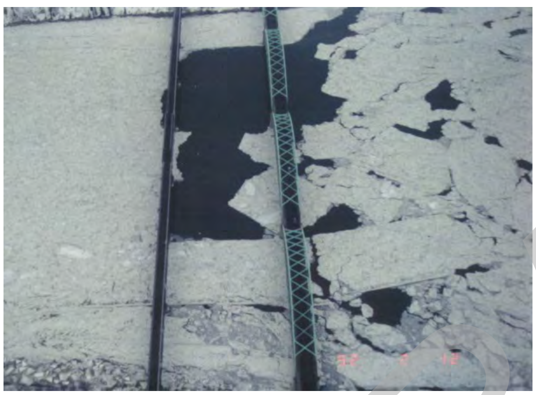

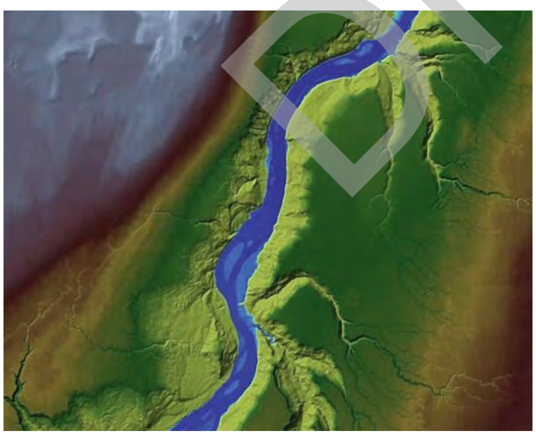

PEACE RIVER HAZARD STUDY

ICE JAM MODELLING ASSESSMENT & FLOOD HAZARD IDENTIFICATION

FINAL REPORT

Prepared for:

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24 October 2022

NHC Ref. No. 1001119

nhc
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APEGA Permit to Practice – P654

Prepared by:

Dan Healy, PhD, PEng
Principal

Reviewed by:

Gary Van Der Vinne, MSc, PEng
Principal

DISCLAIMER

This report has been prepared by Northwest Hydraulic Consultants Ltd. in accordance with generally accepted engineering practices, for the benefit of Alberta Environment and Parks for specific application to the Peace River Hazard Study in Alberta. The information and data contained herein represent Northwest Hydraulic Consultants Ltd.'s best professional judgment based on the knowledge and information available to Northwest Hydraulic Consultants Ltd. at the time of preparation.

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CREDITS AND ACKNOWLEDGEMENTS

Northwest Hydraulic Consultants Ltd. would like to express appreciation to Alberta Environment and Parks for initiating this project and making available extensive background information including annual ice observation reporting. Key AEP representatives were Nadia Kovachis Watson, MSc, PEng (Project Manager), Adam Minke, MSc, CET (Alternate Project Manager), and Patricia Stevenson, BSc (Alternate Project Manager). Jane Eaket, MSc, PEng from AEP also provided her input and guidance in updating the floodway criteria maps.

Thanks are also expressed to the Town of Peace River, BC Hydro, Alberta Transportation, and the Peace River Museum and Archives / Mackenzie Centre for providing additional supporting information.

The following NHC personnel provided the key contributions to the ice jam modelling and related flood hazard mapping component of the Peace River Hazard Study. Dan Healy, PhD, PEng (Project Manager) ensured the overall direction of the project, conducted the frequency analysis and modelling, and was the primary author of this report. A key component of the work was to develop a methodology for calculating ice jam flood frequencies and the basis for this analysis was conceived and developed by David Andres, MSc, PEng. Sarah North, GISP (GIS Specialist) assisted with mapping and database creation.

EXECUTIVE SUMMARY

Northwest Hydraulic Consultants Ltd. was retained in September 2015 by Alberta Environment and Parks to conduct a River Hazard Study for the Peace River through the Town of Peace River. The objectives of this River Hazard Study are to identify and assess river and flood-related hazards along 54 km of the Peace River, from about 6 km upstream of Shaftesbury Ferry to about 5 km downstream of the Highway 986 bridge, and along 1.2 km of the Heart River upstream of its confluence with the Peace River.

This report summarizes the work of the supplementary ice jam modelling assessment and flood hazard identification component of the study. A summary of all work related to the determination of ice jam flood inundation and ice jam floodway criteria mapping is provided, including: documentation of ice jam flood history, an ice jam flood frequency analysis, development of an ice enhanced HEC-RAS model, ice jam flood frequency inundation mapping, and ice jam design flood hazard mapping.

Ice jam flood inundation maps were created based on the computed 50-year, 100-year, and 200-year ice jam flood frequency water surface profiles. Ice jam floodway criteria maps were created for the 100-year design ice jam flood, composed of floodway and flood fringe zones, using the FHIP Guidelines (Alberta Environment, 2011), incorporating technical changes implemented in 2021 regarding how floodways are mapped in Alberta.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

1.1 Study Objectives

The overall objectives of the Peace River Hazard Study are to identify and assess river and flood hazards along the Peace and Heart rivers through the Town of Peace River (TPR). The study is being completed under the provincial Flood Hazard Identification Program (FHIP), the goals of which include enhancement of public safety and reduction of future flood damages through the identification of river and flood hazards. The intent is to reduce potential future flood damage and disaster assistance costs to the federal, provincial, and local governments, including First Nations. New floodplain maps will inform land use planning decisions, assist with developing flood mitigation options, and facilitate emergency response planning.

The Peace River Hazard Study has been structured into the following major project components.

1) Survey and Base Data Collection
2) Open Water Hydrology Assessment
3) Hydraulic Model Creation and Calibration
4) Open Water Flood Inundation Map Production
5) Open Water Flood Hazard Identification
6) Ice Jam Modelling Assessment & Flood Hazard Identification
7) Governing Design Flood Hazard Map Production
8) Flood Risk Assessment and Inventory
9) Channel Stability Investigation

This report summarizes the work of the supplementary ice jam modelling assessment and flood hazard identification component of the Peace River Hazard Study. A summary of all work related to the determination of ice jam flood inundation and ice jam floodway criteria mapping is provided, including: documentation of ice jam flood history, an ice jam flood frequency analysis, development of an ice enhanced HEC-RAS model, ice jam flood frequency inundation mapping, and ice jam design flood hazard mapping.

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Environment, 2011), incorporating technical changes implemented in 2021 regarding how floodways are mapped in Alberta.

The development of an ice enhanced hydraulic model and ice jam floodway criteria map, and associated deliverables, are prerequisites for determining the governing design flood hazards. These products directly support the supplementary governing design flood hazard mapping and flood risk assessment and inventory components of the overall project.

1.2 Study Area and Reach

The Peace River flows into northwestern Alberta from British Columbia, passing through TPR, which is located about 380 km northwest of Edmonton. The extent of the contributing basin for the study reach is shown in **Figure 1**. Peace River flows are regulated by BC Hydro for hydropower production at Bennett Dam and Peace Canyon (PCN) Dam. The primary storage unit that enables regulation is Williston Lake, the reservoir created by Bennett Dam, which has sufficient capacity to provide multi-year storage of inflows.

The study reach consists of a 54 km segment of the Peace River beginning at the west boundary of 1-82-24-W5M about 6 km upstream of the Shaftesbury Ferry crossing (Highway 740) to the north boundary of 24-85-21-W5M about 5 km downstream of the Highway 986 bridge. The location of the study reach is shown in **Figure 1.** TPR is the most developed and populated area along this reach of the Peace River. Also included in the study area is a 1.2 km reach of the Heart River upstream of its confluence with the Peace River and a limited reach of the Smoky River near its confluence with the Peace River. Study limits are shown in **Figure 2**.

2 ICE JAM FLOOD HISTORY

2.1 General Information

2.1.1 Regulation

Flows in the Peace River are regulated by hydropower operations at the WAC Bennet (Bennet) Dam which impounds water to form Lake Williston. Some 20 km downstream of Bennet Dam is a second smaller power generating facility – Peace Canyon Dam. Peace Canyon Dam essentially operates as a run-of-river facility and has little additional effect on flows regulated by Bennet Dam. Both Bennet Dam and Peace Canyon Dam hydro facilities are operated by the British Columbia Hydro and Power Authority (BCH). Construction on the Bennet Dam began in 1968 and was completed in 1972. Peace Canyon Dam was completed in 1980. Church (2015) provides a descriptive account on the effects of regulation on the Peace River in the context of river morphology, and this recently published perspective is based largely on observations collected over the past 40 years (after regulation). Similarly, much of the current knowledge and understanding on the Peace River ice regime is based on river ice observations that were obtained after regulation.

2.1.2 Peace River Ice Jam Regime

The understanding of the Peace River ice regime has evolved from the considerable amount of research and local observations on ice jam processes undertaken over the past 40 plus years. A significant portion of this work has been motivated by concerns for ice jam induced floods at TPR. This section provides an introduction to ice jam classification and a summary of the classes of ice jams used to characterize the Peace River ice jam regime within the project study area.

Ice jams vary in size and shape in accordance to the prevailing hydraulic, geometric, and meteorological conditions during their development. They way in which they form and the prevailing conditions during their genesis gives rise to their classification. The IAHR Working Group on River Ice Hydraulics (IAHR, 1986) defined an ice jam as *"a stationary accumulation of fragmented ice or frazil that restricts flow"*, and proposed a classification system for ice jams that are governed by the following criteria: the season during which the ice jam formed; the dominant formation processes; the spatial extent of the ice jam; and the state of evolution of the ice jam at the moment of classification. Healy (1997) provides a concise overview of ice jam classification and the basic formulations commonly used to simulate an ice jam water level and thickness profile (these same formulations are those applied by the *ice enhanced* HEC-RAS model adopted for this study).

There are two classes of ice jams that are characteristic to the study reach and relevant to this study: freeze-up jams and breakup jams. Their classification is largely based on the former two criteria listed above – season of formation and the dominant processes during formation.

Freeze-up Jams

Pre-Regulation: There is little observational information on the ice regime prior to regulation and the information that is available is generally limited to water levels, and first and last ice dates provided in the WSC historic record. Prior to regulation, flows were lower, depths were relatively shallow, and the water temperature closely followed the air temperature. Everywhere along the Peace River, ice began to form as shore ice and frazil ice in early November. Frazil ice would accumulate and lodge at multiple locations along the river and a stable ice accumulation typically formed at TPR by December. Previous studies completed by Trillium Engineering and Hydrographics Inc. (Trillium) provide a thorough overview on the aspects of the pre-regulated regime (Trillium 1996a and 1996b).

The thickness of freeze-up accumulations would likely vary according to the prevailing temperatures and stream flows as the ice front progressed through the study reach. Pre-regulation flows during the freeze-up period were generally low and relatively constant. The freeze-up through the study reach would be characterized by an initially thin cover comprised of a combination of border ice, juxtaposed floes, and hydraulically thickened slush and floe ice accumulations. It is likely that these initial thin covers would further reconsolidate during the formation period into stable freeze-up ice jams. Prior to regulation, the flows would continue to decrease and further limit stage increases associated with freeze-up effects.

Post-Regulation: For a given reach of river, the rate at which the ice cover advances upstream is largely dependant on the air temperature, water temperature, and river discharge. Air temperatures vary naturally, and unlike pre-regulation, the water temperature and river discharge are largely controlled by the operation of the Dam. After regulation, river freeze-up has been characterized as an orderly progression of a stable ice cover starting from a single point located well downstream of the study reach (i.e. near Vermilion Chutes).

In the mild-sloped reaches of the Peace River, far downstream of the study area, stable ice accumulations are formed by the juxtaposition of ice flows and the rate of progression is driven by the surface velocities and concentration of surface ice floes. For reaches within the study area, where river slopes are greater, stable ice accumulations form as freeze-up jams, which are characterized by the consolidation of slush and floe ice. The rate of progression is controlled primarily by discharge and temperature. If the discharge and air temperature remains relatively constant, the ice cover will thicken until the cover reaches a stable configuration. When an ice jam reaches a stable configuration, it is considered to have reached a state of "equilibrium" where the applied forces are balanced by the resistive forces.

The following excerpt from a previous study (NHC 2006) describes the mechanisms by which freeze-up jams typically evolve and progress through the study area: *"During any short period of time – on a scale of hours or days – the surface ice floes accumulate (or juxtapose) against the downstream ice in a layer that would have an equivalent thickness of about one floe. The ice cover then advances upstream a short distance – say one or two kilometers – and then it collapses and thickens against the downstream cover. This is known as a "primary consolidation" and is common in the development of a stable ice cover on steep rivers. Another type of consolidation is a "secondary consolidation". This is a new collapse of an ice cover that has already consolidated. Secondary consolidations can produce extremely high water levels".* The descriptive account above implicates two importance considerations for the current study: the significance of there being a temporal component associated with a freeze-up jam; and, it introduces another form of freeze-up jam of particular importance with respect to ice jam induced flooding – the secondary consolidation.

The Steady State Assumption

The temporal component of freeze-up jams influences aspects of the ice jam modelling assessment methodology. A key assumption in this assessment is that the analysis of ice jam induced flooding can be approximated with a steady state condition. This is a necessary assumption since the adopted model (HEC-RAS) for calculating ice jam flood levels requires a steady state assumption. Ice jam formation is a dynamic process and the result of a complex combination of natural phenomena. For practical analysis we limit our consideration to the stage at which the ice jam has evolved to a stable condition – the state for which the ice jam will remain stable and will not further evolve under the prevailing hydro-meteorological conditions associated with its genesis. For this study, when an ice jam has reached this stable condition the longitudinal ice thickness and water surface elevation profile is said to be fully developed. And, the fully developed ice jam profile is well approximated by the steady state ice jam stability formulations employed by the adopted HEC-RAS model.

Secondary Consolidations

As the name implies, a secondary consolidation occurs when an otherwise stable ice jam accumulation reconsolidates into a second, thicker consolidation of ice. The secondary consolidation may occur days after the initial freeze-up jam and may form anywhere along the study reach. The highest observed freeze-up water levels recorded at the TPR WSC gauge are attributed to secondary consolidation events which occurred during the 1981-82 and 1991-92 ice seasons.

The reconsolidation of the initial ice jam is due to a change in the prevailing hydro-meteorological conditions that were associated with the initial ice jam development. What ultimately triggers the formation of a secondary consolidation is not well understood; however, based on observation and knowledge of ice processes, previous investigators have identified the following as some the contributing factors for their initiation (NHC 2006):

- A very rapid advance of the ice cover leading to a sudden and large increase in the hydraulic forces (shear and downslope component of weight) acting on the ice accumulation without sufficient time for the growth of thermal ice to provide enough internal strength to resist the additional forces.
- A sudden increase in discharge that disturbs the previously established stable ice jam.
- A sudden rise in temperature that deteriorates the thermal ice on the surface of the ice jam.

Breakup Jams

Breakup jams are classified according to their season of formation (they form during spring breakup) and the likelihood of them occurring depends on the nature of spring breakup. Breakup occurs when the hydrodynamic forces are sufficiently large enough to dislodge and mobilize (*break up*) the ice cover. River ice breakup is driven by a combination of thermal and mechanical processes. When thermal processes dominate, air and water temperature rise causing the ice cover to deteriorate and melt. The cover weakens in place, breaks down, redistributes and flushes downstream. Breakup dominated by thermal processes is the most benign form of breakup and may be referred to as a *mild* or *uneventful*.

Breakup dominated by mechanical processes is considered to be more dramatic and may be characterized as *dynamic* or *severe*. When the breakup is dominated by mechanical processes, the formation of a breakup jam is possible. For mechanical breakup, the hydrodynamic forces (due to a significant rise in discharge and water level) are large enough to dislodge and break up an otherwise competent ice cover that has retained considerable strength. Breakup advances downstream as the ice rubble drives through the competent ice cover. The progressing edge of the ice rubble is referred to as the *breakup front,* and when this front is arrested and stops, the ice rubble following behind consolidates into a thicker accumulation to form a breakup jam.

Pre-Regulation: Before regulation, most of the river far upstream and downstream of the study reach would be covered with ice prior to breakup. The initial weakening of the cover would be due to the input of thermal energy imparted by solar radiation into the top of the ice cover. The cover would deteriorate at nearly the same rate over relatively long reaches of river (longer than the study reach), but would vary along the entire Peace River according to the regional differences in meteorological conditions. The cover would deteriorate until the hydrodynamic forces were sufficient to breakup and mobilize the cover. This would occur at various locations along the river and multiple breakup jams would occur simultaneously along the whole Peace River. At a regional scale, the breakup of the ice cover generally occurred earlier in the season in southern latitudes (upper reaches), and later in northern latitudes (lower reaches). Breakup jams occurred more frequently before regulation than after regulation; although, it may be reasonable to postulate they were less *severe* than after regulation.

Post-Regulation: After regulation, the upper reaches of the river remain free of ice due to the warm water release from PCN. The release of warm water maintains a long stretch of open water between PCN and the established ice cover, throughout the entire ice-affected period. The presence of the open water reach tends to dominate the breakup process over much of the Peace River, including the study reach (NHC 2006). The absence of an ice cover downstream of PCN allows for additional heat input from rising spring air temperatures and increasing solar radiation. The cover weakens in the upper reaches and deterioration progresses downstream from the leading edge of the ice front. Significant deterioration and recession of the cover occurs before spring flows increase to produce a mechanical breakup. On average, the likelihood of a mechanical breakup and subsequent formation of a breakup jam through the study reach is less than before regulation. However, if a breakup jam does occur, it is likely that it will be more severe than before regulation. This is because flows are higher after regulation and higher flows result in thicker accumulations and consequently, higher flood levels.

2.2 Historical and Observed Ice-Affected Floods

Historical flooding refers to major floods that occurred prior to the period of hydrometric data collection and systematic recording of water level and discharge. In some cases, the magnitude of a historic flood can be estimated based on observations or even anecdotal information.

The Peace River at TPR and the Smoky River at Watino were gauged as early as 1917 and 1915, respectively. There are gaps in the data record for Peace River at Peace River between 1931-1957 and for the Smoky River at Watino between 1922-1954. While there are no historical records of ice-affected flooding on the Heart River, there are historical records of ice-affected flooding on Pat's Creek and a single event on the Peace River. Historic and observed ice-affected floods are summarized in **Table 1.** Historic ice-affected flood photos that were collected during this study are provided in Appendix A.

Table 1 Historic and Observed Ice-Affected Floods

Watercourse	Date	Details
Pat's Creek	April 1914	102 Avenue (Rotten Row) was flooded. **Source:** Image 87.1521.46. Peace River Museum and Archives / Mackenzie Centre.
	17 April 1958	Flooding on Pat's Creek resulted in over a foot of water on Main Street. **Source:** Images 83.1308.033 and 87.1536.047. Peace River Museum and Archives / Mackenzie Centre.

Table 1 Historic and Observed Ice-Affected Floods (continued)

Watercourse	Date	Details
Pat's Creek	8 April 2014	A culvert blockage in Pat's Creek caused water to flood downtown Peace River. **Source:** Adam Dietrich/Record-Gazette/QMI Agency. (9 April 2014) Daily Herald Tribune. Accessed 26 July 2016 from: http://www.dailyheraldtribune.com/2014/04/09/downtown-peace-river-floods
Peace River	14 April 1934	Ice jam flood downstream of the Town of Peace River caused water to back up through town. Boats belonging to the Hudson Bay Company floated up from winter storage and one boat was potentially damaged. **Source:** Peace River Record. (20 Apr 1934). Obtained from Peace River Museum and Archives / Mackenzie Centre.
	1948	Ice jam flood. **Source:** Peace Country Advertising Commemorative Edition: Peace River – 1919-1994.
	20 April 1963	An ice jam caused a 4 m increase in water levels at the WSC Gauge. **Source:** Fonstad (1992)

2.3 Recent and Recorded Ice-Affected Floods

There are a number of recorded ice-affected floods that have occurred on the Heart River and Peace River. **Tables 2** and **3** summarize the recent and recorded ice-affected floods for the Heart River and Peace River, respectively.

Table 2 Recent and Recorded Ice-Affected Floods on the Heart River

Date	Details
11 April 1973	An ice jam downstream formed downstream of TPR causing a more than 4 m rise in water levels resulting in minor overtopping of dikes. Unsupported evidence suggest the Smoky River breakup initiated the ice jam. **Source:** Fonstad and Quazi (1994)
15 April 1974	Mechanical breakup on the Heart River caused ice to pile up on the Peace River and induced local flooding. The footbridge to the baseball park was carried away by ice **Source:** Davies et al. (1974)
29 Feb 1992	The Heart River overtopped its banks in the Town of Peace River due to backwater effects from the Peace River. **Source:** Alberta Transportation. Bridge File 2010-1992, Heart River Bridge.
18 Apr 1997	The ice cover on the Heart River reached the bottom of the Heart River Bridge due to backwater effects from the Peace River. **Source:** Images provided by Town of Peace River (electronic filename: IMG_20151216_161610.jpg).
9 Mar 2005	An ice jam formed on the Heart River in the Town of Peace River, resulting in water flooding Twelve Foot Davis Baseball Park, but did not overtop the dikes. **Source:** Friesenhan (2005)
15 Mar 2015	The ice cover on the Heart River broke up during the evening of March 15, forming an ice jam at the confluence with the Peace River. Water and ice were pushed onto the low-lying areas of Twelve Foot Davis baseball park, but no other flooding was reported. **Source:** Emmer and Kovachis (2015)

Table 3 Recent and Recorded Ice-Affected Floods on the Peace River

Date	Details
1963	High breakup level (for the pre-regulation condition) at the Town of Peace River. Maximum jam elevation of 316.14 m. **Source:** H Biberhofer Consulting (1984)
1973	Ice jam event. Maximum jam elevation of 318.18 m. **Source:** H Biberhofer Consulting (1984)
20 Apr 1974	Breakup on the Smoky River caused ice to breakup through the Town of Peace River and caused an ice jam below the Town which backed the river up to within two feet of the level considered critical by local authorities. Mechanical weakening of the ice cover had been performed prior to breakup. **Source:** Davies et al. (1974)
30 Apr 1979	Breakup flood. Max WL 318.61, water level rise of 4.5 m. **Source:** NHC (1982)
January 1982	An abnormally high ice pack occurred at Peace River due to a combination of weather conditions and fluctuating releases upstream. A secondary consolidation formed and came close to overtopping the dikes. Subsurface seepage caused basement flooding in Lower West Peace. **Source:** Neill and Andres (1984); NHC (1982)
29 Feb 1992	A secondary consolidation formed downstream of TPR. The ice jam caused water levels to overtop the dikes in localized areas, a state of emergency was declared, and about 4000 people had to be evacuated. **Source:** Fonstad (1992)
19-23 Apr 1997	Heavy snow packs and rapid snowmelt caused ice jams on the Peace River which backed up the Heart River. In the Town of Peace River 50% of the businesses were damaged, a state of emergency was declared, and about 4000 people were evacuated. **Source:** Public Safety Canada. Canadian Disaster Database. Accessed 14 March 2017: http://cdd.publicsafety.gc.ca
2005	A secondary consolidation event during freeze-up resulted in a high freeze-up level. Unseasonably high temperatures at various times throughout the ice season resulted in maintained high water levels at the Town of Peace River. Subsurface seepage resulted in flooding in Lower West Peace River (Friesenhan 2005).
2007	High freeze-up stage resulted in elevated groundwater levels causing basement flooding of 48 homes in Lower West Peace. **Source:** Annotated neighbourhood site plan provided by Town of Peace River (electronic filename: 94 – Houses that Flooded in Lower West Peace with Elevations 2007.PDF)
Jan-Feb 2008	High freeze-up stage resulted in basement flooding of 7 homes in Lower West Peace. **Source:** Annotated neighbourhood site plan provided by Town of Peace River (electronic filename: 93 – Houses that Flooded in Lower West Peace 2008.PDF)

Ice jam highwater mark data was collected for the 1979, 1982, 1992, and 1997 ice jam events. These flood events were used for calibration of the ice enhanced model. Further details on these events are provided within the model calibration section of this report (Section 4.4).

3 AVAILABLE DATA

3.1 Ice Jam Highwater Marks

Historical highwater data for ice affected flooding in the Town of Peace River are available from a number of sources. Ice jam high water marks for the 1992 and 1997 events were available from the Town of Peace River and Alberta Environment and Parks, respectively. Additional highwater mark data were obtained from BC Hydro, Alberta Environment and Parks; the Town of Peace River; Alberta Transportation, and the Peace River Museum and Archives – Mackenzie Centre. Summaries of the available high water mark data for each of the selected calibration events are provided in **Table 4** through **Table 7**. The streamwise locations of the measurements listed in these tables, are indicated on **Figure 3** – the description or distance from the downstream (d/s) boundary can be used to find each highwater mark location on the figure. The nearest upstream (u/s) model cross section is also provided for reference.

Table 4 Historical Highwater Mark Data for 1979 Event

Measurement Location		Nearby Model Cross Section		1979 Recorded Ice Jam Profile
Description	Distance from d/s Boundary (m)	u/s Model XSEC	Distance from u/s Model XSEC	Max. Water Level (m)
AENV km 830.3	12474.1	XS #14	579	318.04
AENV km 829.3	11411.6	XS #13	398	316.42
AENV km 827.8	9909.3	XS #12	476	316.72
AENV km 826.4	8422.0	XS #11	603	315.56
AENV km 825.7	7693.7	XS #10	-130	316.49
AENV km 824.5	6464.1	XS #09	-193	313.02
AENV km 822.4	4278.6	XS #05	202	310.76

Table 5 Historical Highwater Mark Data for 1982 Event

Measurement Location		Nearby Model Cross Section		Jan 1982 Recorded Ice Jam Profile	
Description	Distance from d/s Boundary (m)	u/s Model XSEC	Distance from u/s Model XSEC	Max. Water Level (m)	Post Consolidation WL (m)
MacKenzie Cairn	39960.8	XS #44	5	322.82	322.02
Correctional Centre	37240.4	XS #42	6	322.34	321.40
Purcell's	35279.4	XS #41	5	322.01	320.99
Old Highway	32784.8	XS #40	781	321.16	320.11
Gravel Pit	29450.7	XS #38	1307	319.77	318.72
Farm Creek	26726.6	XS #35	0	318.93	317.95
West Peace	24140.2	XS #32	6	318.45	317.25
Heart River	23369.3	XS #31	123	318.41	317.10
Hwy 2 Bridge	22001.5	XS #24	6	318.37	316.95
WSC Gauge	21323.8	XS #22	6	318.18	316.84

Table 6 Historical Highwater Mark Data for 1992 Event

Measurement Location		Nearby Model Cross Section		29 Feb 1992 Recorded Ice Jam Profile				
Description	Distance from d/s Boundary (m)	u/s Model XSEC	Distance from u/s Model XSEC	Time (hh:mm)	Water Level (m)	Ice Level (m)	Max. Ice Level (m)	Bank
Shaftsbury Ferry	48294.27	XS #50	3	17:20	321.26		323.07	L
MacKenzie Cairn	39960.84	XS #44	5	16:35	320.96		325.50	L
Correctional Centre	37240.43	XS #42	6	16:02	320.43	322.39	324.91	L
Purcell's	35279.44	XS #41	5			323.49		L
Old Highway	32784.79	XS #40	781	15:20	320.86	324.09		L
Macleod Cairn	31893.48	XS #39	6			322.39		L
Sawchuk's	28102.68	XS #36	6	14:38	319.99	320.52		L
West Peace	24140.22	XS #32	6	14:12	319.30		321.27	L
West Peace Boat Launch	23487.22	XS #31	5	14:08	319.18	319.79		L
Rail Bridge	22095.62	XS #27	5	12:55	318.97	319.42	321.32	L
Hwy 2 Bridge	22001.50	XS #24	6	12:43	318.93	319.87		L
Bewley Island 2	20896.73	XS #21	5	12:22	318.77	319.27	319.84	R
Czuy's House	19600.79	XS #19	133	12:07	318.42	318.84	319.79	R
Six Mile Farm	13921.81	XS #15	669	11:57	316.37	316.80		L
Seven Mile Bend	11804.09	XS #13	6	11:43	315.72	316.27		L
Shell Intake	1565.11	XS #03	817	11:20	312.00			R

Table 7 Historical Highwater Mark Data for 1997 Event

Measurement Location		Nearby Model Cross Section		19 April 1997 Recorded Ice Jam Profile	
Description	Distance from d/s Boundary (m)	u/s Model XSEC	Distance from u/s Model XSEC	Water Level (m)	Bank
Correctional Centre	37240.43	XS #42	6	323.39	L
West Peace Boat Launch	23487.22	XS #31	5	320.70	L
Heart River at Musuem	23448.41	XS #31	44	320.64	R
West Peace North End	23278.81	XS #30	16	320.67	L
W.H.Wood's	22632.36	XS #30	663	320.31	R
Hwy 2 Bridge	22001.50	XS #24	6	320.41	R
84 Avenue Boat Launch	20809.83	XS #21	92	320.13	R
77 Avenue	20088.06	XS #20	496	319.46	R
Good Shepherd School	19161.28	XS #19	572	319.78	R
Six Mile Farm	13921.81	XS #15	669	315.28	R
Daishowa Bridge	4890.15	XS #06	5	312.68	R

3.2 Ice Observation Reports & Documentation

Historical ice observation reports are available from Alberta Environment and Parks. Ice observation reports were provided for the following ice seasons: 1974-1975, 1981-1982, 1982-1983, 1983-1984, 1984-1985, 2004-2005, 2005-2006, 2006-2007, 2008-2009, 2009-2010, 2011-2012, 2012-2013, 2013-2014, and 2014-2015. Annual ice observation reports were not available for the following years: 1975-1981; and, 1985-2004. Individual ice observation reports were available for the 2007-2008 ice season.

3.3 Gauge Data & Rating Curves

The WSC gauge at Peace River at Peace River (WSC Station No. 07HA001) provides the only systematic record of water level and flow data that can be relied on for the direct estimate of ice-affected discharge and water level within the study reach. The other gauges listed in **Table 8** provide limited supporting information that may be used to inform the interpretation of the record at 07HA001 or to help determine the relative timing of break up between the Peace River and Smoky River.

Table 8 List of Hydrometric Gauges

Type	WSC Station No.	Station Name	Period of Record
Discharge	07HA001	Peace River at Peace River	1915-1930, 1958-present
	07FD003	Peace River at Dunvegan Bridge	1960-1969, 1975-present
	07GJ001	Smoky River at Watino	1915-1922, 1955-present
	07HA003	Heart River near Nampa	1963-present
Water Level	07FD901	Peace River above Smoky River Confluence	2000-present

4 HYDRAULIC MODEL ENHANCEMENT

4.1 HEC-RAS Program & Model

The U.S. Army Corps of Engineers computer program "HEC-RAS River Analysis Program" (Version 5.0.3, September 2016) was used to calculate the ice jam thickness and water surface profiles along the study reach. The basic inputs required by the enhanced ice model include those required by the HEC-RAS open water model (i.e. river cross sections along known lengths of channel, roughness coefficients for the channel and overbank areas at each cross section, a specified or computed water level at the downstream model boundary, and a discharge at all upstream model boundaries). In addition to these basic inputs, the enhanced model requires at each model cross section: a prescribed ice cover condition; under ice roughness; and a set of ice jam parameters characterizing the properties of the ice jam. These ice enhanced model inputs are used to solve for the under ice hydraulics and ice jam stability relationship.

The HEC-RAS model allows the user to specify the ice cover condition as an option within the HEC-RAS cross section data editor. If no information is provided for the ice cover, then an open water condition is presumed. If the user assigns a value to the ice cover thickness, then the model assumes an ice cover condition. When an ice cover condition is defined, the user must provide the following:

- Ice cover thickness in left overbank, main channel, and right overbank.
- Ice cover roughness values for the left overbank, main channel, and right overbank.
- Ice cover specific gravity.
- Ice cover condition (*known* geometry or *wide-river* ice jam).
- If ice cover condition is set to *wide-river* ice jam; ice jam strength parameters (internal friction, ice jam porosity, stress ratio constants, maximum under ice velocity).
- Option to use a fixed or variable ice cover roughness.

Additional detail on these parameters and how the model was enhanced for an ice covered conditions is provided in the following sections.

4.2 Enhancement Methodology

Beginning with the calibrated open water model, the following steps were undertaken to develop the ice enhanced model.

1. Adjust and refine the open water geometry for improved performance of the ice jam thickness profile computations.
2. Define ice-specific model parameters.
3. Calibrate the model to observed recorded high water and ice levels by adjusting under ice roughness.

4.2.1 Geometry Improvements

Interpolated cross sections: The first geometry improvement was to add interpolated cross sections to decrease cross section spacing for improved model computations. Ice jam modelling experience by the author and other investigators (Beltaos 2013; Flato and Gerard 1986) suggest that the ice jam solution algorithm requires a maximum cross section spacing near ¼ channel width to adequately resolve the computed ice jam thickness profile. Further, the model performs best when cross section spacing is regular and any changes are gradual.

For purposes of developing the ice enhanced model, the average width for the Peace River study reach was taken as 400 m. This width was based on the portion of the channel that was considered to be representative of the width used by the ice jam stability relationships (described in a subsequent section). The average cross section spacing for the ice enhanced model was then set to 100 m (for comparison, the open water model cross section spacing was about 1000 m).

The HEC-RAS model offers a convenient and powerful cross section interpolation tool. The user simply assigns the spacing for interpolated cross sections, and the model synthesizes model cross sections at the prescribed spacing based on the existing neighbouring model cross sections. For this study it was found by trial and error that cross sections developed by the interpolation tool did not adequately represent the main channel width at all of the interpolated cross sections. Therefore, an alternative approach was developed to provide a better representation of channel width at the interpolated cross sections. First, interpolated cross sections were established to achieve on average a single river width spacing (~400 m). For these *400 m sections* the elevation values in the channel banks and overbank areas were based on the DEM and elevations within the main channel were based on the neighbouring channel cross sections. This provided for a better representation of the variation of ice jam width along the river. The interpolation process was somewhat laborious and required manual adjustments at each cross section. A total of 82 cross sections were interpolated in this manner to achieve an average single river width spacing of about 400 m. To achieve ¼ channel width spacing an additional 469 cross sections were created with the automated HEC-RAS cross section interpolation tool. The final step for adjusting cross section geometry was to remove closely spaced cross sections at bridges to reduce computational instabilities at these locations. Model tests found that the presence of bridge structures introduced computational instabilities in the ice thickness computations. The bridges were removed from the ice enhanced model to improve computations. Their removal was assumed to have no discernable affect on the computed fully developed ice jam profiles. Bridges span the main channel (embankments do not encroach on the main channel) and would have no impact on the ice jam width used for computations. The geometry improvements for the ice enhanced model ended with a total of 600 model cross sections: 49 of the original 54 model cross sections; 82 manually interpolated cross sections at ~400 m spacing; and 469 automatically interpolated cross sections at ~100 m spacing.

Main channel widths: The ice jam profile computations were found to be very sensitive to abrupt changes in the channel width. Bank stations were adjusted along the study reach to improve model stability and to provide for a more representative ice jam width. Adjustments were made so that the modelled main channel (portion between left bank and right bank stations) was representative of an average ice jam width along the river and so that changes in the ice jam width were gradual. The main channel was constrained to a single channel alongside islands and banks stations were placed within the constrained channel. This provides a reasonable approximation of field observations on ice jam widths, which are indicated by the presence of longitudinal shear walls. Observed shear wall lines generally follow a smooth pattern with gradual transitions. As ice jams form alongside islands, it is common for the ice to accumulate and shove first down one side of the island and then the other. Bank stations within the open water main channel were necessary to allow for the transition from single channels to island splits and to ensure gradual changes in ice jam widths for model stability.

Bed roughness: The bed roughness across the channel was affected by modifying the bank station locations. Attempts were made to provide channel roughness values across each section that were equivalent to the open water model. This exercise would have required successive iterations of manual roughness adjustments at each of the 600 cross sections. Therefore, it was not feasible to duplicate results computed by the open water model. Since the ice enhanced model is required to simulate ice jam profiles, its performance for this purpose was a priority over its ability to simulate open water profiles.

Nevertheless, significant efforts were undertaken to develop an ice enhanced model that produced comparable results to the open water model. And despite changes in channel geometry and bed roughness introduced by interpolated cross sections and adjustments of bank stations, the ice enhanced model provided a reasonable analogue for open water conditions. As illustrated in **Figure 4**, the open water levels computed by the ice enhanced model were found to agree well with observed water surface elevations for the 1990 open water calibration event. The open water model calibration profile is provided for comparison. For the ice enhanced model, the main channel and overbank roughness values were set to a constant value across each section. Roughness values in the lower half of the study reach, downstream of the bridges at TPR, were set to n_{bed} = 0.024; and upstream of the bridges the bed roughness was set to n_{bed} = 0.022. These values are the same main channel roughness values calibrated for the open water model (see ***Hydraulic Model Creation and Calibration report***).

Ineffective flow areas: In all instances, the locations of ineffective flow areas were situated so as to account for ineffective flows caused by the blockage due to ice following the formation of a large ice jam. Ineffective flow areas are located in four subreaches along the study reach. The first, most upper subreach is along the right bank of the Peace River through the confluence with the Smoky River. The second subreach is along the right bank and through West Peace upstream of the town. The third subreach is along the downtown area on the right bank. The forth subreach is along the left bank just downstream of Bewley Island. The lateral location and top elevation of ineffective flow areas along the flood protection dikes were set coincident with the top of dikes.

Levees: Model levees were located at the geographic location (and corresponding elevation) of the top of dikes along each cross section. For the surveyed cross sections and the manually interpolated sections, the model levee location matched the crest of the dike as represented by the *surveyed* dike crest. However, for the automatically interpolated cross sections, the levee's horizontal location and elevation did not necessarily match the crest of the dike as depicted by the interpolated model cross section profile. For the automatically interpolated cross sections, the cross section profile is based on an interpolation between the upstream and downstream cross section profiles. Consequently, the resulting interpolated cross section profile does not match the actual dyke cross section profile. At these sections the modelled levee's horizontal location and elevation were manually adjusted to reflect the actual geographical location of the dyke crest.

4.2.2 Ice Cover Condition

The HEC-RAS model allows the user to specify the ice cover condition as either, a *"known geometry"* or a "*wide-river"* ice jam. For a known geometry condition, the user prescribes the ice thickness at each cross section along with a corresponding underside ice roughness (denoted in the model as *Ice Cover Manning's n Values)*. The option to compute an (wide-river) ice jam profile is set in the ice cover editor. When this ice jam option is selected, the model requires additional parameters to characterize the strength properties of the ice jam accumulation. Details on the ice specific modelling parameters are provided in the next section.

HEC-RAS uses the following form of the ice jam stability equation (for the so-called wide jam condition) to characterize the strength of the accumulation. It is a force balance equation where the stresses acting on the jam are ultimately transmitted to the channel banks (USACE 2016).

$$\frac{d(\bar{\sigma}_x t)}{dx} + \frac{2\tau_b t}{B} = \rho' g S_w t + \tau_i \qquad [1]$$

Where:

$\bar{\sigma}_x$ = the longitudinal stress (along stream direction)

t = the accumulation thickness

τ_b = the shear resistance of the banks

B = the accumulation width

ρ' = the ice density

g = the acceleration of gravity

S_w = the water surface slope

τ_i = the shear stress applied to the underside of the ice by the flowing water

The ice jam stability equation can be restated in the following form which includes the ice jam parameters required by the model. This equation includes the parameters required as input to the model.

$$\frac{dt}{dx} = \frac{1}{2k_x\gamma_e}\left[\rho' g S_w + \frac{\tau_i}{t}\right]] - \frac{k_o k_1}{B}t \qquad [2]$$

and

Where:

t = the accumulation thickness

k_x = a coefficient describing the ratio of vertical to longitudinal stress

γ_e = the effective unit weight of the accumulation

ρ' = the ice density

g = the acceleration of gravity

S_w = the water surface slope

τ_i = the shear stress applied by the flow to the underside the accumulation

B = the accumulation width

k_o = a coefficient describing the ratio of longitudinal to transverse stress

k_1 = a coefficient describing the ratio of transverse stress to shear at the banks

HEC-RAS uses an iterative approach to compute the ice jam profile thickness and under ice hydraulics. The under ice hydraulics are solved in a manner akin to the standard step method where the solution progresses in the upstream direction, then the ice jam thickness is found by solving the jam force balance equation (progressing in a downstream direction). The process is repeated until the user specified tolerances for changes in computer water levels are achieved or the maximum number of iterations is exceeded.

4.2.3 Heart River

The approached used toward developing the Heart River portion of the ice enhanced model was the same as that used for the Peace River portion (described in the preceding sections), with the exception that interpolated cross sections were not included. Extensive efforts were undertaken to introduce interpolated cross sections so as to achieve an average spacing of about ¼ channel width. Unfortunately, the computed ice jam profiles were not able to reach a fully developed ice jam condition. Consequently, the Heart River portion of the ice enhanced model relied on only the surveyed cross sections. Bridges were also removed from the geometry, following the same rationale as for the Peace River.

4.3 Ice-Specific Model Parameters

To evaluate the formation of a consolidated ice cover, a number of calibration parameters are required. The primary parameters required to solve the jam stability equation are described as follows.

4.3.1 Composite Roughness n_o

The composite ice roughness is the combined bed and ice roughness factor resisting flow under the ice cover. HEC RAS first computes the composite roughness, n_o, following the familiar Sabeneev relationship as follows:

$$n_o = \left(\frac{{n_1}^{3/2} + {n_2}^{3/2}}{2}\right)^{2/3} \qquad [3]$$

where n_1 and n_2 are the bed and bottom of ice roughness values, respectively.

4.3.2 Jam Stability Parameters

The jam stability parameters required as input to the HEC RAS model to solve Equation [2] include: the internal friction angle of the jam, ϕ; the ice jam porosity (fraction of voids between ice floes), p; and the coefficient of lateral to longitudinal stress in the jam, k_1. All other parameters are solved internally by the model. Ice jam strength properties can not be measured directly in the field and consequently they are not reported for observed events. However, for an idealized *equilibrium* thickness condition, the suite of jam stability parameters can be lumped into a single *jam stability* parameter, commonly denoted as μ. On rare occasions values for the jam stability parameter are reported. These values are deduced by assuming an equilibrium jam condition, ice jam width, and hydraulic properties. Pariset et al. (1966) first introduced this parameter and expressed it as:

$$\mu = k_1 k_x \tan\phi \qquad [4]$$

Beltaos (1978) deduced that the equilibrium jam stability relationships presented by Uzner and Kennedy (1976) could be made equivalent to those of Pariset et al. (1966) by expressing the jam stability parameter as:

$$\mu = \tan\phi\,(1-p) \qquad [5]$$

Then, Flato and Gerard (1986), following the work of Uzner and Kennedy (1976), presented a the following definition of the jam stability parameter,

$$\mu = k_v k_{xy} \tan\phi(1-p) \qquad [6]$$

Equivalence between these relationships is found when k_x/k_v=1 and $k_v k_{xy}$=1 (Healy and Hicks 1997). With these assumptions it was possible to estimate the required input parameters ϕ and k_1, given the more familiar jam stability parameters μ and p.

Ice Jam Porosity: Ice jam porosity represents the volume fraction of the interstitial spaces in the ice accumulation. It is assumed to be the same above and below the water surface. A value of p = 0.4 is commonly used for ice jams and has been used by other investigators for this study reach (NHC 2006). This value was used for the ice enhanced model.

Jam Stability Parameter: Previous investigators have estimated μ to be in the range of 0.8 to 2.0 for the Peace River at TPR, with the larger values being associated with smaller ice jams (Andres 1996). A value of 0.93 was estimated by Neil (1984) for the large 1982 ice jam and this value was adopted value for this study.

Internal Friction and Coefficient of Lateral to Longitudinal Stress: The internal friction and stress coefficient were found by substitution of the adopted values for p = 0.4 and μ = 0.93 into equations [4] through [6] resulting in adopted values of ϕ = 57.17° and k_1 = 0.0868.

4.4 Model Calibration

The model calibration was based on the comparison of the computed ice jam flood level profiles to the recorded ice jam flood level profiles. Computed ice-affected rating curve data was then checked against observations at the WSC gauge (07AH001). Recorded ice jam profile data was found for the following four events. These observational data provided the basis for the calibration of composite ice jam roughness. Descriptions on these calibration events are provided in the following section which summarizes the results of the calibration.

- 1979 Breakup Jam

- 1982 Freeze-up Jam
- 1992 Freeze-up Jam
- 1997 Breakup Jam

4.4.1 Ice Jam Boundary Conditions

For calibration, a fully developed ice jam profile was prescribed between the downstream boundary and upstream boundary by specifying a *wide-river* ice jam condition between these boundaries. Fixed thickness values at the boundaries are required inputs to the model. For all calibration profiles the thickness at the upstream boundary was set to 1.0 m. An initial ice thickness is required by the model at every cross section and this thickness also prescribes the minimum allowable thickness at each section. To achieve a realistic thickness profile the user must prescribe initial values that are below the fully developed ice thickness values. A initial thickness of 1 m was chosen to ensure that initial values were not set to values larger than the fully developed ice thickness values; thus, ensuring the computed thickness profile was not artificially constrained by the initial thickness. However, in the furthest upstream limits of the study reach, the computed thickness profile are forced to gradually reduce down to the prescribed initial value of 1 m at the head (upstream boundary). Therefore, for some distance downstream of the upstream boundary, the computed ice thickness profile is somewhat thinner than a fully developed profile. This results in a slight under prediction in the water levels in the most upper reach. These effects did not extend downstream into reaches where recorded ice jam level data was available and thus, the calibration results were not sensitive to the adopted upstream boundary thickness.

Model tests found that the computed ice jam profiles were somewhat sensitive to the downstream boundary thickness. Downstream ice thickness values that under-predicted the thickness at the downstream boundary would tend to steepen the profile in the lower reach resulting in over-predicted (thicker) ice thickness values and under-predicted (lower) water levels. Values that over predicted the ice thickness would create a local backwater effect resulting in under-predicted (thinner) ice thickness values and over-predicted (higher) water levels. To limit the effects of the choice of the toe thickness on the computed ice jam profiles in the downstream reach, the fully developed ice jam thickness was approximated by an equilibrium thickness value. The equilibrium thickness values were based on: the assumed bed slope for the open water normal depth boundary condition (0.00025); the adopted ice jam stability parameters (as defined in a previous section); ice jam width and discharge for each flow condition. By this approach, the choice on downstream boundary ice thickness had a negligible effect on the computed fully developed ice jam profiles near the downstream boundary and did not extend into reaches where recorded ice jam level data was available.

4.4.2 Composite Ice Jam Roughness

As is the case for open water model calibration, with all other hydraulic parameters and boundary conditions set, roughness remains the sole calibration parameter. For the ice enhanced model calibrations, the composite ice jam roughness values are reported. The composite ice jam roughness represents the combined roughness effects due to the bed and ice as represented in **Equation 3**. For each ice jam profile calculation, the bed roughness was kept constant and the under ice roughness values were adjusted, according to Equation 3, to test a range of composite roughness values, n_o = 0.025 to n_o = 0.050 at 0.005 increments. This range is consistent with values reported by previous investigators (e.g. Neil 1984).

4.4.3 Calibration Approach

In the early stages of model calibration efforts it was determined that it was not technically feasible to develop a single *calibrated* ice jam ice profile for each ice jam calibration event. Initial comparisons between observed and computed profiles affirmed our notion that the recorded ice jam profiles were not representative of a fully developed ice jam corresponding to a single, unique set of hydro-meteorological conditions. Also, the data suggested that the recorded ice jam water levels reflected different evolutionary stages of the ice jam event (corresponding to different formative discharges and possibly roughness values). Since application of the model is limited to a steady state fully developed condition, an alternative to the usual approach for calibration was needed.

The alternative approach was to first develop a suite of ice jam profiles corresponding to a range of roughness and discharge values. Fully developed ice jam profiles were developed for 47 different discharge values (ranging from 400 to 5500 m^3/s) and 8 different composite roughness values (ranging from 0.025 to 0.050). family of 376 ice jam profiles. Data computed by these profiles was also used to create ice-affected rating curves at the WSC gauge that were needed to support the ice jam flood frequency analysis (described in a subsequent section).

Next, the computed ice jam profiles were plotted along with the observed ice jam profiles. Profiles were then selected from the suite of ice jam profiles that best matched the observed data and reported range of discharge and roughness values.

4.5 Calibration Results

4.5.1 The 1979 Breakup Jam

During the 1979 breakup event, a breakup jam on the Smoky River (near the mouth) released and entered the Peace River. When this ice released, it sent a 15-foot high flood wave downstream through TPR, with water levels coming within 0.3 m of the top of dike level (Davies et al. 1981 cited in NHC 1982). The run of ice came to rest downstream of TPR to form another breakup jam. This second breakup jam was surveyed by the Alberta Research Council downstream on 30 Apr 1979. Early accounts of this event reported a discharge estimate of about 4110 m^3/s, however, this value was since refined and revised to the current estimate of 2670 m^3/s. A summary of the reported discharge values and their sources are provided in **Table 9**.

Table 9 Range of Reported Discharges for the 1979 Breakup Event

Breakup Date at TPR	Breakup Date at Watino	Breakup Discharge (m^3/s)	Peak Breakup Level[1] (m)	Data Source
30-Apr		4110	318.6	NHC (1982)
30-Apr		4110	318.61	Fonstad (1982)
30-Apr		4110	318.61	Fonstad and Garner (1984)
30-Apr		4110	318.61	H Biberhofer Consulting (1984)
30-Apr	26-Apr	2670	318.75	Trillium et al. (1996)
30-Apr	26-Apr	2670	318.75	Trillium and NHC (2002)

1. Peak breakup level at the WSC gauge.

Figure 5 presents a comparison between the computed and recorded ice jam profiles for the 1979 breakup ice jam event. The peak water level reported for the WSC gauge is also provided for comparison. The computed profiles correspond to the discharges of 2760 m^3/s and 4110 m^3/s that were reported by previous investigators and a composite ice jam roughness value of $n_o = 0.045$. The recorded maximum water levels in the downstream reach suggest the downstream end of the ice jam (or toe) was located somewhere between the model channel distances of 5000 m and 7000 m (just upstream of the Hwy 986 Bridge). The computed ice jam profile corresponding to a discharge of 4100 m^3/s agrees well with the recorded maximum water levels upstream of the toe, but over estimates the peak breakup level recorded at the gauge (318.75 m) by 2 m. It is likely that a fully developed ice jam associated with a discharge of 4110 m^3/s did not extend all of the way up to the gauge. Previous investigators estimated that the discharge associated with the peak gauge level was 2670 m^3/s. The computed ice jam profile associated with a discharge of 2760 m^3/s computes a water level of 318.62 m which agrees very well with the reported peak breakup level.

The results of the calibration for the 1979 breakup jam suggest that a composite ice jam Manning's roughness value of $n_o = 0.045$ provides a good representation of the roughness associated with the 1979 breakup ice jam.

4.5.2 The 1982 Freeze-up Jam (Secondary Consolidation)

Relatively warm weather in December combined with relatively high releases from Bennett Dam delayed freeze-up at the Town of Peace River until 2 January. Discharges from upstream were reduced by approximately half as an ice cover comprised of frazil pans formed near Dunvegan. Then, discharges were raised again over the following several days (NHC 1982). On 7 January the ice cover, which had since progressed upstream of Dunvegan, consolidated into a large accumulation – the consolidation was considered to be caused by a perturbation in flows due to fluctuations in releases from Bennet Dam (Trillium 1996). The consolidation of ice resulted in the formation of an ice jam about 20 km downstream of Dunvegan which was some 9 m high. This ice jam released and the release of ice then drove downstream towards TPR, breaking up the existing ice cover. The release of ice reached TPR at 22:30 and formed a large secondary consolidation ice jam that extended through the town, raising water levels rose by up to 3.5 m.

A chart of the flood level hydrograph recorded at the WSC gauge is plotted in **Figure 6**. As the initial cover formed on 2 Jan, water levels rose by 2.6 m; some 6 days later on 8 Jan, the cover destabilized and reconsolidated into a larger ice jam. During the formation of this secondary consolidation the water levels rose an additional 3.5 m.

Although the dikes were not overtopped, subsurface seepage led to local basement flooding in the town. The toe of the jam was located about 10 km downstream of TPR, and 12 hours after the peak the head of the ice cover was 40 km upstream of TPR (Neill and Andres 1984).

Estimates on the discharge associated with this event vary. Neill et al (1984) reported a discharge of 2000 to 2100 m^3/s and a corresponding ice jam composite Manning's roughness of n = 0.043. Andres (1996) reported an estimated composite Manning's roughness of n = 0.028 based on hydraulic parameters corresponding to ice and flow conditions several days after the event occurred. The most recent and comprehensive analysis published for this event is presented by Andres (1995). By this account the formative discharge for the ice jam was about 1700 m^3/s, the average ice jam thickness was 4.3 m and a peak surge of roughly 2800 m^3/s may have been experience at the time of the event. A summary the available information reported for this event is provided in **Table 10.**

Table 10 Range of Reported Discharge and Water Levels at TPR WSC Gauge for the 1982 Secondary Consolidation Event

Freeze-up Date	Freeze-up Discharge (m^3/s)	Pre-Freeze-up Level (m)	Base Freeze-up Level (m)	Peak Freeze-up Level (m)	Peak Freeze-up Level Date	Data Source
	1700 / 2600[1]			318.15	08-Jan	NHC (1982)
02-Jan	1900 – 1977	312.17		314.8		H Biberhofer Consulting (1984)
	1700 – 2800					Neill and Andres (1984)
02-Jan	1400 – 2800			314.2		Andres (1995)
01-Jan	1760	311.71	314.8	318.13	08-Jan	Trillium et al. (1996)
01-Jan	1760			318.13		Trillium and NHC (2002)

Notes:

1. Estimated ice jam release flood wave of 2600 m^3/s.

Figure 7 presents a comparison between the computed and recorded ice jam profiles for the 1982 freeze-up ice jam event for a composite roughness values of n_o=0.030. The reported peak freeze-up water level at the WSC gauge is provided for comparison. For a discharge of 2800 m^3/s, the computed profile agrees well with the recorded maximum water levels observed upstream of channel distance 27,000 m. The computed profile under-predicts the maximum water levels observed near TPR by about 1.3 m. It is plausible that the peak discharge associated with the ice-affected water levels near TPR were associated with a higher discharge. Using the same roughness value, n_o=0.030, the computed profile associated with and a discharge of 3800 m^3/s was found to provide a good representation of the recorded maximum water levels through town. It is very plausible that portions of the ice jam, as represented by the recorded maximum water levels, were formed under a discharge as high 3800 m^3/s.

The results of the calibration suggest that a composite ice jam Manning's roughness value of n_o = 0.030 provides a good representation of the roughness associated with the 1982 freeze-up jam (secondary consolidation).

4.5.3 The 1992 Freeze-up Jam (Secondary Consolidation)

The winter of 1991/1992 was very mild in the Peace River Region resulting in a late freeze-up at TPR, which eventually occurred on the night of February 11/12 (Fonstad 1992). Water levels increased by 4.7 m, which at the time was the highest freeze-up level increase on record. Releases from the dam (1,830 m^3/s) were the highest reported during freeze-up since the completion of the dam. The discharge downstream at the Dunvegan gauge were estimated to be between 2180 m^3/s and 2210 m^3/s.

On February 24 the daily air temperatures rose above 0˚C and remained warm for several days (Trillium, 1996). The warm temperatures weakened the ice cover, and the sustained high flows from Peace Canyon Dam combined with minor amounts of local runoff due to warm weather contributed to the formation of a large consolidation upstream of TPR on February 27. The resultant surge of water and ice was noticed about 25 km upstream of town between 21:45 and 22:35 (Trillium 1996). The surge arrived at TPR on February 28 at 6:00 and water levels rose to elevation 319.9 m at 8:15. The secondary consolidation resulted in an ice jam extending some 31 km from about 5 km downstream of the Daishowa Mill to about 9 km upstream of the Highway 2 bridge (Alberta Transportation 1992). The ice jam caused water levels in the Peace River to overtop the dikes at some locations, and the town declared a state of emergency, evacuating about 4000 people. By March 12 the ice front had retreated and the water levels had returned to normal.

Since there were no measurements taken of the ice thickness before or after consolidation, it is difficult to estimate the volume, roughness, or peak discharge associated with the event (Trillium 1996). The surge release was approximated at 400 m^3/s; this surge combined with reported flows at Dunvegan suggest the discharge associated with the formation of the jam was around 2600 m^3/s. A summary of reported water levels values for this event are shown in **Table 11.**

Table 11 Range of Reported Water Levels for the 1992 Freeze-up Event

Freeze-up Date	Freeze-up Discharge (m^3/s)	Pre-Freeze-up Level (m)	Base Freeze-up Level (m)	Peak Freeze-up Level (m) Before and After Secondary Consolidation		Peak Freeze-up Level Date	Data Source
				Before	After		
11-Feb		311.84		316.78	319.78		Fonstad (1992)
11-Feb	1980	312.3	317		319.9	28-Feb	Trillium (1996)
11-Feb	1960	312.29	316.82[1]	316.95		15-Feb	Andres (1996)

Notes:

1. Base freeze-up level denoted as an *average freeze-up* level in the report.

The available recorded data included elevations on ice level and maximum ice level, and this additional information provided insight on the extent of the ice jam profile, prior to the date on which observations were recorded. By inspection of the recorded data, it appears as though the recorded values near TPR and downstream are associated with a fully developed ice jam profile that was in place on the date of observations. Upstream of TPR, the water level data is relatively flat and appears to represent a backwater from the upper limits of the fully developed ice jam between the Smoky River and TRP. The recorded and maximum ice levels upstream of the Smoky River appear to represent remnant high water levels associated with the ice jam as it evolved (prior to the date of recorded observations).

Figure 8 provides a comparison between the computed and recorded ice jam profiles for the 1992 freeze-up ice jam event for composite roughness values of n_o = 0.030. This roughness value is considered to be representative of the composite roughness during the freeze-up period. The fully developed ice jam profile corresponding to the reported peak discharge of 2600 m^3/s under-predicts the recorded observations in the vicinity of TPR and downstream by nearly 3 m. If the composite roughness was indeed n_o = 0.030, then the discharge associated with formation of the jam would have been as high as 5500 m^3/s. The profile for a discharge of 5500 m^3/s is provided for comparison. Previous investigators (Assaf et. al. 1995) suggested that the reported peak discharges underestimates the actual discharge and offer the following scenario for the 1992 ice jam event: …"*the initial breakup of the ice cover, was partly caused by the early rapid rise of the discharge between February 26 and 27… persistently high discharges rapidly built up the head behind the initial jam, and led eventually to its release and the creation of a surge that further broke up the ice cover downstream."* Given that a very large surge wave could have been associated with the recorded ice jam profile, a formative discharge of 5500 m^3/s may be plausible.

The results of the calibration efforts on the 1992 freeze-up jam are not conclusive. It is difficult to offer a calibrated composite ice jam Manning's roughness value for the 1992 ice jam event, owing to the uncertainty on the formative discharge. However, it is possible that the reported peak discharges significantly underestimate the actual formative discharge and thus a composite ice jam Manning's roughness value of n_o = 0.030 may in fact be a good representation of the roughness associated with the 1992 freeze-up jam (secondary consolidation).

4.5.4 The 1997 Breakup Jam

During the spring of 1997 unusually high snow packs and rapid snowmelt contributed to the development of a large breakup jam forming at TPR. Backwater created by the jam also led to high water levels on the Heart River. Flood levels remained below the top of dike elevations along town except at the openings to the 101st Street Bridge. During the flood event, water passed through the openings at the bridge and flooded the town on 19 April 1997. The bridge has since been upgraded to prevent flood waters entering at this location.

Reported discharge and water levels for this event are listed in **Table 12**.

Table 12 Reported Values for the 1997 Breakup Event

Breakup Date at TPR	Breakup Date at Watino	Breakup Discharge (m^3/s)	Peak Breakup Level (m)	Data Source
19-Apr	19-Apr	3600	319.95	Trillium and NHC (2002)

Figure 9 presents a comparison between the computed and recorded ice jam profiles for the 1997 breakup ice jam event. The peak water level reported for the WSC gauge is also provided for comparison. The computed profile corresponds to the peak reported discharge of 3600 m^3/s a composite ice jam roughness value of $n_o = 0.045$. The recorded maximum water levels in the downstream reach suggest the downstream end of the ice jam (or toe) was located somewhere downstream of the WSC gauge between the model channel distances of 15000 m and 18000 m. The computed ice jam profile agrees well with the recorded maximum later levels upstream of the toe through TPR, but over estimates the recorded water level by about 2.5 m further upstream, near channel distance 37000 m, because a jam did not fully develop in this reach. The data in TPR and at the gauge agree very well with the recorded values. The computed ice jam level at the gauge (319.75 m) is slightly below (0.20 m) the maximum level recorded at the WSC gauge (319.95 m).

The results of the calibration for the 1997 breakup jam suggest that a composite ice jam Manning's roughness value of $n_o = 0.045$ provides a good representation of the roughness associated with the 1997 breakup ice jam.

4.5.5 WSC Gauge 07AH001 Peace River at Peace River

Figure 10 presents a comparison between the computed ice jam rating curves for composite ice jam Manning's roughness values of $n_o = 0.030$ and $n_o = 0.045$. The curve associated with $n_o = 0.045$ agrees well with the historic reported peak ice jam water levels recorded at the gauge. The curve associated with $n_o = 0.030$ passes through the peak freeze-up levels for the 1982 and 1992 calibration events (where the reported discharge values were increased as part of the model calibration). The base freeze-up levels for all recorded years are plotted for comparison. As would be expected, these data scatter around the freeze-up ice jam rating curve. The scatter is mainly due to uncertainty in discharge estimates associated with the base freeze-up level; and, the fact that freeze-up conditions at the gauge are not always associated with a fully developed freeze-up jam condition. The wide-channel jam formulation would not apply under different ice cover conditions such as: a partial jam, a juxtaposed cover, or a hydraulically thickened cover. The open water rating curve is provided for comparison and corresponds to WSC's *Stage-Discharge Table No 11, 7-Nov-06*.

4.5.6 Calibration Results Summary

The following summarizes the results of the ice enhanced model calibration.

- The calibrated ice jam profiles capture the general shape and profile of the recorded ice jam profile data.
- The calibrated ice jam roughness value of n_o = 0.045 is representative of breakup ice jams.
- The calibrated ice jam roughness value of n_o = 0.030 is representative of freeze-up ice jams.
- Based on the results of the calibration, there is no discernable variation in ice jam roughness along the study reach. The calibrated ice jam roughness values are considered to be applicable over the full length of the study reach.

5 ICE JAM FLOOD MODELLING ASSESSMENT

5.1 Ice Jam Flood Frequency Analysis

5.1.1 Background on the Approach

Flood frequency values are most familiarly expressed in terms of discharge. And in the common application to a flood hazard study, the discharge is used as the primary input variable for computing flood levels of varying recurrence intervals. Under open water conditions, it is possible to ascribe a unique flood level to each flood frequency discharge. However, for an ice jam flood condition, there are a range of flood levels that could be associated with a single discharge because the flood level magnitude resulting from an ice jam depends on factors other than discharge – for example: ice thickness and under ice roughness. For ice jam flood frequency analysis, a more meaningful approach is to associate the flood frequency with ice jam flood levels. While the approaches are slightly different for the open water and ice jam analysis, the resulting flood frequency are considered technically equivalent. **Tables 13** and **14** provide a list of ice-affected water level data for WSC gauge 07AH001 Peace River at Peace River, summarizing the freeze-up and breakup periods, respectively.

The ice jam flood level frequency relationships presented in this study are based on historic ice jam water level observations collected after regulation. It was not possible to develop ice jam flood frequency relationship for the so-called *naturalized* ice jam condition because of a dearth of pre-regulation data. Two approaches were used to estimate the ice-related peak water level frequency curves: peak ice-affected flood level frequency analysis; and Monte Carlo analysis.

Simple Peak Flood Level Frequency Analysis: An intuitive and simple approach is to review the historical record on a year by year basis to identify freeze-up and breakup water levels, and then undertake a simple frequency analysis of the peak freeze-up, breakup, and annual ice-affected levels. Major problems associated with this approach are: changes in dam operations make some of the severe events that have been experienced in the past, less likely to occur in the future; and past freeze-up levels are not necessarily representative of recent and future levels due to operational controls during freeze-up. Some of the largest ice jam flood levels are attributed to the freeze-up period (e.g. 1981-82, 1991-92, and 2004-05), and flow controls would have a notable effect on the severity of these types of events. It is most likely that any biasing would impact the analysis of freeze-up jams more so than breakup jams. Due to these considerations, an alternative approach was developed.

Monte Carlo Frequency Analysis: Another approach is to use a Monte Carlo analysis. This procedure uses statistical methods to quantify the causative factors that contribute to the characteristics of a whole set of data rather than individual events. The approach is attractive because it can include potential changes in operations when defining the effects of current practice on ice-related water levels. Data from individual events are not addressed explicitly, rather the data are aggregated and used to represent statistical distributions of the independent variables (input distributions) which are then transformed into statistical distributions of dependent variables (output distributions). Watt (1989) provides a clear overview on the use of Monte Carlo analysis for joint frequency applications for use in flood hydrology.

The Monte Carlo frequency analysis was adopted for this study. The next section describes the methodology and results of the analysis.

Table 13 Freeze-up Summary Data – WSC Gauge 07AH001 Peace River at Peace River

Season	Freeze-up Date	Freeze-up Discharge (m^3/s)	Pre-Freeze-up Level (m)	Base Freeze-up Level (m)	Peak Freeze-up Level (m)	Peak Freeze-up Level Date	Data Source
1969 – 1970	26-Nov	940	311.42	312.41	312.41	28-Nov	NHC (2006)
1970 – 1971	24-Nov	910	311.43	312.22	312.41	4-Dec	NHC (2006)
1971 – 1972	13-Dec	970	311.64	312.75	313.21	17-Dec	NHC (2006)
1972 – 1973	22-Dec	1550	311.87	314.61	314.61	23-Dec	NHC (2006)
1973 – 1974	7-Dec	1390	311.73	314.17	314.17	9-Dec	NHC (2006)
1974 – 1975	12-Jan	1530	311.77	315.29	315.29	24-Jan	NHC (2006)
1975 – 1976	11-Dec	1170	311.73	314.65	315.91	17-Dec	NHC (2006)
1976 – 1977	13-Jan	1640	311.96	314.91	314.91	14-Jan	NHC (2006)
1977 – 1978	6-Dec	1840	312.07	314.01	315.18	19-Dec	NHC (2006)
1978 – 1979	30-Dec	1590	311.98	314.66	315.00	11-Jan	NHC (2006)
1979 – 1980	22-Dec	630	311.19	312.97	313.4	31-Dec	NHC (2006)
1980 – 1981	8-Dec	1320	311.33	314.18	314.21	10-Dec	NHC (2006)
1981 – 1982	1-Jan	1760	311.71	314.8	318.13	8-Jan	NHC (2006)
1982 – 1983	4-Jan	1470	312.08	315.37	315.37	5-Jan	NHC (2006)
1983 – 1984	16-Dec	1540	311.93	314.68	314.68	18-Dec	NHC (2006)
1984 – 1985	20-Dec	1580	312.02	315.5	315.91	22-Dec	NHC (2006)
1985 – 1986	3-Dec	1870	312.14	315.09	315.12	12-Dec	NHC (2006)
1986 – 1987	16-Jan	1500	311.83	315.58	315.76	25-Jan	NHC (2006)
1987 – 1988	31-Jan	1970	311.99	314.84	314.84	1-Feb	NHC (2006)
1988 – 1989	1-Jan	990	311.28	314.7	315.76	5-Jan	NHC (2006)
1989 – 1990	21-Dec	1310	311.42	313.77	313.77	23-Dec	NHC (2006)
1990 – 1991	20-Dec	1750	311.84	314.33	314.71	24-Dec	NHC (2006)
1991 – 1992	11-Feb	1980	312.30	317.00	319.90	28-Feb	NHC (2006)
1992 – 1993	29-Dec	1750	311.89	314.17	314.46	2-Jan	NHC (2006)
1993 – 1994	12-Jan	1740	311.90	315.27	315.27	15-Jan	NHC (2006)
1994 – 1995	7-Jan	1880	311.97	315.96	315.96	7-Jan	NHC (2006)
1995 – 1996	11-Dec	1770	311.83	315.5	315.5	11-Dec	NHC (2006)
1996 – 1997	22-Dec	1550	312.03	314.95	314.95	22-Dec	NHC (2006)

Table 13 Freeze-up Summary Data – WSC Gauge 07AH001 Peace River at Peace River (continued)

Season	Freeze-up Date	Freeze-up Discharge (m^3/s)	Pre-Freeze-up Level (m)	Base Freeze-up Level (m)	Peak Freeze-up Level (m)	Peak Freeze-up Level Date	Data Source
1997 – 1998	13-Jan	1600	311.9	314.23	314.84	18-Jan	NHC (2006)
1998 – 1999	6-Jan	1470	311.93	313.91	313.91	6-Jan	NHC (2006)
1999 – 2000	15-Jan	1480	311.82	313.79	315.62	16-Jan	NHC (2006)
2000 – 2001	10-Feb	1540	311.69	315.05	315.23	14-Feb	NHC (2006)
2001 – 2002	21-Jan	1600	312.28	315.29	315.35	20-Jan	NHC (2006)
2002 – 2003	27-Jan	1610	311.93	315.26	315.46	28-Jan	NHC (2006)
2003 – 2004	10-Jan	1620	311.82	314.79	315.30	14-Jan	NHC (2006)
2004 – 2005	3-Jan	1790	311.88	315.71	316.84	7-Jan	NHC (2006)
2005 – 2006	27-Feb	1450	311.93	314.21	314.46	27-Feb	WSC
2006 – 2007	12-Jan	1700	311.99	314.70	315.25	12-Jan	WSC, AEP
2007 – 2008	8-Jan	1850	312.12	316.31	316.63	15-Jan	WSC
2008 – 2009	27-Dec	1590	311.84	314.81	315.58	27-Dec	WSC, AEP
2009 – 2010	31-Dec	1680	312.48	314.77	315.19	1-Jan	WSC
2010 – 2011	25-Dec	1670	312.03	314.67	315.15	29-Dec	WSC
2011 – 2012	11-Feb	1920	311.99	315.5	316.19	13-Feb	WSC, AEP
2012 – 2013	12-Dec	1540	311.63	315.25	315.82	12-Dec	WSC, AEP
2013 – 2014	29-Dec	1620	311.97	315.37	315.62	30-Dec	WSC, AEP
2014 – 2015	26-Dec	1620	311.99	314.66	314.85	26-Dec	WSC

Notes: WSC indicates data obtained from Water Survey Canada historic water level data.
AEP indicates data obtained from Alberta Environment and Parks Ice Observation Reports.

Table 14 Breakup Summary Data – WSC Gauge 07AH001 Peace River at Peace River

Season	Breakup Date	Breakup Discharge (m^3/s)	Peak Breakup Level (m)	Breakup Type	Breakup Type Source	Data Source
1970 – 1971	19-Apr	1460	313.07	*Thermal*		NHC (2002)
1971 – 1972	20-Apr	1190	314.92	*Mechanical*		NHC (2002)
1972 – 1973	12-Apr	2360	318.19	Ice Jam	Fonstad (1992)	NHC (2002)
1973 – 1974	20-Apr	2100	317.52	Ice Jam	Fonstad (1992)	NHC (2002)
1974 – 1975	17-Apr	2250	314.53	Thermal	BC Hydro (1975)	NHC (2002)
1975 – 1976	11-Apr	1910	314.48	Thermal	Szabon (1977)	NHC (2002)
1976 – 1977	23-Mar	1390	313.60	*Thermal*		NHC (2002)
1977 – 1978	15-Apr	1290	313.51	*Mechanical*		NHC (2002)
1978 – 1979	30-Apr	2670	318.75	Ice Jam	Trillium (1996); Fonstad (1992)	NHC (2002)
1979 – 1980	18-Apr	660	313.34	*Mechanical*		NHC (2002)
1980 – 1981	5-Apr	2420	314.20	*Mechanical*		NHC (2002)
1981 – 1982	26-Apr	1900	315.63	Thermal	Trillium (1996)	NHC (2002)
1982 – 1983	24-Apr	800	313.75	Thermal	Fonstad and Garner (1984)	NHC (2002)
1983 – 1984	13-Apr	840	313.30	Thermal	Fonstad and Garner (1986)	NHC (2002)
1984 – 1985	13-Apr	2470	314.80	Thermal	Fonstad and Quazi (1986)	NHC (2002)
1985 – 1986	17-Apr	1930	314.08	*Mechanical*		NHC (2002)
1986 – 1987	5-Apr	2770	315.45	*Thermal*		NHC (2002)
1987 – 1988	12-Mar	2090	314.77	*Thermal*		NHC (2002)
1988 – 1989	23-Apr	1200	314.05	*Mechanical*		NHC (2002)
1989 – 1990	5-Apr	1600	314.45	*Thermal*		NHC (2002)
1990 – 1991	17-Apr	1620	313.83	*Mechanical*		NHC (2002)
1991 – 1992	13-Mar	2230	315.63	Ice Jam	Fonstad (1992)	NHC (2002)
1992 – 1993	28-Mar	1890	313.41	*Thermal*		NHC (2002)
1993 – 1994	10-Apr	1860	315.42	*Mechanical*		NHC (2002)
1994 – 1995	19-Apr	1790	314.70	*Mechanical*		NHC (2002)
1995 – 1996	19-Apr	2570	316.26	*Mechanical*		NHC (2002)
1996 – 1997	19-Apr	3610	319.95	Ice Jam		NHC (2002)

Table 14 Breakup Summary Data – WSC Gauge 07AH001 Peace River at Peace River (continued)

Season	Breakup Date	Breakup Discharge (m^3/s)	Peak Breakup Level (m)	Breakup Type	Breakup Type Source	Data Source
1997 – 1998	26-Mar	2360	313.92	*Mechanical*		NHC (2002)
1998 – 1999	31-Mar	2590	313.70	Thermal	Hicks et al. (2000)	NHC (2002)
1999 – 2000	1-Apr	1260	313.56	*Thermal*		WSC
2000 – 2001	3-Apr	1070	313.53	*Thermal*		WSC
2001 – 2002	22-Apr	1550	313.23	*Thermal*		WSC
2002 – 2003	13-Apr	1710	314.45	*Thermal*		WSC
2003 – 2004	4-Apr	1460	313.71	*Thermal*		WSC
2004 – 2005	3-Apr	1980	315.43	Thermal	Friesenhan (2005)	WSC, AEP
2005 – 2006	4-Apr	1280	314.03	Thermal	Friesenhan (2006)	WSC, AEP
2006 – 2007	21-Apr	2500	314.48	Ice Run	Friesenhan (2007)	WSC, AEP
2007 – 2008	30-Mar	1770	315.38	*Thermal*		WSC
2008 – 2009	15-Apr	2230	314.68	Thermal	Trevor (2009)	WSC
2009 – 2010	22-Mar	1420	313.46	Thermal	Trevor (2010)	WSC
2010 – 2011	20-Apr	1910	312.99	*Thermal*		WSC
2011 – 2012	19-Mar	1750	314.08	Thermal	Kovachis and Trevor (2012)	WSC, AEP
2012 – 2013	14-Apr	1240	313.71	Thermal	Kovachis (2013)	WSC
2013 – 2014	22-Apr	2160	314.36	Ice Jam	Kovachis (2014)	WSC, AEP
2014 – 2015	28-Mar	1420	314.02	Thermal	Emmer and Kovachis (2015)	WSC, AEP

Notes: WSC indicates data obtained from Water Survey Canada Historic water level data.
AEP indicates data obtained from Alberta Environment and Parks Ice Observation Reports.
Breakup types denoted by grey italic text were deduced from reported ice affected gauge data at Peace and Smoky River.

5.1.2 Monte Carlo Frequency Analysis

The first step of the analysis was to develop flood level frequency relationships for the freeze-up and breakup condition and then to develop a single annual relationship that considered both freeze-up and breakup. The analysis accounted for both freeze-up jams and breakup jams – corresponding to two separate populations of data; each of which (freeze-up or breakup) required a separate approach in the analysis.

The methods for developing frequency distributions for the freeze-up and breakup periods required rating curves that are representative of water levels during the ice-affected period for the following ice conditions: a simple-ice cover; a freeze-up jam; an ice-run; and, a breakup jam. These curves were generated with the calibrated ice jam model described in the previous section.

Freeze-up Flood Level Frequency Analysis

For the freeze-up condition, we introduced the notion of a *base freeze-up level*, which is the theoretical water level at TPR that is expected for a given discharge. The difference between the actual and the theoretical base freeze-up level provides a parameter for further statistical analysis. For this analysis it was assumed that the base freeze-up level was well represented by a fully developed ice jam with a composite ice jam roughness, n_o = 0.030. This roughness value corresponds to the calibrated freeze-up jam roughness and is consistent with values adopted by previous investigators (NHC 2002). The observed base freeze-up levels are listed in **Table 13** and plotted on the ice jam rating curve (**Figure 10**). The assumption of a fully developed ice jam condition provides for a somewhat conservatively high estimate on the base freeze-up level since it assumes the ice jam has fully developed and achieved it's maximum thickness for the given discharge and set of ice jam parameters.

The following outlines the steps undertaken to apply the Monte Carlo approach for estimating the peak freeze-up water level frequency relationship.

- For each recorded year, determine the expected base freeze-up level. This is the level expected to occur if a fully developed freeze-up jam of composite roughness, n_o = 0.030 were to form at the given freeze-up discharge.
- Determine the difference between the expected base freeze-up level and the recorded peak freeze-up level for each year. This series of water level differences provide the population of data characterizing the differences between the expected base and peak freeze-up levels.
- Conduct a frequency analysis on these differences. **Figure 11** plots frequency curves of the difference between the base and peak freeze-up water levels. Based on the experience found by previous investigators (Trillium, 1996), the 3 Parameter Log Normal distribution provides the best fit to the observed data. Further, this distribution provides a better representation of the largest recorded events (proximate to the 100 year recurrence interval).

- Adopt a base freeze-up level and synthesize a very long series of values of peak freeze-up levels (10,000 values) by randomly selecting a water level difference from the adopted distribution and adding it to the adopted base freeze-up level.
- Order and rank the synthetic population of values to form the frequency distribution for the peak freeze-up levels and compare to the recorded values.

The results of the Monte Carlo frequency analysis are shown in **Figure 12.** The adopted base freeze-up level was set to 315.0 m. This reflects the target freeze-up elevation recommended in the *Operating Procedures for Influencing Freeze-up and Breakup of the Peace River at the Town of Peace River* for the Alberta – British Columbia Joint Task Force on Peace River Ice.

Breakup Flood Level Frequency Analysis

The breakup flood level frequency analysis relies on stage-elevation relationships for different ice conditions. **Figure 13** provides ice-affected rating curves associated with breakup at the WSC gauge. Three ice-affected curves are plotted: a breakup ice jam rating curve; a partial jam or ice run rating curve; and a simple ice cover rating curve. The open water rating curve is provided for comparison. The breakup and open water rating curves are the same as those plotted in **Figure 10**. The simple ice cover rating curve corresponds to an ice thickness of 0.6 m. This thickness is representative of the thinnest of ice thickness values measured near the end of the ice-affected period (Environment Canada 1974); and, thus reflects the lower range of expected thermal breakup levels.

The partial jam or ice run rating curve was created to provide an elevation-discharge relationship corresponding to a mechanical breakup condition under which a fully developed ice jam does not occur. This curve was created by adding the submerged portion of the computed fully developed ice jam thickness to the open water rating curve. The rational for this curve is that during a mechanical breakup, the ice rubble will shove and accumulate somewhere upstream of the gauge and that some portion of the accumulation will achieve a fully developed ice jam thickness. When the accumulation releases, a surge of water and ice "runs" downstream. The peak water level associated with the ice run is approximated by the open water rating curve elevation plus the submerged thickness of the ice run. Albeit somewhat crude, the ice run "rating curve" provides a physically based approximation on water levels for ice runs and partially developed ice jams. The curve passes through the observed data (**Figure 13)**.

The breakup discharges used in the Monte Carlo analysis were generated by randomly selecting values for discharge from the frequency distribution derived from the recorded breakup discharges. The frequency curve of breakup discharges is plotted in **Figure 14**. The 3 Parameter Log Normal distribution was adopted based on a visual "goodness of fit". Similarly, as for the freeze-up level analysis, this distribution provides a better representation of the largest recorded events – those near the 100 year recurrence interval. The Pearson 3 distribution is shown for comparison.

The Monte Carlo analysis synthesizes a very long series of peak breakup levels (10,000 events) according to the probability of occurrence of the following three ice conditions: (i) a mechanical breakup causing a breakup jam; (ii) a mechanical breakup causing an ice run or partially developed jam; and (iii) a thermal breakup. The probability of occurrence of the various ice conditions was based on breakup types deduced from the historic record. Breakup types deduced from the historical record are listed in **Table 14** and were categorized according to observational accounts found in study reports or, where no accounts were found, by inspection of the breakup dates for the Peace and Smoky rivers. For this investigation it was assumed that if breakup on the Smoky River preceded breakup on the Peace River, a mechanical breakup would ensue. This assumption provides for a somewhat conservatively high number of mechanical breakups. The last date upon which WSC reported an ice-affected condition at the gauge was assumed to be representative of the timing of breakup. This approximation reasonably predicts breakup timing where observational data is limited. A more exhaustive and possibly more accurate accounting of breakup timing would rely on the examination of the original, unedited, stream flow chart records archived by WSC. **Table 15** summarizes the deduced ice conditions at breakup on the Peace River at TPR based on historical observations.

Table 15 Summary of Historic Ice Conditions at Breakup Peace River at TPR

Breakup Type		Number of Historic Events	Percentage of Total Recorded Events
Thermal		27	60%
Mechanical	Ice run or partial jam	12	27%
	Fully developed jam	6	13%

The following steps (referred to herein as a Monte Carlo analysis) were used to determine the breakup flood level frequency.

1. First, a very long series of breakup instances were synthesized (10,000 events or "years"), and for each "year", a breakup type was assigned based on the probabilities associated with each breakup type.
2. For each "year" a breakup water level was assigned according to breakup type as follows:
   a. **Thermal:** For a thermal type of breakup, a breakup value was randomly selected from the recorded thermal breakup water level frequency distribution. The frequency curve for the recorded thermal breakup water levels is plotted in **Figure 15**. The Pearson 3 distribution was adopted based on a visual "goodness of fit". The Normal distribution is shown for comparison.

   b. Mechanical: For a mechanical breakup type, a breakup discharge value was randomly selected from the breakup discharge distribution (as depicted in **Figure 14**) and the corresponding breakup water level was determined by the appropriate ice-affected breakup rating curve (as depicted in **Figure 13**).
3. The synthesized data were ranked and plotted as a frequency curve of peak breakup levels and compared to recorded peak breakup levels (**Figure 16**). Further discussion on **Figure 16** follows below.

Two probability factors were required to synthesize the breakup type: the probability of a mechanical breakup, P_{MECH}, and the probability of a fully developed ice jam given a mechanical breakup, $P_{ICE\ JAM\ IF\ MECH}$. Initially, the probability factors were applied irrespective of the magnitude of the synthesized breakup discharge. Attempts to fit the synthesized distribution to the observed distribution, by adjusting P_{MECH} and $P_{ICE\ JAM\ IF\ MECH}$, proved unsuccessful when trying to match the full range of return periods. Adjusting the probability factors to match the higher return periods overestimated values for the lower return periods and conversely, adjustments to match the lower return periods underestimated values for the higher return periods. It was found that without any consideration of discharge magnitude it would not be possible to synthesize a distribution that followed the full distribution of observed values. Thus, discharge-based adjustments on the probability factors were introduced to account for the following assumptions on the influence of discharge on ice conditions at breakup.

- At very high discharges, a mechanical breakup is much more likely to occur than a thermal breakup and the mechanical breakup condition will almost always result in a fully developed ice jam.
- At moderately high discharges, a mechanical breakup is more likely to occur than a thermal breakup and at low discharges, a thermal breakup is more likely to occur than a mechanical breakup.

A simple approach was adopted for making discharge-based adjustments to the probability factors by introducing the notion of a so-called *threshold discharge* value where the probability factors were adjusted for instances when the threshold was exceeded. Threshold discharge values and the corresponding probability factors are listed in **Table 16**. Three scenarios were examined for this study: No discharge-based adjustments; a single discharge-based adjustment; and, a dual discharge-based adjustment. For each scenario, the resulting distribution of synthesized ice conditions match the historic ice conditions listed in **Table 15**.

The first scenario, denoted as **MC 0** on **Figure 16**, did not account for any influence of discharge on the probability factors. It provided a reasonably good fit to the observed values for return periods less than about 10 years but underestimated the observed values for return periods larger than 10 years.

The second scenario, denoted as **MC 1** on **Figure 16**, applied a single discharge-based adjustment to probability factors. When discharge exceeded a value of 3000 m^3/s, P_{MECH} and $P_{ICE\ JAM\ IF\ MECH}$ were adjusted to 0.98 and 0.98, respectively. This adjustment enforced the notion that beyond some very large breakup discharge, a fully developed ice jam would most always occur. Of the 45 observations on breakup data (**Figure 13**), a single fully developed ice jam event was recorded beyond a breakup discharge value of 3000 m^3/s; there are no reported thermal breakups or ice runs reported beyond the threshold value. The probability factors associated with discharges below the threshold value of 3000 m^3/s, were adjusted to P_{MECH} = 0. 37 and $P_{ICE\ JAM\ IF\ MECH}$ = 0.23 so that the apportion of breakup conditions in the synthesized series reflected the historic ice conditions, as listed in **Table 15**.

The third scenario, denoted as **MC 2** on **Figure 16**, applied a dual discharge-based adjustment to probability factors. The threshold discharge value of 3000 m^3/s and corresponding adjustments to the

$P_{ICE\ JAM\ IF\ MECH}$ used for the single discharge-based adjustment scenario were also adopted for this dual discharge-based adjustment scenario. That is, for discharge instances larger than 3000 m^3/s, $P_{ICE\ JAM\ IF\ MECH}$ = 0.98 and for values less than 3000 m^3/s, $P_{ICE\ JAM\ IF\ MECH}$ = 0.23. Then, a second threshold discharge value of 2300 m^3/s was introduced to reflect the influence of moderately high discharge values on the probability of a mechanical breakup. For discharge instances larger than 2300 m^3/s, P_{MECH} was initially set to 0.70 since the historic ice conditions, as depicted in **Figure 13**, suggested that about 70% of the peak breakup levels beyond this discharge were of the mechanical type. For discharges below 2300 m^3/s, P_{MECH} was set to 0.30. These values were then adjusted slightly to 0.72 and 0.32, respectively, so that the total number of synthesized mechanical breakup conditions were consistent with the historic ice conditions (that is, 40% of the synthesized breakups were of the mechanical type).

Three additional hypothetical scenarios were included to help inform interpretation of the results of the Monte Carlo analysis: thermal breakups only; mechanical breakups only without any ice jams; and fully developed ice jams only. The probability factors corresponding to these hypothetical scenarios are listed in **Table 16** and their resulting frequency curves are depicted on **Figure 16**.

Table 16 Summary of Probability Factors for Monte Carlo Analysis

Threshold Discharge	Probability Factor		Summary of Synthesized Events
No discharge-based adjustments			
none	P_{MECH} = 0.40	$P_{ICE\ JAM\ IF\ MECH}$ = 0.33	6039 Thermal Breakups (60%) 3961 Mechanical Breakups (40%) 1288 Ice Jams (13%)
Single discharge-based adjustment: $Q_{THRESHOLD}$ = 3000 m^3/s			
$Q_{BREAKUP}$ < 3000 m^3/s	P_{MECH} = 0.37	$P_{ICE\ JAM\ IF\ MECH}$ = 0.23	6021 Thermal Breakups (60%) 3979 Mechanical Breakups (40%) 1277 Ice Jams (13%)
$Q_{BREAKUP}$ > 3000 m^3/s	P_{MECH} = 0.98	$P_{ICE\ JAM\ IF\ MECH}$ = 0.98	
Dual discharge-based adjustment: $Q_{THRESHOLD1}$ = 2300 m^3/s; $Q_{THRESHOLD2}$ = 3000 m^3/s			
$Q_{BREAKUP}$ < 2300 m^3/s	P_{MECH} = 0.32		6005 Thermal Breakups (60%) 3995 Mechanical Breakups (40%) 1211 Ice Jams (12%)
$Q_{BREAKUP}$ > 2300 m^3/s	P_{MECH} = 0.72		
$Q_{BREAKUP}$ < 3000 m^3/s	$P_{ICE\ JAM\ IF\ MECH}$ = 0.23		
$Q_{BREAKUP}$ > 3000 m^3/s	$P_{ICE\ JAM\ IF\ MECH}$ = 0.98		
Thermal breakups only (hypothetical scenario)			
none	P_{MECH} = 0.0	$P_{ICE\ JAM\ IF\ MECH}$ = 0.0	10,000 Thermal Breakups (100%) 0 Mechanical Breakups (0%) 0 Ice Jams (0%)
Mechanical breakups only without any ice jams (hypothetical scenario)			
none	P_{MECH} = 1.0	$P_{ICE\ JAM\ IF\ MECH}$ = 0.0	0 Thermal Breakups (0%) 10,000 Mech. Breakups (100%) 0 Ice Jams (0%)
Mechanical breakups with only ice jams (hypothetical scenario)			
none	P_{MECH} = 1.0	$P_{ICE\ JAM\ IF\ MECH}$ = 1.0	0 Thermal Breakups (0%) 10,000 Mech. Breakups (100%) 10,000 Ice Jams (100%)

Discussion on Breakup Flood Level Frequency Analysis

The hypothetical ice condition scenarios provide insight into the Monte Carlo analysis. The observed data plotted on **Figure 16** are colour coded according to breakup type to provide additional context to the hypothetical frequency distributions and the following generalizations relating to breakup type:

- The thermal breakup and *ice-run-or-partial-jam* frequency curves envelope the observed data up to about the 10 year return period. The *ice-jam-only* frequency curve envelopes the upper limit of extreme breakup levels.
- The data suggest that the distribution of peak breakup water levels transitions from lower to higher magnitudes according to breakup type as follows: lower, more frequent levels are mostly associated with a thermal breakup; moderate, less frequent levels can be associated with either thermal or mechanical breakup with an ice run or partial jam; and the most severe breakup levels are associated with a fully developed ice jam condition.
- Beyond approximately the 10 year return period, there is a departure from the frequency distribution associated with non-ice jam breakup types towards the frequency distribution associated with ice-jam-only breakup types.

By using probability factors for breakup type, the Monte Carlo analysis can combine all breakup types into a single distribution. The initial analysis (Scenario MC 0) results in a frequency curve that gradually transitions from a non jam to an ice-jam-only condition while the observed data indicates a more rapid transition towards an ice-jam-only condition (beginning around the 10 year return period). For this investigation, the transition from a non ice jam to an ice-jam-only condition was attributed to changes in the dominant mechanisms driving the breakup process. For an ice jam condition, hydrodynamic forces dominant the breakup process (recall Section 2.1.2) and the variable used in the analysis that is most representative of the magnitude of the hydrodynamic forces is discharge. Thus, it was considered most appropriate to adjust the probability factors according to discharge. The somewhat crude threshold discharge approach introduced in this study resulted in discharge-affected distributions (MC 1 and MC 2) that appeared to follow the transition from a non ice jam to ice-jam-only condition better than the approach that did consider discharge magnitude (MC 0). There is room for refinement on the choice of threshold discharge values and the corresponding probability factors. And, more elegant methods could be pursued to better capture the frequency distribution of observed data between the 10 to 50 year return periods. Fortunately, the return periods of interest for this investigation are of 50 years and larger. At these higher return periods, fitting the “transition” region is of much less critical importance than fitting the higher return period values. The ice-jam-only condition curve offers a physically-based, defensible manner for extrapolating the frequency curve beyond the highest observed value and on into the 200 year plus return periods.

The finding that the ice jam frequency curve is applicable for the higher return periods is significant because it supports the underlining assumption required to extend the flood frequency levels at the WSC gauge throughout the study reach. That is, the application of a fully developed ice jam profile model is an appropriate method for extrapolating the ice-affected design flood level profile for the return periods of interest (i.e. 50 years and larger).

Ice Jam Flood Level Frequency Analysis Upstream of Smoky River

Sufficient data did not exist to support a frequency analysis, directly, at a location along the study reach upstream of the Smoky River confluence. Alternatively, the estimates on the ice jam flood level frequencies upstream of the confluence were derived by conducting the analysis at the WSC gauge at TPR with flow conditions that were representative of the reach of river upstream of the Smoky River. This approach follows the assumption that differences in ice jam flood level frequencies upstream of the Smoky River confluence were dominated by changes in flow, upstream and downstream of the Smoky River.

The following analysis derived flood level frequency values at the WSC gauge according to flows that were "representative" of the conditions upstream of the Smoky River. The resulting flood level frequency values were entered into the ice jam rating curve at the WSC gauge to provide estimates on the discharge values used to determine the flood level frequency profiles upstream of the Smoky River.

- *Freeze-up:* The base freeze-up level is indicative of the average discharge conditions at breakup. Thus, the base freeze-up level was adjusted to reflect the average flow conditions upstream of the confluence. The discharge recorded on the Smoky River (at the Watino gauge) is, on average, 4% of the discharge on the Peace River (at TPR gauge). The base freeze-up level was adjusted accordingly, down from 315 m to 314.8 m to represent the reduction in freeze-up discharge that would be experienced upstream of the Smoky River. Using a base freeze-up level of 314.8 m, the same approach for generating the peak freeze-up flood level frequency values at TPR (as depicted in **Figure 12**) was applied. This approach assumed that the variability between the expected base freeze-up level and actual peak freeze-up level would be similar both upstream and downstream of the Smoky River. The resulting peak freeze-up water level frequency curve is plotted on **Figure 17**, the values computed for a base freeze-up level of 315.0 m is shown for comparison.
- *Breakup*: It was assumed that the same variation in ice conditions (thermal, mechanical, ice-run, ice jam) used for the Monte Carlo Analysis at the WSC gauge were also representative of the variation in ice conditions upstream of the Smoky River. And, any differences would have been dominated by changes in the discharge inputs provided by the break-up discharge frequency relationship. A modified breakup discharge frequency relationship was calculated using the average daily discharge values upstream of the Smoky River synthesized under the open water hydrology study component. The resulting frequency curve of breakup discharges, upstream of the Smoky River confluence, is plotted on **Figure 18**. The 3 Parameter Log Normal distribution was adopted based on a visual "goodness of fit", and to be consistent with the same distribution used for breakup discharges at the WSC Gauge in TPR. The distribution derived for the gauge at TPR (downstream of the confluence) is plotted for comparison. The same steps used to determine the breakup flood level frequency (Monte Carlo analysis), described previously, were followed using the breakup discharge frequency upstream of the Smokey River. The synthesized

data were ranked and plotted as a frequency curve of peak breakup levels (**Figure 19**). The breakup flood level frequencies based on the discharge frequency curve for TPR is plotted for comparison.

Peak Annual Ice-affected Flood Level Frequency Analysis

The peak annual ice-affected flood level frequency analysis was conducted by combining the two data sets for the peak freeze-up and peak breakup water levels. The order of the synthesized series of 10,000 events (or "years") was persevered and the peak annual ice-affected flood level was taken as the greater of the two values for each given year. The resulting series were then ranked and plotted as a frequency curve of peak annual ice-affected breakup levels and compared to the recorded peak annual ice-affected breakup levels (**Figure 20**). **Table 17** lists the peak annual ice-affected flood levels for a range of return periods. The open water flood level frequency values are plotted and listed for comparison.

Table 17 Peak Annual Ice-affected Flood Level Frequency Values at Town of Peace River WSC Gauge 07AH001 For Variable Flow Conditions

Return Period (Years)	Peak Annual Ice-affected Flood Level (m)		Open Water Flood Level (m)
	Based on Flow Conditions at TPR	Based on Flow Conditions Upstream of Smoky River	
50	319.92	319.40	318.76
100	320.43	320.00	319.54
200	321.06	320.70	320.54

5.1.3 Heart River Ice-Affected Flood Frequency Analysis

A first assumption for the Heart River analysis is that the peak annual ice-affected flood levels are governed by breakup flood levels because all available accounts of ice-related flooding are attributed to breakup events. Thus, the analysis of breakup flood levels is assumed to be representative of the peak annual ice-affected flood levels.

Breakup flood conditions on the Heart River study reach are affected by the flood levels and ice conditions on the Peace River. Therefore, the analysis required an accounting for the affects of Peace River ice conditions and flood levels on ice conditions and flood levels for the Heart River. Two primary aspects of these interactions were accounted for in the analysis: the backwater effects of Peace River breakup levels on computed Heart River flood levels; and, the presence or absence of an ice cover on the Peace River. The first aspect influenced the choice in the downstream boundary condition used to compute flood levels on the Heart River and the second aspect influenced the assumed ice condition on the Heart River. It was assumed that breakup ice conditions on the Peace River influence ice conditions on the Heart River as follows: for a mechanical breakup condition, a fully developed ice jam is likely to occur when ice is present on the Peace River, and when there is no ice on the Peace River a fully developed ice jam is not likely to occur.

The breakup discharges used in the Monte Carlo analysis were generated by randomly selecting values for discharge from the frequency distribution derived from the recorded breakup discharges reported for WSC gauge 07AH003 Heart River at Nampa. The discharges at Nampa were increased by a factor of 1.14 to account for the accretion of inflows to the Heart River between the gauge and the study reach near town. The factor of 1.14 was chosen to be consistent with the open water study for flood frequency discharge estimates of the Heart River at the mouth. This factor was considered to be applicable since the breakup spring flood events were associated with snowmelt runoff where flood magnitude scales well with drainage area. The frequency curve of breakup discharges is plotted on **Figure 21**. The Pearson 3 distribution provided the best “fit” to the breakup discharge data and was the same distribution adopted under the open water hydrology study component. The breakup discharge was defined as the discharge reported on the last ice-affected discharge date preceding breakup (denoted by the symbol “B” in the WSC historic record).

As was done for the Peace River, the Monte Carlo analysis for the Heart River synthesized a very long series of peak breakup levels (10,000 events) according to the probability of occurrence of the following three ice conditions: (i) a mechanical breakup causing a breakup jam; (ii) a mechanical breakup causing an ice run; and (iii) a thermal breakup.

It was assumed that the probability of a mechanical or thermal breakup on the Heart River was independent of the ice conditions on the Peace River. The WSC archived water level record for the Heart River at Nampa (WSC gauge 07HA003) at breakup was examined to identify those years with a significant, sharp increase in water level at breakup. These years were classed as a mechanical breakup. Of the 45 years observed, 13 were deemed to be a mechanical breakup, thus, the probability of a mechanical breakup on the Heart River was assumed to be 0.33. Given a mechanical breakup, it was assumed that the ice condition also depended on the presence of ice in the Peace River. For an ice free condition on the Peace River, it was assumed that there would be an ice run. For the condition when ice is present on the Peace River, it was assumed that a fully developed ice jam (breakup jam) would occur.

The probability of ice being present on the Peace River during breakup on the Heart River was deduced by comparing the timing of breakup indicated by the gauge data at WSC gauges at Nampa (07HA003) and TPR (07HA001). The last date upon which WSC reported an ice-affected condition at the gauge was assumed to be representative of the timing of breakup. An ice free condition on the Peace River was assumed when the last recorded ice-affected discharge date on the Peace River gauge at TPR preceded the last recorded ice-affected discharge date on the Heart River gauge at Nampa. For 23 of the 45 years (51% of all the observations), breakup on the Peace River preceded breakup on the Heart River. Therefore, the probability of an ice-free condition on the Peace River during a Heart River breakup was assumed to be 0.51.

Two approaches were considered for determining the flood frequency levels along the Heart River study reach. The first approach was to determine the flood frequency levels at each individual cross section based on rating curve relationships derived for each cross section. A family of curves would be required for each ice condition in order to account for varying water level conditions on the Peace River at the mouth of the Heart River (downstream boundary). The second approach was to determine the flood frequency levels at all sections, simultaneously, through the calculation of an ice-affected flood level profile for each breakup instance. Although the second approach required the computation of a very large number of profiles (10,000), it was preferred since it allowed for an explicit accounting of the interactions with the Peace River along the full Heart River study reach for every breakup instance.

The following summarizes the procedure used to synthesize the breakup flood levels along the study reach.

1. A very long series of breakup instances were synthesized (10,000 "years"), and for each year, a breakup type was assigned based on the probabilities associated with each breakup type.
2. Then, the breakup discharges, ice conditions, and water levels at TPR that were derived previously for the Peace River Monte Carlo Analysis (corresponding to the flood frequency data series denoted by MC2 on **Figure 16**) were paired with the Heart River breakup instances.
    - **a.** The Peace River ice condition (ice covered or ice free) was used to inform the type of mechanical breakup on the Heart River (ice jam or ice run).
    - **b.** The water level at TPR was used to estimate the water level at the mouth of the Heart River. Estimates were made by increasing the water level at TPR according to the appropriate ice-affected stage increase rating curves depicted in **Figure 22**. The rating curves in **Figure 22** plot the stage increase in water level elevation from TPR (07HA001) to the mouth of the Heart River along gradually varied flow profiles for different ice conditions. The curves (solid lines) are polynomial fits to computed values (symbols) derived by calculating ice-affected water surface profiles along the Peace River for a range of discharges. The stage increase is comparable for the simple ice cover and fully developed ice jam conditions. And, for simple ice covers, the stage increase is not sensitive to ice thickness for a given discharge.
    - **c.** The downstream boundary condition value for the Heart River was then set was set to the Peace River water level at the mouth of the Heart River.
3. For each "year" an ice affected water surface profile was computed according to the following ice conditions:
    - **a. Thermal:** For a thermal type of breakup, a breakup discharge value was randomly selected from the breakup discharge frequency distribution (as depicted in **Figure 21**). Then, the ice-affected water surface profile was computed by assuming an average thickness of 0.8 m. Unfortunately, there is insufficient measured ice thickness data available for the study reach to suggest a typical ice thickness at breakup. Based on reports of late winter ice thicknesses on the Peace River at TPR (Environment Canada 1974), late winter ice thickness on the Heart River may range from about 0.6 m to 1.4 m, with an average of 0.8 m.

b. Mechanical: For a mechanical breakup type, a breakup discharge value was randomly selected from the breakup discharge distribution (as depicted in **Figure 21**). The mechanical breakup type (ice-run or ice jam) was determined based on the presence of ice in the Peace River: an ice-run was prescribed if ice was not present in the Peace River and an ice jam condition was prescribed if ice was present. For an ice jam condition, an ice jam profile was computed using an assumed composite roughness value of n_o = 0.045. For an ice-run condition, a representative submerged ice-run thickness value was superimposed along the full length of the corresponding open water surface profile (for the given breakup discharge). The submerged ice thickness value was based on an ice jam thickness rating curve computed at a representative model cross section location, XS #63. This crude approximation on the ice run water level follows the same rationale used for the Peace River analysis (refer to Section 5.1.2).

4. The resulting ice-affected breakup profiles provided a series of synthesized breakup water level values at each cross section. The water level values at each section were then ranked and plotted as a frequency curve of peak breakup levels. The resulting frequency curves for selected cross sections along the study reach are plotted on **Figure 23**.

5.2 Uncertainty and Confidence

The primary sources of uncertainty and ultimately, confidence in the adopted ice jam flood level frequency estimates are identified in this section. There are a number of contributors towards uncertainty and they are difficult to quantify. Relatively speaking, the most significant contributors towards uncertainty in the ice jam flood level frequency curves are errors in the reported peak flood water levels and peak discharges. These are the data upon which the frequency analysis is conducted. Accurate discharge estimates are very difficult to achieve during ice jam formation – Hicks and Healy (2003) found that during the early breakup period, minor ice movements in the vicinity of a gauging station can lead to errors well over 100% in the published discharge record. After errors on flood level and flood discharge, the next major contributor to uncertainty may be attributed to the mischaracterization of the dominant ice condition associated with the peak ice-affected water level.

The sections that follow provide an assessment on the confidence in the adopted frequency distributions by comparing values found in this study to previous studies. The section on sensitivity analysis provides a measure of uncertainty that is considered to be representative of the potential range of errors associated with the sources of uncertainty identified in this section.

5.3 Comparison to Previous Studies

There were four major studies found during this investigation for which there were reported ice jam flood level frequencies. The published values for these studies are listed in **Table 18**. All of these previous investigators quantify the ice jam flood level frequency at the TPR WSC gauge. The comparisons are limited to the Peace River. Prior to this investigation there are no known available published ice jam flood level frequency values for the Heart River near the Town of Peace River.

Table 18 Comparison of Current to Previous Estimates on Ice-affected Flood Level Frequency Values at TPR WSC Gauge 07AH001 for Various Ice Conditions

Ice Condition	Return Period (Years)	Previous Studies			Current Study
		Trillium (1996)	Trillium (2002)	Lindenschmidt (2015)	NHC (2018)
Freeze-up					
	50	319.18	319.0		318.79
	100	320.18	320.0		319.74
	200	321.18	321.4		320.59
Breakup					
	50		320.2		319.55
	100		321.9	320.8	320.00
	200		323.5		320.37
Annual Ice-affected					
	50	319.9	321.1		319.92
	100	320.4	322.2		320.43
	200	321.0	323.7		321.06

The previous study by Trillium (1996) compares most closely with the values computed for this study. The largest variations from previous studies are those compared to the later Trillium (2002) study. The current operational procedures for freeze-up and breakup on the Peace River (Joint Task Force Technical Advisors/Operators, 2010) imply a 1:100 year freeze-up flood level of 320.0 m – only slightly higher than the value of 319.74 m, computed for the current study.

5.4 Computed Ice Jam Flood Frequency Profiles

Flood frequency profiles for the Peace River and Heart River study reaches are plotted on **Figures 24** through **28**. Different approaches were used for the Peace and Heart rivers when developing the flood frequency profiles.

5.4.1 Peace River Ice Jam Flood Frequency Profiles

The ice jam flood level frequency profiles were based on the flood level analysis conducted at the TPR WSC gauge. The flood levels at the gauge were then used to estimate a corresponding flood frequency profile along the full study reach. A somewhat simple approach would have been to simply extend the flood levels along the reach by projecting the flood level value at the gauge upstream and downstream along an average river slope. A more rigorous approach was adopted by extending the flood frequency level at the gauge along a profile that followed a gradually varied water surface profile that was representative of the hydraulic characteristics of the study reach. A further refinement was to account for ice conditions when computing a representative gradually varied profile. Since the ice conditions associated with the larger floods were well-approximated by a fully developed ice jam (refer to the mechanical ice jam enveloping curve on **Figure 16**), a fully developed ice jam profile was considered to provide the best representation of the shape of the ice jam flood level frequency profile along the study reach.

For each return period, a fully developed ice jam profile, extending along the full study reach, was computed for a discharge corresponding to an ice jam rating curve. The ice jam properties used to compute the fully developed ice jam profile were for a breakup ice jam (n_o = 0.045, ϕ = 57.17°, p = 0.04, k_1 = 0.0868, μ = 0.93). The breakup jam was adopted since many of the recorded fully developed ice jam events were of the breakup type, and the observed data were fitted well by a simple ice jam rating curve (refer to **Figure 13**). **Table 19** summarizes the representative discharges used to develop the ice jam flood frequency profiles upstream and downstream off the Smoky River. The *associated flood level at TPR* in **Table 19** describes the flood level expected at the TPR WSC gauge for the flow conditions upstream of the Smoky River (recall **Table 17**).

The computed ice jam flood frequency profile data for the 50-year, 100-year, and 200-year ice-affected floods are listed in **Table 20**. The three corresponding flood frequency profiles for the Peace River are all plotted on **Figure 24** for comparison.

Table 19 Representative Peace River Discharges for Various Flood Level Frequencies

Return Period (Years)	Downstream of the Smoky River (TPR)		Upstream of the Smoky River	
	Peak Annual Ice-affected Flood Level (m)	Representative Discharge (m³/s)	Associated Flood Level at TPR (m)	Representative Discharge (m³/s)
50	319.92	3620	319.40	3190
100	320.43	4020	320.00	3620
200	321.06	4570	320.70	4190

Figures 25 through **27**, plot the resulting fully developed ice jam profiles used to represent the 50-year, 100-year, and 200-year return periods, respectively. The figures depict the top and bottom of ice and water levels profiles for a fully developed ice jam. The computed water level profile passes through the corresponding flood frequency level at the WSC gauge. The thickness at the upper model boundary (or "head" of the jam) was adjusted until it approached a fully developed thickness condition. A fully developed state was estimated by gradually increasing the thickness in the head region through successive iterations until the upstream limits of the ice jam approached a near constant water surface slope and maximum thickness profile.

Table 20 Computed Ice Jam Flood Frequency Water Levels on the Peace River

Peace R. Cross Section	Flood Return Period			Peace R. Cross Section	Flood Return Period		
	50-year	100-year	200-year		50-year	100-year	200-year
	Water Surface Elevation (m)				Water Surface Elevation (m)		
XS #1	313.16	314.04	314.98	XS #28	na	na	na
XS #2	313.51	314.31	315.22	XS #29	320.28	320.80	321.46
XS #3	313.98	314.69	315.54	XS #30	320.65	321.19	321.87
XS #4	314.28	314.95	315.79	XS #31	320.73	321.28	321.96
XS #5	314.53	315.19	316.02	XS #32	320.95	321.50	322.19
XS #6	314.64	315.29	316.11	XS #33	321.26	321.81	322.50
XS #7	na	na	na	XS #34	321.70	322.23	322.89
XS #8	314.77	315.41	316.23	XS #35	321.97	322.50	323.14
XS #9	315.12	315.72	316.49	XS #36	322.27	322.80	323.43
XS #10	315.51	316.10	316.84	XS #37	322.51	323.05	323.71
XS #11	315.93	316.50	317.21	XS #38	323.08	323.64	324.34
XS #12	316.34	316.90	317.60	XS #39	323.41	324.00	324.71
XS #13	316.73	317.29	317.97	XS #40	323.80	324.42	325.17
XS #14	317.11	317.67	318.35	XS #41	324.35	324.99	325.77
XS #15	317.55	318.10	318.79	XS #42	324.98	325.62	326.42
XS #16	317.86	318.41	319.10	XS #43	325.50	326.15	326.97
XS #17	318.18	318.70	319.39	XS #44	325.85	326.51	327.34
XS #18	318.61	319.10	319.70	XS #45	326.27	326.92	327.74
XS #19	319.13	319.62	320.22	XS #46	326.57	327.21	328.02
XS #20	319.61	320.11	320.73	XS #47	326.81	327.45	328.26
XS #21	319.77	320.28	320.90	XS #48	327.20	327.82	328.61
XS #22	319.92	320.43	321.06	XS #49	327.68	328.32	329.12
XS #23	320.08	320.59	321.23	XS #50	327.98	328.64	329.46
XS #24	na	na	na	XS #51	328.41	329.09	329.93
XS #25	na	na	na	XS #52	328.72	329.40	330.26
XS #26	320.17	320.69	321.34	XS #53	329.10	329.77	330.62
XS #27	na	na	na	XS #54	329.53	330.20	331.05

na denotes cross sections that were omitted from the ice enhanced model for improved model performance (refer to Section 4.2.1)

5.4.2 Heart River Ice Jam Flood Frequency Profiles

The computed ice jam flood frequency profile data for the 50-year, 100-year, and 200-year ice-affected floods are listed in **Table 21**. The three corresponding flood frequency profiles for the Heart River are all plotted on **Figure 28** for comparison. The ice jam flood level frequency profiles were based on the flood level frequency analysis conducted for the Heart River described in Section 5.1.3. The profiles are very flat in the lower portion of the Heart River as they are dominated by backwater effects from the Peace River. The computed flood level frequency values through the downstream limits of the Heart River varied slightly from the corresponding flood level frequency value on the Peace River at the mouth of the Heart River. This was primarily due to the assumption that the Heart River peak annual ice-affected flood levels were attributed only to breakup, while the Peace River values were based on the peak annual (maximum of either freeze-up or breakup). For the 100-year and 200-year flood frequencies, the values differed by only 1 cm, for the 50-year flood frequency, the values in the Heart River were about 15 cm lower than the Peace River. Where the computed water levels in the downstream limits of the Heart River were less than the values on the Peace River, they were set to the computed values on the Peace River at the mouth of the Heart. That is, the adopted flood level frequency values in the lower portion of the Heart River were governed by the Peace River backwater elevation.

Table 21 Computed Ice Jam Flood Frequency Water Levels on the Heart River

Heart R. Cross Section	Flood Return Period			Heart R. Cross Section	Flood Return Period		
	50-year	100-year	200-year		50-year	100-year	200-year
	Water Surface Elevation (m)				Water Surface Elevation (m)		
XS #55	320.69	321.25	321.92	XS #69	320.69	321.33	321.92
XS #56	320.69	321.25	321.92	XS #70	320.71	321.35	322.04
XS #57	320.69	321.25	321.92	XS #71	320.73	321.36	322.09
XS #58	320.69	321.25	321.92	XS #72	320.74	321.38	322.11
XS #59	320.69	321.25	321.92	XS #73	320.79	321.42	322.13
XS #60	320.69	321.25	321.92	XS #74	320.83	321.48	322.14
XS #61	320.69	321.25	321.92	XS #75	320.87	321.50	322.14
XS #62	320.69	321.26	321.92	XS #76	320.94	321.55	322.16
XS #63	320.69	321.26	321.92	XS #77	321.09	321.61	322.17
XS #64	320.69	321.26	321.92	XS #78	321.25	321.70	322.21
XS #65	320.69	321.26	321.92	XS #79	321.41	321.83	322.23
XS #66	320.69	321.32	321.92	XS #80	321.63	322.03	322.37
XS #67	320.69	321.32	321.92	XS #81	321.94	322.31	322.66
XS #68	320.69	321.32	321.92				

5.5 Model Sensitivity Analysis

A sensitivity analysis was conducted to determine the effects of changing the key model input parameters on computed hydraulic properties. The sensitivity of the computed hydraulic properties to changes in model parameters was evaluated in terms of changes in computed water levels, since: the computed water level is the hydraulic property of primary interest for a flood hazard study; and, changes in water level provide a good characterization of changes in other hydraulic properties including: depth, velocity, flow area, and extent of inundation. The sensitivity analysis was limited to the Peace River since there was no feasibly practical approach to test sensitivities on the Heart River. This was primarily due to the level of effort and complexity required to test each parameter - the Heart River flood level frequency profiles was determined by ranking a suite of 10,000 computed water levels at each model cross section according to one of three randomly selected ice conditions. Also, unlike the Peace River analysis, the flood level frequency profile on the Heart River could not be characterized by a single representative ice condition.

Table 22 lists the model parameters tested for the sensitivity analysis. They are grouped according to boundary conditions, ice jam stability parameters, and composite roughness. The values were selected for testing so as to span a range of plausible values for the study reach. Sensitivity of computed water levels to changes in model parameters was evaluated by varying the input values of the respective sensitivity parameters in the 100-year ice enhanced model (denoted as the baseline in **Table 22**). The fully developed ice jam profile was calculated in the same iterative manner that was used to compute the flood frequency profiles, as outlined in Section 5.4.1.

Table 22 Model Sensitivity Analysis Parameters

Sensitivity Parameter	Baseline Value	Sensitivity Test Values	
Boundary Conditions			
Downstream water level (d/s WL)	d/s WL = 314.04 m S_f = 0.00025	d/s WL = 313.54 m (S_f = 0.000292)	d/s WL = 314.54 m (S_f = 0.000216)
Upstream Ice Thickness (t_{head})	t_{head} = 3.2 m	t_{head} = 2.7 m	t_{head} = 3.7 m
Ice Jam Stability Parameters			
Jam strength parameter (μ)	μ = 0.93 p = 0.4; ϕ = 57.17°; k_1 = 0.0868	μ = 0.80 p = 0.4; ϕ = 53.13°; k_1 = 0.111	μ = 1.2 p = 0.4; ϕ = 63.43°; k_1 = 0.0557
Composite Roughness			
Composite Roughness (n_o)	n_o = 0.045	n_o = 0.040	n_o = 0.050

Figure 29 through **Figure 32** provide charts of the computed ice jam water level profiles for variations in the downstream water level, upstream ice thickness, jam strength parameter, and composite roughness, respectively. **Table 23** through **Table 26** list the computed values plotted in the aforementioned charts. A description of the sensitivity parameters and testing values is provided below and followed by a summary on the sensitivity analysis.

5.5.1 Boundary Conditions

Boundary conditions were required as inputs for the upstream and downstream boundaries of the ice enhanced model. A downstream water level was required to initiate the hydraulic calculations which progress from downstream to upstream and an upstream ice thickness was required to initiate the ice jam thickness profile calculations (jam stability equation) which progress from upstream to downstream.

Downstream water level: A normal depth approximation (with an energy grade slope, S_f = 0.00025) was used to determine the downstream water level boundary condition. This was the same value adopted for the open water model. As for the open water model, a plausible range of uncertainty on the downstream water level was assumed to be ±0.5 m. For the 100-year ice enhanced model, a +0.5 m and -0.5 m variation in the downstream water level boundary condition was ascribed by testing energy grade slopes of S_f = 0.000216 and S_f = 0.000292, respectively, for the normal depth approximation.

Upstream ice thickness: The same range of uncertainty applied to the downstream boundary was applied to the upstream boundary. The upstream ice jam thickness (or thickness at the *head*) was adjusted about the baseline value of, t_{head} = 3.2 m by ±0.5 m, from t_{head} = 2.7 m to t_{head} = 3.7 m.

5.5.2 Ice Jam Stability Parameters

The jam stability parameters required as input to the HEC RAS model include: the internal friction angle of the jam, ϕ; the ice jam porosity (fraction of voids between ice floes), p; and the coefficient of lateral to longitudinal stress in the jam, k_1 (recall Section 5.3 and Equation [2]). The combined effect of these parameters was expressed as a single jam stability parameter, μ, (recall equations [4] through [6]). The calibrated jam stability parameter, μ = 0.93, was ascribed by setting the corresponding model input parameters to values of: p = 0.4, ϕ = 57.17° and k_1 = 0.0868. The model sensitivity analysis tested the range of μ between values of 0.80 and 1.2. The values of μ for the sensitivity tests were ascribed according to the following model input parameter values: p = 0.4, ϕ = 53.13° and k_1 = 0.111 for μ = 0.80; and p = 0.4, ϕ = 63.43° and k_1 = 0.0557 for μ = 1.2.

5.5.3 Composite Roughness

The composite roughness was varied above and below the calibrated roughness, n_o=0.045, from n_o=0.040 and n_o=0.050. The model automatically computes the composite roughness based on the bed and ice roughness values. For the sensitivity tests, the bed roughness values were held constant at n_{bed} = 0.023, and the ice cover roughness values were adjusted to n_{ice} = 0.0539 and n_{ice} = 0.0709, to achieve composite roughness values of n_o=0.040 and n_o=0.050, respectively.

Table 23 Sensitivity of Computed Ice Jam Water Levels to Variation in Downstream Water Levels

Peace R. Cross Section	Downstream Water Level			Peace R. Cross Section	Downstream Water Level		
	313.54 m (decrease)	313.04 m (baseline)	314.54 m (increase)		313.54 m (decrease)	313.04 m (baseline)	314.54 m (increase)
	Computed Ice Jam Water Level (m)				Computed Ice Jam Water Level (m)		
XS #1	313.54	314.04	314.54	XS #28	na	na	na
XS #2	313.95	314.31	314.73	XS #29	320.80	320.80	320.80
XS #3	314.47	314.69	315.00	XS #30	321.19	321.19	321.19
XS #4	314.79	314.95	315.21	XS #31	321.28	321.28	321.28
XS #5	315.06	315.19	315.40	XS #32	321.50	321.50	321.50
XS #6	315.17	315.29	315.48	XS #33	321.81	321.81	321.81
XS #7	na	na	na	XS #34	322.24	322.23	322.24
XS #8	315.32	315.41	315.58	XS #35	322.51	322.50	322.51
XS #9	315.66	315.72	315.83	XS #36	322.81	322.80	322.81
XS #10	316.06	316.10	316.16	XS #37	323.06	323.05	323.06
XS #11	316.48	316.50	316.53	XS #38	323.65	323.64	323.64
XS #12	316.89	316.90	316.92	XS #39	324.00	324.00	323.99
XS #13	317.28	317.29	317.29	XS #40	324.42	324.42	324.41
XS #14	317.67	317.67	317.67	XS #41	324.99	324.99	324.99
XS #15	318.10	318.10	318.10	XS #42	325.62	325.62	325.62
XS #16	318.41	318.41	318.40	XS #43	326.15	326.15	326.15
XS #17	318.70	318.70	318.69	XS #44	326.51	326.51	326.51
XS #18	319.09	319.10	319.08	XS #45	326.92	326.92	326.92
XS #19	319.62	319.62	319.61	XS #46	327.21	327.21	327.21
XS #20	320.11	320.11	320.10	XS #47	327.45	327.45	327.45
XS #21	320.27	320.28	320.27	XS #48	327.82	327.82	327.82
XS #22	320.43	320.43	320.42	XS #49	328.32	328.32	328.32
XS #23	320.59	320.59	320.59	XS #50	328.64	328.64	328.64
XS #24	na	na	na	XS #51	329.09	329.09	329.09
XS #25	na	na	na	XS #52	329.40	329.40	329.40
XS #26	320.69	320.69	320.69	XS #53	329.77	329.77	329.77
XS #27	na	na	na	XS #54	330.20	330.20	330.20

na denotes cross sections that were omitted from the ice enhanced model for improved model performance (refer to Section 4.2.1)

Table 24 Sensitivity of Computed Ice Jam Water Levels to Variation in the Upstream Ice Thickness

Peace R. Cross Section	Upstream Ice Thickness			Peace R. Cross Section	Upstream Ice Thickness		
	t_{head}=2.7m (decrease)	t_{head}=3.2m (baseline)	t_{head}=3.7m (increase)		t_{head}=2.7m (decrease)	t_{head}=3.2m (baseline)	t_{head}=3.7m (increase)
	Computed Ice Jam Water Level (m)				Computed Ice Jam Water Level (m)		
XS #1	314.04	314.04	314.04	XS #28	na	na	na
XS #2	314.31	314.31	314.33	XS #29	320.81	320.80	320.83
XS #3	314.69	314.69	314.74	XS #30	321.19	321.19	321.23
XS #4	314.95	314.95	315.01	XS #31	321.28	321.28	321.33
XS #5	315.19	315.19	315.25	XS #32	321.50	321.50	321.56
XS #6	315.29	315.29	315.35	XS #33	321.82	321.81	321.88
XS #7	na	na	na	XS #34	322.24	322.23	322.29
XS #8	315.41	315.41	315.47	XS #35	322.51	322.50	322.54
XS #9	315.72	315.72	315.77	XS #36	322.82	322.80	322.82
XS #10	316.10	316.10	316.15	XS #37	323.07	323.05	323.06
XS #11	316.50	316.50	316.55	XS #38	323.66	323.64	323.64
XS #12	316.90	316.90	316.96	XS #39	324.00	324.00	323.98
XS #13	317.28	317.29	317.33	XS #40	324.41	324.42	324.41
XS #14	317.67	317.67	317.72	XS #41	324.97	324.99	325.01
XS #15	318.09	318.10	318.16	XS #42	325.59	325.62	325.67
XS #16	318.39	318.41	318.49	XS #43	326.10	326.15	326.25
XS #17	318.70	318.70	318.79	XS #44	326.44	326.51	326.63
XS #18	319.11	319.10	319.13	XS #45	326.84	326.92	327.08
XS #19	319.62	319.62	319.59	XS #46	327.14	327.21	327.40
XS #20	320.11	320.11	320.13	XS #47	327.41	327.45	327.66
XS #21	320.28	320.28	320.30	XS #48	327.83	327.82	328.03
XS #22	320.43	320.43	320.46	XS #49	328.30	328.32	328.49
XS #23	320.59	320.59	320.62	XS #50	328.60	328.64	328.80
XS #24	na	na	na	XS #51	329.02	329.09	329.24
XS #25	na	na	na	XS #52	329.32	329.40	329.56
XS #26	320.69	320.69	320.72	XS #53	329.65	329.77	329.96
XS #27	na	na	na	XS #54	330.03	330.20	330.42

na denotes cross sections that were omitted from the ice enhanced model for improved model performance (refer to Section 4.2.1)

Table 25 Sensitivity of Computed Ice Jam Water Levels to Variation in the Ice Jam Stability Parameter

Peace R. Cross Section	Jam Stability Parameter			Peace R. Cross Section	Jam Stability Parameter		
	μ = 0.80 (decrease)	μ = 0.93 (baseline)	μ = 1.2 (increase)		μ = 0.80 (decrease)	μ = 0.93 (baseline)	μ = 1.2 (increase)
	Computed Ice Jam Water Level (m)				Computed Ice Jam Water Level (m)		
XS #1	314.04	314.04	314.04	XS #28	na	na	na
XS #2	314.43	314.31	314.27	XS #29	321.28	320.80	320.06
XS #3	314.95	314.69	314.56	XS #30	321.67	321.19	320.47
XS #4	315.25	314.95	314.78	XS #31	321.76	321.28	320.57
XS #5	315.52	315.19	314.97	XS #32	321.98	321.50	320.81
XS #6	315.63	315.29	315.06	XS #33	322.29	321.81	321.14
XS #7	na	na	na	XS #34	322.70	322.23	321.59
XS #8	315.77	315.41	315.16	XS #35	322.96	322.50	321.87
XS #9	316.11	315.72	315.41	XS #36	323.26	322.80	322.17
XS #10	316.51	316.10	315.75	XS #37	323.51	323.05	322.42
XS #11	316.92	316.50	316.09	XS #38	324.10	323.64	323.03
XS #12	317.33	316.90	316.47	XS #39	324.44	324.00	323.38
XS #13	317.72	317.29	316.82	XS #40	324.85	324.42	323.80
XS #14	318.10	317.67	317.19	XS #41	325.42	324.99	324.37
XS #15	318.53	318.10	317.61	XS #42	326.03	325.62	325.02
XS #16	318.84	318.41	317.92	XS #43	326.53	326.15	325.58
XS #17	319.15	318.70	318.23	XS #44	326.87	326.51	325.97
XS #18	319.56	319.10	318.58	XS #45	327.24	326.92	326.43
XS #19	320.10	319.62	318.96	XS #46	327.51	327.21	326.78
XS #20	320.59	320.11	319.37	XS #47	327.75	327.45	327.07
XS #21	320.75	320.28	319.52	XS #48	328.19	327.82	327.45
XS #22	320.90	320.43	319.66	XS #49	328.69	328.32	327.91
XS #23	321.07	320.59	319.83	XS #50	329.00	328.64	328.22
XS #24	na	na	na	XS #51	329.43	329.09	328.66
XS #25	na	na	na	XS #52	329.73	329.40	328.99
XS #26	321.17	320.69	319.94	XS #53	330.06	329.77	329.40
XS #27	na	na	na	XS #54	330.44	330.20	329.89

na denotes cross sections that were omitted from the ice enhanced model for improved model performance (refer to Section 4.2.1)

Table 26 Sensitivity of Computed Ice Jam Water Levels to Variation in the Composite Roughness

Peace R. Cross Section	Composite Roughness n_o= 0.040 (decrease)	Composite Roughness n_o= 0.045 (baseline)	Composite Roughness n_o= 0.050 (increase)	Peace R. Cross Section	Composite Roughness n_o= 0.040 (decrease)	Composite Roughness n_o= 0.045 (baseline)	Composite Roughness n_o= 0.050 (increase)
	Computed Ice Jam Water Level (m)				Computed Ice Jam Water Level (m)		
XS #1	313.22	314.04	314.57	XS #28	na	na	na
XS #2	313.52	314.31	314.86	XS #29	320.14	320.80	321.42
XS #3	313.94	314.69	315.26	XS #30	320.51	321.19	321.82
XS #4	314.21	314.95	315.55	XS #31	320.60	321.28	321.91
XS #5	314.45	315.19	315.80	XS #32	320.82	321.50	322.13
XS #6	314.56	315.29	315.90	XS #33	321.12	321.81	322.45
XS #7	na	na	na	XS #34	321.55	322.23	322.85
XS #8	314.69	315.41	316.03	XS #35	321.79	322.50	323.12
XS #9	315.01	315.72	316.34	XS #36	322.09	322.80	323.42
XS #10	315.40	316.10	316.73	XS #37	322.35	323.05	323.67
XS #11	315.81	316.50	317.12	XS #38	322.96	323.64	324.27
XS #12	316.22	316.90	317.53	XS #39	323.33	324.00	324.60
XS #13	316.59	317.29	317.91	XS #40	323.75	324.42	325.03
XS #14	316.96	317.67	318.29	XS #41	324.33	324.99	325.60
XS #15	317.41	318.10	318.71	XS #42	324.98	325.62	326.23
XS #16	317.73	318.41	319.01	XS #43	325.52	326.15	326.75
XS #17	318.04	318.70	319.30	XS #44	325.89	326.51	327.10
XS #18	318.46	319.10	319.66	XS #45	326.34	326.92	327.48
XS #19	318.99	319.62	320.18	XS #46	326.65	327.21	327.75
XS #20	319.48	320.11	320.69	XS #47	326.90	327.45	327.99
XS #21	319.64	320.28	320.85	XS #48	327.26	327.82	328.38
XS #22	319.79	320.43	321.01	XS #49	327.71	328.32	328.90
XS #23	319.95	320.59	321.18	XS #50	328.02	328.64	329.23
XS #24	na	na	na	XS #51	328.45	329.09	329.69
XS #25	na	na	na	XS #52	328.77	329.40	330.00
XS #26	320.04	320.69	321.29	XS #53	329.16	329.77	330.35
XS #27	na	na	na	XS #54	329.62	330.20	330.76

na denotes cross sections that were omitted from the ice enhanced model for improved model performance (refer to Section 4.2.1)

5.5.4 Sensitivity Analysis Summary

Table 27 provides a summary of statistics on the results of the sensitivity analysis. For each sensitivity test, the differences between computed ice jam flood level for the baseline and test case were calculated. Statistics were then computed on these differences. Negative differences indicate a decrease from the baseline condition and positive differences indicate an increase from the baseline condition. Sensitivity to changes in the downstream water level are local and diminish upstream. For a 0.5 m increase or decrease in the downstream water level, the effects diminish to about 1 cm or less near cross section XS #12 (approximately 10 km upstream of the boundary – refer to **Figure 29**). The computed ice jam flood level profile was found to be less sensitive to changes in the upstream ice thickness. Changes in the upstream ice thickness of 0.5 m resulted in changes in the compute water levels of up to only 0.23 m. The tests found that increases in the upstream thickness had a slighter greater influence on the computed ice jam thickness profile (and consequently the computed water level) than decreases in upstream thickness (refer to **Table 24** and **Figure 30**). A decrease in the jam strength parameter resulted in a thicker ice jam profile and consequently, an overall increase in ice jam flood levels. Conversely, an increase in the ice jam strength parameter resulted in a thinner ice jam profile and caused an overall decrease in ice jam flood levels (refer to **Table 25** and **Figure 31**). Lastly, as for open water, an increase or decrease in Manning's roughness correspondingly increases or decreases the computed ice jam flood levels (refer to **Table 26** and **Figure 32**).

Table 27 Sensitivity Analysis Summary Statistics

Sensitivity Parameter	Parameter Change	Difference between Computed Flood Levels for Baseline and Sensitivity Test Condition (m)		
		Min.	Mean	Max.
Downstream water level (d/s WL)	Decrease d/s WL from 314.04 m to 313.54 m	0.01	-0.03	-0.50
	Increase d/s WL from 314.04 m to 314.54 m	-0.01	0.05	0.50
Upstream Ice Thickness (t_{head})	Decrease t_{head} from 3.2 m to 2.7 m	0.02	-0.02	-0.17
	Increase t_{head} from 3.2 m to 3.7 m	-0.03	0.07	0.23
Jam strength parameter (μ)	Decrease μ from 0.93 to 0.80	0.00	0.39	0.48
	Increase μ from 0.93 to 1.2	0.00	-0.49	-0.77
Composite Roughness (n_o)	Decrease n_o from 0.045 to 0.040	-0.55	-0.67	-0.82
	Increase n_o from 0.045 to 0.050	0.52	0.60	0.64

6 ICE JAM FLOOD INUNDATION MAPS

The ice jam flood inundation maps depict the extent of inundation associated with the 50-year, 100-year, and 200-year, ice jam design floods. The results of the analysis and mapping are provided in Appendix B (*Ice Jam Flood Inundation Maps*).

6.1 Methodology

The methodology for developing the ice jam flood inundation maps followed the same methods used for developing the open water flood inundation maps as described under a separate cover in the ***Open Water Flood Inundation Mapping*** report. The extent of inundation mapping was determined by conducting a spatial analysis on two primary data sets: computed water surface elevation planes and flood plain topography. The computed water surface elevation planes were determined by interpolation of the projection of water surface elevation values along and between model cross section transect lines. The flood plain topography was represented by the digital terrain model (DTM) supplied by AEP. Standard ArcGIS toolsets were applied to conduct the spatial analysis. The following provides an overview of the methodology.

A cross section polyline feature data set was prepared in ArcGIS as follows to support the flood inundation mapping:

- A water surface elevation field was created in the cross section data set for each of the three flood frequency scenarios. Then, the computed water surface elevation values were assigned to the corresponding flood frequency fields for each individual cross section features (cross section lines).
- Left and right endpoints of the cross section lines were extended outward, as needed, such that straight lines connecting the endpoints of adjacent cross sections remained outside the 200-year flood extents. This ensured that the intersection of the flood elevation planes and the DTM would capture the full extent of inundation.

A boundary polygon was generated that enclosed all of the cross sections; this polygon defined the limits of the spatial analysis (or clipping extent) for determining inundated areas. Automated routines were then used to complete the following tasks in ArcGIS for each of the flood scenarios:

- A triangular irregular network (TIN) representing a continuous water surface elevation (WSE) profile along the study reach was generated for each flood scenario, based on the computed WSE at each cross section line; between cross section lines, WSE was linearly interpolated.
- The WSE TIN was converted to a tiled set of preliminary WSE grids. The WSE grid tiles matched the alignment and horizontal resolution of the LiDAR-derived bare earth DTM tiles supplied by AEP.

- Each bare earth DTM grid tile was subtracted from the corresponding WSE grid tile to generate a tiled set of flood depth grids. Grid cells with depth values less than 0 m, which represent dry areas, were assigned a value of *NoData*.
- Based on the depth grids, all areas with depths greater than 0 m were converted to inundation polygons. A simplification was applied in the raster to polygon conversion, so that the polygon boundaries do not exactly follow the edge of each raster cell.
- Filtering was used to remove isolated inundation areas smaller than 100 m^2. Holes less than 100 m^2 in area were also removed from the inundation extents.

The resulting inundation polygons were then reviewed to identify direct overtopping in overbank areas. An adjusted version of the WSE TIN was created to reflect any edits made, and the above steps were repeated to produce adjusted WSE grids, depth grids, and inundation polygons.

The adjusted inundation polygons were smoothed in ArcGIS. A *PAEK* smoothing algorithm was applied with a 20 m tolerance. This allowed for an inundation boundary that is smoothed, but remains very similar to the original inundation polygon output. The smoothed inundation polygons were further reviewed in ArcGIS and classified to identify inundation of isolated areas and areas of potential flood control structure failure.

The final smoothed inundation extent polygons were used to clip the WSE grid tiles. The resulting WSE grids have *NoData* values for all dry areas, but retain WSE values wherever inundation is shown.

GIS deliverables include (for each flood scenario):

- Model cross sections with computed ice jam flood frequency levels attached as attributes (polyline layer in Esri file geodatabase format).
- Preliminary WSE TIN, based on computed ice jam flood frequency levels, without adjustments to account for overtopping areas (Esri TIN format).
- Adjusted WSE TIN, including adjustments to account for direct overtopping in overbank areas (Esri TIN format).
- Tiled flood depth grids (Esri file geodatabase grid feature class format).
- Smoothed flood inundation extent polygons, with polygons classified as inundation extents, isolated areas, or potential flood control structure failure areas (polygon layer in Esri file geodatabase format).
- Tiled WSE grids, clipped to the inundation extent polygons (Esri file geodatabase grid feature class format).

6.2 Direct Flood Inundation Areas

Direct 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. Areas showing extensive overbank flooding directly 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 cases where the adjustments resulted in a new overtopping point, the water surface elevations in the overbank area were re-adjusted such that they were interpolated linearly between the upstream overtopping point and the ground elevation at the new downstream overtopping point. The direct inundation area behind the dike in Lower West Peace was treated in this manner; however, an exception was made for areas behind the dike through TPR downstream of the Heart River confluence.

Exception: An exception to the approach for direct inundation was made for the 50-year and 100-year ice jam design floods where water entered overtop of or around the dike into the Town of Peace River, near the Heart River confluence. For these cases, the water surface profile behind the dike was assumed to follow the water surface profile in the main channel. It was assumed that if water entered behind the dikes during a major flood, the flows would eventually re-enter at some point further downstream and establish a water level profile that followed the river profile in the adjacent main channel.

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 6.1 above.

6.3 Indirect Flood Inundation Areas

Indirect flood inundation areas were identified as having ground elevations below the water surface but no direct overland connection to the actively flowing river channel based on the surrounding topography. Two types of indirect flood inundation areas were identified for mapping purposes: isolated areas and areas of potential flooding due to flood control structure failure.

6.3.1 Inundation of Isolated Areas

Isolated areas, mapped using water surface elevations interpolated between cross sections, could potentially become inundated during a flood due to subsurface flow through porous media or flooding of buried pipes and culverts. Inundated areas behind embankments not identified as dedicated flood control structures, such as roads, railways, and berms, were also considered isolated areas.

6.3.2 Inundation Due to Potential Flood Control Structure Failure

Inundation due to flood control structure failure was handled as follows for the various ice jam flooding scenarios.

Lower West Peace, 50-year Ice Jam Flood: For the 50-year ice jam flood, the dike was not overtopped and the area behind the flood control structure was treated as inundation due to potential failure in the usual manner. The inundation extent of the protected area was determined by extending the water surface elevation from the river in main channel into the area behind the flood control structure.

Lower West Peace, 100-year Ice Jam Flood: For the 100-year ice jam flood, the downstream portion of the dike was overtopped with the point of overtopping located approximately 55 m upstream of XS #31. The extent of inundation, was determined by the usual methods for both direct inundation and inundation due to potential flood control structure failure. The differences in water levels by the two methods varied by up to 0.5 m, yet since the extents of inundation followed a steep bank, the differences in the extent of inundated areas were imperceptively small. The areas behind the dike depicted in the 100-year ice jam flood inundation mapping (Appendix B) were mapped according to the methods for direct inundation described in Section 6.2. The small additional area due to a potential flood control structure failure were not included as they would have been imperceptible in the mapping.

Lower West Peace, 200-year Ice Jam Flood: For the 200-year ice jam flood, the entire length of the dike was overtopped and the water surface profile followed that of the river in the main channel. Thus, the extent of inundation behind the dike was determined by the usual methods for direct inundation.

Town of Peace River, 50-year and 100-year Ice Jam Floods: For the 50-year and 100-year ice jam floods, the dike is overtopped in the upstream portions near the Heart River confluence and beside the bridge over the Heart River at 101st Street. As described in the previous section (Section 6.2), the area of direct inundation behind the dikes were assumed to follow the same water surface profile as the river in the main channel. Consequently, the extent of inundation is the same as that would have been determined for a potential flood control structure failure. The areas behind the dike depicted in the 50-year and 100-year ice jam flood inundation mapping (Appendix B) were mapped according to the methods for direct inundation as was assumed for this particular case. Areas associated with flooding due to a potential flood control structure are the same and thus do not appear on the mapping.

Town of Peace River, 200-year Ice Jam Flood: For the 200-year ice jam flood, the entire length of the dike was overtopped and the water surface profile followed that of the river in the main channel. Thus, the extent of inundation behind the dike was determined by the usual methods for direct inundation.

6.4 Areas Affected by Flooding

6.4.1 Flooding of Residential Areas

The majority of residential areas and buildings affected by flooding are behind the dikes within the Town of Peace River and Lower West Peace. Areas affected by flooding in Lower West Peace result from direct overtopping of the dike for the 100-year and 200-year ice jam floods. Flooding by direct overtopping in the Town of Peace River result from the 50-year, 100-year, and 200-year ice jam floods. There are also a number of residential areas upstream of town along Shaftesbury trail, on the left bank of the Peace River that are affected by flooding from the 50-year, 100-year, and 200-year ice jam floods including: residences about 1 km upstream of Shaftesbury Crossing (near cross section # 51); and residences about 1.5 km downstream of the Correctional Centre (near cross section # 41).

Further statistics regarding impacted structures are presented within the ***Flood Risk Assessment and Inventory*** report provided under a separate cover.

6.4.2 Flooding of Non-Residential Areas

Most of the non-residential areas (including commercial and light industrial buildings) subjected to flooding are located behind the dikes within the Town of Peace River. There are also a number of other non-residential areas affected by flooding upstream and downstream of the townsite including: Shaftesbury Ferry (cross section # 50); the Correctional Centre (cross section # 42); water treatment plant intake building (between cross sections # 36 & # 37); and the Diaishowa pulp mill (between cross sections # 2 & # 6).

Further statistics regarding these impacted areas are presented within the ***Flood Risk Assessment and Inventory*** report provided under a separate cover.

6.4.3 Flooding of Bridges

The low chord elevation of all bridges crossings along the Peace River study reach are all above the 200-year ice jam flood level. Along the Heart River, the low chord of all bridges will be impacted by flooding from the 50-year, 100-year, and 200-year ice jam floods with the exception of the CNR bridge crossing, which spans the top of the valley and is some 30 m higher than the 200-year ice jam flood level. A summary of flood level elevations relative to the low chord elevation at each bridge is presented within the ***Flood Risk Assessment and Inventory*** report provided under a separate cover.

7 ICE JAM FLOOD HAZARD IDENTIFICATION

7.1 Ice Jam Design Flood Selection

The 100-year ice jam flood (as presented in Section 5) was selected as the ice jam design flood for flood hazard identification. The ice jam design flood, as is depicted by the fully developed ice jam flood profile plot and flood inundation mapping, is not necessarily meant to represent an actual single, static, ice jam flood event. In fact, it is rather unlikely that a single, fully developed, ice jam accumulation would extend along the entire Peace River study reach as a single mass, at a single point in time. The more appropriate way to interpret the ice jam design flood event scenario is that, anywhere along the study reach, a 100-year ice jam may develop and produce the 100-year ice jam flood levels. The flood levels would extend over some distance along the river within the study reach. It is assumed that there is an equal likelihood everywhere along the study reach of being impacted up to the full 100-year ice jam flood levels.

7.2 Floodway & Flood Fringe Terminology

Flood Hazard Area

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

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.

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 100-year 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 100-year 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.

7.3 Ice Jam 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 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.

Flood hazard identification for the design flood governed by an ice jam flood uses modified criteria from the open water flood hazard identification. Flow velocities are not considered when defining the floodway due to the backwater conditions associated with an ice jam.

The stations delineating the floodway limits are listed by cross section for the Peace River and Heart River in **Tables 28** and **29**, respectively.

The floodway boundary extending between cross sections was delineated based on the adjacent governing criteria and drawn such that the resulting lines followed a hydraulically-smooth path. In most instances, the lines followed along the 1 m depth contour. When the width of the flood fringe was impractically small, the floodway line was drawn coincident with the edge of inundation. In areas adjacent to dedicated flood berms, the floodway was drawn along the river-side of the dedicated flood berm if not overtopped, or along the centreline of the dedicated flood berm if overtopped.

Table 28 Floodway Stations and Determination Criteria on the Peace River

Peace R. Cross Section	Left Overbank		Right Overbank		Peace R. Cross Section	Left Overbank		Right Overbank	
	Station (m)	Criteria	Station (m)	Criteria		Station (m)	Criteria	Station (m)	Criteria
XS #1	80.7	1m D.	992.9	1m D.	XS #28	na	na	na	na
XS #2	196.6	1m D.	1213.9	1m D.	XS #29	133.4	1m D.	549.7	FCS
XS #3	745.7	1m D.	1369.3	1m D.	XS #30	332.0	FCS	826.7	FCS
XS #4	892.5	1m D.	1439.9	1m D.	XS #31	287.7	FCS	794.6	FCS
XS #5	573.3	1m D.	1087.4	1m D.	XS #32	427.7	FCS	958.4	FCS
XS #6	209.8	1m D.	771.3	1m D.	XS #33	182.0	1m D.	1200.3	1m D.
XS #7	na	na	na	na	XS #34	160.0	1m D.	1259.2	1m D.
XS #8	295.4	1m D.	1077.3	1m D.	XS #35	287.0	1m D.	1286.1	1m D.
XS #9	219.3	1m D.	1314.3	1m D.	XS #36	327.4	1m D.	1254.1	1m D.
XS #10	137.3	1m D.	1206.6	1m D.	XS #37	386.5	1m D.	1707.6	1m D.
XS #11	147.3	1m D.	916.2	1m D.	XS #38	647.1	1m D.	1724.6	1m D.
XS #12	301.4	1m D.	1059.9	1m D.	XS #39	516.4	1m D.	1147.3	1m D.
XS #13	122.1	1m D.	895.7	1m D.	XS #40	584.6	1m D.	1074.6	1m D.
XS #14	120.6	1m D.	972.3	1m D.	XS #41	434.4	1m D.	1322.2	1m D.
XS #15	528.7	1m D.	1362.8	1m D.	XS #42	643.8	IB (HW)	1429.1	1m D.
XS #16	383.3	1m D.	1259.7	1m D.	XS #43	463.5	1m D.	1581.0	1m D.
XS #17	261.0	1m D.	1270.6	1m D.	XS #44	369.7	1m D.	1429.3	1m D.
XS #18	554.0	1m D.	2019.4	1m D.	XS #45	750.8	1m D.	1722.2	1m D.
XS #19	167.3	1m D.	1356.1	FCS	XS #46	1013.1	1m D.	1918.0	1m D.
XS #20	158.8	1m D.	1272.5	FCS	XS #47	1007.6	1m D.	1927.1	1m D.
XS #21	218.9	1m D.	1173.9	FCS	XS #48	553.0	1m D.	1644.4	1m D.
XS #22	162.7	1m D.	898.4	FCS	XS #49	306.0	1m D.	876.0	1m D.
XS #23	162.9	1m D.	697.8	FCS	XS #50	200.4	1m D.	800.1	1m D.
XS #24	na	na	na	na	XS #51	598.0	1m D.	1112.9	1m D.
XS #25	na	na	na	na	XS #52	826.9	1m D.	1537.9	1m D.
XS #26	244.8	1m D.	700.3	FCS	XS #53	557.8	1m D.	1313.8	1m D.
XS #27	na	na	na	na	XS #54	288.5	1m D.	1340.8	1m D.

na denotes cross sections that were omitted from the ice enhanced model for improved model performance (refer to Section 4.2.1)
1m D. denotes the 1 m depth criterion
FCS denotes the flood control structure criterion and floodway limit is specified along the river-side of the dedicated flood berm if not overtopped, or along the centreline of the dedicated flood berm if overtopped
IB (HW) denotes the interior boundary condition and floodway limit is specified on interior side of highway

Table 29 Floodway Stations and Determination Criteria on the Heart River

Heart R. Cross Section	Left Overbank		Right Overbank		Heart R. Cross Section	Left Overbank		Right Overbank	
	Station (m)	Criteria	Station (m)	Criteria		Station (m)	Criteria	Station (m)	Criteria
XS #55	312.7	FCS	377.5	FCS	XS #69	11.7	1m D.	135.7	1m D.
XS #56	272.5	FCS	327.7	FCS	XS #70	13.9	1m D.	149.4	1m D.
XS #57	248.2	FCS	299.8	FCS	XS #71	21.5	1m D.	155.1	1m D.
XS #58	190.0	FCS	238.7	FCS	XS #72	20.8	1m D.	115.1	1m D.
XS #59	152.8	FCS	213.2	FCS	XS #73	19.4	1m D.	108.7	1m D.
XS #60	140.4	FCS	200.6	FCS	XS #74	18.4	1m D.	115.1	1m D.
XS #61	116.8	FCS	169.7	FCS	XS #75	23.7	1m D.	115.7	1m D.
XS #62	90.1	FCS	144.1	FCS	XS #76	27.6	1m D.	115.7	1m D.
XS #63	80.8	FCS	137.9	FCS	XS #77	9.8	1m D.	113.6	1m D.
XS #64	77.6	FCS	112.0	1m D.	XS #78	31.0	1m D.	125.7	1m D.
XS #65	79.7	FCS	110.6	1m D.	XS #79	41.4	1m D.	129.8	1m D.
XS #66	73.5	FCS	125.1	1m D.	XS #80	62.7	1m D.	120.2	1m D.
XS #67	54.4	FCS	160.4	1m D.	XS #81	27.4	1m D.	129.9	1m D.
XS #68	15.0	FCS	141.7	1m D.					

na denotes cross sections that were omitted from the ice enhanced model for improved model performance (refer to Section 4.2.1)
1m D. denotes the 1 m depth criterion
FCS denotes the flood control structure criterion and floodway limit is specified along the river-side of the dedicated flood berm if not overtopped, or along the centreline of the dedicated flood berm if overtopped

7.4 Ice Jam Design Flood Levels

The ice jam design flood levels are those computed by the 100-year ice jam flood level profile. **Table 30** and **Table 31** summarize the ice jam design flood levels.

Table 30 Ice Jam Design Flood Levels on the Peace River

Peace R. Cross Section	Ice Jam Design Flood Level (m)	Peace R. Cross Section	Ice Jam Design Flood Level (m)
XS #1	314.04	XS #28	na
XS #2	314.31	XS #29	320.80
XS #3	314.69	XS #30	321.19
XS #4	314.95	XS #31	321.28
XS #5	315.19	XS #32	321.50
XS #6	315.29	XS #33	321.81
XS #7	na	XS #34	322.23
XS #8	315.41	XS #35	322.50
XS #9	315.72	XS #36	322.80
XS #10	316.10	XS #37	323.05
XS #11	316.50	XS #38	323.64
XS #12	316.90	XS #39	324.00
XS #13	317.29	XS #40	324.42
XS #14	317.67	XS #41	324.99
XS #15	318.10	XS #42	325.62
XS #16	318.41	XS #43	326.15
XS #17	318.70	XS #44	326.51
XS #18	319.10	XS #45	326.92
XS #19	319.62	XS #46	327.21
XS #20	320.11	XS #47	327.45
XS #21	320.28	XS #48	327.82
XS #22	320.43	XS #49	328.32
XS #23	320.59	XS #50	328.64
XS #24	na	XS #51	329.09
XS #25	na	XS #52	329.40
XS #26	320.69	XS #53	329.77
XS #27	na	XS #54	330.20

Table 31 Ice Jam Design Flood Levels on the Heart River

Heart R. Cross Section	Ice Jam Design Flood Level (m)	Heart R. Cross Section	Ice Jam Design Flood Level (m)
XS #55	321.25	XS #69	321.33
XS #56	321.25	XS #70	321.35
XS #57	321.25	XS #71	321.36
XS #58	321.25	XS #72	321.38
XS #59	321.25	XS #73	321.42
XS #60	321.25	XS #74	321.48
XS #61	321.25	XS #75	321.50
XS #62	321.26	XS #76	321.55
XS #63	321.26	XS #77	321.61
XS #64	321.26	XS #78	321.70
XS #65	321.26	XS #79	321.83
XS #66	321.32	XS #80	322.03
XS #67	321.32	XS #81	322.31
XS #68	321.32		

7.5 Ice Jam Floodway Criteria Maps

The ice jam floodway criteria maps depict the results of the ice jam flood hazard assessment and delineation of the floodway boundary. The floodway mapping, provided in Appendix C (*Ice Jam Floodway Criteria Map*), illustrate the following:

- inundation extents for the 100-year ice jam design flood;
- areas where the depth of water is 1 m or greater and the corresponding 1 m depth contour;
- the floodway station locations;
- the floodway boundary;
- stranded areas of high ground within the flood hazard area; and
- the location and extent of all cross sections used in the HEC-RAS model.

Additional information concerning the flood criteria map production is provided below.

7.6 Methodology

The calibrated HEC-RAS model was used to generate water surface elevations for the ice jam design flood which was based on the water surface elevations for the 100-year ice jam flood – as previously described under Section 7.2. The extent of inundation was mapped using the general procedure described under in Section 6.1; a water surface elevation (WSE) triangular irregular network (TIN), WSE grid, and flood depth grid for the ice jam design flood were also generated as part of the above process.

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 (see also Section 6.1).

A short segment of the Smoky River above the mouth was included in the study area; however, this reach was not included in the hydraulic model, as discussed under separate cover in the ***Hydraulic Model Creation and Calibration*** report. The 1 m depth criterion was also the governing criteria when determining the floodway limits along this segment.

7.7 Areas in the Floodway

Notable overbank areas in the floodway include:

- Twelve Foot Davis Park.

The floodway boundaries were carried into the mouths of small tributaries, following the governing criteria established for adjacent cross sections on the Peace River.

More information and statistics regarding existing infrastructure and property within the floodway can be found in the ***Flood Risk Assessment and Inventory*** report, provided under separate cover.

7.8 Areas in the High Hazard Flood Fringe

The high hazard flood fringe includes areas outside of the floodway that are directly inundated by the 100-year ice jam design flood and deeper than 1 m. The notable overbank areas in the high hazard flood fringe include:

- the Lower West Peace townsite;
- low-lying portions of downtown Peace River between the Heart River and the Canadian National Railway (CNR) bridge over the Peace River; and
- low-lying portions of the Peace River townsite adjacent to the east dike downstream of the Highway 2 bridges.

More information regarding infrastructure and property within the high hazard flood fringe can be found in the ***Flood Risk Assessment and Inventory*** report, provided under separate cover.

7.9 Areas in the Flood Fringe

The flood fringe includes the remaining area directly inundated by the 100-year ice jam design flood, but outside of both the floodway and the high hazard flood fringe. Significant areas in the flood fringe include low-lying:

- portions of downtown Peace River upstream of the CNR bridge; and
- residential and commercial developments downstream of the Highway 2 bridge on the east side of the Peace River.

More information regarding infrastructure and property within the flood fringe can be found in the ***Flood Risk Assessment and Inventory*** report, provided under separate cover.

8 ICE JAM FLOOD ELEVATION GRIDS

Water surface elevation grids were prepared for each flood scenario and provided with the GIS deliverables for this study component, along with the WSE TINs, flood depth grids, and inundation extent polygons. A description of the water surface elevation grids is provided below.

8.1 Water Surface Elevation Grid Specifications

For each of the flood scenarios, the adjusted WSE TINs described in Section 6.1 were converted to a tiled set of WSE grids matching the alignment, horizontal resolution, and tiling boundaries of the LiDAR-derived DTM supplied by AEP. Water surface elevations in metres are provided as 32-bit floating point grid cell values. The WSE grids at this stage were used to compute the flood depth grids, as described in Section 6.1.

As a final step, the inundation extent polygons generated from the flood depth grids were used to clip the WSE grids such that a value of *NoData* is provided for all dry areas and the water surface elevation values are indicated only where inundation is shown.

8.2 General Comments

WSE grids are provided for information only. Grid cell values are based on linear interpolation between cross sections in the hydraulic model, and as such, discrete cell values should be considered approximate. Since the adjusted WSE grids have been clipped using the smoothed inundation extent polygons, water's edge boundaries implied by the raster WSE grids correspond to the inundation extent boundaries presented on the inundation maps.

9 FLOOD DEPTH GRIDS

Flood depth grids were prepared for each flood scenario and provided with the GIS deliverables for this study component, along with the WSE TINs, WSE grids, and inundation extent polygons. A description of the flood depth grids is provided below.

9.1 Flood Depth Grid Specifications

For each of the flood scenarios, each bare earth DTM grid tile was subtracted from the corresponding adjusted WSE grid tile (prior to clipping) to generate a set of flood depth grid tiles representing water depth in metres as 32-bit floating point values. All flood depth grids maintained the same alignment, horizontal resolution, and tiling boundaries as the LiDAR-derived bare earth DTM supplied by AEP. Grid cells with depth values less than 0 m, which represent dry areas, were assigned a value of *NoData*.

9.2 General Comments

The flood depth grids are provided for information only. Grid values are based on linear interpolation of water surface elevations between cross sections in the hydraulic model, and as such, discrete cell values should be considered approximate. Water's edge boundaries implied by the raster depth grids may deviate slightly from the inundation extent boundaries presented on the inundation maps. This is because the depth grids are computed by subtracting the bare earth DTM grids from the adjusted water surface grids, whereas the mapped inundation extent boundaries, which were derived from the depth grids, have been further filtered and smoothed as discussed in Section 6.1.

Also, since the LiDAR-derived DTM indicates the approximate water surface elevation at the time of the LiDAR survey for submerged portions of river beds and other ground covered by water, depth values in those areas should not be considered accurate. Elsewhere, the depth grids may be used for many purposes, such as to identify areas in the floodplain that exceed a specified depth criteria. For example, these data were used to delineate the 1 m depth contour to support flood hazard identification for this study.

10 CONCLUSIONS

The objectives of this study were to assess river and flood-related hazards along a 54 km reach of the Peace River and a 1.1 km reach of the Heart River that includes the Town of Peace River. The Peace River Hazard Study was divided into nine major project components. This report summarizes the work of the sixth component – ***Ice Jam Modelling Assessment & Flood Hazard Identification***.

The Peace River and Heart River ice jam flood history was documented, including a summary of historic ice jam flood events. The historic flood accounts were supported with an overview of the Peace River ice regime. Different types of ice accumulations were used to characterize the ice regime including: freeze-up ice jams; break-up ice jams; and secondary consolidations. An understanding of the ice regime was necessary for developing a method to calculate ice jam flood frequencies.

An ice jam flood frequency analysis was conducted using a Monte Carlo analysis which used statistical methods to quantify the causative factors contributing to the characteristics of the observed flood level data as a whole. Flood frequency estimates were made for freeze-up, breakup, and peak annual conditions. Flood frequency estimates for the Heart River used Monte Carlo methods to account for interactions with the Peace River.

An ice enhanced model was created based on modifications to the calibrated open water model. The model was enhanced by adjusting the model geometry and accounting for ice jam properties. Ice jam roughness was calibrated to match computed ice jam profiles to recorded historic ice jam high water level profiles. The calibrated ice enhanced model was then used to calculate the ice jam flood frequency profiles on the Peace River and Heart Rivers for the 50-year, 100-year, and 200-year ice jams.

Water levels computed by the ice enhanced model were used to develop the ice jam flood inundation maps. The methods used to develop the maps were the same as those used for the open water mapping. The results of the inundation mapping analysis identified notable flooding within the Lower West Peace townsite; low-lying portions of downtown Peace River between the Heart River and the Canadian National Railway (CNR) bridge over the Peace River; low-lying portions of the Peace River townsite adjacent to the east dike downstream of the Highway 2 bridges; and Twelve Foot Davis park. More information and statistics regarding infrastructure and property within flooded areas can be found in the ***Flood Risk Assessment and Inventory*** report, provided under separate cover.

The velocity criteria was not applicable for 100-year ice jam design flood and the location of the floodway limits were mostly specified at the 1 m depth. In areas adjacent to dedicated flood berms, the floodway was drawn along the river-side of the dedicated flood berm if not overtopped, or along the centreline of the dedicated flood berm if overtopped. The results of the ice jam flood hazard identification work formed the basis of information used in the subsequent flood hazard mapping work, summarized in the ***Governing Design Flood Hazard Map Production*** report, provided under separate cover.

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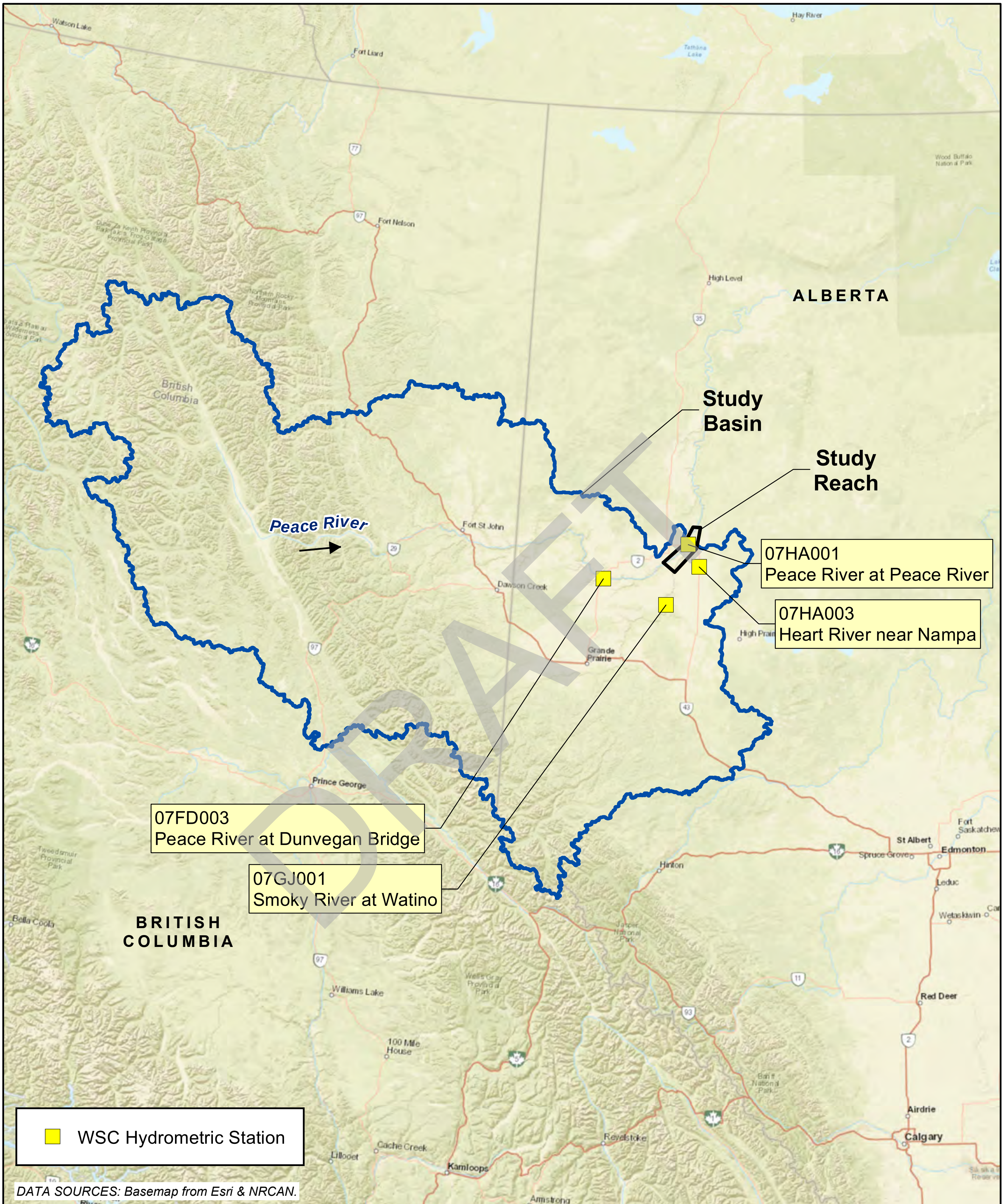
Figures



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SCALE - 1:5,000,000

0 100 200 KM

N

Coordinate System: NAD 1983 CSRS 10TM AEP FOREST
Units: METRES

Job: 1001119

Date: 15-JUN-2018

PEACE RIVER HAZARD STUDY

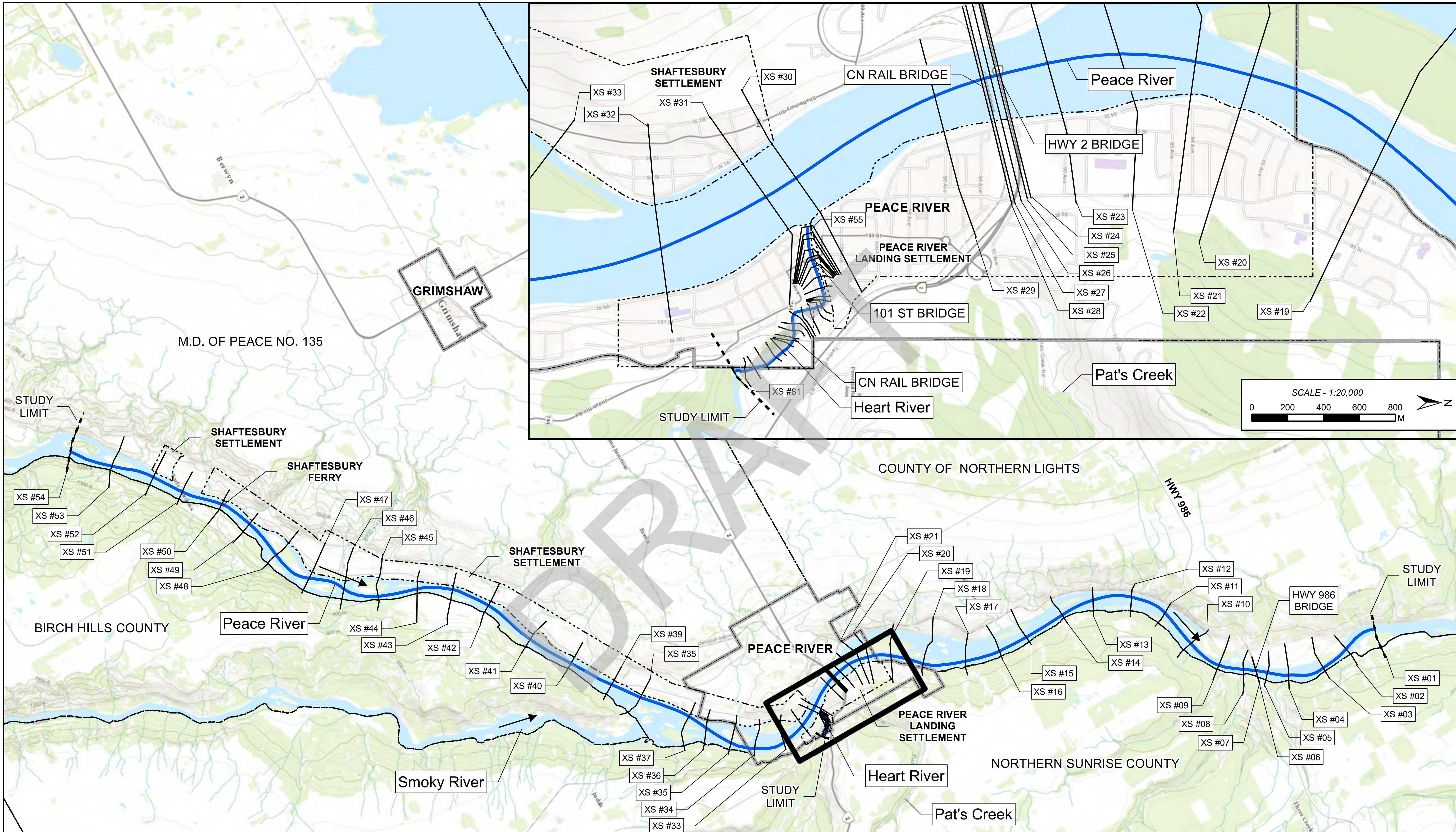
ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION

LOCATION MAP

FIGURE 1

MSN, \\mainfile-van\Projects\Active\1001119 Peace River Flood Hazard Study\GIS\1001119_MSN_Fig_T600_LocnMap2.mxd

Classification: Public



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Model Stream Network
Model Cross Section
Settlement
Town
County or Municipal District

DATA SOURCES: Basemap from Esri & NRCAN.

SCALE - 1:130,000
0 1 2 3 4 5 KM

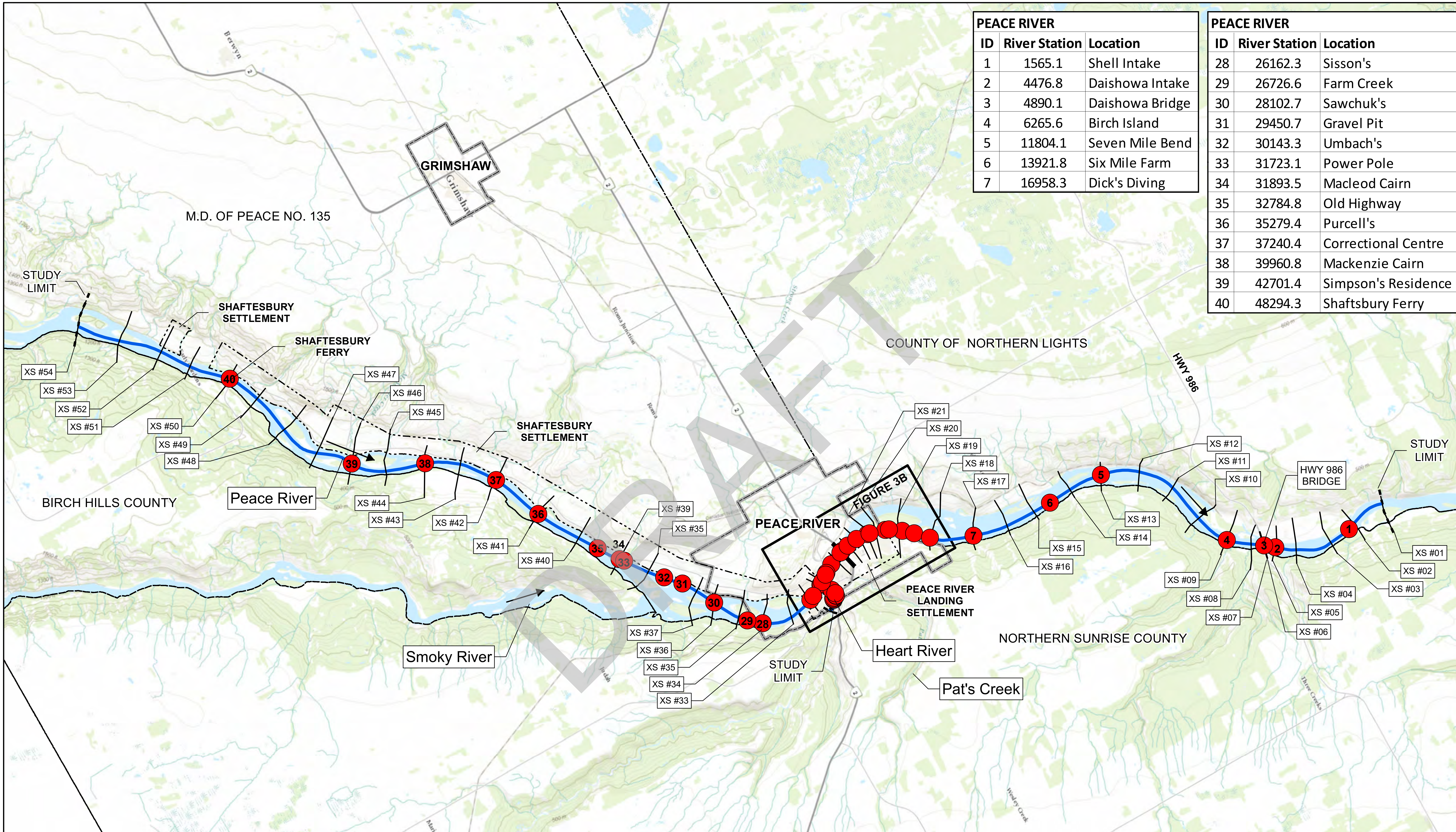
Coordinate System: NAD 1983 CSRS 3TM 117
Units: METRES

Job: 1001119 Date: 15-JUN-2018

PEACE RIVER HAZARD STUDY
ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION
STUDY AREA
FIGURE 2

MSN_\\nanfile-van\Projects\Active\1001119 Peace River Flood Hazard Study\GIS\1001119_MSN_Fig_T600_StudyAreaB4.mxd

Classification: Public



PEACE RIVER		
ID	River Station	Location
1	1565.1	Shell Intake
2	4476.8	Daishowa Intake
3	4890.1	Daishowa Bridge
4	6265.6	Birch Island
5	11804.1	Seven Mile Bend
6	13921.8	Six Mile Farm
7	16958.3	Dick's Diving

PEACE RIVER		
ID	River Station	Location
28	26162.3	Sisson's
29	26726.6	Farm Creek
30	28102.7	Sawchuk's
31	29450.7	Gravel Pit
32	30143.3	Umbach's
33	31723.1	Power Pole
34	31893.5	Macleod Cairn
35	32784.8	Old Highway
36	35279.4	Purcell's
37	37240.4	Correctional Centre
38	39960.8	Mackenzie Cairn
39	42701.4	Simpson's Residence
40	48294.3	Shaftsbury Ferry

Model Stream Network
Model Cross Section
Highwater Mark
Settlement
Town
County or Municipal District

Highwater marks are presented along the river centreline to show their approximate locations along the study reach. Precise measurement locations are unknown for most highwater mark observations.

DATA SOURCES: Basemap from Esri & NRCAN.

SCALE - 1:130,000

0 1 2 3 4 5 KM

Coordinate System: NAD 1983 CSRS 3TM 117
Units: METRES

Job: 1001119 *Date: 15-JUN-2018*

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PEACE RIVER HAZARD STUDY

ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION

HIGHWATER HAZARD MARK LOCATIONS

FIGURE 3A

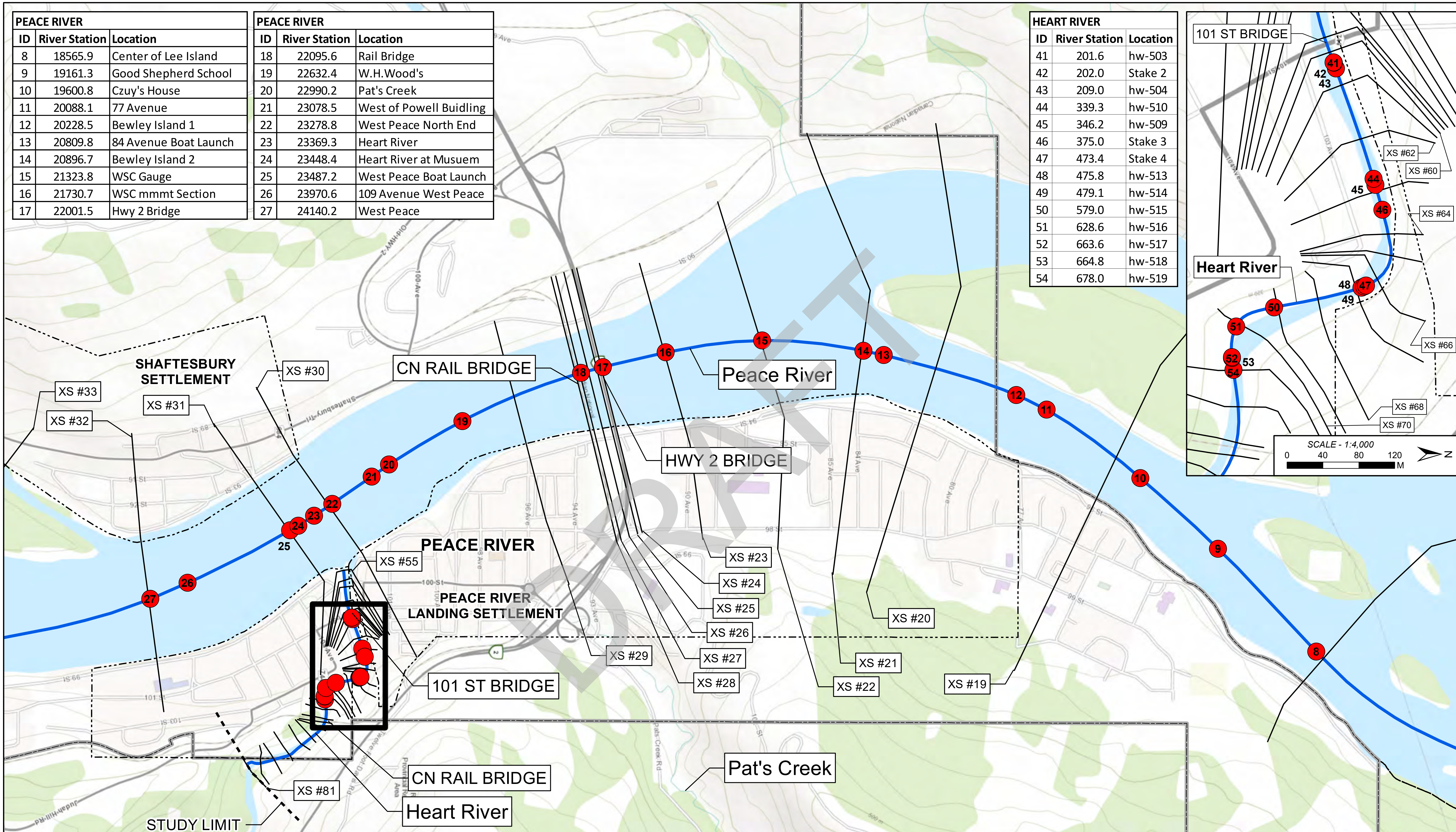
MSN_\\nhcfile-van\Projects\Active\1001119 Peace River Flood Hazard Study\GIS\1001119_MSN_Fig_T600_HWM4_Sheet1.mxd

Classification: Public

PEACE RIVER		
ID	River Station	Location
8	18565.9	Center of Lee Island
9	19161.3	Good Shepherd School
10	19600.8	Czuy's House
11	20088.1	77 Avenue
12	20228.5	Bewley Island 1
13	20809.8	84 Avenue Boat Launch
14	20896.7	Bewley Island 2
15	21323.8	WSC Gauge
16	21730.7	WSC mmmt Section
17	22001.5	Hwy 2 Bridge

PEACE RIVER		
ID	River Station	Location
18	22095.6	Rail Bridge
19	22632.4	W.H.Wood's
20	22990.2	Pat's Creek
21	23078.5	West of Powell Buidling
22	23278.8	West Peace North End
23	23369.3	Heart River
24	23448.4	Heart River at Musuem
25	23487.2	West Peace Boat Launch
26	23970.6	109 Avenue West Peace
27	24140.2	West Peace

HEART RIVER		
ID	River Station	Location
41	201.6	hw-503
42	202.0	Stake 2
43	209.0	hw-504
44	339.3	hw-510
45	346.2	hw-509
46	375.0	Stake 3
47	473.4	Stake 4
48	475.8	hw-513
49	479.1	hw-514
50	579.0	hw-515
51	628.6	hw-516
52	663.6	hw-517
53	664.8	hw-518
54	678.0	hw-519



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Model Stream Network
Model Cross Section
Highwater Mark
Settlement
Town
County or Municipal District

Highwater marks are presented along the river centreline to show their approximate locations along the study reach. Precise measurement locations are unknown for most highwater mark observations.

DATA SOURCES: Basemap from Esri & NRCAN.

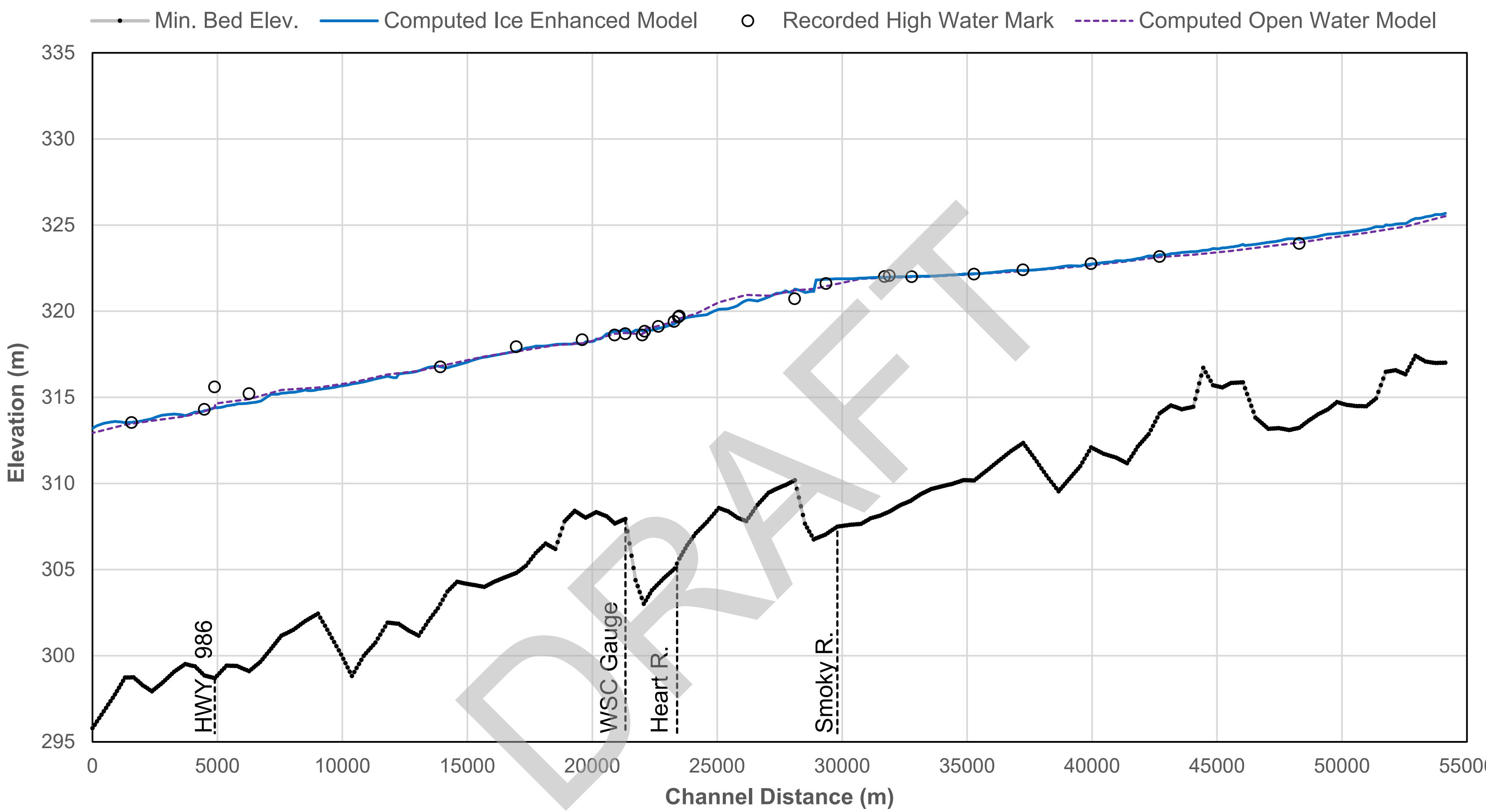
SCALE - 1:15,000
0 100 200 300 400 500 600 M

Coordinate System: NAD 1983 CSRS 3TM 117
Units: METRES

Job: 1001119 | Date: 15-JUN-2018

PEACE RIVER HAZARD STUDY
ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION
HIGHWATER MARK LOCATIONS
FIGURE 3B

MSN_\\nanfile-van\Projects\Active\1001119 Peace River Flood Hazard Study\GIS\1001119_MSN_Fig_T600_HWM4_Sheet2.mxd



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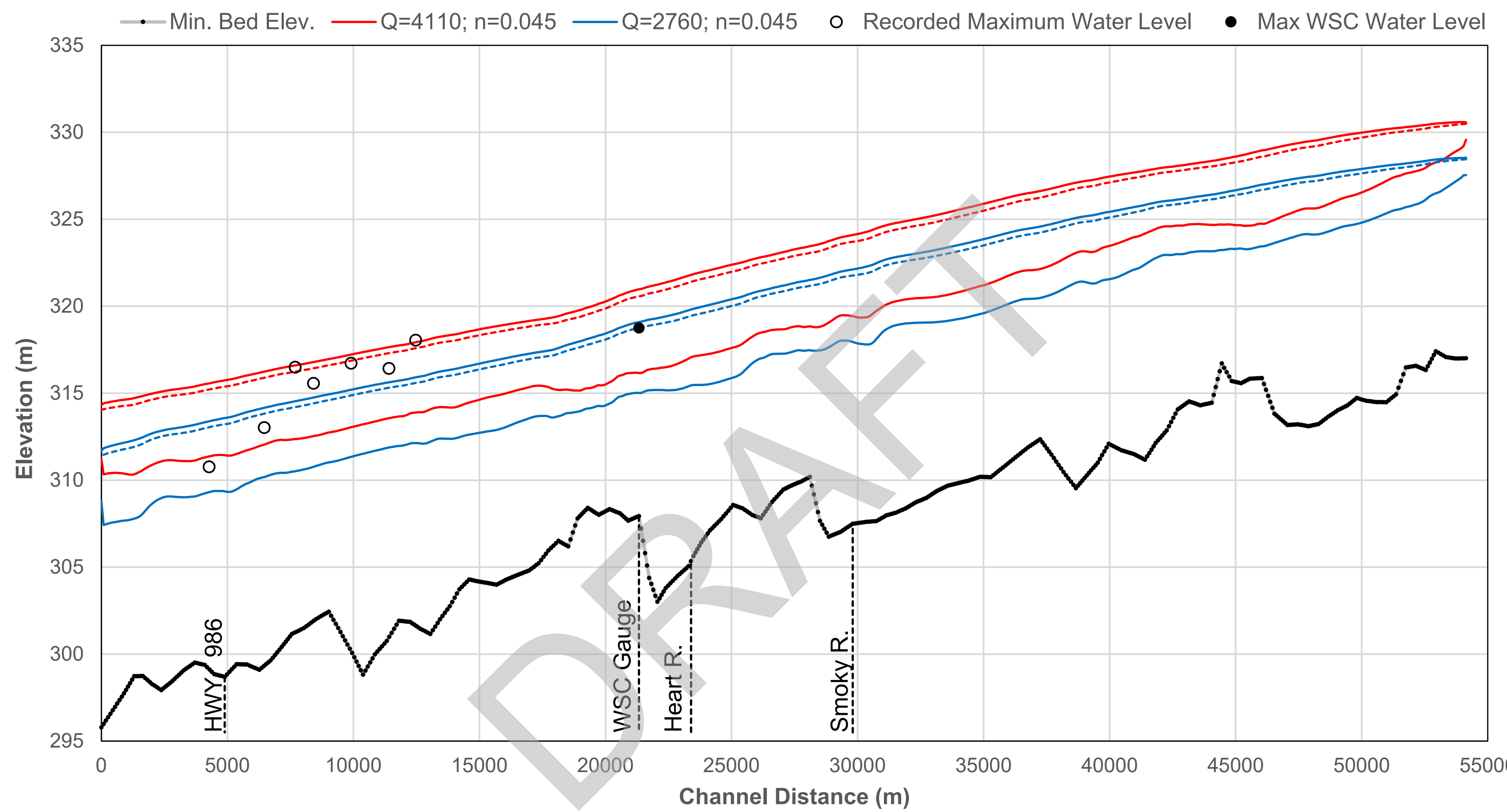
ALBERTA ENVIRONMENT AND PARKS		
PEACE RIVER HAZARD STUDY ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION **1990 OPEN WATER FLOOD CALIBRATION PROFILE FOR ICE ENHANCED MODEL GEOMETRY**		
1001119	15 JUN 2018	**FIGURE 4**

Classification: Public



Notes:
1. Symbols denote observed values
2. Solid lines denote the computed top and bottom of ice
3. Dotted lines denote the computed water surface

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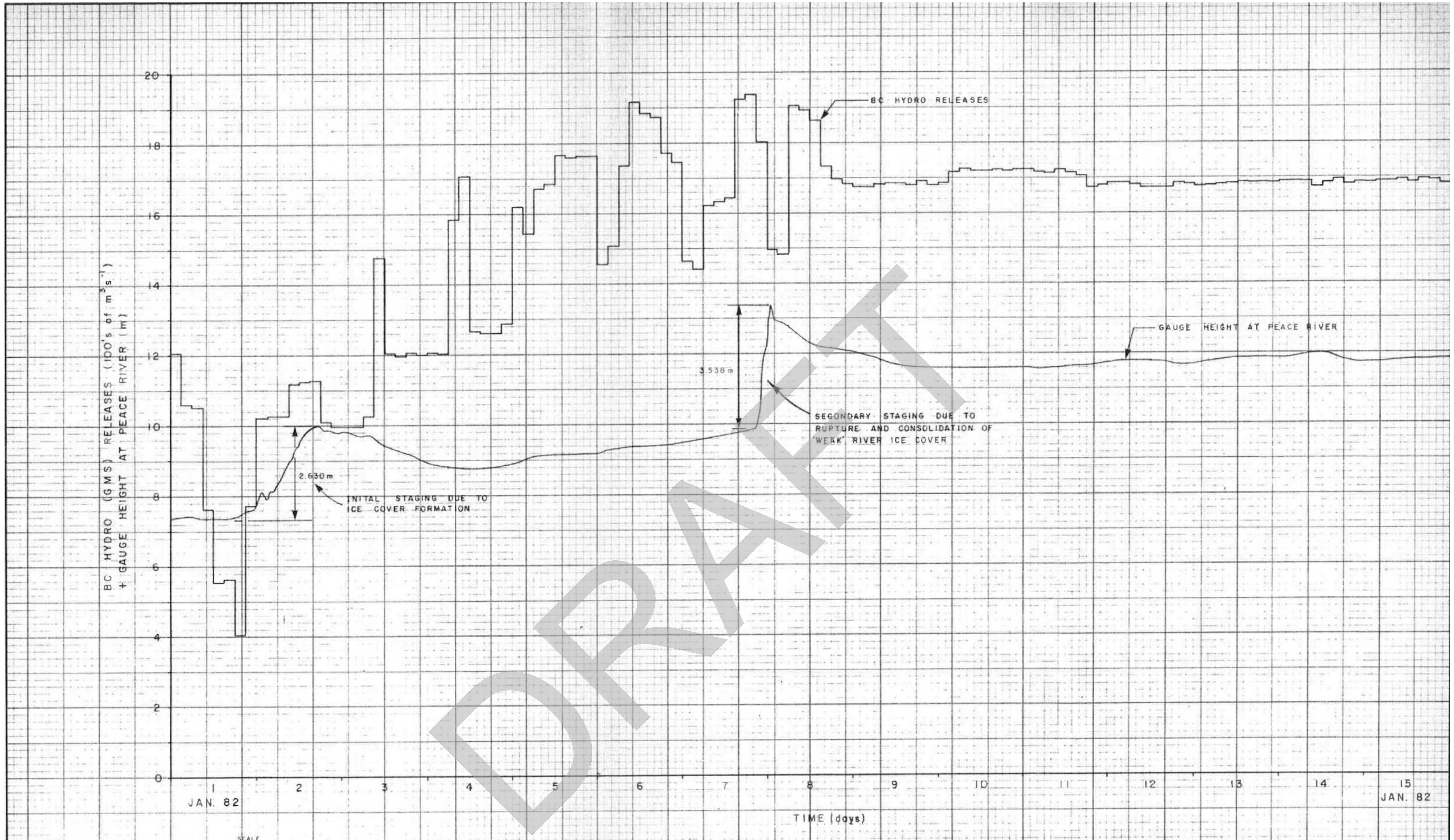
ALBERTA ENVIRONMENT AND PARKS		
PEACE RIVER HAZARD STUDY ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION **1979 ICE JAM CALIBRATION PROFILES** **Q = 4110 m^3/s: n_o=0.045 & Q = 2760 m^3/s: n_o=0.045**		
1001119	15 JUN 2018	**FIGURE 5**



Alberta ENVIRONMENT	RIVER ENGINEERING BRANCH
SUBMITTED / DATE	DESIGNED / CHECKED
APPROVED / DATE	DRAWN / CHECKED

PEACE RIVER 1981-82 ICE STUDY

B.C. HYDRO 3-HOURLY FLOW RELEASES AND GAUGE HEIGHT AT PEACE RIVER

SCALE AS SHOWN	SHEET 2 OF 9
DATE AUGUST, 1982	FIG. No 1

Notes: 1. Figure excerpt taken from: *PEACE RIVER 1981/82 ICE OBSERVATION REPORT* (Alberta Environment, 1982)

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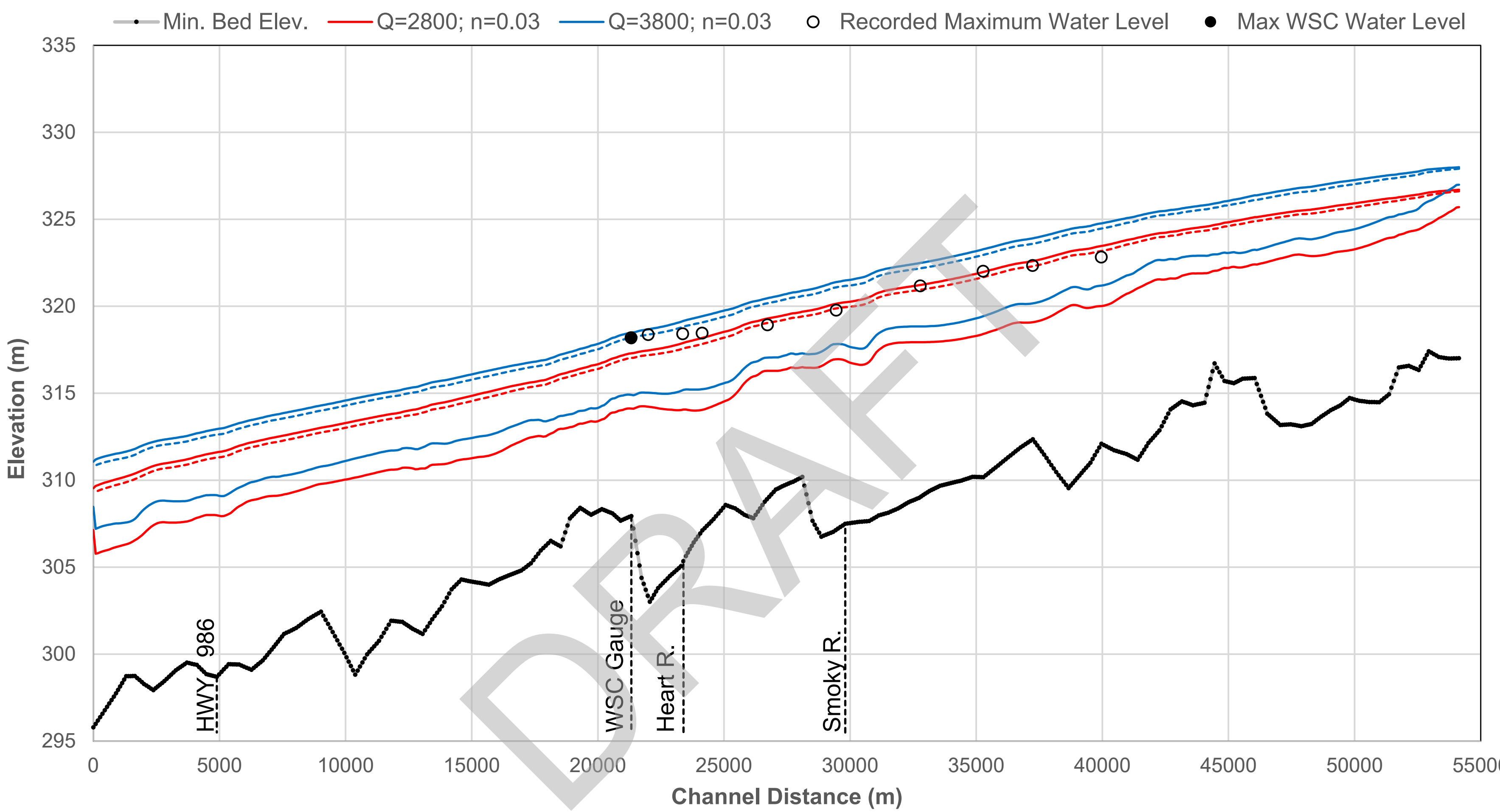
PEACE RIVER HAZARD STUDY
ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION

FLOOD LEVEL HYDROGRAPH FOR THE 8 JAN 1982 SECONDARY CONSOLIDATION

1001119	15 JUN 2018	**FIGURE 6**



Notes:
1. Symbols denote observed values
2. Solid lines denote the computed top and bottom of ice
3. Dotted lines denote the computed water surface

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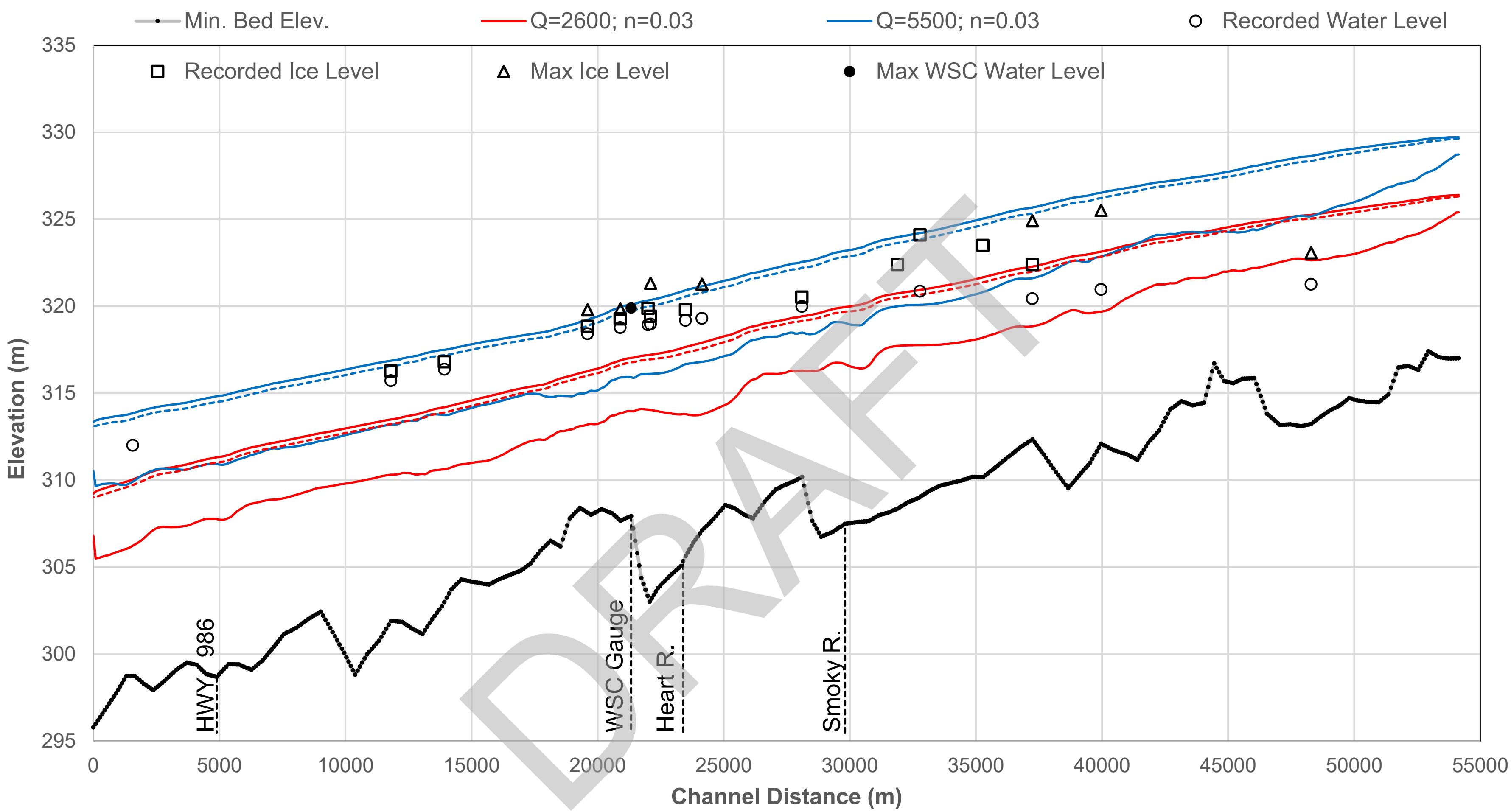
ALBERTA ENVIRONMENT AND PARKS		
PEACE RIVER HAZARD STUDY ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION **1982 ICE JAM CALIBRATION PROFILES** **Q = 3800 m^3/s: n_o=0.030 & Q = 2800 m^3/s: n_o=0.030**		
1001119	15 JUN 2018	**FIGURE 7**



Notes:
1. Symbols denote observed values
2. Solid lines denote the computed top and bottom of ice
3. Dotted lines denote the computed water surface

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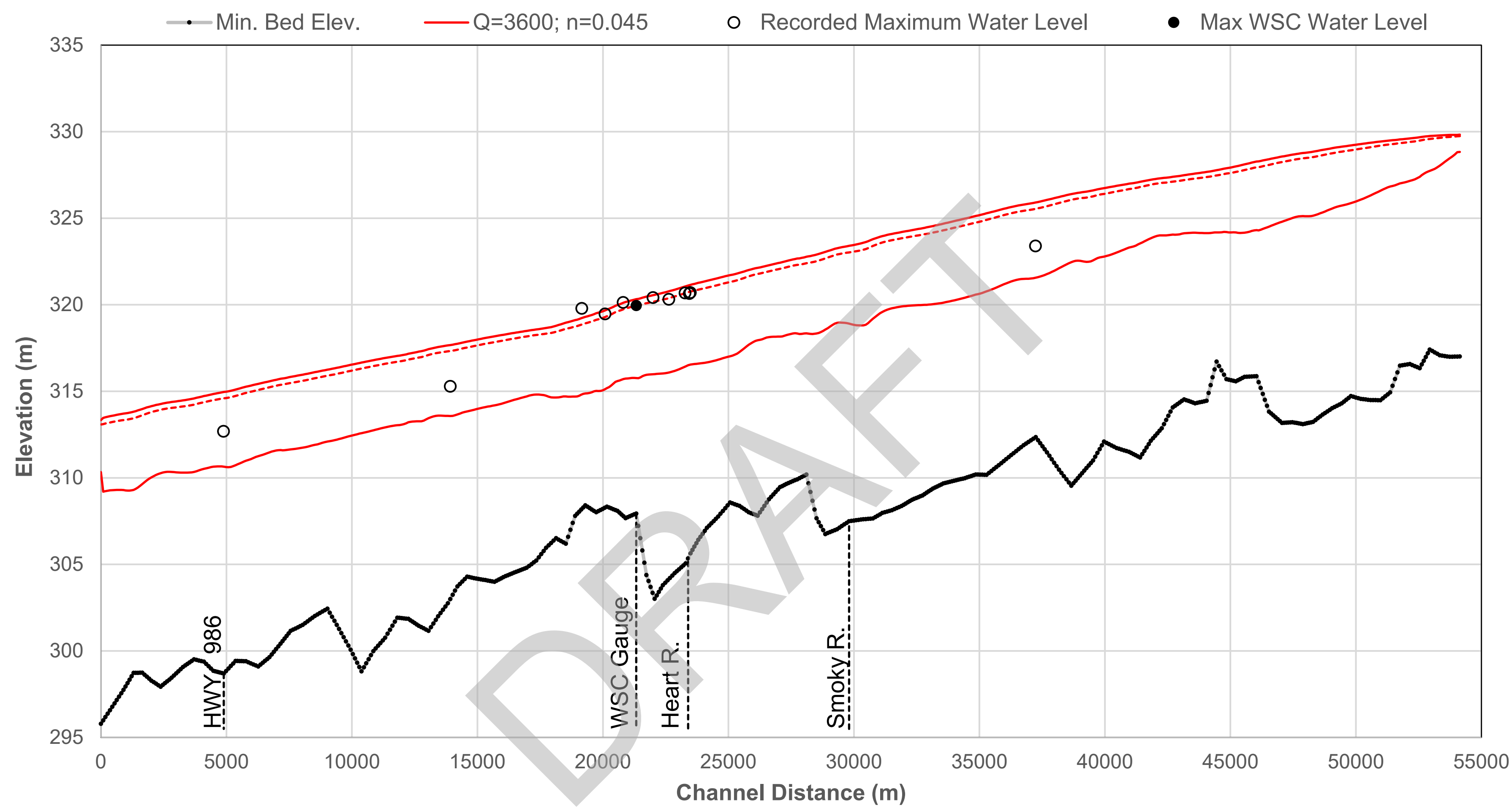
ALBERTA ENVIRONMENT AND PARKS		
PEACE RIVER HAZARD STUDY ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION **1992 ICE JAM CALIBRATION PROFILES** **Q = 2600 m^3/s: n_o=0.030 & Q = 5500 m^3/s: n_o=0.030**		
1001119	15 JUN 2018	**FIGURE 8**



Notes:
1. Symbols denote observed values
2. Solid lines denote the computed top and bottom of ice
3. Dotted line denote the computed water surface

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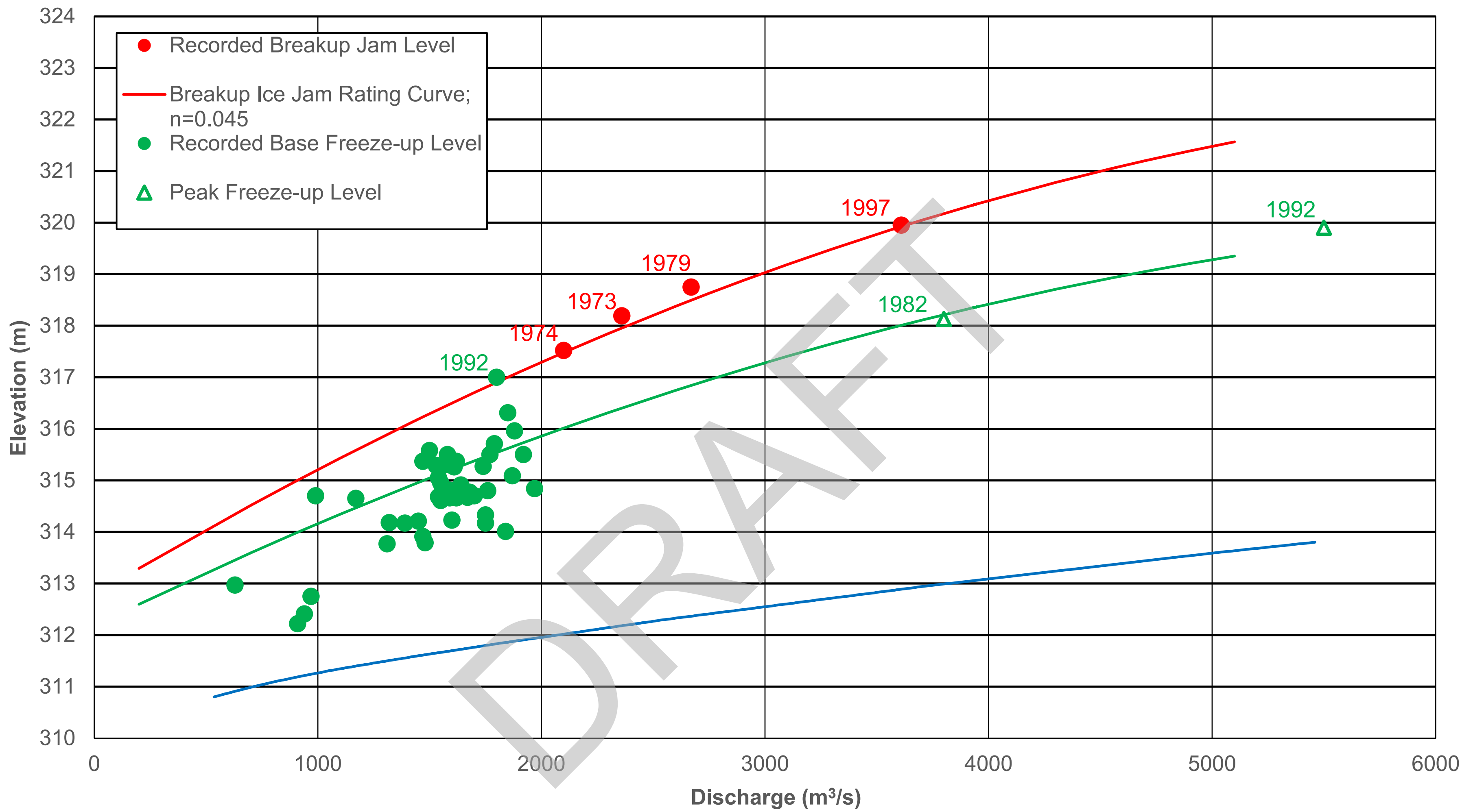
ALBERTA ENVIRONMENT AND PARKS		
PEACE RIVER HAZARD STUDY ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION **1997 ICE JAM CALIBRATION PROFILES** **Q = 3600 m^3/s: n_o=0.045**		
1001119	15 JUN 2018	**FIGURE 9**



Notes: 1. Peak freeze-up levels reflect values for discharge adjusted during model calibration.

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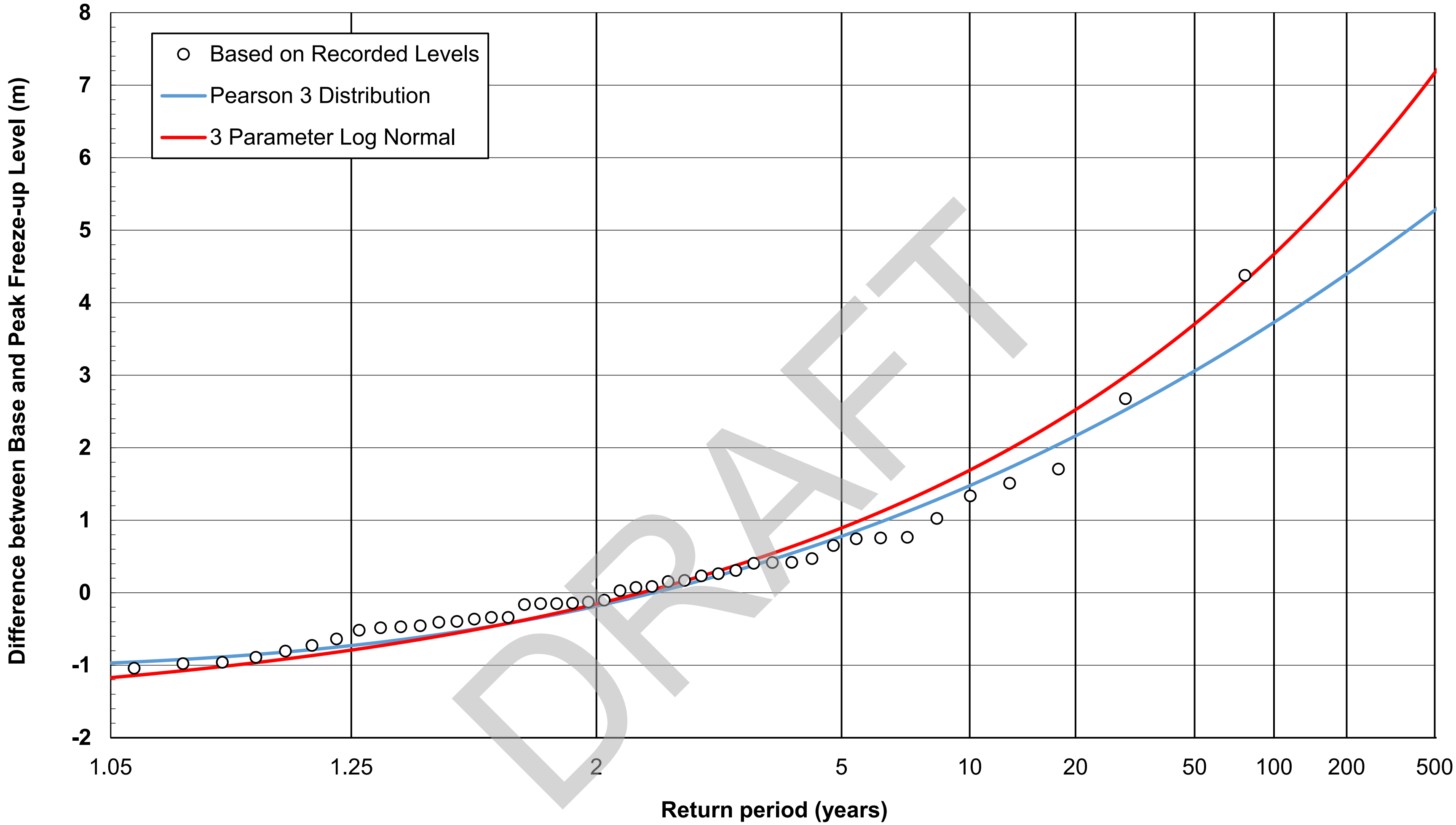
ALBERTA ENVIRONMENT AND PARKS		
PEACE RIVER HAZARD STUDY ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION **ICE JAM RATING CURVES** **WSC GAUGE 07AH001 PEACE RIVER AT PEACE RIVER**		
1001119	15 JUN 2018	**FIGURE 10**



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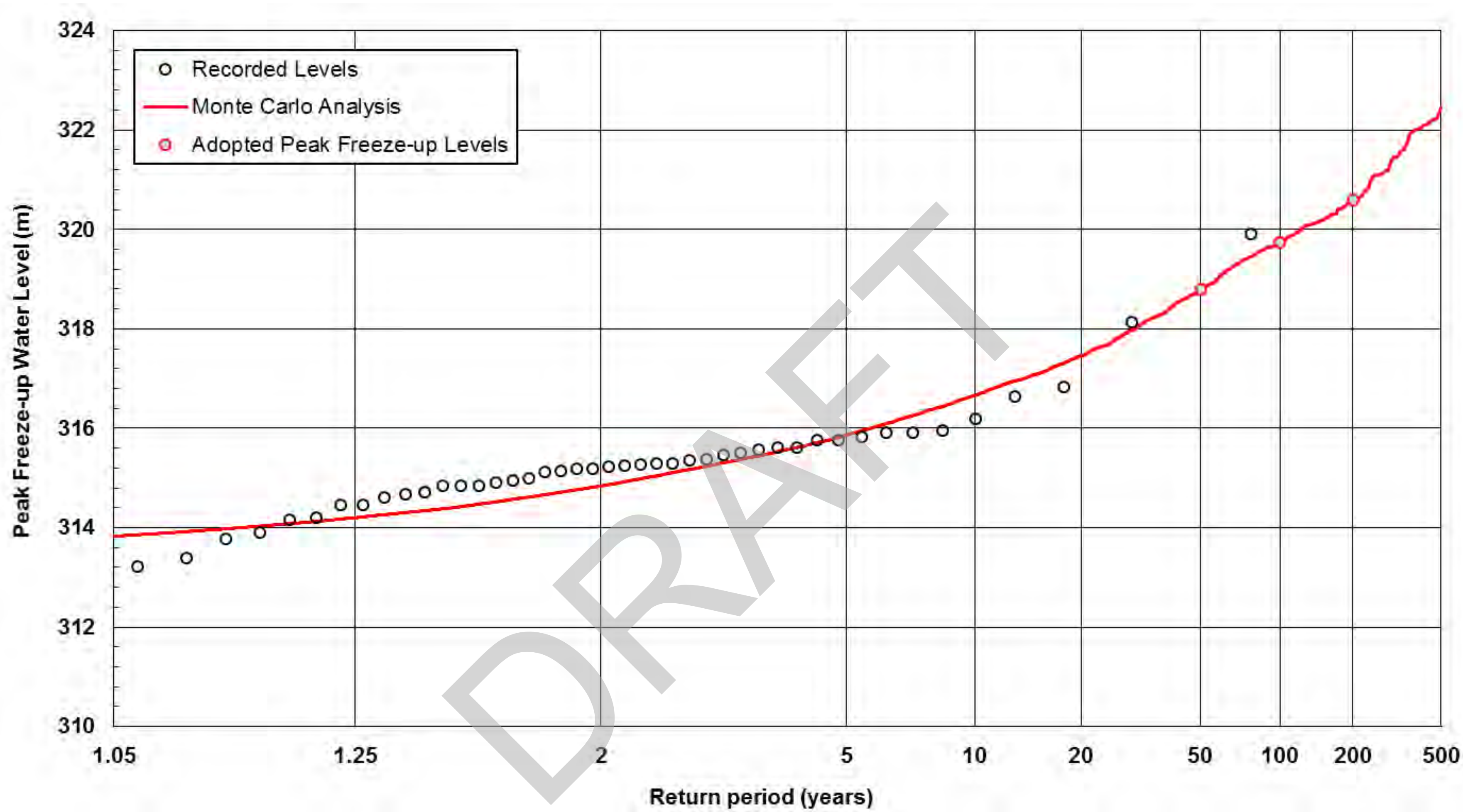
ALBERTA ENVIRONMENT AND PARKS

PEACE RIVER HAZARD STUDY
ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION

FREQUENCY CURVE OF DIFFERENCE BETWEEN BASE AND PEAK FREEZE-UP WATER LEVELS AT PEACE RIVER TOWN WSC GAUGE (07AH001)

1001119	15 JUN 2018	**FIGURE 11**



Notes: 1. Adopted base freeze-up level = 315.0 m

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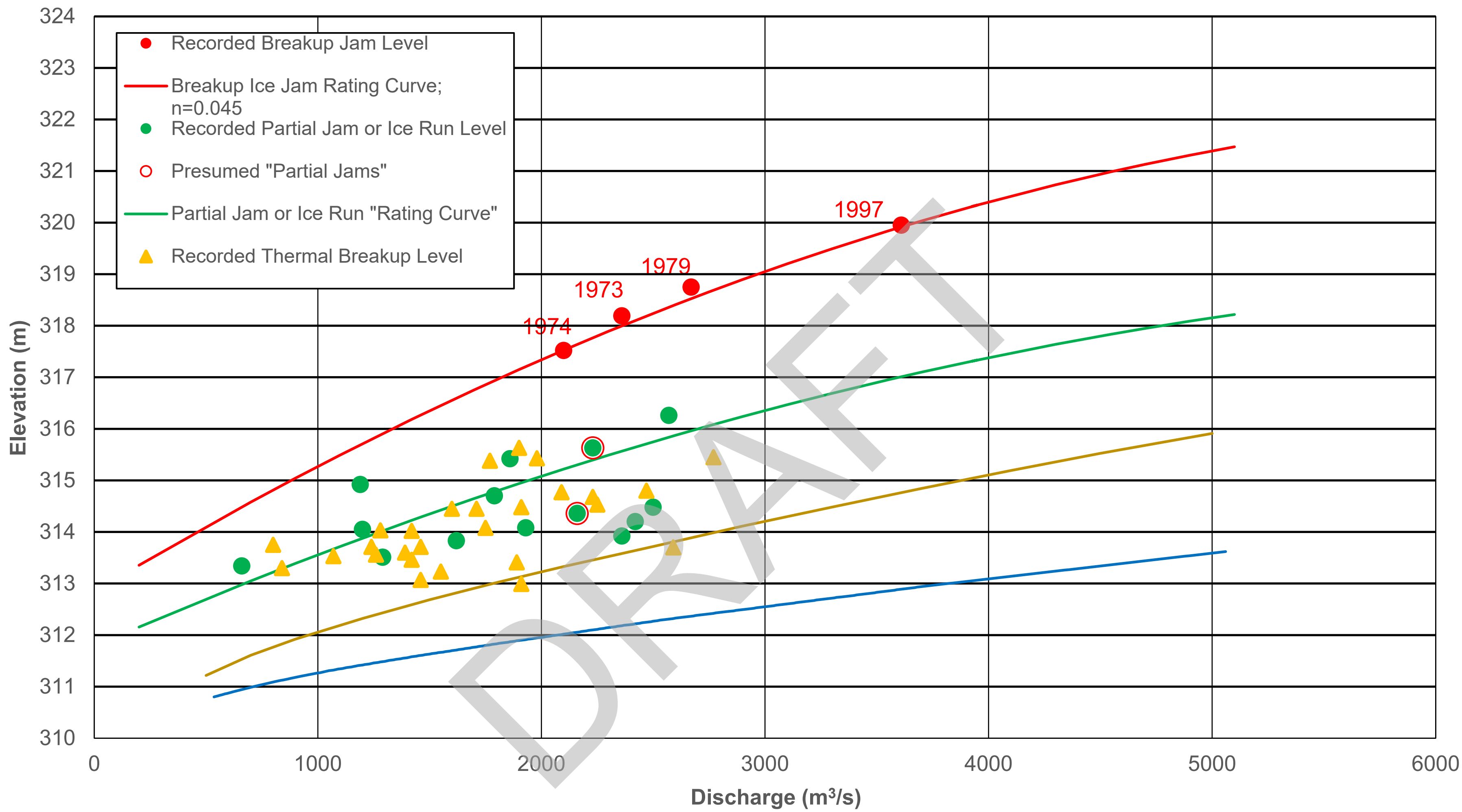
ALBERTA ENVIRONMENT AND PARKS

PEACE RIVER HAZARD STUDY
ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION

FREQUENCY CURVE OF PEAK FREEZE-UP LEVELS AT PEACE RIVER TOWN WSC GAUGE (07AH001) USING MONTE CARLO APPROACH

1001119	15 JUN 2018	**FIGURE 12**



Notes: 1. Peak freeze-up levels reflect values for discharge adjusted during model calibration.

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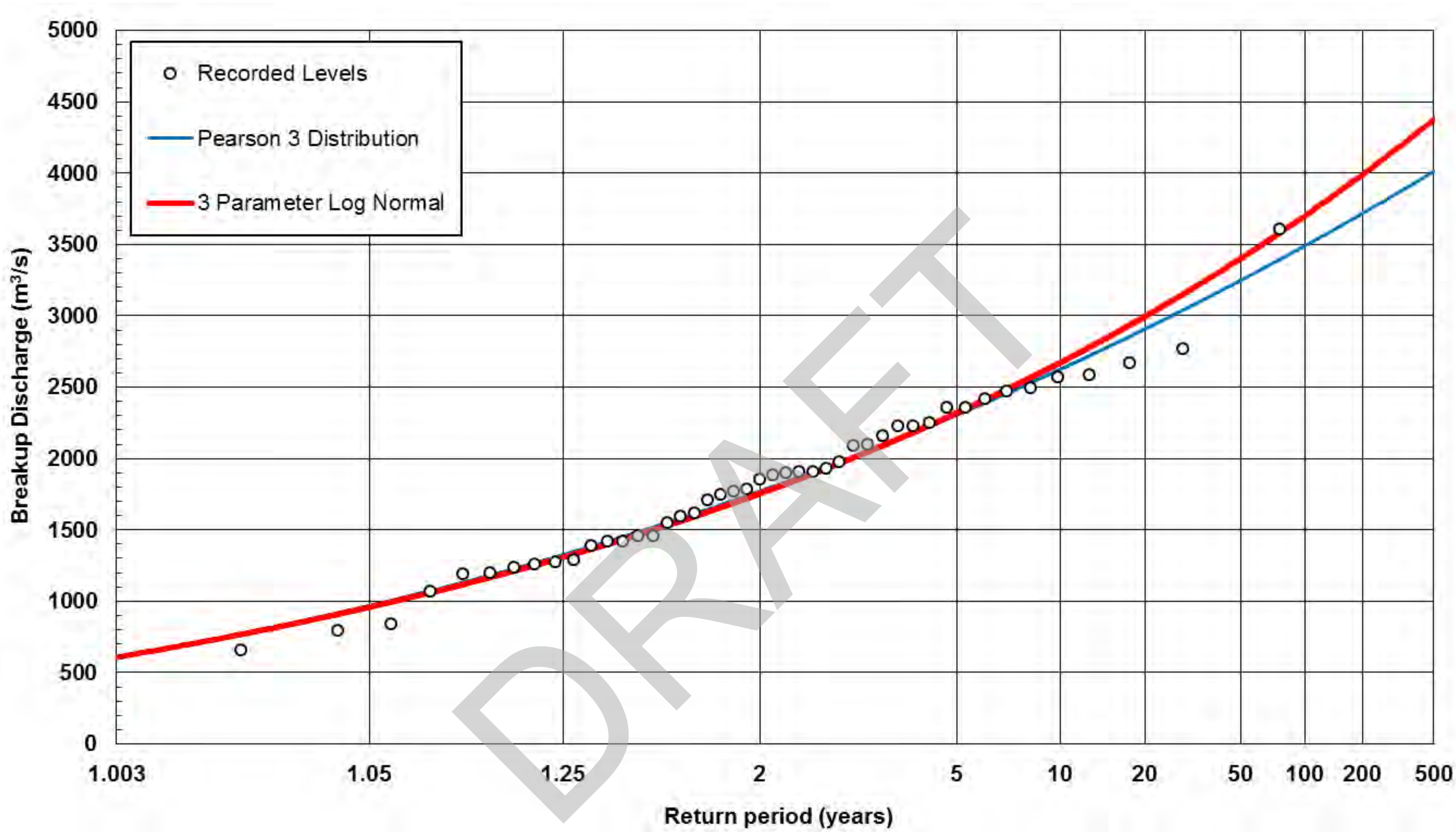
ALBERTA ENVIRONMENT AND PARKS		
PEACE RIVER HAZARD STUDY ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION **ICE-AFFECTED RATING CURVES FOR BREAKUP** **WSC GAUGE 07AH001 PEACE RIVER AT PEACE RIVER**		
1001119	15 JUN 2018	**FIGURE 13**



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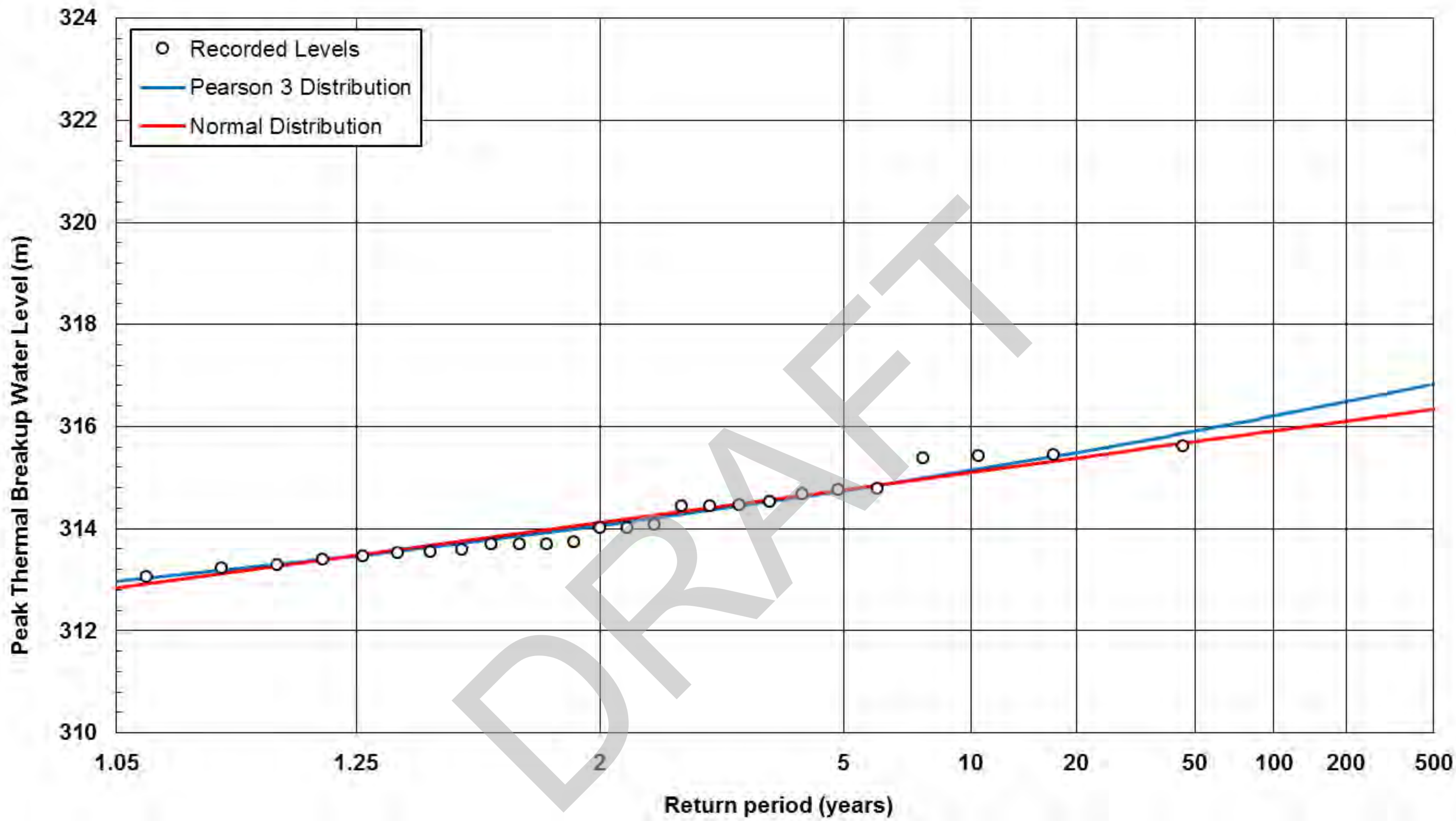
ALBERTA ENVIRONMENT AND PARKS		
PEACE RIVER HAZARD STUDY ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION **FREQUENCY CURVE OF BREAKUP DISCHARGES AT PEACE RIVER TOWN WSC GAUGE (07AH001) RECORDED AND SYNTHETIC DISTRIBUTIONS**		
1001119	15 JUN 2018	**FIGURE 14**



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PEACE RIVER HAZARD STUDY
ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION

FREQUENCY CURVE OF PEAK THERMAL BREAKUP WATER LEVELS AT PEACE RIVER TOWN WSC GAUGE (07AH001)

1001119	15 JUN 2018	**FIGURE 15**

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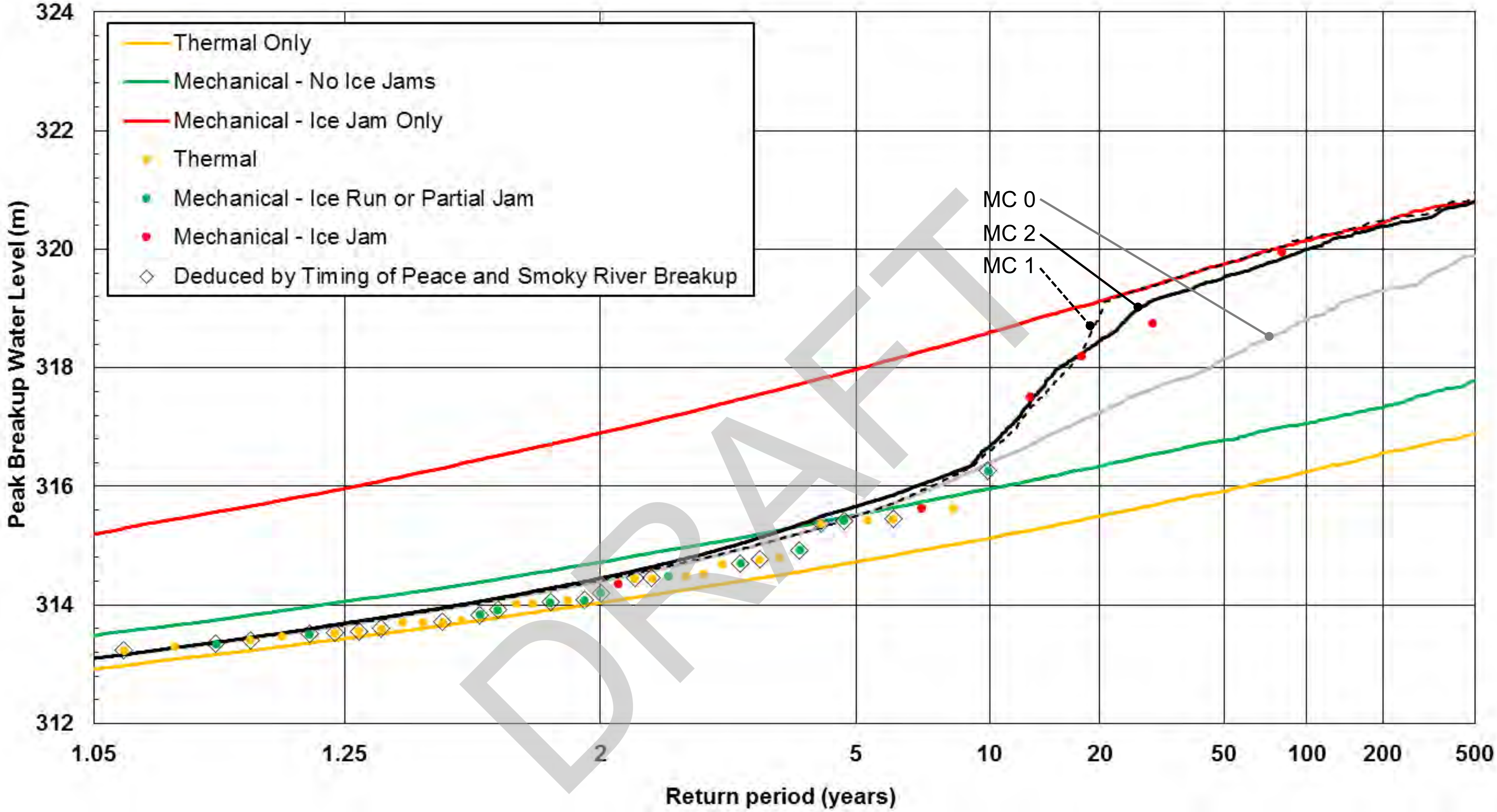

Notes:
1. MC 0 denotes no discharge-based adjustments
2. MC 1 denotes a single discharge-based adjustment
3. MC 2 denotes a dual discharge-based adjustment

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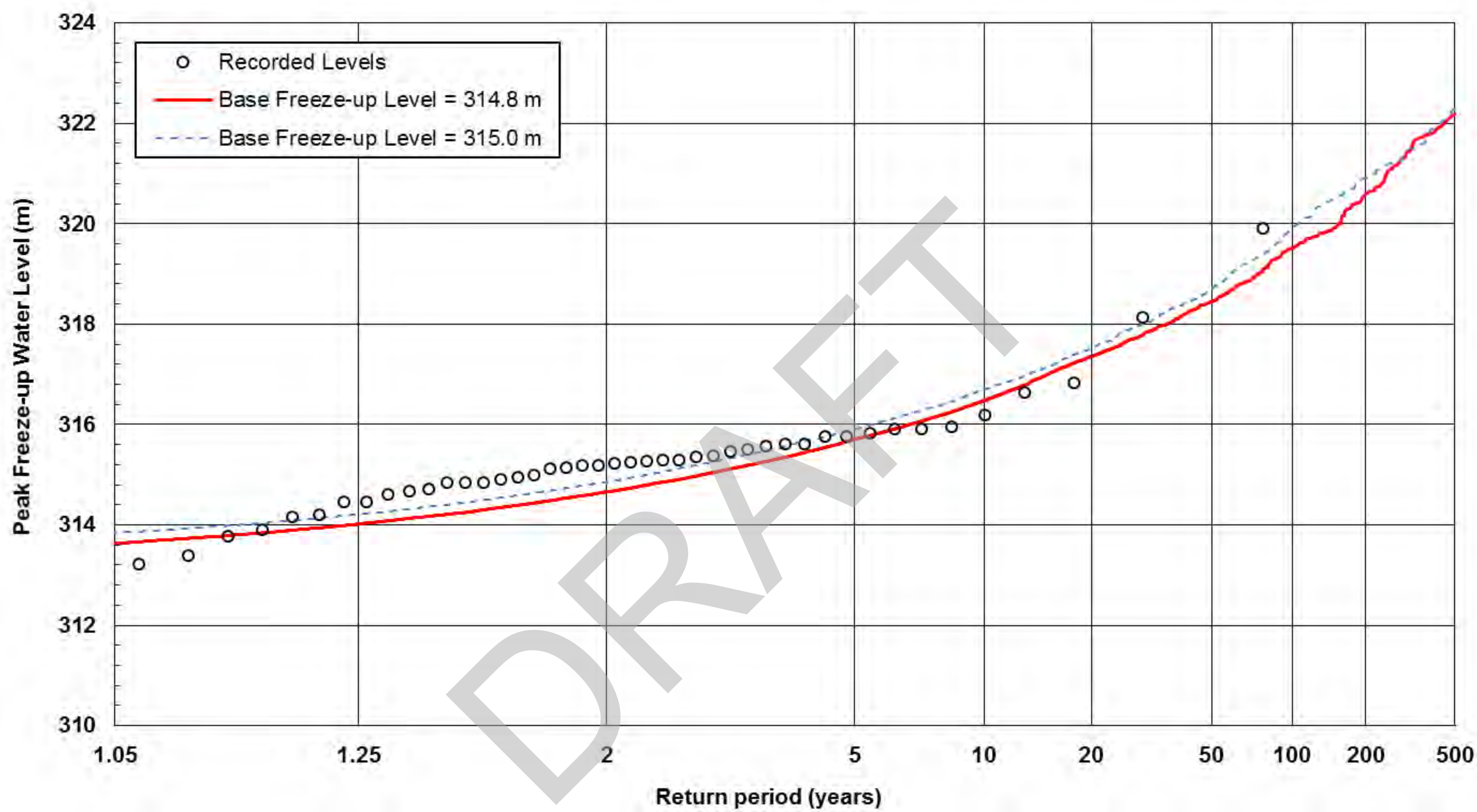
ALBERTA ENVIRONMENT AND PARKS		
PEACE RIVER HAZARD STUDY ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION **FREQUENCY CURVES OF PEAK BREAKUP LEVELS AT PEACE RIVER TOWN WSC GAUGE (07AH001)**		
1001119	15 JUN 2018	**FIGURE 16**



Notes: 1. Base freeze-up level = 314.8 m reflects flow conditions upstream of the Smoky River.

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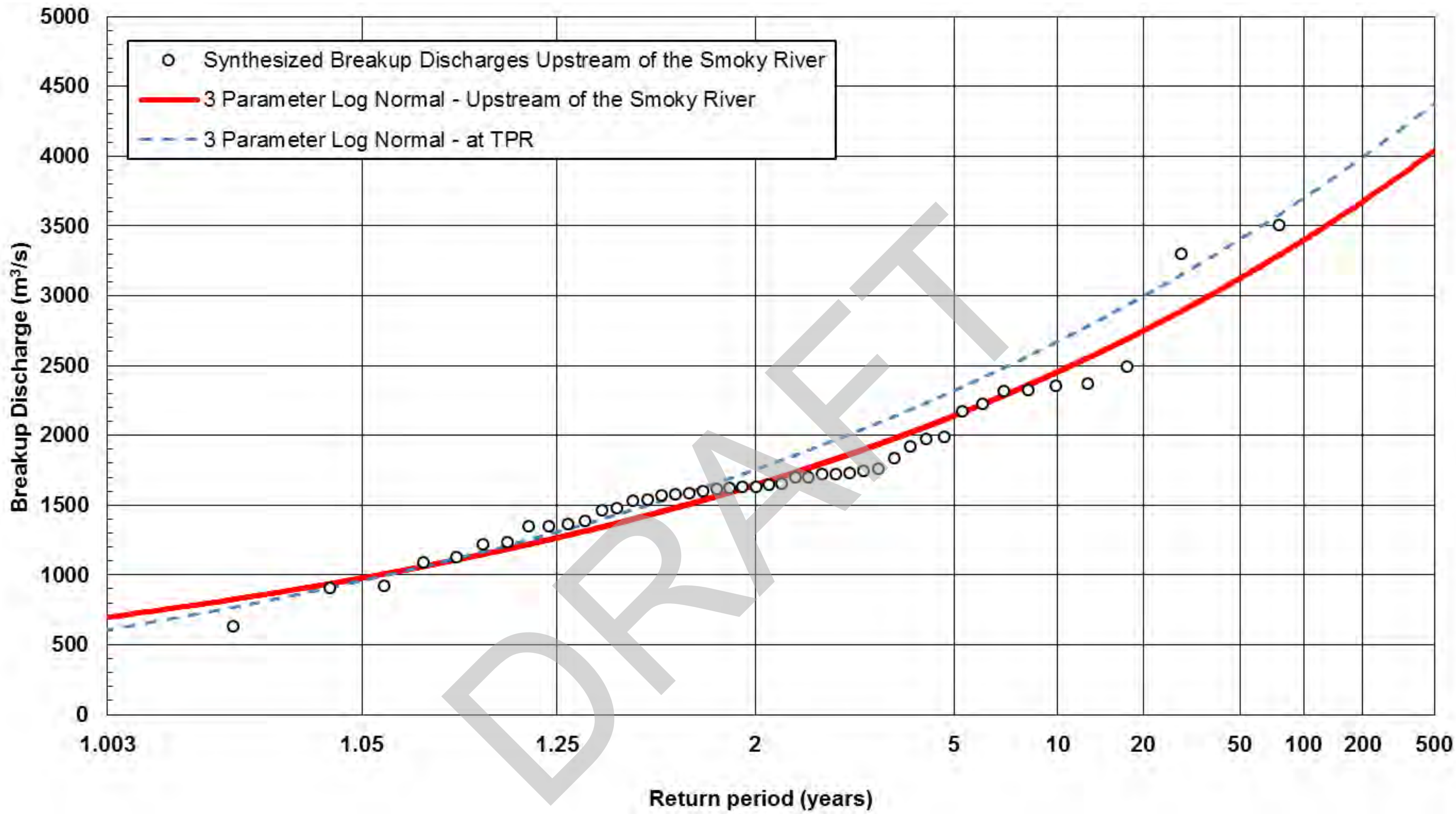
ALBERTA ENVIRONMENT AND PARKS		
PEACE RIVER HAZARD STUDY ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION **FREQUENCY CURVE OF PEAK FREEZE-UP LEVELS AT PEACE RIVER TOWN WSC GAUGE (07AH001) FOR BASE FREEZE-UP LEVELS OF 314.8 m and 315.0 m**		
1001119	15 JUN 2018	**FIGURE 17**



ALBERTA ENVIRONMENT AND PARKS		
PEACE RIVER HAZARD STUDY ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION **FREQUENCY CURVE OF BREAKUP DISCHARGES UPSTREAM OF SMOKY RIVER CONFLUENCE**		
1001119	15 JUN 2018	**FIGURE 18**

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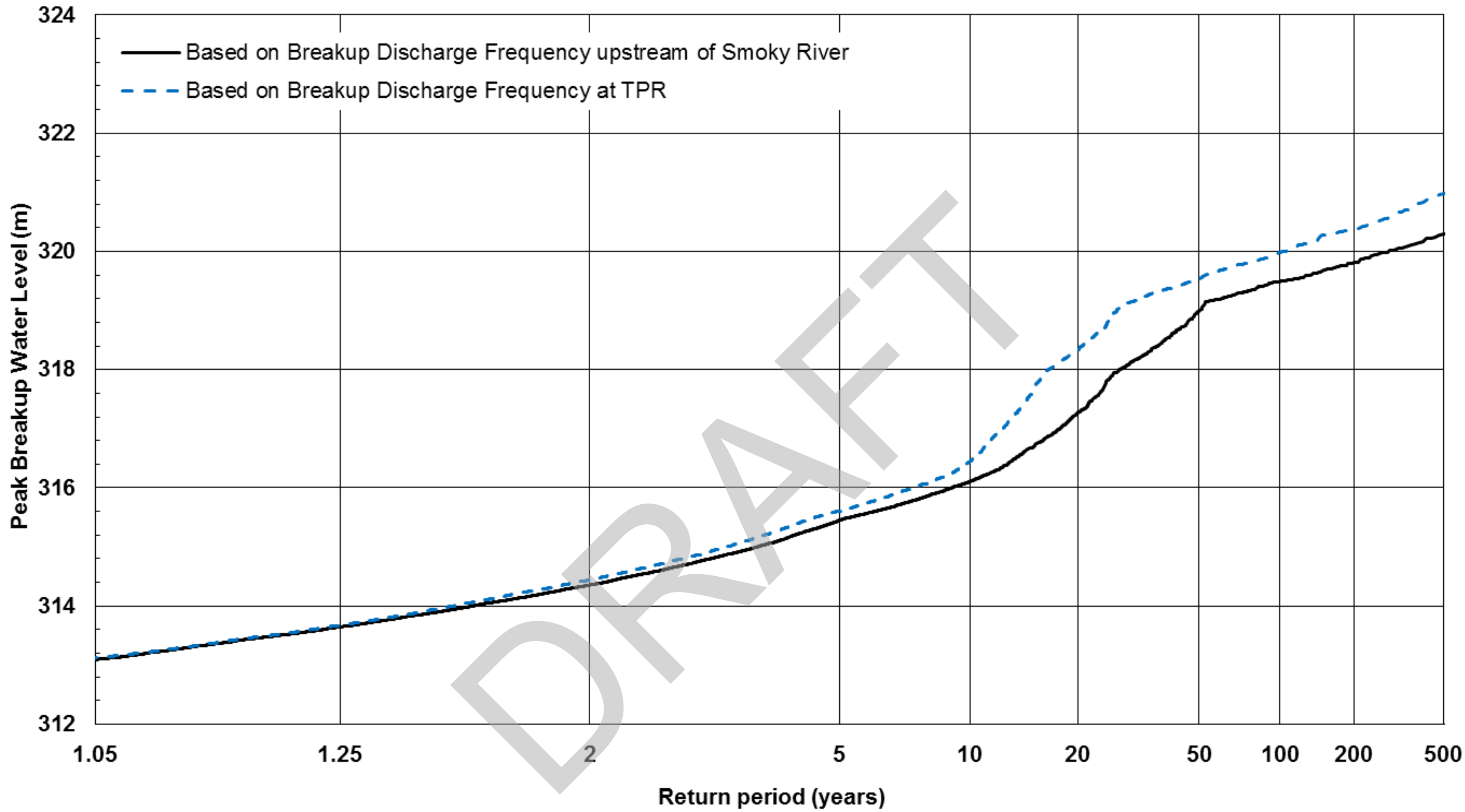

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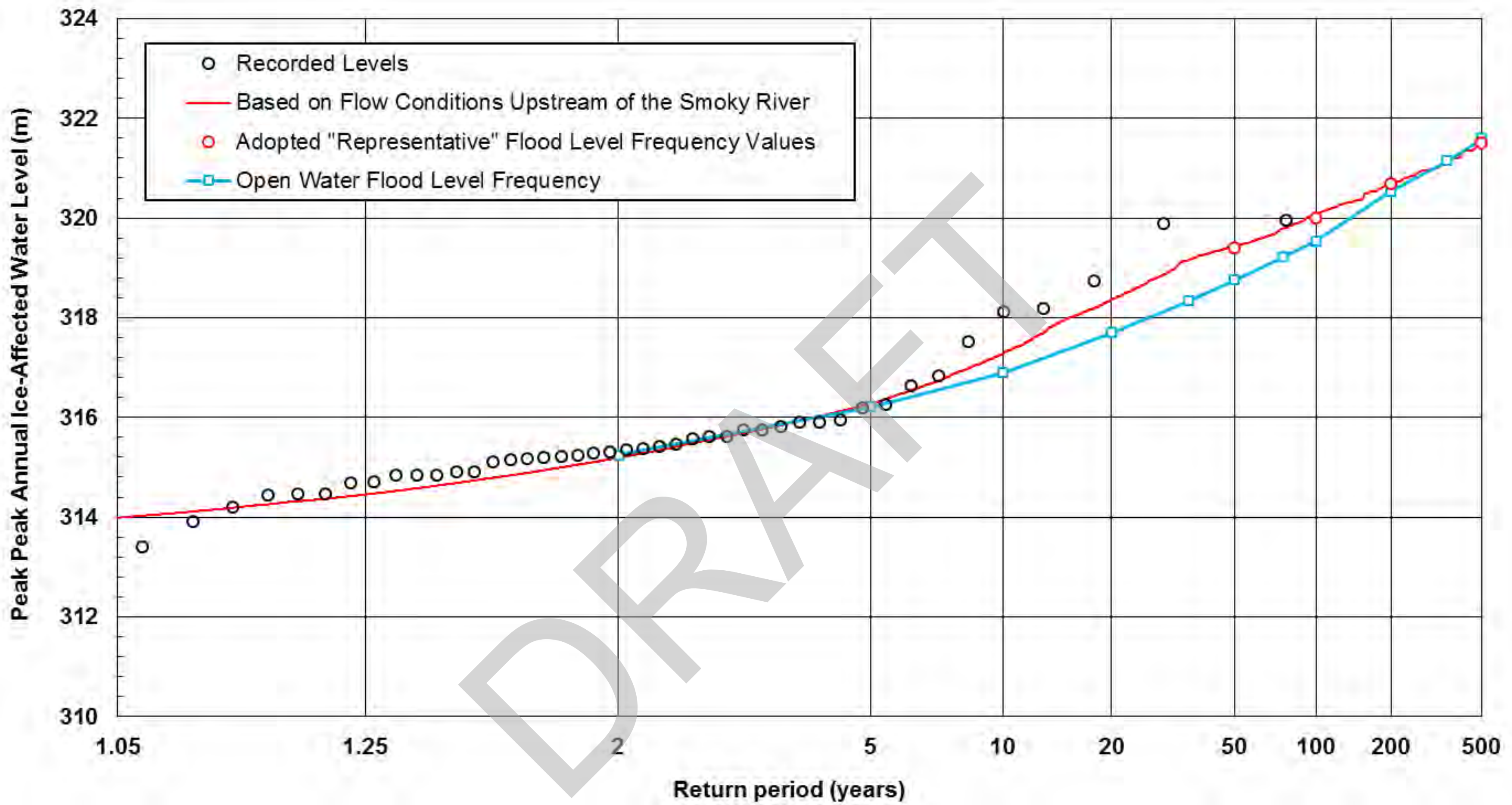
ALBERTA ENVIRONMENT AND PARKS		
PEACE RIVER HAZARD STUDY ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION **BREAKUP FLOOD LEVEL FREQUENCIES BASED ON BREAKUP DISCHARGE FREQEUNCY UPSTREAM OF THE SMOKY RIVER AND AT TPR**		
1001119	15 JUN 2018	**FIGURE 19**



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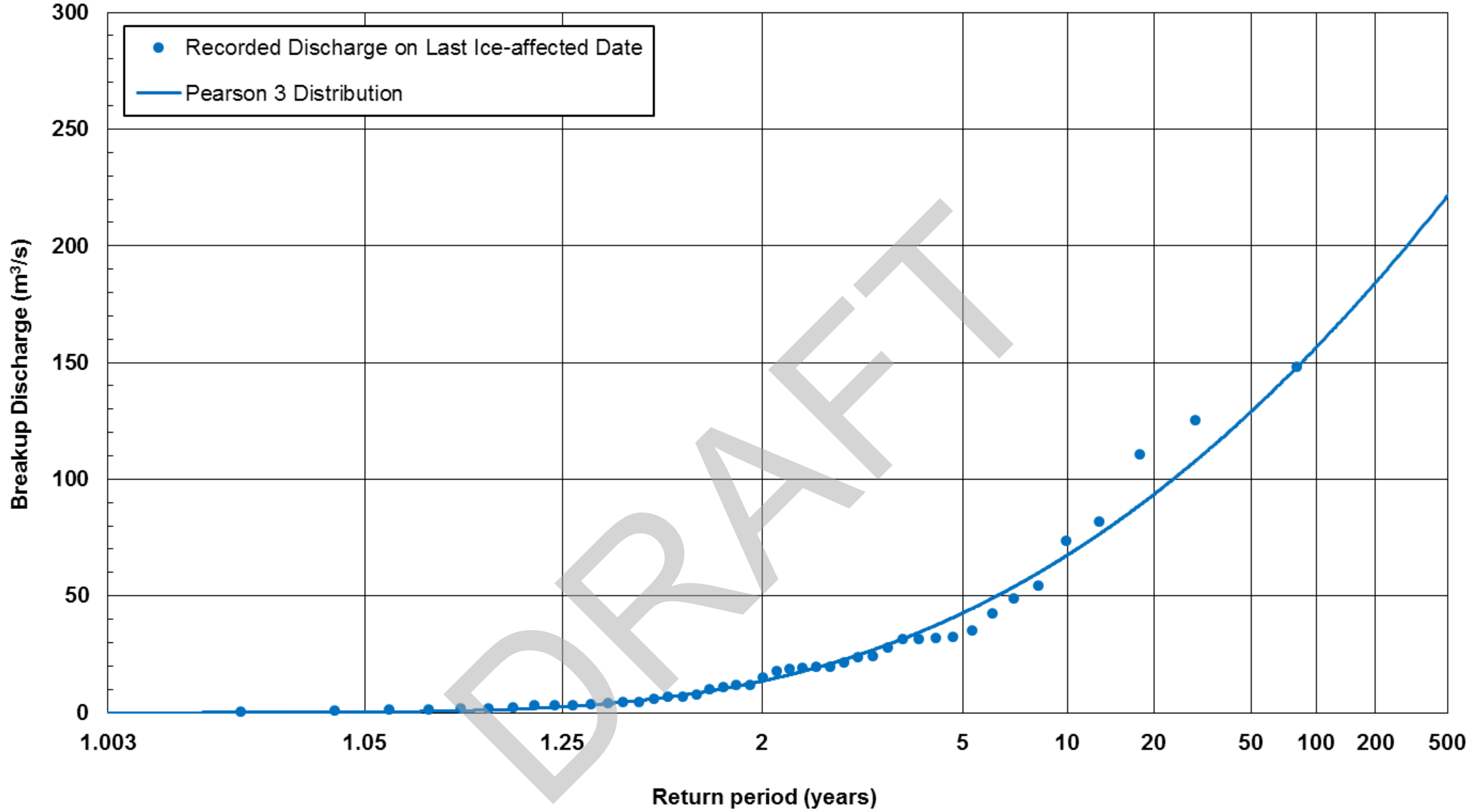
ALBERTA ENVIRONMENT AND PARKS		
PEACE RIVER HAZARD STUDY ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION **FREQUENCY CURVES OF PEAK ANNUAL ICE-AFFECTED WATER LEVEL AT PEACE RIVER TOWN WSC GAUGE (07AH001)**		
1001119	15 JUN 2018	**FIGURE 20**



ALBERTA ENVIRONMENT AND PARKS		
PEACE RIVER HAZARD STUDY ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION **FREQUENCY CURVE OF BREAKUP DISCHARGES FOR THE HEART RIVER AT NAMPA**		
1001119	15 JUN 2018	**FIGURE 21**

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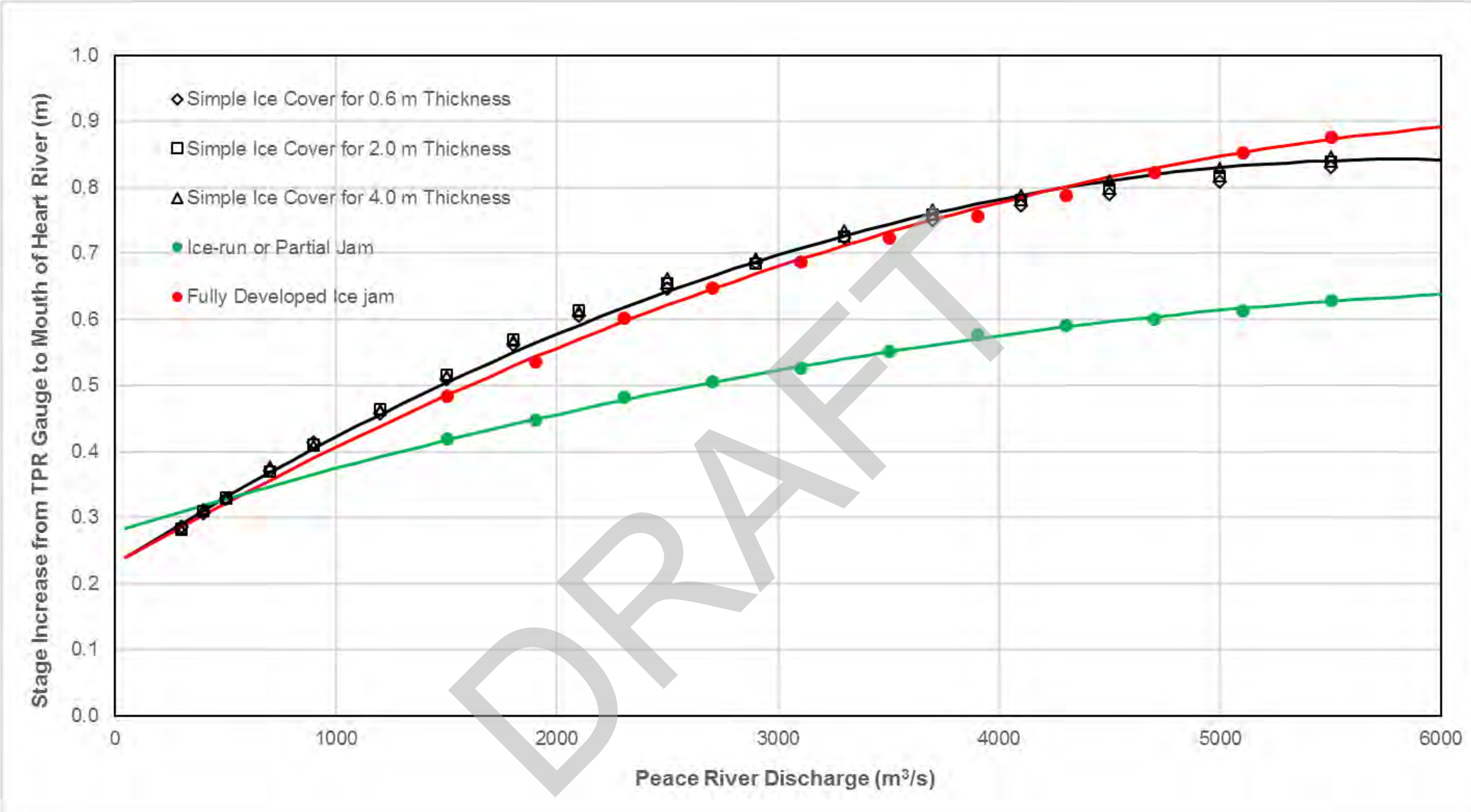

Notes: 1. The simple ice cover thickness rating curve corresponds to the stage increase for a thermal breakup condition.

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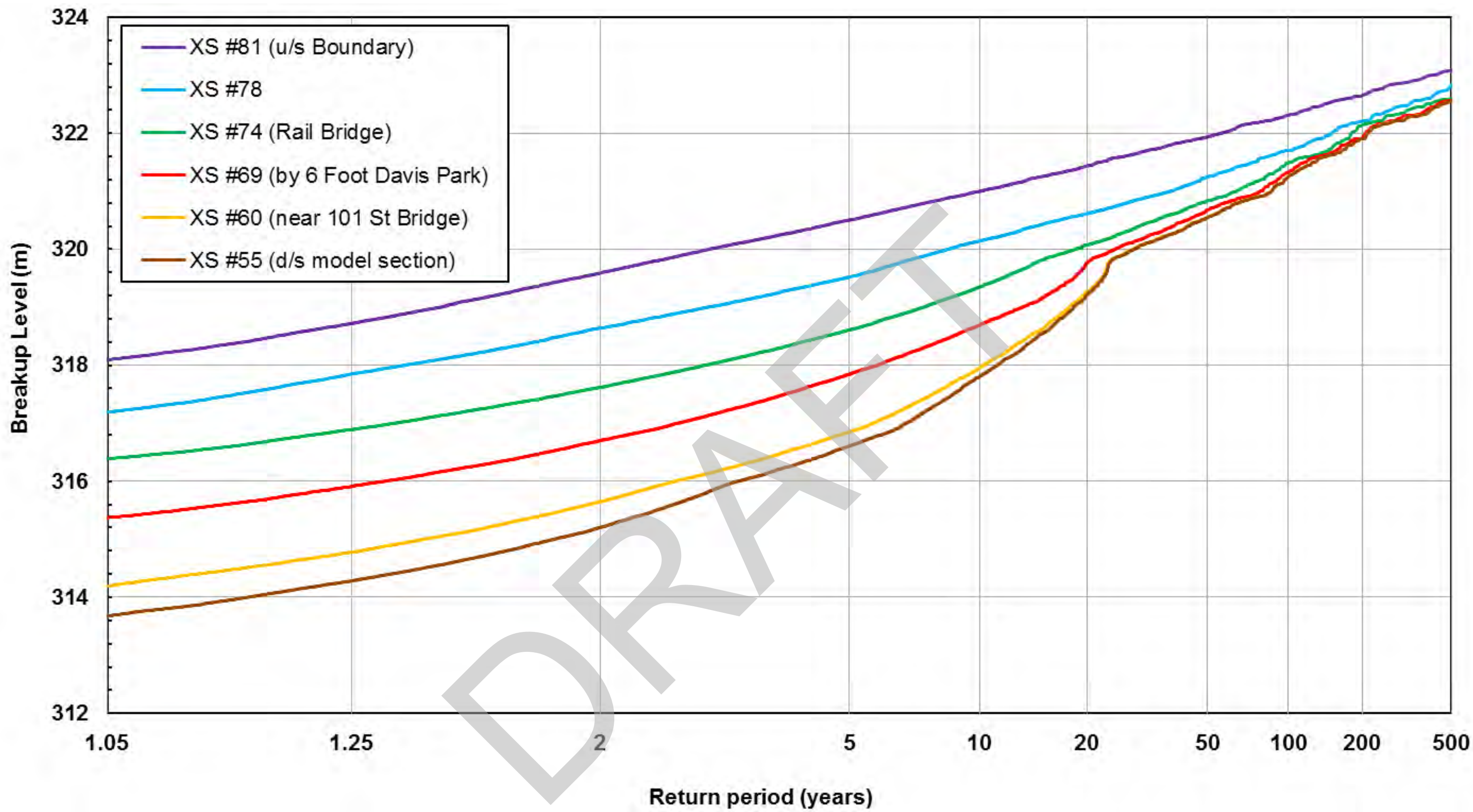
ALBERTA ENVIRONMENT AND PARKS		
PEACE RIVER HAZARD STUDY ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION **STAGE INCREASE FROM TPR TO THE MOUTH OF THE HEART RIVER FOR VARIOUS ICE CONDITONS**		
1001119	15 JUN 2018	**FIGURE 22**

Classification: Public



Notes: 1. The frequency curves represents the maxima of values from the computed ice-affected flood level profile for each breakup instance.

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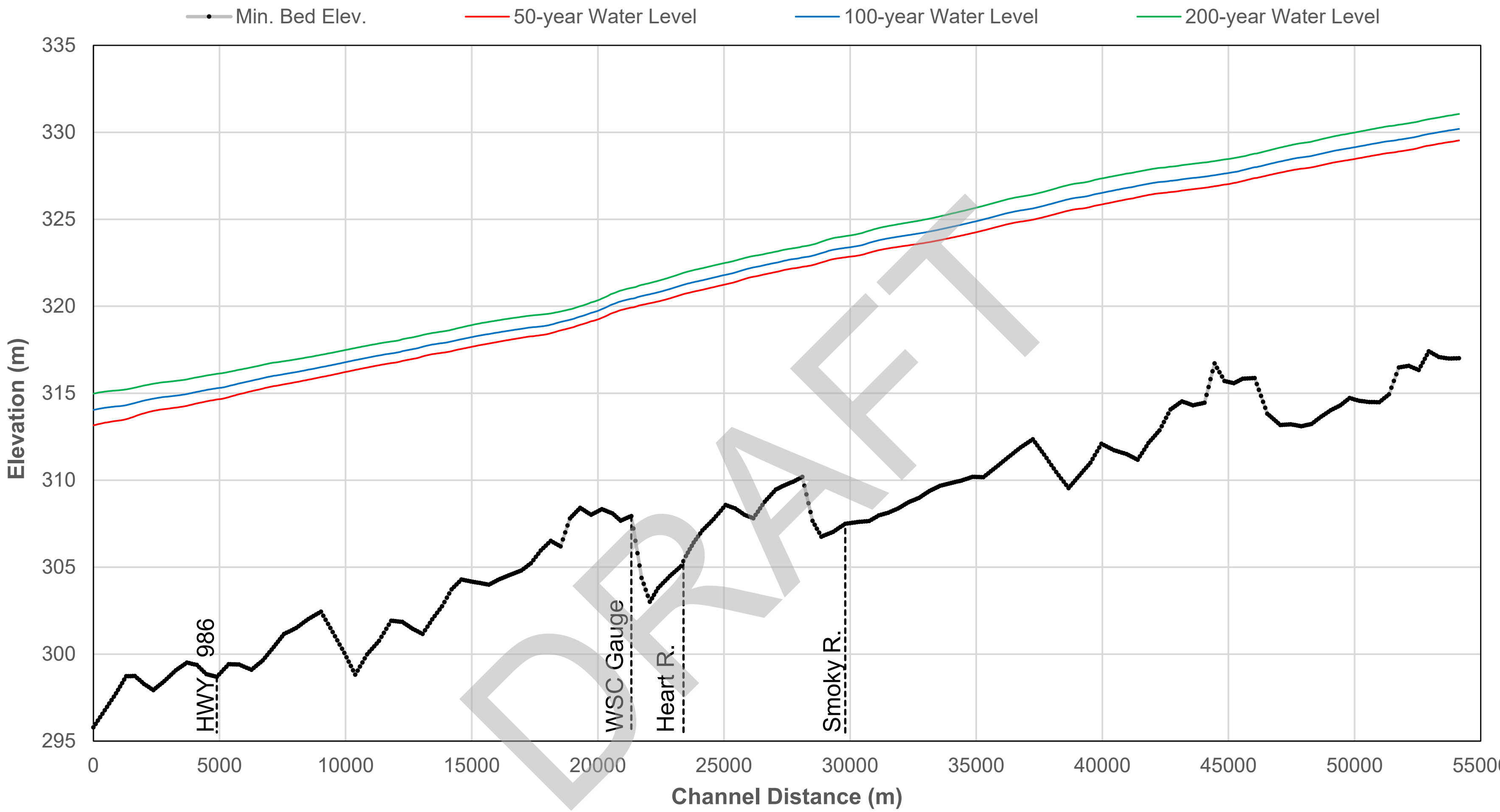
ALBERTA ENVIRONMENT AND PARKS		
PEACE RIVER HAZARD STUDY ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION **FREQUENCY CURVES OF PEAK BREAKUP LEVELS ALONG THE HEART RIVER AT SELECTED CROSS SECTION LOCATIONS**		
1001119	15 JUN 2018	**FIGURE 23**



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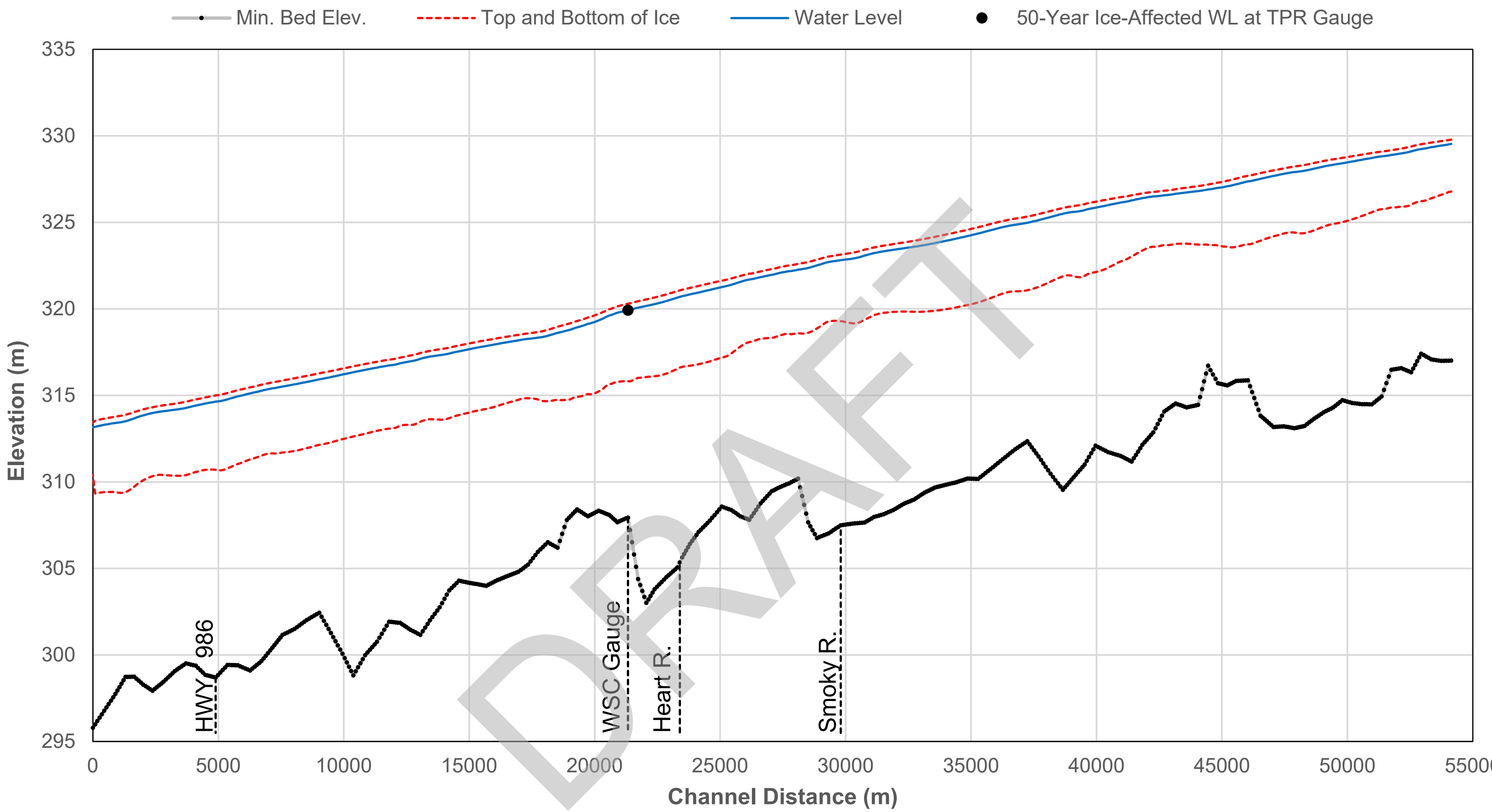
ALBERTA ENVIRONMENT AND PARKS

PEACE RIVER HAZARD STUDY
ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION

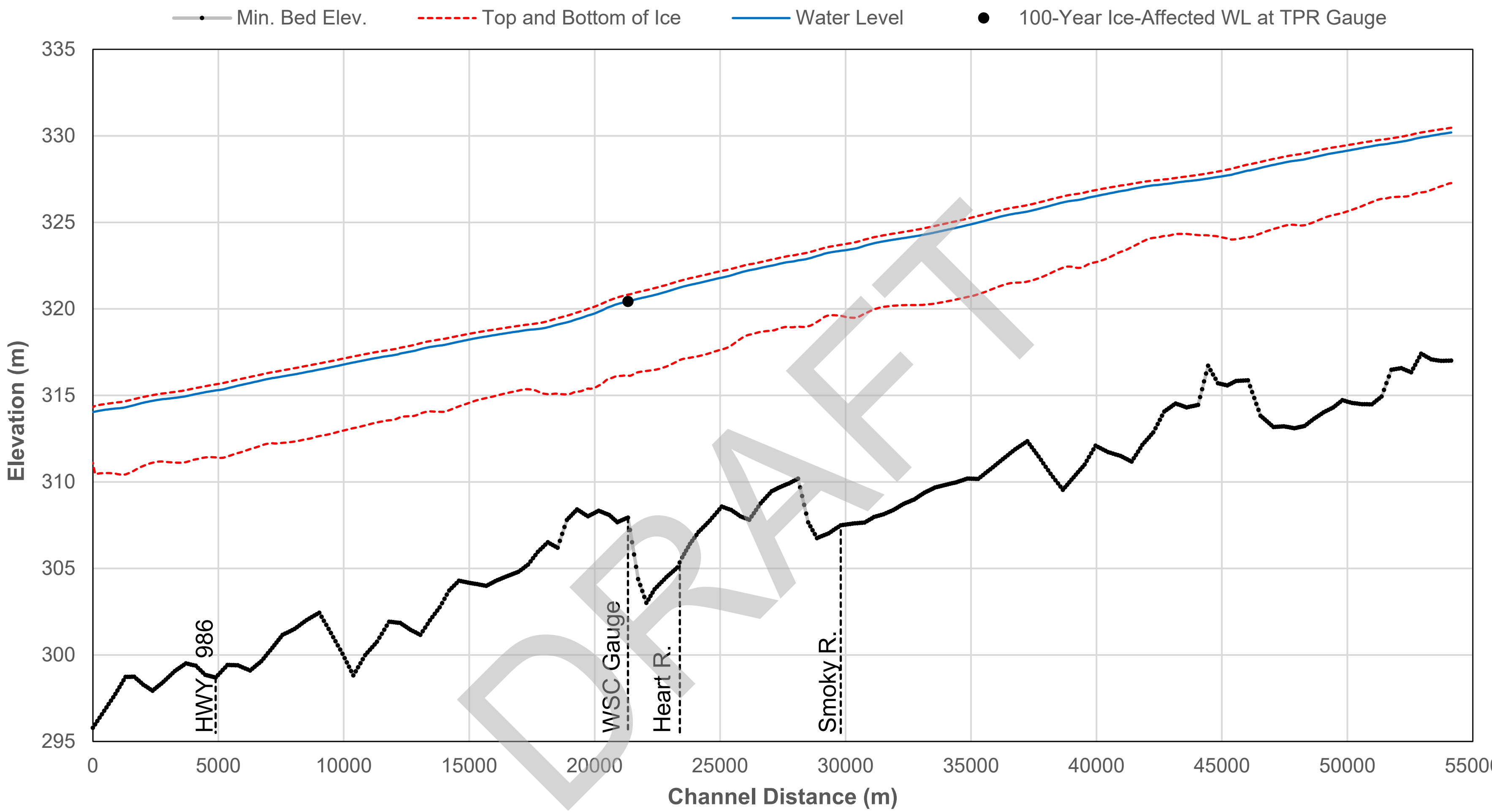
50-YEAR, 100-YEAR, AND 200-YEAR
ICE JAM FLOOD FREQUECNY PROFILES
PEACE RIVER

1001119	15 JUN 2018	**FIGURE 24**



Notes:
1. Solid blue line denotes the ice-affected flood level profile.
2. Dotted red lines denote the computed top and bottom of ice profiles for the representative fully developed ice jam.

ALBERTA ENVIRONMENT AND PARKS		
PEACE RIVER HAZARD STUDY ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION **FULLY DEVELOPED ICE JAM PROFILE USED FOR ESTIMATION OF THE 50-YEAR ICE JAM FLOOD FREQUENCY PROFILE**		
1001119	15 JUN 2018	**FIGURE 25**



Notes:
1. Solid blue line denotes the ice-affected flood level profile.
2. Dotted red lines denote the computed top and bottom of ice profiles for the representative fully developed ice jam.

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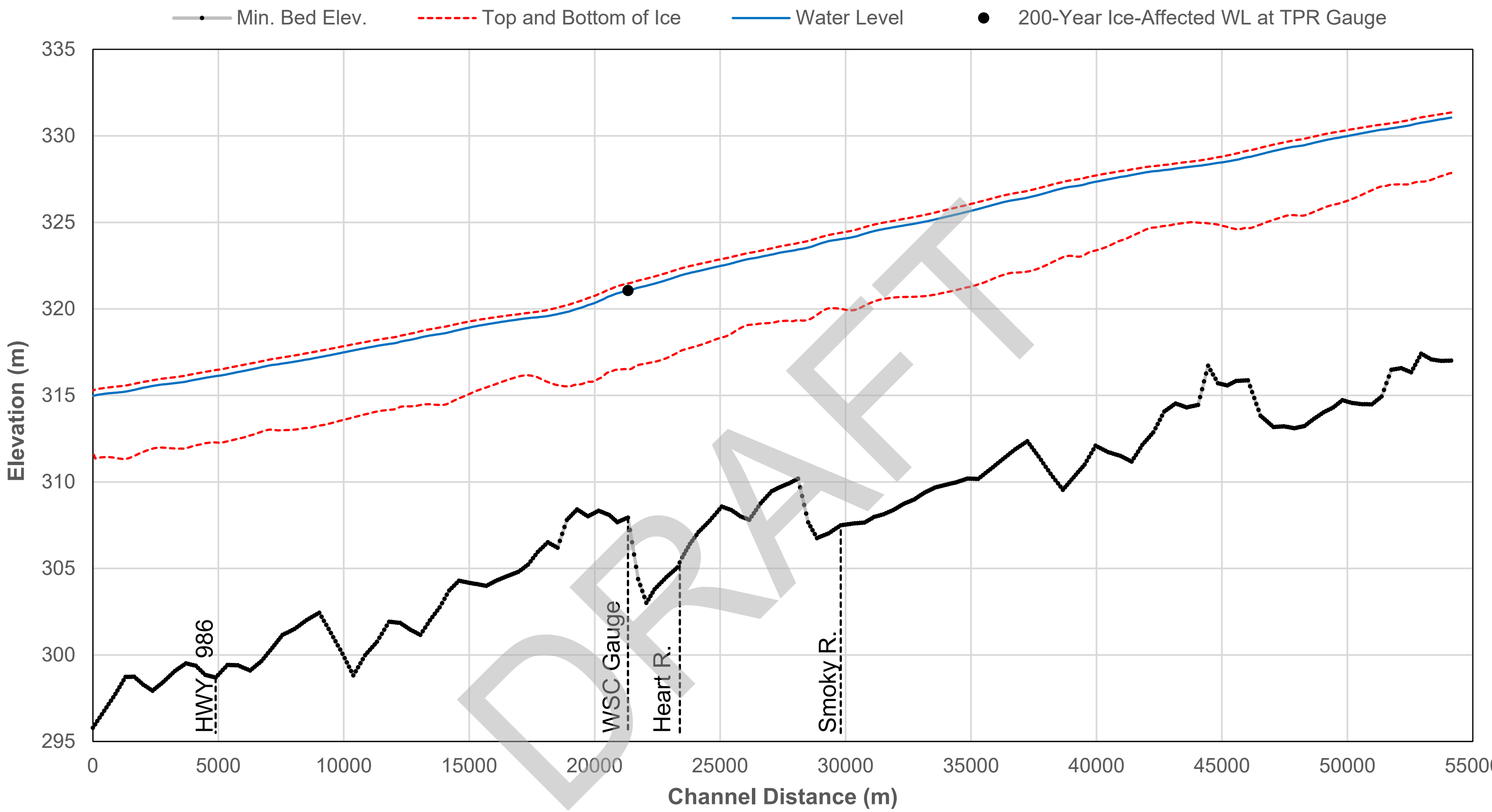
ALBERTA ENVIRONMENT AND PARKS		
PEACE RIVER HAZARD STUDY ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION **FULLY DEVELOPED ICE JAM PROFILE USED FOR ESTIMATION OF THE 100-YEAR ICE JAM FLOOD FREQUENCYPROFILE**		
1001119	15 JUN 2018	**FIGURE 26**



Notes:
1. Solid blue line denotes the ice-affected flood level profile.
2. Dotted red lines denote the computed top and bottom of ice profiles for the representative fully developed ice jam.

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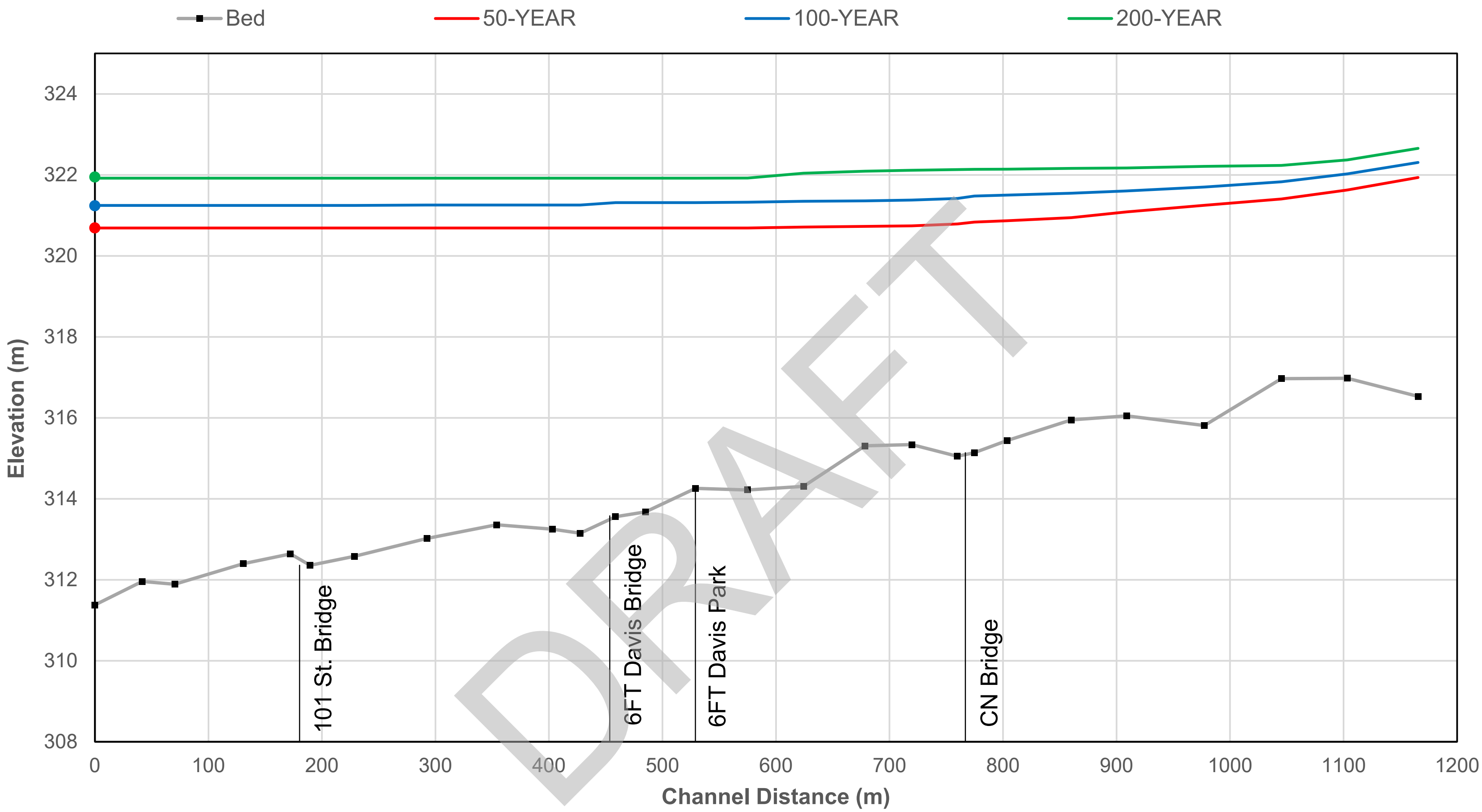
ALBERTA ENVIRONMENT AND PARKS		
PEACE RIVER HAZARD STUDY ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION **FULLY DEVELOPED ICE JAM PROFILE USED FOR ESTIMATION OF THE 200-YEAR ICE JAM FLOOD FREQUENCYPROFILE**		
1001119	15 JUN 2018	**FIGURE 27**



ALBERTA ENVIRONMENT AND PARKS

PEACE RIVER HAZARD STUDY
ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION

50-YEAR, 100-YEAR, AND 200-YEAR
ICE JAM FLOOD FREQUECNY PROFILES
HEART RIVER

1001119	15 JUN 2018	**FIGURE 28**

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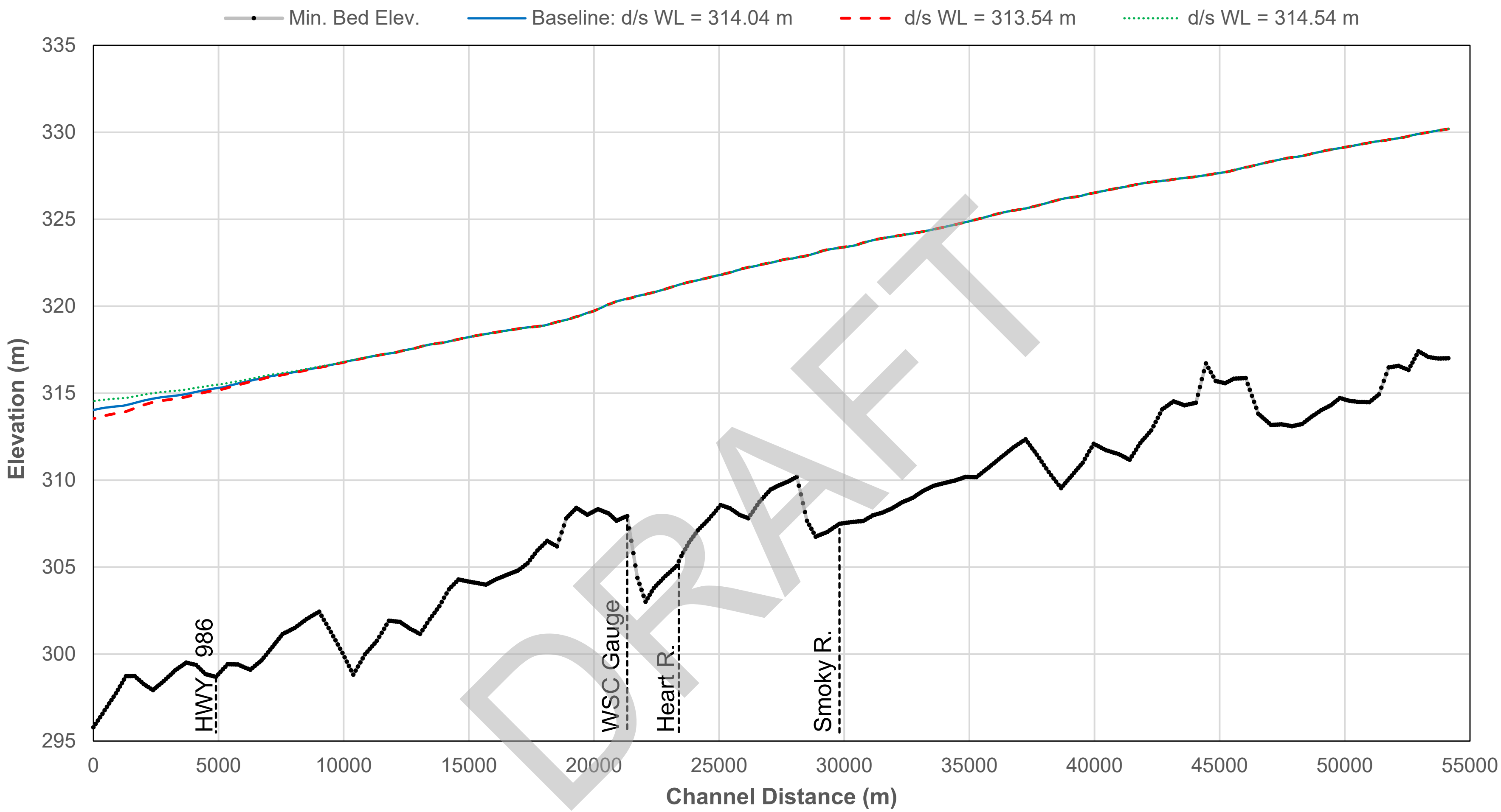

Notes:
1. The baseline condition denotes the 100-year ice jam flood frequency profile.
2. d/s WL denotes “downstream water level”

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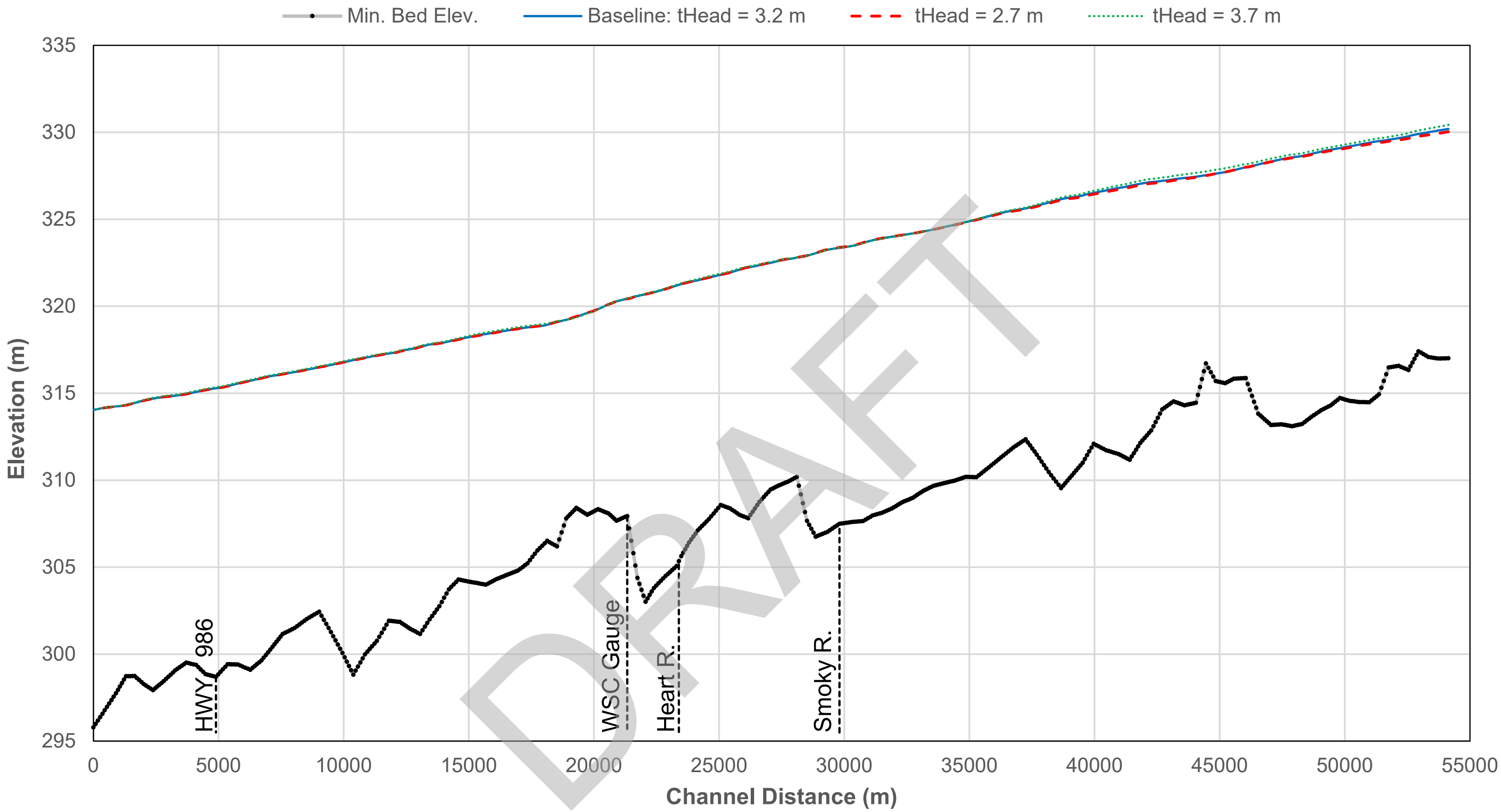
ALBERTA ENVIRONMENT AND PARKS		
PEACE RIVER HAZARD STUDY ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION **SENSITIVITY OF COMPUTED 100-YEAR ICE JAM FLOOD LEVELS ON THE PEACE RIVER TO VARIATION IN THE DOWNSTREAM WATER LEVEL**		
1001119	15 JUN 2018	**FIGURE 29**

Classification: Public



Notes:
1. The baseline condition denotes the 100-year ice jam flood frequency profile.
2. tHead denotes the upstream ice thickness (thickness at the "head")

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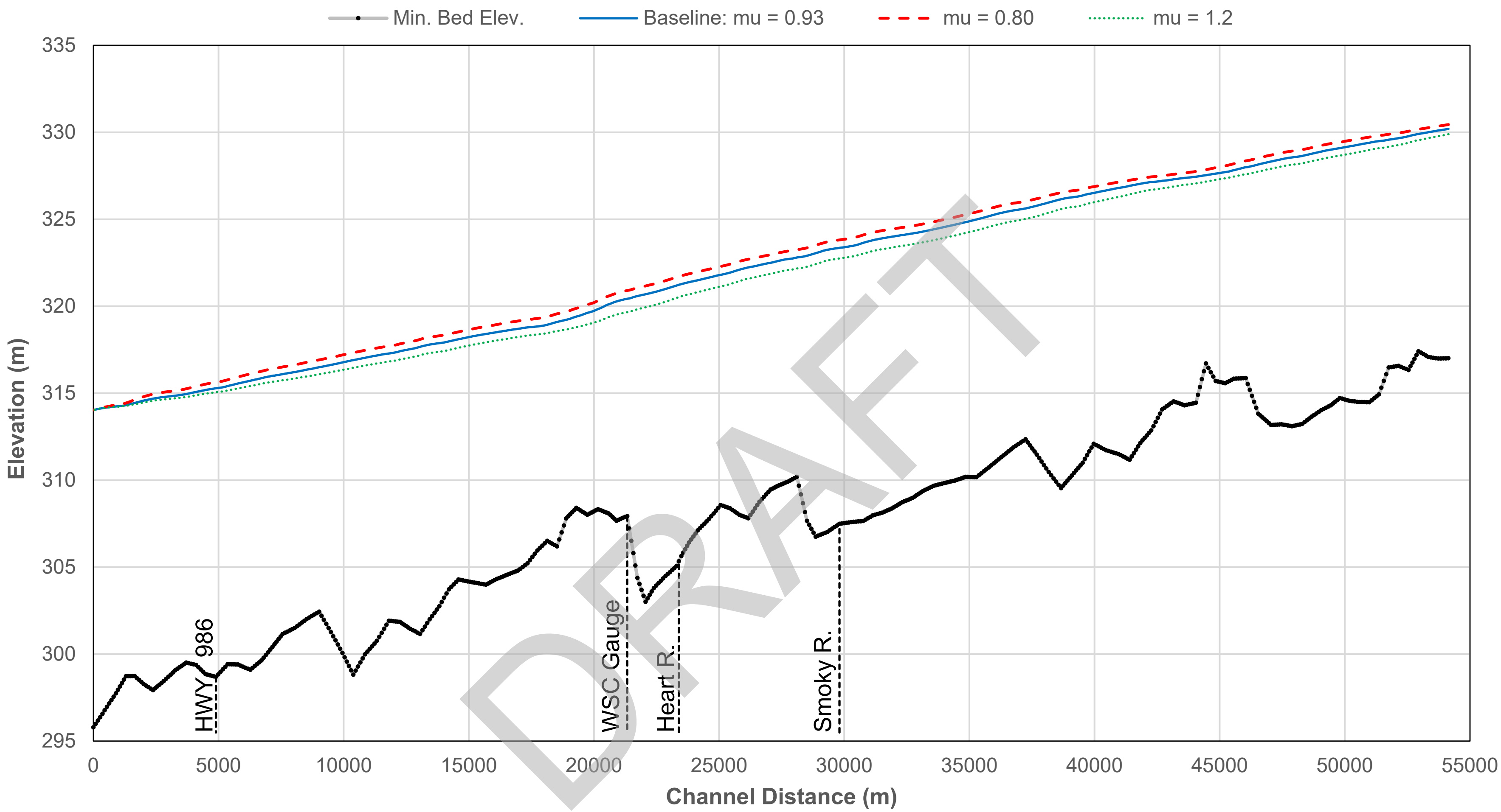
ALBERTA ENVIRONMENT AND PARKS		
PEACE RIVER HAZARD STUDY ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION **SENSITIVITY OF COMPUTED 100-YEAR ICE JAM FLOOD LEVELS ON THE PEACE RIVER TO VARIATION IN THE UPSTREAM ICE THICKNESS**		
1001119	15 JUN 2018	**FIGURE 30**



Notes:
1. The baseline condition denotes the 100-year ice jam flood frequency profile.
2. mu denotes the jam stability parameter, μ, according to equations [4] through [6].

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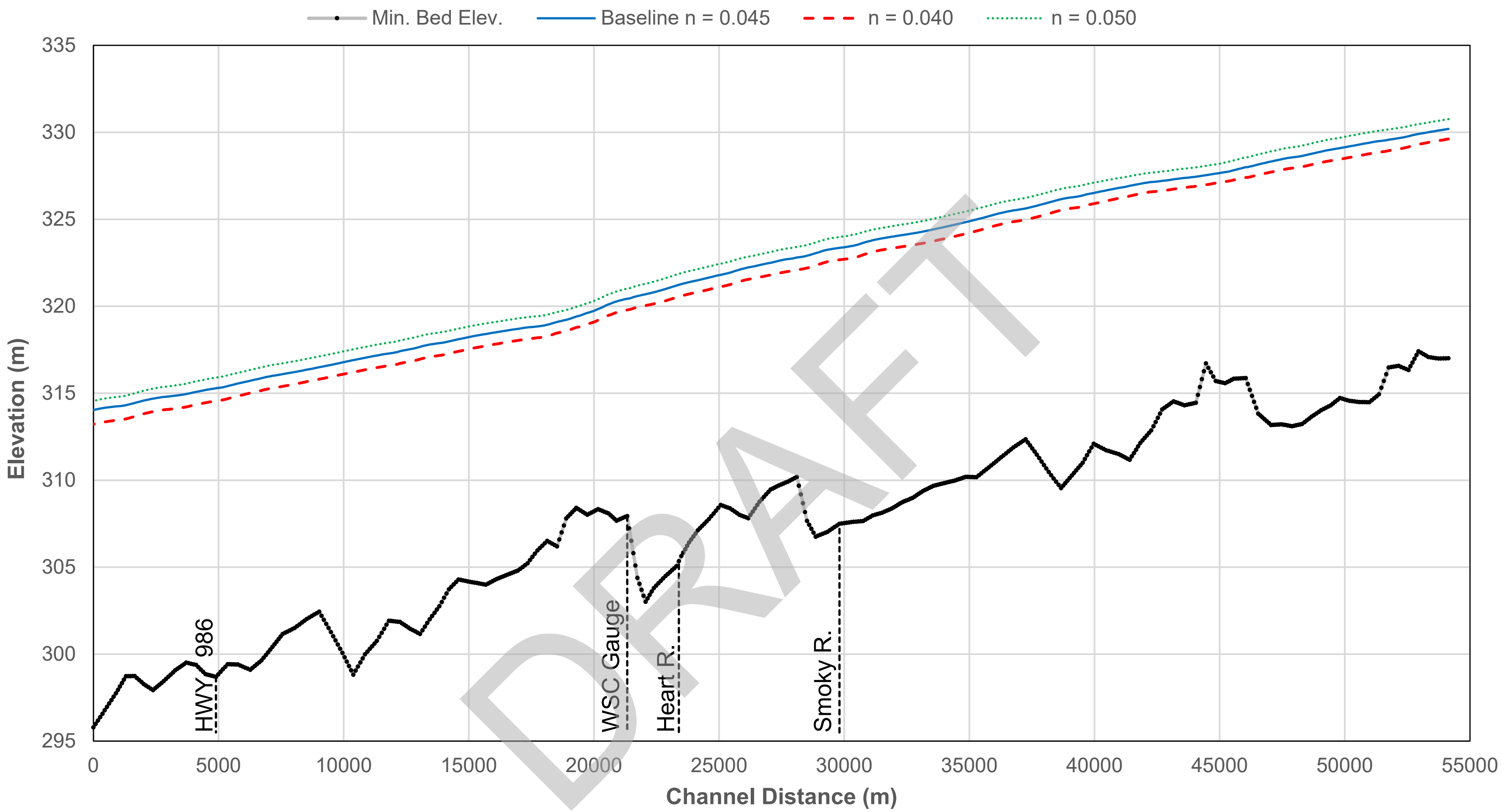
ALBERTA ENVIRONMENT AND PARKS		
PEACE RIVER HAZARD STUDY ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION **SENSITIVITY OF COMPUTED 100-YEAR ICE JAM FLOOD LEVELS ON THE PEACE RIVER TO VARIATION IN THE JAM STRENGTH PARAMETERS**		
1001119	15 JUN 2018	**FIGURE 31**



Notes:
1. The baseline condition denotes the 100-year ice jam flood frequency profile.
2. n denotes composite roughness

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ALBERTA ENVIRONMENT AND PARKS		
PEACE RIVER HAZARD STUDY ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION **SENSITIVITY OF COMPUTED 100-YEAR FLOOD ICE JAM FLOOD LEVELS ON THE PEACE RIVER TO VARIATION IN THE COMPOSITE ROUGHNESS**		
1001119	15 JUN 2018	**FIGURE 32**

Appendix A
Historic Ice Affected Flooding Photos

Notes: 1. Looking south showing 102 Avenue (Rotten Row) flooded in 1914. Image 87.1521.46.

[Image from Peace River Museum and Archives / Mackenzie Centre]

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ALBERTA ENVIRONMENT AND PARKS		
PEACE RIVER HAZARD STUDY ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION **HISTORICAL ICE AFFECTED FLOODING** **APRIL 1914 – PAT'S CREEK**		
1001119	15 JUN 2018	**FIGURE A-1**

Notes:

1. (Left) April 17, 1958. Looking south down Main (100th) Street – where the side of the Fire Hall is located is 99th Avenue. Image 83.1308.033.
2. (Right) Pat's Creek water rushing up against a bridge in Peace River, Alberta. Possibly the bridge where Main Street crossed Pat's Creek. Looking East from the edge of 100th Avenue. Image 87.1536.047.

[Images from Peace River Museum and Archives / Mackenzie Centre]

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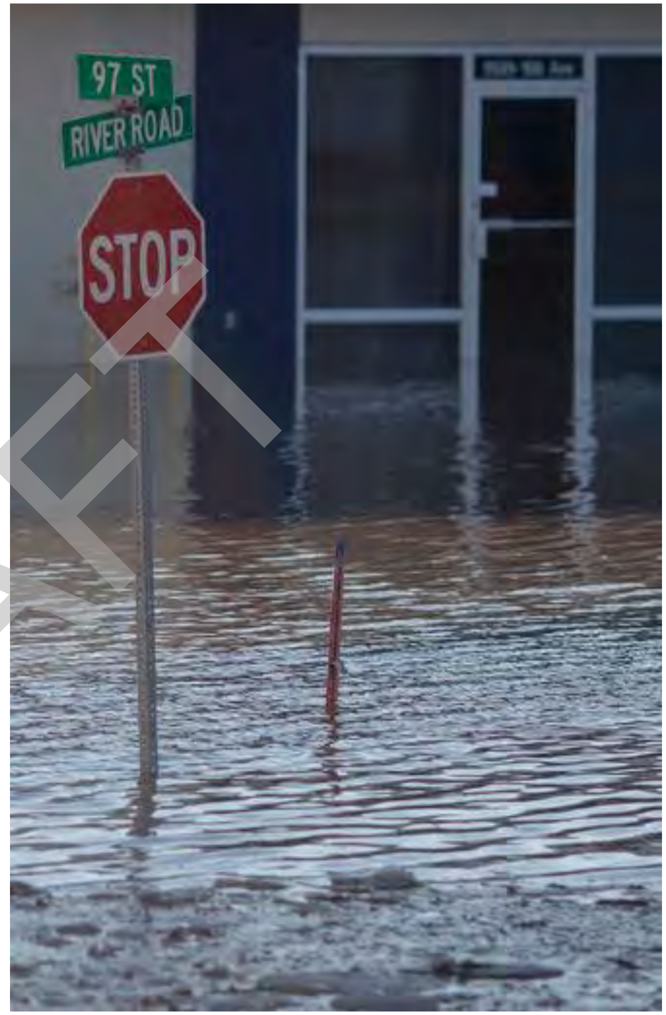
ALBERTA ENVIRONMENT AND PARKS		
PEACE RIVER HAZARD STUDY ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION **HISTORICAL ICE AFFECTED FLOODING** **17 APRIL 1958 – PAT'S CREEK**		
1001119	15 JUN 2018	**FIGURE A-2**



Notes: Images from: Adam Dietrich/Record-Gazette/QMI Agency. (9 April 2014) Daily Herald Tribune. Accessed 26 July 2016 from http://www.dailyheraldtribune.com/2014/04/09/downtown-peace-river-floods

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PEACE RIVER HAZARD STUDY
ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION

HISTORICAL ICE AFFECTED FLOODING
8 APRIL 2014 – PAT'S CREEK

1001119	15 JUN 2018	**FIGURE A-3**

Notes:
1. (Left) Looking upstream. River ice intact.
2. (Right) Looking downstream. Water had overtopped berms. Crews pumping flood water back into river.

[Images from Alberta Transportation, Bridge File 2010-1992, Heart River Bridge.]

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ALBERTA ENVIRONMENT AND PARKS		
PEACE RIVER HAZARD STUDY ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION **RECORDED ICE AFFECTED FLOODING 29 FEB 1992 – HEART RIVER DUE TO PEACE RIVER BACKWATER EFFECTS**		
1001119	15 JUN 2018	**FIGURE A-4**

Notes: 1. 18 April flooding on the Heart River.

[Images from Town of Peace River.]

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ALBERTA ENVIRONMENT AND PARKS		
PEACE RIVER HAZARD STUDY ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION **RECORDED ICE AFFECTED FLOODING 18 APRIL 1997 – HEART RIVER DUE TO PEACE RIVER BACKWATER EFFECTS**		
1001119	15 JUN 2018	**FIGURE A-5**

Notes:
1. (Left) Flooding in Twelve Foot Davis Baseball Park.
2. (Right) Ice jam in the Heart River at the Town of Peace River.

[Image Source: Alberta Environment (2005). Peace River Ice Observations 2004 – 2005.]

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ALBERTA ENVIRONMENT AND PARKS

PEACE RIVER HAZARD STUDY
ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION

RECORDED ICE AFFECTED FLOODING
9 MARCH 2005 – HEART RIVER

1001119	15 JUN 2018	**FIGURE A-6**

Notes:

1. (Left) March 23, open channel through where the ice previously was on the Heart River in the Town of Peace River at Twelve Foot Davis Baseball Diamond.
2. (Right) March 28, view of the Heart River as it flows through Peace River from right to left.

[Images from Alberta Environment (2015). Peace River Ice Observations 2014 – 2015.]

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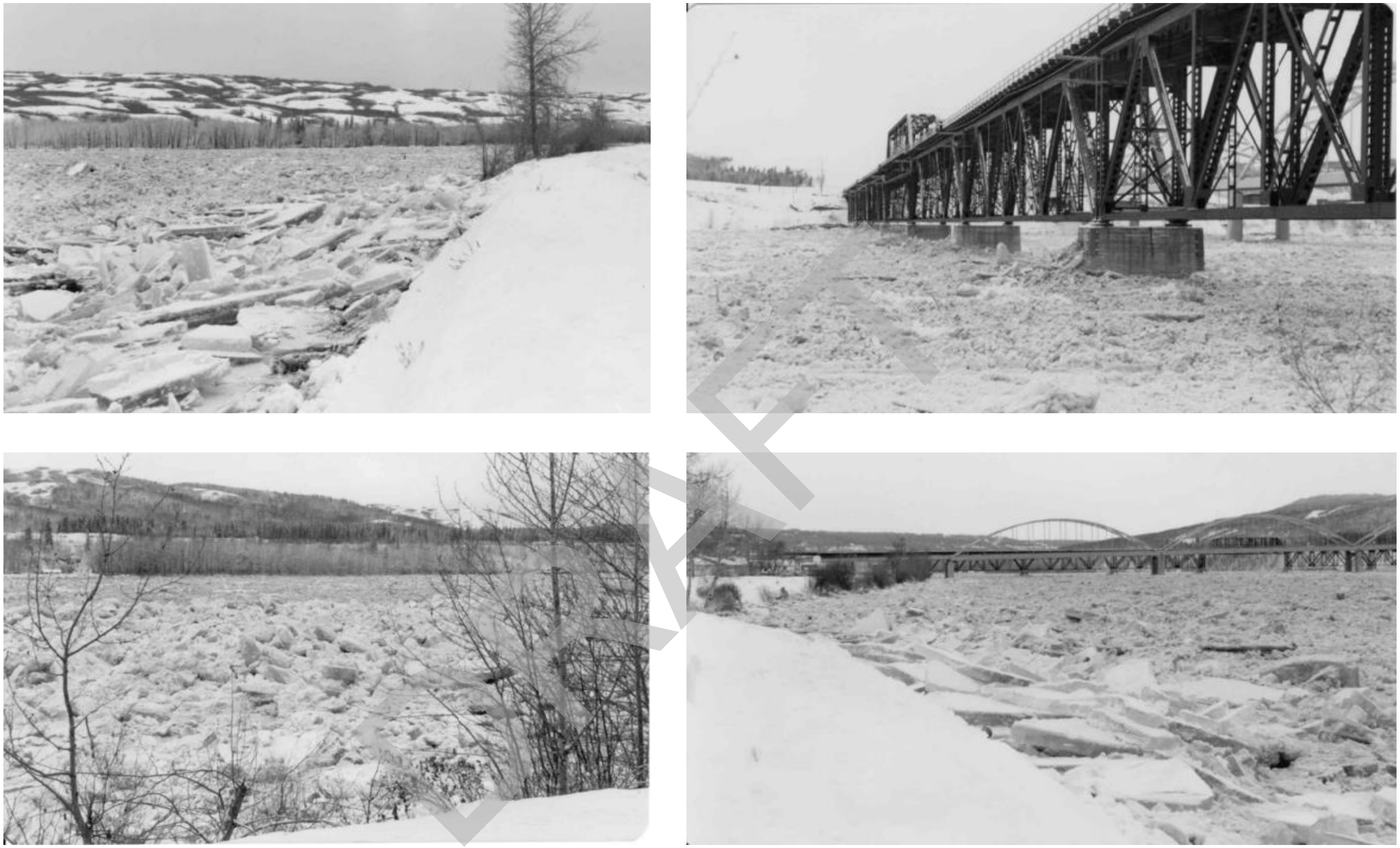
ALBERTA ENVIRONMENT AND PARKS		
PEACE RIVER HAZARD STUDY ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION **RECORDED ICE AFFECTED FLOODING 15 MARCH 2015 – HEART RIVER**		
1001119	15 JUN 2018	**FIGURE A-7**



Notes:

1. (Left) Photos of the January 1982 ice consolidation at TPR – views from the dike along the Kinsmen Park.
2. (Right) Photos of the January 1982 ice consolidation at TPR: (top) looking upstream to NAR bridge; (bottom) looking downstream to Highway 2 Bridge.

[Images from Hicks F, Andrishak R and She Y (2009) Modelling Ice Cover Consolidation during Freeze-up on the Peace River, AB. Proceedings of the CGU HS Committee on River Ice Processes and the Environment 15th Workshop on River Ice.]

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ALBERTA ENVIRONMENT AND PARKS

PEACE RIVER HAZARD STUDY
ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION

RECORDED ICE AFFECTED FLOODING
JAN 1982 – PEACE RIVER

1001119	15 JUN 2018	**FIGURE A-8**

Notes:

1. (Top left) 28 Feb 9:00 am, Railroad bridge in Peace River.
2. (Top right) 28 Feb 9:00 am, Peace River bridge.
3. (Bottom left) 29 Feb, Looking northeast at north residential area subject to worst flooding.
4. (Bottom right) 28 Feb 9:00 am, Ice level in Town of Peace River

[Images from Alberta Transportation, Bridge File 75946-1992, Highway 2 Bridge.]

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ALBERTA ENVIRONMENT AND PARKS		
PEACE RIVER HAZARD STUDY ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION **RECORDED ICE AFFECTED FLOODING 27 FEB – 2 MAR 1992 – PEACE RIVER**		
1001119	15 JUN 2018	**FIGURE A-9**

Notes:

1. (Left) Flooding in Peace River on 19 April. *[Images from Town of Peace River]*

2. (Right) 1997 Flood *[Image from Peace River Museum and Archives / Mackenzie Centre]*

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ALBERTA ENVIRONMENT AND PARKS		
PEACE RIVER HAZARD STUDY ICE JAM MODELLING & FLOOD HAZARD IDENTIFICATION **RECORDED ICE AFFECTED FLOODING 18-23 APR 1997 – PEACE RIVER**		
1001119	15 JUN 2018	**FIGURE A-10**

Appendix B
Ice Jam Flood Inundation Maps

(provided under separate cover)

Appendix C
Ice Jam Flood Criteria Map

TABLE OF CONTENTS

ICE JAM FLOODWAY CRITERIA INDEX MAP

Alberta Government

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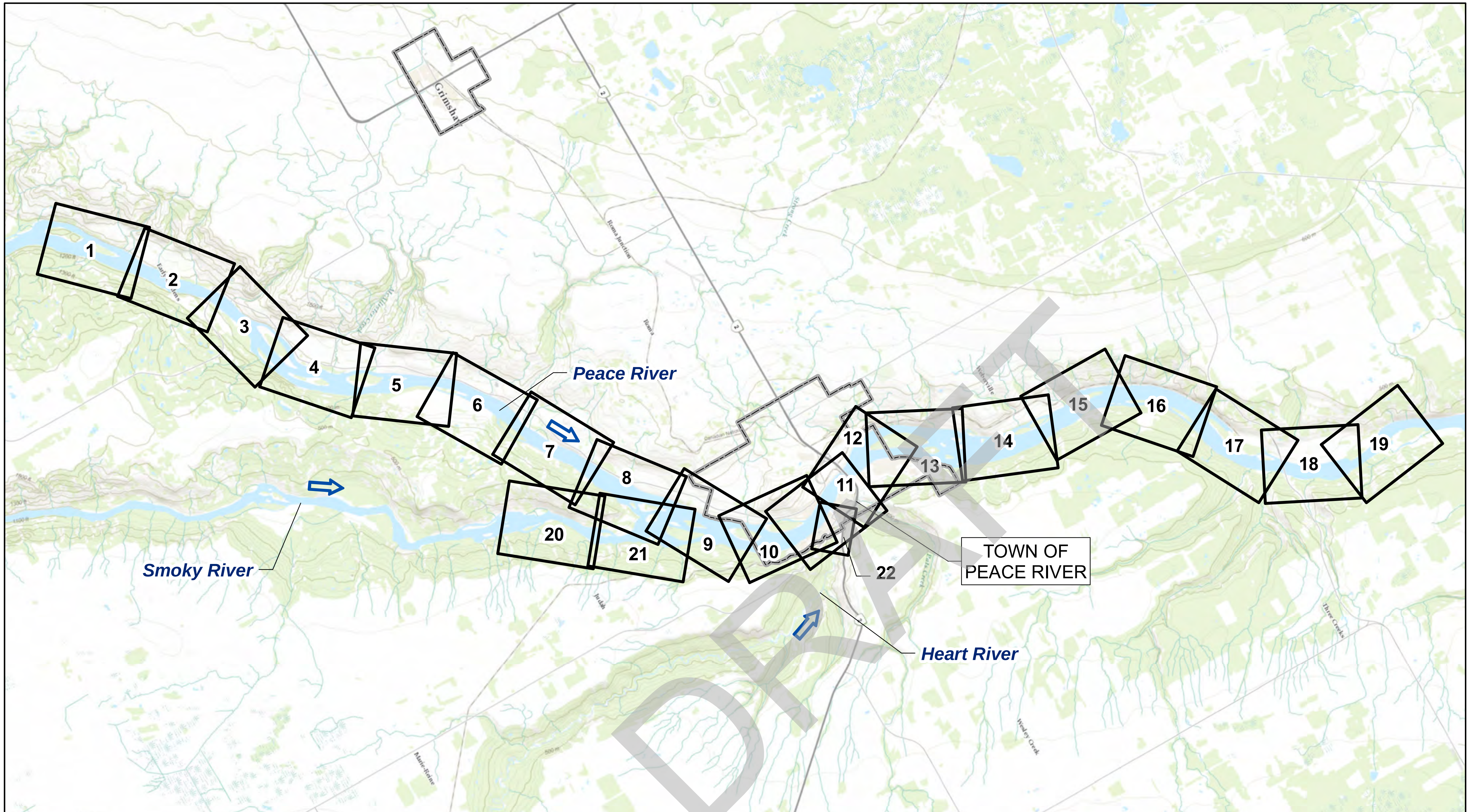


SCALE - 1:150,000

0 2,900 5,800 M

Coordinate System: NAD 1983 CSRS 3TM 117
Units: METRES

Job: 1001119 | Date: 07-OCT-2022

PEACE RIVER HAZARD STUDY

ICE JAM FLOODWAY CRITERIA INDEX MAP

INDEX MAP

Notes to Users:

1. Please refer to the accompanying **Peace River Hazard Study – Ice Jam Modelling Assessment and Flood Hazard Identification 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 have not been considered, and structures such roads, railways or barriers such as levees can restrict water flow and affect local flood levels. Channel obstruction, local stormwater inflow, groundwater seepage or other land drainage can cause flood levels to exceed those indicated on the map. Lands adjacent to a flooded area may be subject to flooding from tributary streams not indicated on the maps.
4. Backwater flood inundation along the Smoky River near the mouth was considered using simulated water levels from the Peace River near the mouth of the Smoky River.
5. The flood inundation area is shown above the line work for bridges and flood control structures that are below flood levels.

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.

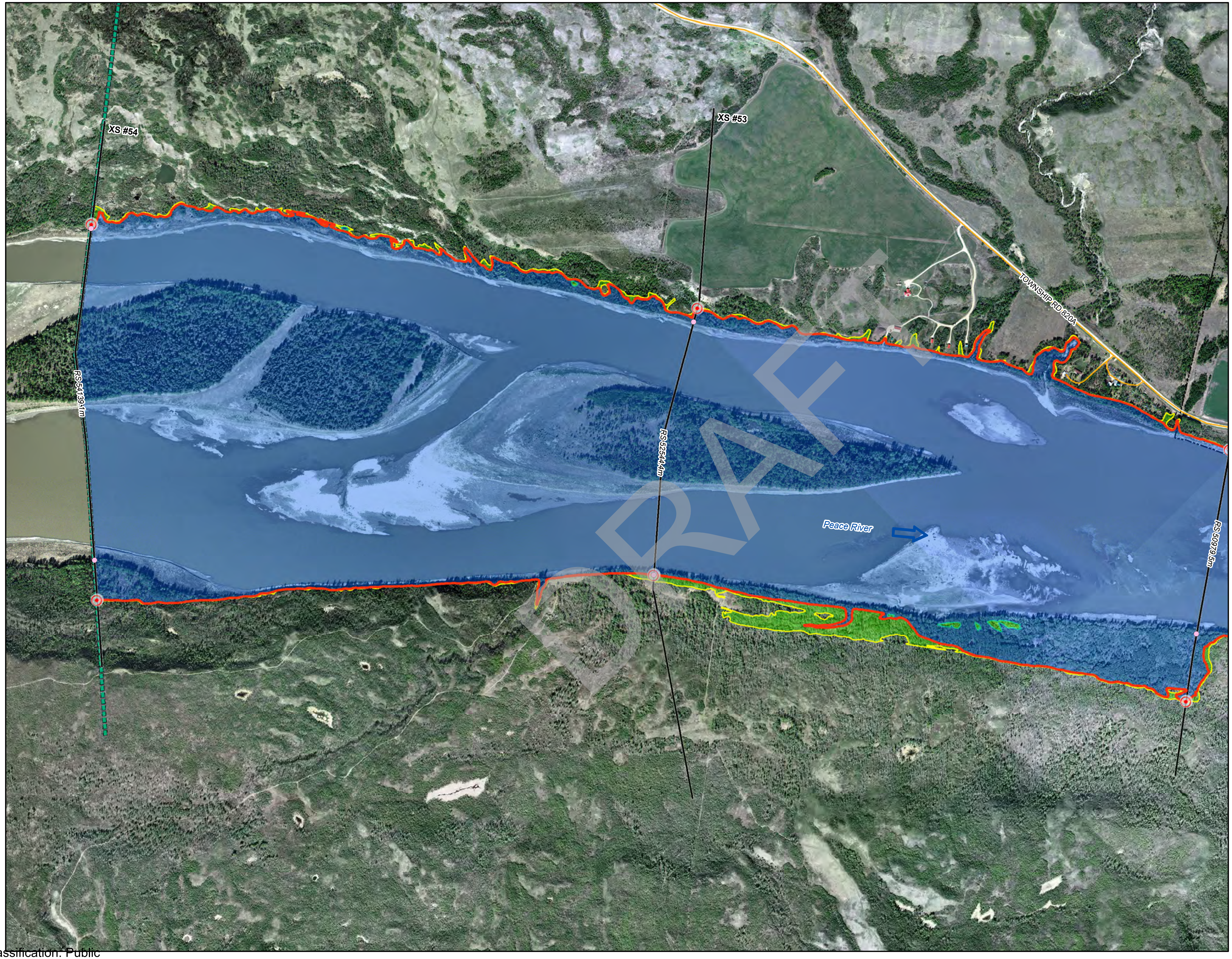
Data Sources and References:

1. Orthophoto imagery acquired by ORTHOSHOP Geomatics Ltd. (3 May 2016) for Alberta Environment and Parks.
2. Base data from Town of Peace River, Alberta Environment and Parks, AltaLIS, and NRCan.
3. Additional base mapping from Esri.

MSN, P:_Projects (Active)\1001119 Peace River Hazard Study\90_GIS_2022Update\PeaceRHS_Ice_Map_FloodwayCriteriaIndex_2022Update.mxd

ICE JAM FLOODWAY CRITERIA MAP

(SHEETS 1 TO 22)



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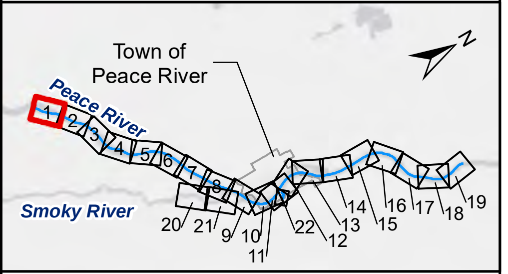


FLOW DIRECTION
BANK STATION
PROPOSED FLOODWAY LIMIT
PROPOSED FLOODWAY BOUNDARY
BRIDGE
CROSS SECTION
(RS denotes river station - distance from most downstream cross section.)
STUDY BOUNDARY
FLOOD CONTROL STRUCTURE
100-YEAR ICE JAM DESIGN FLOOD EXTENT
DEPTH ≥ 1 m
RAILWAY
MAJOR ROAD
LOCAL ROAD
FERRY ROUTE
PEACE RIVER TOWN
SETTLEMENT BOUNDARY

SCALE - 1:10,000

0 200 400 M

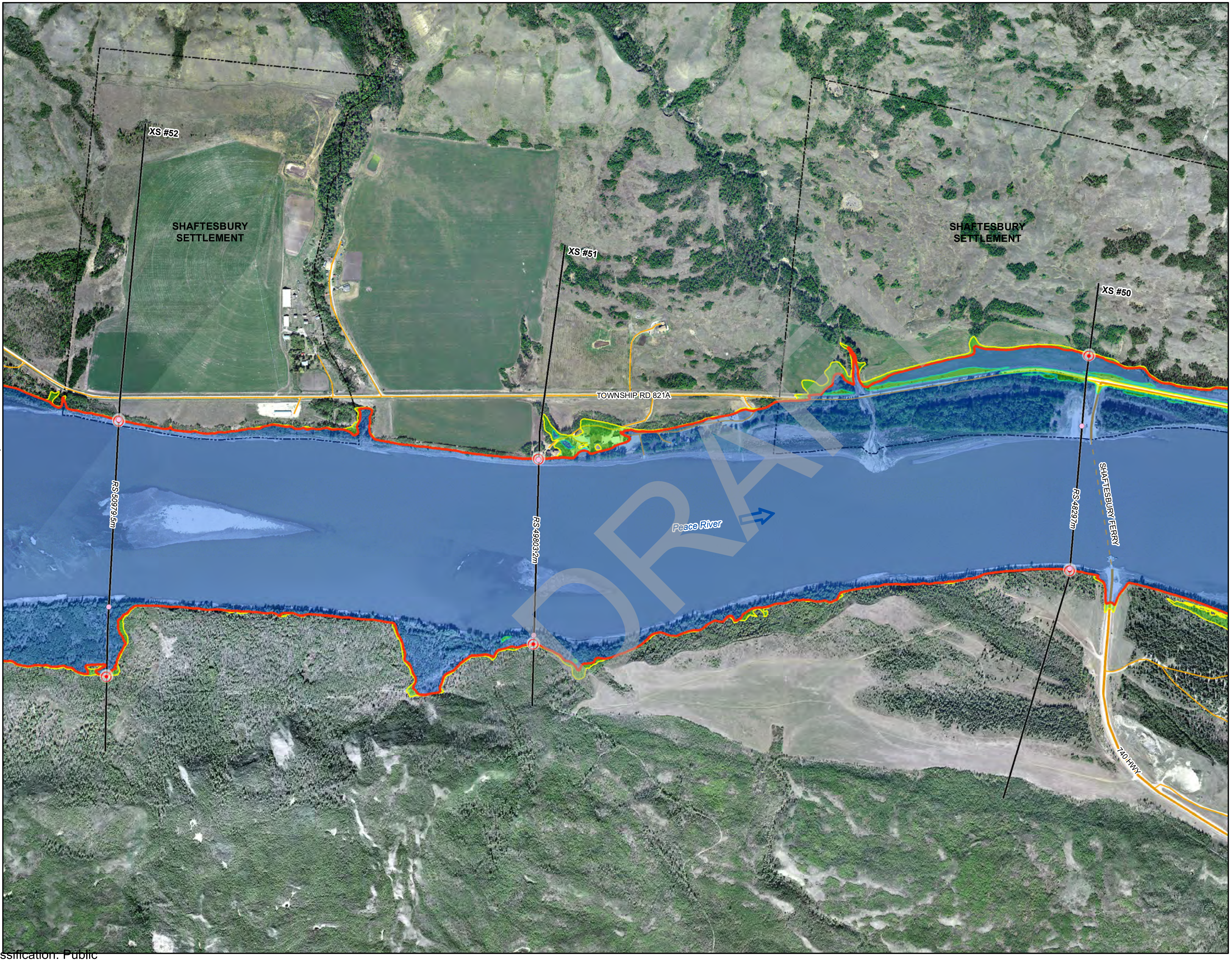
Coordinate System: NAD 1983 CSRS 3TM 117
Units: METRES

Job: 1001119	Date: 05-OCT-2022

PEACE RIVER HAZARD STUDY

ICE JAM FLOODWAY CRITERIA MAP

SHEET 1 OF 22



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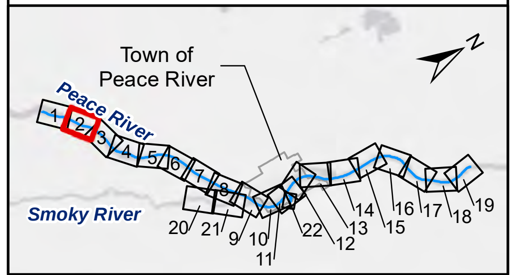


FLOW DIRECTION
BANK STATION
PROPOSED FLOODWAY LIMIT
PROPOSED FLOODWAY BOUNDARY
BRIDGE
CROSS SECTION (*RS denotes river station - distance from most downstream cross section.*)
STUDY BOUNDARY
FLOOD CONTROL STRUCTURE
100-YEAR ICE JAM DESIGN FLOOD EXTENT
DEPTH ≥ 1 m
RAILWAY
MAJOR ROAD
LOCAL ROAD
FERRY ROUTE
PEACE RIVER TOWN
SETTLEMENT BOUNDARY

SCALE - 1:10,000
0 200 400 M

Coordinate System: NAD 1983 CSRS 3TM 117
Units: METRES

Job: 1001119 | *Date: 05-OCT-2022*

PEACE RIVER HAZARD STUDY

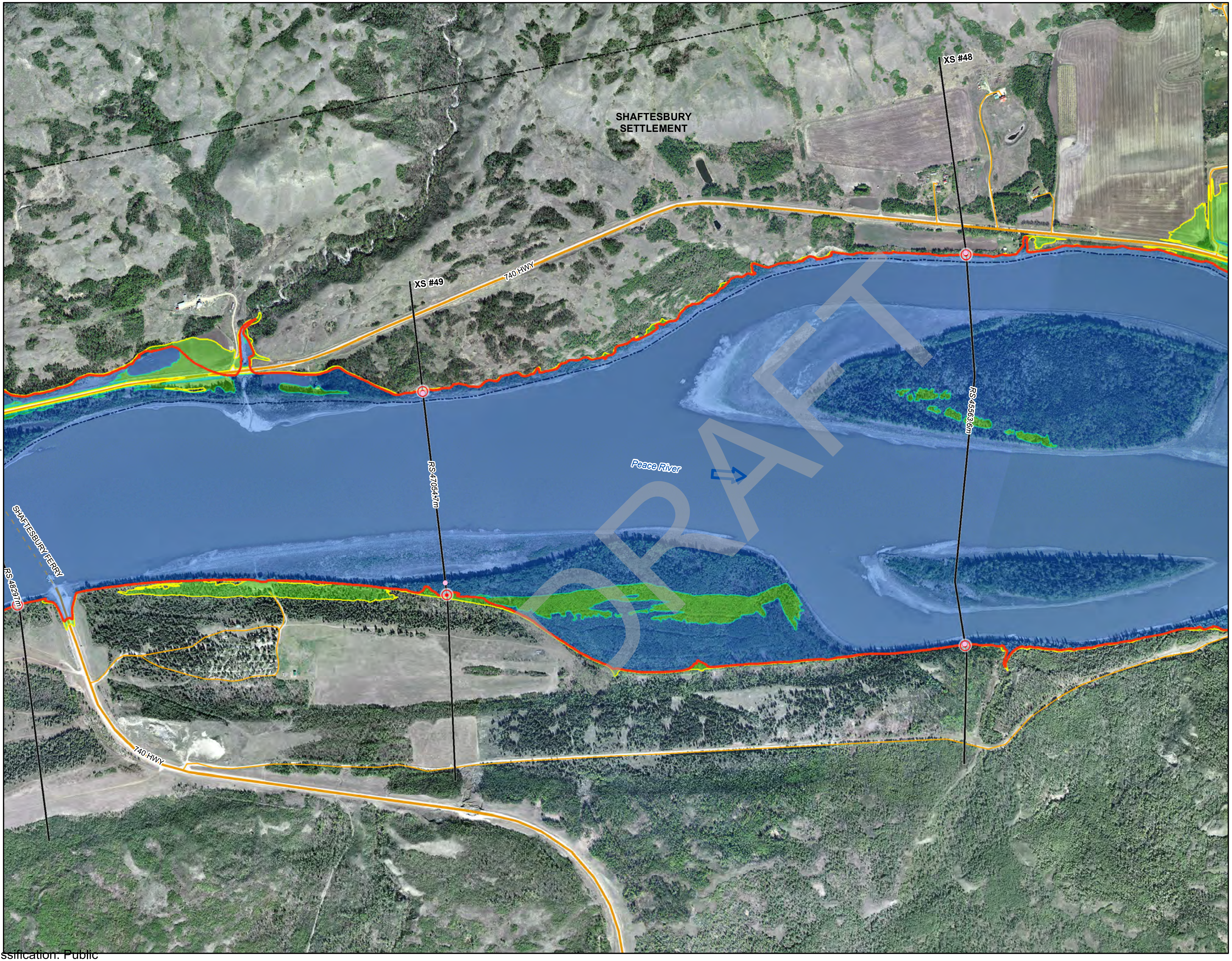
ICE JAM FLOODWAY CRITERIA MAP

SHEET 2 OF 22

MSN: P:_Projects (Active)\1001119 Peace River Hazard Study\90_GIS_2022Update\PeaceRHS_Ice_Map_FloodwayCriteria_2022Update.mxd

Classification: Public

SHEET 2 ↑



SHEET 4 ↓

Alberta Government

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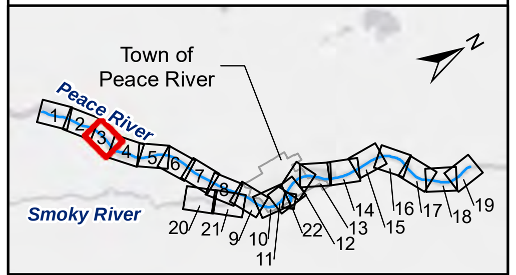

- FLOW DIRECTION
- BANK STATION
- PROPOSED FLOODWAY LIMIT
- PROPOSED FLOODWAY BOUNDARY
- BRIDGE
- CROSS SECTION *(RS denotes river station - distance from most downstream cross section.)*
- STUDY BOUNDARY
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- MAJOR ROAD
- LOCAL ROAD
- FERRY ROUTE
- PEACE RIVER TOWN
- SETTLEMENT BOUNDARY

SCALE - 1:10,000

0 200 400 M

N

Coordinate System: NAD 1983 CSRS 3TM 117
Units: METRES

Job: 1001119	Date: 05-OCT-2022

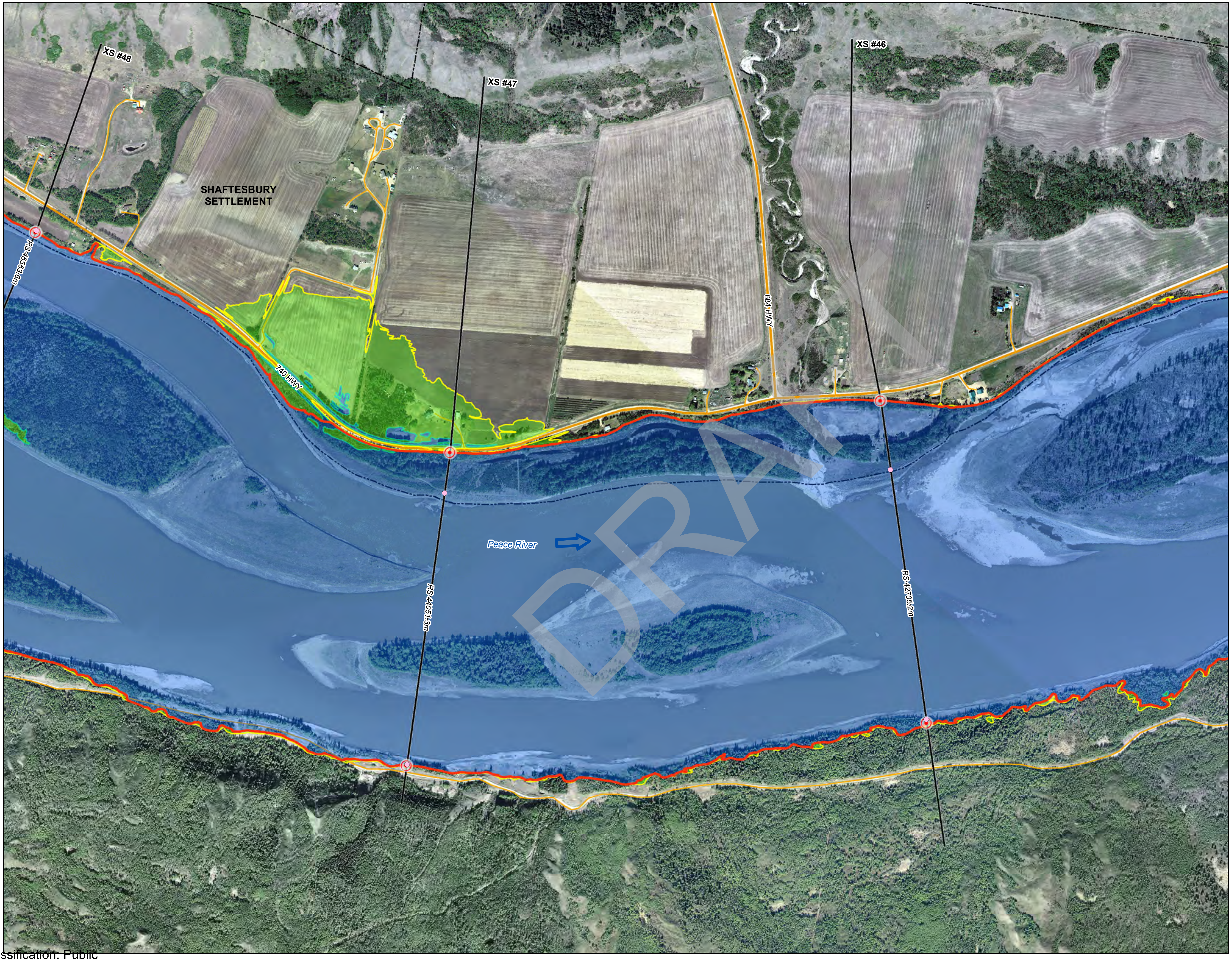
PEACE RIVER HAZARD STUDY

ICE JAM FLOODWAY CRITERIA MAP

SHEET 3 OF 22

Classification: Public

SHEET 3 ↑



SHEET 5 ↓

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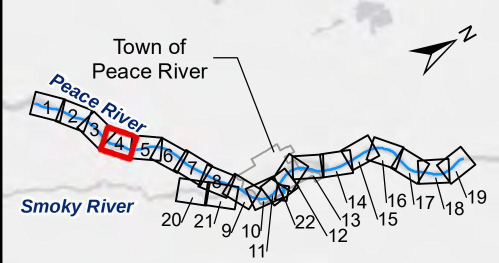

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- LOCAL ROAD
- FERRY ROUTE
- PEACE RIVER TOWN
- SETTLEMENT BOUNDARY

SCALE - 1:10,000

0 200 400 M

Coordinate System: NAD 1983 CSRS 3TM 117
Units: METRES

Job: 1001119	*Date: 05-OCT-2022*

PEACE RIVER HAZARD STUDY

ICE JAM FLOODWAY CRITERIA MAP

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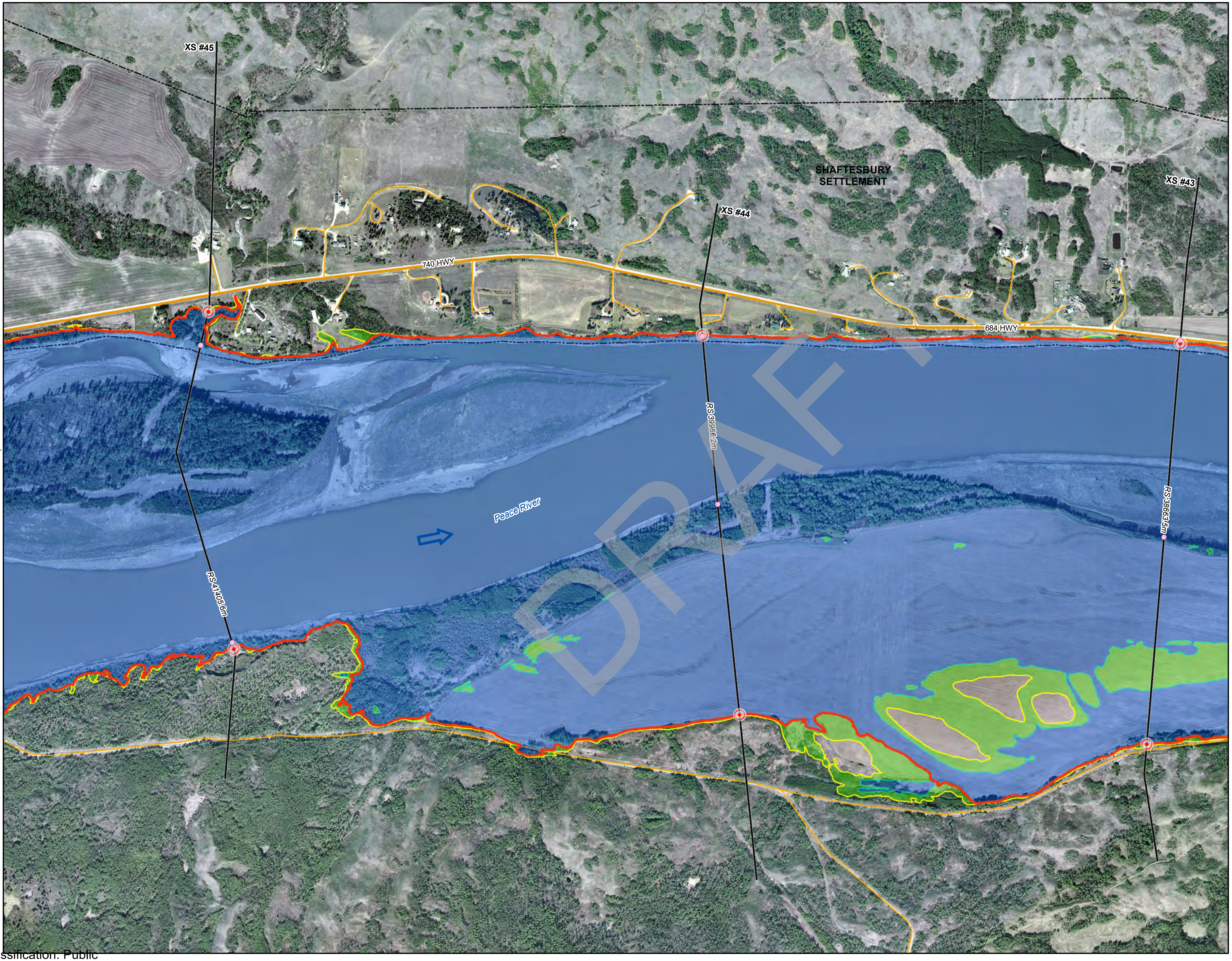

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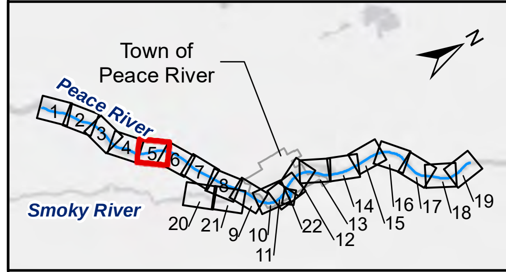


FLOW DIRECTION
BANK STATION
PROPOSED FLOODWAY LIMIT
PROPOSED FLOODWAY BOUNDARY
BRIDGE
CROSS SECTION
(RS denotes river station - distance from most downstream cross section.)
STUDY BOUNDARY
FLOOD CONTROL STRUCTURE
100-YEAR ICE JAM DESIGN FLOOD EXTENT
DEPTH ≥ 1 m
RAILWAY
MAJOR ROAD
LOCAL ROAD
FERRY ROUTE
PEACE RIVER TOWN
SETTLEMENT BOUNDARY

SCALE - 1:10,000
0 200 400 M

Coordinate System: NAD 1983 CSRS 3TM 117
Units: METRES

Job: 1001119 Date: 05-OCT-2022

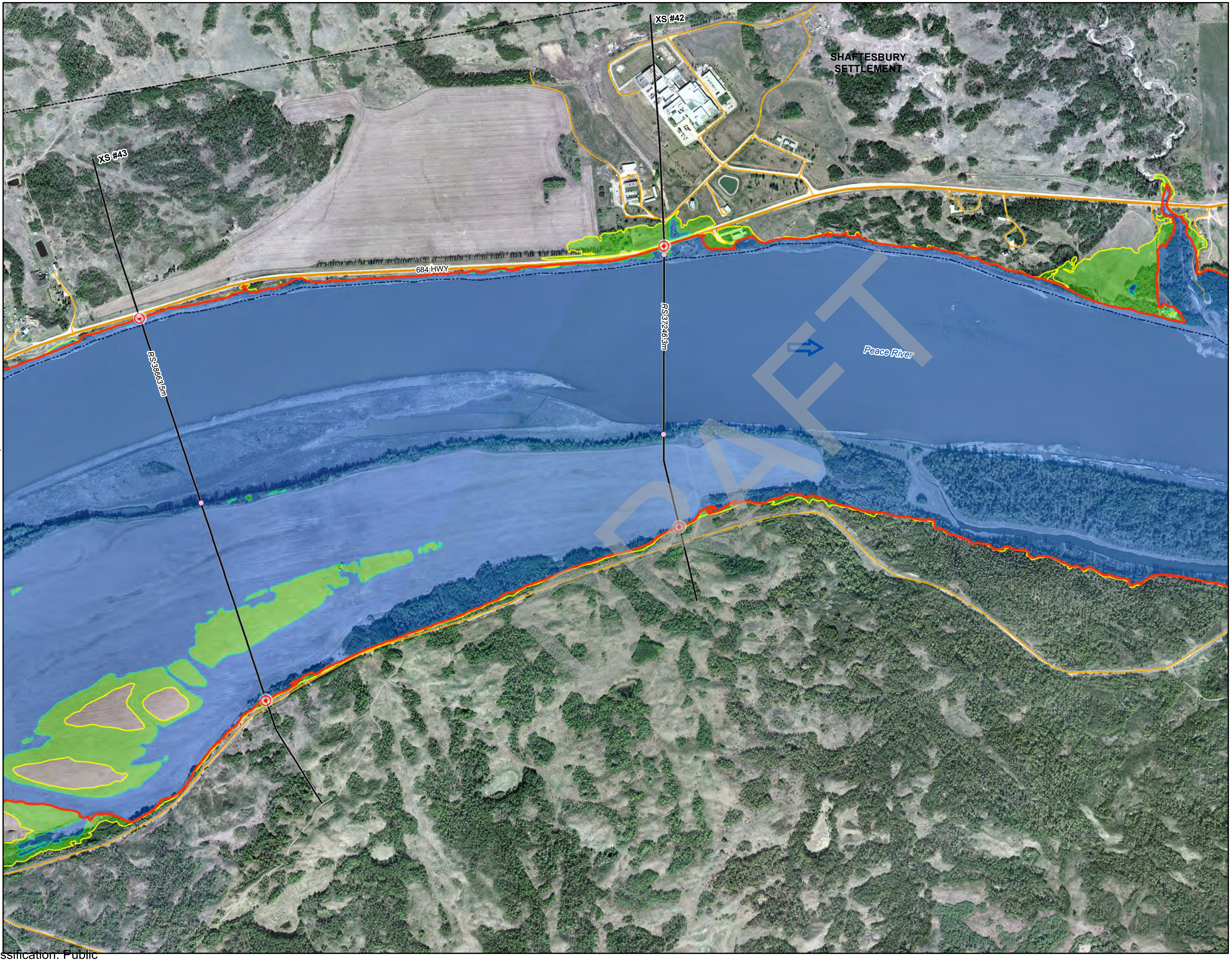
PEACE RIVER HAZARD STUDY

ICE JAM FLOODWAY CRITERIA MAP

SHEET 5 OF 22

MSN, P:_Projects (Active)\1001119 Peace River Hazard Study\90_GIS_2022Update\PeaceRHS_Ice_Map_FloodwayCriteria_2022Update.mxd

SHEET 5 ↑



SHEET 7 ↑

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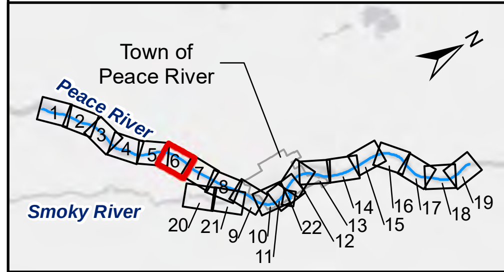

- FLOW DIRECTION
- BANK STATION
- PROPOSED FLOODWAY LIMIT
- PROPOSED FLOODWAY BOUNDARY
- BRIDGE
- CROSS SECTION *(RS denotes river station - distance from most downstream cross section.)*
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- FLOOD CONTROL STRUCTURE
- 100-YEAR ICE JAM DESIGN FLOOD EXTENT
- DEPTH ≥ 1 m
- RAILWAY
- MAJOR ROAD
- LOCAL ROAD
- FERRY ROUTE
- PEACE RIVER TOWN
- SETTLEMENT BOUNDARY

SCALE - 1:10,000

0 200 400 M

Coordinate System: NAD 1983 CSRS 3TM 117
Units: METRES

Job: 1001119 | *Date: 05-OCT-2022*

PEACE RIVER HAZARD STUDY

ICE JAM FLOODWAY CRITERIA MAP

SHEET 6 OF 22

Classification: Public

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Town of Peace River
Peace River
Smoky River

- FLOW DIRECTION
- BANK STATION
- PROPOSED FLOODWAY LIMIT
- PROPOSED FLOODWAY BOUNDARY
- BRIDGE
- CROSS SECTION *(RS denotes river station - distance from most downstream cross section.)*
- STUDY BOUNDARY
- FLOOD CONTROL STRUCTURE
- 100-YEAR ICE JAM DESIGN FLOOD EXTENT
- DEPTH ≥ 1 m
- RAILWAY
- MAJOR ROAD
- LOCAL ROAD
- FERRY ROUTE
- PEACE RIVER TOWN
- SETTLEMENT BOUNDARY

SCALE - 1:10,000
0 200 400 M

Coordinate System: NAD 1983 CSRS 3TM 117
Units: METRES

Job: 1001119	Date: 05-OCT-2022

PEACE RIVER HAZARD STUDY

ICE JAM FLOODWAY CRITERIA MAP

SHEET 7 OF 22

Classification: Public

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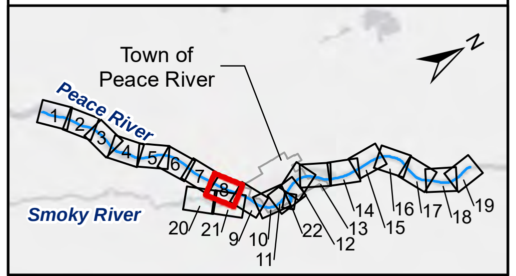


- FLOW DIRECTION
- BANK STATION
- PROPOSED FLOODWAY LIMIT
- PROPOSED FLOODWAY BOUNDARY
- BRIDGE
- CROSS SECTION *(RS denotes river station - distance from most downstream cross section.)*
- STUDY BOUNDARY
- FLOOD CONTROL STRUCTURE
- 100-YEAR ICE JAM DESIGN FLOOD EXTENT
- DEPTH ≥ 1 m
- RAILWAY
- MAJOR ROAD
- LOCAL ROAD
- FERRY ROUTE
- PEACE RIVER TOWN
- SETTLEMENT BOUNDARY

SCALE - 1:10,000

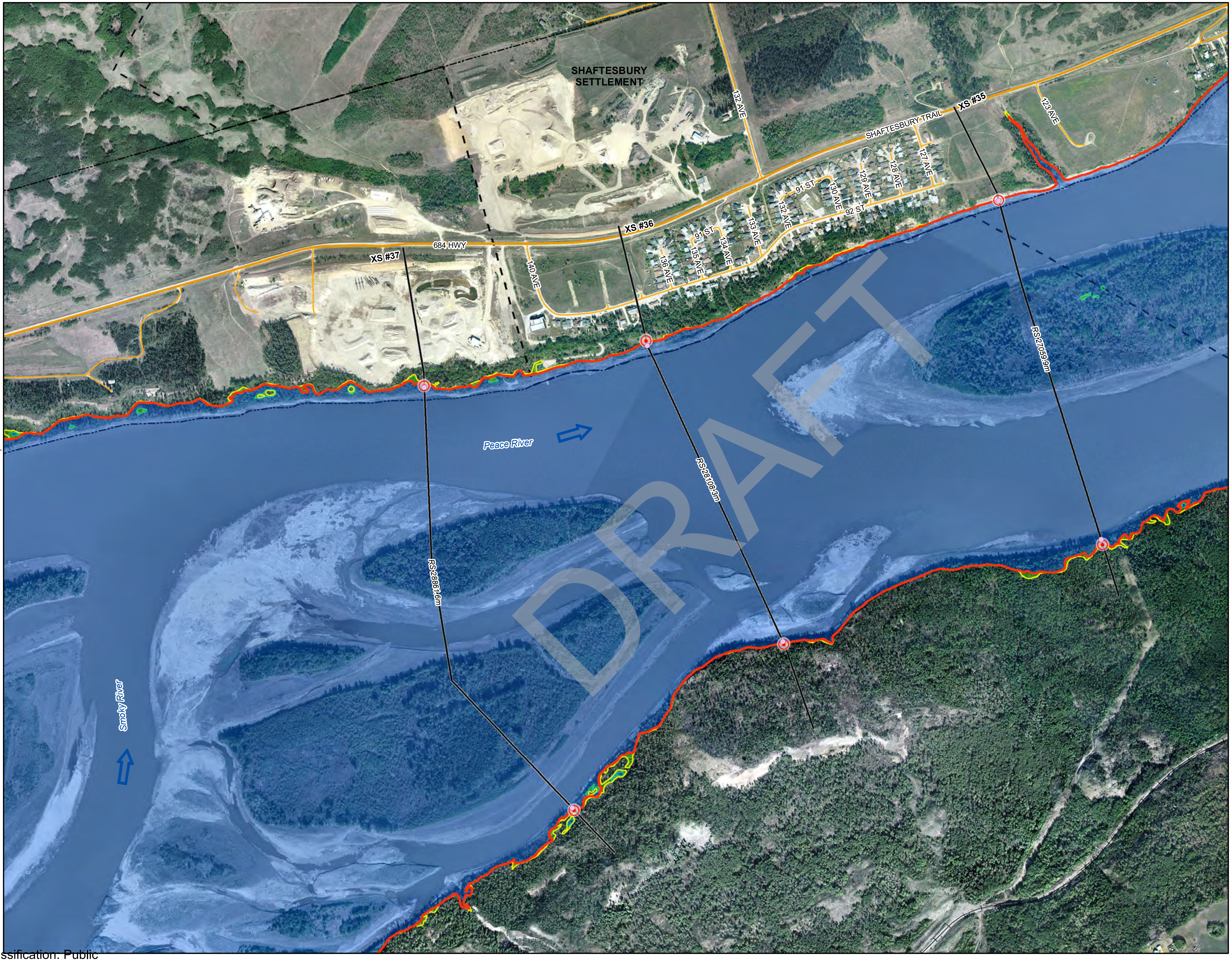
0 200 400 M

Coordinate System: NAD 1983 CSRS 3TM 117
Units: METRES

Job: 1001119	*Date: 05-OCT-2022*

PEACE RIVER HAZARD STUDY

ICE JAM FLOODWAY CRITERIA MAP



SHEET 8 ↑

SHEET 10 ↓

Classification: Public

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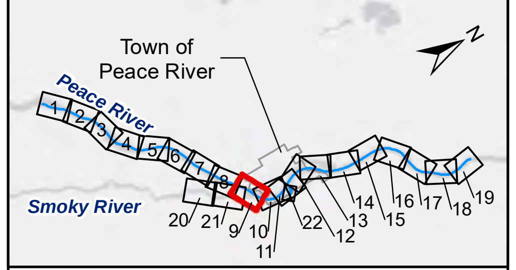


FLOW DIRECTION

BANK STATION

PROPOSED FLOODWAY LIMIT

PROPOSED FLOODWAY BOUNDARY

BRIDGE

CROSS SECTION
(RS denotes river station - distance from most downstream cross section.)

STUDY BOUNDARY

FLOOD CONTROL STRUCTURE

100-YEAR ICE JAM DESIGN FLOOD EXTENT

DEPTH ≥ 1 m

RAILWAY

MAJOR ROAD

LOCAL ROAD

FERRY ROUTE

PEACE RIVER TOWN

SETTLEMENT BOUNDARY

SCALE - 1:10,000

0 200 400 M

N

Coordinate System: NAD 1983 CSRS 3TM 117
Units: METRES

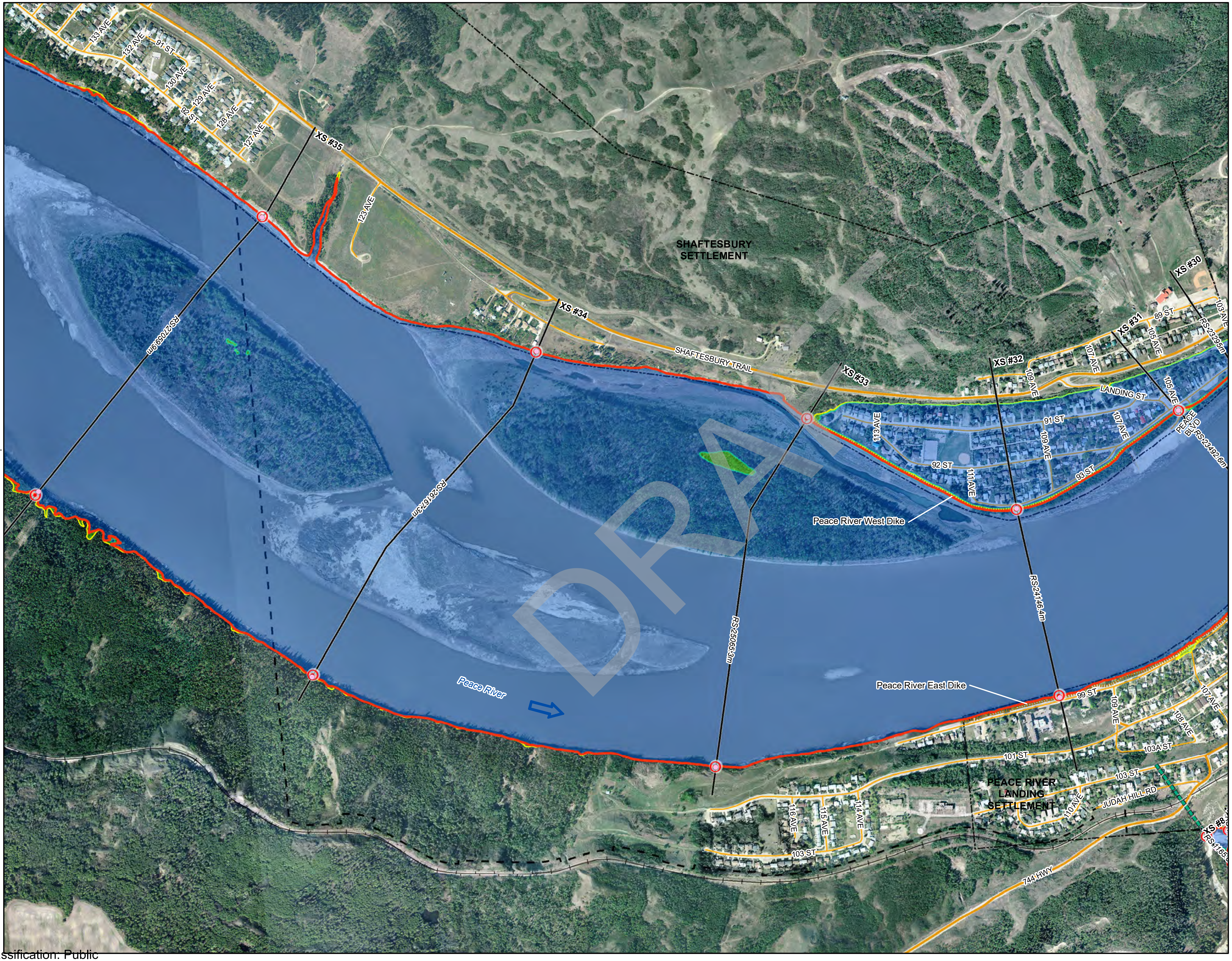
Job: 1001119	*Date: 05-OCT-2022*

PEACE RIVER HAZARD STUDY

ICE JAM FLOODWAY CRITERIA MAP

SHEET 9 OF 22

MSN, P:_Projects (Active)\1001119 Peace River Hazard Study\90_GIS_2022Update\PeaceRHS_Ice_Map_FloodwayCriteria_2022Update.mxd



Classification: Public

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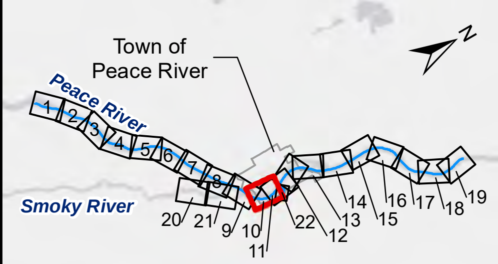

- FLOW DIRECTION
- BANK STATION
- PROPOSED FLOODWAY LIMIT
- PROPOSED FLOODWAY BOUNDARY
- BRIDGE
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- LOCAL ROAD
- FERRY ROUTE
- PEACE RIVER TOWN
- SETTLEMENT BOUNDARY

SCALE - 1:10,000

0 200 400 M

Coordinate System: NAD 1983 CSRS 3TM 117
Units: METRES

Job: 1001119	Date: 05-OCT-2022

PEACE RIVER HAZARD STUDY

ICE JAM FLOODWAY CRITERIA MAP

SHEET 10 OF 22

Classification: Public

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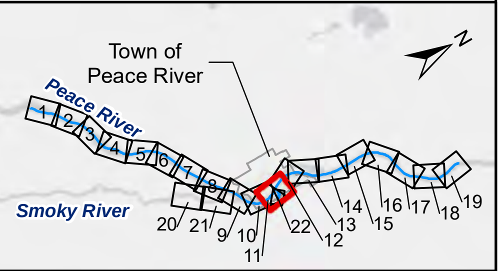


FLOW DIRECTION
BANK STATION
PROPOSED FLOODWAY LIMIT
PROPOSED FLOODWAY BOUNDARY
BRIDGE
CROSS SECTION (RS denotes river station - distance from most downstream cross section.)
STUDY BOUNDARY
FLOOD CONTROL STRUCTURE
100-YEAR ICE JAM DESIGN FLOOD EXTENT
DEPTH ≥ 1 m
RAILWAY
MAJOR ROAD
LOCAL ROAD
FERRY ROUTE
PEACE RIVER TOWN
SETTLEMENT BOUNDARY

SCALE - 1:10,000
0 200 400 M

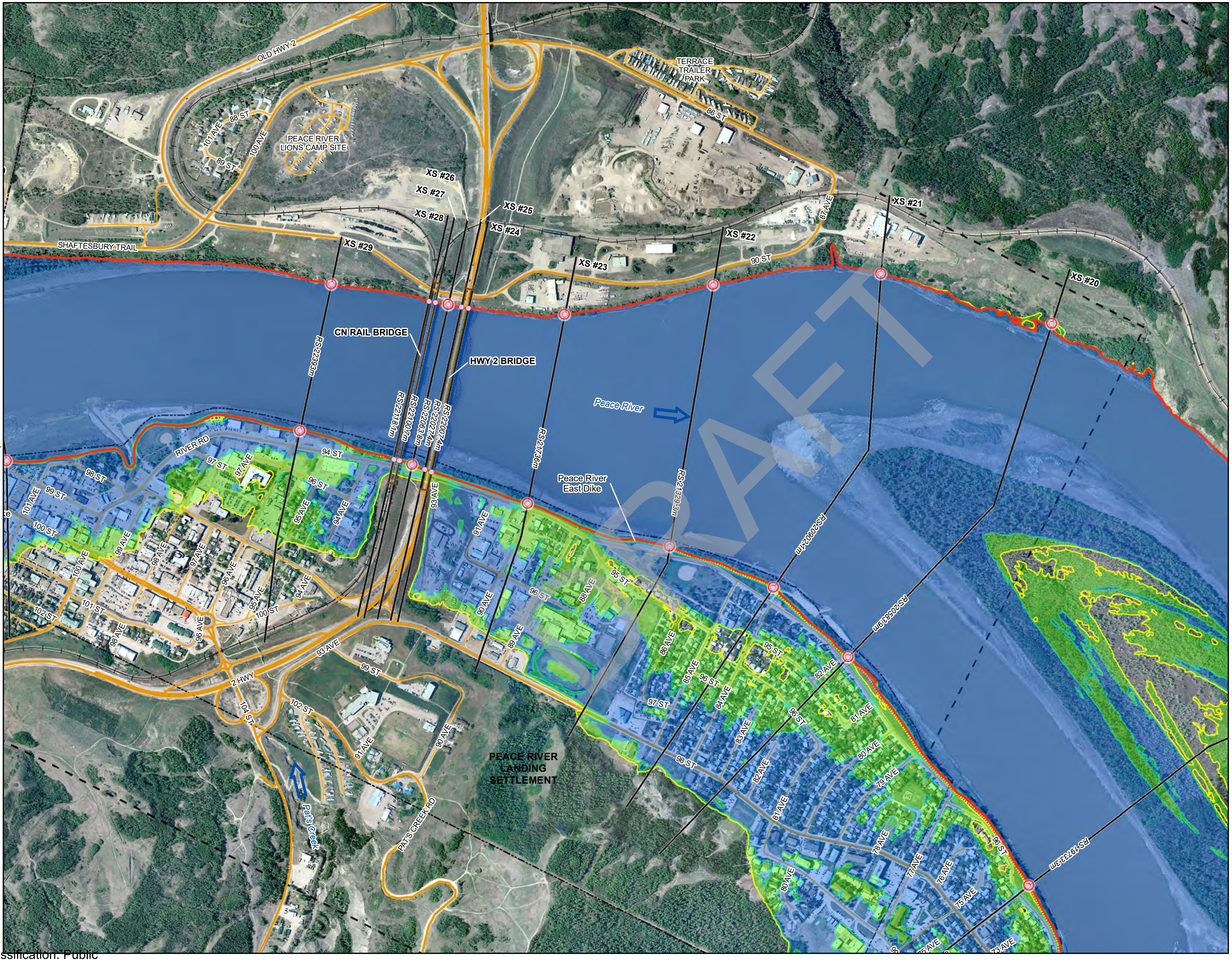
Coordinate System: NAD 1983 CSRS 3TM 117
Units: METRES

Job: 1001119 | Date: 05-OCT-2022

PEACE RIVER HAZARD STUDY

ICE JAM FLOODWAY CRITERIA MAP

SHEET 11 OF 22



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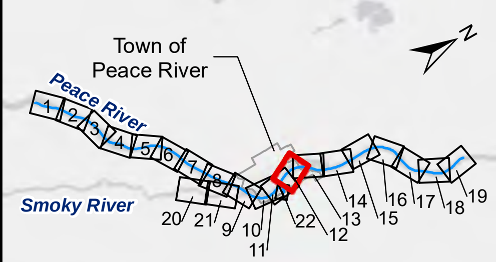

- FLOW DIRECTION
- BANK STATION
- PROPOSED FLOODWAY LIMIT
- PROPOSED FLOODWAY BOUNDARY
- BRIDGE
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- 100-YEAR ICE JAM DESIGN FLOOD EXTENT
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- FERRY ROUTE
- PEACE RIVER TOWN
- SETTLEMENT BOUNDARY

SCALE - 1:10,000

0 200 400 M

Coordinate System: NAD 1983 CSRS 3TM 117
Units: METRES

Job: 1001119	Date: 05-OCT-2022

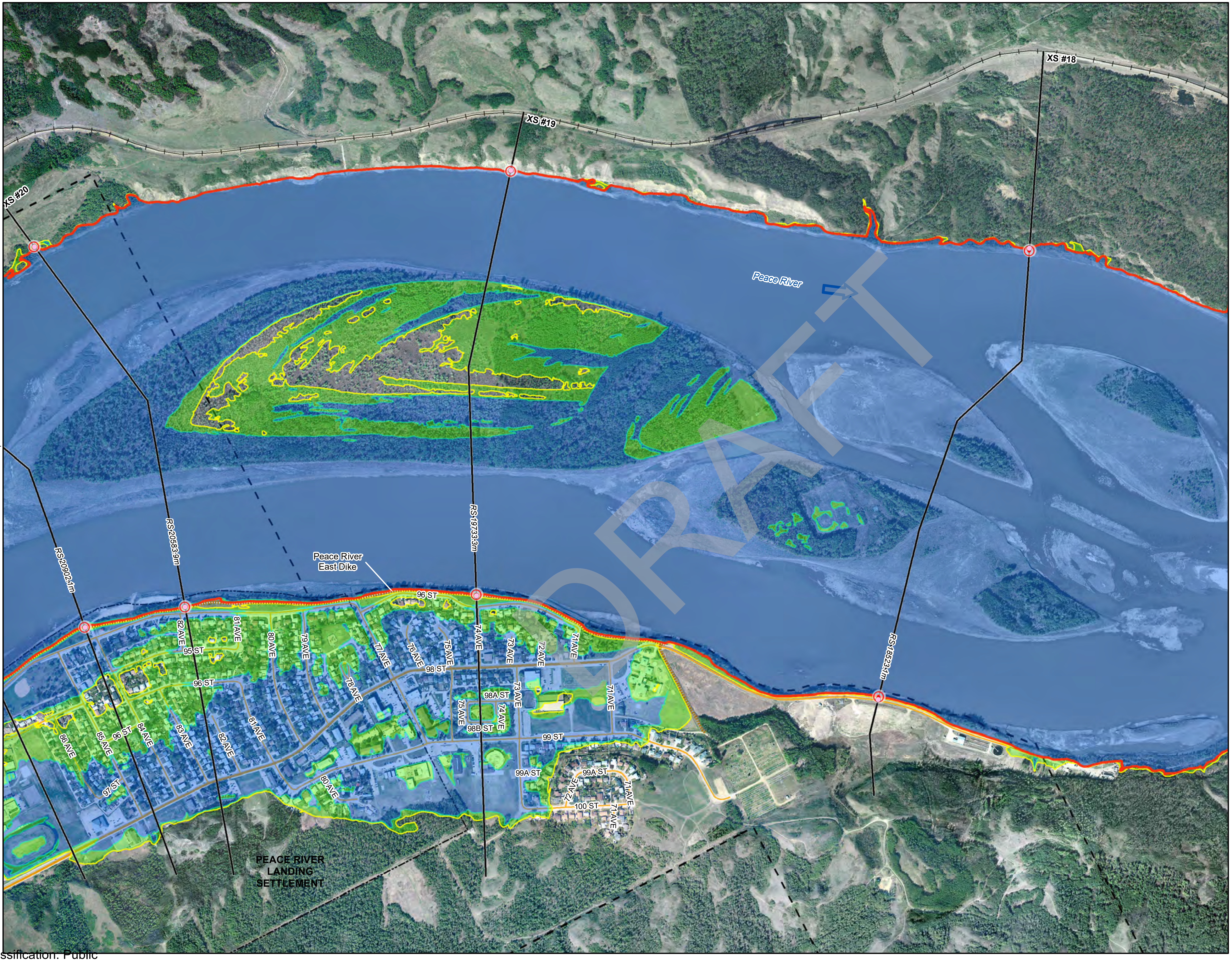
PEACE RIVER HAZARD STUDY

ICE JAM FLOODWAY CRITERIA MAP

SHEET 12 OF 22

Classification: Public

MSN_P:_Projects (Active)\1001119 Peace River Hazard Study\90_GIS_2022Update\PeaceRHS_Ice_Map_FloodwayCriteria_2022Update.mxd



Alberta Government

nhc northwest hydraulic consultants

Town of Peace River

Peace River

Smoky River

FLOW DIRECTION

BANK STATION

PROPOSED FLOODWAY LIMIT

PROPOSED FLOODWAY BOUNDARY

BRIDGE

CROSS SECTION
(RS denotes river station - distance from most downstream cross section.)

STUDY BOUNDARY

FLOOD CONTROL STRUCTURE

100-YEAR ICE JAM DESIGN FLOOD EXTENT

DEPTH ≥ 1 m

RAILWAY

MAJOR ROAD

LOCAL ROAD

FERRY ROUTE

PEACE RIVER TOWN

SETTLEMENT BOUNDARY

SCALE - 1:10,000

0 200 400 M

Coordinate System: NAD 1983 CSRS 3TM 117
Units: METRES

Job: 1001119	Date: 05-OCT-2022

PEACE RIVER HAZARD STUDY

ICE JAM FLOODWAY CRITERIA MAP

SHEET 13 OF 22

MSN_P:_Projects (Active)\1001119 Peace River Hazard Study\90_GIS_2022Update\PeaceRHS_Ice_Map_FloodwayCriteria_2022Update.mxd

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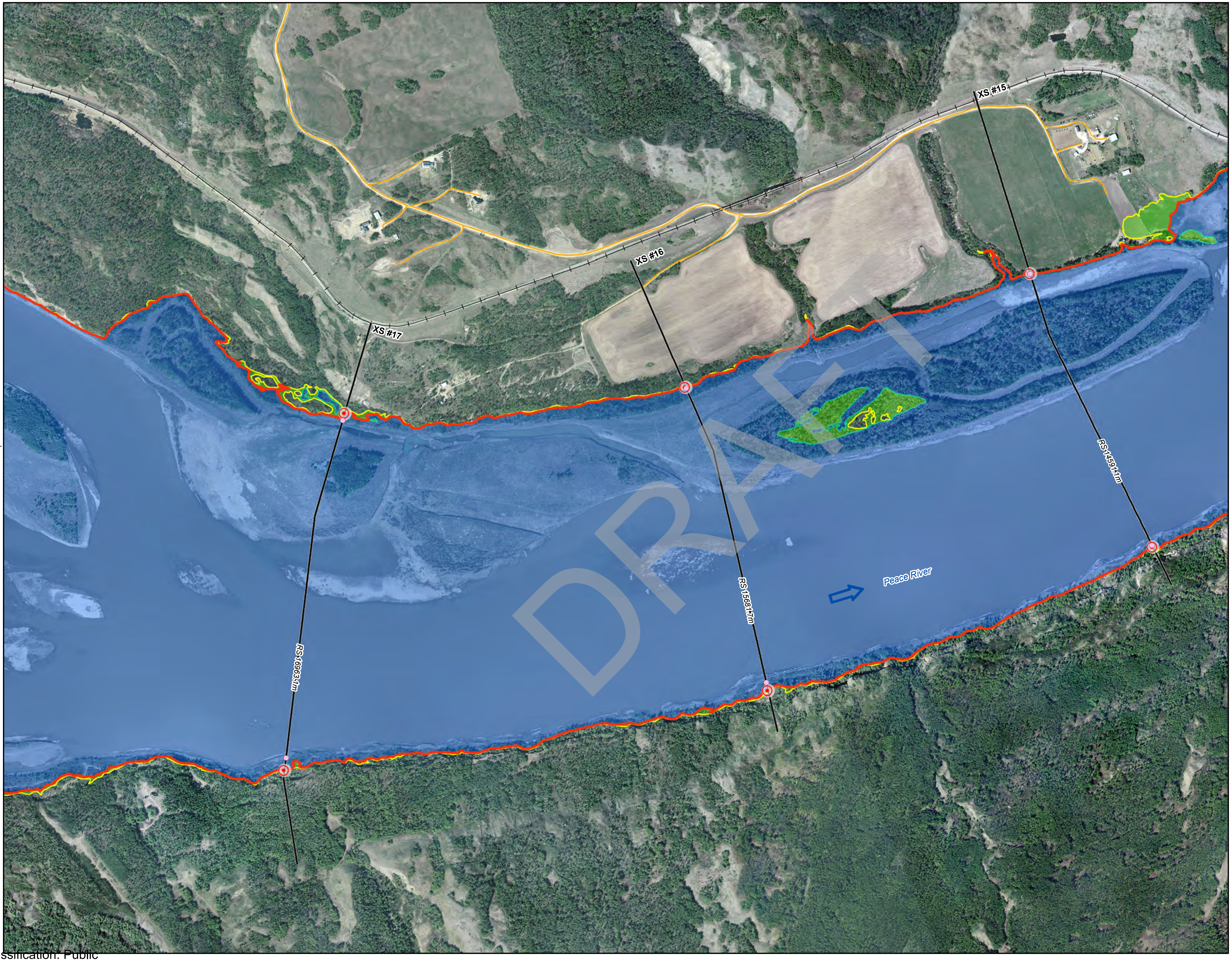

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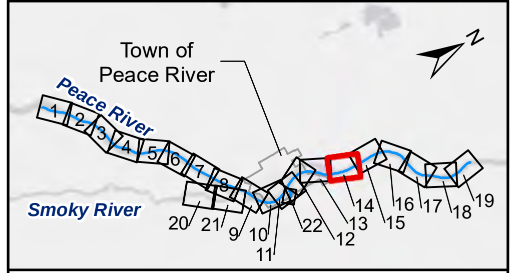

FLOW DIRECTION
BANK STATION
PROPOSED FLOODWAY LIMIT
PROPOSED FLOODWAY BOUNDARY
BRIDGE
CROSS SECTION
(RS denotes river station - distance from most downstream cross section.)
STUDY BOUNDARY
FLOOD CONTROL STRUCTURE
100-YEAR ICE JAM DESIGN FLOOD EXTENT
DEPTH ≥ 1 m
RAILWAY
MAJOR ROAD
LOCAL ROAD
FERRY ROUTE
PEACE RIVER TOWN
SETTLEMENT BOUNDARY

SCALE - 1:10,000
0 200 400 M

Coordinate System: NAD 1983 CSRS 3TM 117
Units: METRES

Job: 1001119	*Date: 05-OCT-2022*

PEACE RIVER HAZARD STUDY

ICE JAM FLOODWAY CRITERIA MAP

SHEET 14 OF 22

MSN, P:_Projects (Active)\1001119 Peace River Hazard Study\90_GIS_2022Update\PeaceRHS_Ice_Map_FloodwayCriteria_2022Update.mxd

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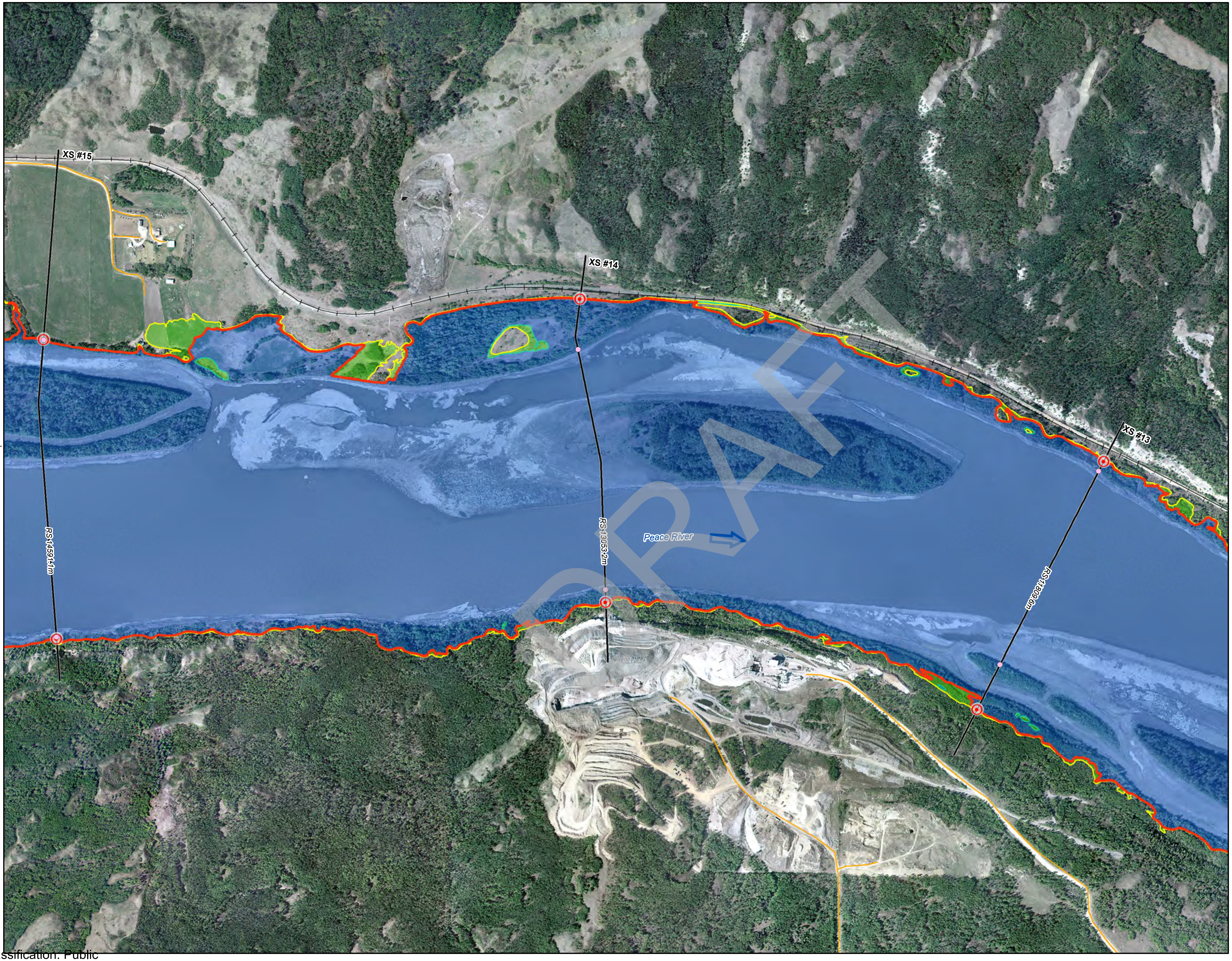

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SHEET 16 ↓

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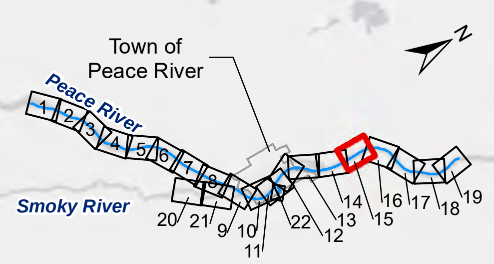

FLOW DIRECTION
BANK STATION
PROPOSED FLOODWAY LIMIT
PROPOSED FLOODWAY BOUNDARY
BRIDGE
CROSS SECTION
(RS denotes river station - distance from most downstream cross section.)
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100-YEAR ICE JAM DESIGN FLOOD EXTENT
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MAJOR ROAD
LOCAL ROAD
FERRY ROUTE
PEACE RIVER TOWN
SETTLEMENT BOUNDARY

SCALE - 1:10,000
0 200 400 M

Coordinate System: NAD 1983 CSRS 3TM 117
Units: METRES

Job: 1001119 | *Date: 05-OCT-2022*

PEACE RIVER HAZARD STUDY

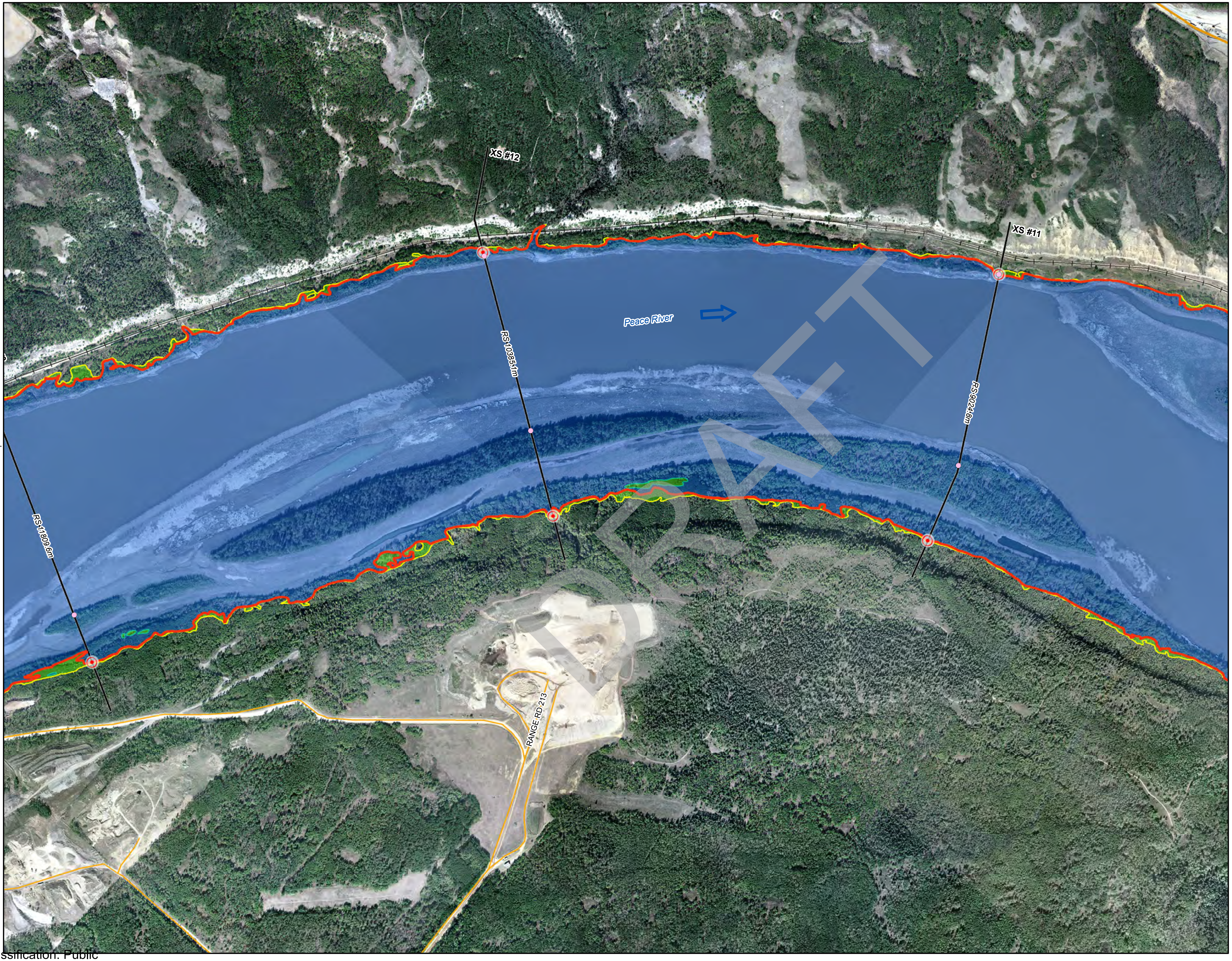
ICE JAM FLOODWAY CRITERIA MAP

SHEET 15 OF 22

MSN_P:\1_Projects (Active)\1001119 Peace River Hazard Study\90_GIS_2022Update\PeaceRHS_Ice_Map_FloodwayCriteria_2022Update.mxd

Classification: Public

SHEET 15 ↑



SHEET 17 ↓

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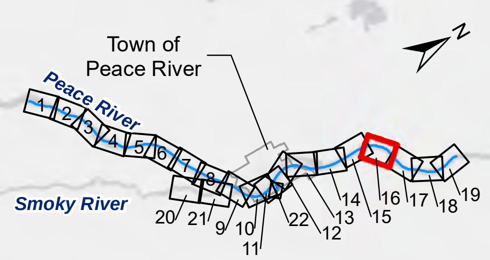


FLOW DIRECTION

BANK STATION

PROPOSED FLOODWAY LIMIT

PROPOSED FLOODWAY BOUNDARY

BRIDGE

CROSS SECTION
(RS denotes river station - distance from most downstream cross section.)

STUDY BOUNDARY

FLOOD CONTROL STRUCTURE

100-YEAR ICE JAM DESIGN FLOOD EXTENT

DEPTH ≥ 1 m

RAILWAY

MAJOR ROAD

LOCAL ROAD

FERRY ROUTE

PEACE RIVER TOWN

SETTLEMENT BOUNDARY

SCALE - 1:10,000

0 200 400 M

Coordinate System: NAD 1983 CSRS 3TM 117
Units: METRES

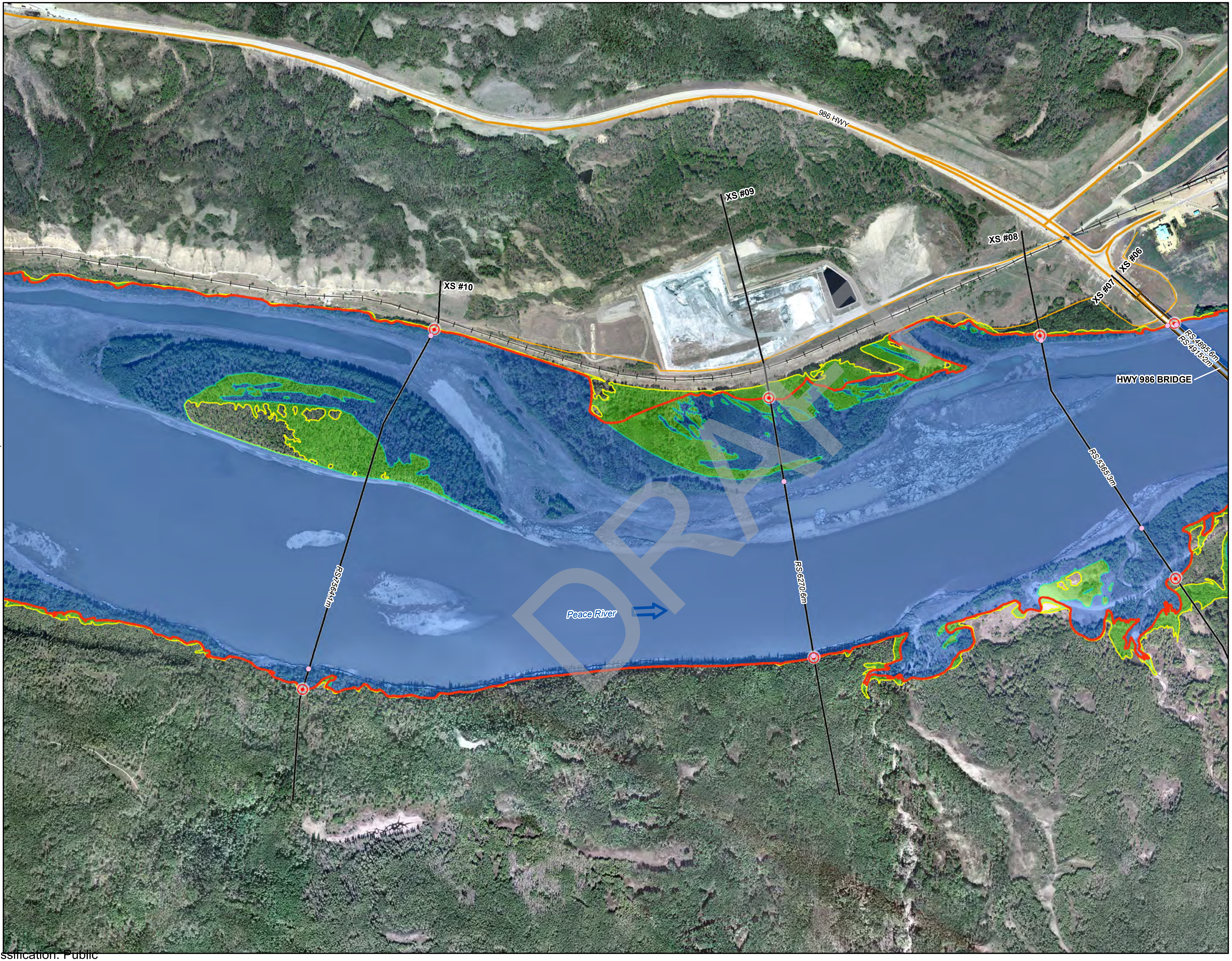
Job: 1001119	*Date: 05-OCT-2022*

PEACE RIVER HAZARD STUDY

ICE JAM FLOODWAY CRITERIA MAP

SHEET 16 OF 22

Classification: Public



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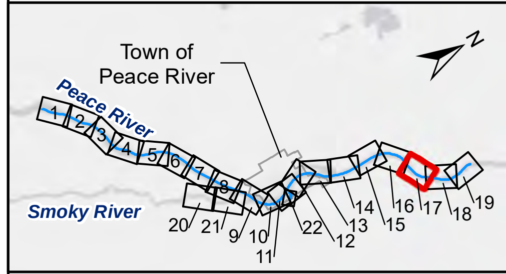

- FLOW DIRECTION
- BANK STATION
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- PROPOSED FLOODWAY BOUNDARY
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- LOCAL ROAD
- FERRY ROUTE
- PEACE RIVER TOWN
- SETTLEMENT BOUNDARY

SCALE - 1:10,000

0 200 400 M

N

Coordinate System: NAD 1983 CSRS 3TM 117
Units: METRES

Job: 1001119	Date: 05-OCT-2022

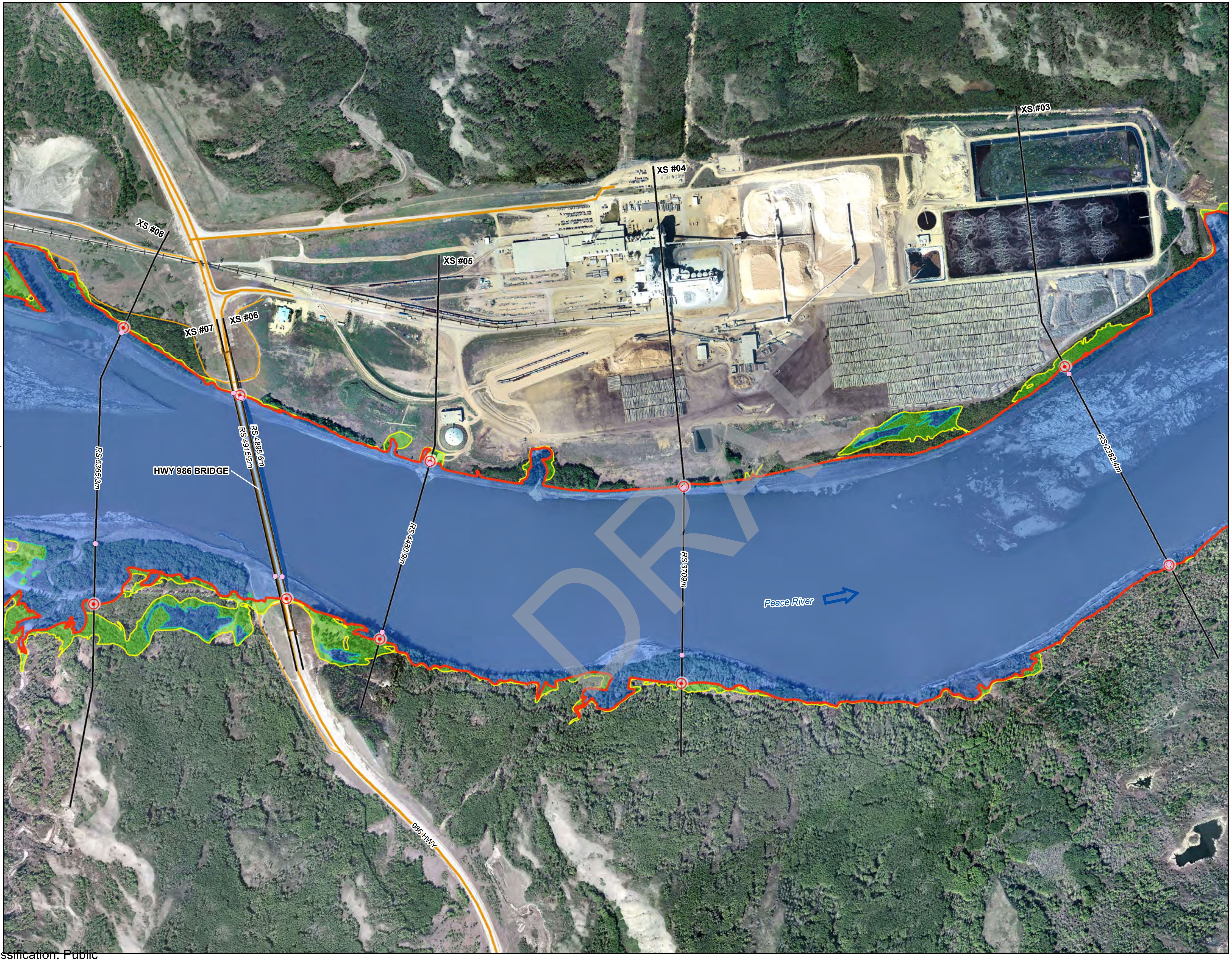
PEACE RIVER HAZARD STUDY

ICE JAM FLOODWAY CRITERIA MAP

SHEET 17 OF 22

MSN, P:_Projects (Active)\1001119 Peace River Hazard Study\90_GIS_2022Update\PeaceRHS_Ice_Map_FloodwayCriteria_2022Update.mxd

Classification: Public



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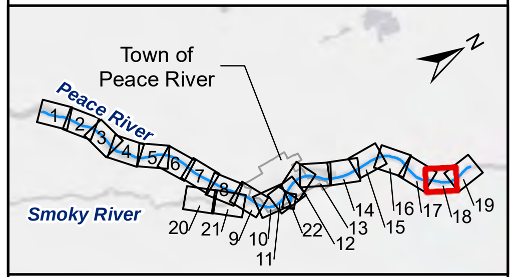

- FLOW DIRECTION
- BANK STATION
- PROPOSED FLOODWAY LIMIT
- PROPOSED FLOODWAY BOUNDARY
- BRIDGE
- CROSS SECTION *(RS denotes river station - distance from most downstream cross section.)*
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- PEACE RIVER TOWN
- SETTLEMENT BOUNDARY

SCALE - 1:10,000

0 200 400 M

N

Coordinate System: NAD 1983 CSRS 3TM 117
Units: METRES

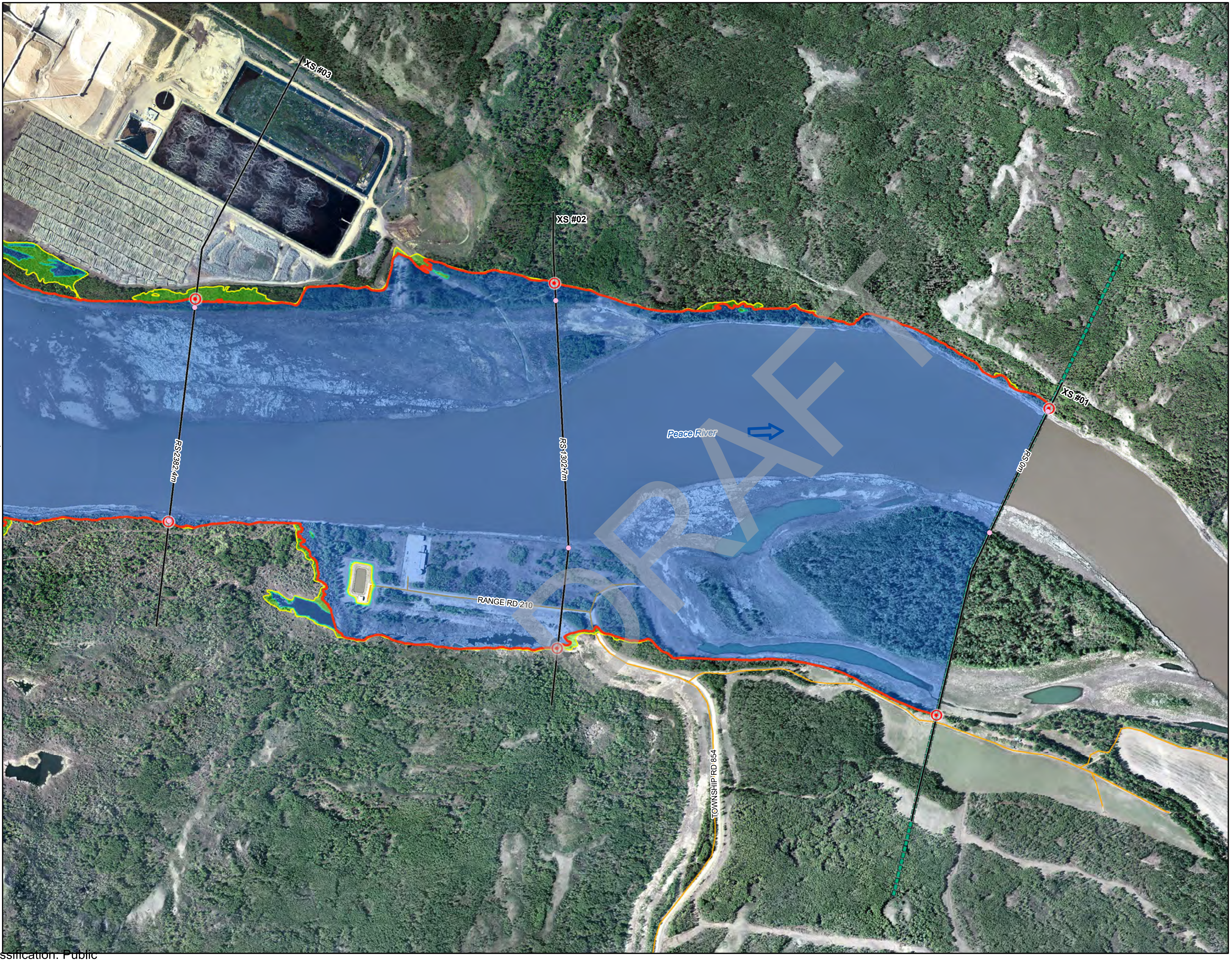
Job: 1001119	Date: 05-OCT-2022

PEACE RIVER HAZARD STUDY

ICE JAM FLOODWAY CRITERIA MAP

SHEET 18 OF 22

MSN: P:_Projects (Active)\1001119 Peace River Hazard Study\90_GIS_2022Update\PeaceRHS_Ice_Map_FloodwayCriteria_2022Update.mxd



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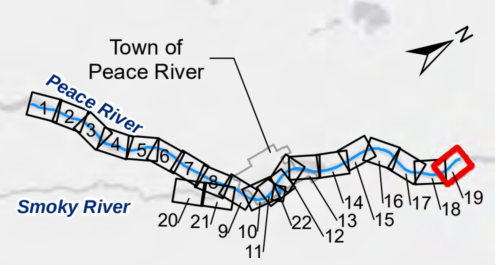


FLOW DIRECTION
BANK STATION
PROPOSED FLOODWAY LIMIT
PROPOSED FLOODWAY BOUNDARY
BRIDGE
CROSS SECTION *(RS denotes river station - distance from most downstream cross section.)*
STUDY BOUNDARY
FLOOD CONTROL STRUCTURE
100-YEAR ICE JAM DESIGN FLOOD EXTENT
DEPTH ≥ 1 m
RAILWAY
MAJOR ROAD
LOCAL ROAD
FERRY ROUTE
PEACE RIVER TOWN
SETTLEMENT BOUNDARY

SCALE - 1:10,000

0 200 400 M

Coordinate System: NAD 1983 CSRS 3TM 117
Units: METRES

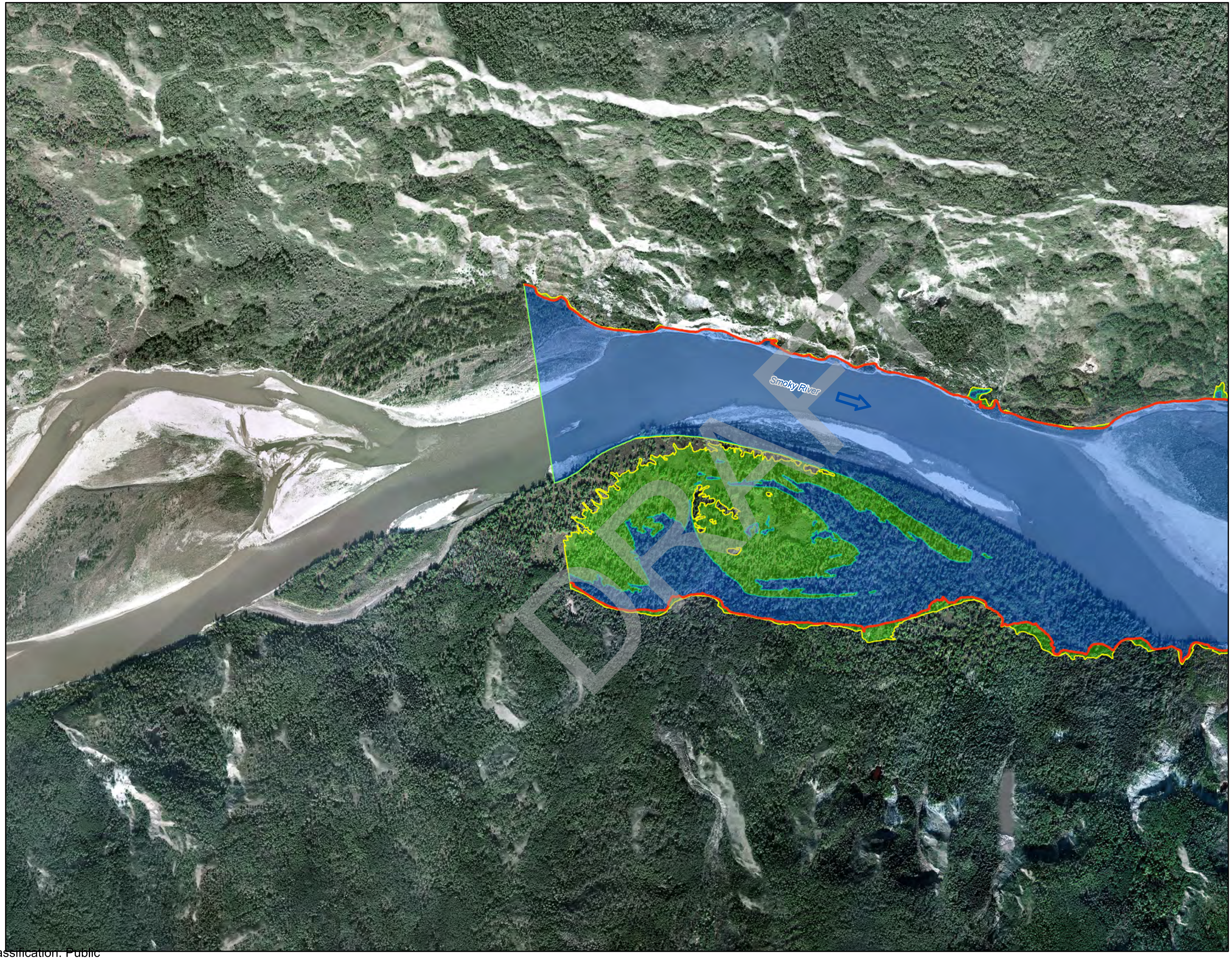
Job: 1001119 *Date: 05-OCT-2022*

PEACE RIVER HAZARD STUDY

ICE JAM FLOODWAY CRITERIA MAP

SHEET 19 OF 22

Classification: Public



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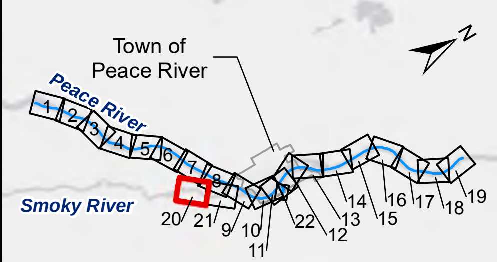

FLOW DIRECTION
BANK STATION
PROPOSED FLOODWAY LIMIT
PROPOSED FLOODWAY BOUNDARY
BRIDGE
CROSS SECTION
(RS denotes river station - distance from most downstream cross section.)
STUDY BOUNDARY
FLOOD CONTROL STRUCTURE
100-YEAR ICE JAM DESIGN FLOOD EXTENT
DEPTH ≥ 1 m
RAILWAY
MAJOR ROAD
LOCAL ROAD
FERRY ROUTE
PEACE RIVER TOWN
SETTLEMENT BOUNDARY

SCALE - 1:10,000

0 200 400 M

Coordinate System: NAD 1983 CSRS 3TM 117
Units: METRES

Job: 1001119	*Date: 05-OCT-2022*

PEACE RIVER HAZARD STUDY

ICE JAM FLOODWAY CRITERIA MAP

SHEET 20 OF 22

MSN, P:_Projects (Active)\1001119 Peace River Hazard Study\90_GIS_2022Update\PeaceRHS_Ice_Map_FloodwayCriteria_2022Update.mxd

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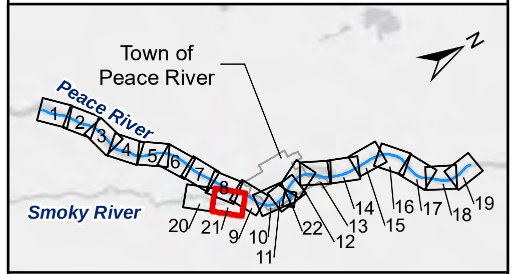

FLOW DIRECTION
BANK STATION
PROPOSED FLOODWAY LIMIT
PROPOSED FLOODWAY BOUNDARY
BRIDGE
CROSS SECTION
(RS denotes river station - distance from most downstream cross section.)
STUDY BOUNDARY
FLOOD CONTROL STRUCTURE
100-YEAR ICE JAM DESIGN FLOOD EXTENT
DEPTH ≥ 1 m
RAILWAY
MAJOR ROAD
LOCAL ROAD
FERRY ROUTE
PEACE RIVER TOWN
SETTLEMENT BOUNDARY

SCALE - 1:10,000
0 200 400 M

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Units: METRES

Job: 1001119	Date: 05-OCT-2022

PEACE RIVER HAZARD STUDY

ICE JAM FLOODWAY CRITERIA MAP

SHEET 21 OF 22

MSN, P:_Projects (Active)\1001119 Peace River Hazard Study\90_GIS_2022Update\PeaceRHS_Ice_Map_FloodwayCriteria_2022Update.mxd

Classification: Public

Classification: Public

Alberta Government

nhc northwest hydraulic consultants

Town of Peace River

Peace River

Smoky River

FLOW DIRECTION

BANK STATION

PROPOSED FLOODWAY LIMIT

PROPOSED FLOODWAY BOUNDARY

BRIDGE

CROSS SECTION
(RS denotes river station - distance from most downstream cross section.)

STUDY BOUNDARY

FLOOD CONTROL STRUCTURE

100-YEAR ICE JAM DESIGN FLOOD EXTENT

DEPTH ≥ 1 m

RAILWAY

MAJOR ROAD

LOCAL ROAD

FERRY ROUTE

PEACE RIVER TOWN

SETTLEMENT BOUNDARY

SCALE - 1:5,000

0 100 200 M

Coordinate System: NAD 1983 CSRS 3TM 117
Units: METRES

Job: 1001119	Date: 05-OCT-2022

PEACE RIVER HAZARD STUDY

ICE JAM FLOODWAY CRITERIA MAP

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