort Macleod

A variety of theoretical probability distributions were tested and compared on their suitability to describe naturalized flood peaks for Oldman River at Fort Macleod. Based on these comparisons, considerations of potential uncertainties in the analyses and professional judgements, it is recommended that LP3 distribution be adopted for Oldman River at Fort Macleod.

The resulting flood frequency estimates for Oldman River at Fort Macleod are summarized in **Table 11**. The table also includes the estimates from previous studies by AENV (1985 and 1995) to provide a comparison. The current estimates are very close to those from the AENV 1995 study, while they are higher than those from the 1985 study, which was based on the data for a shorter period of record with no floods comparable to the 1995 event.

Table 11: Flood frequency estimates of natural/naturalized flows for Oldman River at Fort Macleod

Return Period (Years)	Annual Probability of Exceedance (%)	Peak Instantaneous Discharge (m^3/s)		AENV (1985)	AENV (1995)
		Value	95% Confidence Limit		
1000	0.1	4,850	3,660 - 6,880		4,740
750	0.13	4,450	3,380 - 6,240		
500	0.2	3,920	3,010 - 5,410		
350	0.29	3,500	2,720 - 4,770		
200	0.5	2,910	2,300 - 3,880	2,296	2,870
100	1	2,300	1,860 - 2,980	1,954	2,270
75	1.3	2,080	1,690 - 2,660		
50	2	1,790	1,480 - 2,250	1,620	1,770
35	2.9	1,560	1,300 - 1,940		
20	5	1,250	1,060 - 1,510		1,230
10	10	920	800 - 1,080	892	900
5	20	649	576 - 743		
2	50	353	316 - 394		325

5.2 Oldman River below Willow Creek

Flood frequency estimates of naturalized flows for Oldman River below Willow Creek are summarized in **Table 12**. These estimates were based on a LP3 frequency curve.

Table 12: Flood frequency estimates of naturalized flows for Oldman River below Willow Creek

Return Period (Years)	Annual Probability of Exceedance (%)	Peak Instantaneous Discharge (m^3/s)	
		Value	95% Confidence Limit
1000	0.1	6,180	4,580 - 8,950
750	0.13	5,630	4,210 - 8,070
500	0.2	4,920	3,730 - 6,940
350	0.29	4,370	3,350 - 6,070
200	0.5	3,600	2,810 - 4,880
100	1	2,800	2,240 - 3,690
75	1.3	2,520	2,030 - 3,280
50	2	2,150	1,760 - 2,750
35	2.9	1,860	1,540 - 2,350
20	5	1,470	1,240 - 1,810
10	10	1,070	921 - 1,270
5	20	740	652 - 854
2	50	391	348 - 439

5.3 Willow Creek at Highway No. 811

Flood frequency estimates of naturalized flows for Willow Creek at Highway No. 811 (05AB046) are summarized in **Table 13**. These estimates are based on a LP3 distribution.

Table 13: Flood frequency estimates of naturalized flows for Willow Creek at Highway No. 811

Return Period (Years)	Annual Probability of Exceedance (%)	Peak Instantaneous Discharge (m^3/s)	
		Value	95% Confidence Limit
1000	0.1	1,950	1,340 - 3,110
750	0.13	1,780	1,230 - 2,810
500	0.2	1,560	1,090 - 2,420
350	0.29	1,380	974 - 2,110
200	0.5	1,130	812 - 1,690
100	1	864	637 - 1,250
75	1.3	769	572 - 1,100
50	2	646	487 - 907
35	2.9	549	420 - 758
20	5	417	325 - 559
10	10	282	226 - 364
5	20	175	145 - 218
2	50	70	59 - 84

6 CLIMATE CHANGE COMMENTARY

This section provides a summary of a qualitative interpretation of climate and hydrologic projections obtained from the scientific literature that would be pertinent to evaluating future changes in flood hazards in the study area.

Current global climate models indicate that temperature will increase in the upper SSR basin due to projected increases in CO_2 concentrations in the atmosphere. Increased temperatures in the winter months will likely results in smaller snowpacks and earlier snowmelt runoff.

Martz et al. (2007) used calibrated hydrologic models forced by selected down-scaled general circulation model (GCM) scenarios to assess effects of climate change on streamflow of major rivers in the South Saskatchewan River basin, including the Oldman River. Some of the key findings of the study are noted as follows:

- Temperature increases over the South Saskatchewan River basin could range from 1.5°C to 2.8°C for a projection period centred on 2050.
- The selected GCM models differ in their predictions of changes to annual precipitation, ranging from -3.8% (reduction) to +11.5% (increase), with the overall average of all models being a modest increase of +3.6%.

- Projected changes in annual natural streamflow volumes in the Oldman River basin have considerable variation among different scenarios: from -18% to +4% with an average of -6% in its headwaters, from -14% to +7% with an average of -3% near Lethbridge, and from -14% to +7% with an average of -4% near the mouth.

Poitras et al. (2011) investigated projected changes in average and extreme streamflows of ten major river basins across western Canada. The streamflows were derived from climate simulations performed with the fourth generation of the CRCM forced with the A2 emission scenario. The mean annual flow in the South Saskatchewan River is projected to increase by 12%; and peak discharges are predicted to increase by about 20% and occur one or two weeks earlier.

According to DFO (2013), annual precipitation over large basins in the Prairies is projected to generally increase; however, projections are more uncertain for the Saskatchewan River basin as both an increase and a decrease have been predicted. Higher precipitation expected in winter compared to summer. Type of precipitation will change (e.g. more winter rain vs. snow). It is expected that there will be fewer precipitation events, but at higher intensity or more extreme weather events. During the summer months, streamflow volumes in the Saskatchewan river sub-basin could decrease by up to 50%.

Islam and Gan (2015) applied a physically based land surface scheme, the Modified Interaction Soil Biosphere Atmosphere (MISBA), to assess the future streamflow of the SSR basin under combined impacts of climate change and El Niño Southern Oscillation (ENSO). Under climate projections alone or under the combined condition with ENSO, annual mean flows are projected to decrease. However, the mean spring (March to May) flows under climate projections alone are projected to increase by 6%, 16% and 23% for the Bow River at Calgary, and by 9%, 22% and 29% for the Oldman River near Lethbridge, in 2020s, 2050s and 2080s, respectively. In contrast, the mean summer (June to August) flows are projected to decrease. When climate change is combined with El Niño episodes, the spring flows are projected to decrease. On the other hand, they are projected to increase further when climate change is combined with La Niña episodes.

More recently, Gizaw (2017) assessed possible changes to extreme precipitation in the Bow and Oldman river basins using six extreme climate indices based on two downscaled climate scenarios. The results suggest that more frequent and severe intensive storm events may impact the upper and middle Oldman river basin, between May and August in 2050s and 2080s. While more frequent and severe intensive storm events tend to increase peak runoff discharges, it is difficult to predict their impacts on future flood risk at Fort Macleod. Higher temperature and less snowfall in winter would result in a higher snow line in the Rocky Mountains and increased snow-free area in the lower elevation bands of the river basin, which tends to reduce the total runoff during a spring rain-on-snow event.

In general, the annual and season temperatures are expected to increase over the next 50 years or so as what has been experienced in the last 100 years. The expected changes in annual precipitation over the SSR basin are somewhat equivocal with the GCMs suggesting that the annual precipitation could change by between a 3.8% decrease and 11.5% increase, reflecting an increase in rainfall and a decrease in snowfall. Projected changes in annual mean flows in the South Saskatchewan River basin are also different among different studies, while more studies predicted a decreasing trend. However, increase in spring flows is expected although the forecast becomes more complicated and inconclusive in some recent studies that considers ENSO effects.

Overall, there is insufficient information to be able to identify all the linkages between precipitation and runoff to make any forecasts about how climate change might affect flood peaks.

This is consistent with the conclusions of the Intergovernmental Panel on Climate Change – that at present there is low confidence in global climate model predictions of changes in flood magnitudes due to limited evidence (Jiménez et al., 2014). In general, increased precipitation may lead to higher flood peaks due to increased precipitation intensity but this will be mitigated by reduced snowpack and drier antecedent moisture conditions due to higher temperatures. Loss of tree cover and soil changes associated with beetle infestation, wildfires, and changing land use could also contribute to higher runoff volumes and peaks – possibly even having a greater impact than the changing climate.

7 REFERENCES

AENV (2008). Hydrologic and Hydraulic Guidelines for Flood Hazard Area Delineation. Alberta Environment, March 2008.

AENV (1995). 1995 Flood Frequency Analysis for South Saskatchewan River Basin – Draft Report (an internal document from Alberta Environment).

AENV (1991). Oldman River at Fort Macleod Flood Risk Mapping Study. Alberta Environment, November 1991.

AENV (1985). Flood Frequency Analysis of Oldman River at Town of Fort Macleod. Alberta Environment, December 1985.

AT (2001). Guidelines on Flood Frequency Analysis. Alberta Transportation, April 2001.

DFO (2013). Risk-based Assessment of Climate Change Impacts and Risks on the Biological Systems and Infrastructure within Fisheries and Ocean Canada's mandate – Freshwater Large Aquatic Basin. DFO Canada, Science Advisory Secretariat, Science Response 2013/011, July 2013.

Gizaw, M.S. (2017). Global Warming Impacts on Hydrologic Extremes. A thesis for the degree of Doctor Philosophy in Water Resources Engineering, University of Alberta, 2017.

Islam, Z. and Gan, T.Y. (2015). Potential Combined Hydrologic Impacts of Climate Change and El Niño Southern Oscillation to South Saskatchewan River Basin. Journal of Hydrology, 523(2015), 34-48.

Jiménez, B.E.C., et al., 2014. Freshwater resources. In: C.B. Field, et al., eds. Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [online]. Cambridge University Press, 229–269. Available from: http://www.ipcc.ch/report/ar5/wg2/

Kite, G.W. (1977). Frequency and Risk Analyses in Hydrology, Water Resources Publications, Colorado.

Martz, L., Bruneau, J. and Rolfe, J.T. (2007). Climate Change and Water – SSRB Final Technical Report.

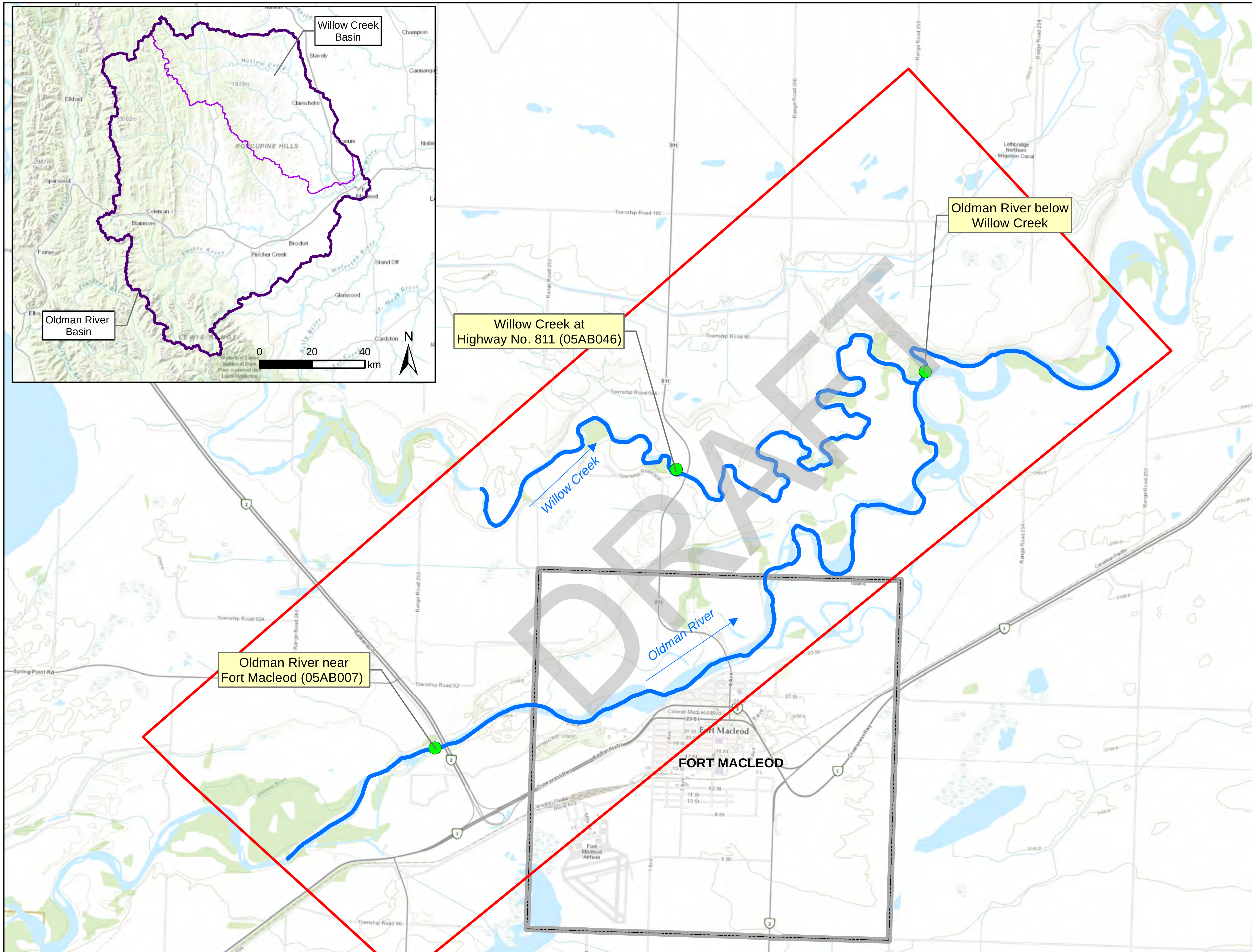
NHC (2019). Medicine Hat River Hazard Study – Open Water Hydrology Assessment. Report prepared for Alberta Environment and Parks. Northwest Hydraulic Consultants Ltd., July 2019.

Poitras, V., Sushama, L., Seglenieks, F., Khaliq, M.N., and Soulis, E. (2011). Projected Changes to Streamflow Characteristics over Wester Canada as Simulated by the Canadian RCM. Journal of Hydrometeorology, 12, 1395-1413.

USGS (1982). Guidelines for Determining Flood Flow Frequency – Bulletin 17B, U.S. Geological Survey.

USGS (2018). Guidelines for Determining Flood Flow Frequency – Bulletin 17C, U.S. Geological Survey, Reston, Virginia, 2018.

FIGURES



Alberta

nhc northwest hydraulic consultants

Legend

- Flood Frequency Estimate Location
- Study Reach
- River Hazard Study Area
- Town Boundary

DATA SOURCES: Watershed boundaries based on Canadian Water Survey of Canada data. Basemap from Esri & NRCAN.

SCALE - 1:50,000

0 0.5 1 2 Km

N

Coordinate System: NAD 1983 CSRS 3TM 111
Units: METERS

Job: 3004660 *Date: 09-AUG-2019*

FORT MACLEOD FLOOD HAZARD STUDY OPEN WATER HYDROLOGY ASSESSMENT

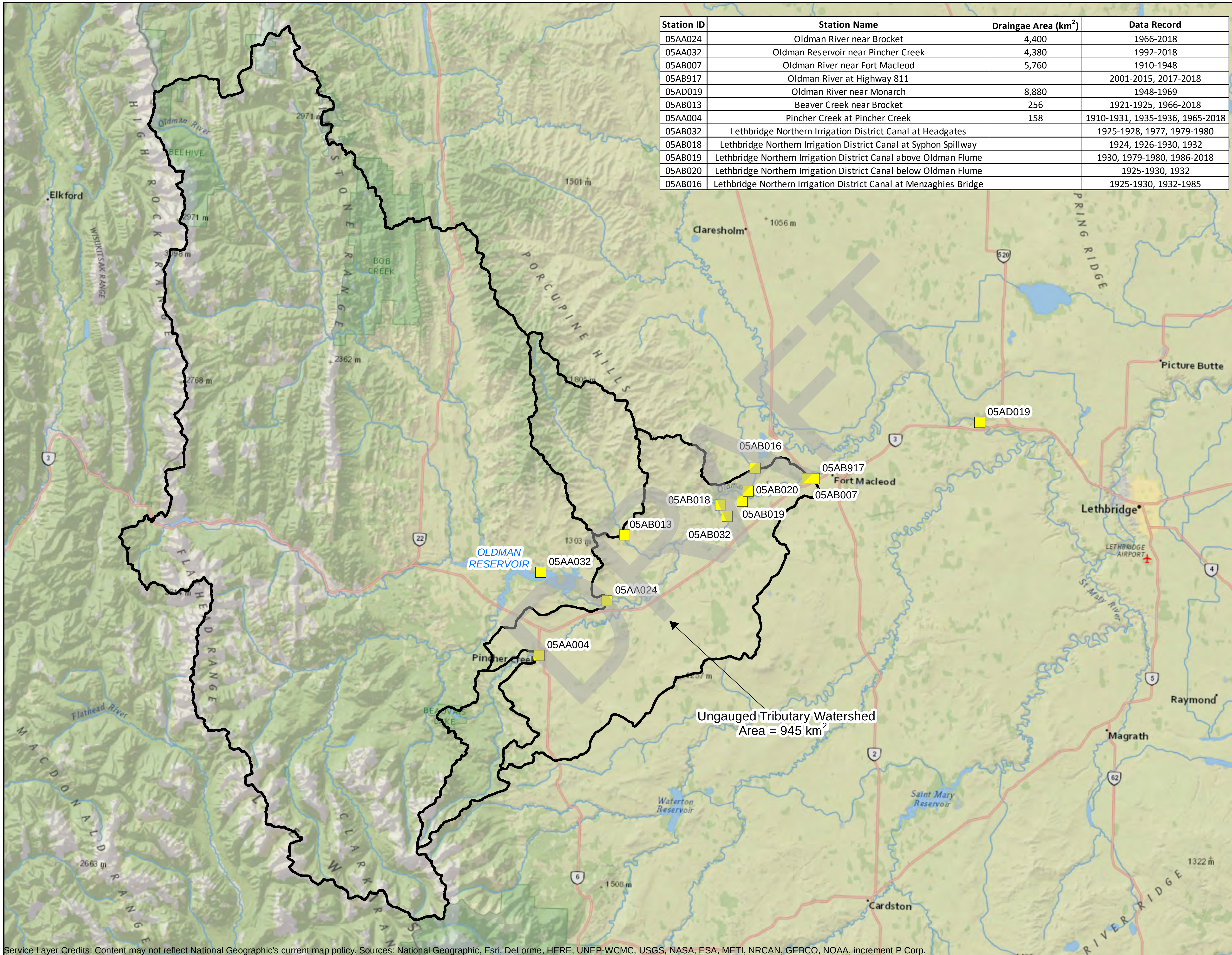
River Hazard Study Area and Flood Frequency Estimate Locations

FIGURE 1

Service Layer Credits: Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

Classification: Public

Station ID	Station Name	Draingae Area (km^2)	Data Record
05AA024	Oldman River near Brocket	4,400	1966-2018
05AA032	Oldman Reservoir near Pincher Creek	4,380	1992-2018
05AB007	Oldman River near Fort Macleod	5,760	1910-1948
05AB917	Oldman River at Highway 811		2001-2015, 2017-2018
05AD019	Oldman River near Monarch	8,880	1948-1969
05AB013	Beaver Creek near Brocket	256	1921-1925, 1966-2018
05AA004	Pincher Creek at Pincher Creek	158	1910-1931, 1935-1936, 1965-2018
05AB032	Lethbridge Northern Irrigation District Canal at Headgates		1925-1928, 1977, 1979-1980
05AB018	Lethbridge Northern Irrigation District Canal at Syphon Spillway		1924, 1926-1930, 1932
05AB019	Lethbridge Northern Irrigation District Canal above Oldman Flume		1930, 1979-1980, 1986-2018
05AB020	Lethbridge Northern Irrigation District Canal below Oldman Flume		1925-1930, 1932
05AB016	Lethbridge Northern Irrigation District Canal at Menzaghies Bridge		1925-1930, 1932-1985



Service Layer Credits: Content may not reflect National Geographic's current map policy. Sources: National Geographic, Esri, DeLorme, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp.

Alberta

nhc
northwest hydraulic consultants

Legend

- Hydrometric Station
- Oldman River Sub Basin

DATA SOURCES: Watershed boundaries based on Canadian Water Survey of Canada data. Basemap from Esri & NRCAN.

SCALE - 1:500,000

0 5 10 20 Km

N

Coordinate System: NAD 1983 CSRS 3TM 111
Units: METERS

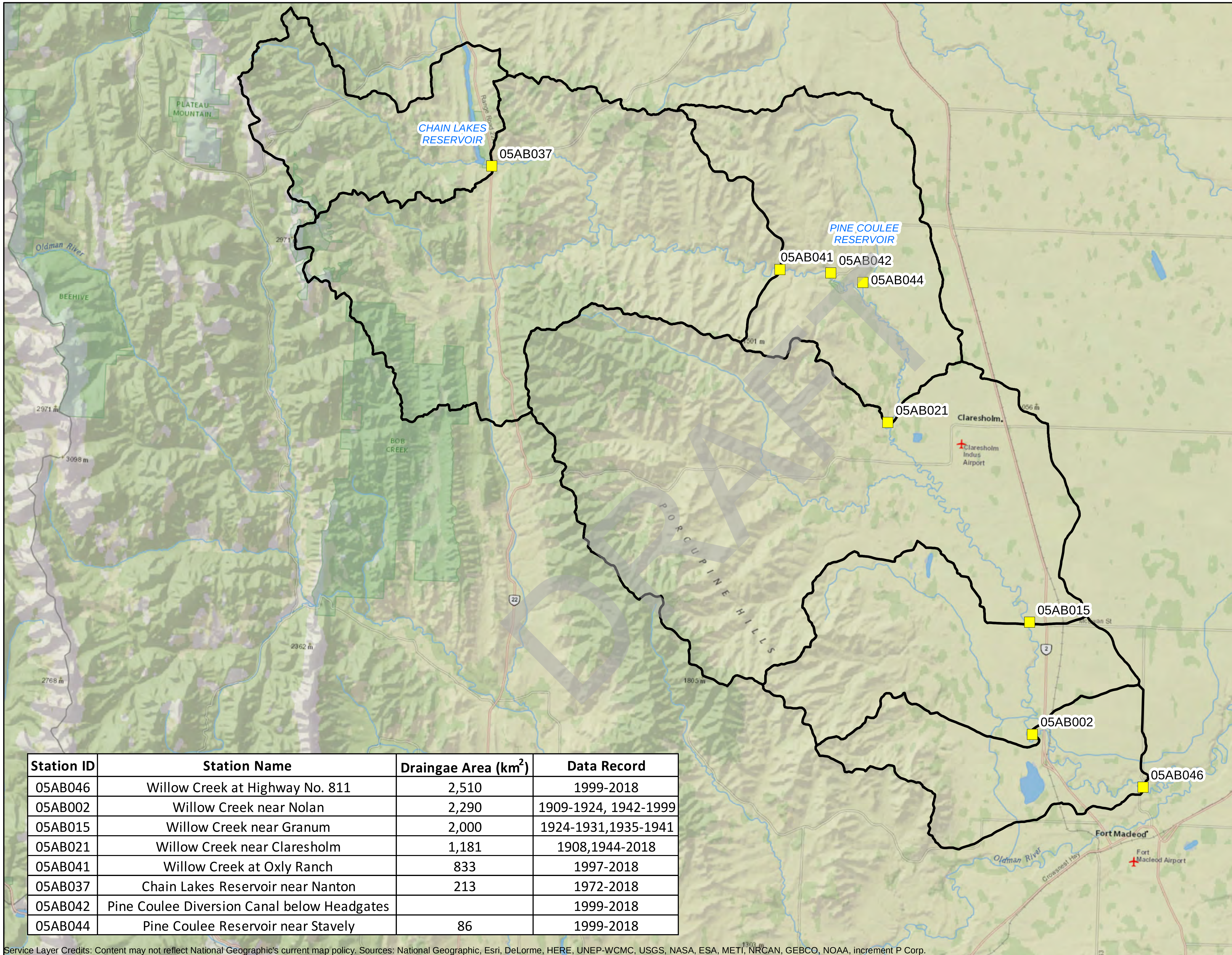
Job: 3004660 | *Date: 09-AUG-2019*

FORT MACLEOD FLOOD HAZARD STUDY OPEN WATER HYDROLOGY ASSESSMENT

OLDMAN RIVER SUB-BASIN UPSTREAM OF FORT MACLEOD

FIGURE 2

MSN, Z:\Active\3004660 Fort Macleod FHS\02 Hydrology\02_Calculations\GIS\Figure 2_Oldman_River_Sub_basin.mxd



Station ID	Station Name	Draingae Area (km^2)	Data Record
05AB046	Willow Creek at Highway No. 811	2,510	1999-2018
05AB002	Willow Creek near Nolan	2,290	1909-1924, 1942-1999
05AB015	Willow Creek near Granum	2,000	1924-1931,1935-1941
05AB021	Willow Creek near Claresholm	1,181	1908,1944-2018
05AB041	Willow Creek at Oxly Ranch	833	1997-2018
05AB037	Chain Lakes Reservoir near Nanton	213	1972-2018
05AB042	Pine Coulee Diversion Canal below Headgates		1999-2018
05AB044	Pine Coulee Reservoir near Stavely	86	1999-2018

Alberta

nhc northwest hydraulic consultants

Legend

WSC Hydrometric Station

Willow Creek Sub Basin

DATA SOURCES: Watershed boundaries based on Canadian Water Survey of Canada data. Basemap from Esri & NRCAN.

SCALE - 1:300,000

0 5 10 Km

N

Coordinate System: NAD 1983 CSRS 3TM 111
Units: METERS

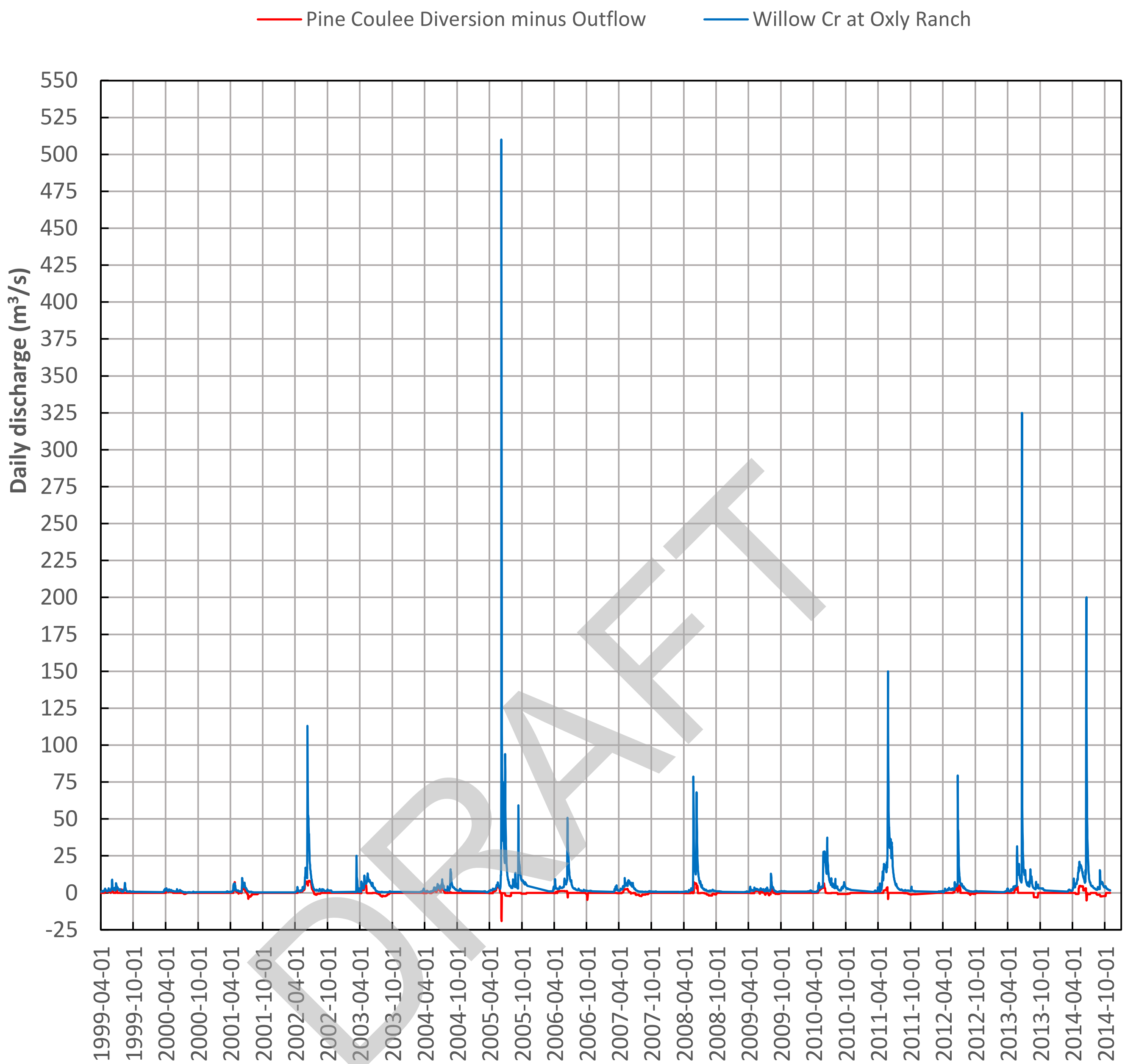
Job: 3004660 | Date: 09-AUG-2019

FORT MACLEOD FLOOD HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

WILLOW CREEK SUB-BASIN

FIGURE 3

MSN, Z:\Active\3004660 Fort Macleod FHS\02 Hydrology\02_Calculations\GIS\Figure 3_Willow_Creek_Sub_basin.mxd



SCALE – AS SHOWN

Coordinate System:
Units: As Shown

northwest hydraulic consultants

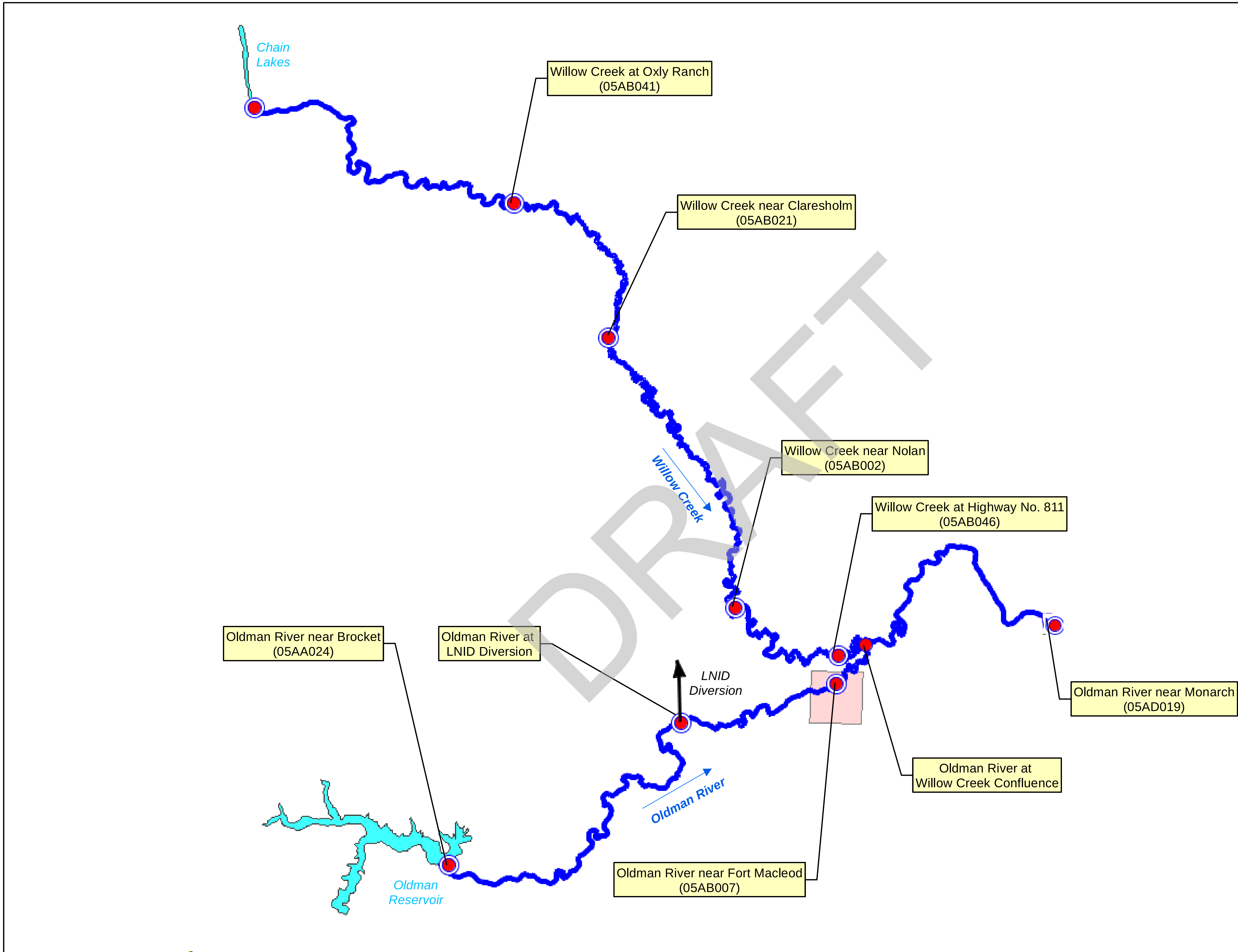
FORT MACLEOD FLOOD HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

EFFECTS OF PINE COULEE RESERVOIR ON WILLOW CREEK FLOWS

Job: 3004660 | *Date: Jul-2019*

FIGURE 4

Classification: Public



Alberta

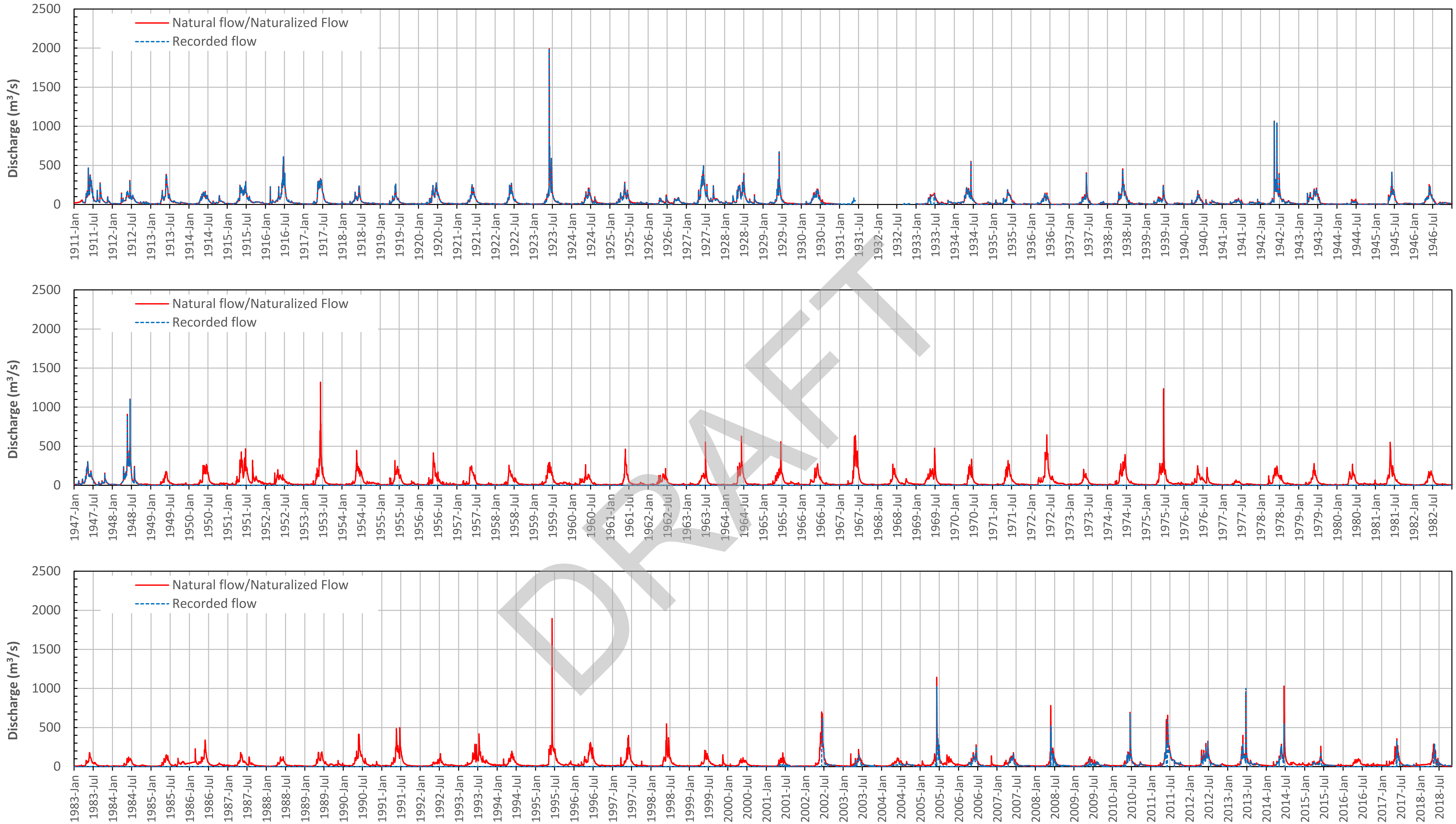
nhc northwest hydraulic consultants

Job: 3004660 | Date: 12 JUN 2019

FORT MACLEOD FLOOD HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

HEC-RESSIM MODEL SCHEMATIC

FIGURE 5



Alberta

nhc northwest hydraulic consultants

Notes:

1. Oldman River near Fort Macleod (WSC Station 05AB007) provides gauged natural flows for 1911-1922
2. Naturalized flows were estimated for the period of 1923-1930 and 1933-2018.

SCALE – AS SHOWN

Coordinate System:
Units: As Shown

Job: 3004660

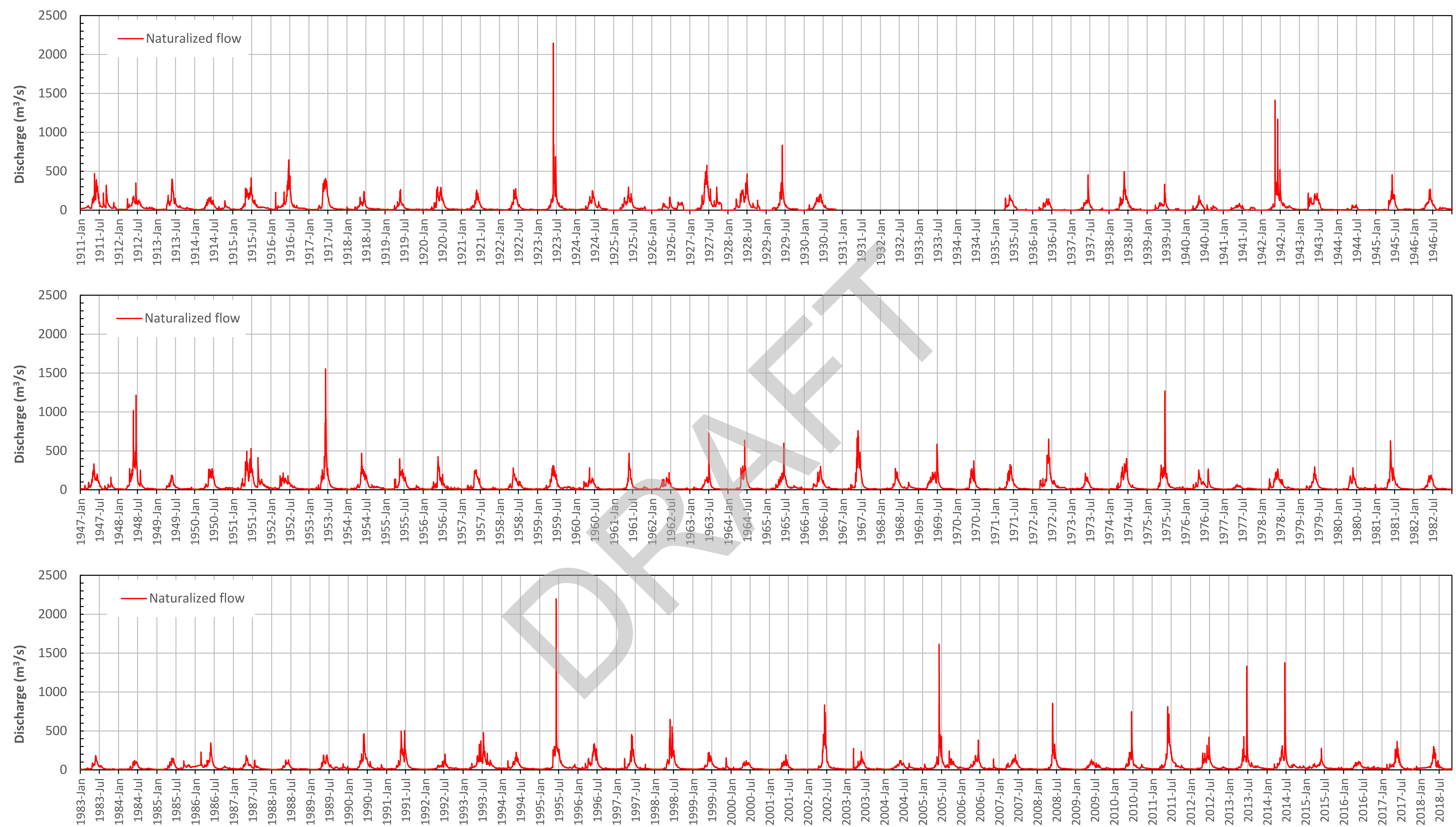
Date: Jul-2019

FORT MACLEOD FLOOD HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

NATURAL AND NATURALIZED DAILY FLOWS FOR OLDMAN RIVER NEAR FORT MACLEOD

FIGURE 6

Classification: Public



Alberta

nhc northwest hydraulic consultants

SCALE – AS SHOWN

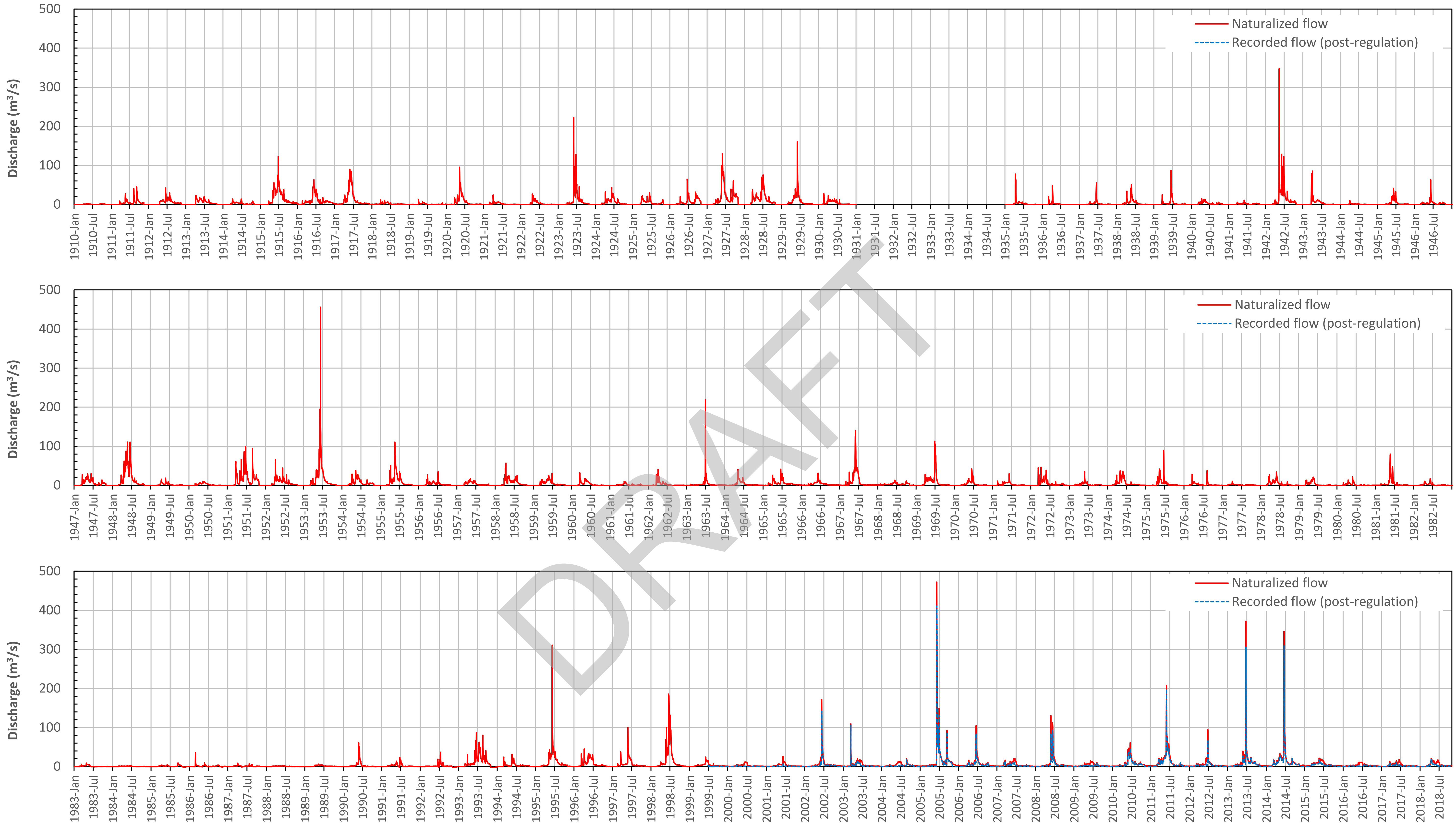
Coordinate System:
Units: As Shown

Job: 3004660 | Date: Jul-2019

FORT MACLEOD FLOOD HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

NATURALIZED DAILY FLOWS FOR OLDMAN RIVER BELOW WILLOW CREEK

FIGURE 7



FORT MACLEOD FLOOD HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

NATURALIZED DAILY FLOWS FOR WILLOW CREEK AT HIGHWAY NO. 811

FIGURE 8

Alberta

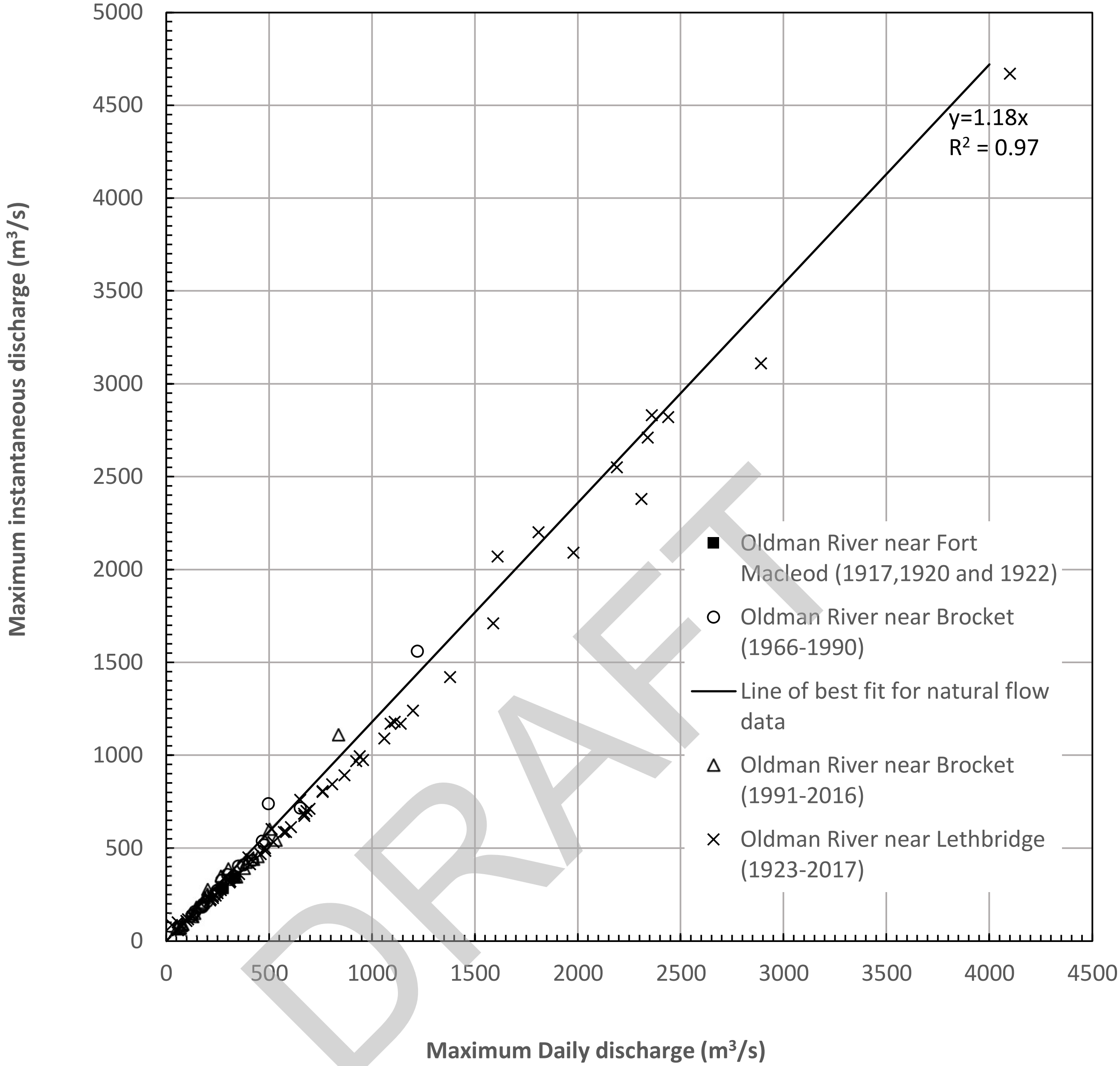
nhc northwest hydraulic consultants

SCALE – AS SHOWN

Coordinate System:
Units: As Shown

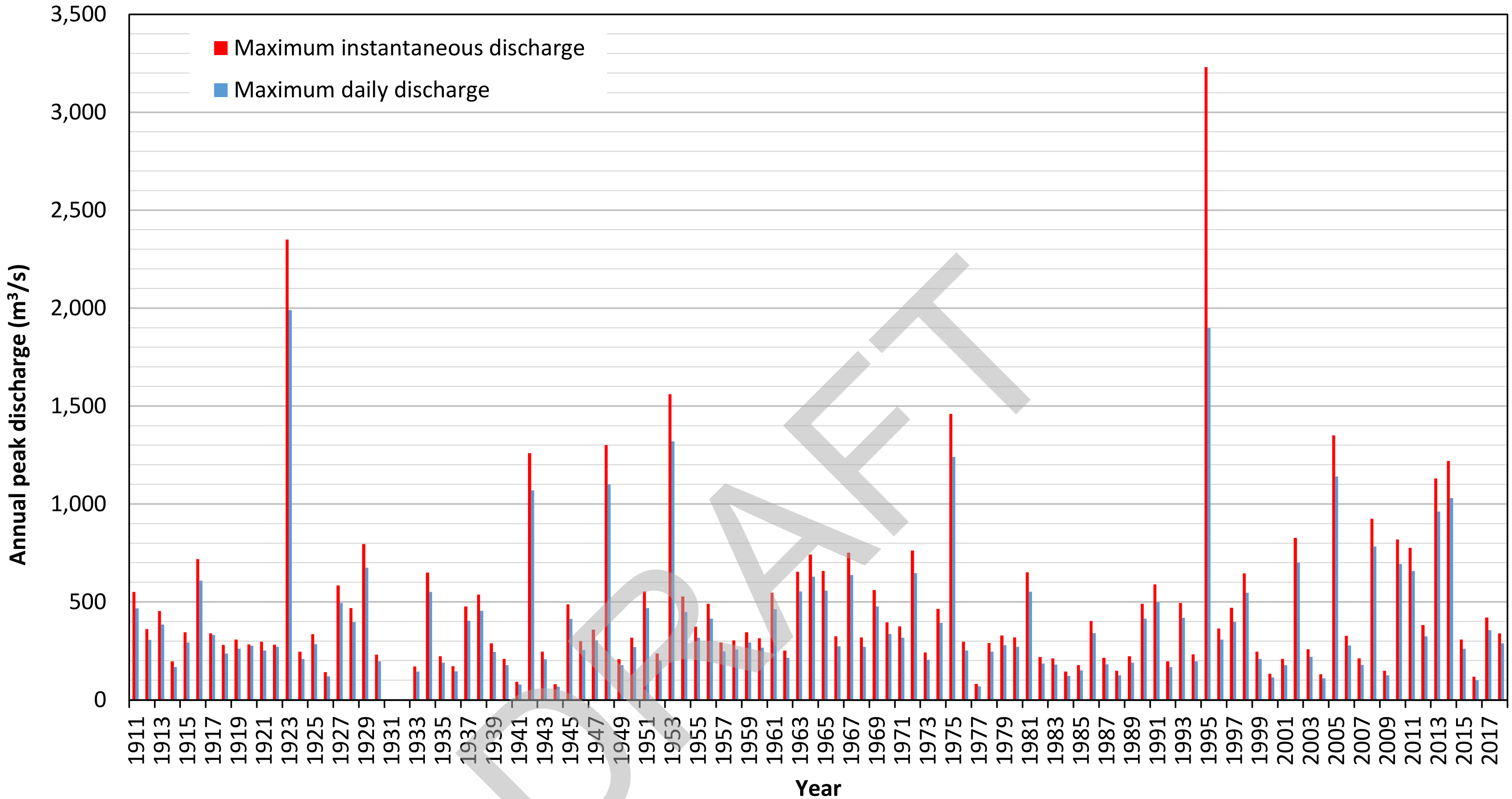
Job: 3004660 | Date: Jul-2019

Classification: Public



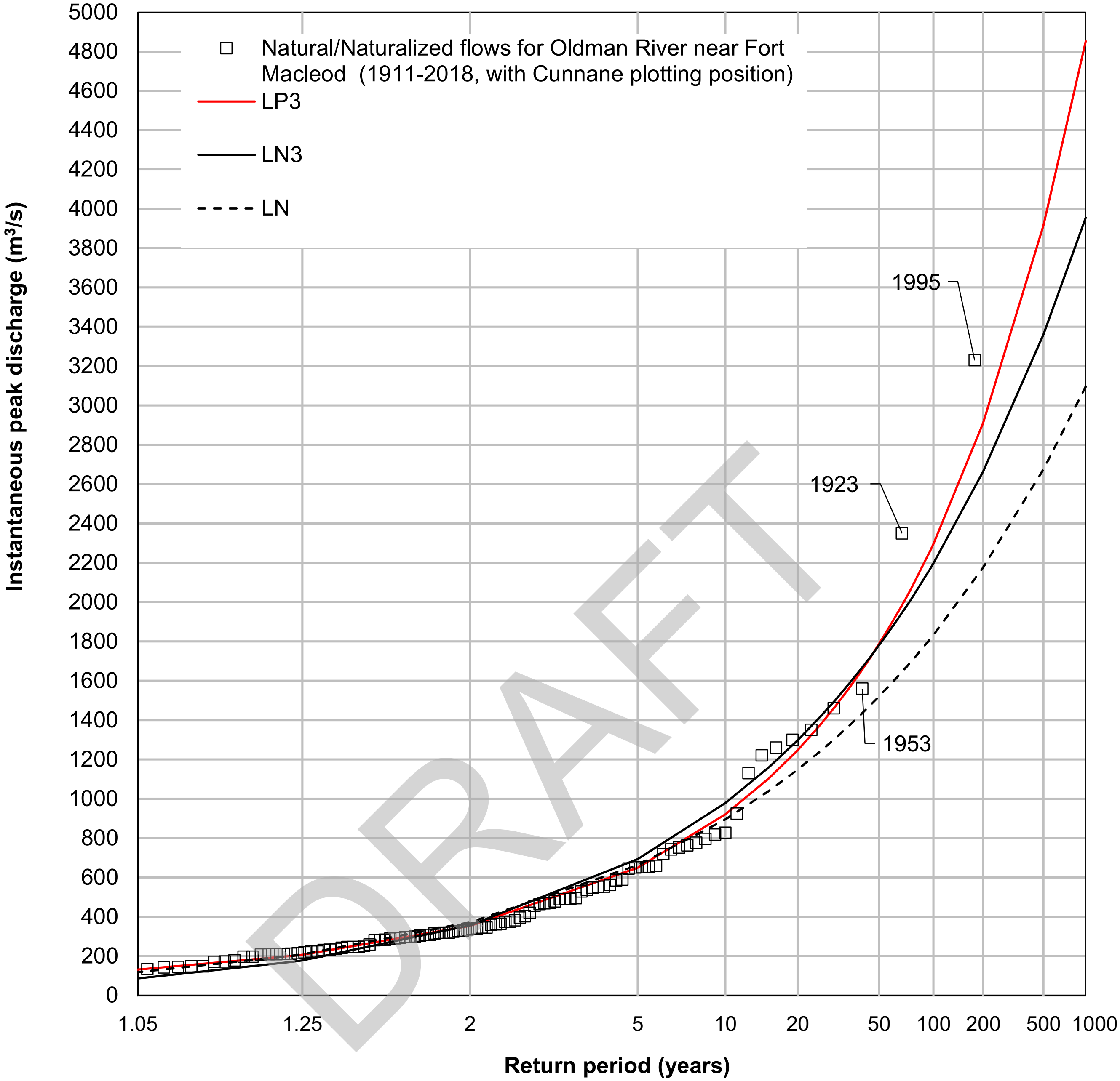
Notes: 1. The line of best fit is based on pre-regulation natural flow data from Oldman River near Fort MacLeod (05AB007) for 1917,1920 and 1922; and from Oldman River near Brocket (05AA024) for the period of 1966-1990.

Alberta	SCALE – AS SHOWN	*FORT MACLEOD FLOOD HAZARD STUDY OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*OLDMAN RIVER STUDY REACH MAXIMUM INSTANTANEOUS TO DAILY DISCHARGE RATIO*
	Job: 3004660 | *Date: Jul-2019*	*FIGURE 9*

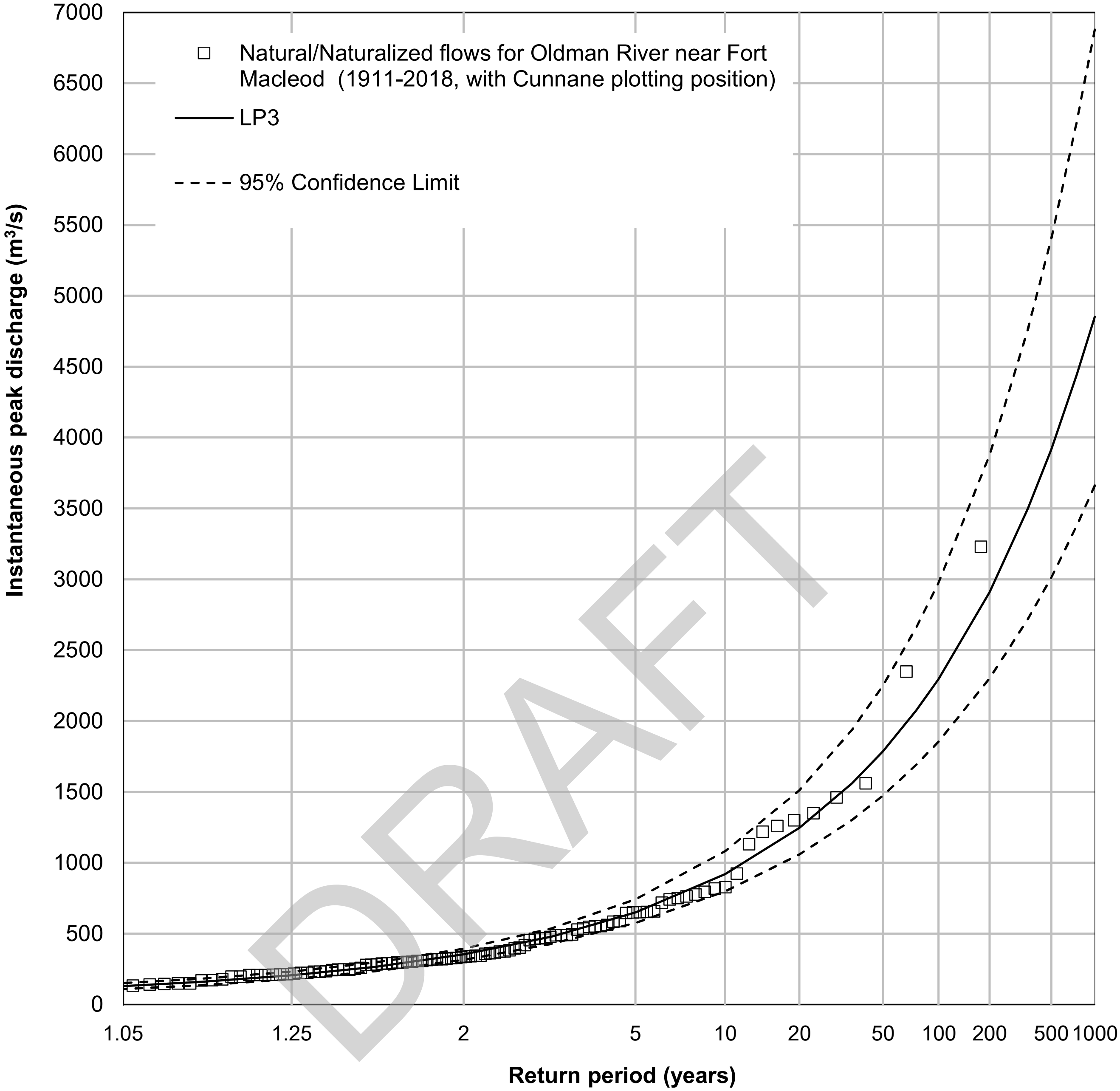


Notes: 1. The 1911-1922 data are from the pre-regulation flow records for Oldman River near Fort Macleod (05AB007).
2. The 1923-1930 and 1933-2018 data are from flow naturalization.

Alberta	SCALE – AS SHOWN	*FORT MACLEOD FLOOD HAZARD STUDY OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*ANNUAL PEAK DISCHARGES FOR OLDMAN RIVER NEAR FORT MACLEOD*
	Job: 3004660 / *Date: Jul-2019*	*FIGURE 10*



Alberta	SCALE – AS SHOWN	*FORT MACLEOD FLOOD HAZARD STUDY OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*COMPARISON OF FLOOD FREQUENCY CURVES FOR OLDMAN RIVER NEAR FORT MACLEOD*
	Job: 3004660 | *Date: Jul-2019*	*FIGURE 11*



Alberta

nhc northwest hydraulic consultants

SCALE – AS SHOWN

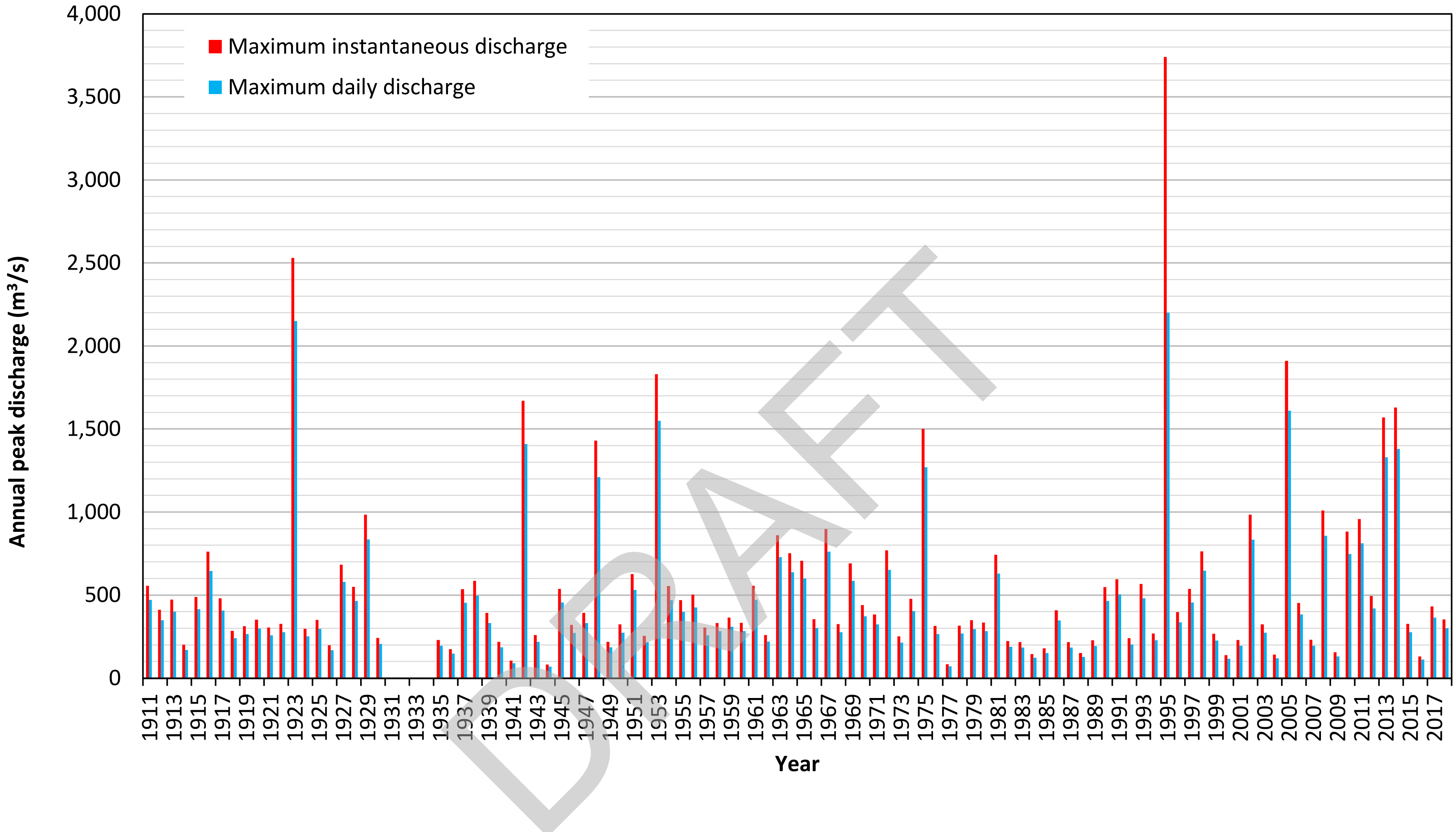
Coordinate System:
Units: As Shown

Job: 3004660 | *Date: Jul-2019*

FORT MACLEOD FLOOD HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

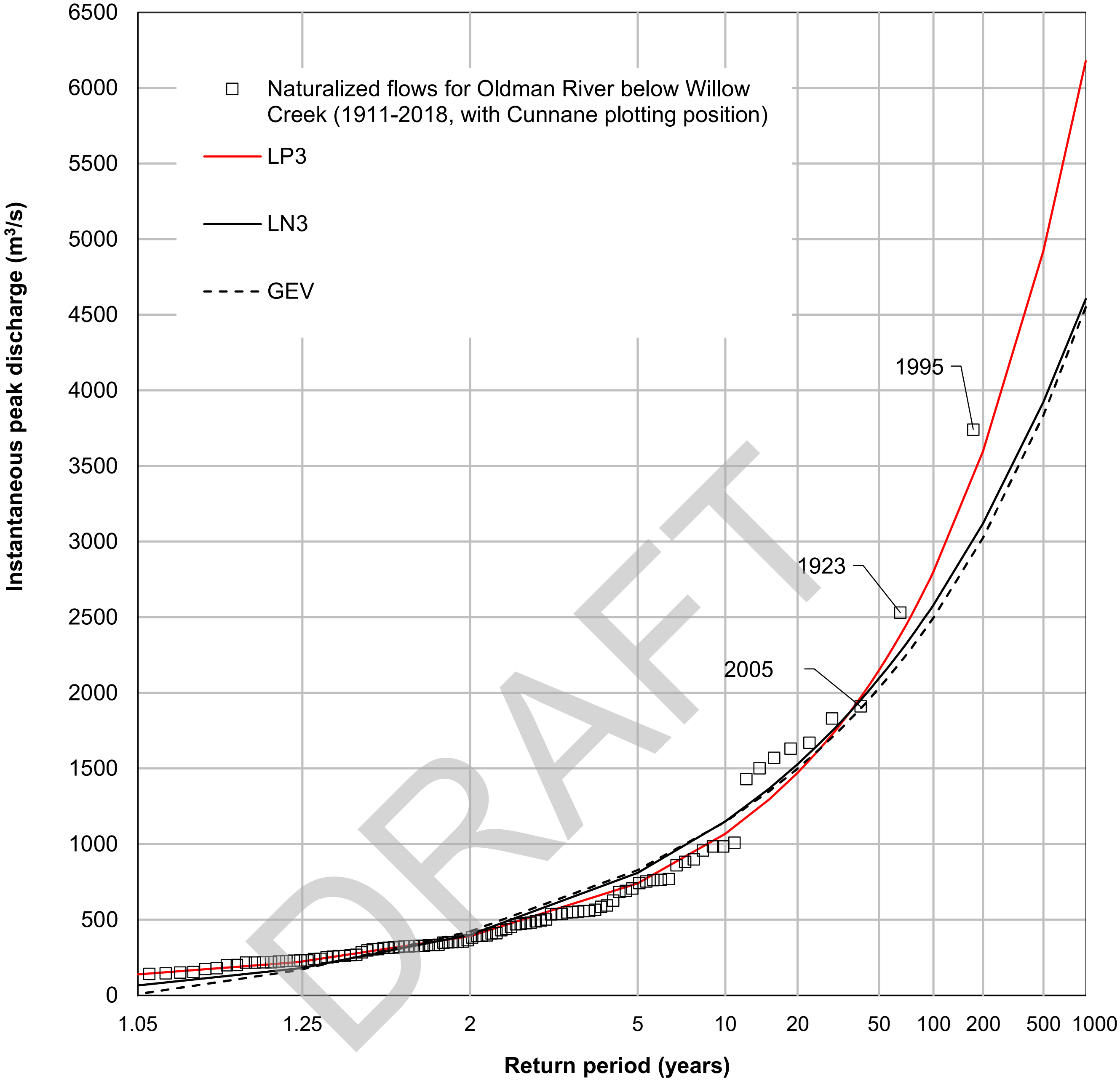
ADOPTED FLOOD FREQUENCY CURVE FOR OLDMAN RIVER NEAR FORT MACLEOD

FIGURE 12

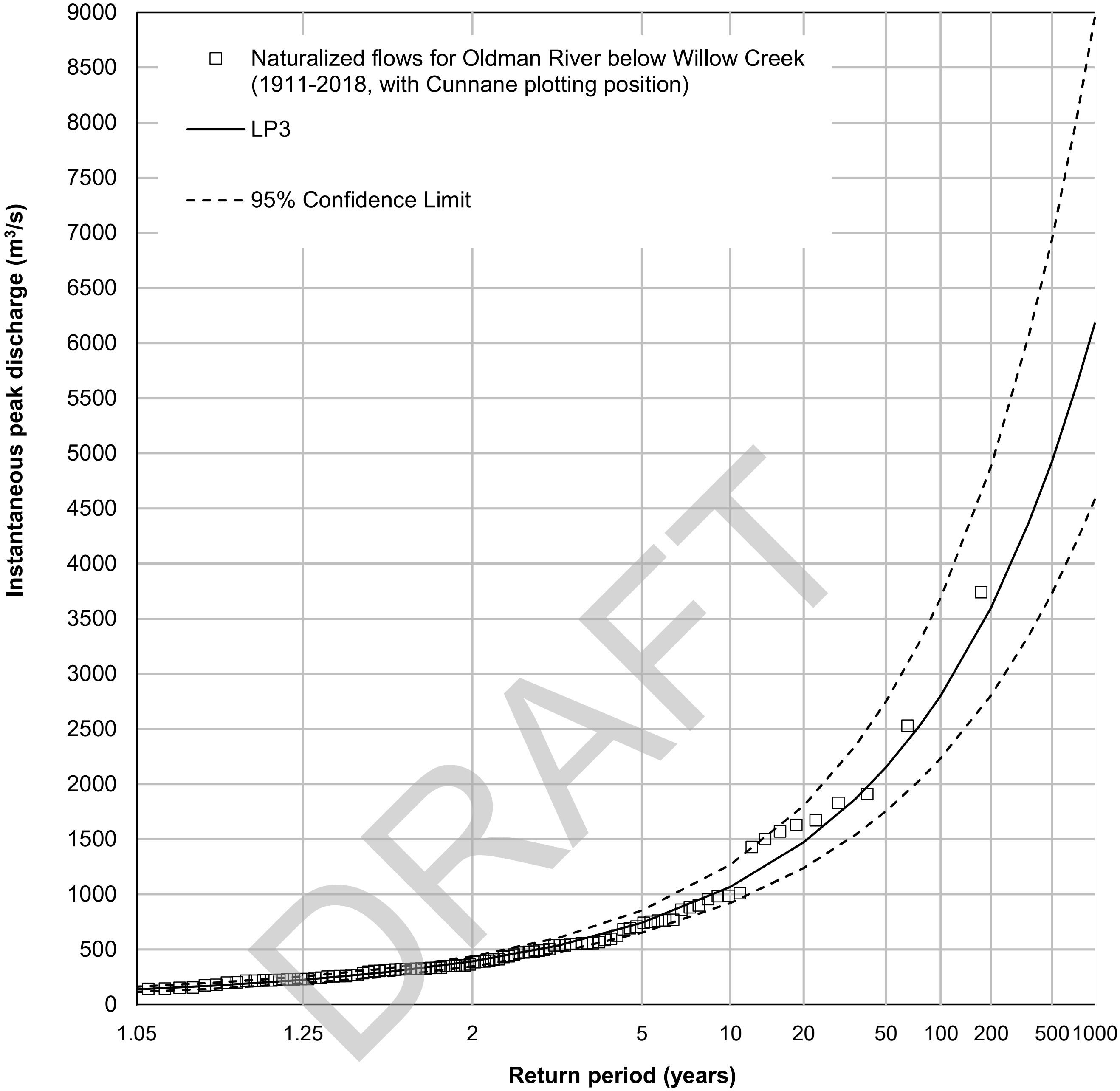


Notes: 1. The 1911-1930 and 1935-2018 data are from flow naturalization.

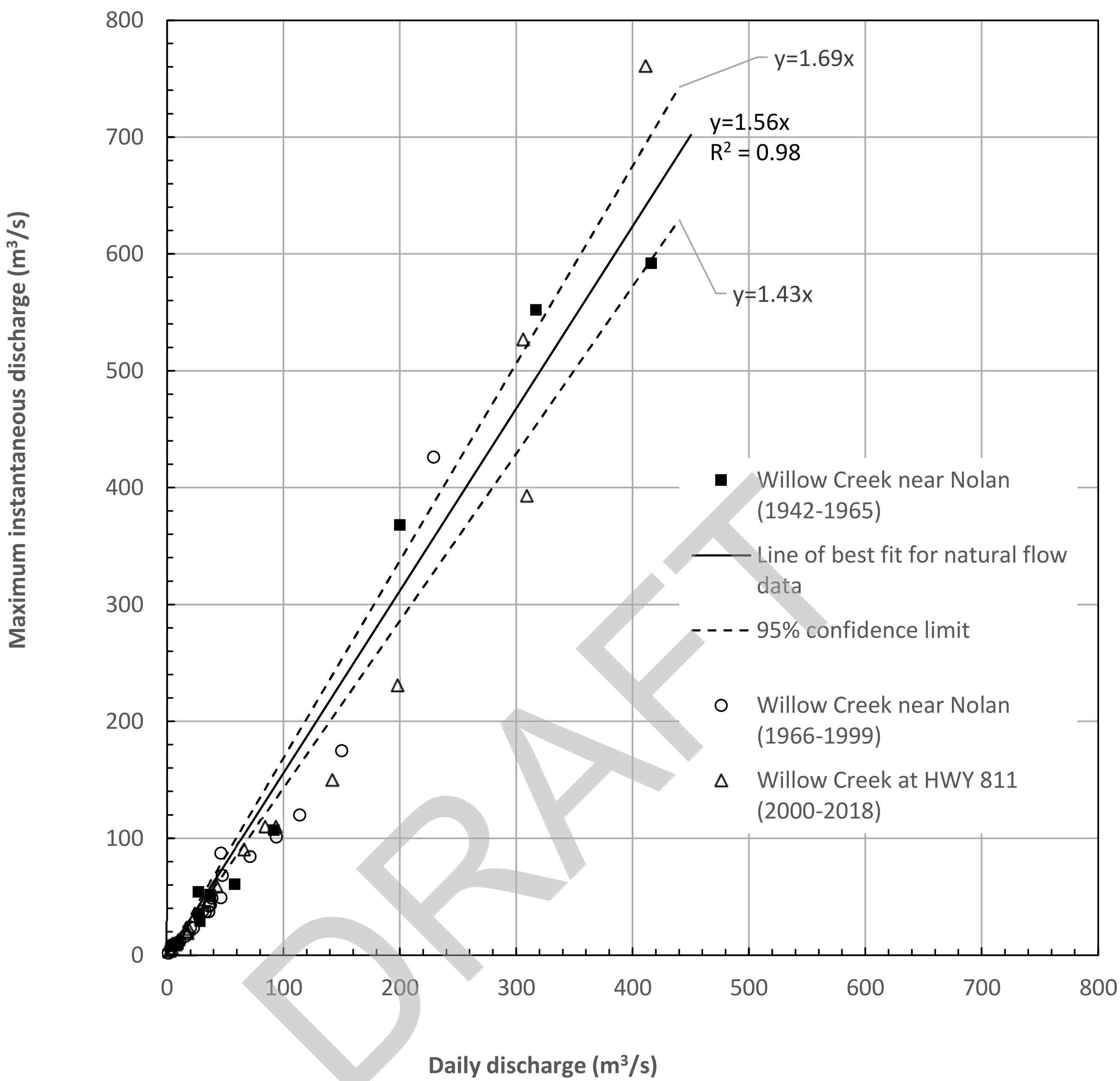
Alberta	SCALE – AS SHOWN	*FORT MACLEOD FLOOD HAZARD STUDY* *OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*ANNUAL PEAK DISCHARGES FOR OLDMAN RIVER BELOW WILLOW CREEK*
	Job: 3004660 *Date: Jul-2019*	*FIGURE 13*



Alberta	SCALE – AS SHOWN	*FORT MACLEOD FLOOD HAZARD STUDY OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*COMPARISON OF FLOOD FREQUENCY CURVES FOR OLDMAN RIVER BELOW WILLOW CREEK*
	Job: 3004660 / *Date: Jul-2019*	*FIGURE 14*

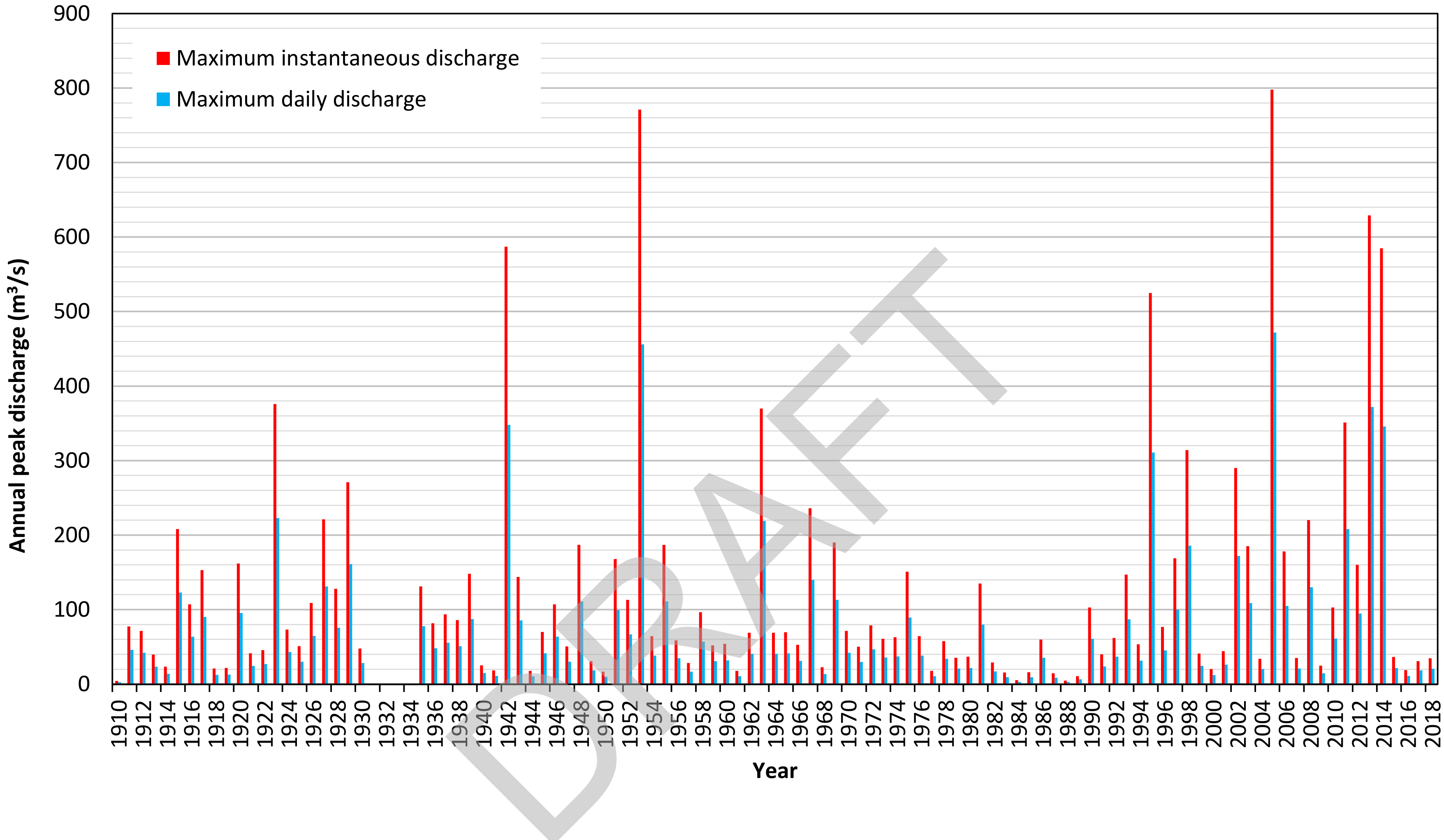


Alberta	SCALE – AS SHOWN	*FORT MACLEOD FLOOD HAZARD STUDY OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*ADOPTED FLOOD FREQUENCY CURVE FOR OLDMAN RIVER BELOW WILLOW CREEK*
	Job: 3004660 | *Date: Jul-2019*	*FIGURE 15*



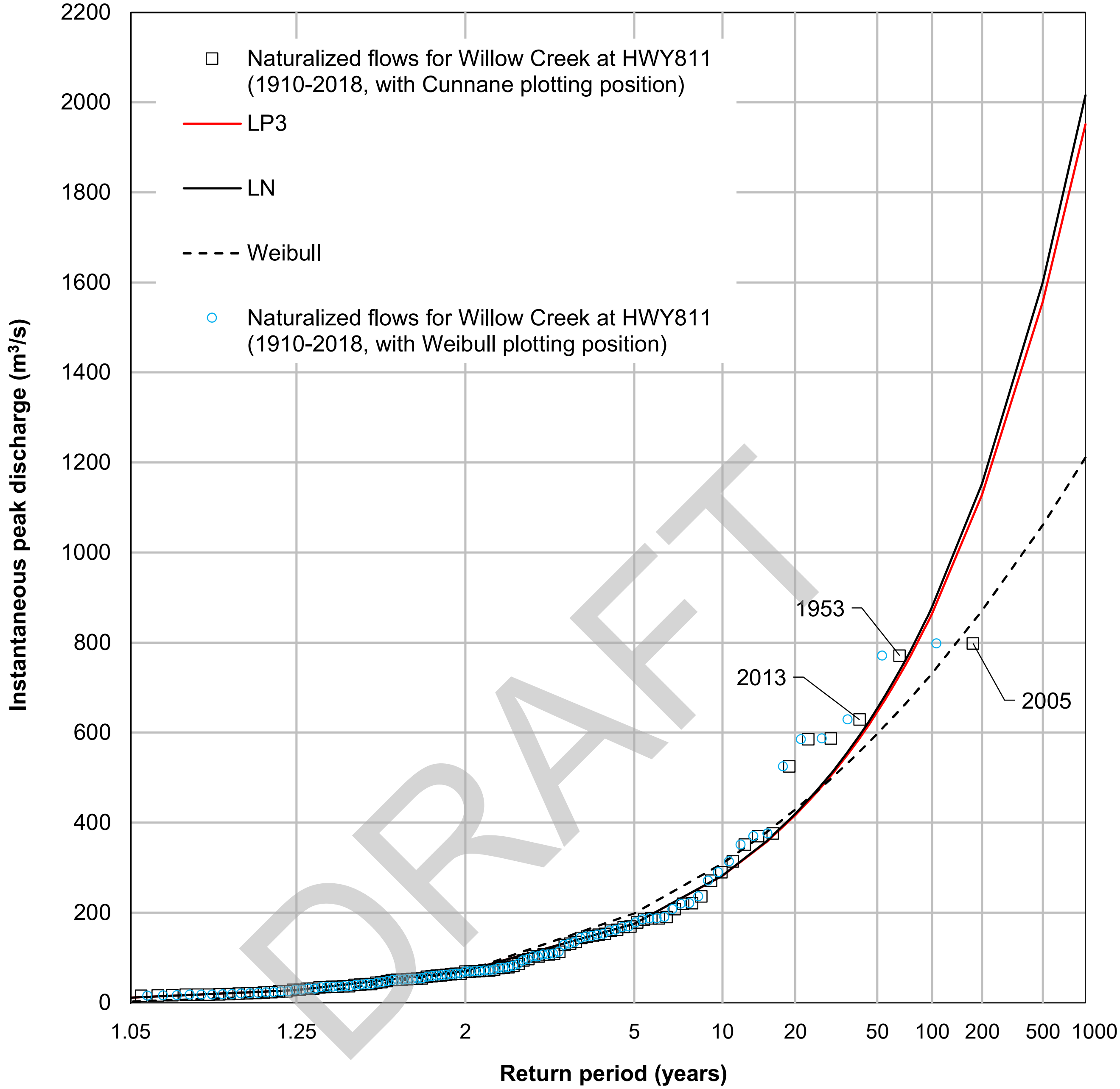
Notes: 1. The line of best fit is based on natural flow data from Willow Creek near Nolan (05AB002) for the pre-regulation period (1942-1965).

Alberta	SCALE – AS SHOWN	FORT MACLEOD FLOOD HAZARD STUDY OPEN WATER HYDROLOGY ASSESSMENT WILLOW CREEK STUDY REACH MAXIMUM INSTANTANEOUS TO DAILY DISCHARGE RATIO
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	
	Job: 3004660 *Date: Jul-2019*	*FIGURE 16*



Notes: 1. The 1910-1930 and 1935-2018 data are from flow naturalization.

Alberta	SCALE – AS SHOWN	FORT MACLEOD FLOOD HAZARD STUDY OPEN WATER HYDROLOGY ASSESSMENT *ANNUAL PEAK DISCHARGES FOR WILLOW CREEK AT HIGHWAY NO. 811*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	
	Job: 3004660 | *Date: Jul-2019*	*FIGURE 17*



Alberta

nhc northwest hydraulic consultants

SCALE – AS SHOWN

Coordinate System:
Units: As Shown

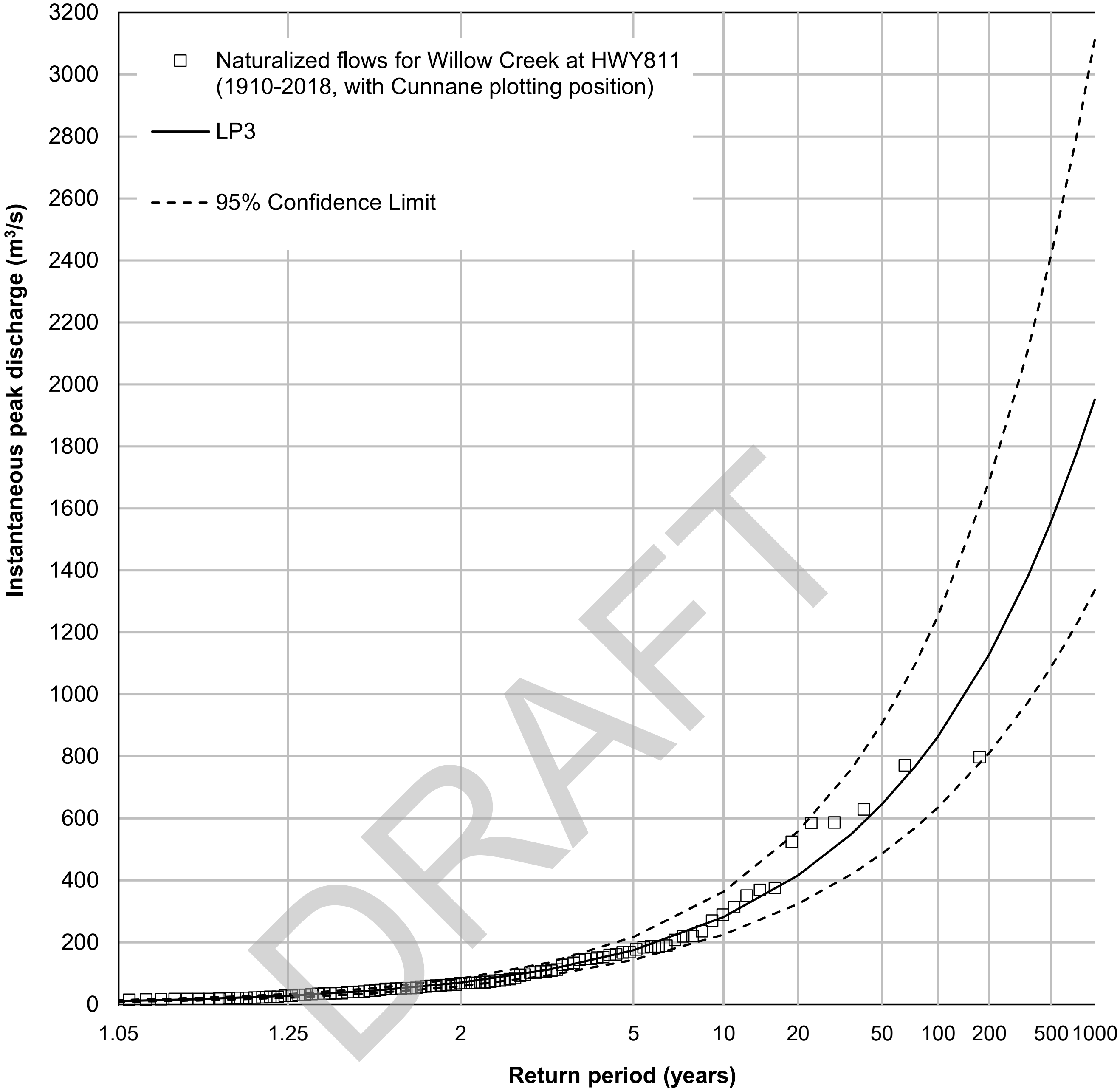
Job: 3004660

Date: Jul-2019

FORT MACLEOD FLOOD HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

COMPARISON OF FLOOD FREQUENCY CURVES FOR WILLOW CREEK AT HIGHWAY NO. 811

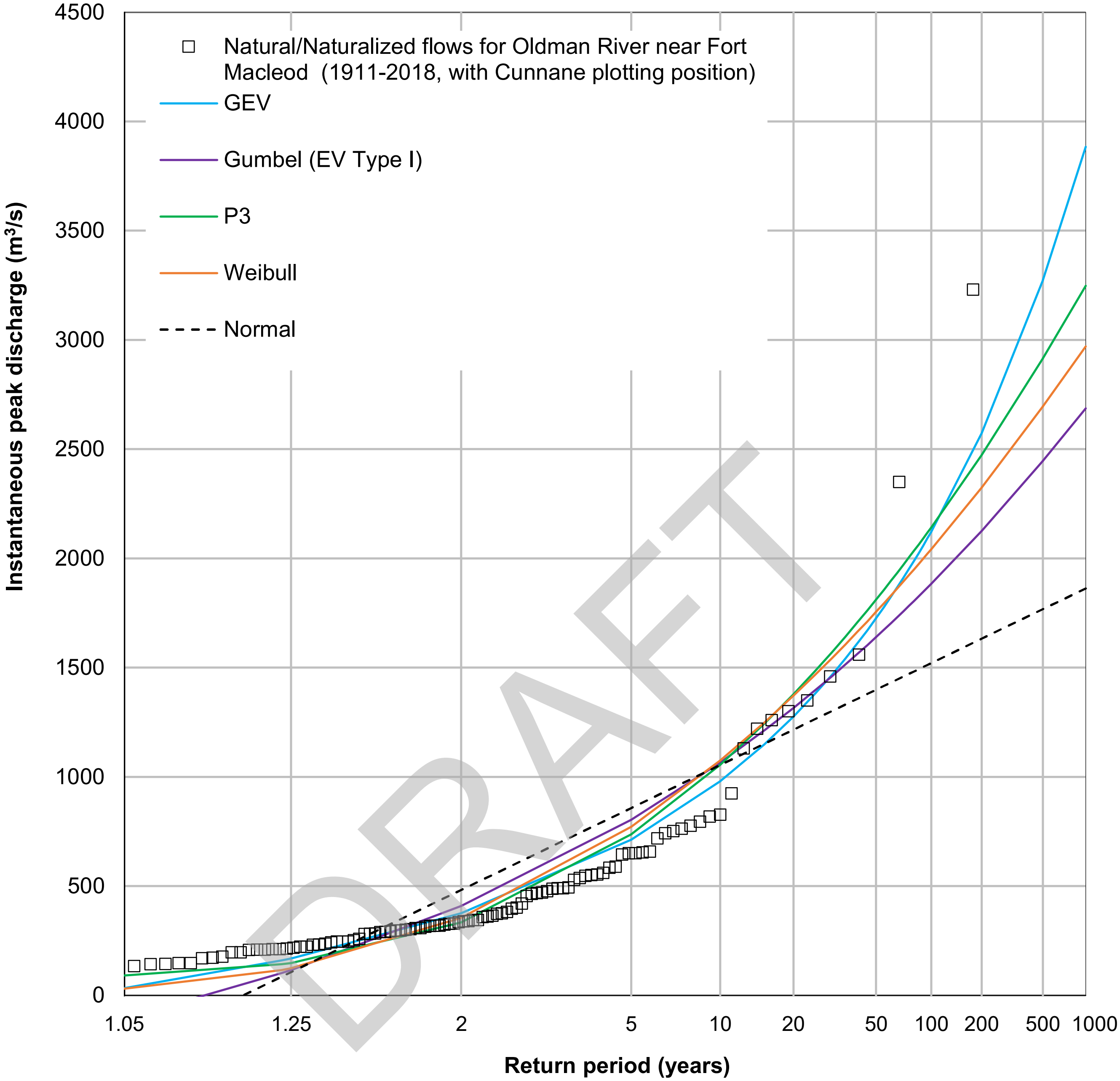
FIGURE 18



Alberta	SCALE – AS SHOWN	*FORT MACLEOD FLOOD HAZARD STUDY OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*ADOPTED FLOOD FREQUENCY CURVE FOR WILLOW CREEK AT HIGHWAY NO. 811*
	Job: 3004660 / *Date: Jul-2019*	*FIGURE 19*

Classification: Public

APPENDIX A
Additional Evaluated Frequency Distribution



SCALE – AS SHOWN

Coordinate System:
Units: As Shown

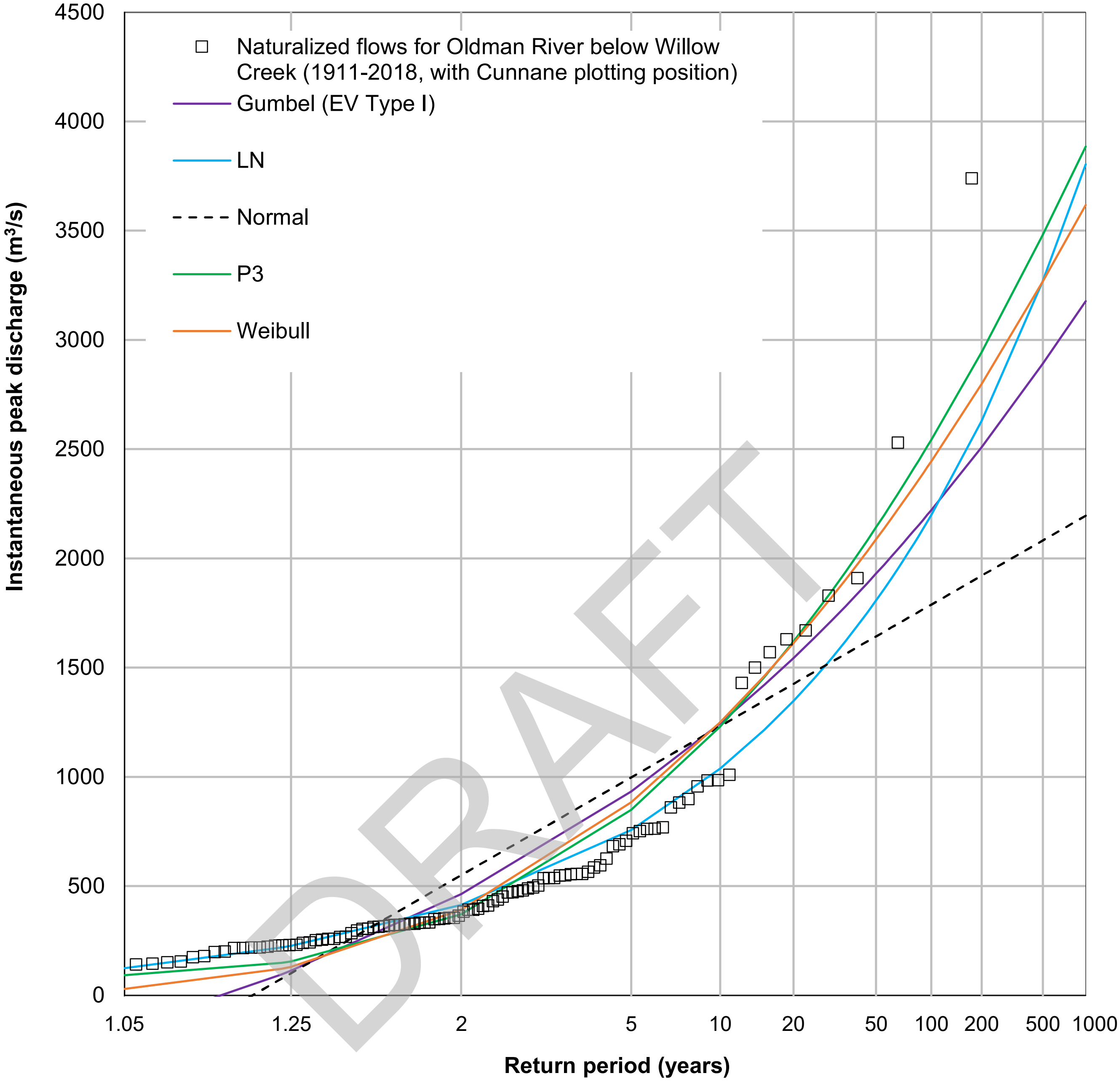
Job: 3004660 | *Date: Jul-2019*

FORT MACLEOD FLOOD HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

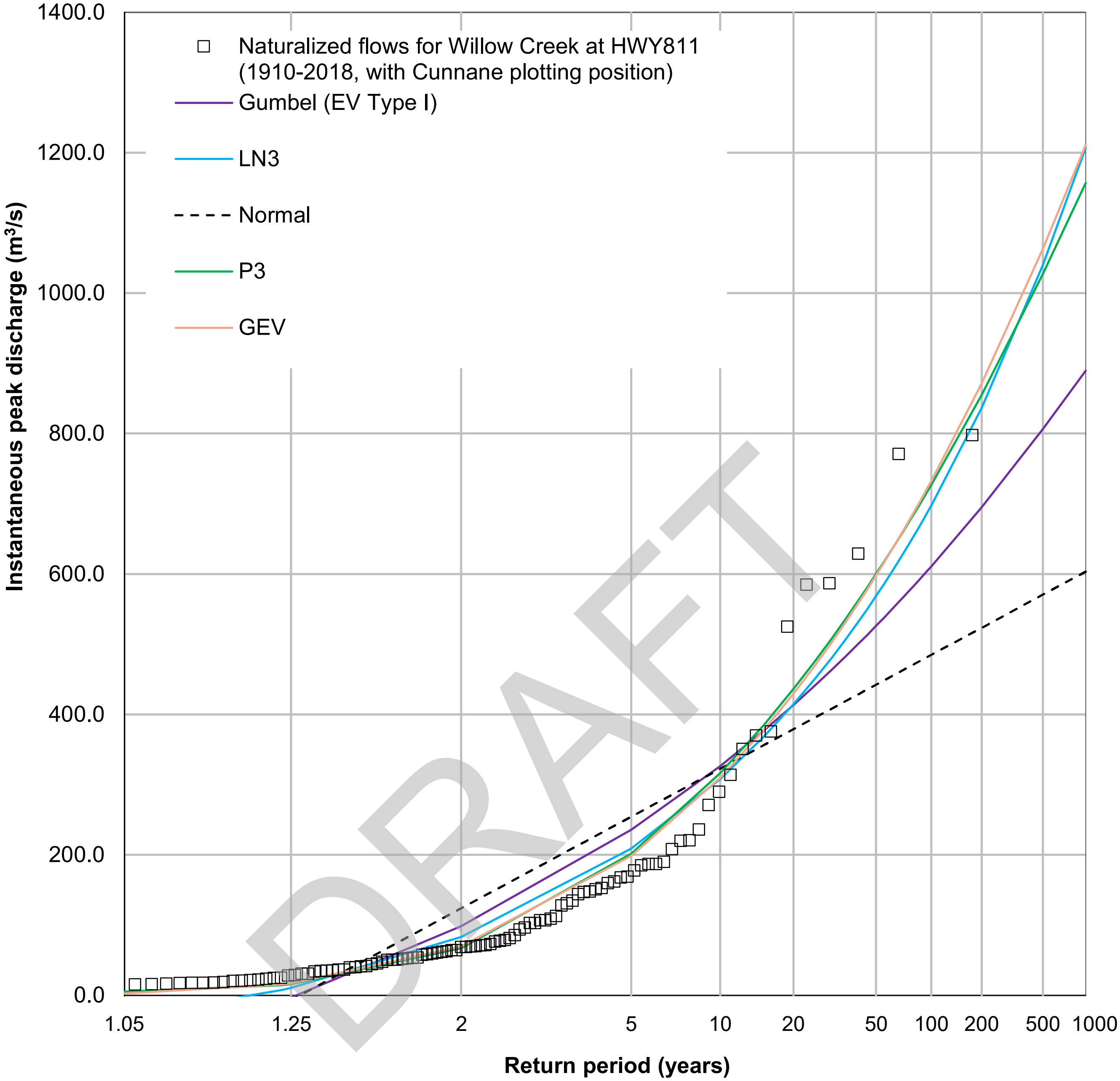
COMPARISON OF FLOOD FREQUENCY CURVES FOR OLDMAN RIVER NEAR FORT MACLEOD (05AB007)

FIGURE A-1

nhc northwest hydraulic consultants



Alberta	SCALE – AS SHOWN	*FORT MACLEOD FLOOD HAZARD STUDY OPEN WATER HYDROLOGY ASSESSMENT*
nhc northwest hydraulic consultants	Coordinate System: Units: As Shown	*COMPARISON OF FLOOD FREQUENCY CURVES FOR OLDMAN RIVER BELOW WILLOW CREEK*
	Job: 3004660	*Date: Jul-2019*
		FIGURE A-2




SCALE – AS SHOWN

FORT MACLEOD FLOOD HAZARD STUDY
OPEN WATER HYDROLOGY ASSESSMENT

COMPARISON OF FLOOD FREQUENCY CURVES FOR WILLOW CREEK AT HIGHWAY NO. 811 (05AB046)

Coordinate System:
Units: As Shown

northwest hydraulic consultants

Job: 3004660 | *Date: Jul-2019*

FIGURE A-3

northwest hydraulic consultants
water resource specialists

Appendix F: Detailed Model Data

Table F1 – Bridge Details
Table F2 – Culvert Details
Table F3 - Computed Flood Frequency Water Levels – Willow Creek
Table F4 - Computed Flood Frequency Water Levels – Oldman River

Table F1 Bridge Details

Reach	Description	River Station (m)	Municipality	Design Drawing /Info	Span (m)	Width (m)	Number of Piers	Pier Width (m)	Skew (°)	Minimum Elevation		Modelling Approach
										High Chord	Low Chord	
Oldman River	HWY 811 (Mackenzie Bridge)	13,756	Fort Macleod	Yes	168.4	5.0	3	1.7	N/A	941.66	940.74	Energy Only (Standard Step)
Oldman River	HWY 2	18,362	Municipal District of Willow Creek	Yes	134.0	12.2	3	0.92	N/A	951.07	949.13	Energy Only (Standard Step)
Oldman River	Abandoned Railway Bridge	19,248	Municipal District of Willow Creek	No	183.1	4.5	5	2.5	N/A	950.32	948.77	Energy Only (Standard Step)
Oldman River	Abandoned Railway Bridge	19,248	Municipal District of Willow Creek	No	10.4	4.5	0	N/A	N/A	952.11	951.50	Energy Only (Standard Step)
Willow Creek	HWY 811	11,301	Municipal District of Willow Creek	Yes	71.2	7.3	2	0.62	N/A	939.87	938.58	Energy Only (Standard Step)

Table F2 Culvert Details

Stream Name	Descript.	River Station (km)	Munic.	Culvert Shape	Mat.	Entrance Condition	Number of Barrels	Barrel Length (m)	Diameter (m)	U/S Invert Elev (m)	D/S Invert Elev (m)	Loss Coefficient		Manning's n	
												Entrance	Exit	Top	Bottom
Oldman River Drainage	Hwy 2 (00509)	18,362	Municipal District of Willow Creek	Circular	CSP	Mitered to slope	1	81.9	0.9m	944.13	944.01	0.5	1	0.024	0.024
Oldman River Drainage	Hwy 2 (00509)	18,363	Municipal District of Willow Creek	Circular	CSP	Mitered to slope	1	94.3	0.9m	943.15	942.97	0.5	1	0.024	0.024
Oldman River Drainage	Hwy 811 (02062)	13,756	Fort Macleod	Circular	CSP	Projecting from Fill	1	25.2	0.9m	935.03	934.95	0.9	1	0.024	0.024
Oldman River Drainage	Hwy 811 (02063)	13,756	Fort Macleod	Circular	CSP	Projecting from Fill	1	24.7	0.9m	935.405	935.504	0.9	1	0.024	0.024

Table F3 Computed Flood Frequency Water Levels – Willow Creek

River Station	Flood Return Period												
	1000-Year	750-Year	500-Year	350-Year	200-Year	100-Year	75-Year	50-Year	35-Year	20-Year	10-Year	5-Year	2-Year
	Water Surface Elevation (m)												
17,645	947.01	946.83	946.57	946.33	945.93	945.48	945.30	945.05	944.85	944.54	944.17	943.75	942.90
17,474	946.85	946.67	946.41	946.17	945.77	945.30	945.12	944.86	944.64	944.33	943.95	943.54	942.61
17,194	946.71	946.53	946.28	946.04	945.63	945.15	944.96	944.70	944.46	944.13	943.71	943.18	942.09
16,760	946.37	946.19	945.93	945.69	945.27	944.78	944.58	944.29	944.02	943.63	943.14	942.59	941.53
16,670	946.25	946.07	945.82	945.59	945.18	944.69	944.50	944.22	943.95	943.58	943.09	942.50	941.43
15,735	945.96	945.77	945.51	945.27	944.81	944.26	944.01	943.66	943.34	942.85	942.20	941.53	940.49
15,604	944.48	944.30	944.02	943.50	943.23	942.61	942.46	942.24	942.04	941.72	941.33	940.81	939.84
15,294	943.79	943.52	943.32	943.16	942.86	942.50	942.35	942.14	941.95	941.64	941.25	940.71	939.74
15,031	943.03	942.91	942.71	942.54	942.28	941.94	941.80	941.60	941.42	941.12	940.73	940.25	939.38
14,779	942.58	942.42	942.19	942.00	941.72	941.41	941.30	941.14	940.98	940.73	940.38	939.91	939.04
14,600	942.30	942.14	941.92	941.73	941.41	941.03	940.88	940.67	940.50	940.22	939.89	939.53	938.78
14,223	941.94	941.78	941.56	941.38	941.09	940.75	940.61	940.42	940.26	940.01	939.71	939.37	938.58
13,943	941.40	941.25	941.05	940.88	940.61	940.28	940.15	939.96	939.80	939.56	939.21	938.81	938.01
13,772	940.94	940.81	940.62	940.46	940.21	939.86	939.72	939.53	939.38	939.16	938.87	938.52	937.78
13,605	940.76	940.63	940.45	940.29	940.05	939.68	939.52	939.32	939.17	938.93	938.61	938.27	937.50
13,478	940.64	940.50	940.31	940.14	939.88	939.50	939.32	939.10	938.93	938.66	938.33	937.96	937.21
13,288	940.07	939.93	939.73	939.59	939.43	939.08	938.88	938.64	938.50	938.32	938.02	937.67	936.87
13,158	940.19	940.05	939.85	939.70	939.50	939.11	938.88	938.60	938.42	938.16	937.81	937.40	936.58
13,011	940.09	939.96	939.76	939.61	939.42	939.01	938.75	938.38	938.16	937.88	937.61	937.30	936.53
12,698	940.06	939.92	939.73	939.58	939.40	939.00	938.73	938.37	938.14	937.86	937.56	937.24	936.48
12,577	940.01	939.88	939.69	939.54	939.37	938.96	938.68	938.29	938.04	937.73	937.38	936.99	936.21
12,086	939.97	939.84	939.64	939.50	939.34	938.93	938.64	938.24	937.99	937.68	937.32	936.91	936.04
11,780	939.73	939.61	939.42	939.30	939.17	938.75	938.44	937.95	937.65	937.27	936.81	936.37	935.39
11,369	939.58	939.46	939.28	939.17	939.08	938.65	938.32	937.79	937.45	937.05	936.50	935.96	934.88
11,309	939.43	939.32	939.15	939.06	939.00	938.58	938.23	937.67	937.31	936.69	936.12	935.59	934.62

River Station	Flood Return Period												
	1000-Year	750-Year	500-Year	350-Year	200-Year	100-Year	75-Year	50-Year	35-Year	20-Year	10-Year	5-Year	2-Year
	Water Surface Elevation (m)												
11,301	939.34	939.24	939.07	938.99	938.95	938.52	938.13	936.91	936.70	936.40	936.01	935.57	934.60
11,292	938.68	938.60	938.56	938.35	937.81	936.96	936.87	936.71	936.57	936.32	935.97	935.55	934.60
11,219	937.82	937.70	937.55	937.41	937.21	936.90	936.80	936.65	936.50	936.26	935.92	935.51	934.58
10,954	937.35	937.25	937.10	936.98	936.78	936.53	936.43	936.28	936.14	935.94	935.66	935.28	934.38
10,693	936.97	936.88	936.76	936.65	936.50	936.31	936.23	936.10	935.99	935.81	935.55	935.14	934.09
10,342	936.72	936.61	936.48	936.37	936.20	936.00	935.92	935.82	935.69	935.53	935.30	934.93	933.87
10,076	936.60	936.49	936.35	936.24	936.06	935.85	935.76	935.65	935.52	935.32	935.03	934.59	933.57
9,795	936.40	936.29	936.16	936.05	935.89	935.69	935.60	935.49	935.37	935.16	934.80	934.29	933.17
9,431	935.78	935.68	935.55	935.43	935.24	935.03	934.96	934.81	934.72	934.50	934.30	933.99	932.97
9,248	935.62	935.53	935.41	935.30	935.15	934.96	934.88	934.75	934.66	934.49	934.25	933.90	932.89
8,873	935.19	935.12	935.03	934.95	934.83	934.69	934.62	934.51	934.44	934.30	934.05	933.66	932.64
7,979	934.39	934.31	934.19	934.09	933.93	933.74	933.69	933.62	933.51	933.34	933.07	932.80	932.03
7,530	934.10	934.01	933.90	933.80	933.64	933.47	933.40	933.29	933.19	933.02	932.74	932.41	931.66
6,477	933.41	933.34	933.24	933.17	933.02	932.77	932.69	932.56	932.44	932.21	932.05	931.53	930.48
5,929	932.77	932.67	932.53	932.40	932.14	931.85	931.78	931.68	931.60	931.46	931.40	931.06	930.12
5,600	932.53	932.45	932.32	932.21	932.01	931.75	931.68	931.59	931.50	931.33	931.25	930.78	929.87
5,400	932.26	932.17	932.03	931.92	931.71	931.44	931.38	931.28	931.18	931.01	930.92	930.43	929.47
4,671	932.00	931.92	931.75	931.60	931.35	931.12	931.07	931.00	930.88	930.67	930.57	930.09	929.08
3,752	931.05	930.98	930.86	930.74	930.55	930.32	930.23	929.97	929.92	929.83	929.78	929.47	928.60
3,355	930.63	930.55	930.37	930.22	929.99	929.79	929.74	929.66	929.59	929.45	929.39	929.06	928.22
2,773	930.24	930.15	929.97	929.82	929.62	929.44	929.39	929.31	929.23	929.08	929.01	928.61	927.71
2,369	930.05	929.95	929.75	929.58	929.33	929.11	929.02	928.92	928.81	928.65	928.59	928.20	927.35
1,545	929.86	929.74	929.53	929.34	929.05	928.76	928.65	928.49	928.35	928.11	927.90	927.45	926.62
839	929.53	929.41	929.23	929.08	928.84	928.56	928.45	928.28	928.12	927.85	927.51	927.04	926.31

Table F4 Computed Flood Frequency Water Levels – Oldman River

River Station	Flood Return Period												
	1000-Year	750-Year	500-Year	350-Year	200-Year	100-Year	75-Year	50-Year	35-Year	20-Year	10-Year	5-Year	2-Year
	Water Surface Elevation (m)												
21,298	953.90	953.70	953.44	953.18	952.82	952.38	952.20	951.95	951.72	951.37	950.91	950.42	949.63
21,058	953.42	953.24	952.99	952.76	952.41	951.99	951.82	951.57	951.38	951.07	950.62	950.08	949.23
20,806	952.98	952.79	952.56	952.34	951.99	951.56	951.36	951.09	950.85	950.48	950.01	949.53	948.77
20,588	952.78	952.59	952.35	952.13	951.79	951.38	951.18	950.91	950.67	950.31	949.83	949.33	948.58
20,334	951.77	951.61	951.38	951.18	950.89	950.52	950.38	950.17	950.00	949.72	949.33	948.92	948.27
19,815	950.85	950.69	950.46	950.28	949.98	949.65	949.50	949.26	949.05	948.77	948.46	948.13	947.56
19,357	950.25	950.08	949.81	949.59	949.13	948.70	948.51	948.21	947.93	947.50	946.94	946.46	945.57
19,253	950.09	949.93	949.66	949.45	949.00	948.58	948.39	948.09	947.82	947.44	946.97	946.47	945.63
19,233	949.65	949.46	949.20	949.01	948.69	948.31	948.16	947.92	947.67	947.34	946.91	946.43	945.61
18,975	949.64	949.45	949.21	949.02	948.72	948.32	948.16	947.87	947.60	947.21	946.76	946.29	945.49
18,797	949.50	949.31	949.07	948.89	948.58	948.17	947.99	947.65	947.32	946.87	946.34	945.81	945.11
18,545	949.42	949.24	949.00	948.82	948.52	948.12	947.94	947.60	947.26	946.79	946.25	945.69	944.89
18,480	949.40	949.21	948.98	948.80	948.50	948.10	947.92	947.58	947.23	946.73	946.17	945.60	944.79
18,391	949.37	949.19	948.95	948.78	948.48	948.08	947.90	947.55	947.20	946.69	946.12	945.51	944.63
18,287	948.42	948.26	948.04	947.84	947.53	947.15	947.00	946.78	946.56	946.23	945.79	945.27	944.43
17,885	947.59	947.43	947.19	946.98	946.65	946.28	946.13	945.92	945.72	945.44	945.05	944.61	943.86
17,221	946.25	946.08	945.85	945.65	945.33	944.96	944.81	944.60	944.42	944.15	943.81	943.44	942.83
16,806	945.36	945.20	944.98	944.78	944.48	944.14	944.01	943.82	943.65	943.40	943.10	942.79	942.20
16,442	944.80	944.63	944.39	944.19	943.89	943.53	943.39	943.18	943.01	942.76	942.43	942.11	941.57
16,244	944.59	944.42	944.17	943.96	943.65	943.27	943.13	942.91	942.72	942.46	942.08	941.68	941.14
16,017	944.20	944.04	943.80	943.59	943.28	942.92	942.77	942.55	942.34	942.04	941.63	941.18	940.49
15,769	943.84	943.68	943.44	943.24	942.95	942.60	942.46	942.25	942.06	941.78	941.36	940.92	940.24
15,639	942.95	942.83	942.67	942.54	942.35	942.11	942.00	941.82	941.64	941.40	941.00	940.59	939.99
15,323	942.05	941.92	941.73	941.56	941.30	940.97	940.81	940.62	940.45	940.19	939.89	939.59	939.14
15,121	941.44	941.31	941.14	940.98	940.74	940.46	940.34	940.18	940.03	939.81	939.49	939.16	938.65

River Station	Flood Return Period												
	1000-Year	750-Year	500-Year	350-Year	200-Year	100-Year	75-Year	50-Year	35-Year	20-Year	10-Year	5-Year	2-Year
	Water Surface Elevation (m)												
14,747	941.02	940.90	940.73	940.56	940.32	940.04	939.92	939.75	939.60	939.37	939.06	938.75	938.26
14,261	940.65	940.54	940.38	940.22	939.99	939.71	939.59	939.43	939.28	939.06	938.77	938.50	938.06
13,984	940.23	940.11	939.94	939.80	939.56	939.28	939.17	939.01	938.88	938.67	938.43	938.22	937.85
13,772	939.66	939.54	939.37	939.23	939.02	938.77	938.67	938.53	938.42	938.25	938.05	937.96	937.02
13,745	939.41	939.30	939.13	938.99	938.76	938.50	938.39	938.23	938.09	937.88	937.62	937.32	936.77
13,622	939.01	938.89	938.73	938.59	938.38	938.13	938.02	937.86	937.71	937.50	937.23	936.94	936.43
13,325	938.37	938.25	938.08	937.94	937.73	937.49	937.39	937.24	937.11	936.91	936.65	936.36	935.88
12,910	937.72	937.60	937.43	937.29	937.08	936.83	936.74	936.60	936.47	936.28	936.00	935.69	935.13
12,586	937.21	937.09	936.93	936.80	936.59	936.34	936.23	936.08	935.95	935.72	935.44	935.14	934.64
12,107	936.28	936.18	936.04	935.91	935.72	935.48	935.38	935.23	935.10	934.87	934.58	934.29	933.86
11,838	935.52	935.42	935.29	935.17	934.99	934.76	934.66	934.52	934.39	934.18	933.92	933.65	933.24
11,520	934.84	934.75	934.61	934.50	934.32	934.11	934.02	933.88	933.77	933.59	933.32	933.04	932.61
11,085	934.38	934.28	934.15	934.03	933.85	933.64	933.55	933.42	933.31	933.14	932.88	932.59	932.07
10,767	933.96	933.87	933.74	933.63	933.47	933.27	933.18	933.06	932.95	932.77	932.49	932.14	931.54
9,821	933.20	933.11	932.98	932.87	932.73	932.53	932.45	932.32	932.20	932.01	931.65	931.26	930.67
9,472	932.73	932.63	932.49	932.38	932.22	932.04	931.96	931.84	931.74	931.56	931.20	930.81	930.22
9,137	932.26	932.15	932.01	931.89	931.72	931.52	931.43	931.30	931.18	930.97	930.60	930.27	929.72
8,856	932.02	931.91	931.77	931.66	931.49	931.30	931.21	931.08	930.96	930.76	930.38	930.03	929.45
8,438	931.55	931.42	931.30	931.19	931.04	930.82	930.73	930.59	930.46	930.25	929.86	929.49	928.88
8,157	931.18	931.03	930.89	930.77	930.56	930.24	930.07	929.83	929.62	929.31	928.89	928.56	928.00
7,703	930.65	930.52	930.38	930.27	930.07	929.73	929.56	929.30	929.07	928.71	928.17	927.72	927.04
7,554	929.80	929.67	929.53	929.42	929.24	928.96	928.83	928.64	928.47	928.18	927.75	927.37	926.79
7,288	929.36	929.24	929.09	928.97	928.79	928.55	928.44	928.27	928.11	927.85	927.45	927.07	926.53
7,098	929.25	929.12	928.97	928.85	928.66	928.42	928.30	928.13	927.98	927.71	927.31	926.90	926.30
6,786	928.97	928.83	928.65	928.49	928.26	927.99	927.88	927.72	927.57	927.31	926.96	926.51	925.78
6,598	928.77	928.63	928.44	928.28	928.05	927.77	927.66	927.49	927.34	927.10	926.75	926.29	925.53

River Station	Flood Return Period												
	1000-Year	750-Year	500-Year	350-Year	200-Year	100-Year	75-Year	50-Year	35-Year	20-Year	10-Year	5-Year	2-Year
	Water Surface Elevation (m)												
6,465	928.64	928.50	928.31	928.15	927.91	927.63	927.52	927.36	927.21	926.98	926.63	926.17	925.36
6,246	928.45	928.31	928.12	927.96	927.73	927.46	927.36	927.20	927.06	926.84	926.50	926.05	925.21
5,985	928.24	928.10	927.91	927.75	927.53	927.27	927.17	927.02	926.88	926.66	926.34	925.88	924.98
5,612	927.99	927.85	927.67	927.53	927.31	927.08	926.99	926.86	926.71	926.51	926.19	925.72	924.77
4,791	927.51	927.34	927.12	926.93	926.67	926.35	926.25	926.08	925.91	925.62	925.15	924.57	923.60
4,362	926.94	926.74	926.47	926.24	925.88	925.45	925.27	925.01	924.80	924.49	924.12	923.71	922.99
3,990	926.51	926.32	926.06	925.84	925.52	925.13	924.98	924.77	924.59	924.32	923.95	923.50	922.76
3,685	926.12	925.94	925.68	925.48	925.15	924.76	924.61	924.38	924.19	923.90	923.51	923.08	922.40
3,368	925.66	925.47	925.22	925.02	924.71	924.33	924.18	923.95	923.76	923.47	923.10	922.67	922.03
3,079	925.21	925.05	924.80	924.61	924.32	923.93	923.79	923.56	923.36	923.05	922.65	922.23	921.56
2,730	924.84	924.68	924.44	924.26	923.99	923.58	923.43	923.21	922.98	922.66	922.22	921.75	921.00
2,235	923.16	923.04	922.90	922.72	922.30	921.95	921.76	921.47	921.29	920.92	920.53	920.12	919.66
1,855	922.91	922.74	922.48	922.28	921.95	921.58	921.43	921.22	921.03	920.73	920.35	919.92	919.28
1,165	922.31	922.13	921.87	921.67	921.35	921.00	920.85	920.65	920.47	920.20	919.82	919.41	918.83
632	921.97	921.79	921.54	921.33	920.99	920.63	920.49	920.30	920.13	919.87	919.47	919.06	918.44
286	921.75	921.57	921.33	921.12	920.78	920.42	920.28	920.09	919.91	919.65	919.24	918.82	918.17

Appendix G: Sensitivity Analysis Results

Table G1 Sensitivity analysis results for flood frequency estimates

River Station (m)	100-Year Flood Levels (m) for Varying Flood Frequency Estimates		
	Lower Limit of Flood Frequency Estimates	Adopted Flood Frequency Estimates	Upper Limit of Flood Frequency Estimates
Oldman River			
21,298	952.01	952.38	952.86
21,058	951.63	951.99	952.45
20,806	951.16	951.56	952.04
20,588	950.98	951.38	951.83
20,334	950.23	950.52	950.92
19,815	949.33	949.65	950.02
19,357	948.29	948.70	949.18
19,253	948.16	948.58	949.04
19,233	947.98	948.31	948.73
18,975	947.94	948.32	948.76
18,797	947.74	948.17	948.62
18,545	947.69	948.12	948.56
18,480	947.67	948.10	948.54
18,391	947.65	948.08	948.52
18,287	946.83	947.15	947.57
17,885	945.97	946.28	946.69
17,221	944.65	944.96	945.37
16,806	943.87	944.14	944.52
16,442	943.23	943.53	943.93
16,244	942.97	943.27	943.68
16,017	942.61	942.92	943.32
15,769	942.31	942.60	942.98
15,639	941.86	942.11	942.37
15,323	940.67	940.97	941.33
15,121	940.22	940.46	940.77
14,747	939.79	940.04	940.35
14,261	939.47	939.71	940.02
13,984	939.05	939.28	939.59
13,772	938.57	938.77	939.04
13,745	938.27	938.50	938.80
13,622	937.90	938.13	938.41
13,325	937.28	937.49	937.76
12,910	936.63	936.83	937.11
12,586	936.12	936.34	936.61
12,107	935.27	935.48	935.74
11,838	934.56	934.76	935.01

River Station (m)	100-Year Flood Levels (m) for Varying Flood Frequency Estimates		
	Lower Limit of Flood Frequency Estimates	Adopted Flood Frequency Estimates	Upper Limit of Flood Frequency Estimates
11,520	933.93	934.11	934.35
11,085	933.46	933.64	933.87
10,767	933.09	933.27	933.49
9,821	932.36	932.53	932.77
9,472	931.87	932.04	932.28
9,137	931.33	931.52	931.78
8,856	931.11	931.30	931.55
8,438	930.63	930.82	931.11
8,157	929.90	930.24	930.65
7,703	929.36	929.73	930.16
7,554	928.69	928.96	929.31
7,288	928.31	928.55	928.85
7,098	928.18	928.42	928.71
6,786	927.76	927.99	928.29
6,598	927.54	927.77	928.08
6,465	927.40	927.63	927.94
6,246	927.24	927.46	927.76
5,985	927.06	927.27	927.56
5,612	926.89	927.08	927.34
4,791	926.11	926.35	926.70
4,362	925.08	925.45	925.92
3,990	924.82	925.13	925.56
3,685	924.44	924.76	925.19
3,368	924.01	924.33	924.75
3,079	923.62	923.93	924.37
2,730	923.27	923.58	924.04
2,235	921.53	921.95	922.30
1,855	921.28	921.58	921.99
1,165	920.70	921.00	921.39
632	920.35	920.63	921.03
286	920.14	920.42	920.82
Willow Creek			
17,645	945.03	945.48	946.13
17,474	944.84	945.30	945.97
17,194	944.68	945.15	945.83
16,760	944.27	944.78	945.48
16,670	944.20	944.69	945.38
16,140	943.63	944.26	945.03

River Station (m)	100-Year Flood Levels (m) for Varying Flood Frequency Estimates		
	Lower Limit of Flood Frequency Estimates	Adopted Flood Frequency Estimates	Upper Limit of Flood Frequency Estimates
15,735	942.22	942.61	943.36
15,604	942.13	942.50	943.01
15,294	941.59	941.94	942.41
15,031	941.13	941.41	941.85
14,779	940.66	941.03	941.56
14,600	940.41	940.75	941.23
14,223	939.95	940.28	940.74
13,943	939.52	939.86	940.33
13,772	939.31	939.68	940.16
13,605	939.08	939.50	940.00
13,478	938.62	939.08	939.47
13,288	938.57	939.11	939.57
13,158	938.36	939.01	939.48
13,011	938.34	939.00	939.46
12,698	938.27	938.96	939.42
12,577	938.22	938.93	939.38
12,086	937.93	938.75	939.18
11,780	937.76	938.65	939.06
11,369	937.64	938.58	938.96
11,309	936.89	938.52	938.89
11,292	936.70	936.96	938.25
11,219	936.63	936.90	937.31
10,954	936.26	936.53	936.88
10,693	936.09	936.31	936.58
10,342	935.79	936.00	936.29
10,076	935.63	935.85	936.15
9,795	935.48	935.69	935.97
9,431	934.80	935.03	935.34
9,248	934.76	934.96	935.23
8,873	934.53	934.69	934.89
7,979	933.58	933.74	934.01
7,530	933.29	933.47	933.72
6,477	932.52	932.77	933.03
5,929	931.65	931.85	932.13
5,600	931.55	931.75	932.00
5,400	931.23	931.44	931.70
4,671	930.94	931.12	931.34
3,752	929.95	930.32	930.55

River Station (m)	100-Year Flood Levels (m) for Varying Flood Frequency Estimates		
	Lower Limit of Flood Frequency Estimates	Adopted Flood Frequency Estimates	Upper Limit of Flood Frequency Estimates
3,355	929.63	929.79	929.99
2,773	929.28	929.44	929.61
2,369	928.89	929.11	929.32
1,545	928.50	928.76	929.06
8,39	928.31	928.56	928.86

Table G2 Sensitivity analysis results for downstream boundary conditions

River Station (m)	100-Year Flood Levels (m) for Varying Downstream Boundary Conditions		
	Lower Limit S = 0.0002 m/m	Adopted Normal Depth S = 0.001 m/m	Upper Limit S = 0.0042 m/m
Oldman River			
21,298	952.38	952.38	952.38
21,058	951.99	951.99	951.99
20,806	951.56	951.56	951.56
20,588	951.38	951.38	951.38
20,334	950.52	950.52	950.52
19,815	949.65	949.65	949.65
19,357	948.70	948.70	948.70
19,253	948.58	948.58	948.58
19,233	948.31	948.31	948.31
18,975	948.32	948.32	948.32
18,797	948.17	948.17	948.17
18,545	948.12	948.12	948.12
18,480	948.10	948.10	948.10
18,391	948.08	948.08	948.08
18,287	947.15	947.15	947.15
17,885	946.28	946.28	946.28
17,221	944.96	944.96	944.96
16,806	944.14	944.14	944.14
16,442	943.53	943.53	943.53
16,244	943.27	943.27	943.27
16,017	942.92	942.92	942.92
15,769	942.60	942.60	942.60
15,639	942.11	942.11	942.11
15,323	940.97	940.97	940.97
15,121	940.46	940.46	940.46
14,747	940.04	940.04	940.04
14,261	939.71	939.71	939.71
13,984	939.28	939.28	939.28
13,772	938.77	938.77	938.77
13,745	938.50	938.50	938.50
13,622	938.13	938.13	938.13
13,325	937.49	937.49	937.49
12,910	936.83	936.83	936.83
12,586	936.34	936.34	936.34
12,107	935.48	935.48	935.48
11,838	934.76	934.76	934.76

River Station (m)	100-Year Flood Levels (m) for Varying Downstream Boundary Conditions		
	Lower Limit S = 0.0002 m/m	Adopted Normal Depth S = 0.001 m/m	Upper Limit S = 0.0042 m/m
11,520	934.11	934.11	934.11
11,085	933.64	933.64	933.64
10,767	933.27	933.27	933.27
9,821	932.53	932.53	932.53
9,472	932.04	932.04	932.04
9,137	931.52	931.52	931.52
8,856	931.30	931.30	931.30
8,438	930.82	930.82	930.82
8,157	930.24	930.24	930.24
7,703	929.73	929.73	929.73
7,554	928.96	928.96	928.96
7,288	928.55	928.55	928.55
7,098	928.42	928.42	928.42
6,786	927.99	927.99	927.99
6,598	927.77	927.77	927.77
6,465	927.63	927.63	927.63
6,246	927.46	927.46	927.46
5,985	927.27	927.27	927.27
5,612	927.08	927.08	927.08
4,791	926.35	926.35	926.35
4,362	925.45	925.45	925.45
3,990	925.13	925.13	925.13
3,685	924.76	924.76	924.76
3,368	924.33	924.33	924.33
3,079	923.93	923.93	923.93
2,730	923.58	923.58	923.58
2,235	921.95	921.95	921.95
1,855	922.12	921.58	921.54
1,165	921.91	921.00	920.88
632	921.82	920.63	920.34
286	921.78	920.42	919.56
Willow Creek			
17,645	945.48	945.48	945.48
17,474	945.30	945.30	945.30
17,194	945.15	945.15	945.15
16,760	944.78	944.78	944.78
16,670	944.69	944.69	944.69
16,140	944.26	944.26	944.26

River Station (m)	100-Year Flood Levels (m) for Varying Downstream Boundary Conditions		
	Lower Limit S = 0.0002 m/m	Adopted Normal Depth S = 0.001 m/m	Upper Limit S = 0.0042 m/m
15,735	942.61	942.61	942.61
15,604	942.50	942.50	942.50
15,294	941.94	941.94	941.94
15,031	941.41	941.41	941.41
14,779	941.03	941.03	941.03
14,600	940.75	940.75	940.75
14,223	940.28	940.28	940.28
13,943	939.86	939.86	939.86
13,772	939.68	939.68	939.68
13,605	939.50	939.50	939.50
13,478	939.08	939.08	939.08
13,288	939.11	939.11	939.11
13,158	939.01	939.01	939.01
13,011	939.00	939.00	939.00
12,698	938.96	938.96	938.96
12,577	938.93	938.93	938.93
12,086	938.75	938.75	938.75
11,780	938.65	938.65	938.65
11,369	938.58	938.58	938.58
11,309	938.52	938.52	938.52
11,292	936.96	936.96	936.96
11,219	936.90	936.90	936.90
10,954	936.53	936.53	936.53
10,693	936.31	936.31	936.31
10,342	936.00	936.00	936.00
10,076	935.85	935.85	935.85
9,795	935.69	935.69	935.69
9,431	935.03	935.03	935.03
9,248	934.96	934.96	934.96
8,873	934.69	934.69	934.69
7,979	933.74	933.74	933.74
7,530	933.47	933.47	933.47
6,477	932.77	932.77	932.77
5,929	931.85	931.85	931.85
5,600	931.75	931.75	931.75
5,400	931.44	931.44	931.44
4,671	931.12	931.12	931.12
3,752	930.32	930.32	930.32

River Station (m)	100-Year Flood Levels (m) for Varying Downstream Boundary Conditions		
	Lower Limit S = 0.0002 m/m	Adopted Normal Depth S = 0.001 m/m	Upper Limit S = 0.0042 m/m
3,355	929.79	929.79	929.79
2,773	929.44	929.44	929.44
2,369	929.11	929.11	929.11
1,545	928.76	928.76	928.76
8,39	928.56	928.56	928.56

Table G3 Sensitivity analysis results for overbank roughness

River Station (m)	100-Year Flood Levels (m) for Varying Overbank Roughness		
	Low Overbank Roughness (-20%)	Adopted Roughness	High Overbank Roughness (+20%)
Oldman River			
21,298	952.26	952.38	952.49
21,058	951.87	951.99	952.08
20,806	951.46	951.56	951.65
20,588	951.28	951.38	951.46
20,334	950.42	950.52	950.61
19,815	949.48	949.65	949.80
19,357	948.64	948.70	948.76
19,253	948.51	948.58	948.66
19,233	948.28	948.31	948.37
18,975	948.28	948.32	948.40
18,797	948.16	948.17	948.21
18,545	948.12	948.12	948.16
18,480	948.11	948.10	948.13
18,391	948.09	948.08	948.11
18,287	946.98	947.15	947.30
17,885	946.12	946.28	946.41
17,221	944.85	944.96	945.04
16,806	944.02	944.14	944.25
16,442	943.37	943.53	943.66
16,244	943.09	943.27	943.43
16,017	942.74	942.92	943.07
15,769	942.44	942.60	942.73
15,639	942.00	942.11	942.21
15,323	940.80	940.97	941.07
15,121	940.27	940.46	940.61
14,747	939.84	940.04	940.20
14,261	939.53	939.71	939.86
13,984	939.14	939.28	939.40
13,772	938.72	938.77	938.82
13,745	938.31	938.50	938.66
13,622	937.95	938.13	938.27
13,325	937.31	937.49	937.64
12,910	936.66	936.83	936.98
12,586	936.19	936.34	936.46
12,107	935.36	935.48	935.58
11,838	934.60	934.76	934.89

River Station (m)	100-Year Flood Levels (m) for Varying Overbank Roughness		
	Low Overbank Roughness (-20%)	Adopted Roughness	High Overbank Roughness (+20%)
11,520	933.94	934.11	934.25
11,085	933.49	933.64	933.77
10,767	933.11	933.27	933.40
9,821	932.41	932.53	932.65
9,472	931.92	932.04	932.14
9,137	931.41	931.52	931.63
8,856	931.18	931.30	931.40
8,438	930.71	930.82	930.93
8,157	930.11	930.24	930.34
7,703	929.58	929.73	929.86
7,554	928.80	928.96	929.09
7,288	928.38	928.55	928.68
7,098	928.25	928.42	928.55
6,786	927.83	927.99	928.12
6,598	927.60	927.77	927.90
6,465	927.46	927.63	927.78
6,246	927.27	927.46	927.62
5,985	927.10	927.27	927.42
5,612	926.92	927.08	927.22
4,791	926.27	926.35	926.44
4,362	925.28	925.45	925.58
3,990	924.97	925.13	925.27
3,685	924.61	924.76	924.89
3,368	924.16	924.33	924.47
3,079	923.74	923.93	924.10
2,730	923.40	923.58	923.75
2,235	921.87	921.95	922.03
1,855	921.36	921.58	921.79
1,165	920.72	921.00	921.22
632	920.40	920.63	920.84
286	920.19	920.42	920.62
Willow Creek			
17,645	945.28	945.48	945.65
17,474	945.11	945.30	945.47
17,194	944.97	945.15	945.31
16,760	944.61	944.78	944.93
16,670	944.53	944.69	944.85
16,140	944.11	944.26	944.41

River Station (m)	100-Year Flood Levels (m) for Varying Overbank Roughness		
	Low Overbank Roughness (-20%)	Adopted Roughness	High Overbank Roughness (+20%)
15,735	942.54	942.61	942.67
15,604	942.39	942.50	942.59
15,294	941.79	941.94	942.07
15,031	941.26	941.41	941.53
14,779	940.87	941.03	941.17
14,600	940.58	940.75	940.89
14,223	940.14	940.28	940.39
13,943	939.71	939.86	939.98
13,772	939.51	939.68	939.80
13,605	939.32	939.50	939.62
13,478	938.86	939.08	939.17
13,288	938.87	939.11	939.22
13,158	938.76	939.01	939.11
13,011	938.74	939.00	939.09
12,698	938.70	938.96	939.05
12,577	938.66	938.93	939.01
12,086	938.49	938.75	938.79
11,780	938.39	938.65	938.68
11,369	938.31	938.58	938.58
11,309	936.29	938.52	938.51
11,292	936.85	936.96	936.86
11,219	936.79	936.90	937.07
10,954	936.40	936.53	936.64
10,693	936.20	936.31	936.40
10,342	935.89	936.00	936.09
10,076	935.73	935.85	935.95
9,795	935.57	935.69	935.77
9,431	934.98	935.03	935.11
9,248	934.85	934.96	935.04
8,873	934.60	934.69	934.76
7,979	933.66	933.74	933.84
7,530	933.36	933.47	933.57
6,477	932.69	932.77	932.81
5,929	931.81	931.85	931.94
5,600	931.66	931.75	931.82
5,400	931.36	931.44	931.51
4,671	931.05	931.12	931.19
3,752	930.25	930.32	930.36

River Station (m)	100-Year Flood Levels (m) for Varying Overbank Roughness		
	Low Overbank Roughness (-20%)	Adopted Roughness	High Overbank Roughness (+20%)
3,355	929.71	929.79	929.86
2,773	929.38	929.44	929.49
2,369	929.00	929.11	929.17
1,545	928.62	928.76	928.86
8,39	928.43	928.56	928.67

Table G4 Sensitivity analysis results for channel roughness

River Station (m)	100-Year Flood Levels (m) for Varying Channel Roughness		
	Low Channel Roughness (-15%)	Adopted Roughness	High Channel Roughness (+15%)
Oldman River			
21,298	952.13	952.38	952.55
21,058	951.82	951.99	952.12
20,806	951.41	951.56	951.68
20,588	951.31	951.38	951.44
20,334	950.26	950.52	950.72
19,815	949.57	949.65	949.74
19,357	948.50	948.70	948.84
19,253	948.49	948.58	948.67
19,233	948.16	948.31	948.46
18,975	948.27	948.32	948.41
18,797	948.10	948.17	948.26
18,545	948.09	948.12	948.19
18,480	948.07	948.10	948.17
18,391	948.05	948.08	948.15
18,287	947.17	947.15	947.16
17,885	946.14	946.28	946.40
17,221	944.76	944.96	945.10
16,806	944.00	944.14	944.26
16,442	943.40	943.53	943.63
16,244	943.20	943.27	943.33
16,017	942.84	942.92	942.97
15,769	942.54	942.60	942.62
15,639	941.95	942.11	942.11
15,323	941.04	940.97	941.11
15,121	940.36	940.46	940.53
14,747	940.01	940.04	940.05
14,261	939.71	939.71	939.71
13,984	939.28	939.28	939.28
13,772	938.77	938.77	938.77
13,745	938.50	938.50	938.50
13,622	938.13	938.13	938.13
13,325	937.48	937.49	937.49
12,910	936.82	936.83	936.85
12,586	936.28	936.34	936.38
12,107	935.41	935.48	935.54
11,838	934.69	934.76	934.81

River Station (m)	100-Year Flood Levels (m) for Varying Channel Roughness		
	Low Channel Roughness (-15%)	Adopted Roughness	High Channel Roughness (+15%)
11,520	934.07	934.11	934.14
11,085	933.58	933.64	933.68
10,767	933.23	933.27	933.30
9,821	932.48	932.53	932.58
9,472	931.99	932.04	932.08
9,137	931.45	931.52	931.57
8,856	931.27	931.30	931.33
8,438	930.79	930.82	930.87
8,157	930.10	930.24	930.33
7,703	929.74	929.73	929.76
7,554	928.69	928.96	929.15
7,288	928.43	928.55	928.65
7,098	928.35	928.42	928.47
6,786	927.93	927.99	928.05
6,598	927.68	927.77	927.84
6,465	927.58	927.63	927.69
6,246	927.44	927.46	927.49
5,985	927.27	927.27	927.28
5,612	927.12	927.08	927.06
4,791	926.29	926.35	926.40
4,362	925.31	925.45	925.61
3,990	925.04	925.13	925.22
3,685	924.61	924.76	924.87
3,368	924.23	924.33	924.40
3,079	923.86	923.93	923.99
2,730	923.55	923.58	923.62
2,235	922.03	921.95	921.90
1,855	921.56	921.58	921.60
1,165	920.94	921.00	921.03
632	920.59	920.63	920.67
286	920.37	920.42	920.46
Willow Creek			
17,645	945.43	945.48	945.52
17,474	945.23	945.30	945.36
17,194	945.09	945.15	945.20
16,760	944.70	944.78	944.84
16,670	944.64	944.69	944.74
16,140	944.23	944.26	944.29

River Station (m)	100-Year Flood Levels (m) for Varying Channel Roughness		
	Low Channel Roughness (-15%)	Adopted Roughness	High Channel Roughness (+15%)
15,735	942.49	942.61	942.91
15,604	942.32	942.50	942.65
15,294	941.83	941.94	942.03
15,031	941.32	941.41	941.48
14,779	940.93	941.03	941.10
14,600	940.68	940.75	940.80
14,223	940.21	940.28	940.34
13,943	939.78	939.86	939.94
13,772	939.63	939.68	939.73
13,605	939.48	939.50	939.54
13,478	938.99	939.08	939.19
13,288	939.09	939.11	939.19
13,158	938.98	939.01	939.11
13,011	938.98	939.00	939.08
12,698	938.95	938.96	939.05
12,577	938.91	938.93	939.02
12,086	938.71	938.75	938.88
11,780	938.64	938.65	938.78
11,369	938.58	938.58	938.71
11,309	938.51	938.52	938.66
11,292	936.82	936.96	937.09
11,219	936.79	936.90	937.00
10,954	936.46	936.53	936.58
10,693	936.32	936.31	936.31
10,342	935.95	936.00	936.03
10,076	935.83	935.85	935.85
9,795	935.68	935.69	935.67
9,431	935.05	935.03	935.09
9,248	934.91	934.96	934.98
8,873	934.66	934.69	934.68
7,979	933.76	933.74	933.78
7,530	933.48	933.47	933.47
6,477	932.69	932.77	932.79
5,929	931.84	931.85	931.93
5,600	931.75	931.75	931.76
5,400	931.35	931.44	931.50
4,671	931.08	931.12	931.15
3,752	930.36	930.32	930.30

River Station (m)	100-Year Flood Levels (m) for Varying Channel Roughness		
	Low Channel Roughness (-15%)	Adopted Roughness	High Channel Roughness (+15%)
3,355	929.76	929.79	929.81
2,773	929.43	929.44	929.45
2,369	929.02	929.11	929.14
1,545	928.70	928.76	928.79
8,39	928.52	928.56	928.60

Appendix H: Open Water Inundation Maps

Provided under separate cover

Appendix I: Floodway Determination Criteria and Design WL

Table I1 Selected Floodway Limiting Stations and Limiting Criteria

River	Reach	River Station (m)	Left		Right	
			Floodway Limiting Station (m)	Limiting Criteria	Floodway Limiting Station (m)	Limiting Criteria
Oldman River	KM 000	2,235	19.0	1m Depth	941.7	1 m/s Velocity
Oldman River	KM 000	2,730	23.8	Mixed	1370.1	1m Depth
Oldman River	KM 000	3,079	79.4	1m Depth	1179.0	1m Depth
Oldman River	KM 000	3,368	48.3	1m Depth	1230.1	1 m/s Velocity
Oldman River	KM 000	3,685	48.0	1m Depth	1018.2	1 m/s Velocity
Oldman River	KM 000	3,990	18.4	1m Depth	908.2	1 m/s Velocity
Oldman River	KM 000	4,362	96.8	1m Depth	1199.5	1 m/s Velocity
Oldman River	KM 000	4,791	83.1	1m Depth	1729.6	1m Depth
Oldman River	KM 000	5,612	24.0	1m Depth	1689.7	1m Depth
Oldman River	KM 000	5,985	19.8	1m Depth	1730.0	1m Depth
Oldman River	KM 000	6,246	56.9	1m Depth	1866.8	Inundation Limit[1]
Oldman River	KM 000	6,465	63.6	1 m/s Velocity	2121.0	Inundation Limit[1]
Oldman River	KM 000	6,598	511.1	1m Depth	2627.6	Inundation Limit[1]
Oldman River	KM 006	6,786	N/A[2]	N/A[2]	1880.3	Inundation Limit[1]
Oldman River	KM 006	7,098	N/A[2]	N/A[2]	1573.2	Inundation Limit[1]
Oldman River	KM 006	7,288	N/A[2]	N/A[2]	1311.0	Inundation Limit[1]
Oldman River	KM 006	7,554	N/A[2]	N/A[2]	1145.8	Inundation Limit[1]
Oldman River	KM 006	7,703	N/A[2]	N/A[2]	1280.8	Main Channel[3]
Oldman River	KM 006	8,157	N/A[2]	N/A[2]	1939.4	Inundation Limit[1]
Oldman River	KM 006	8,438	N/A[2]	N/A[2]	1978.3	Previous Floodway

River	Reach	River Station (m)	Left		Right	
			Floodway Limiting Station (m)	Limiting Criteria	Floodway Limiting Station (m)	Limiting Criteria
Oldman River	KM 006	8,856	N/A[2]	N/A[2]	2205.6	Previous Floodway
Oldman River	KM 006	9,137	N/A[2]	N/A[2]	2072.0	Previous Floodway
Oldman River	KM 006	9,472	N/A[2]	N/A[2]	2213.3	Inundation Limit[1]
Oldman River	KM 006	9,821	N/A[2]	N/A[2]	2048.0	Previous Floodway
Oldman River	KM 006	10,767	N/A[2]	N/A[2]	1835.5	Previous Floodway
Oldman River	KM 006	11,085	N/A[2]	N/A[2]	2098.0	Main Channel[3]
Oldman River	KM 006	11,520	N/A[2]	N/A[2]	1845.9	Previous Floodway
Oldman River	KM 006	11,838	89.4	Inundation Limit[4]	1821.7	Previous Floodway
Oldman River	KM 006	12,107	12.7	Inundation Limit[1]	1664.4	Previous Floodway
Oldman River	KM 006	12,586	49.8	Previous Floodway	1795.7	Previous Floodway
Oldman River	KM 006	12,910	46.6	Inundation Limit[1]	1827.2	Previous Floodway
Oldman River	KM 006	13,325	245.5	Previous Floodway	1812.9	Previous Floodway
Oldman River	KM 006	13,622	724.3	Inundation Limit[4]	1894.2	Previous Floodway
Oldman River	KM 006	13,745	896.2	Previous Floodway	2049.1	Inundation Limit[1]
Oldman River	KM 006	13,772	904.8	Previous Floodway	2048.5	Inundation Limit[1]
Oldman River	KM 006	13,984	940.8	Previous Floodway	1843.3	Previous Floodway
Oldman River	KM 006	14,261	730.4	Previous Floodway	1582.4	Main Channel[3]
Oldman River	KM 006	14,747	424.7	Previous Floodway	1491.9	Inundation Limit[1]
Oldman River	KM 006	15,121	100.9	Previous Floodway	1214.5	Inundation Limit[1]
Oldman River	KM 006	15,323	58.8	Inundation Limit[1]	1259.4	Inundation Limit[1]
Oldman River	KM 006	15,639	20.6	Previous Floodway	926.1	Previous Floodway

River	Reach	River Station (m)	Left		Right	
			Floodway Limiting Station (m)	Limiting Criteria	Floodway Limiting Station (m)	Limiting Criteria
Oldman River	KM 006	15,769	54.0	Previous Floodway	978.9	Inundation Limit[1]
Oldman River	KM 006	16,017	34.1	Previous Floodway	1002.6	Previous Floodway
Oldman River	KM 006	16,244	26.7	Inundation Limit[4]	962.3	Main Channel[3]
Oldman River	KM 006	16,442	39.3	Previous Floodway	838.3	Previous Floodway
Oldman River	KM 006	16,806	33.7	Inundation Limit[4]	862.0	Previous Floodway
Oldman River	KM 006	17,221	22.5	Inundation Limit[4]	821.6	Previous Floodway
Oldman River	KM 006	17,885	170.5	Inundation Limit[4]	762.3	Previous Floodway
Oldman River	KM 006	18,287	25.8	Inundation Limit[4]	796.6	Previous Floodway
Oldman River	KM 006	18,391	28.6	Inundation Limit[4]	1097.2	Inundation Limit[4]
Oldman River	KM 006	18,480	14.2	Inundation Limit[4]	1184.5	Inundation Limit[4]
Oldman River	KM 006	18,545	39.8	Inundation Limit[4]	1239.4	Inundation Limit[4]
Oldman River	KM 006	18,797	22.9	Previous Floodway	1147.2	1m Depth
Oldman River	KM 006	18,975	29.7	Previous Floodway	1165.0	1m Depth
Oldman River	KM 006	19,233	434.7	Previous Floodway	834.6	1m Depth
Oldman River	KM 006	19,253	441.4	Main Channel[3]	859.8	1m Depth
Oldman River	KM 006	19,357	509.1	Main Channel[3]	1064.4	1m Depth
Oldman River	KM 006	19,815	621.9	Inundation Limit[4]	1512.8	1m Depth
Oldman River	KM 006	20,334	728.9	Mixed	1402.7	1m Depth
Oldman River	KM 006	20,588	453.5	1 m/s Velocity	1307.2	1m Depth
Oldman River	KM 006	20,806	348.5	1 m/s Velocity	1267.3	1 m/s Velocity
Oldman River	KM 006	21,058	514.5	1 m/s Velocity	1600.9	1 m/s Velocity

River	Reach	River Station (m)	Left		Right	
			Floodway Limiting Station (m)	Limiting Criteria	Floodway Limiting Station (m)	Limiting Criteria
Willow Creek	KM 000	839	494.8	1m Depth	N/A[2]	N/A[2]
Willow Creek	KM 000	1,545	194.5	1m Depth	N/A[2]	N/A[2]
Willow Creek	KM 000	2,369	29.7	1m Depth	N/A[2]	N/A[2]
Willow Creek	KM 000	2,773	172.2	1m Depth	N/A[2]	N/A[2]
Willow Creek	KM 000	3,355	396.2	1m Depth	N/A[2]	N/A[2]
Willow Creek	KM 000	3,752	495.8	1m Depth	N/A[2]	N/A[2]
Willow Creek	KM 000	4,671	284.9	1m Depth	N/A[2]	N/A[2]
Willow Creek	KM 000	5,400	300.0	1m Depth	N/A[2]	N/A[2]
Willow Creek	KM 000	5,600	311.7	1m Depth	N/A[2]	N/A[2]
Willow Creek	KM 000	5,929	508.5	1m Depth	N/A[2]	N/A[2]
Willow Creek	KM 000	6,477	477.6	1m Depth	N/A[2]	N/A[2]
Willow Creek	KM 000	7,530	55.3	1 m/s Velocity	N/A[2]	N/A[2]
Willow Creek	KM 000	7,979	32.1	1 m/s Velocity	N/A[2]	N/A[2]
Willow Creek	KM 000	8,873	38.1	1 m/s Velocity	N/A[2]	N/A[2]
Willow Creek	KM 000	9,248	26.1	1 m/s Velocity	918.1	1 m/s Velocity
Willow Creek	KM 000	9,431	16.7	1 m/s Velocity	803.8	Mixed
Willow Creek	KM 000	9,795	19.0	1 m/s Velocity	539.8	1m Depth
Willow Creek	KM 000	10,076	102.2	1 m/s Velocity	665.3	1m Depth
Willow Creek	KM 000	10,342	528.3	1 m/s Velocity	1014.6	1m Depth
Willow Creek	KM 000	10,693	591.7	1 m/s Velocity	1028.2	1m Depth
Willow Creek	KM 000	10,954	713.8	1 m/s Velocity	1108.0	1 m/s Velocity

River	Reach	River Station (m)	Left		Right	
			Floodway Limiting Station (m)	Limiting Criteria	Floodway Limiting Station (m)	Limiting Criteria
Willow Creek	KM 000	11,219	738.5	1m Depth	1102.7	1m Depth
Willow Creek	KM 000	11,292	486.2	1m Depth	921.9	1 m/s Velocity
Willow Creek	KM 000	11,309	503.9	Mixed	955.4	1m Depth
Willow Creek	KM 000	11,369	493.4	Mixed	920.3	1m Depth
Willow Creek	KM 000	11,780	449.8	1m Depth	781.4	1m Depth
Willow Creek	KM 000	12,086	342.1	1m Depth	765.9	1m Depth
Willow Creek	KM 000	12,577	263.1	1m Depth	869.7	1m Depth
Willow Creek	KM 000	12,698	52.4	1m Depth	874.7	1m Depth
Willow Creek	KM 000	13,011	25.3	1m Depth	788.9	1m Depth
Willow Creek	KM 000	13,158	37.6	1m Depth	729.2	1m Depth
Willow Creek	KM 000	13,288	148.1	1m Depth	848.9	1m Depth
Willow Creek	KM 000	13,478	552.5	1m Depth	858.5	1 m/s Velocity
Willow Creek	KM 000	13,605	361.3	1m Depth	795.7	1 m/s Velocity
Willow Creek	KM 000	13,772	85.9	1 m/s Velocity	552.7	1m Depth
Willow Creek	KM 000	13,943	51.9	1 m/s Velocity	448.2	1m Depth
Willow Creek	KM 000	14,223	43.3	1 m/s Velocity	368.8	1 m/s Velocity
Willow Creek	KM 000	14,600	138.8	1m Depth	406.1	1m Depth
Willow Creek	KM 000	14,779	19.9	1 m/s Velocity	229.8	1m Depth
Willow Creek	KM 000	15,031	200.9	1 m/s Velocity	401.3	1m Depth
Willow Creek	KM 000	15,294	501.3	1 m/s Velocity	743.9	Inundation Limit[4]
Willow Creek	KM 000	15,604	617.0	1m Depth	771.3	Inundation Limit[4]

River	Reach	River Station (m)	Left		Right	
			Floodway Limiting Station (m)	Limiting Criteria	Floodway Limiting Station (m)	Limiting Criteria
Willow Creek	KM 000	15,735	680.8	1m Depth	823.4	1 m/s Velocity
Willow Creek	KM 000	16,140	689.0	1 m/s Velocity	970.7	1m Depth
Willow Creek	KM 000	16,670	510.6	1 m/s Velocity	879.8	1m Depth
Willow Creek	KM 000	16,760	384.7	1 m/s Velocity	817.1	1m Depth
Willow Creek	KM 000	17,194	50.1	1 m/s Velocity	634.1	1m Depth
Willow Creek	KM 000	17,474	37.9	1 m/s Velocity	505.7	1m Depth

Notes:

[1] Previous floodway is outside inundation limit.

[2] At the confluence.

[3]Previous floodway is inside the main channel.

[4]No viable flood fringe.

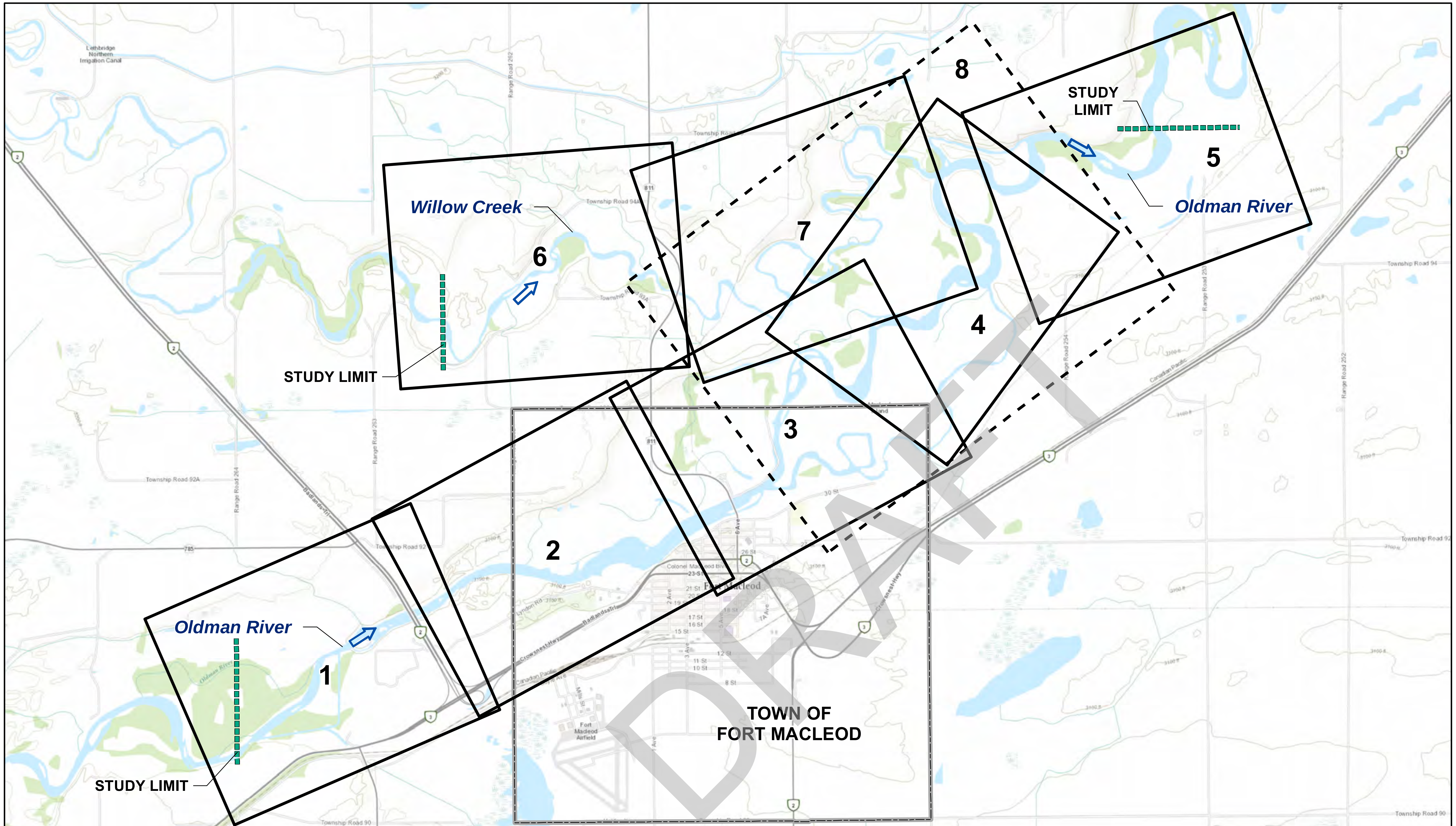
Table I2 Governing Design Flood Levels

River	Reach	River Station (m)	Design Flood WSE (m)
Oldman River	KM 000	286	920.42
Oldman River	KM 000	632	920.63
Oldman River	KM 000	1,165	921.00
Oldman River	KM 000	1,855	921.58
Oldman River	KM 000	2,235	921.95
Oldman River	KM 000	2,730	923.58
Oldman River	KM 000	3,079	923.93
Oldman River	KM 000	3,368	924.33
Oldman River	KM 000	3,685	924.76
Oldman River	KM 000	3,990	925.13
Oldman River	KM 000	4,362	925.45
Oldman River	KM 000	4,791	926.35
Oldman River	KM 000	5,612	927.08
Oldman River	KM 000	5,985	927.27
Oldman River	KM 000	6,246	927.46
Oldman River	KM 000	6,465	927.63
Oldman River	KM 000	6,598	927.77
Oldman River	KM 006	6,786	927.99
Oldman River	KM 006	7,098	928.42
Oldman River	KM 006	7,288	928.55
Oldman River	KM 006	7,554	928.96
Oldman River	KM 006	7,703	929.73
Oldman River	KM 006	8,157	930.24
Oldman River	KM 006	8,438	930.82
Oldman River	KM 006	8,856	931.30
Oldman River	KM 006	9,137	931.52
Oldman River	KM 006	9,472	932.04
Oldman River	KM 006	9,821	932.53
Oldman River	KM 006	10,767	933.27
Oldman River	KM 006	11,085	933.64
Oldman River	KM 006	11,520	934.11
Oldman River	KM 006	11,838	934.76
Oldman River	KM 006	12,107	935.48
Oldman River	KM 006	12,586	936.34
Oldman River	KM 006	12,910	936.83
Oldman River	KM 006	13,325	937.49
Oldman River	KM 006	13,622	938.13
Oldman River	KM 006	13,745	938.50
Oldman River	KM 006	13,772	938.77
Oldman River	KM 006	13,984	939.28

River	Reach	River Station (m)	Design Flood WSE (m)
Oldman River	KM 006	14,261	939.71
Oldman River	KM 006	14,747	940.04
Oldman River	KM 006	15,121	940.46
Oldman River	KM 006	15,323	940.97
Oldman River	KM 006	15,639	942.11
Oldman River	KM 006	15,769	942.60
Oldman River	KM 006	16,017	942.92
Oldman River	KM 006	16,244	943.27
Oldman River	KM 006	16,442	943.53
Oldman River	KM 006	16,806	944.14
Oldman River	KM 006	17,221	944.96
Oldman River	KM 006	17,885	946.28
Oldman River	KM 006	18,287	947.15
Oldman River	KM 006	18,391	948.08
Oldman River	KM 006	18,480	948.10
Oldman River	KM 006	18,545	948.12
Oldman River	KM 006	18,797	948.17
Oldman River	KM 006	18,975	948.32
Oldman River	KM 006	19,233	948.31
Oldman River	KM 006	19,253	948.58
Oldman River	KM 006	19,357	948.70
Oldman River	KM 006	19,815	949.65
Oldman River	KM 006	20,334	950.52
Oldman River	KM 006	20,588	951.38
Oldman River	KM 006	20,806	951.56
Oldman River	KM 006	21,058	951.99
Oldman River	KM 006	21,298	952.38
Willow Creek	KM 000	839	928.56
Willow Creek	KM 000	1,545	928.76
Willow Creek	KM 000	2,369	929.11
Willow Creek	KM 000	2,773	929.44
Willow Creek	KM 000	3,355	929.79
Willow Creek	KM 000	3,752	930.32
Willow Creek	KM 000	4,671	931.12
Willow Creek	KM 000	5,400	931.44
Willow Creek	KM 000	5,600	931.75
Willow Creek	KM 000	5,929	931.85
Willow Creek	KM 000	6,477	932.77
Willow Creek	KM 000	7,530	933.47
Willow Creek	KM 000	7,979	933.74
Willow Creek	KM 000	8,873	934.69
Willow Creek	KM 000	9,248	934.96

River	Reach	River Station (m)	Design Flood WSE (m)
Willow Creek	KM 000	9,431	935.03
Willow Creek	KM 000	9,795	935.69
Willow Creek	KM 000	10,076	935.85
Willow Creek	KM 000	10,342	936.00
Willow Creek	KM 000	10,693	936.31
Willow Creek	KM 000	10,954	936.53
Willow Creek	KM 000	11,219	936.90
Willow Creek	KM 000	11,292	936.96
Willow Creek	KM 000	11,309	938.52
Willow Creek	KM 000	11,369	938.58
Willow Creek	KM 000	11,780	938.65
Willow Creek	KM 000	12,086	938.75
Willow Creek	KM 000	12,577	938.93
Willow Creek	KM 000	12,698	938.96
Willow Creek	KM 000	13,011	939.00
Willow Creek	KM 000	13,158	939.01
Willow Creek	KM 000	13,288	939.11
Willow Creek	KM 000	13,478	939.08
Willow Creek	KM 000	13,605	939.50
Willow Creek	KM 000	13,772	939.68
Willow Creek	KM 000	13,943	939.86
Willow Creek	KM 000	14,223	940.28
Willow Creek	KM 000	14,600	940.75
Willow Creek	KM 000	14,779	941.03
Willow Creek	KM 000	15,031	941.41
Willow Creek	KM 000	15,294	941.94
Willow Creek	KM 000	15,604	942.50
Willow Creek	KM 000	15,735	942.61
Willow Creek	KM 000	16,140	944.26
Willow Creek	KM 000	16,670	944.69
Willow Creek	KM 000	16,760	944.78
Willow Creek	KM 000	17,194	945.15
Willow Creek	KM 000	17,474	945.30
Willow Creek	KM 000	17,645	945.48

Appendix J: Open Water Floodway Criteria Maps



Alberta

nhc northwest hydraulic consultants

MAP SHEET

1:10,000 SCALE

1:15,000 SCALE

SCALE - 1:50,000

0 500 1,000 1,500 2,000 M

N

Coordinate System: NAD 1983 CSRS 3TM 114
Units: METRES; Vertical Datum: CGVD28 HTv2.0

Engineer VCCB	GIS MSN/JY	Reviewer RBA
Job Number 3004660	Date 15-DEC-2022	

FORT MACLEOD FLOOD HAZARD STUDY

FLOODWAY CRITERIA INDEX MAP

INDEX MAP

JY P:_Projects (Active)\3004660 Fort Macleod\2022\Update\90 GIS\3004660_JY_2022_Map_T5_OWFloodwayCriteriaMapIndex.mxd

Notes to Users:

1. Please refer to the accompanying **Fort Macleod Flood Hazard Study – Report** for important information concerning these maps.
2. Within the flood inundation areas shown on this map, there may be isolated pockets of high ground. To determine whether or not a particular site is subject to flooding, reference should be made to the computed flood levels in conjunction with site-specific surveys where detailed definition is required.
3. Non-riverine and local sources of water including local snow melt and rain-sourced stormwater have not been considered, and structures such as roads, railways or barriers (such as dikes) can restrict water flow and affect local flood levels. Channel obstruction, local stormwater inflow, groundwater seepage or other land drainage and tributaries can cause flood levels and extents to exceed those indicated on the maps.
4. Line work for bridges is shown above flood inundation areas, even in cases where bridges are inundated.
5. Validated inundation mapping is limited to the area within the study limits.
6. Model geometry is based on channel conditions as surveyed in 2019. Channel variations, such as aggradation, degradation, erosion and blockage, may alter flood levels and inundation extents beyond those mapped.
7. Floodplain maps are a tool that provides a representation of particular flood event(s). A qualified professional must be consulted for site-specific engineering analysis.

Definitions:

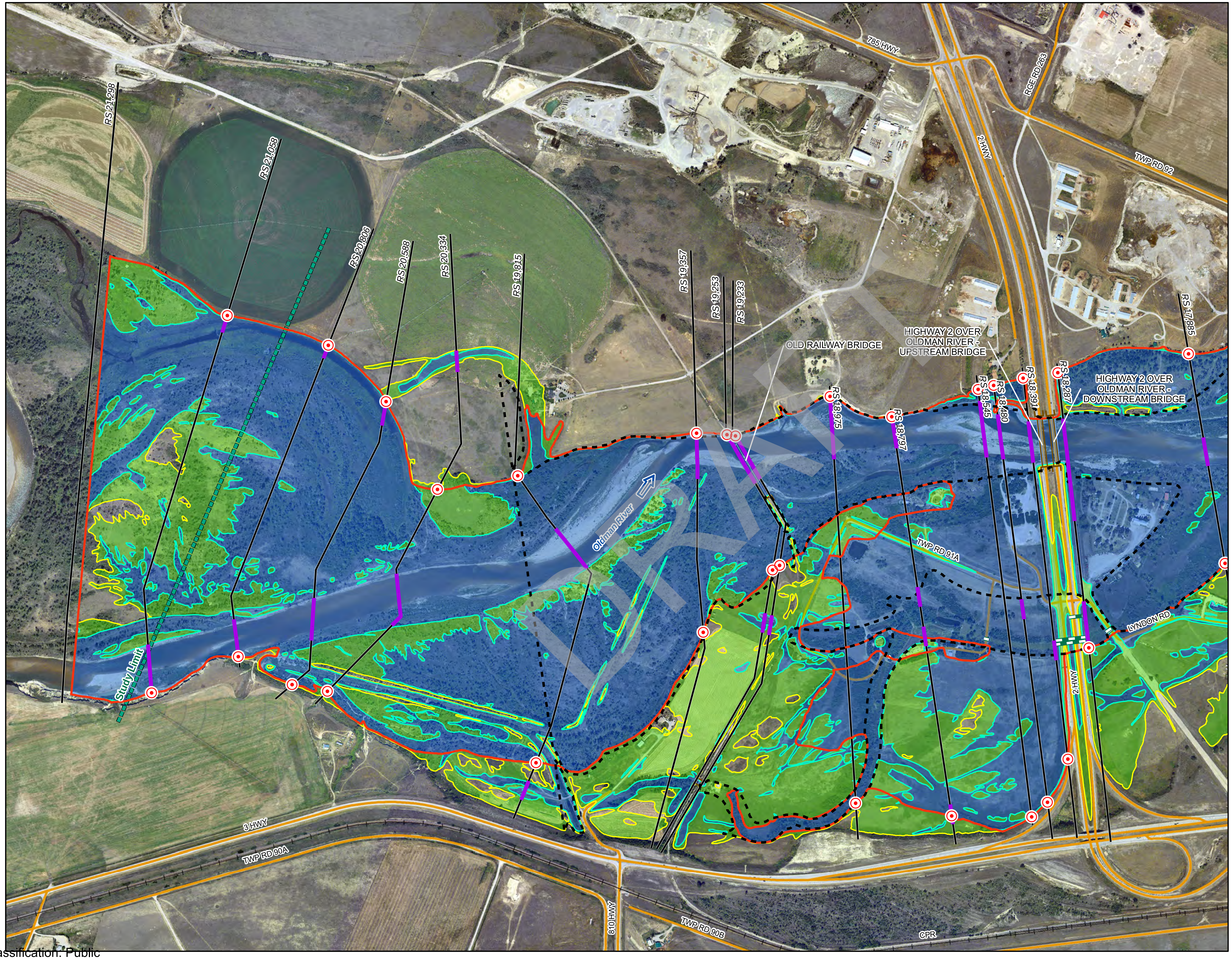
Flood Hazard Map - A flood hazard map is a specific type of flood map that identifies the area flooded for the 1:100 design flood, and divides that flood hazard area into floodway and flood fringe zones. Flood hazard maps can also show additional flood hazard information, including the incremental areas at risk for more severe floods like the 1:200 and 1:500 floods. Flood hazard maps are typically used for long-term flood hazard area management and land-use planning.
Design Flood - The design flood standard in Alberta is the 1:100 flood, which is a flood that has a 1% chance of being equaled or exceeded in any given year. The design flood is typically based on the 1:100 open water flood, but it can also reflect 1:100 ice jam flood levels or be based on a historical flood event. Different sized floods have different chances of occurring – for example, a 1:200 flood has a 0.5% chance of occurring in any given year and a 1:500 flood has a 0.2% chance of occurring in any given year – but only the 1:100 design flood is used to define the floodway and flood fringe zones on flood hazard maps.
Floodway - When a floodway is first defined on a flood hazard map, it typically represents the area of highest flood hazard where flows are deepest, fastest, and most destructive during the 1:100 design flood. When a flood hazard map is updated, the floodway will not get larger in most circumstances to maintain long-term regulatory certainty, even if the flood hazard area gets larger or design flood levels get higher.
Flood Fringe - The flood fringe is the area outside of the floodway that is flooded or could be flooded during the 1:100 design flood. The flood fringe typically represents areas with shallower, slower, and less destructive flooding, but it may also include "high hazard flood fringe" areas. Areas at risk of flooding behind flood berms may also be mapped as "protected flood fringe" areas.

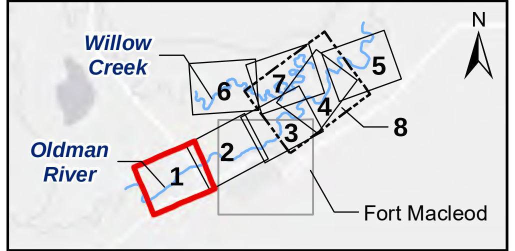
Definitions (continued):

High Hazard Flood Fringe - The high hazard flood fringe identifies areas within the flood fringe with deeper or faster moving water than the rest of the flood fringe. High hazard flood fringe areas are likely to be most significant for flood maps that are being updated, but they may also be included in new flood maps.
Protected Flood Fringe - The protected flood fringe identifies areas that could be flooded if dedicated flood berms fail or do not work as designed during the 1:100 design flood, even if they are not overtopped. Protected flood fringe areas are part of the flood fringe and do not differentiate between areas with deeper or faster moving water and shallower or slower moving water.

Data Sources and References:

1. Orthophoto imagery acquired by Orthoshop Geomatics Ltd. (26 July 2019) for Alberta Environment and Parks.
2. 2015 orthophoto imagery licensed under the Open Government Licence – Alberta Municipal Data Sharing Partnership (AMDSP).
3. Flood extent mapping is based on a digital terrain model derived from 2019 LiDAR data collected by Airborne Imaging and 2019 bathymetric and topographic survey data collected by Northwest Hydraulic Consultants Ltd.
4. Base data from Town of Fort Macleod, M.D. Willow Creek, Alberta Environment and Parks, and Natural Resources Canada.
5. Additional base mapping from Esri.





Alberta

nhc
northwest hydraulic consultants

FLOW DIRECTION
RS 12,345 RIVER STATION
CROSS SECTION
BRIDGE
CULVERT
RAILWAY
MAJOR ROAD
LOCAL ROAD
FORT MACLEOD
STUDY LIMIT
100-YEAR OPEN WATER DESIGN FLOOD EXTENT
DEPTH >= 1m
1m DEPTH CONTOUR
VELOCITY > 1 m/s
PROPOSED FLOODWAY LIMIT
PROPOSED FLOODWAY BOUNDARY
PreviousFloodway

SCALE - 1:10,000
0 100 200 300 400 M
N

Coordinate System: NAD 1983 CSRS 3TM 114
Units: METRES; Vertical Datum: CGVD28 HTv2.0

Engineer	GIS	Reviewer
VCCB	MSN/JY	RBA

Job Number	Date
3004660	15-DEC-2022

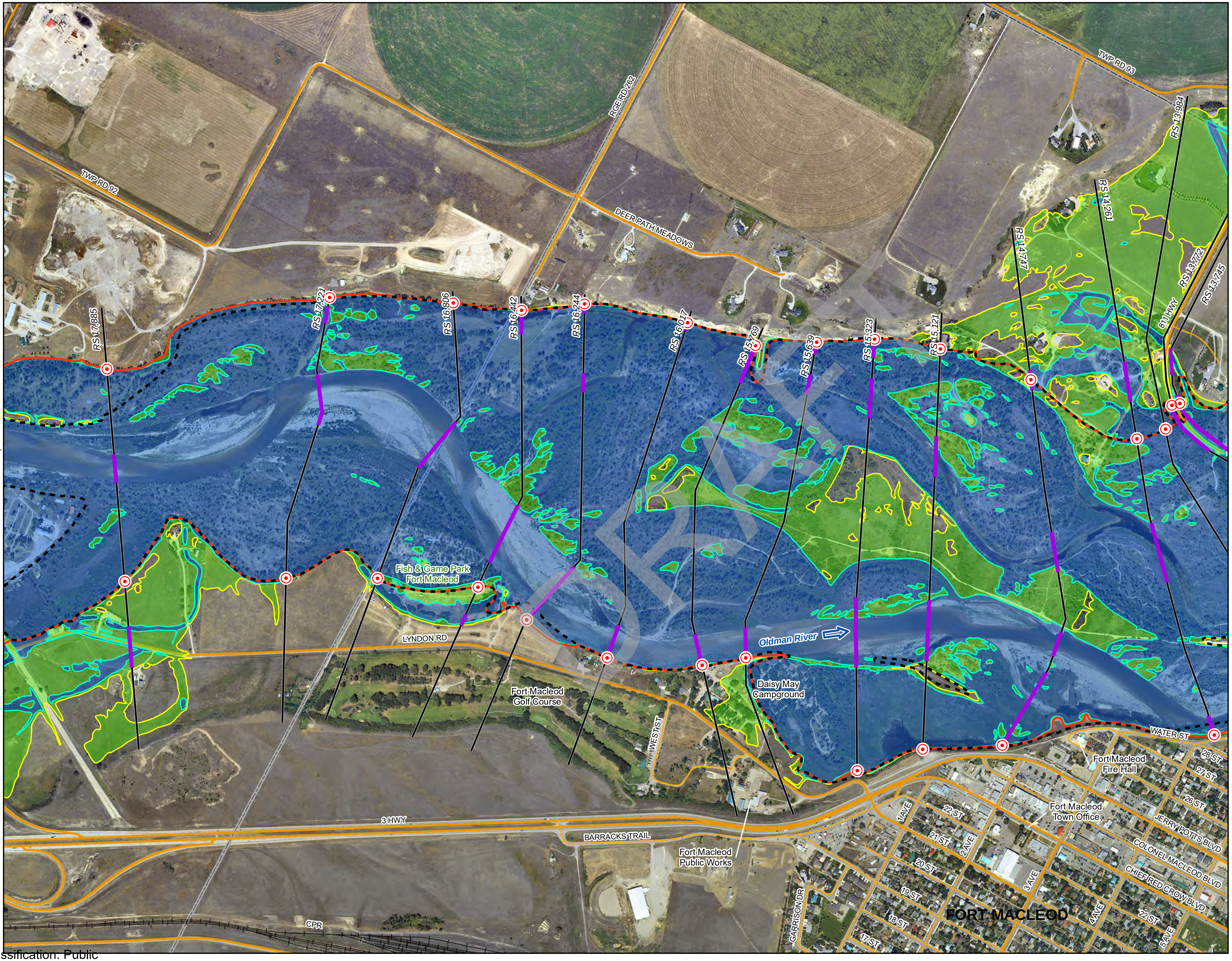
FORT MACLEOD FLOOD HAZARD STUDY

FLOODWAY CRITERIA MAP

SHEET 1 OF 8

JY, P:_Projects (Active)\3004660 Fort Macleod\2022Update\90 GIS\3004660_JY_2022_Map_T5_OWFloodwayCriteriaMap.mxd

Classification: Public



Classification: Public

Alberta

nhc northwest hydraulic consultants

Willow Creek
Oldman River
Fort Macleod
1 2 3 4 5 6 7 8
N

- FLOW DIRECTION
- RS 12,345 RIVER STATION
- CROSS SECTION
- BRIDGE
- CULVERT
- RAILWAY
- MAJOR ROAD
- LOCAL ROAD
- FORT MACLEOD
- STUDY LIMIT
- 100-YEAR OPEN WATER DESIGN FLOOD EXTENT
- DEPTH >= 1m
- 1m DEPTH CONTOUR
- VELOCITY > 1 m/s
- PROPOSED FLOODWAY LIMIT
- PROPOSED FLOODWAY BOUNDARY
- PreviousFloodway

SCALE - 1:10,000
0 100 200 300 400 M

Coordinate System: NAD 1983 CSRS 3TM 114
Units: METRES; Vertical Datum: CGVD28 HTv2.0

Engineer	GIS	Reviewer
VCCB	MSN/JY	RBA

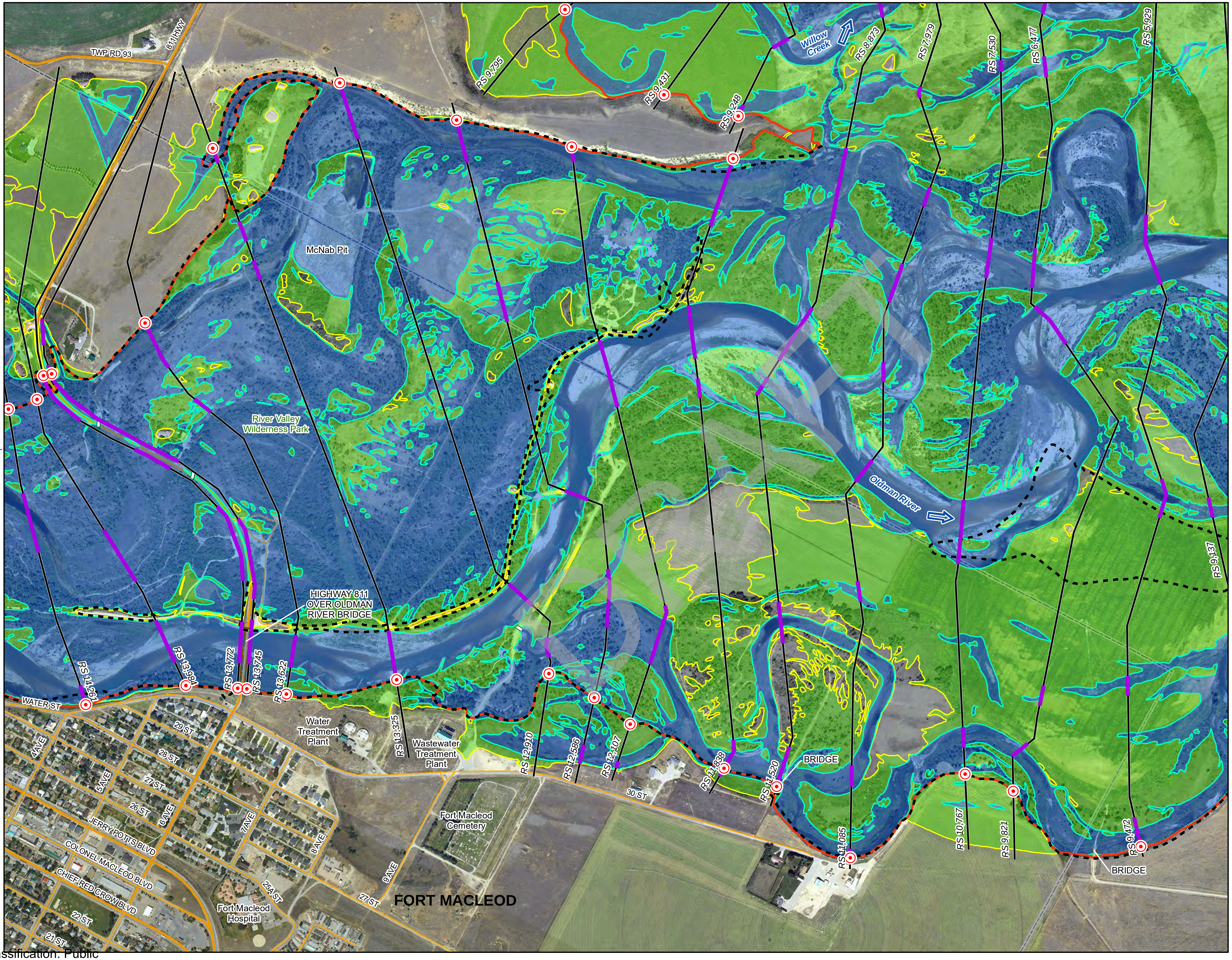
Job Number	Date
3004660	15-DEC-2022

FORT MACLEOD FLOOD HAZARD STUDY

FLOODWAY CRITERIA MAP

SHEET 2 OF 8

JY_P:_Projects (Active)\3004660 Fort Macleod\2022Update\90 GIS\3004660_JY_2022_Map_T5_OWFloodwayCriteriaMap.mxd



Alberta

nhc
northwest hydraulic consultants

Willow Creek
Oldman River
1 2 3 4 5 6 7 8
Fort Macleod
N

FLOW DIRECTION
RS 12,345 RIVER STATION
CROSS SECTION
BRIDGE
CULVERT
RAILWAY
MAJOR ROAD
LOCAL ROAD
FORT MACLEOD
STUDY LIMIT
100-YEAR OPEN WATER DESIGN FLOOD EXTENT
DEPTH >= 1m
1m DEPTH CONTOUR
VELOCITY > 1 m/s
PROPOSED FLOODWAY LIMIT
PROPOSED FLOODWAY BOUNDARY
PreviousFloodway

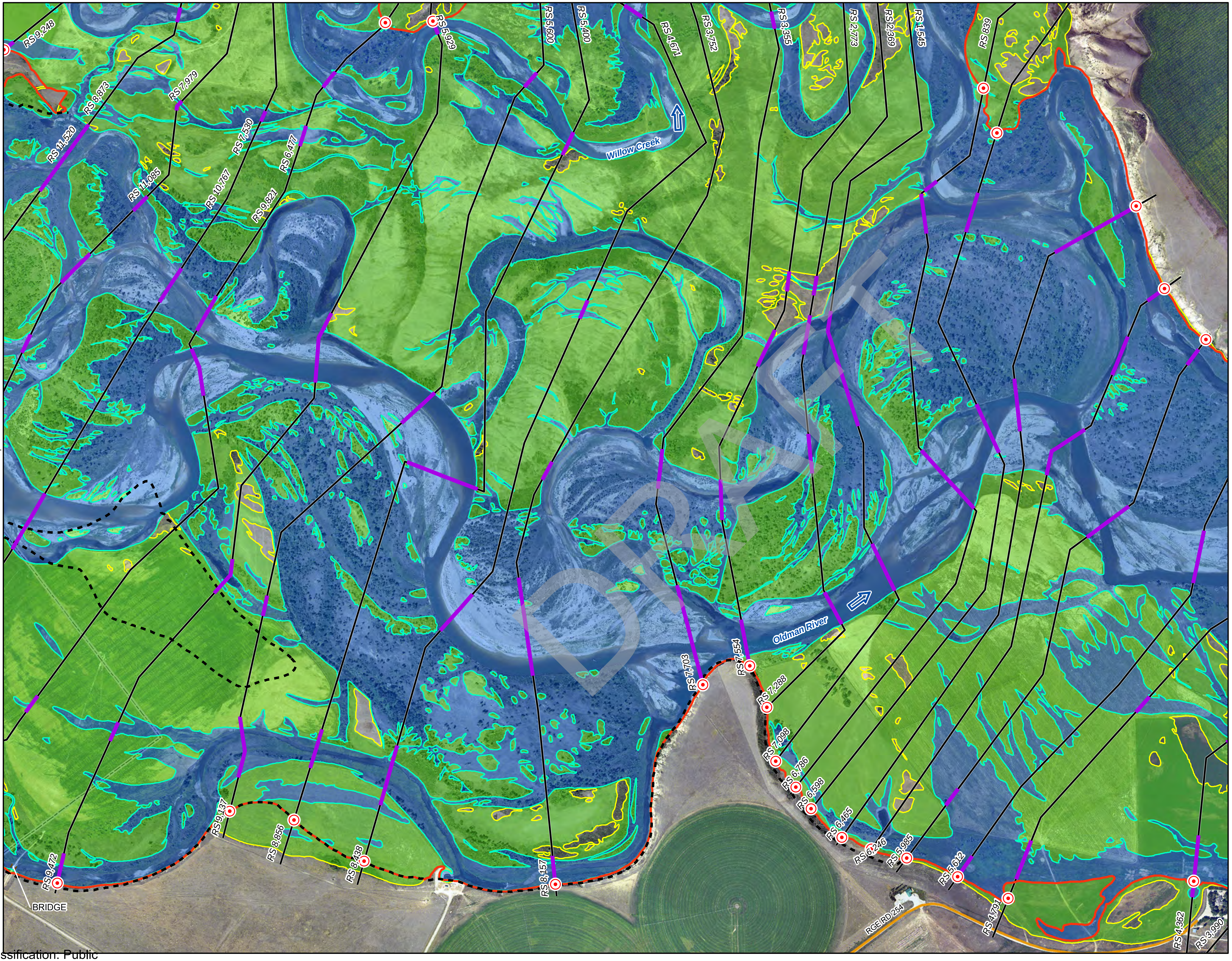
SCALE - 1:10,000
0 100 200 300 400 M

Coordinate System: NAD 1983 CSRS 3TM 114
Units: METRES; Vertical Datum: CGVD28 HTv2.0

Engineer VCCB	GIS MSN/JY	Reviewer RBA
Job Number 3004660	Date 15-DEC-2022	

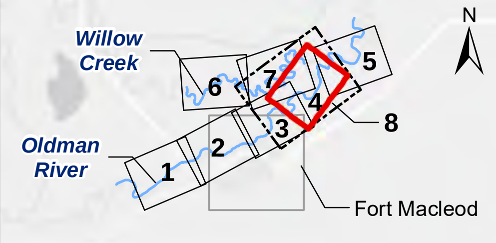
FORT MACLEOD FLOOD HAZARD STUDY

FLOODWAY CRITERIA MAP



Alberta

nhc northwest hydraulic consultants



FLOW DIRECTION
RS 12,345 RIVER STATION
CROSS SECTION
BRIDGE
CULVERT
RAILWAY
MAJOR ROAD
LOCAL ROAD
FORT MACLEOD
STUDY LIMIT
100-YEAR OPEN WATER DESIGN FLOOD EXTENT
DEPTH >= 1m
1m DEPTH CONTOUR
VELOCITY > 1 m/s
PROPOSED FLOODWAY LIMIT
PROPOSED FLOODWAY BOUNDARY
PreviousFloodway

SCALE - 1:10,000

0 100 200 300 400 M

Coordinate System: NAD 1983 CSRS 3TM 114
Units: METRES; Vertical Datum: CGVD28 HTv2.0

Engineer	GIS	Reviewer
VCCB	MSN/JY	RBA

Job Number	Date
3004660	15-DEC-2022

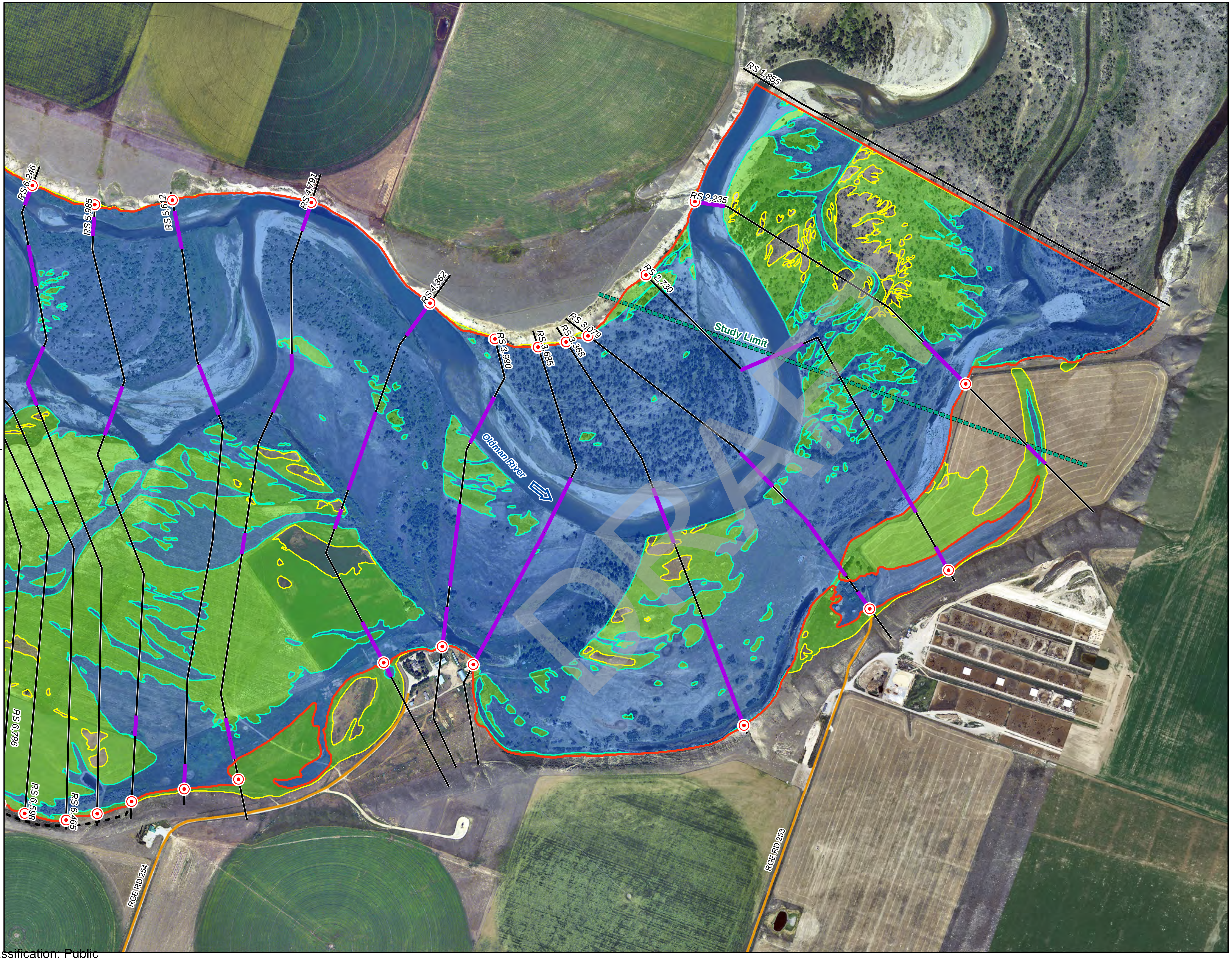
FORT MACLEOD FLOOD HAZARD STUDY

FLOODWAY CRITERIA MAP

SHEET 4 OF 8

JY: P:_Projects (Active)\3004660 Fort Macleod\2022\Update\90 GIS\3004660_JY_2022_Map_T5_OWFloodwayCriteriaMap.mxd

Classification: Public



Alberta

nhc
northwest hydraulic consultants

Willow Creek
Oldman River
Fort Macleod
1 2 3 4 5 6 7 8
N

FLOW DIRECTION
RS 12,345 RIVER STATION
CROSS SECTION
BRIDGE
CULVERT
RAILWAY
MAJOR ROAD
LOCAL ROAD
FORT MACLEOD
STUDY LIMIT
100-YEAR OPEN WATER DESIGN FLOOD EXTENT
DEPTH >= 1m
1m DEPTH CONTOUR
VELOCITY > 1 m/s
PROPOSED FLOODWAY LIMIT
PROPOSED FLOODWAY BOUNDARY
PreviousFloodway

SCALE - 1:10,000
0 100 200 300 400 M
N

Coordinate System: NAD 1983 CSRS 3TM 114
Units: METRES; Vertical Datum: CGVD28 HTv2.0

Engineer	GIS	Reviewer
VCCB	MSN/JY	RBA

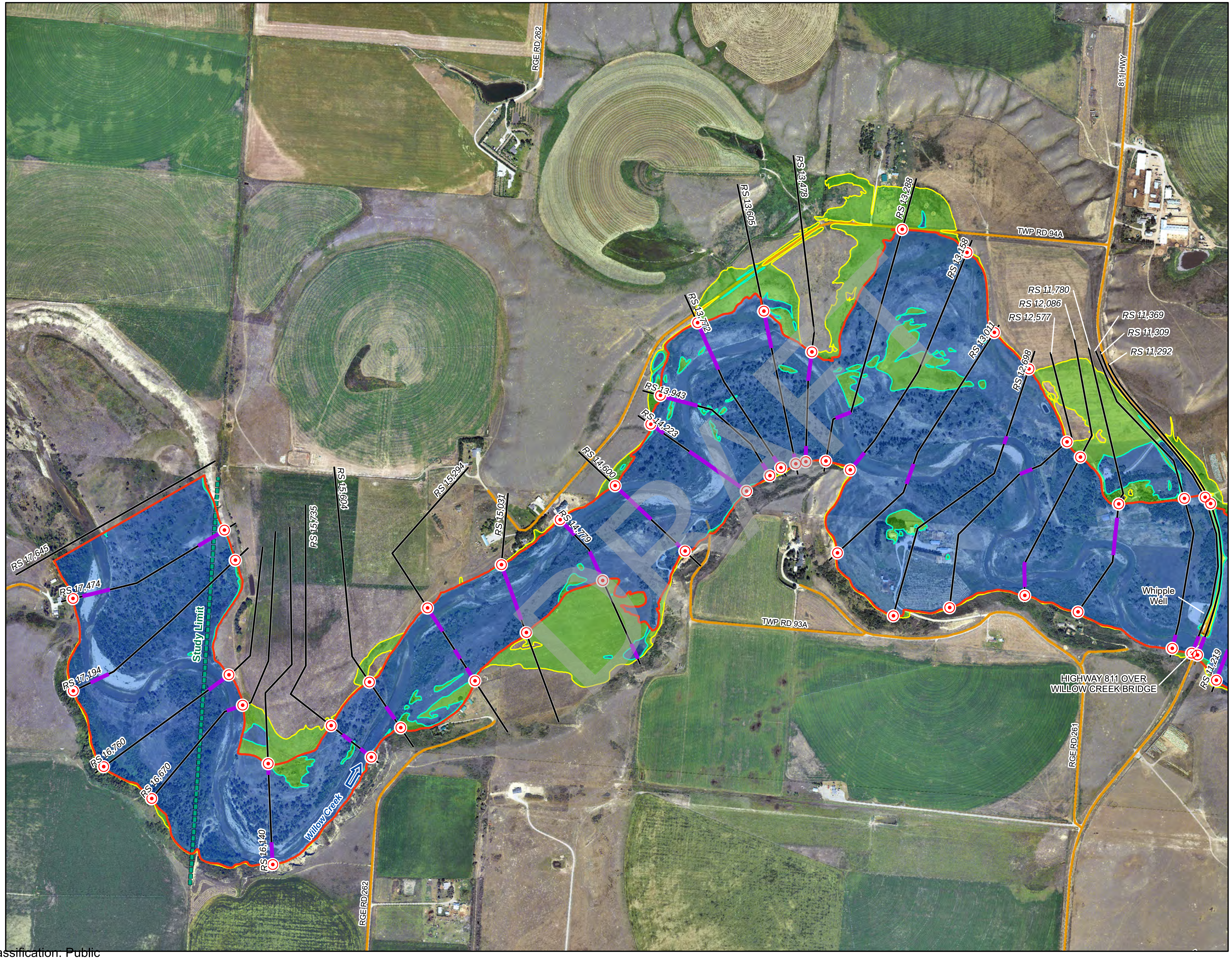
Job Number	Date
3004660	15-DEC-2022

FORT MACLEOD FLOOD HAZARD STUDY

FLOODWAY CRITERIA MAP

SHEET 5 OF 8

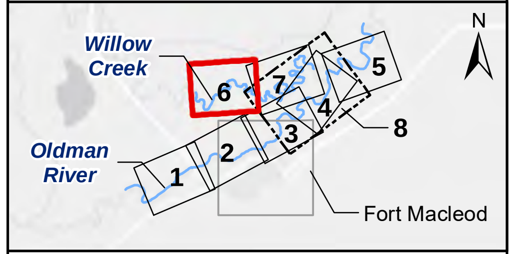
JY, P:_Projects (Active)\3004660 Fort Macleod\2022Update\90 GIS\3004660_JY_2022_Map_T5_OWFloodwayCriteriaMap.mxd



Classification: Public

Alberta

nhc northwest hydraulic consultants



FLOW DIRECTION
RS 12,345 RIVER STATION
CROSS SECTION
BRIDGE
CULVERT
RAILWAY
MAJOR ROAD
LOCAL ROAD
FORT MACLEOD
STUDY LIMIT
100-YEAR OPEN WATER DESIGN FLOOD EXTENT
DEPTH >= 1m
1m DEPTH CONTOUR
VELOCITY > 1 m/s
PROPOSED FLOODWAY LIMIT
PROPOSED FLOODWAY BOUNDARY
PreviousFloodway

SCALE - 1:10,000
0 100 200 300 400 M

Coordinate System: NAD 1983 CSRS 3TM 114
Units: METRES; Vertical Datum: CGVD28 HTv2.0

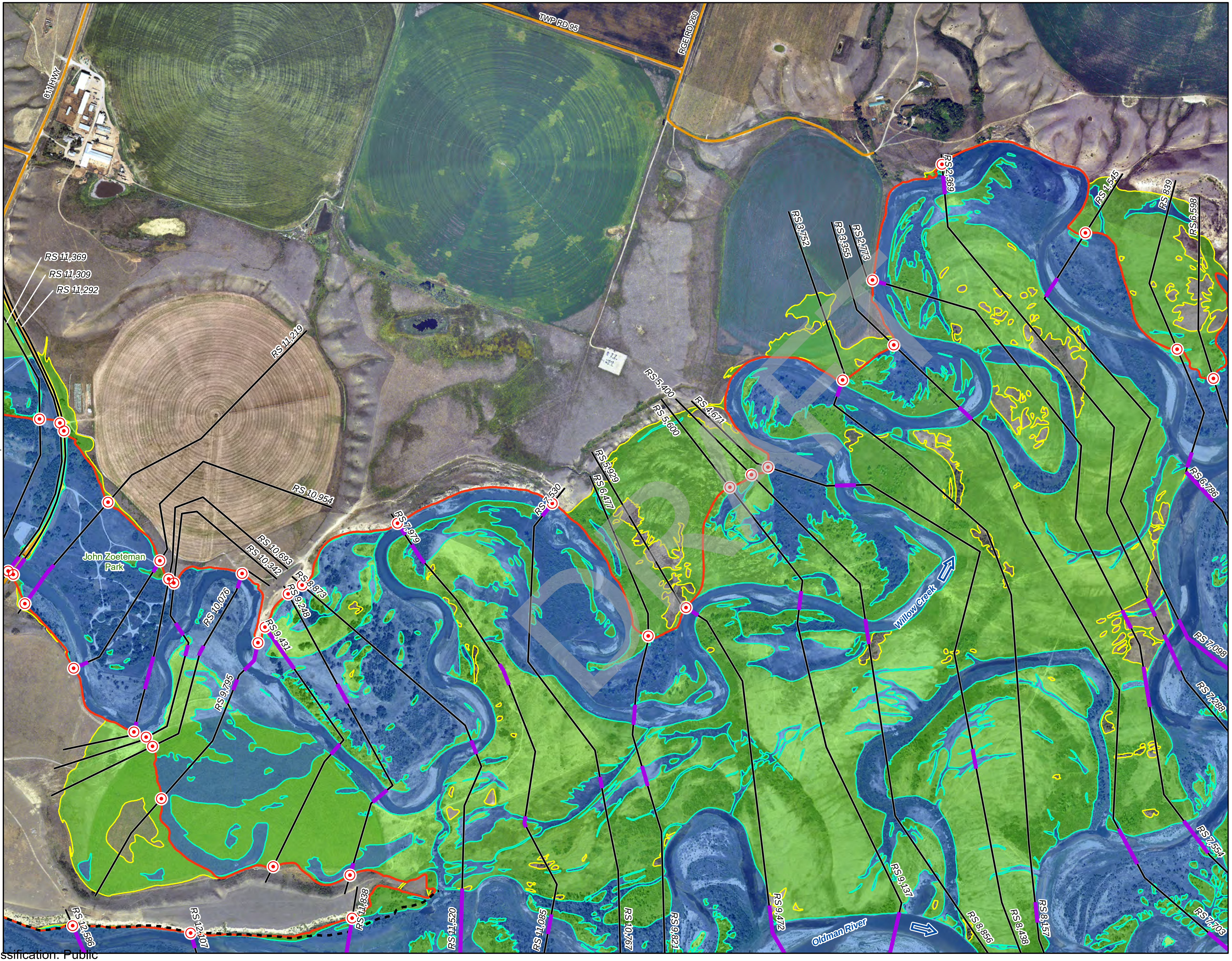
Engineer	GIS	Reviewer
VCCB	MSN/JY	RBA

Job Number	Date
3004660	15-DEC-2022

FORT MACLEOD FLOOD HAZARD STUDY

FLOODWAY CRITERIA MAP

JY, P:_Projects (Active)\3004660 Fort Macleod\2022Update\90 GIS\3004660_JY_2022_Map_T5_OWFloodwayCriteriaMap.mxd



Alberta

nhc
northwest hydraulic consultants

Willow Creek
Oldman River
Fort Macleod
1 2 3 4 5 6 7 8

- FLOW DIRECTION
- RS 12,345 RIVER STATION
- CROSS SECTION
- BRIDGE
- CULVERT
- RAILWAY
- MAJOR ROAD
- LOCAL ROAD
- FORT MACLEOD
- STUDY LIMIT
- 100-YEAR OPEN WATER DESIGN FLOOD EXTENT
- DEPTH >= 1m
- 1m DEPTH CONTOUR
- VELOCITY > 1 m/s
- PROPOSED FLOODWAY LIMIT
- PROPOSED FLOODWAY BOUNDARY
- PreviousFloodway

SCALE - 1:10,000
0 100 200 300 400 M
N

Coordinate System: NAD 1983 CSRS 3TM 114
Units: METRES; Vertical Datum: CGVD28 HTv2.0

Engineer	GIS	Reviewer
VCCB	MSN/JY	RBA

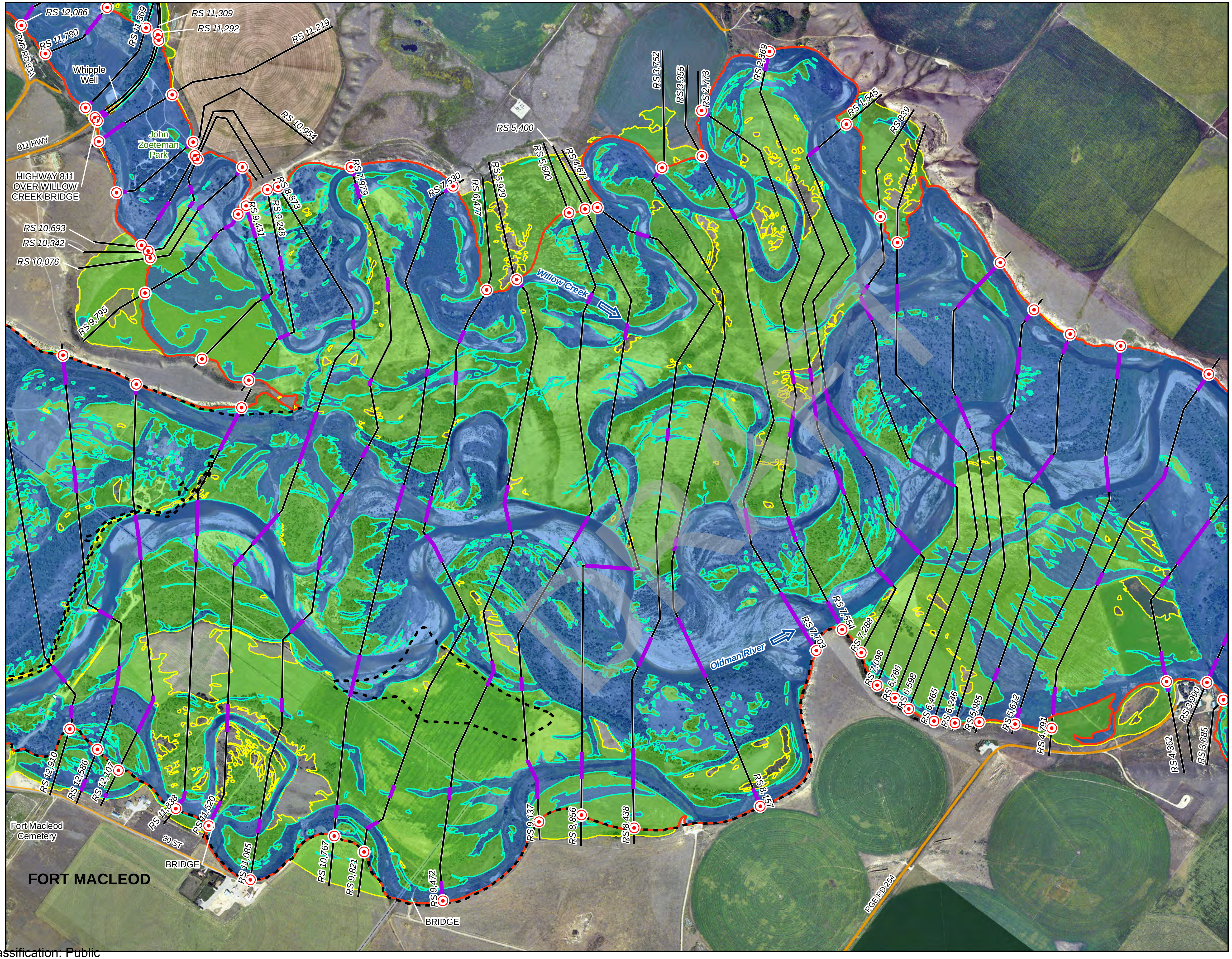
Job Number	Date
3004660	15-DEC-2022

FORT MACLEOD FLOOD HAZARD STUDY

FLOODWAY CRITERIA MAP

SHEET 7 OF 8

JY, P:_Projects (Active)\3004660 Fort Macleod\2022Update\90 GIS\3004660_JY_2022_Map_T5_OWFloodwayCriteriaMap.mxd



Alberta

nhc northwest hydraulic consultants

Willow Creek
Oldman River
Fort Macleod
1 2 3 4 5 6 7 8
N

FLOW DIRECTION
RS 12,345 RIVER STATION
CROSS SECTION
BRIDGE
CULVERT
RAILWAY
MAJOR ROAD
LOCAL ROAD
FORT MACLEOD
STUDY LIMIT
100-YEAR OPEN WATER DESIGN FLOOD EXTENT
DEPTH >= 1m
1m DEPTH CONTOUR
VELOCITY > 1 m/s
PROPOSED FLOODWAY LIMIT
PROPOSED FLOODWAY BOUNDARY
PreviousFloodway

SCALE - 1:15,000
0 100 200 300 400 500 600 M

Coordinate System: NAD 1983 CSRS 3TM 114
Units: METRES; Vertical Datum: CGVD28 HTv2.0

Engineer	GIS	Reviewer
VCCB	MSN/JY	RBA

Job Number	Date
3004660	15-DEC-2022

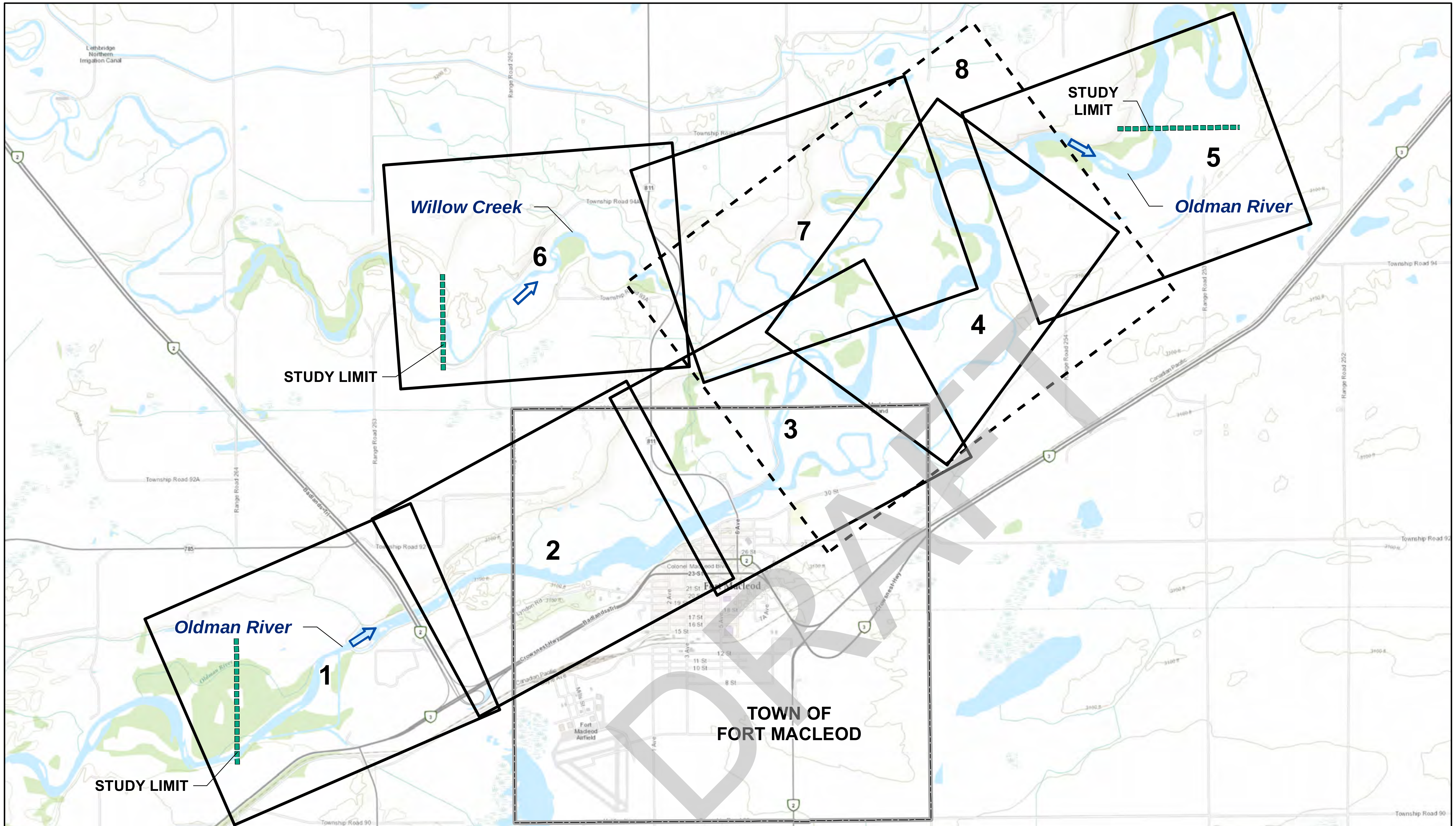
FORT MACLEOD FLOOD HAZARD STUDY

FLOODWAY CRITERIA MAP

SHEET 8 OF 8

Classification: Public

Appendix K: Flood Hazard Maps



northwest hydraulic consultants

MAP SHEET

1:10,000 SCALE

1:15,000 SCALE

SCALE - 1:50,000

0 500 1,000 1,500 2,000 M

N

Coordinate System: NAD 1983 CSRS 3TM 114
Units: METRES; Vertical Datum: CGVD28 HTv2.0

Engineer	GIS	Reviewer
VCCB	MSN/JY	RBA

Job Number	Date
3004660	15-DEC-2022

FORT MACLEOD FLOOD HAZARD STUDY

FLOOD HAZARD INDEX MAP

INDEX MAP

JY: P:_Projects (Active)\3004660 Fort Macleod\2022Update\90 GIS\3004660_JY_2022_Map_T6_OWFloodHazardIndex.mxd

Notes to Users:

1. Please refer to the accompanying **Fort Macleod Flood Hazard Study – Report** for important information concerning these maps.
2. Within the flood inundation areas shown on this map, there may be isolated pockets of high ground. To determine whether or not a particular site is subject to flooding, reference should be made to the computed flood levels in conjunction with site-specific surveys where detailed definition is required.
3. Non-riverine and local sources of water including local snow melt and rain-sourced stormwater have not been considered, and structures such as roads, railways or barriers (such as dikes) can restrict water flow and affect local flood levels. Channel obstruction, local stormwater inflow, groundwater seepage or other land drainage and tributaries can cause flood levels and extents to exceed those indicated on the maps.
4. Line work for bridges is shown above flood inundation areas, even in cases where bridges are inundated.
5. Validated inundation mapping is limited to the area within the study limits.
6. Model geometry is based on channel conditions as surveyed in 2019. Channel variations, such as aggradation, degradation, erosion and blockage, may alter flood levels and inundation extents beyond those mapped.
7. Floodplain maps are a tool that provides a representation of particular flood event(s). A qualified professional must be consulted for site-specific engineering analysis.

Definitions:

Flood Hazard Map - A flood hazard map is a specific type of flood map that identifies the area flooded for the 1:100 design flood, and divides that flood hazard area into floodway and flood fringe zones. Flood hazard maps can also show additional flood hazard information, including the incremental areas at risk for more severe floods like the 1:200 and 1:500 floods. Flood hazard maps are typically used for long-term flood hazard area management and land-use planning.
Design Flood - The design flood standard in Alberta is the 1:100 flood, which is a flood that has a 1% chance of being equaled or exceeded in any given year. The design flood is typically based on the 1:100 open water flood, but it can also reflect 1:100 ice jam flood levels or be based on a historical flood event. Different sized floods have different chances of occurring – for example, a 1:200 flood has a 0.5% chance of occurring in any given year and a 1:500 flood has a 0.2% chance of occurring in any given year – but only the 1:100 design flood is used to define the floodway and flood fringe zones on flood hazard maps.
Floodway - When a floodway is first defined on a flood hazard map, it typically represents the area of highest flood hazard where flows are deepest, fastest, and most destructive during the 1:100 design flood. When a flood hazard map is updated, the floodway will not get larger in most circumstances to maintain long-term regulatory certainty, even if the flood hazard area gets larger or design flood levels get higher.
Flood Fringe - The flood fringe is the area outside of the floodway that is flooded or could be flooded during the 1:100 design flood. The flood fringe typically represents areas with shallower, slower, and less destructive flooding, but it may also include "high hazard flood fringe" areas. Areas at risk of flooding behind flood berms may also be mapped as "protected flood fringe" areas.

Definitions (continued):

High Hazard Flood Fringe - The high hazard flood fringe identifies areas within the flood fringe with deeper or faster moving water than the rest of the flood fringe. High hazard flood fringe areas are likely to be most significant for flood maps that are being updated, but they may also be included in new flood maps.
Protected Flood Fringe - The protected flood fringe identifies areas that could be flooded if dedicated flood berms fail or do not work as designed during the 1:100 design flood, even if they are not overtopped. Protected flood fringe areas are part of the flood fringe and do not differentiate between areas with deeper or faster moving water and shallower or slower moving water.

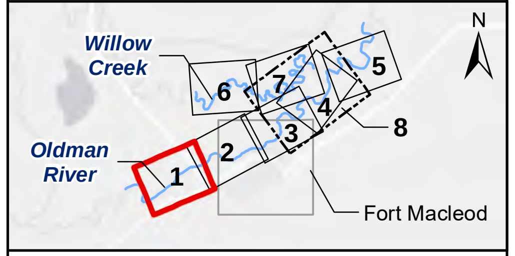
Data Sources and References:

1. Orthophoto imagery acquired by Orthoshop Geomatics Ltd. (26 July 2019) for Alberta Environment and Parks.
2. 2015 orthophoto imagery licensed under the Open Government Licence – Alberta Municipal Data Sharing Partnership (AMDSP).
3. Flood extent mapping is based on a digital terrain model derived from 2019 LiDAR data collected by Airborne Imaging and 2019 bathymetric and topographic survey data collected by Northwest Hydraulic Consultants Ltd.
4. Base data from Town of Fort Macleod, M.D. Willow Creek, Alberta Environment and Parks, and Natural Resources Canada.
5. Additional base mapping from Esri.

Classification: Public

Alberta

nhc northwest hydraulic consultants



FLOW DIRECTION
RS 12,345 RIVER STATION
CROSS SECTION
BRIDGE
CULVERT
RAILWAY
MAJOR ROAD
LOCAL ROAD
FORT MACLEOD
STUDY LIMIT
FLOODWAY
FLOOD FRINGE
HIGH HAZARD FLOOD FRINGE
200-YEAR FLOOD EXTENT
500-YEAR FLOOD EXTENT

DISCHARGE
OLDMAN RIVER ABOVE WILLOW CREEK = 2,300 m³/s

SCALE - 1:10,000
0 100 200 300 400 M
N

Coordinate System: NAD 1983 CSRS 3TM 114
Units: METRES; Vertical Datum: CGVD28 HTv2.0

Engineer	GIS	Reviewer
VCCB	MSN/JY	RBA

Job Number	Date
3004660	15-DEC-2022

FORT MACLEOD FLOOD HAZARD STUDY

FLOOD HAZARD MAP

SHEET 1 OF 8

JY: P:_Projects (Active)\3004660 Fort Macleod\2022\Update\90 GIS\3004660_JY_2022_Map_T6_OWFloodHazardMap.mxd

Classification: Public

Alberta

nhc northwest hydraulic consultants

Willow Creek
Oldman River
1 2 3 4 5 6 7 8
Fort Macleod

- FLOW DIRECTION
- RS 12,345 RIVER STATION
- CROSS SECTION
- BRIDGE
- CULVERT
- RAILWAY
- MAJOR ROAD
- LOCAL ROAD
- FORT MACLEOD
- STUDY LIMIT
- FLOODWAY
- FLOOD FRINGE
- HIGH HAZARD FLOOD FRINGE
- 200-YEAR FLOOD EXTENT
- 500-YEAR FLOOD EXTENT

DISCHARGE
OLDMAN RIVER ABOVE WILLOW CREEK = 2,300 m³/s

SCALE - 1:10,000
0 100 200 300 400 M

Coordinate System: NAD 1983 CSRS 3TM 114
Units: METRES; Vertical Datum: CGVD28 HTv2.0

Engineer	GIS	Reviewer
VCCB	MSN/JY	RBA

Job Number	Date
3004660	15-DEC-2022

FORT MACLEOD FLOOD HAZARD STUDY

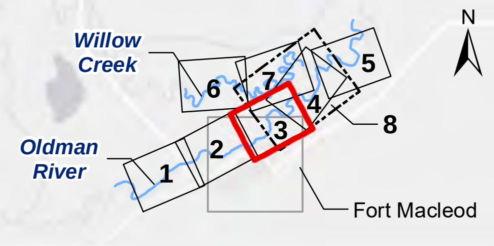
FLOOD HAZARD MAP

SHEET 2 OF 8

JY; P:_Projects (Active)\3004660 Fort Macleod\2022Update\90 GIS\3004660_JY_2022_Map_T6_OWFloodHazardMap.mxd

Alberta

nhc
northwest hydraulic consultants



- FLOW DIRECTION
- RS 12,345 RIVER STATION
- CROSS SECTION
- BRIDGE
- CULVERT
- RAILWAY
- MAJOR ROAD
- LOCAL ROAD
- FORT MACLEOD
- STUDY LIMIT
- FLOODWAY
- FLOOD FRINGE
- HIGH HAZARD FLOOD FRINGE
- 200-YEAR FLOOD EXTENT
- 500-YEAR FLOOD EXTENT

DISCHARGE
OLDMAN RIVER ABOVE WILLOW CREEK = 2,300 m³/s

SCALE - 1:10,000
0 100 200 300 400 M
N

Coordinate System: NAD 1983 CSRS 3TM 114
Units: METRES; Vertical Datum: CGVD28 HTv2.0

Engineer	GIS	Reviewer
VCCB	MSN/JY	RBA

Job Number	Date
3004660	15-DEC-2022

FORT MACLEOD FLOOD HAZARD STUDY

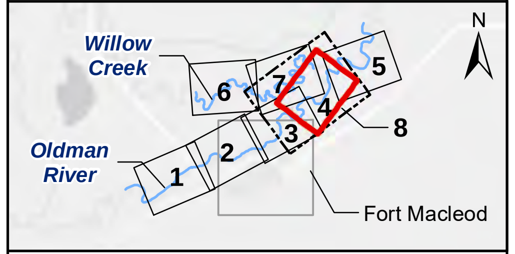
FLOOD HAZARD MAP

JY P:_Projects (Active)\3004660 Fort Macleod\2022Update\90 GIS\3004660_JY_2022_Map_T6_OWFloodHazardMap.mxd

Classification: Public

Alberta

nhc
northwest hydraulic consultants



FLOW DIRECTION
RS 12,345 RIVER STATION
CROSS SECTION
BRIDGE
CULVERT
RAILWAY
MAJOR ROAD
LOCAL ROAD
FORT MACLEOD
STUDY LIMIT
FLOODWAY
FLOOD FRINGE
HIGH HAZARD FLOOD FRINGE
200-YEAR FLOOD EXTENT
500-YEAR FLOOD EXTENT

DISCHARGE
OLDMAN RIVER ABOVE WILLOW CREEK = 2,300 m³/s
OLDMAN RIVER BELOW WILLOW CREEK = 2,800 m³/s
WILLOW CREEK = 864 m³/s

SCALE - 1:10,000
0 100 200 300 400 M

Coordinate System: NAD 1983 CSRS 3TM 114
Units: METRES; Vertical Datum: CGVD28 HTv2.0

Engineer	GIS	Reviewer
VCCB	MSN/JY	RBA

Job Number	Date
3004660	15-DEC-2022

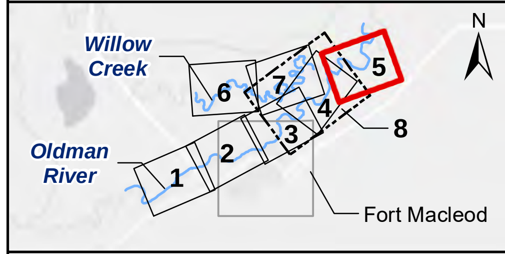
FORT MACLEOD FLOOD HAZARD STUDY

FLOOD HAZARD MAP

JY P:_Projects (Active)\3004660 Fort Macleod\2022Update\90 GIS\3004660_JY_2022_Map_T6_OWFloodHazardMap.mxd

Alberta

nhc
northwest hydraulic consultants



FLOW DIRECTION
RS 12,345 RIVER STATION
CROSS SECTION
BRIDGE
CULVERT
RAILWAY
MAJOR ROAD
LOCAL ROAD
FORT MACLEOD
STUDY LIMIT
FLOODWAY
FLOOD FRINGE
HIGH HAZARD FLOOD FRINGE
200-YEAR FLOOD EXTENT
500-YEAR FLOOD EXTENT

DISCHARGE
OLDMAN RIVER BELOW WILLOW CREEK = 2,800 m³/s

SCALE - 1:10,000
0 100 200 300 400 M
N

Coordinate System: NAD 1983 CSRS 3TM 114
Units: METRES; Vertical Datum: CGVD28 HTv2.0

Engineer	GIS	Reviewer
VCCB	MSN/JY	RBA

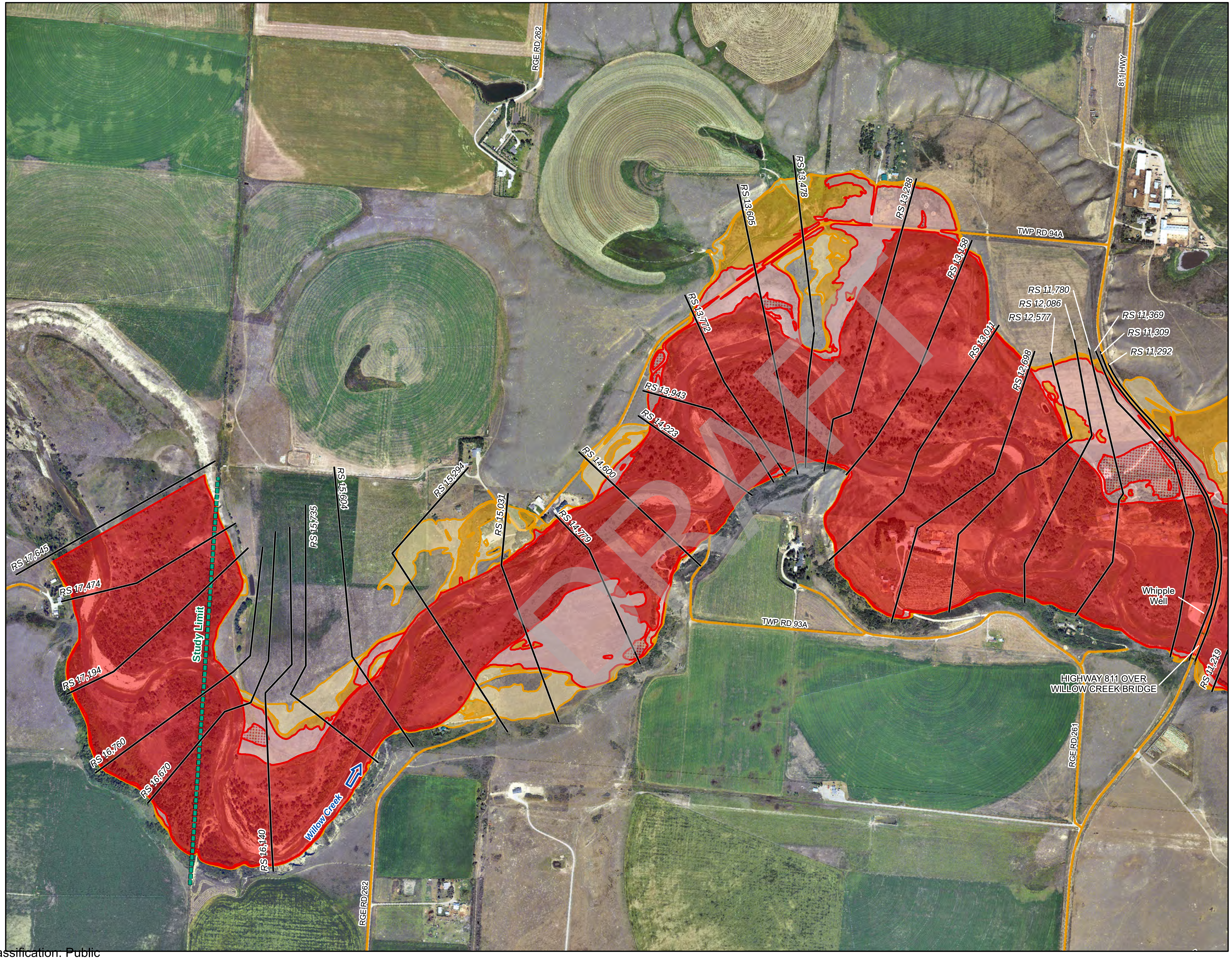
Job Number	Date
3004660	15-DEC-2022

FORT MACLEOD FLOOD HAZARD STUDY

FLOOD HAZARD MAP

SHEET 5 OF 8

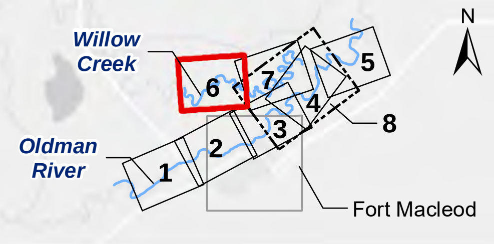
JY, P:_Projects (Active)\3004660 Fort Macleod\2022Update\90 GIS\3004660_JY_2022_Map_T6_OWFloodHazardMap.mxd



Classification: Public

Alberta

nhc
northwest hydraulic consultants



FLOW DIRECTION
RS 12,345 RIVER STATION
CROSS SECTION
BRIDGE
CULVERT
RAILWAY
MAJOR ROAD
LOCAL ROAD
FORT MACLEOD
STUDY LIMIT
FLOODWAY
FLOOD FRINGE
HIGH HAZARD FLOOD FRINGE
200-YEAR FLOOD EXTENT
500-YEAR FLOOD EXTENT

DISCHARGE
WILLOW CREEK = 864 m³/s

SCALE - 1:10,000
0 100 200 300 400 M
N

Coordinate System: NAD 1983 CSRS 3TM 114
Units: METRES; Vertical Datum: CGVD28 HTv2.0

Engineer	GIS	Reviewer
VCCB	MSN/JY	RBA

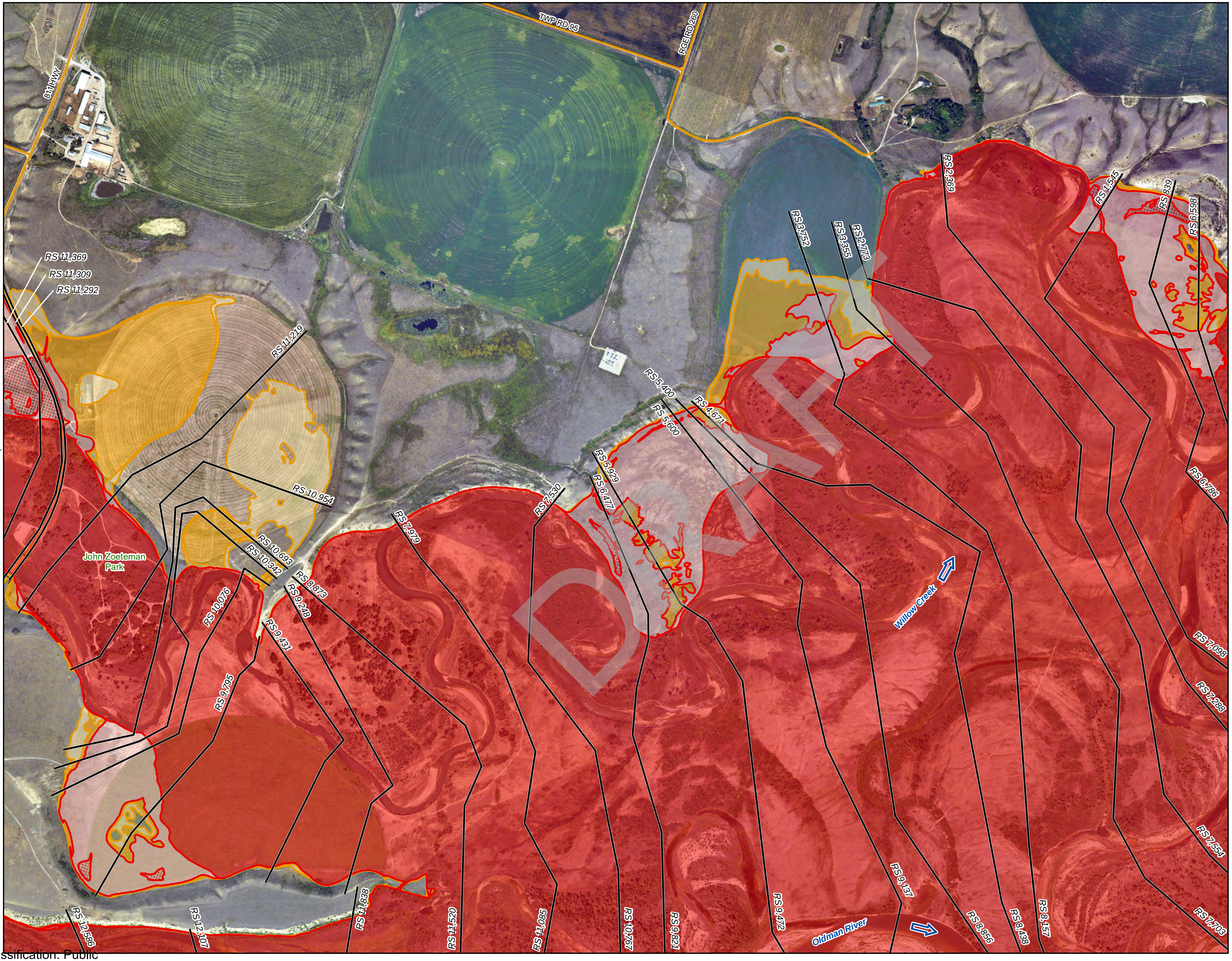
Job Number	Date
3004660	15-DEC-2022

FORT MACLEOD FLOOD HAZARD STUDY

FLOOD HAZARD MAP

SHEET 6 OF 8

JY P:_Projects (Active)\3004660 Fort Macleod\2022Update\90 GIS\3004660_JY_2022_Map_T6_OWFloodHazardMap.mxd



Classification: Public

Alberta

nhc
northwest hydraulic consultants

Willow Creek
Oldman River
Fort Macleod
1 2 3 4 5 6 7 8
N

FLOW DIRECTION
RS 12,345 RIVER STATION
CROSS SECTION
BRIDGE
CULVERT
RAILWAY
MAJOR ROAD
LOCAL ROAD
FORT MACLEOD
STUDY LIMIT
FLOODWAY
FLOOD FRINGE
HIGH HAZARD FLOOD FRINGE
200-YEAR FLOOD EXTENT
500-YEAR FLOOD EXTENT

DISCHARGE
OLDMAN RIVER ABOVE WILLOW CREEK = 2,300 m³/s
WILLOW CREEK = 864 m³/s

SCALE - 1:10,000
0 100 200 300 400 M

Coordinate System: NAD 1983 CSRS 3TM 114
Units: METRES; Vertical Datum: CGVD28 HTv2.0

Engineer	GIS	Reviewer
VCCB	MSN/JY	RBA

Job Number	Date
3004660	15-DEC-2022

FORT MACLEOD FLOOD HAZARD STUDY

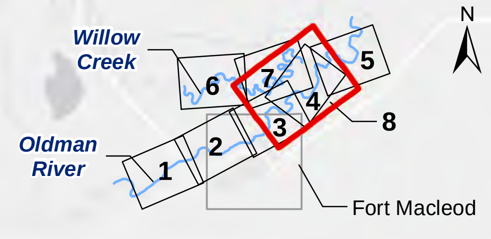
FLOOD HAZARD MAP

SHEET 7 OF 8

JY, P:_Projects (Active)\3004660 Fort Macleod\2022Update\90 GIS\3004660_JY_2022_Map_T6_OWFloodHazardMap.mxd

Alberta

nhc northwest hydraulic consultants



FLOW DIRECTION
RS 12,345 RIVER STATION
CROSS SECTION
BRIDGE
CULVERT
RAILWAY
MAJOR ROAD
LOCAL ROAD
FORT MACLEOD
STUDY LIMIT
FLOODWAY
FLOOD FRINGE
HIGH HAZARD FLOOD FRINGE
200-YEAR FLOOD EXTENT
500-YEAR FLOOD EXTENT

DISCHARGE
OLDMAN RIVER ABOVE WILLOW CREEK = 2,300 m³/s
OLDMAN RIVER BELOW WILLOW CREEK = 2,800 m³/s
WILLOW CREEK = 864 m³/s

SCALE - 1:15,000
0 100 200 300 400 500 600 M

Coordinate System: NAD 1983 CSRS 3TM 114
Units: METRES; Vertical Datum: CGVD28 HTv2.0

Engineer	GIS	Reviewer
VCCB	MSN/JY	RBA

Job Number	Date
3004660	15-DEC-2022

FORT MACLEOD FLOOD HAZARD STUDY

FLOOD HAZARD MAP

SHEET 8 OF 8

JY P:_Projects (Active)\3004660 Fort Macleod\2022Update\90 GIS\3004660_JY_2022_Map_T6_OWFloodHazardMap.mxd

Classification: Public

Appendix L: GIS Metadata

Spatial Data Summary - Survey Data

CATEGORY	TITLE	DESCRIPTION	KEY ATTRIBUTE DESCRIPTION	FOLDER or GDB	FILE
SURVEY AND BASE DATA					
	Survey Points	Processed point survey data from NHC's April-May and June 2019 ground and bathymetric surveys of Oldman River and Willow Creek. Comma delimited text (CSV) format.	Fld_Easting, Fld_Northing = easting and northing coordinates in NAD83 CSRS 3TM 114 metres; Fld_Elevation = point elevation in metres; GIS_FieldCode = field code; GIS_Description = description based on field code; Date_YYYYMMDD = survey date; Usage = type of survey point (HWM = high water mark, WSE = water surface elevation, WSE profile, bridge, culvert, section, survey control, other).	-	FMFHS_SurveyPts.csv
	Survey Points	Processed point survey data from NHC's April-May and June 2019 ground and bathymetric surveys of Oldman River and Willow Creek. Esri file geodatabase point feature class.	Fld_Easting, Fld_Northing = easting and northing coordinates in NAD83 CSRS 3TM 114 metres; Fld_Elevation = point elevation in metres; GIS_FieldCode = field code; GIS_Description = description based on field code; Date_YYYYMMDD = survey date; Usage = type of survey point (HWM = high water mark, WSE = water surface elevation, WSE profile, bridge, culvert, section, survey control, other).	FMFHS_Survey.gdb\	SurveyPts
	Survey Field Photos	Photos from NHC's spring 2019 field survey. Georeferenced JPEG images.	n.a.	Photos\	*.jpg
	Survey Field Photo Points	Point locations of georeferenced photos from NHC's spring 2019 field survey. Esri file geodatabase point feature class.	Name = photo filename; DateTime = date and time of photo; Date_YMD = date based on DateTime, or estimated if DateTime was not automatically recorded by camera; Direction = direction of photo (not necessarily accurate); RelativePath = relative path to photo image location.	FMFHS_Survey.gdb\	SurveyPhotoPts
	Stream Centreline	Stream network centrelines, developed for identifying chainage of features along river. Calibrated with reach length. Esri file geodatabase polyline feature class.	River = stream name; Reach = reach name.	FMFHS_Survey.gdb\	StreamCentrelines
	Cross Section Locations	Cross section lines. Created for survey and model planning, updated to reflect survey data collected and model layout hydraulic modelling. Esri file geodatabase polyline feature class.	River = stream name; Reach = reach name; Station = river station value (metres); RS = river station value (metres); RS_int = river station value to nearest metre; ModelXS = merge of River, Reach and RS.	FMFHS_Survey.gdb\	CrossSections
	Hydraulic Structures - Bridges	Processed point survey data for bridges from NHC's April-May and June 2019 surveys. Esri file geodatabase point feature class.	See Survey Points, above.	FMFHS_Survey.gdb\	SurveyPts_Bridges
	Hydraulic Structures - Culverts	Processed point survey data for culverts from NHC's April-May and June 2019 surveys. Esri file geodatabase point feature class.	See Survey Points, above.	FMFHS_Survey.gdb\	SurveyPts_Culverts

Spatial Data Summary - Open Water Hydraulic Modelling

CATEGORY	TITLE	DESCRIPTION	KEY ATTRIBUTE DESCRIPTION	FOLDER or GDB	FILE
HYDRAULIC MODEL					
	Stream Centrelines	Stream network centrelines, developed for hydraulic modelling. Calibrated with reach length. Esri file geodatabase polyline feature class.	River = stream name; Reach = reach name.	FMFHS_HydraulicModel.gdb\	StreamCentrelines
	Model Cross Sections	Cross section lines. Created for hydraulic modelling. Esri file geodatabase polyline feature class.	River = stream name; Reach = reach name; Interp = indicates whether section was surveyed (NO) or interpolated (YES); Station = river station value (metres); RS = river station value (metres); RS_int = river station value to nearest metre; ModelXS = merge of River, Reach and RS.	FMFHS_HydraulicModel.gdb\	CrossSections
	Bridge Sections	Modelled bridge sections. Esri file geodatabase polyline feature class.	Name = bridge name.	FMFHS_HydraulicModel.gdb\	BridgeSections
	Culverts	Modelled culverts. Esri file geodatabase polyline feature class.	River = stream name; Reach = reach name; RS = river station location (metres).	FMFHS_HydraulicModel.gdb\	Culverts
	Bank Lines	Modelled bank lines. Esri file geodatabase polyline feature class.	None.	FMFHS_HydraulicModel.gdb\	BankLines
	Bank Points	Modelled bank points. Each feature includes a left bank and a right bank point. Esri file geodatabase multipoint feature class.	River = stream name; Reach = reach name; River_Stat = river station location (metres); Node_name = indicates if points are located on an interpolated section; Left_Bank = left bank station location on section (metres); Right_Bank = right bank station location on section (metres).	FMFHS_HydraulicModel.gdb\	BankPoints
	Flow Path Centrelines	Flow path centrelines. Esri file geodatabase polyline feature class.	LineType = indicates whether flow path is on left bank or right bank.	FMFHS_HydraulicModel.gdb\	FlowPathCentrelines
	Roughness Polygons	Roughness polygons. Land cover was mapped in reference to 2015 orthophotos and 2018 Lidar bare earth and full feature data. Roughness values were assigned based on land cover. Esri file geodatabase polygon feature class.	Category = land cover description; N_value = Manning's n value	FMFHS_HydraulicModel.gdb\	Roughness
	Bathymetry Extents	Portion of each model cross section where elevation values were extracted from bathymetric survey data rather than Lidar DEM data. For sections where no bathymetric survey data was used, a small polygon is included (required for HEC-GeoRAS use). Esri file geodatabase polygon feature class.	None.	FMFHS_HydraulicModel.gdb\	BathyExtents

Spatial Data Summary - Open Water Flood Inundation

CATEGORY	TITLE	DESCRIPTION	KEY ATTRIBUTE DESCRIPTION	FOLDER or GDB	FILE
OPEN WATER FLOOD INUNDATION MAPPING					
	Water Surface Elevation TINs	WSE TINs for each of thirteen naturalized open water flood scenarios: 2-, 5-, 10-, 20-, 35-, 50-, 75-, 100-, 200-, 350-, 500-, 750-, and 1000-year floods. Created from model sections, perimeter breaklines, and additional breaklines for backwater modifications. Esri TIN format.	All values are water surface elevations in metres.	FMFHS_OpenWaterInundationWSTINs\	tWL????y
	Water Surface Elevation Grids	WSE grids for each of thirteen naturalized open water flood scenarios: 2-, 5-, 10-, 20-, 35-, 50-, 75-, 100-, 200-, 350-, 500-, 750-, and 1000-year floods. Created from WSE TINs (final draft), tiled, and clipped to flood inundation extents. There is a separate WSE grid for each flood scenario and each DEM tile. Esri file geodatabase grid feature class format.	All values are water surface elevations in metres.	FMFHS_OpenWaterInundationWSGrids.gdb\	gWL????y2_DEMTile
	Note: Water surface elevation TINs and grids are based on existing conditions, available data, and assumptions applicable to the Fort Macleod Flood Hazard Study at the time these data were generated. Water surface elevation TINs and grids are provided for information only. Use of or reliance upon this information for any other purpose, including but not limited to future flood inundation mapping updates, is the sole responsibility of the user and is not recommended by Northwest Hydraulic Consultants Ltd.				
	Flood Depth Grids	Flood depth grids for thirteen naturalized open water flood scenarios: 2-, 5-, 10-, 20-, 35-, 50-, 75-, 100-, 200-, 350-, 500-, 750-, and 1000-year floods. Based on final WSE TINs and the digital elevation model (DEM). There is a separate depth grid for each flood scenario and each DEM tile. Esri file geodatabase grid feature class format.	All values are flood depths in metres.	FMFHS_OpenWaterInundationDepths.gdb\	gDP????y_DEMTile
	Flood Inundation Extents	Flood inundation extents for thirteen naturalized open water flood scenarios: 2-, 5-, 10-, 20-, 35-, 50-, 75-, 100-, 200-, 350-, 500-, 750-, and 1000-year floods. Derived from flood depth grids, with polygon simplification and smoothing applied. Esri file geodatabase polygon feature class format.	DESCRIP = flood inundation scenario description; SCENARIO = flood inundation scenario number. Mapped flood inundation scenarios include: 0 - X-year Flood Inundation Extent [direct inundation].	FMFHS_OpenWaterInundation.gdb\	OWFloodExtent????Y
	Model Sections	Model cross sections, attributed with computed open water flood frequency levels for each of thirteen naturalized open water flood scenarios: 2-, 5-, 10-, 20-, 35-, 50-, 75-, 100-, 200-, 350-, 500-, 750-, and 1000-year floods. Esri file geodatabase polyline feature class format.	River = stream name; Reach = reach name; Interp = indicates whether section was surveyed (NO) or interpolated (YES); Station = river station value (metres); RS = river station value (metres); RS_int = river station value to nearest metre; ModelXS = merge of River, Reach and RS; WSE_????Y = computed water level for each flood scenario.	FMFHS_OpenWaterInundation.gdb\	OW_XSLines

CATEGORY	TITLE	DESCRIPTION	KEY ATTRIBUTE DESCRIPTION	FOLDER or GDB	FILE
	Survey Points	Selected processed point survey data from NHC's May 2019 ground and bathymetric surveys, with some 2018 Lidar data points added at select cross sections. Data are used for inserting bathymetry into cross sections in HEC-GeoRAS. Esri file geodatabase point feature class.	FieldCode = code describing survey point; Description = description corresponding to FieldCode; Date_YYYYMMDD = data of data collection; Source = indicates NHC survey or Lidar; Elev = elevation (metres)	FMFHS_HydraulicModel.gdb\	BathyPts
	Highwater Marks	Highwater marks. Esri file geodatabase point feature class.	Name = HWM identifier code; Year = year; HWM_WL = indicates if the point represents a highwater mark or water level; Elevation = elevation (metres CGVD28); Location = general location of HWM; Descriptio = additional description of HWM location; RevComment = modeller's review notes based on original files; River = stream name; Stn = station location along stream centreline (metres).	FMFHS_HydraulicModel.gdb\	HWMpts

Spatial Data Summary - Flood Hazard

CATEGORY	TITLE	DESCRIPTION	KEY ATTRIBUTE DESCRIPTION	FOLDER or GDB	FILE
DESIGN FLOOD HAZARD MAPPING					
	Water Surface Elevation TIN	Water surface elevation (WSE) TIN for the governing design flood. Created from extended model sections and perimeter breaklines. Esri TIN format.	All values are water surface elevations in metres.	FMFHS_HazardWSTINs\	tWLGVDesign
	Water Surface Elevation Grids	WSE grids for the governing design flood. Created from WSE TIN, tiled, and clipped to design flood extents. There is a separate WSE grid for each DEM tile. Esri file geodatabase grid feature class format.	All values are water surface elevations in metres.	FMFHS_HazardWSGrids.gdb\	gWL0100Y2_DEMTile
	Note: Water surface TINs are based on existing conditions, available data, and assumptions applicable to the Fort Macleod Flood Hazard Study at the time these data were generated. Water surface TINs are provided for information only. Use of or reliance upon this information for any other purpose, including but not limited to future flood inundation mapping updates, is the sole responsibility of the user and is not recommended by Northwest Hydraulic Consultants Ltd.				
	Flood Depth Grids	Flood depth grids for the governing design flood. Based on water surface elevation TIN and the digital elevation model (DEM). There is a separate depth grid for each DEM tile. Esri file geodatabase grid feature classes.	All values are flood depths in metres.	FMFHS_HazardDepths.gdb\	gDP0100Y2_DEMTile
	Flood Hazard Area	Flood hazard area, floodway, and flood fringe for the governing design flood. Esri file geodatabase polygon feature class.	ONE_ZONE = Flood Hazard Area; TWO_ZONE = Floodway or Flood Fringe; MULTI_ZONE = Floodway, Flood Fringe, or High Hazard Flood Fringe.	FMFHS_Hazard.gdb\	FloodHazardArea_2022Update
	Model Sections	Model cross sections, attributed with computed governing design levels. Esri file geodatabase polyline feature class format.	River = stream name; Reach = reach name; Interp = indicates whether section was surveyed (NO) or interpolated (YES); Station = river station value (metres); RS = river station value (metres); RS_int = river station value to nearest metre; ModelXS = merge of River, Reach and RS; WSE_GVDesign = computed open water design level (m).	FMFHS_Hazard.gdb\	Hazard_XSLines
	Proposed Floodway Limits	Floodway limits for the open water design flood attributed with criterion that defines floodway boundary location. Esri file geodatabase point feature class.	River = stream name; ModelXS = merge of River, Reach and RS; ModelCriteria = floodway criteria.	FMFHS_Hazard.gdb\	OWFloodwayLimits_2022Update
	Proposed Floodway Boundary	Hydraulically smooth floodway limit line delineated based on the 100-year open water design flood, the 1 metre depth contour, 1 m/s velocity contours, channel banklines, and previously delineated floodways. Esri file geodatabase polyline feature class.	ZONE = "Floodway"	FMFHS_Hazard.gdb\	OWFloodwayLine_2022Update

nhc
northwest hydraulic consultants
water resource specialists