July 2022

FORT MCMURRAY RIVER HAZARD STUDY

Ice Jam Modelling and Flood Hazard Identification Report

Submitted to:
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REPORT

HATCH

Golder Associates

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Executive Summary

Alberta Environment and Parks (AEP) retained Golder Associates Ltd. (Golder), in collaboration with SG1 Water Consulting Ltd. (SG1) and Hatch Ltd. (Hatch), in September 2016 to conduct the Fort McMurray River Hazard Study. The primary purpose of the study is to assess and identify river and flood hazards along the Athabasca River, the Clearwater River (including the Snye), and the Hangingstone River through Fort McMurray, Alberta in the Regional Municipality of Wood Buffalo (RMWB).

The study was conducted 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. Project stakeholders include the Government of Alberta, the RMWB, and the public.

The study includes multiple components and deliverables. This report documents the methodology and results of the ice jam flood inundation study, including the ice jam and flood hydraulic modelling, inundation maps for the 50-, 100-, and 200-year ice jam related floods and the ice jam floodway criteria map.

The ice jam flood inundation and ice jam floodway criteria maps were prepared using ArcGIS and are based on the simulated ice jam flood levels at the cross sections. Several special areas were identified for the three flood events and manual edits to the water level surface TIN were made.

Based on the simulation results, the main areas affected by ice jam flooding have been identified as follows:

- There would be no residential flooding along the Athabasca River. However, there would be large portions of the Clearwater River floodplain affected by ice jam flood events with return periods of 50 years or higher, leading to significant residential flooding;
- For the case of an ice jam flood event with a return period of 200 years (the largest return period considered in this study), residential areas up to Alberta Drive would experience some form of flooding in the Lower Townsite.
- An ice jam flood event with a return period of 50 years or more would result in flooding of commercial and industrial areas along Highway 63, properties in the TaigaNova Eco-Industrial Park, and flooding of the Underground Services and Water Metering.
- An ice jam flood with a return period of 100 years or higher would cause flooding in the commercial and industrial areas between Prairie Loop Boulevard and Franklin Avenue, also restricting access to the Northern Lights Regional Health Centre in the Old Townsite. An ice jam flood with return period of 200 years or higher will flood the commercial and industrial area up to Highway 63 in this area.

Acknowledgements

This component of the Fort McMurray River Hazard Study was led by Joe Groeneveld, and executed by Dr. Soheil Zare, Dave Andres, and Joe Groeneveld. Overall project management was provided by Dr. Wolf Ploeger and directed by Dr. Dejiang Long. The flood inundation mapping was prepared by Dr. Soheil Zare, and reviewed by Peter Thiede and Dr. Wolf Ploeger.

The authors express their special thanks to Abdullah Mamun, Patricia Stevenson and Jim Choles, Project Managers for Alberta Environment and Parks as well as Nadia Kovachis Watson, River Hydraulics and Ice Engineer at Alberta Environment and Parks, who provided overall study management, background data, and technical guidance.

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1.0 INTRODUCTION

Alberta Environment and Parks (AEP) retained Golder Associates Ltd. (Golder), in collaboration with SG1 Water Consulting Ltd. (SG1) and Hatch Ltd. (Hatch), in September 2016 to conduct the Fort McMurray River Hazard Study. The primary purpose of the study is to assess and identify river and flood hazards along the Athabasca River, the Clearwater River (including the Snye Channel), and the Hangingstone River through Fort McMurray, AB in the Regional Municipality of Wood Buffalo (RMWB).

The study is being completed under the provincial Flood Hazard Identification Program (FHIP). The goals of this program include enhancement of public safety and reduction of future flood damages through the identification of river and flood hazards. Project stakeholders include the Government of Alberta, the RMWB, and the public.

While open water floods are of interest on all three of the rivers, particularly on the Hangingstone River, ice-related flooding during spring breakup on the Athabasca River produces the most severe flooding on the Athabasca and Clearwater Rivers. Ice jams that form downstream of the Clearwater River confluence cause water levels to rise above bankfull and inundate significant areas along the banks of both the Clearwater and Hangingstone Rivers. This report documents the methodology and results of the ice jam flood assessment component of the study.

1.1 Study Objectives

The objective of the Fort McMurray River Hazard Study project is to assess and identify river and flood hazards along the Athabasca, Clearwater, and Hangingstone Rivers through Fort McMurray in the RMWB. This component of the study assesses flood risks in the community associated with ice-related high water events during breakup on the Athabasca River.

Compared to open water floods, the determination of a unique reach-based water level profile that reflects a given probability of occurrence of an ice-related event is quite complex. The relationship between the flow experienced at breakup and the subsequent water level is not as strong as it may be for open water events. Furthermore, owing to the non-uniform characteristics of the ice-related water level profile, the water level that is expressed each year can vary significantly throughout the study reach, depending on (i) the type of breakup, (ii) the location and extent of a jam if one forms, and (iii) the volume of ice that is available to contribute to a jam. Therefore water levels can vary considerably, even if the flow during breakup is the same each year. To overcome these complexities, an analytical framework is required to transform this myriad of factors into a systematic, probabilistic definition of the ice-related flood hazard that reflects the historical record. An approach has been adopted and followed in this study based on the following:

- The historical record of annual ice-related peak water levels at the mouth of the Clearwater River is the adopted basis for a stage-frequency analysis of ice-related flood peaks at that specific location.
- While each of the historical water levels reflects a unique set of circumstances, it is expected that the most severe events that would be of interest from a flood hazard perspective would be a result of the formation of a fully developed equilibrium ice jam with its toe being located somewhere downstream of the Clearwater River confluence.
- Given the limited extent of the study reach, an ice-related water level at the mouth of the Clearwater River that corresponds to a particular return period can be extrapolated upstream and downstream by assuming that that water level is the product of an equilibrium ice jam with its toe located downstream of the study reach, its head located upstream of the study reach, and that the study reach is located entirely within the equilibrium portion of the jam. The non-uniformity of the ice jam profile is therefore related only to changes in the channel geometry and slope within the study reach.

Given the above, the specific scope of work for this component of the study includes:

- Review and documentation of the ice jam flood history
- Ice jam flood frequency analysis
- Enhancement and calibration of the HEC-RAS model for ice conditions
- Ice jam modelling to simulate ice jam profiles specific to a given return period event
- Model sensitivity analysis
- Review and verification of the 1875 flood event – largest ice jam event in recorded history (see Appendix A)
- Production of ice jam flood inundation maps
- Determination of the ice jam floodway (and associated floodway criteria maps) based on the design ice jam flood event

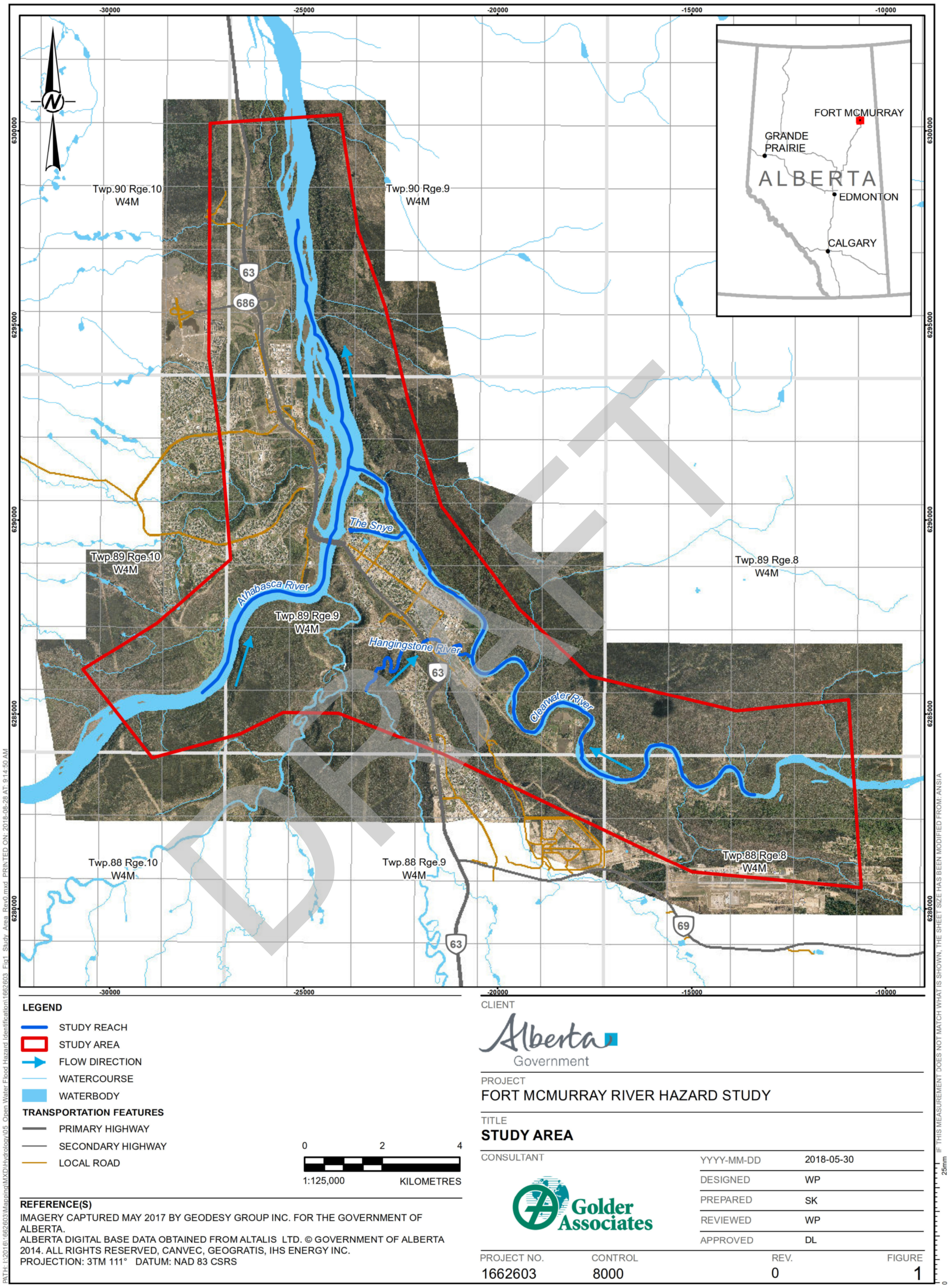
As part of this work, breakup ice processes and their contribution to ice-related flood mechanisms have been described, and ice-related measurements at the Water Survey of Canada (WSC) gauge on the Athabasca River downstream of Fort McMurray have been summarized and interpreted. A Monte Carlo model has been developed and tested to assess the effects of flows at breakup on ice-related water levels from a more deterministic perspective – something that might be useful in the future to address the potential effects of climate change on ice-related water levels.

1.2 Project Area and Study Reach

The study area includes approximately 15 km of the Athabasca River, approximately 20 km of the Clearwater River (including 1.5 km of the Snye), and approximately 5 km of the Hangingstone River through Fort McMurray (see Figure 1).

The Athabasca River study reach extends through the community of Fort McMurray, from the south boundary of SE 12- 89- 10- W4M to the north boundary of SW 17- 90- 9- W4M.

The Clearwater River study reach extends upstream from its confluence with the Athabasca River, through the community of Draper and to the eastern border of SW 33- 88- 8- W4M, approximately 4 km upstream of WSC Gauge Station No. 07CD001 (Clearwater River at Draper). The Hangingstone River study reach extends 5 km upstream from its confluence with the Clearwater River to the eastern boundary of SW 33- 88- 8- W4M.



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PROJECTION: 3TM 111° DATUM: NAD 83 CSRS

CLIENT
Alberta Government

PROJECT
FORT MCMURRAY RIVER HAZARD STUDY

TITLE
STUDY AREA

CONSULTANT
Golder Associates

YYYY-MM-DD	2018-05-30
DESIGNED	WP
PREPARED	SK
REVIEWED	WP
APPROVED	DL

PROJECT NO.	CONTROL	REV.	FIGURE
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Figure 1: Study Reach

2.0 ICE JAM FLOOD HISTORY

2.1 Historical Background

The Fort McMurray area has been subjected to flooding due to ice jam development for as long as records have been kept at the community. This record began in 1870 when the earliest fur traders arrived at the confluence of the Clearwater and Athabasca Rivers. Severe ice jams have caused water levels to equal or exceed 247.5 m at this location six times since that time. The most severe floods, which occurred in 1875, 1885, 1928, and 1936, have all caused considerable damage. The 1875 flood event represents the largest recorded event on the river, and formed the focus of a detailed review which is presented in Appendix A and summarized below. In the modern era, notable ice jams have occurred in 1972, 1976, 1977, 1978, 1979, 1984, 1986, 1987, 1996, and 1997. The highest ice jam water level occurred in 1977, when a peak water level of 247.6 m occurred at the mouth of the Clearwater River. The most recent notable flood occurred in 1997 when the river peaked at an elevation of 247.5 m. A few of the more notable events are briefly presented below to help describe the nature of these very rapid and destructive events.

1875 Ice Jam Event:

The 1875 flood event was the largest ice event in recorded history on the Athabasca River at Fort McMurray. The event was noted to have occurred in late April, and produced a peak water level at the Hudson's Bay Company (HBC) post that has been estimated to be between el 251.5 m (825 ft) and 253.0 m (830 ft) (Blench, 1964) – some 15 m above the normal winter water level at this location.

The majority of details associated with the 1875 ice jam event were contained in three short letters that were penned by members of the Hudson Bay Company, and archived in the HBC post journals. Based on these descriptions, it is understood that the winter preceding the 1875 flood event was quite cold. There were some short periods of warm temperatures, but overall, it was characterized as a long, bitter winter that lasted until mid-April. The records indicate this long, cold winter was followed by a very sudden and dramatic rise in temperature around April 16th – just days before the ice jam occurred.

The records also indicated snow depths were above average, and the sudden melt of this snowpack likely led to a very concentrated spring runoff event. These high freshet flows were reported to have led to the sudden breakup of an 85 mile stretch of the Athabasca River upstream of Fort McMurray. The journal notes indicate that on the morning of April 20th, the river ice first broke up and began to run, but that a jam quickly formed with the influx of upstream ice just downstream of the Athabasca and Clearwater confluence – a typical jam location.

The water levels rose quickly, forcing immediate evacuations of the HBC post. It is reported that in escaping the resultant flood, staff had to partially wade and partially swim from the Post to a nearby ridge of high land. The river flow at breakup is not known.

1977 Ice Jam Event:

Over the next century, ice events were continuing to occur on this river reach. The event of 1977 was likely the highest event to occur in the modern era. The 1977 ice jam event occurred from April 12th to 14th. The Athabasca River broke up at the Town of Athabasca on April 12, after a week of unseasonably warm temperatures. A large breakup flood wave arrived in Fort McMurray early in the morning of April 14, resulting in an ice jam at the highway bridge which increased local water levels by approximately 5 m. An hour later, the ice jam broke and moved downstream, where a second jam formed downstream of the Clearwater confluence. For this event, the jam toe was located approximately 4 km downstream of the McEwan Bridge, and extended upstream for a distance of approximately 26 km (Anders and Doyle, 1984). Water levels at the bridge peaked at 5.7 m above pre-freeze-up levels, and flooding occurred in the town of Fort McMurray along the Snye (Clearwater River) (Public Safety Canada, 2013). The water surface elevation reached a peak level of 247.6 m at the Athabasca-Clear water confluence. Flows at breakup were estimated to be between 760 and 850 m^3/s.

1986 Ice Jam Event:

In 1986, breakup occurred on the Athabasca River between April 19th and April 24th. Winter temperatures and flows resulted in an ice cover that was between 0.8 and 1.0 m thick (Malkovich et.al, 1988) prior to breakup. The toe of the jam was located near the mouth of Parsons Creek, which is about 7 km downstream of McEwan Bridge. Ice levels were recorded for this event between Mountain Rapids and Suncor Oil Sands Development. The jam extended upstream to a point that is approximately 3 km downstream of Mountain Rapids. The maximum water level observed at the Athabasca River below Fort McMurray WSC gauge (WSC Gauge Station No. 07DA001) during the breakup was about 240.8 m. Flows on the Athabasca River during the jam event were estimated to be between approximately 400 m^3/s and 1100 m^3/s.

1997 Ice Jam Event:

The 1997 ice jam event occurred in April, following a very rapid melt of the snowpack in the Athabasca watershed. The flood wave generated by the melting snow caused the river ice cover to rise, breakup, and begin to run. This run of river ice suddenly formed a jam on April 20, initiated at a point that is approximately 2 km downstream of the confluence between the Athabasca and Clearwater rivers (Public Safety Canada, 2013) . The ice jam caused the water levels on the Clearwater River to rise quickly. Water raised to the elevation of 247.5 m near the confluence. This caused the Clearwater River to overtop its banks in the vicinity of the Riedel Street trailer park, and the Waterways neighbourhood, flooding low lying areas. Approximately 75 trailers and/or houses required evacuation, and some 20 businesses were affected. This prompted the municipality to declare a state of emergency on April 21st. (Public Safety Canada, 2013).

Flood Mitigation History:

Substantial work has been undertaken in the past to study the breakup processes and to investigate methods to reduce the ice jam-related flood damages within the urban area of the Regional Municipality of Wood Buffalo (RMWB). Blench (1964) undertook the first quantitative assessment of flood hazards. Based upon historical ice jam records, but on a somewhat limited appreciation of the breakup processes, he suggested that ice jams were caused in part by the outflow of water up the Clearwater River (as the ice jam breaking front moved past the mouth) and the subsequent loss of conveyance in the Athabasca River channel downstream. His recommendation to construct the Snye Dike to reduce the outflow of water was followed, and the dike was constructed to an elevation of 252.0 m in the mid 1960s, and it effectively prevented the Snye Channel from being hydraulically linked with the Athabasca River at this location. Although the dike is not effective in preventing ice jams, it reduces the ice-related water levels in the Clearwater River because the effective backwater levels from the Athabasca River were moved downstream a distance of about 1.5 km.

After a few years with benign breakups, interests in ice jam flooding and its mitigation resurfaced because of the damages suffered during the 1977 spring breakup event. The Fort McMurray Flood Damage Abatement Technical Committee, composed of personnel from the Fort McMurray, AEP, Alberta Transportation and Utilities, and Alberta Municipal Affairs, was established to investigate flood mitigation measures. In addition to updating the flood risks and identifying the damages that resulted from the 1977 event, several flood mitigation/protection schemes were examined. These included the following:

1. Channel modification on the Athabasca River downstream to prevent ice jams from occurring.

2. Diking along the Clearwater River to contain the high ice-related water levels.

3. Improved flood forecasting and disaster management.

4. Various flood proofing schemes to minimize flood damages.

5. An ice control structure upstream of MacEwan Bridge to prevent ice runs from occurring at the confluence of the Athabasca and Clearwater Rivers.

A design flood level (100-year ice jam level) of 252.0 m was adopted (NHC, 1979), and damages due to the 1977 event were estimated to be about $4 million in 1977 dollars (IBI Group and ECOS Engineering Service Ltd.,1982). However, most of the ice control schemes proved to be either ineffective or too costly to implement. Only diking and flood proofing appeared to warrant more investigation.

The diking concept was re-examined in the early 1980's. Stage damage curves were derived for the urban area, flood damages were defined, and a more detailed design of the dikes was carried out. In 1985, it was estimated that the average annual cost of flooding was $5.8 million, with damages for the 25-, 50-, and 100-year floods estimated to be $35 million, $119 million, and $220 million respectively. The capital costs of providing diking to protect to an elevation of 252.0 m was estimated to be $48 million, in 1982 dollars. The cost of diking was somewhat inflated due to the adopted dike alignment, which followed along low lying land near the Clearwater River, thus requiring large quantities of fill and extensive bank protection works.

The impact that the dikes would have made on the landscape and high cost of diking ultimately made the diking option unattractive, even though cost benefit studies at the time suggested that the dikes would be good investment. Instead, a rigorous flood plain management plan was implemented, with flood proofing to an elevation of 249 m or higher being required for all new development and backwater valves, etc. provided for all existing development.

In addition to examining methods to reduce flood damages, a more rigorous flood forecasting scheme was implemented after the 1977 flood. AEP, in co-operation with the Alberta Research Council (ARC) began systematically monitoring breakup and measuring ice jams when they formed. A good understanding of the basin-wide breakup process, from the Pembina River down through the upper Athabasca River between Athabasca town and Fort McMurray, was developed. The hydromechanical characteristics of the ice jams were measured and ice jam models were calibrated so that ice jam levels could be simulated for a wide range of flows during breakup. Although work is still required to develop a procedure to forecast snowmelt runoff in the Athabasca River during breakup, the installation of a continuous monitoring stations upstream and throughout Fort McMurray has provided some advanced notice of breakup to residents.

The ice jam flood vulnerability in Fort McMurray was re-examined as part of the Canada-Alberta Flood Damage Reduction Program in 1991. AEP (1993) conducted a frequency analysis of ice jam levels using data up to 1990, including the historical (pre-1977) data. Two methods of analysis were undertaken: the perception stage method (Gerard and Karpuk, 1979) and the approach recommended by United States Geological Survey in Bulletin 17B (USGS, 1982). The perception stage method was developed in Alberta and tested at several sites in the province. The methodology allows for a weighting of the historical measurements based on the length of time during when they may have exceeded a particular reference level that would have been significant to residents during a particular period of time. The return period of an event is prescribed, and the frequency curve is estimated by eye using the plotted data. Usually, as areas are more regularly or consistently inhabited, observations become more systematic, and the perception stage will begin to decrease over time. This approach is attractive since it allows varying perception levels to be adopted over time, as an area becomes developed and greater attention paid to the impacts of high water levels. The disadvantage of this approach is that, while the plotting position of each data point can be specified based on the perception level and the length of time that it would have prevailed, the plotted points can only be extrapolated by eye to longer return periods.

The Bulletin 17B procedure weights the historical data according to the period that the data represented and a critical or threshold elevation for which historical floods below that elevation would not have been recorded. The adopted statistical parameters (mean, standard deviation, and skew) are weighted according to the length of record associated with the selected critical elevation and the frequency curve is calculated using the method of moments to fit the parameters to either the Pearson III or log-Pearson III distribution to the annual peak ice-related stages relative to an adopted baseline elevation. This procedure provides a mechanism to calculate the theoretical frequency curve based on the statistical properties of the data that is not possible in the perception stage method. However, it only allows for two perception level periods and their corresponding perception levels to be adopted – a period of a given length in which only historical events above a certain threshold have been recorded and a period when all events would have been recorded systematically without reference to a threshold level.

The two methods appeared to give similar values for the return periods of the rarer flood events, thus providing some comfort in the adopted flood frequencies. The 100-year flood was estimated to be at an elevation of 250.0 m (two metres below the Blench value) and the 50-year flood level was lowered also by about two metres to 248.9 m.

The updated flood frequency curve affected the average annual flood damages. In 1994, in an internal AEP report, the average annual flood damages were estimated to be $5.9 million in 1992 dollars, while the capital cost of the lower dike was estimated to be $48 million, as reported by Trillium Engineering and Hydrographics Inc. (Trillium, 2000). The reduction in cost due to the lower dike was offset by an increase in the cost of construction and land acquisition. In the end, dike construction was not pursued because of the large capital cost and the huge effect that the dike would have had on the landscape.

Following the 1997 flood, there was a renewed interest in providing better flood protection for the community- at least up to the level of the 1997 flood. Trillium undertook a study to update the historical ice-related frequency curve reported in 1993 and to investigate the potential to provide phased flood protection to the entire urban area. This phased protection considered the incorporation of existing flood proofing structures along with positive topographic features to help minimize land acquisition and construction costs (Trillium, 2000). One of the factors that allowed for flood protection to be provided at a more reasonable cost was the implementation of a strategy that would take advantage of the natural landscape to reduce the height of the proposed dike by locating it further away from the Clearwater River where ground elevations were higher. Although less undeveloped land would have been protected than under the 1993 scheme (land immediately adjacent to the Clearwater River was basically undeveloped), most of the land already developed in 1997 could be protected at a reduced and more manageable cost. The 1997 analysis indicated that the 1993 ice-related flood frequency curve was still valid, and that the entire urban area could be protected at a cost of $16.6 million and $26.3 million for the 40- and 100-year flood events respectively.

The most recent flood mitigation study at Fort McMurray (NHC, 2014) updated the Trillium (2000) ice-related flood frequency curve and provided a detailed conceptual plan to protect the urban area against a 100-year ice-related flood. The added record, up to 2013, did not substantially change the frequency curves developed previously. The 100-year ice-related flood level of 250.0 m that was recommended by AEP (1993) was confirmed and adopted. Protection against the 100-year flood event through a combination of dikes, flood walls, and raised streets was estimated to cost approximately $150 million.

2.2 Break Up Processes and Ice Related Flood Mechanisms

Data collected by WSC, monitoring by AEP, and ice jam documentation programs undertaken by ARC and the U of A have all contributed to developing an understanding of the breakup process and the characteristics of the ice jams that from on the Athabasca River at Fort McMurray. What has become clear over the 30 to 40 years that these observations have been made is that severe ice-related flooding on the Athabasca, Clearwater, and Hangingstone Rivers is related to breakup on the Athabasca River. Backwater from ice jams on the Athabasca River raises water levels on the Clearwater and Hangingstone Rivers above their respective banks and inundates their respective floodplains. Inflows from both the Clearwater and Hangingstone Rivers do little to exacerbate the high ice-related water levels. Understanding the breakup process on the Athabasca River is the key to understanding the flood hazards along the margin of the other two rivers.

Breakup on the Athabasca River occurs in a downstream direction (from the warmer southern regions to the colder northern regions). The process begins each spring at the mouth of the Pembina River, which contributes the earliest significant contribution of snowmelt runoff to the Athabasca River (Andres and Rickert, 1985). Initially, the ice cover will begin to deteriorate as river flows simultaneously begin to increase. Eventually, the ice cover upstream of the Town of Athabasca breaks up (due to a combination of mechanical and thermal processes), and segments of intermittent ice cover and open water form as the mobilized ice accumulates against the remaining intact ice. As the ice cover continues to deteriorate, these small accumulations of ice cascade downstream through the steep reaches upstream of Fort McMurray, forming ice runs or surges (javes). As the breakup front progresses downstream, the individual ice runs typically aggregate into a single run or jave at some point just upstream of Fort McMurray before moving past Fort McMurray and into the lower Athabasca River.

At Fort McMurray, the river profile transitions from a steep and narrow post-glacial valley upstream of the confluence of the Clearwater River to a much wider and milder pre-glacial water course downstream of the confluence. This change in slope, the presence of numerous islands and channel bars, and the corresponding widening of the river increases the tendency for jams to form as the ice transport capacity decreases. The surges (or javes) and the resulting ice jams that develop in this reach of the river produce high water levels both upstream and downstream of the confluence with the Clearwater River and cause back-flooding up the Clearwater River.

The Athabasca River discharge can be highly unsteady during the breakup period due to the presence of the intermittent ice cover and javes. The jave heights are related to the height of backwater created by the instigating ice jams, which themselves are related to the carrier discharge and the local channel characteristics. The carrier discharge is defined as the background flow that increases over time as the spring snowmelt runoff concentrates in the Athabasca River. Typically, the carrier discharge during breakup is relatively low (relative to the spring peak flow) because the ice-related hydraulic processes occur early in the spring runoff period, well before the spring runoff peaks in the lower part of the Athabasca River basin. In years with high snowmelt runoff, an ice jam will form under a higher carrier discharge, causing a more significant backwater effect, and the subsequent jave will be more severe when the jam releases. In years with low snowmelt runoff, the carrier discharge will be less and both the jam backwater and corresponding javes will be less severe. Further detail on the estimation of the carrier discharge is given in Section 5.4.

Observations suggest that breakup can be classified into three basic types, any one of which would produce the peak ice-related water level: (i) a thermal breakup, (ii) a mechanical breakup that results in a stable ice jam forming downstream of the confluence, and (iii) a mechanical type of breakup that produces javes that do not reform into an ice jam downstream of the confluence. For a given carrier discharge, a thermal breakup would be the least severe of the three in terms of peak water level, followed by a jave and then a stable ice jam.

Fundamentally, a thermal breakup is defined as one where there is insufficient increase in the carrier discharge to mechanically break the ice cover before significant amounts of ice melt in place. This typically results in a mild, benign breakup with very little ice-related stage increase above pre-breakup water levels. At Fort McMurray, a thermal breakup can occur in two ways. In one case (as occurred in 1982 and 1983) there may be insufficient snowmelt runoff to mobilize the ice cover and the cover simply melts in place. In another case (as occurred in 1978) the breakup upstream of Fort McMurray may be dynamic, but the breakup ice run and associated surge is arrested (jams without releasing) before it reaches Fort McMurray. In this case, the ice jam remains intact and melts in place. A typical water level response during a thermal breakup at the WSC gauge is shown in Figure 2.

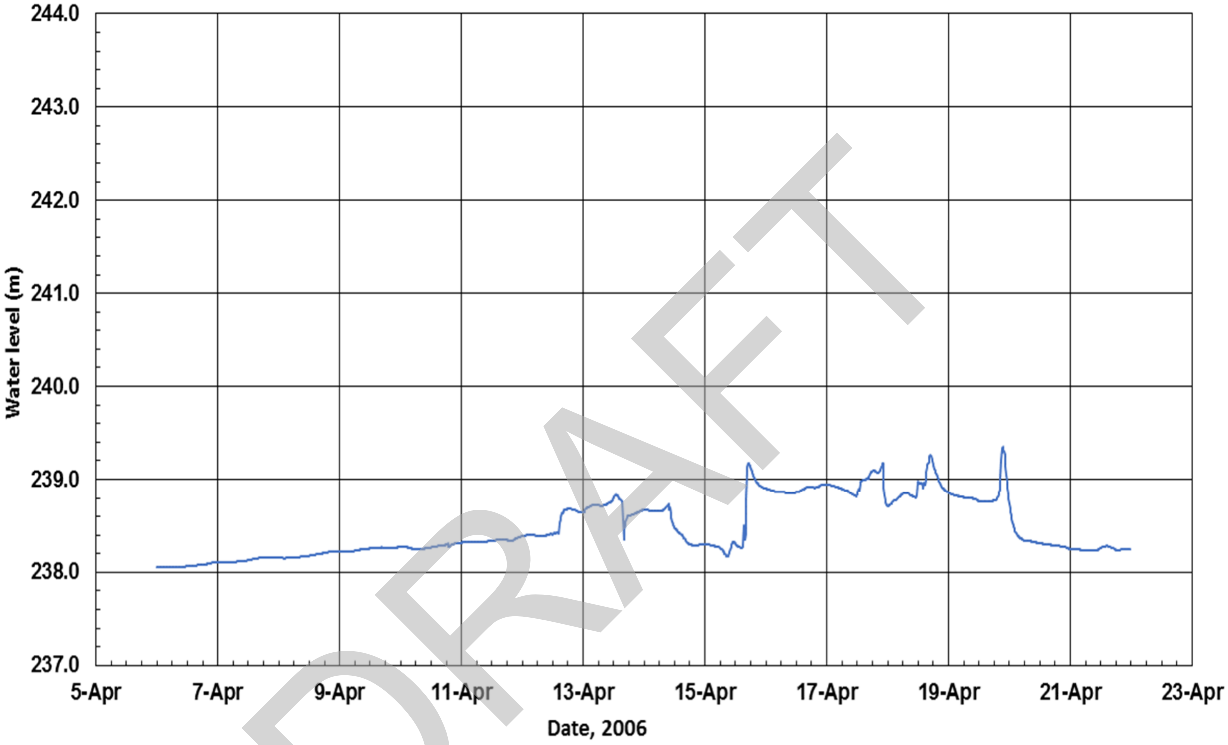


Figure 2: Typical Water Level Response During a Thermal Breakup at WSC Gauge Station No. 07DA001, Athabasca River Below Fort McMurray

A mechanical breakup occurs when there is a sufficient increase in the carrier discharge to significantly mobilize the ice cover while it still has some integrity. When this happens, broken ice accumulates to produce ice runs or javes upstream Fort McMurray. These ice runs may or may not jam downstream of Fort McMurray, depending on the resistance of the ice sheet and the momentum of the ice run and associated jave. If the ice run and jave is not stopped downstream of Fort McMurray, water levels at Fort McMurray may surge and fall as the jave passes and no jam will form. Alternatively, if a jam occurs downstream of Fort McMurray, water levels will rise to some steady-state level that is a function of the carrier discharge and the local channel geometry. Typically, for the same carrier discharge water levels associated with an ice jam are greater than those associated with a surge or jave. Typical water level responses to the passage of a jave and to the formation of a stable ice jam at WSC Gauge Station No. 07DA001(Athabasca River below Fort McMurray) are shown in Figure 3 and Figure 4 respectively- the water level responses are dramatically different in the two cases.

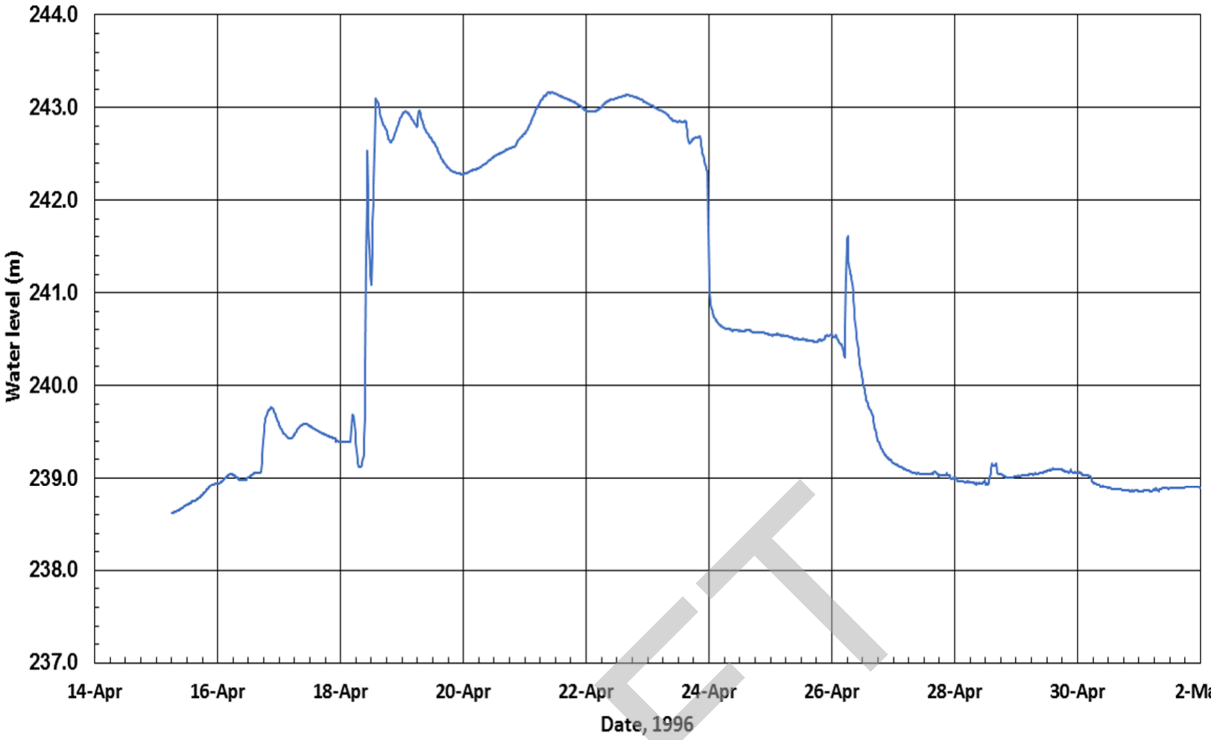


Figure 3: Typical Water Level Response During Formation of a Stable Ice Jam at WSC Gauge Station No. 07DA001, Athabasca River below Fort McMurray

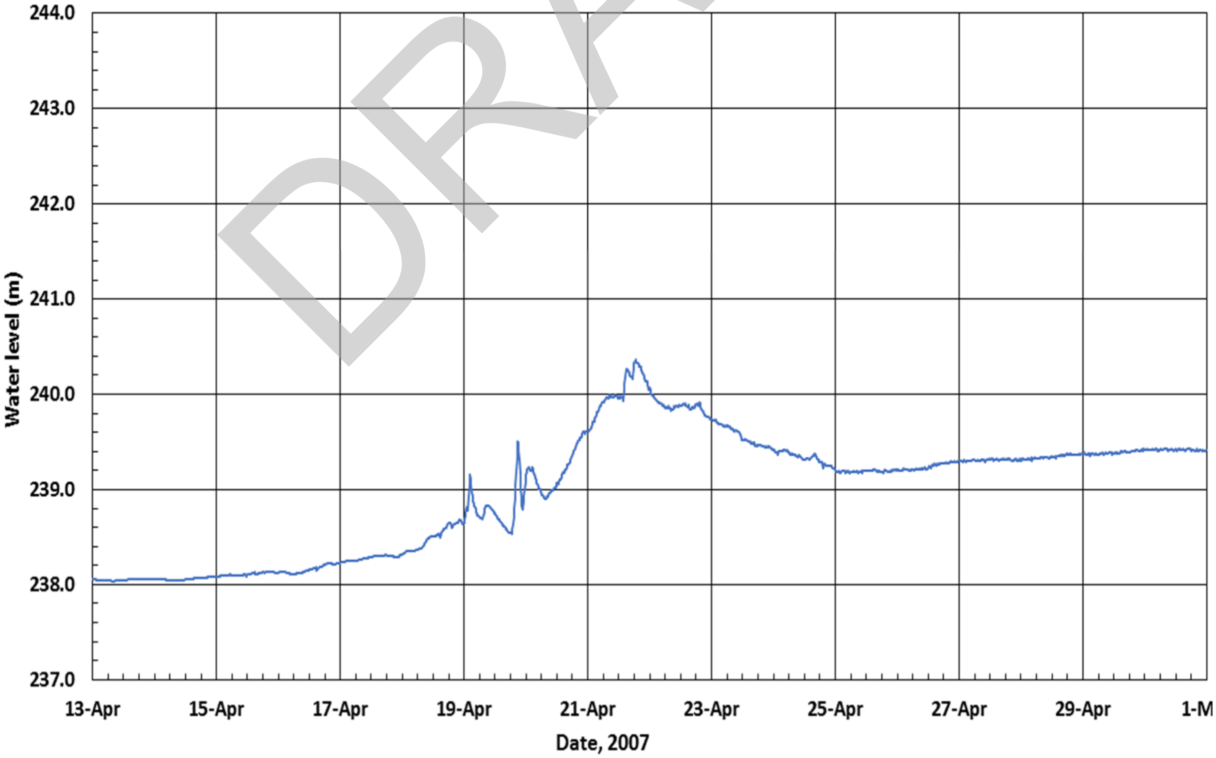


Figure 4: Typical Water Level Response During Passage of Jave at WSC Gauge Station No.07DA001, Athabasca River below Fort McMurray

3.0 AVAILABLE DATA

3.1 Ice Jam Observation Reports

In addition to those studies described above that assess ice-related flood hazards and describe flood mitigation measures, considerable work has been directed towards understanding breakup processes in the Fort McMurray area. Reports arising out of this work (Appendix B) cover a range of ice-related topics in three general areas:

- Observed/measured ice-related annual peak water levels at a variety of locations upstream and downstream of the Clearwater River confluence.
- Descriptions of the general characteristics/mechanics of the breakup process, including factors that affect the timing and severity of breakup and the corresponding ice conditions that cause the peak ice-related water level – thermal breakup, ice surge (jave), and/or fully developed equilibrium ice jam – within the context of the flow at breakup.
- Documentation of salient ice jam processes related to the numerical simulation of specific breakup processes such as surge characteristics, breaking front characteristics, and the coupling between ice and water waves.

A series of reports arising out of ARC and AEP that were published in the 1980s provide valuable observations of general river ice breakup conditions in a number of years, mainly on the Athabasca River (Joliffe and Gerard, 1982; Rickert,1982a; Rickert,1982b; Andres and Doyle,1984; Andres and Rickert,1984; Andres and Rickert,1985a; Andres and Rickert,1985b; Andres,1988; Malcovish et al., 1988; Winhold,1988). The reports provide a description of the mechanics of the breakup as they were observed and interpreted at the time, and contain summaries of pre- and post-breakup conditions, ice jam profiles, hydraulic characteristics of the ice jams, and peak ice-related water levels at salient locations. These reports are a key data resource for the modelling component of this assignment described in following sections. Additional discussion of these data sets is provided in following sections.

After that flurry of activity, several researchers at the University of Alberta, in cooperation with AEP, have conducted follow-up studies on different aspects of the ice breakup at Fort McMurray, including discharge measurements (Hicks et al., 2000), ice jam related surges and waves (Hutchison and Hicks, 2007; Kowalczyk and Hicks, 2003; Kowalczyk, 2005; She and Hicks, 2006), and general observations of ice events (Mahabir and Garner, 2007; Robichaud, 2006; She et al., 2009). There have also been numerous reports on forecasting ice jam events on the Athabasca River (Mahabir et al., 2006, for example). Also of interest, an M.Sc. thesis at the University of Alberta focussed on developing a 2-D hydraulic model of the freeze-up processes downstream of Fort McMurray (Wojtowicz, 2010).

3.2 Peak Ice Related Water Levels

Monitoring of ice-related water levels has and continues to be carried out by AEP and RMWB as part of a continuing program to collect operation data to assist with flood forecasting and disaster mitigation activities. The data collection has taken various levels of intensity, varying from automatic water level measurements at a number of WSC gauges with few concurrent on-site observations to post-breakup highwater mark surveys supported by limited observations of ice processes.

WSC maintains three long-term hydrometric stations within the study area, shown on Figure 5 below.

- WSC Gauge Station No. 07DA001 – Athabasca River below Fort McMurray, 1957-present;

- WSC Gauge Station No. 07CD001 – Clearwater River at Draper; 1957-present, and
- WSC Gauge Station No. 07CD004 – Hangingstone River at Fort McMurray, 1965-present.

In addition, there are a number of discontinued hydrometric stations that provide valuable seasonal water level data from the period prior to the construction of the existing stations. These include the following.

- WSC Gauge Station No. 07CC002 – Athabasca River at McMurray, 1937-1959
- WSC Gauge Station No. 07CD001 – Clearwater River below Waterways, 1950-1975, and
- WSC Gauge Station No. 07CD004 – Clearwater River at Upper Wingdam, 1960-1975.

Figure 5: Location of Current and Discontinued WSC Stations within the Study Area

The two most salient stations on the Athabasca River are the Athabasca River below McMurray, where both water level and flow data are available from 1958 to the present, and the Athabasca River at McMurray, where open water level data is available in the period between 1937 and 1959. Hydrometric stations on the Clearwater River provide an indication of Athabasca River levels at the confluence. WSC Gauge Station No.07CD001 (Clearwater River at Draper), WSC Gauge Station No. 07CD002 (Clearwater River at Upper Wingdam) and WSC Gauge Station No. 07CD003 (Clearwater River below Waterways) are all useful to fill in missing records. The Draper gauge provides continuous water level and flow records from the present back to 1958. WSC Gauge Station No.

07CD003 (Clearwater River below Waterways) provides daily water level data for the period from 1950 -1975 for the open water period with the odd measurement during the April breakup period in some years. The record for WSC Gauge Station No. 07CD002 (Clearwater River at Upper Wingdam) provides daily water levels from 1960 to 1974, again mostly in the open water period but with some ice-related water levels recorded in April in some years.

The ice-related data provided by WSC is important in identifying long term trends related to flows prior to and after the breakup period, water levels during the breakup period, and dates of breakup. Interpretation of the stage data also provides an indication of the type of breakup. However, the effects of changing ice conditions on the both the ice-related and open water rating curve makes it difficult to estimate flows during the breakup period. Regardless, the WSC provides valuable synoptic information on ice-related processes.

Supplementary water level data, typically collected at locations such as the mouth of the Clearwater River, McEwan Bridge, and at the now decommissioned docks of the Northern Transportation Company Ltd. (NTCL) on the Clearwater River, provide valuable stage records that can be used to extend and refine the stage frequency analysis. The WSC data form a part of this data set but given the location of the hydrometric station on the Athabasca River relative to the mouth of the Clearwater River, these data alone do not provide reliable estimates of ice-related water levels at Fort McMurray. However, they can be used to infer the severity of breakup when the year to year variation in water levels is assessed.

Table 1 summarizes the salient ice-related breakup data extracted from the WSC record at the Athabasca River hydrometric station (WSC Gauge Station No. 07DA001 Athabasca River below Fort McMurray). The table provides the following information for each year in which some ice-related observations are available.

1. Last date of stable ice cover when the late-winter ice-related rating curve is assumed to apply. This parameter is deduced from the water level trends and represents the day before the ice cover appears to destabilize and significant shifts from the winter curve start to occur. In some years this appears to occur well before breakup due to gauge malfunction. The data are disregarded in these cases.
2. Water level on date of last stable ice cover.
3. Reported discharge on date of last stable ice cover, based on WSC extrapolations of the winter rating curve. This is a good estimate of the minimum flow that could have occurred during breakup. Section 3.3 discusses the reliability of the pre-breakup discharge estimate. Even though the ice cover is more or less stable, and the year to year ice thickness not that variable, the technique to estimate the discharge on the basis of the water level is quite coarse. At high pre-breakup flows the discharge estimate could easily be out by ±50 percent (note the discharge range at a water level of 239.0 m).
4. Date of peak daily water level during the breakup period.
5. Peak daily water level during the breakup period.
6. Peak instantaneous water level, either on basis of gauge data or measured from highwater marks.
7. Date of instantaneous peak water level, if available.

Table 1: Historical Ice Jam Information

Year	Athabasca River below Fort McMurray – WSC Gauge Station No. 07DA001													Peak Level at MacEwan Bridge (m)	Peak Water Level at Clearwater River	Maximum Miscellaneous April Water Level on Clearwater River (m)		Adopted Peak Ice-Related Water Level at Clearwater River Confluence for Frequency Analysis (m)	Year
	Last Stable Ice Cover			Peak Daily Water Level		Peak Instant Water Level		First Open Water			Dates of Missing Data	Breakup Type	Notes						
	Date	Water Level (m)	Discharge (m^3/s)	Date	Water Level (m)	Water Level (m)	Date	Date	Water Level (m)	Discharge (m^3/s)						Waterways	Wingwall		
1875														252.5				251.3[a]	1875
1876-1884		No observations																	1876
1885														249.0				247.9	1885
1886-1924		No observations																	1886
1925															247.4			247.4	1925
1926		No observations																	1926
1927		No observations																	1927
1928															248.6			248.6	1928
1929-1935		No observations																	1929
1936															250.1			250.1	1936
1937-1949		No observations																	1937
1950																243.9			1950
1951																242.1			1951
1952																243.6			1952
1953																240.8			1953
1954		No observations																	1954
1955		No observations																	1955
1956		No observations																	1956
1957																242.6			1957
1958								May 02	237.479	1110			No relevant ice record			241.9			1958
1959								May 06	236.370	470			No relevant ice record						1959
1960								May 04	236.476	501			No relevant ice record			241.3			1960
1961								May 11	237.098	883			No relevant ice record			242.1			1961
1962													No relevant ice record		246.2	246.0		246.2	1962
1963													No relevant ice record		247.5	242.5		247.5	1963
1964	Apr 23	238.485	240					May 07	238.028	651	Apr 24 - May 6		Missing breakup data			241.1			1964
1965								May 01	240.466	2740	all		No relevant ice record			242.3			1965
1966	May01	239.149	413					May 12	238.860	1320			Missing breakup data				242.5		1966
1967	Apr 26	238.320	510					May 11	238.954	1380	Apr 28 - May 10		Ice record incomplete			241.5			1967
1968	Apr 20	238.351	309	Apr 22	238.485			Apr 29	237.412	368		T	Good record				241.3		1968
1969	Apr 14	238.762	479								Apr 16 - Apr 27	M	Missing breakup data			242.1	243.5		1969
1970	Apr 17	239.171	685	Apr 22	240.649			May 04	238.226	912		M	High ice-related water levels for a week or more				242.4		1970

Year	Athabasca River below Fort McMurray – WSC Gauge Station No. 07DA001													Peak Level at MacEwan Bridge (m)	Peak Water Level at Clearwater River	Maximum Miscellaneous April Water Level on Clearwater River (m)		Adopted Peak Ice-Related Water Level at Clearwater River Confluence for Frequency Analysis (m)	Year
	Last Stable Ice Cover			Peak Daily Water Level		Peak Instant Water Level		First Open Water			Dates of Missing Data	Breakup Type	Notes						
	Date	Water Level (m)	Discharge (m^3/s)	Date	Water Level (m)	Water Level (m)	Date	Date	Water Level (m)	Discharge (m^3/s)						Waterways	Wingwall		
1971	Apr 19	238.811	442	Apr 21	239.802			Apr 27	239.594	1990		M	Ice jamming evident from stage record			242.0	243.8		1971
1972	Apr 22	239.579	753			244.416	-	May 08	239.442	1840	Apr 23 - May 07	M	Severe ice jamming - record missing, flows estimated	245.3				244.0	1972
1973	Apr 17	238.839	251	Apr 20	239.811	240.524	Apr 19	Apr 30	238.366	912		T/M	Good record - mild jamming, maybe a surge			241.0	242.6	242.6	1973
1974	Apr 18	239.265	677	Apr 19	235.821			Apr 28	241.106	2580		M	Missing breakup data	247.2	246.7		246.4	246.7	1974
1975	Apr 24	238.790	566	Apr 29	235.821			May 05	238.643	1030	Apr 26 - Apr 28		Missing breakup data						1975
1976	Apr 12	238.930	878	Apr 14	241.896			Apr 20	239.018	1430		M	Severe jamming						1976
1977	Apr 13	238.829	767	Apr 15	241.460	243.197	Apr 15	Apr 30	238.278	855		M	Severe jamming	248.7	247.6			247.6	1977
1978	April 6	238.421	309	Apr 20	239.829			May 04	239.058	1560	Apr 07 - Apr 09	M/S	Jam formed at bridge, surge only at gauge		242.0			242.0	1978
1979	Apr 27	239.262	578					May 12	238.948	1430	Apr 27 - May 05	M	Severe jamming	247.5	246.5			246.9	1979
1980	Apr 15	238.902	484	Apr 17	239.328			Apr 24	238.495	999		T							1980
1981	Apr 09	238.970	590								Apr 10 - May 25	T?	Missing breakup data		244.0			244.0	1981
1982								May 02	238.802	1240	Mar 18 - Apr 29	T?	Missing breakup data	246.8	242.2			242.2	1982
1983	Apr 20	238.682	455	Apr 21	238.973			Apr 26	238.303	859		T		244.8	242.3			242.3	1983
1984	Apr 10	238.356	468	Apr 12	240.485	240.908	Apr 11	Apr 18	237.756	557	all	T		244.5				243.5	1984
1985	Apr 13	239.009	420					Apr 27	238.440	960	Apr 15 - Apr 18	T?	Missing breakup data		243.5			243.5	1985
1986	Apr 19	238.997	485	Apr 20	240.737			Apr 24	238.594	1070		M	Good data during breakup		244.0			244.0	1986
1987	Apr 14	239.093	910	Apr 17	240.611			Apr 18	239.945	1550		M		246.5	245.1			245.1	1987
1988	Apr 15	238.241	262	Apr 17	240.284			Apr 29	237.929	526		M		244.8	244.5			244.5	1988
1989	Apr 22	238.180	282					May 07	238.050	711	Apr 23 - May 06		Missing breakup data		243.1			243.1	1989
1990	Apr 20	238.600	530	Apr 26	239.084			Apr 27	238.995	1340	Apr 21	T	Small increase in ice-related stage - a surge likely occurred		243.0			243.0	1990
1991	Apr 15	238.751	310	Apr 16	239.247			Apr 20	238.127	813	Apr 17	T						241.5	1991
1992	Apr 02	238.665	419	Apr 03	239.007			Apr 22	237.828	726		T			241.4			241.4	1992
1993	Apr 18	238.410	296					May 01	237.756	462	Apr 21- Apr 30		Missing breakup data					243.4	1993
1994	Apr 10	238.678	415	Apr 13	239.430			Apr 23	236.662	1180		M	Good record, a surge likely occurred		244.0			244.0	1994
1995	Apr 20	238.532	352	Apr 22	238.734			May 01	237.756	514		T	Good record					240.9	1995
1996	Apr 16	238.203	588	Apr 22	243.074	243.176	Apr 21	Apr 29	239.073	1410		M	Good record		245.9			245.9	1996
1997								May 14	239.114	1520	all	M?	No relevant ice record		247.5			247.5	1997
1998	Apr 09	238.696	437	Apr 10	238.861			Apr 16	238.822	1260		T			242.8			242.8	1998
1999	Apr 19	237.742	414	Apr 20	238.392	238.494	Apr 20	Apr 22	238.164	695		T		241.2	240.4			240.9	1999
2000	Apr 21	238.173	203					May 02	237.573	356	Apr 23 - May 01	M	Incomplete record		240.6			240.6	2000
2001											Mar 29 - May 07	T?	No relevant ice record	242.1	240.9			240.9	2001
2002	Apr 25	237.698	181	Apr 27	238.146	238.417	Apr 27	May 14	237.656	392	Apr 29 - May 13	T							2002

Year	Athabasca River below Fort McMurray – WSC Gauge Station No. 07DA001													Peak Level at MacEwan Bridge (m)	Peak Water Level at Clearwater River	Maximum Miscellaneous April Water Level on Clearwater River (m)		Adopted Peak Ice-Related Water Level at Clearwater River Confluence for Frequency Analysis (m)	Year
	Last Stable Ice Cover			Peak Daily Water Level		Peak Instant Water Level		First Open Water			Dates of Missing Data	Breakup Type	Notes						
	Date	Water Level (m)	Discharge (m^3/s)	Date	Water Level (m)	Water Level (m)	Date	Date	Water Level (m)	Discharge (m^3/s)						Waterways	Wingwall		
2003	Apr 20	238.514	310					May 05	238.392	853		M	Incomplete record, ice run or jam likely occurred						2003
2004	Apr 14	238.880	533	Apr 19	239.353	239.667	Apr 18	Apr 26	238.013	624		T							2004
2005	Apr 08	239.021	360	Apr 18	239.949	240.373	Apr 18	Apr 22	238.708	1140		M	Two ice-related events		242.5			242.5	2005
2006	Apr 15	238.514	591	Apr 17	238.946	239.262	Apr 18	Apr 20	238.337	839		T			241.6			241.6	2006
2007	Apr 17	238.277	237	Apr 21	240.023	240.023	Apr 21	Apr 24	239.335	1530		M			244.3			244.3	2007
2008	Apr 30	238.968	470					May 08	239.007	1420	May 01 - May 07	M?	Late breakup, missing data, likely due to ice run		242.0			242.0	2008
2009	Apr 15	238.256	250					May 06	237.940	640	Apr 17 - May 05	M	Missing breakup data		241.7			241.7	2009
2010	Apr 14	238.251	226					Apr 22	237.851	541		M/S	No relevant ice record		241.4			241.4	2010
2011	Apr 18	238.259	257					May 01	238.293	835		T	No relevant ice record		240.7			240.7	2011
2012	Apr 19	238.339	493					Apr 30	238.598	1070	Apr 16 - Apr 20	T			241.1			241.1	2012
2013	Apr 27	238.499	331	Apr 28	238.837	238.979	Apr 28	May 07	239.741	2150	Apr 29 - May 05	M	Missing breakup data		244.5			244.5	2013
2014	Apr 22	238.950	223					May 12	238.685	1110	Apr 24 - May 11	M							2014
2015	Apr 06	238.587	350	Apr 08	241.627			Apr 22	238.114	650	Apr 15 - Apr 21	M		245.3	244.8			244.8	2015
2016								Apr 26		475		M		245.8	243.9			243.9	2016
2017												M/S	Jam formed at bridge, surge only at gauge	243.7	242.9			242.9	2017

Notes: [a] Note this level was initially reported as 252.0 m in Appendix A, 1875 Ice Jam Assessment Report. The level at the MacEwan Bridge was identical in both reports, but it was necessary to estimate a headloss in the reach between the bridge and the Clearwater confluence to estimate the level at the confluence. In the 1875 assessment report, this loss was not well known and a conservatively low estimate of 0.5 m was adopted. Further work was undertaken since that original assessment, which showed that the loss in this short reach was more likely to have been 1.2 m,

8. First date of open water when ice effects have vanished, and the open water rating curve would apply. In some years the record indicates that this occurs well after breakup because of gauge malfunction. The data are disregarded in these cases.
9. Water level on first date of open water.
10. Reported discharge on first date of open water. This is a good estimate of the maximum flow that could have occurred during breakup. Compared to the estimates of the pre-breakup flows, the post-breakup flow (Figure 6) is estimated reasonably well from the water level, as it should be since the open water rating curve should once again apply. It appears that the post-breakup outliers are likely due to datum shifts in the early days of the station operation. Frequency curves of these two flows, which more or less provide an indication of the upper and lower bounds of the operative flow during the breakup period, are presented later in Section 5.4.
11. Periods of missing data during the breakup period.
12. Breakup type, either thermal or mechanical, and if mechanical either a surge or a stable ice jam, as inferred from the gauge record. This is somewhat of an interpretive exercise that requires experience.
13. Salient notes about the quality of the data and the breakup characteristics.

The table also contains salient miscellaneous peak ice-related water level data derived from a variety of locations as provided by AEP (Appendix C), as follows.

1. Peak measured water level at Grant McEwan Bridge. These levels should be classified as instantaneous values. McEwan Bridge was the first bridge constructed at the Highway 63 crossing. It has been rehabilitated several times and three bridges now comprise the crossing. In some years, it is the only record at Fort McMurray, and the challenge is to adjust this water level to represent the water level at the Clearwater River confluence.
2. Peak ice-related water level at the Clearwater River confluence.
3. Peak April daily ice-related water level at the WSC gauge at Waterways.
4. Peak April daily ice-related water level at the WSC gauge at Wingwall. These data at both Waterways and Wingwall are mostly incomplete and should be considered as lower bounds to the possible ice-related water levels at the confluence.
5. Adopted ice-related water level at the Clearwater River confluence that is the basis for the frequency analysis of historical ice-related flood peaks. This water level is either a direct measurement or inferred from data at McEwan Bridge.

The peak ice-related water levels in Table 1 at McEwan Bridge and the confluence are derived from a variety of sources. All data prior to 1991 have been extracted from AEP (1993). These data are derived from two sources – the pre-1972 data reported by Blench (1964) and termed the Schott data set, and the post-1971 data that was assembled from various existing reports by AEP. The reported water levels measured along the Clearwater River and/or at the confluence have been assumed to apply to the confluence without adjustment. However, the 1875 and 1885 measurements at the Hudson's Bay Company (HBC) post at the present-day McEwan Bridge, along with recent measurements at that location, have been adjusted to the confluence using elevation offsets based on measured events (see later discussion).

Data from 1991 to 1999 (inclusive) was extracted from the Trillium (2000) report. That water level data was provided by RMWB, and it differs slightly from that in the AEP data base, as shown in Table 2. Except for 1996 and 1997, the years in that period exhibit low breakup levels and the accuracy of the water level estimates are inconsequential. However, to be conservative, the higher of the two elevations reported in each of the years has been adopted herein. For the post-1999 record, the peak water levels in the AEP data base were adopted verbatim.

Table 2: Comparison of RMWB Ice Level Data (Trillium, 2000) with AEP Record for the Period 1991 to 1999, Inclusive

Year	Peak Ice-Related Water Level at the Clearwater River Confluence (m)		
	Trillium (2000)	AEP Data Base	Adopted Level In Table 1
1991	241.5	-	241.5
1992	241.4	241.4	241.4
1993	243.4	-	243.4
1994	244.0	244.0	244.0
1995	240.9	-	240.9
1996	245.8	245.9	245.9
1997	247.5	247.0	247.5
1998	242.8	-	242.8
1999	240.9	240.4	240.9

In a few years (Table 1) peak ice-related water levels were observed only at Grant McEwan Bridge. These water levels require adjustment to represent water levels at the Clearwater River confluence. In the frequency analyses carried out to date, a simple one metre offset that reflects the nominal open water slope of the Athabasca River, was applied to the Grant McEwan Bridge water level to transfer the water level from there down to the confluence. This may be more or less appropriate for open water conditions when non-uniform flow effects are not as significant as during an ice jam event. However, during an ice jam event when fully developed jams form, the non-uniformity of the channel may contribute to deviations from that assumption over the expected range of jam heights.

Event-based water level differentials between the two locations were derived from measured ice jam profiles in 1977, 1979, 1984, 1986, and 1987 (Andres and Doyle, 1984; Malcovish, Andres, and Mostert, 1988) and from four simulated ice jams that reflect carrier discharges of 750, 1000, 1500, and 2250 m^3/s – ice jam water level profiles that are associated with a range of levels at McEwan Bridge between the highest event in 1875 and more moderate events like those in the mid 1980s. The water level differences vary slightly with the water level at McEwan Bridge, with the water level differential ranging from 0.5 to 1.5 m and averaging 1.0 m (Figure 7). Nonconcurrent water level differentials are also shown in Figure 7. These were extracted from Table 1 and reflect peak water levels measured at both McEwan Bridge and the confluence but are not necessarily associated with the same event or time frame. As expected, these data exhibit more scatter than the event-based offsets. Based on this figure, it would be reasonable to use a water level offset of between 1.0 to 1.2 m, with the differential increasing as the severity of the ice event increases. On the whole, however, the estimated water level differential is quite consistent for a wide spectrum of events and flows. Previous studies (AEP, 1993 and NHC, 2014, for example) have adopted a one metre differential between the two locations. Given the accuracy of the ice jam measurements (at best plus or minus 0.5 m in some cases) there is no compelling reason to break with this approach.

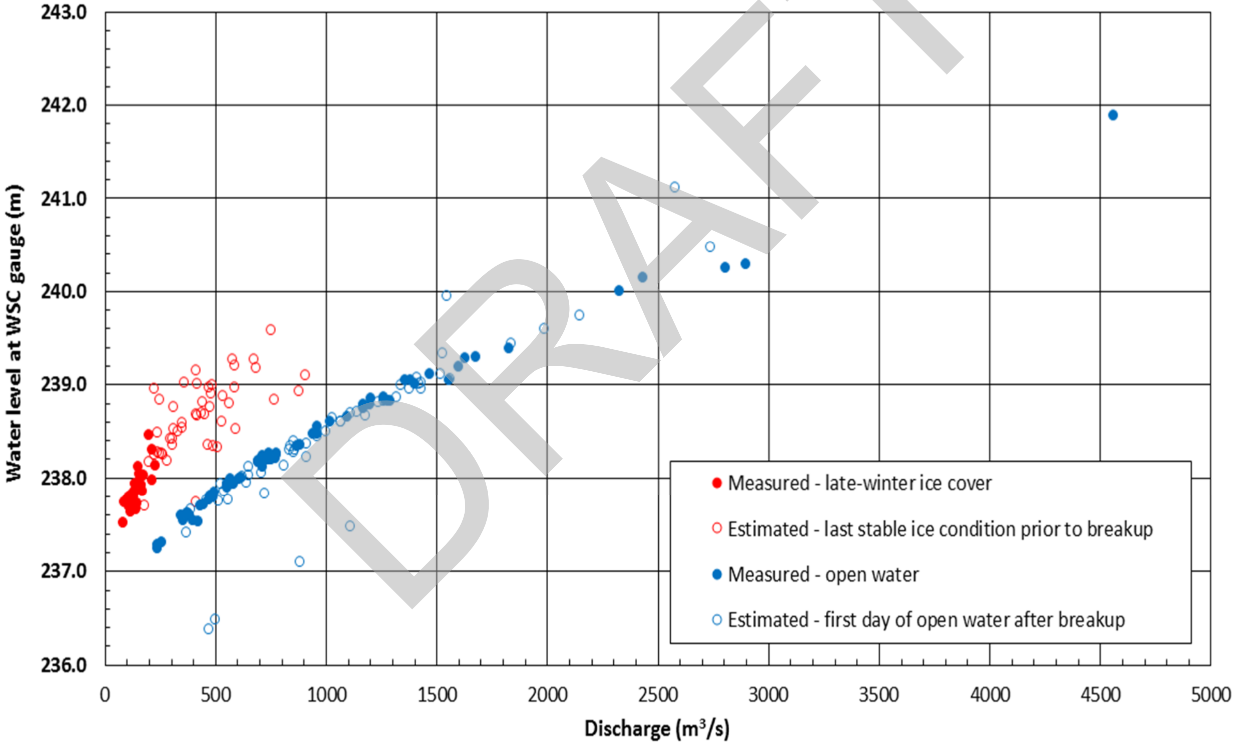


Figure 6: Rating Curves - Athabasca River below Fort McMurray, at WSC Gauge Station No. 07DA001

3.3 Gauge Data and Rating Curves

Water Survey of Canada maintains the following long term gauging stations within the study area:

- WSC Gauge Station No. 07DA001 – Athabasca River below McMurray;
- WSC Gauge Station No. 07CD001 – Clearwater River at Draper; and
- WSC Gauge Station No. 07CD004 – Hangingstone River at Fort McMurray.

The long-term WSC Gauge Station No. 07DA001 on the Athabasca River below Fort McMurray has been in operation since 1957 recording river flow data. However, since 2012 both flow and water level have been recorded at this station. Water level information for this gauge is plotted below to summarize the applicable rating curves (end of winter and open water) based on the water level data provided through WSC, and summarized in Table 1.

The data points corresponding to peak flood levels during ice jam events will plot above these rating curves. The nature of ice jam events, having varying severity means that creating a single rating curve for these events is not possible.

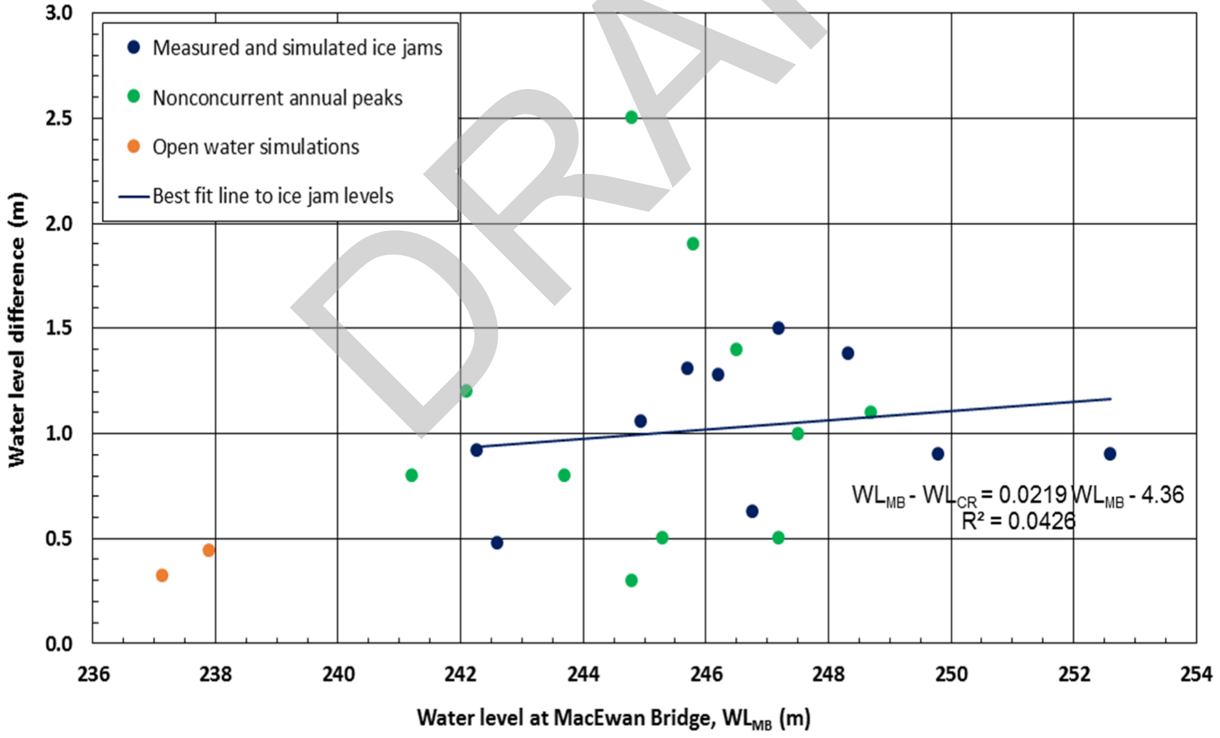


Figure 7: Water Level Differential between Grant McEwan Bridge and Clearwater River Confluence

4.0 HYDRAULIC MODEL ENHANCEMENT

4.1 General

As noted in the previous sections, ice breakup processes on the Athabasca River near Fort McMurray can be very dynamic in nature. The severe water levels associated with the long return periods that are of most interest when describing flood hazards suggest that they result from the formation of an equilibrium ice jam throughout the Fort McMurray reach. The water level at the confluence that is associated with a particular return period can be uniquely related to the carrier discharge and the local channel geometry, given that the ice jam characteristics are similar from year to year. Furthermore, by assuming that the jam (ice accumulation) is in equilibrium throughout the reach, water levels specific to a given return period (and its unique corresponding carrier discharge) can be extrapolated upstream and downstream from the confluence based on the shape of the ice jam profile to provide a reach-based delineation of water levels that would correspond to the water level at the confluence.

Clearly, being able to simulate ice jams within the Fort McMurray reach is critical to defining the ice-related flood hazards throughout the study domain Fortunately, sufficient information has been collected (Rickert and Quazi, 1982; Andres and Rickert, 1984-1985; Andres and Doyle, 1984; Malcovish, Andres and Mostert, 1988) on the characteristics of these jams to allow the calibration and use of physically based numerical models to simulate the impacts of these types of jam events.

To assess the hazard of flooding induced by ice jams on the Athabasca River near Fort McMurray, the open-water HEC-RAS model was enhanced to perform ice jam simulations. The model was already calibrated/validated for low and high open water flows, and all that was required was to enhance the capabilities of that open water model to simulate ice jam events and their associated water levels. After reviewing the available data records, three recorded ice jam events were selected for winter calibration of the model. Once calibrated, the model was also used to simulate two additional jam events to validate its efficacy. The following sections summarize the modifications made to the open water model, and the results of the calibration and validation simulations.

4.2 HEC-RAS Model and Function

While the HEC-RAS has traditionally been used to simulate open water levels using conventional non-uniform backwater solution techniques, it has also been enhanced by its developers to accommodate non-uniform ice accumulations. This model is able to simulate the non-uniform characteristics of the stationary floating granular ice cover and the flowing water under the jam to calculate water level profiles along the jam, assuming a “wide channel” condition. The model calculates the thickness of an ice jam by balancing the combined longitudinal mobilizing forces of gravity and water drag (shear) on its underside with the resisting forces provided by friction that is developed between the ice and the river bank. The ice enhanced HEC-RAS model makes some simplifying assumptions to allow it to solve the equations in an efficient manner. Given the 1D nature of the model, the longitudinal stress in the jam, the thickness of the jam, and the applied shear stress from the flow under the jam are assumed to be constant across the section. No longitudinal stress is passed to the channel banks through changes in stream width or due to changes in horizontal alignments (river bends).

In addition to defining the bed roughness, two ice-related parameters are required – the roughness of the underside of the ice jam and the internal strength of the ice jam. The hydraulic resistance coefficient can be specified explicitly by the user or it can be calculated implicitly from the Nezhikovsky (1964) ice thickness-roughness relationships in which the roughness is assumed to increase as thickness increases. The roughness-thickness approach is somewhat tenuous and not well verified. The user specified roughness approach is recommended for use in this study.

The solution method in HEC-RAS is similar to the standard step method. The solution works from a known ice thickness at the upstream end of the ice jam and progresses downstream. An ice jam thickness at the next section is assumed, and the force balance calculated. This allows the calculation of the downstream ice thickness. This is compared to the assumed value. The new assumed value is set equal to the original assumption plus 1/3 of the difference between the calculated value and the previous assumption. A local relaxation is required to allow the model to converge smoothly and avoid numerical instability. This calculation is iterated until the assumed and the calculated values match to within a specified tolerance or after a specified number of iterations. The default is 0.03 m or 25 iterations,

Several checks are made after the thickness of the jam is calculated. The ice must leave at least 0.3 m between the channel bottom and the ice cover. The water velocity beneath the ice must be less than 1.5 m/s (or a user defined maximum velocity) and the ice jam thickness cannot be less than the user-supplied minimum thickness. The program will adjust the ice cover thickness as required to satisfy these conditions.

HEC-RAS uses a novel approach to solve simultaneously the ice jam force balance equation (starting from upstream) and the energy equation (starting from downstream). The user specifies a “first guess” of the ice jam thickness, and the program solves the energy equation using the standard step method working from downstream to upstream. Once this has been completed, the program solves the ice jam force balance equation from upstream to downstream. This is repeated until the jam thicknesses and water surface elevations converge at each cross-section, resulting in a global convergence. As with the ice jam force balance, a relaxation is required to allow for a smooth convergence as well. The ice jam thickness is varied by 1/4 of the difference between the previous value and the new calculated value.

The HEC-RAS algorithm for the solution of equilibrium ice jam thickness, is limited to 100 iterations. For a particularly long or complex jam event, this number of iterations is often not sufficient to ensure that the solution has fully converged. When this occurs, it is necessary to adjust the solution procedure to include additional iteration cycles. This can be done by modifying the ice conditions and repeating the iteration cycle until full convergence has been achieved.

4.3 Ice Jam Model Setup

The 2017 open water HEC-RAS model formed the basis for this assessment. The open water model reach of the Athabasca River extends from just upstream of Moberly Rapids to Poplar Island (from approximately 6 km upstream to approximately 10 km downstream of the McEwan Bridge). In reviewing available data on recorded ice jam events on the Athabasca River near Fort McMurray, it was noted that all recorded jam toe locations were not necessarily within the predefined model extents that had been used for the open water modelling. The open water model was extended to include an additional 20 km reach of the river downstream of its downstream boundary to provide a framework to incorporate some of the ice jam profiles that were measured by ARC in the 1970s and 1980s. This change also ensured that the enhanced model reach was of adequate length for the jam to reach an equilibrium thickness that all of the toe locations of interest to the study could be captured. With the extension, the downstream boundary of the enhanced model could be relocated from Poplar Island down to the Suncor Oil Sands project area.

This also provided valuable insight into the characteristics of the severe 1979 jam, thereby improving both the model calibrations and the definition of the downstream boundary conditions for the production runs.

The cross sections in the downstream domain were extracted from the ARC data base that was established as part of a study of ice jam characteristics within the cooperative research program in river engineering established by ARC, AEP, and AT. The cross sections themselves were surveyed by ARC and the vertical datum was established by the Survey Branch of AEP when the ice jam markers (ARC, 1983) were installed in the reach between Suncor and Crooked Rapids. This work was done from 1982 to 1983. The raw data is contained in the now-defunct ARC data base, and the data in the modified HEC-RAS channel geometry is a digital representation of what is in the ARC data base.

Model extension involved the following steps:

- An updated and extended terrain model was created by combining the supplied 1m LiDAR dataset with available LiDAR15 data in this area.
- Cross sections contained in the earlier HEC-RAS model were spatially located, and georeferenced within the new terrain model.
- New spatially referenced cross sections were then extracted from the terrain model and imported into the 2017 HEC-RAS model. The floodplain geometry for these new cross sections was therefore based on the available information contained in the newly developed terrain file – either with the 1 m LiDAR data (circa 2016) or the LiDAR15 data (circa 2010). In areas where the two datasets overlapped, the match in topographic data was excellent, providing confidence that both datasets were consistent.
- Compared to open water modelling requirements, ice models generally require a tighter cross sectional spacing to better define the geometry of the ice jam toe, and sections of the ice jam profile that are particularly complex in nature. Given the geometry of the channel(s) in the Athabasca River, additional cross sections were interpolated at, on average, a 150 m spacing to provide sufficient resolution to accurately simulate the jam formation.
- As a final step, the underwater bathymetry contained in the earlier model was extracted and added to the newly cut sections in the 2017 model.

The extended model boundaries are shown in Figure 8, and a comparison of the original and extended cross sectional data sets is shown in Figure 9. Additional cross sections were interpolated between the surveyed sections to provide smoother flow transitions and to allow for a more refined calculation of ice jam profiles, particularly at toe locations. These interpolated cross sections were then manually checked in terms of their geometric transition (single channel to multiple channel), their overall match with the underlying terrain, and with respect to channel roughness. Bank stations were modified, where necessary, to better represent expected spill elevations and shear-wall locations, and to ensure a smooth transition between cross sections. Past experience has shown that the cross sectional spacing in these models should be more frequent in areas where gradients (and ice forces) may be high. Upon completing the interpolation, all sections were carefully reviewed to ensure the roughness distribution within the interpolated sections was consistent with the expected transition between the bounding upstream and downstream sections.

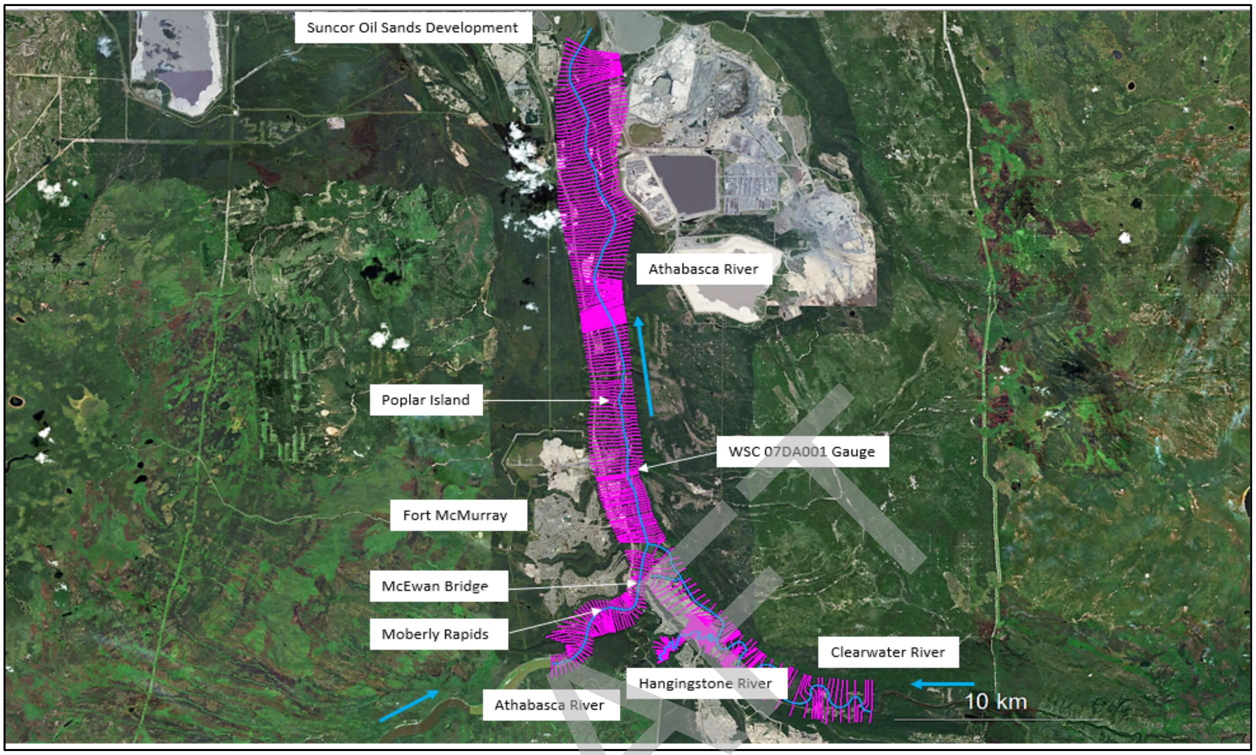
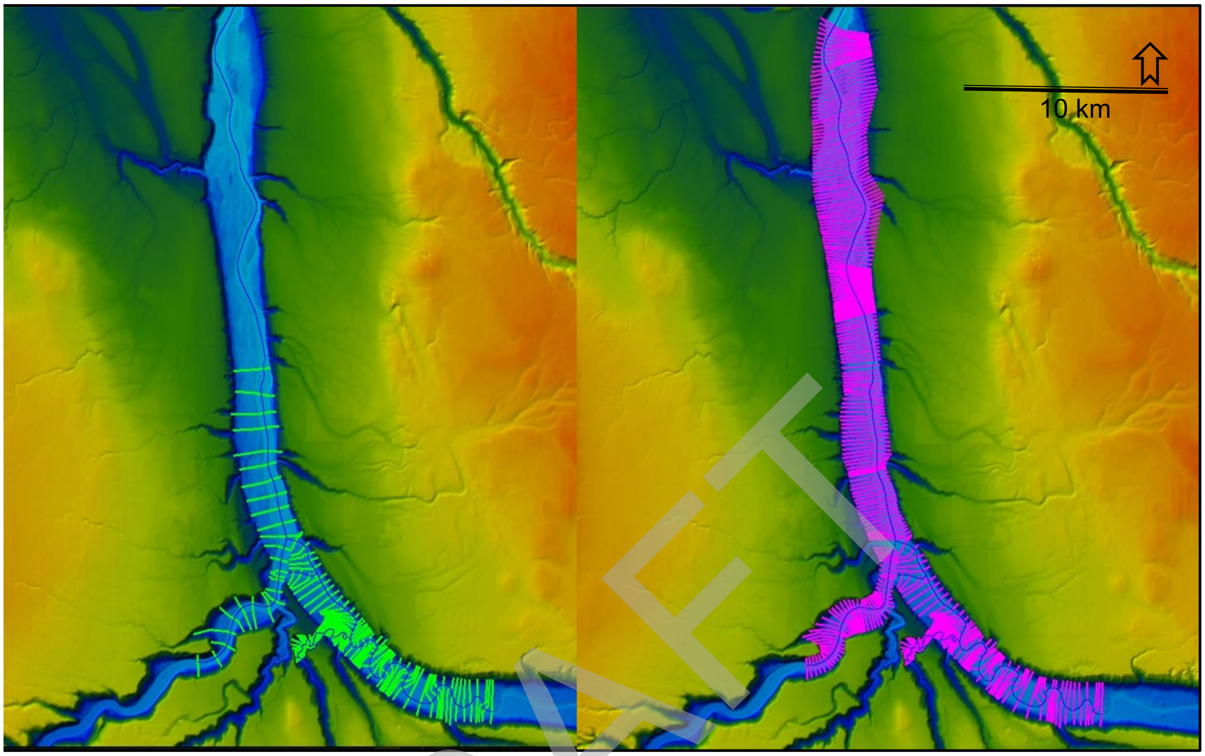


Figure 8: Schematic of the HEC-RAS Model (Ice Jam) and Reference Features



a) Open Water Model b) Ice Jam Model

Figure 9: Comparison of Open Water And Ice Jam Model Geometries

4.4 Calibration

4.4.1 Open Water Calibration

Once the model had been modified and extended, open water simulations were performed to ensure that the enhanced and extended model was able to consistently match the results of the un-extended model that has been used to simulate all open water conditions. Both models were used to simulate water levels for a range of flows between 100 and 2000 m^3/s - which is expected to bracket the flow range associated with measured ice jams and historical ice-related water levels. The simulated water levels were compared for both models.

Figure 10 summarizes the results of the model comparison for open water levels at the WSC gauge located on the Athabasca River downstream of Fort McMurray (WSC Gauge Station No. 07DA001). The model was set up with identical Manning’s bed roughness values, and a very good match was obtained for all flows within the expected ice jam flow range. The match obtained is nearly perfect at lower discharges (i.e. less than 1 cm difference), and the maximum difference is about 15 cm at high flows (~ 2000 m^3/s). The updated version of the model was then considered ready for its calibration to historical ice events.

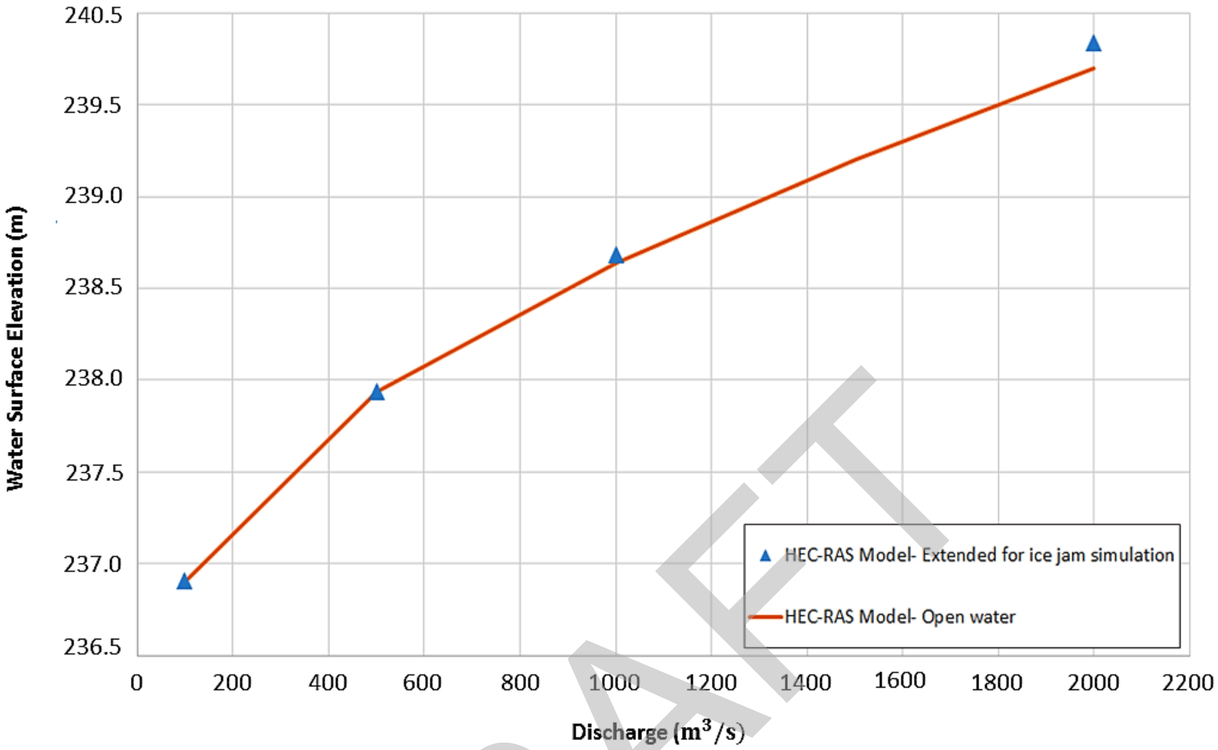


Figure 10: Calibrated Open Water And Extended Reach Model Performance for Open Water Simulation

4.4.2 Ice Jam Calibration

4.4.2.1 Selection of Events

A number of well-documented historical ice jam events have been experienced on the Athabasca River since the mid-1970s. These events have been summarized in various documents, and detailed and comprehensive ice jam measurements (i.e. water levels, toe locations, flows, etc.) exist for a handful of these events. The strategy followed for calibration/validation of the model was to select (i) events for which relatively detailed hydrometric data (flow/water surface profile) exists, (ii) events that represent the full range of conditions that can occur, in terms of their formation flow, ice jam toe location, resulting ice jam profile, etc., and (iii) events that were in place long enough to represent a quasi-steady state condition in the reach. It should be noted that identical parameter sets (ice specific gravity, porosity, internal friction angle and stress ratio) were used for all years in both the calibration and validation runs. The 1986, 1987, and 1996 events were selected for calibration of the model and the 1978 and 1979 events were adopted for verification/validation of the calibrated model.

1986 Ice Jam Event:

Field investigations during the 1986 break-up season revealed that the toe of the 1986 jam was located near the mouth of Parsons Creek, about 7 km downstream of McEwan Bridge. Ice levels were recorded between Mountain Rapids and Suncor Oil Sands Development.

The breakup period lasted for five days from April 19th to April 24th. Ice floes with a thickness of between 0.8 and 1.0 m were observed during the winter season on the river (Malkovich et.al, 1988). The maximum water level observed at the Athabasca River WSC gauge (WSC Gauge Station No. 07DA001) during the breakup was about 240.8 m. Flows on the Athabasca River during the jam event were estimated to be between approximately 400 m^3/s and 1100 m^3/s (Table 1).

The ice jam was reported to extend from the mouth of Parsons Creek to a point that is approximately 3 km downstream of Mountain Rapids. Therefore, the Clearwater River confluence was included within the equilibrium portion of the jam. The ice jam extents and related information are presented in Figure 11. In addition, maximum water surface profiles were available at a number of key points along the jam profile, making this year an excellent candidate for calibration.

1987 Ice Jam Event:

Ground and aerial reconnaissance was conducted prior to the 1987 breakup season to assess the pre-breakup conditions and to observe the downstream progression of breakup on the Athabasca River. Mid-winter solid (thermal) ice thickness at Fort McMurray was 0.8 m. The ice thickness increased to about 0.92 m at the end of winter and remained at that thickness over the breakup period.

Breakup began on April 15th and lasted for three days. Water staged up to an elevation of 246.5 m at McEwan Bridge and the maximum water surface elevation at the Athabasca River WSC gauge (WSC Gauge Station No. 07DA001) was about 242.5m. Flows on the Athabasca River during the jam event were estimated to be between approximately 800 m^3/s and 1600 m^3/s (Table 1).

The ice jam was observed to extend from a point 1 km downstream of the WSC Gauge Station No. 07DA001 to a point 5 km downstream of Mountain Rapids. The equilibrium portion of the jam was estimated to be about 10 km long, extending from approximately 1 km upstream of the WSC gauge to 6 km downstream of the rapids. The jam stage was found to be 7 m above the mean bed level, and about 4 m above the typical summer water level. Figure 12 illustrates the ice jam extents. As shown in the figure, about 2.5 km downstream of Poplar Island, the ice regime was observed to consist of a mixture of large open water reaches and some areas with a smooth residual solid ice cover. Again, maximum water surface profiles were available at a number of key points along the jam profile, also making this year an excellent candidate for calibration.

1996 Ice Jam Event:

The 1996 ice jam was selected as a third event for calibration. Although the available data for this event was more limited, the jam formed at a relatively high discharge and it represents a relatively severe event, when compared to other events with recorded ice jam and flow data, to have occurred in recent history.

The jam occurred on April 21st . Water staged up to an elevation of 245.9 m at the Clearwater River confluence and the maximum water level at the Athabasca River WSC Station (WSC Gauge Station No. 07DA001) was approximately 243.2m. Flows on the Athabasca River during the jam event were estimated to be between approximately 600 m^3/s and 1400 m^3/s (Table 1).

There appears to be little additional background information on this event. ARC was no longer involved in monitoring the ice jams and the reporting format did not follow the earlier ARC protocols.

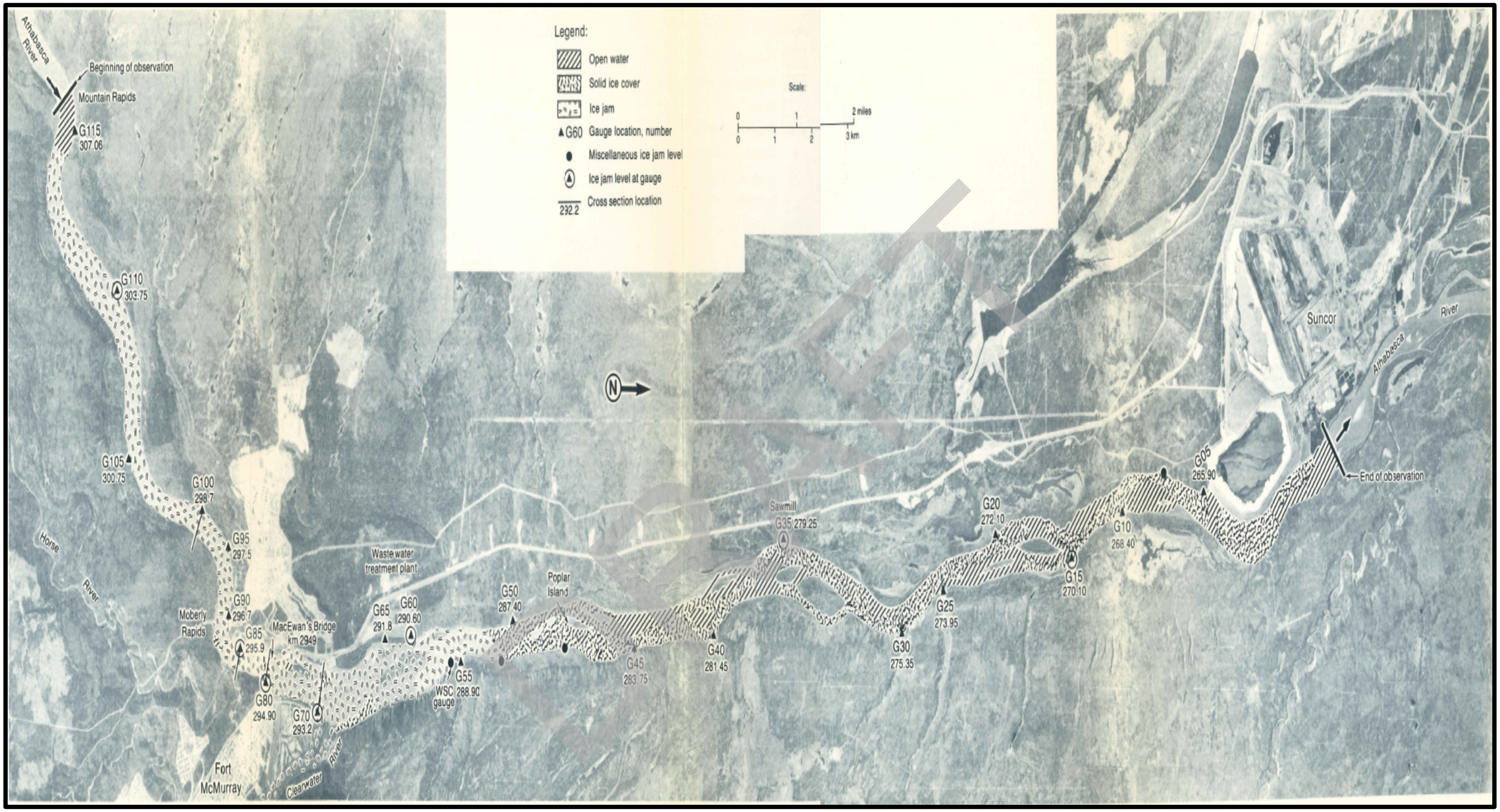


Figure 11: The 1986 Ice Jam Event Illustration (After Andres, 1988)

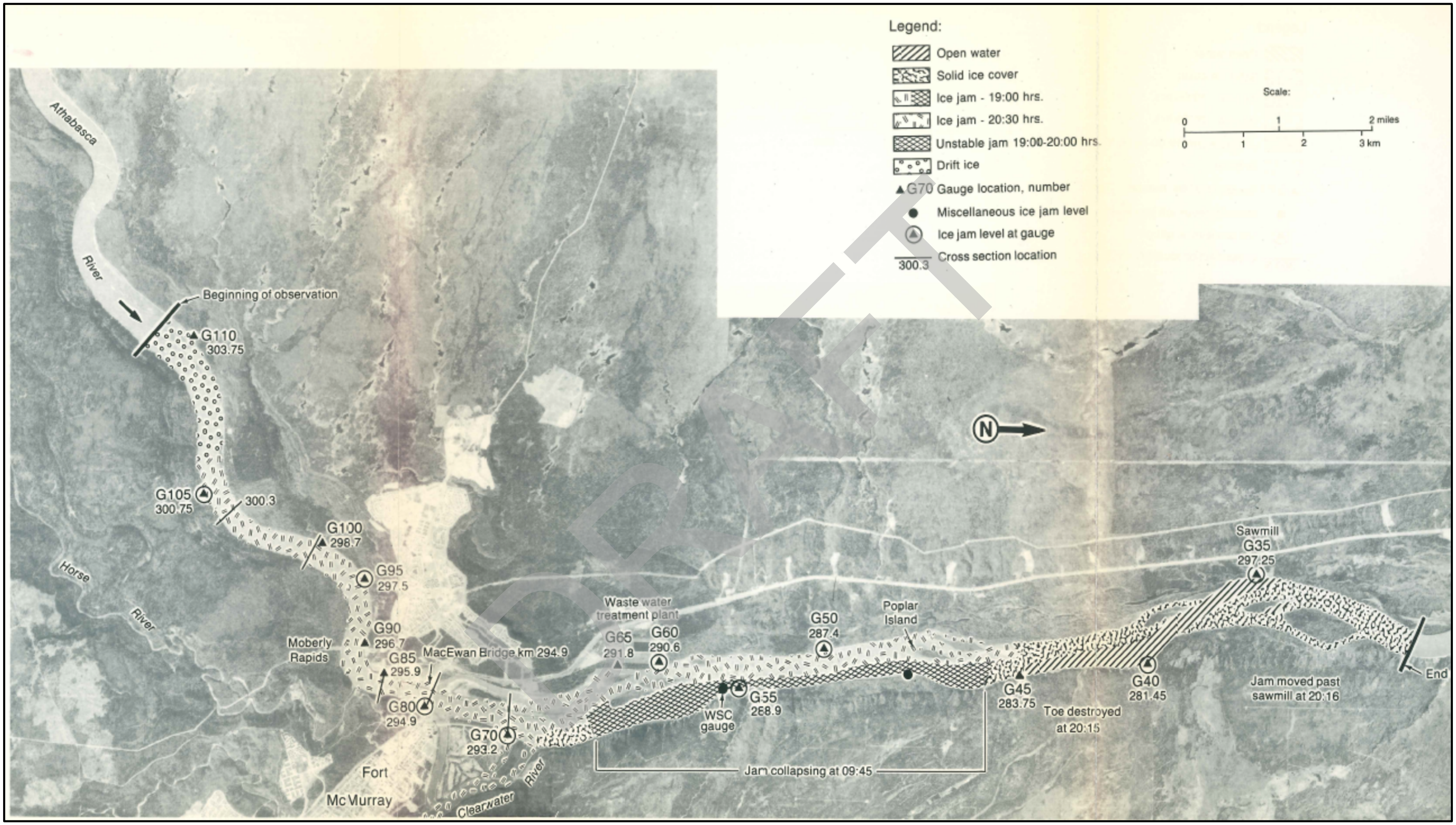


Figure 12: The 1987 Ice Jam Event Illustration (After Andres, 1987)

4.4.2.2 Calibration Approach and Selection of Ice Jam Parameters

Calibration of the ice jam portion of the model (Ice enhanced HEC-RAS model) requires the selection of a number of ice related parameters. Various sets of parameters were tested until a single set of parameters was able to consistently achieve the best match between measured and calculated ice cover elevations as well as the water stage recorded during the ice jam. Care was taken to ensure these parameters remained within theoretically expected ranges.

After specifying the internal strength of the jam (embodied by the friction angle and the porosity of the jam, which typically take on universally constant values) the two remaining challenges are to define (i) the discharge at which the ice jam forms and (ii) the roughness of the ice cover. Neither are separable from each other unless one or the other is measured. The discharge is highly variable during the breakup period and the WSC gauge provides an imperfect estimate of flows during that period. The gauge often becomes inoperative or the effects of ice on the rating curve are unknown. Only two flows are known with any degree of confidence: (i) the pre-breakup flow when the ice cover is still intact, and the late-winter rating curve may still be in effect and (ii) the post-breakup flow when ice effects vanish, and the open water rating curve is in effect. The range between the two can be very large – easily up to a factor of five – and the day to day variability in the flow between those two times is difficult to quantify and can easily be misrepresented by a factor of 200 to 300 percent.

The ice jam roughness is also variable from jam to jam and from year to year. However, experience indicates that the jams that form at Fort McMurray are composed of relatively similar floe thicknesses and floe sizes, and the resulting jams are of similar thicknesses. Therefore, it would be expected that the configuration of the underside of the jams also would be more or less similar from year to year. Notwithstanding second order effects that might be attributed to the effects of flow depth (hence discharge), it would be expected that the year to year variability in ice jam roughness would be quite low – less than 30 percent – compared to the year to year variability in formative discharge.

Trying to estimate the discharge and then calculate the roughness in each year, without explicitly using information from other years, will produce relatively subjective estimates of both discharge and roughness that could be in significant error. Alternatively, adopting a constant roughness that, from experience, fits into a relatively narrow range, and then calculating the discharge increases the reliability of the discharge estimates, thereby maintaining some semblance of objectivity in the estimates of the overall ice jam characteristics.

Considering the above, the calibration proceeded as follows:

- The recorded field data was reviewed and the toe location of each of the ice jams was identified based on the field observations and air reconnaissance conducted during the jam events. The chainage of the toe location was translated into relative model coordinates (model boundaries) and applied to the appropriate cross section. The toe of the 1996 jam was not known, and was assumed to be at or near Poplar island – a relatively common jam initiation point.

- An initial sheet ice thickness of 1.0 m was adopted for all calibration years. This provides the initial ice thickness for the model to start the ice jam calculations and also is very close to the solid ice cover thickness observed at the site during the Calibration/validation years. The model was then set to compute a dynamic ice jam in both the channel and overbank areas for all cross sections located at and upstream of the toe. It should be noted that although this was the initial thickness specified in the model, the model iterated to determine the stable ice thickness at each cross section location.. The adopted initial ice thickness is not related to the ultimate thickness of the jam. Also note that the ice cover formation at McEwan Bridge was set to allow a dynamic ice computation to proceed through the bridge cross section.
- Physical ice cover properties such as ice specific gravity, ice jam internal friction angle and ice jam porosity were set to typical values found in the literature for wide ice jams during breakup (0.916, 45° and 0.4 respectively) (Beltaos, 1995). The ice erosion velocity was set to 2 m/s (Michel, 1971).
- The roughness of the ice cover was set and left as a fixed variable for all simulations. The final ice cover roughness for each jam varied slightly along the reach, but ranged from 0.060 to 0.065. Composite roughness values are calculated within HEC-RAS using the well known Belokon-Sabaneev method, and varied between 0.03 and 0.07 depending on the channel/floodplain and under-ice roughness values. These values are certainly within the range of values suggested by other researchers and practitioners for mechanically thickened ice covers (Nezhikovskey, 1964). It should be noted that various roughness values were tested (0.045 – 0.08), to determine which set of values would provide a consistently good fit to field water level measurements.
- As previously described, flows were then selected for each calibration year by considering the range in river flow possible during the jam event. The range was established by considering recorded flows just prior to breakup, and just after breakup after open water conditions had been re-established. The jam flow was considered to be somewhere in between these two limits. Setting the ice roughness by the procedure described above, the discharge was adjusted within this range until ice jam geometries and simulated water levels began to consistently match the historical numbers recorded through the past field campaigns at the study site. In addition, for many of the profiles, water levels were also recorded downstream of the ice jam event. Where this data was available, it provided a very good clue as to whether flows were near the upper, mid, or lower part of the range. The possible range in flow during the 1986 event was estimated to be between 400 m^3/s and 1100 m^3/s. The final flow utilized in the simulation was 600 m^3/s, in the low to middle of the identified range. The range in flow estimated for the 1987 event was between 800 m^3/s and 1600 m^3/s. The final flow utilized in the simulation was 830 m^3/s – near the low end of the identified range. For 1996, the possible range in flow was estimated to be between 600 m^3/s and 1400 m^3/s. The final flow utilized in the simulation was 1000 m^3/s, which was in the middle of the identified range.
- Internal strength of the ice jam is represented by μ, which is a dimensionless coefficient. The coefficient μ scales with the internal friction angle, φ and the longitudinal to lateral stress transformation coefficient within the jam. A value of 45 degrees was selected for the internal friction angle whereas the stress ratio value was selected from a range between 0.33 to 0.825. Higher values were adopted for multi-channel reaches downstream of the Clearwater River confluence. This is described in more detail below.

During initial calibration runs, the model appeared to over-predict equilibrium ice thicknesses (and water levels) in reaches downstream of the Clearwater River confluence. In these areas, the multi-channel nature of the river planform results in significant grounding of the ice on mid river islands, and possible development of multiple shearlines along the banks and islands. Initially, the model bank stations were adjusted (i.e. narrowed) based on an assumption that during a severe jam event, only one of the channels around an island would be activated. However, initial run results only showed a small improvement in the fit to the observed water surface profile data, and the model continued to significantly overpredict water levels. It was rationalized that the reason for this is that more than one of the channels may remain active in these braided channels during a typical jam event.

Given the likelihood that multiple shearlines may develop, the longitudinal/lateral stress coefficient (K1) was therefore increased (where appropriate) to account for the grounding processes and the existence of multiple shearlines. The presence of these multiple shearlines along each island will provide additional strength to the cover. In other models, like ICESIM/ICEDYN (developed by Hatch), this is handled by specifying an increased shoreline length to compensate for these islands. This same effect can be simulated by artificially increasing the K1 lateral stress coefficient, which is normally, (and somewhat arbitrarily) set as 0.33 for a single channel. Using this strategy/philosophy, the coefficient in the model was increased (up to 0.825 depending on the number of active shearlines expected in a reach) for areas where multiple shearlines would have existed but left at the default value 0.33 in all other areas. Model results were then reviewed to assess/confirm the number of shearlines expected in each reach, depending on the depth of flow in each branch of a bifurcated channel, and whether the ice cover had actually lifted above the island causing the bifurcation (which occurred in some cases). Increasing the value of K1 to 0.825 more than doubles the lateral stress coefficient – an increase that is considered reasonable to account for other possible grounding effects in the multi-channelled areas below Fort McMurray. The adjustment of the lateral stress coefficient provided a much better match with measured ice profile data for each calibration year.

The final adopted ice jam calibration parameters can be found in Table 3.

Table 3: Final Ice Jam Calibration Parameters

Manning's n (Solid Cover)	Manning's n (Ice Jam)	Ice jam specific gravity	Friction angle	Porosity	Lateral stress coefficient of ice jam	Maximum water velocity under the Ice jam (m/s)	Ice cohesion
0.01	0.06-0.065	0.916	45	0.4	0.33/-0.825	2	0

4.4.2.3 Calibration Results

Model calibration results for the years of 1986, 1987, and 1996 are presented in Figure 13, Figure 14, and Figure 15 respectively. Table 4, Table 5 and Table 6 summarize the difference between simulation results and recorded water levels at highwater marks along the reach for the 1986, 1987, and 1996 calibration years.

In 1986, the average deviation between the computed and observed profiles is approximately +/- 0.18 m, with a maximum deviation of approximately 0.35 m. In 1987, the average deviation between the computed and observed profiles is approximately 0.33 m, with a maximum deviation of approximately 0.88 m. The larger difference of 0.88 m occurred at the toe of the jam, where the water surface is relatively steep. In this area, even small differences in the adopted toe location can lead to relatively large deviations between the modelled results and historical observations, and therefore this is considered to be acceptable. Also of note, in the 1987 calibration, the approximate thickness of the cover had been estimated at spot locations based on the remaining shear walls left behind after the cover released. As it is shown in Figure 14, the modelled jam thicknesses also reconcile quite well with the field estimates. The red markers, triangles and rectangles, shown in this figure represent the top and bottom of the ice cover respectively, as estimated based on shear wall thicknesses surveyed after the jam had released. The simulated bottom of the ice cover is shown as a dashed grey line in this figure, and as shown, it corresponds quite well to the field estimates.

In 1996, simulated water levels at the WSC gauge were within 0.02 m of the recorded values, and were within 0.74 m of the recorded value at the Clearwater confluence.

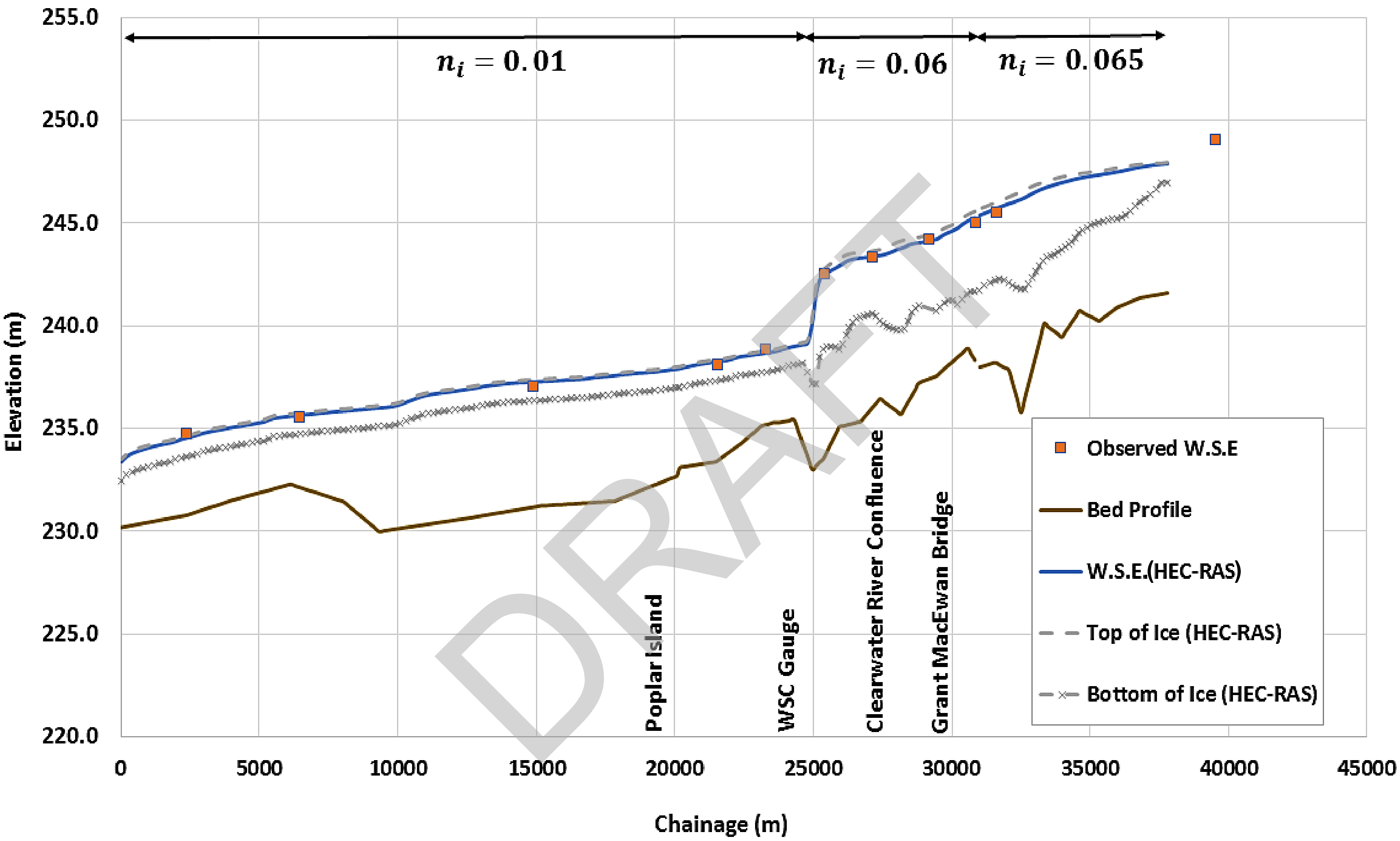


Figure 13: Calibration Results for 1986 Ice Jam

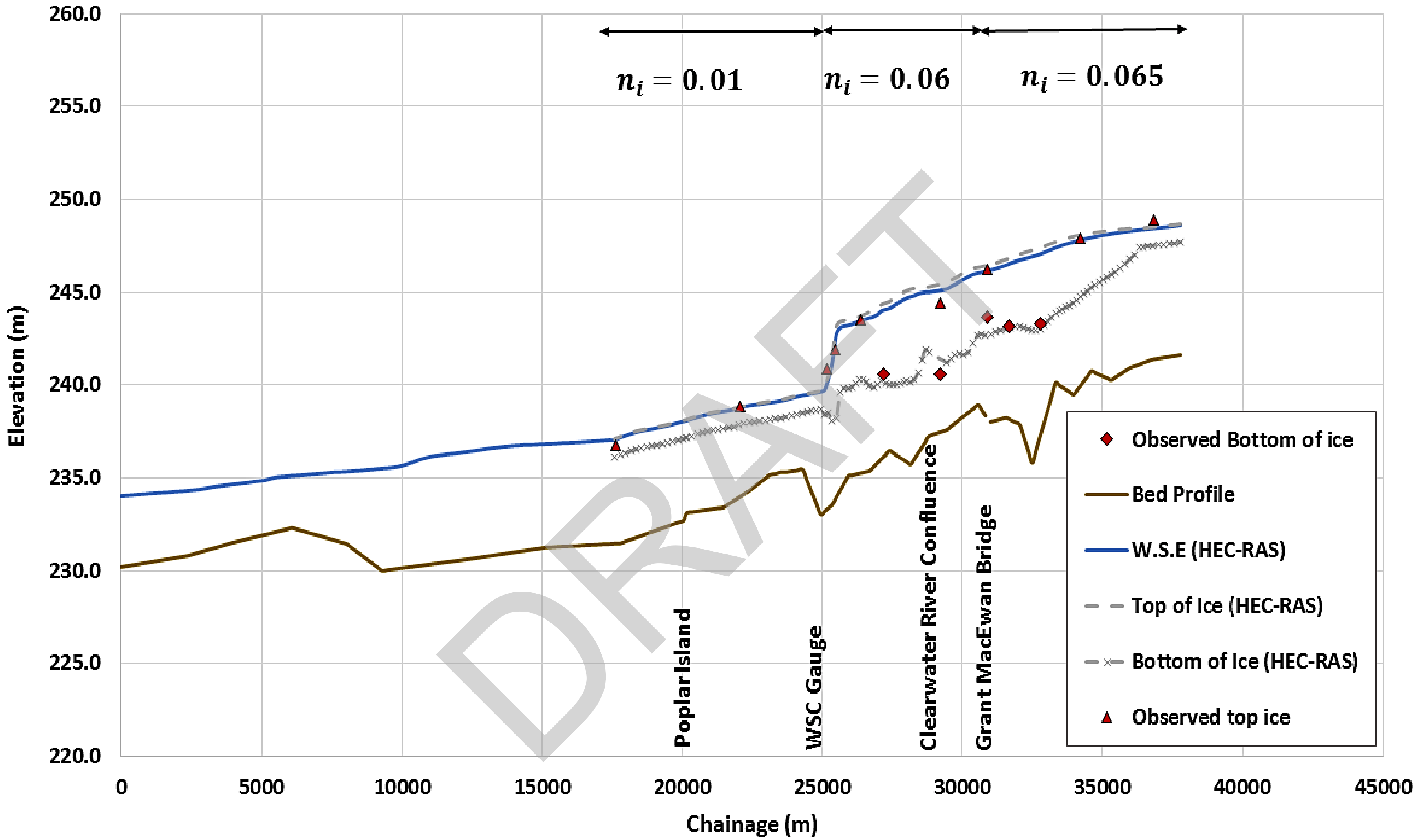


Figure 14: Calibration Results for 1987 Ice Jam

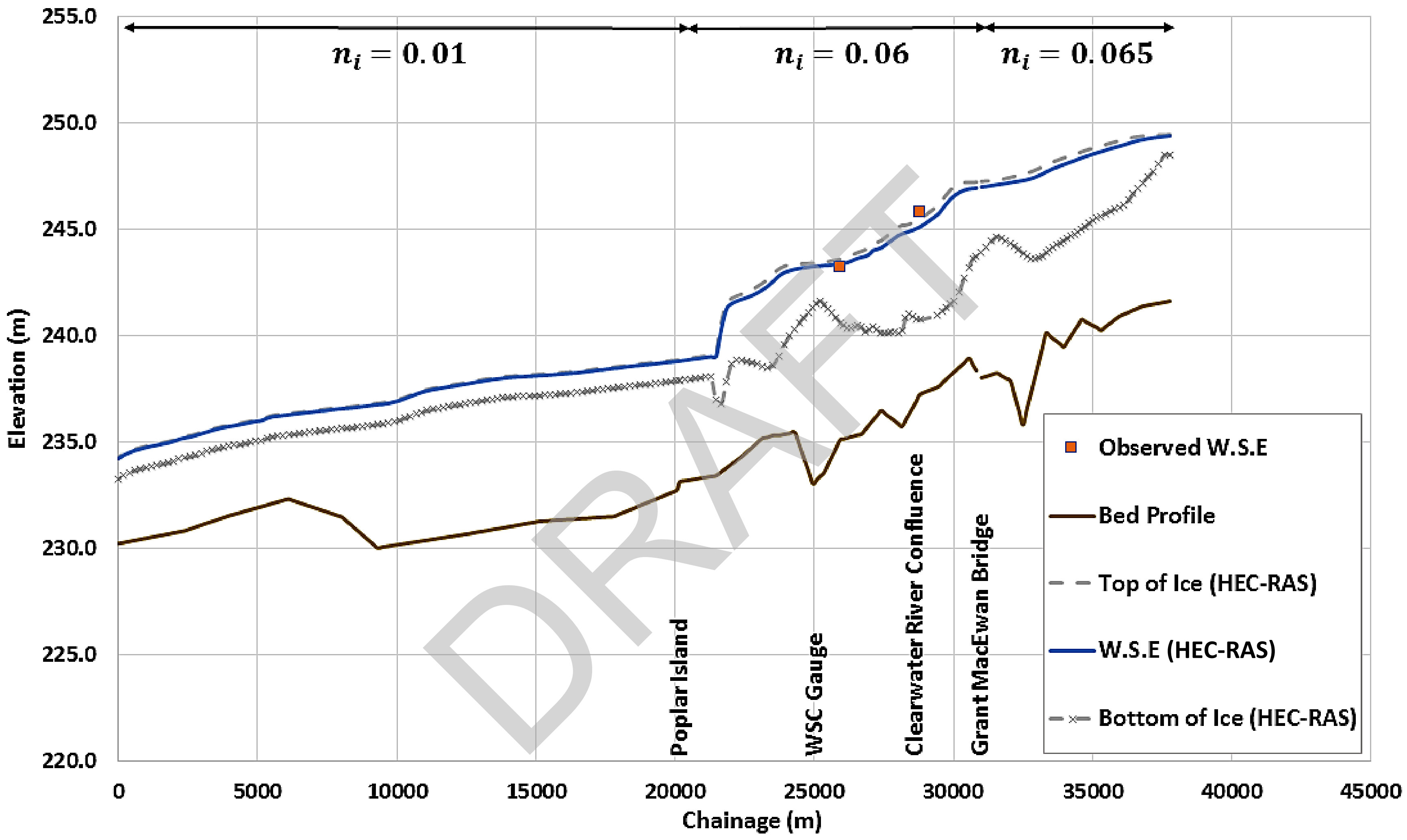


Figure 15: Calibration Results for 1996 Ice Jam

Table 4: Comparison of Simulated and Observed Water Levels for 1986 Jam Event

HWM No.	Chainage (m)	Observed Level (m)	Simulated Level (m)	Difference
1	6476	235.49	235.66	-0.17
2	14916	237.02	237.28	-0.26
3	21596	238.04	238.27	-0.23
4	23296	238.81	238.68	0.13
5	25456	242.50	242.53	-0.03
6	27176	243.25	243.39	-0.14
7	29216	244.17	244.14	0.03
8	30886	244.94	245.29	-0.35
9	31656	245.45	245.73	-0.28

Table 5: Comparison of Simulated and Observed Top of Ice Level for 1987 Jam Event

HWM No.	Chainage (m)	Observed Level (m)*	Simulated Level (m)	Difference
1	17626	236.77	237.12	-0.35
2	22086	238.81	238.82	0.01
3	25156	240.85	240.2	0.6588
4	25456	241.87	241.51	0.36
5	26366	243.53	243.69	0.16
6	29216	244.43	245.29	-0.86
7	30886	246.21	246.42	-0.21
8	34206	247.84	248.03	-0.16

**No water levels were recorded for this event. Instead, the elevation of the top and bottom of the ice jam was estimated based on the shearwall thickness survey.*

Table 6: Comparison of Simulated and Observed Water Levels for 1996 Jam Event

HWM No.	Chainage (m)	Observed Level (m)	Simulated Level (m)	Difference
1	25930	243.2	243.22	0.02
2	28813	245.8	245.06	-0.74

4.4.3 Model Validation

Two years were originally selected to validate the model calibrations - the 1978 and 1979 ice jam events. Following completion of the study, a major ice jam event occurred during the spring of 2020, and it was added as a third validation case, and is described in detail in Appendix G of this report.

The 1978 and 1979 validation events are described in this section, and were selected because both jams are well documented, and their respective profiles are well established by numerous water level measurements. Furthermore, the characteristics of the two jams are quite different. The 1978 jam was situated in the steeper reach upstream of McEwan Bridge, with its toe located at or just below McEwan Bridge. The characteristics of the 1978 jam reflect a steep, single-channel planform with a well-defined channel. The toe of the 1979 jam was located about 25 km downstream of McEwan Bridge, and the jam profile reflects a complex multi-channel planform. The jam likely contains more than one toe due to multiple independent consolidations as the discharge increased while the jam was in place that results in at least three unique profiles, each representing a different carrier discharge.

Model parameters (density, porosity, erosion velocity, friction strength, lateral stress coefficients, etc.) remained identical to those in the calibration simulations. However, some adjustment of the ice roughness upstream of the McEwan Bridge was necessary to better match the high staging patterns observed in this area in 1978 (an increase from 0.065 up to 0.075). Given the thicker nature of the jam in this area, this was considered to be a reasonable and justifiable modification for this year.

Flows were again selected for each validation year considering the range in river flow possible during the jam event. For 1978, the possible range in flow was estimated to be between 300 m^3/s and 1,600 m^3/s (Table 1). The final flow utilized in the simulation was 1,500 m^3/s – this allowed the best fit against the historical water level data (both upstream and downstream of the jam). For 1979, the possible range in flow was estimated to be between 500 m^3/s and 1,400 m^3/s. The final flow utilized in the simulation was 1,200 m^3/s, near the upper end of this range. This flow provided the best fit to the observed water level data.

Table 7 and Table 8 summarize the deviation between simulated and recorded water surface elevations for the 1978 and 1979 validation year simulations respectively. The results of the model simulations and recorded ice cover information are presented in Figure 16 and Figure 17 for the two validation years.

The performance of the ice enhanced HEC-RAS model was considered to be acceptable in both validation simulations. It is notable that the ice jam toe locations and the channel planform within the equilibrium portions of the jams were considerably different in each of these years, resulting in substantially different ice jam profiles. The adopted parameter set was able to do a good job of representing not only the toe, but also the length and shape of the jam thickness profile within the equilibrium section of each of the jams in both simulation. In all years (validation and calibration), the equilibrium portion of the jam was relatively well simulated. This was especially encouraging for the 1979 simulation, as the jam was over 30 km in length with a complex genesis.

The average deviation between the computed and observed profiles of the 1978 jam is approximately 0.3 m, with a maximum deviation of approximately 0.97 m. The model appears to under predict the water level at the head of the jam by a maximum of 0.97 m, as shown in Figure 16. This is at the most upstream end of the model domain, and the model does not properly incorporate the effects of the ice accumulation upstream of Mountain Rapids that would have led to a thicker ice cover immediately below the rapids – the head of the jam was about 22 km upstream of the model boundary. However, the model does a very good job of simulating the toe of the jam and the equilibrium thickness of the jam upstream of the bridge. The simulated cover is too thin in the upper reaches, given the model's more limited extent. Considering this, even in this "specific" case, the model performance is assessed to be quite acceptable in the reach under consideration for this study. Extension of the model to fully capture the jam length upstream of the current model boundary was not considered to be necessary, but if done, model performance will be even more precise.

In 1979, the average deviation between the computed and observed profiles is approximately 0.58 m, with a maximum deviation of approximately 1.35 m. As noted earlier, in 1979 the jam profile was quite complex. It reflects a complex multi-channel planform and is possibly composed of multiple profiles, each representing a different carrier discharge. In addition it is postulated that two separate jams may have occurred at two different times. Taking this into consideration, the overall match in water levels achieved is still considered to be reasonable. The maximum deviation of 1.35 m actually occurred in a region where a secondary toe may have formed in the field. Although the model reproduced a similar thickening as was measured in the field, its location is not reproduced exactly in the model – hence the larger deviation in local water levels.

Table 7: Comparison of Simulated and Observed Water Levels for 1978 Jam Event

HWM No.	Chainage (m)	Observed Level (m)	Simulated Level (m)	Difference
1	25626	241.04	240.86	0.18
2	29311	241.98	242.00	-0.02
3	30890	245.88	245.69	0.19
4	31153	246.30	245.83	0.47
5	31486	247.71	246.76	0.95
6	32048	248.75	248.41	0.34
7	32732	249.79	249.58	0.21
8	33784	250.42	250.54	-0.13
9	34837	250.73	250.91	-0.18
10	36416	252.39	251.43	0.97

Table 8: Comparison of Simulated and Observed Water Levels for 1979 Jam Event

HWM No.	Chainage (m)	Observed Level (m)	Simulated Level (m)	Difference
1	1942	234.95	235.28	0.34
2	3784	235.73	235.95	0.22
3	5626	237.34	238.11	0.77
4	6679	237.92	238.58	0.66
5	8890	238.44	239.05	0.61
6	9837	238.44	239.37	0.93

7	10837	239.63	239.99	0.35
8	12416	239.90	240.34	0.44
9	14995	240.00	240.41	0.41
10	16574	240.00	241.35	1.35
11	16679	240.42	241.45	1.03
12	16784	240.78	241.47	0.69
13	16837	241.15	241.48	0.33
14	16942	241.56	241.50	-0.07
15	20626	243.54	242.58	-0.96
16	25626	245.10	244.39	-0.71
17	29048	246.56	245.90	-0.66
18	30890	246.77	247.62	0.85
19	32205	247.97	248.33	0.36
20	34837	249.53	249.51	-0.02

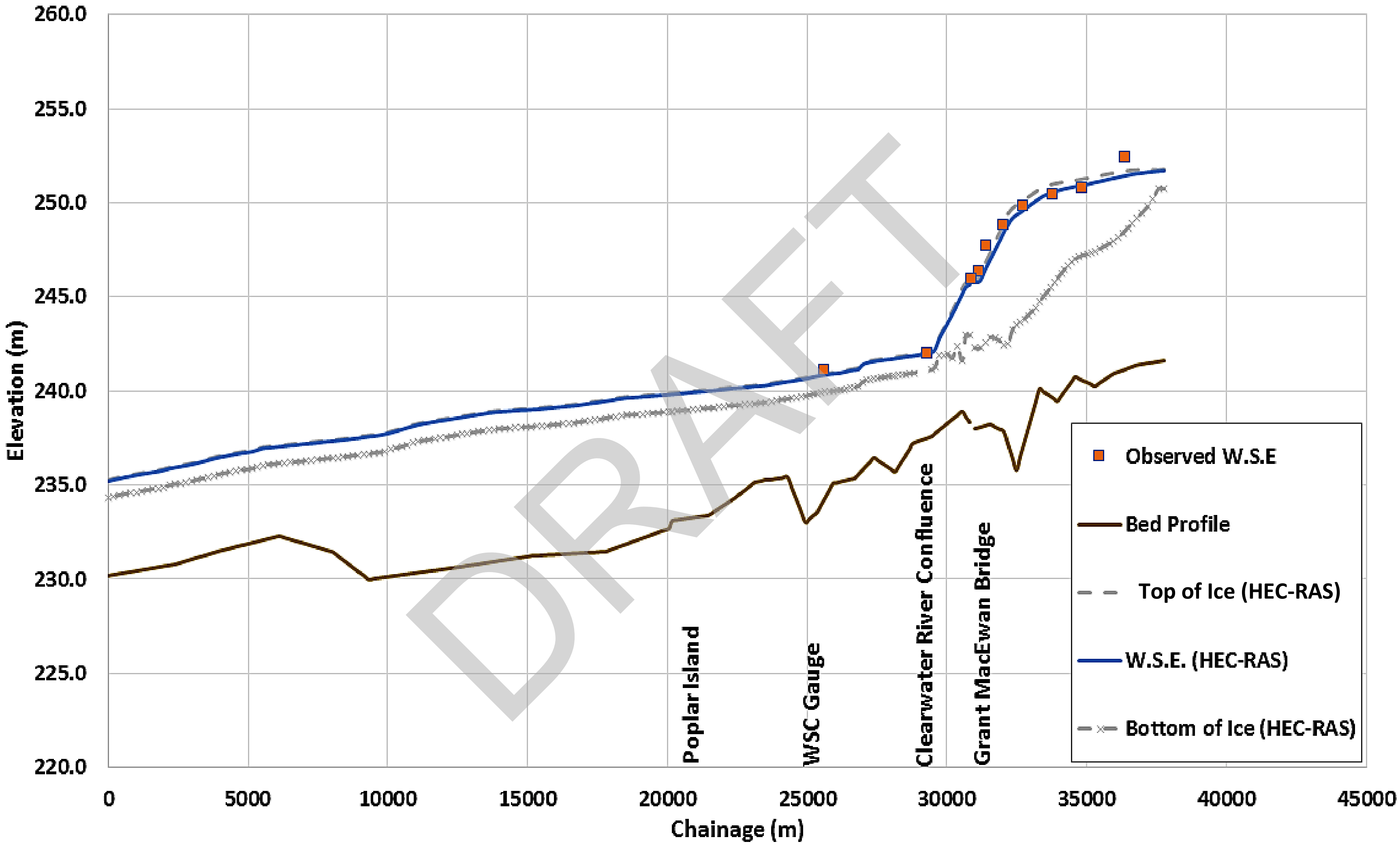


Figure 16: Model Validation Results for 1978 Ice Jam Simulation

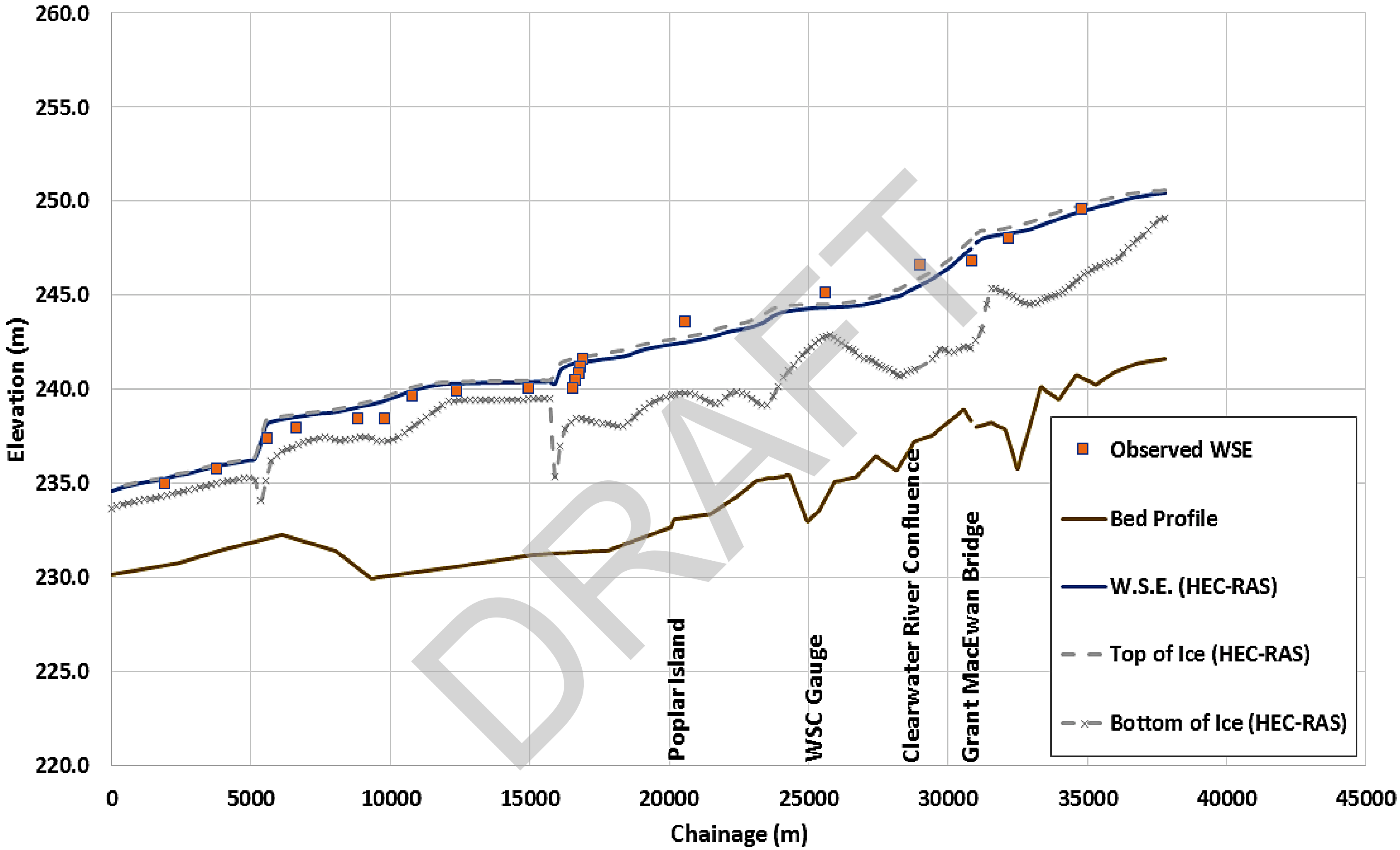


Figure 17: Model Validation Results for 1979 Ice Jam Simulation

4.4.4 Summary

The ice enhanced HEC-RAS model development, calibration, and validation activities were successfully completed and a final model has been developed. The model has been able to successfully simulate the ice-related water levels recorded in five historical ice jam events. The calibrated model is considered to be suitable for use in simulating a range of ice jam events.

5.0 STAGE FREQUENCY ANALYSIS AT THE CLEARWATER RIVER CONFLUENCE

The quantification and assessment of flood risk posed by ice jam events is a complex task. The likelihood, nature, and severity of these events are influenced by a myriad of factors, including the magnitude of the Athabasca River flow at the time of breakup, the location of the toe of the jam, the nature and timing of breakup on the Clearwater River (whether dynamic or thermal, or coincident with breakup on the Athabasca River).

The objective of this section is to update the frequency analysis of the historical peaks to provide an assessment of the ice-related flood hazards that reflects the current understanding of the ice-related flood mechanisms and the contribution of the post-1990 record. Frequency based assessments were conducted of the observed or historical water levels using the two techniques employed by AEP (1993), as follows.

i) A standard frequency assessment of water levels using the threshold approach described in Bulletin 17B, with considerations of the applicability of the more esoteric approach suggested in the Bulletin 17C document.

ii) The perception method that was first applied by Gerard and Karpuk (1979).

As described in Section 3.2, Table 1 contains a record of the adopted historical ice-related water peak breakup water levels on the Athabasca River at the Clearwater River confluence. This record is composed of annual peak ice-related water level for those years in which credible observations were made at the confluence during (i) the historical record prior to 1972 and (ii) the systematic record from 1972 to 2017. The analysis in this section of the report was based on this record. Following completion of this study, a major ice jam event occurred during the spring of 2020, and the assessment was updated to include additional data collected up to the spring of 2020. The results of the updated study are provided in Appendix G of this report.

These adopted values form the basis for the frequency analysis described herein. The trend in the peak water levels between 1871 and 2017 is shown in Figure 18, along with the adopted historical and systematic measurement periods, the adopted historical perception levels, and the adopted Bulletin 17B threshold level. The methodology applied to the frequency analysis and the results of that analysis are described in the following sections.

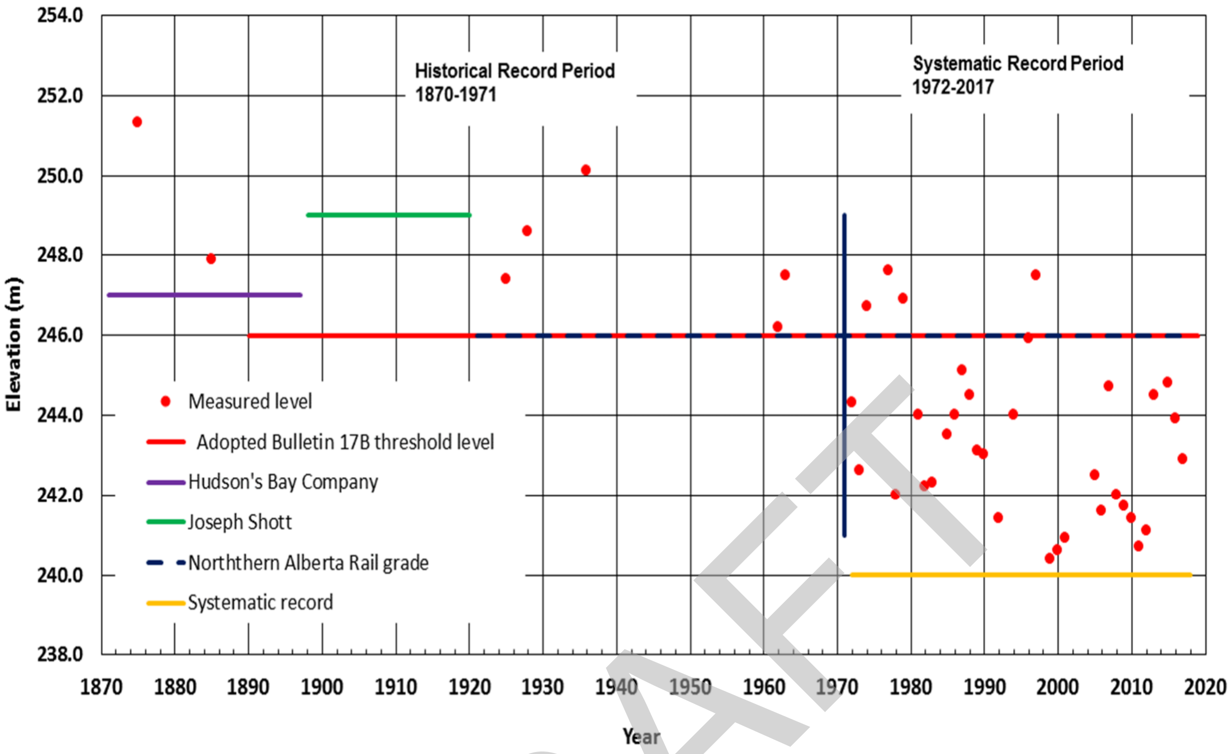


Figure 18: Historical Ice Related Peak Annual Water Levels: Athabasca River at Clearwater River Confluence

5.1 Method 1: Perception Level Analysis

The perception level frequency analysis that was carried out by AEP (1993) was updated to include an additional 24 years of record. The AEP perception levels (Table 9) that reflect four historical periods were reviewed, and they were judged to still be representative. It might be argued that a perception level of 247.0 m for the period when the Hudson's Bay post was being operated might be too low, but there is insufficient evidence to suggest that flooding of pasture lands located at an elevation of about 247.0 m in the areas adjacent to the Clearwater River would not have been noticed even if water levels were well below the structural levels of the post. The periods that the various perception levels would have been in place were also examined. The only discrepancy that appears is the timing of the arrival of the railway at Waterways. AEP (1993) indicates that it was around 1909, whereas the historical records[1] suggest that it was in 1921. The main implication of this change is that it extends the time over which the Joseph Shott's observations (1898 to 1908) would make up the perception level, and reduces the record length of all the historical data points that fall between elevation 246.0 and 249.0 m. It is beyond the scope of this work to examine the implications of this discrepancy, but it likely will not have a big effect on what now will be an outdated frequency curve. In summary, Table 10 provides the record length associated with each of the perception levels that could be considered for an expanded perception level analysis.

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[1] http://railways.library.ualberta.ca/Chapters-11-6/

Table 9: Comparison of Adopted Perception Levels

Characteristic	AEP (1993) (1)	This Study
Hudson's Bay Company established trading post in 1870 – first breakup would have been observed in 1871	1870-1897	1871-1897
Perception elevation based on flooding of pasture lands adjacent to Clearwater River (m)	247.0	247.0
Length of time perception level would apply (years)	28	27
Joseph Shott – early resident could recall severe flood levels	1898-1908	1898-1920
Perception elevation based on observation of the 1928 flood – could recall no larger flood	249.0	249.0
Length of time perception level would apply (years)	11	23
Construction of Northern Alberta Railway Company rail line (2)	1909-1990	1921-2017
Grade elevation in Waterways (m)	246.0	246.0
Length of time perception level would apply, including years when observations were not made in systematic observation period (years)	70	63
Systematic gauging/observations at confluence of Athabasca and Clearwater Rivers	1977-1990	1972-2017
Adopted gauge zero for ice jams during period of systematic record	240.0	240.0
Length of systematic record (years)	12	34
Total record length (years)	121	147

(1) *Information in this column was extracted from Table B2 and Figure 4 of the AEP (1993) report.*

(2) *Archival materials suggest that the railway arrived in Waterways in 1921.*

Table 10: Record Length Associated with each of the Perception Levels

Source	Perception Level (m)	Perception Stage (m)	Record length (years)
Shott Recollection	249.0	9.0	147
Hudson’s Bay Company Flooded Pasture Lands	247.0	7.0	124
Grade of Northern Alberta Company Railway	246.0	6.0	96
Gauge zero for systematic ice jam observations	240.0	0.0	34

Table 11 summarizes the ranked flood peaks along with their corresponding perception levels and exceedance probabilities. It also includes the Cunnane Plotting Position, which helps to rank the data. A similar threshold approach was undertaken based on the techniques and methodologies presented in Bulletin 17B (see Section 5.2). The peak levels are plotted and compared for both approaches on Figure 19 . According to what is shown, it is evident that perception level plotting positions reconcile well with the Bulletin 17B plotting positions with adopted thresholds of 246 and 247 m. This is probably because those levels are the same as the two perception levels with the longest duration in the perception level analysis. A curve has not been applied to the data since there is no theoretical way to develop it.

Table 11: Summary of Perception Level Analysis (Reference Elevation for Stage Calculations is 240.0 m)

Year - Ranked	Peak Stage (m)	Perception Stage in Year (m)	Record Length (years)	Rank	Cunnane Plotting Position (percent)
1875	11.3	7.0	147	1	0.41
1936	10.1	6.0	147	2	1.09
1928	8.6	6.0	124	3	2.09
1885	7.9	7.0	124	4	2.90
1977	7.6	0.0	124	5	3.70
1963	7.5	6.0	124	6	4.51
1997	7.5	0.0	124	7	5.31
1925	7.4	6.0	124	8	6.12
1979	6.9	0.0	96	7	6.86
1974	6.7	0.0	96	8	7.90
1962	6.2	6.0	96	9	8.94
1996	5.9	0.0	34	5	13.45
1987	5.1	0.0	34	6	16.37
2015	4.8	0.0	34	7	19.30
2007	4.7	0.0	34	8	22.22
1988	4.5	0.0	34	9	25.15
2013	4.5	0.0	34	10	28.07
1972	4.3	0.0	34	11	30.99
1981	4.0	0.0	34	12	33.92
1986	4.0	0.0	34	13	36.84
1994	4.0	0.0	34	14	39.77
2016	3.9	0.0	34	15	42.69
1985	3.5	0.0	34	16	45.61
1989	3.1	0.0	34	17	48.54
1990	3.0	0.0	34	18	51.46
2017	2.9	0.0	34	19	54.39
1973	2.6	0.0	34	20	57.31
2005	2.5	0.0	34	21	60.23
1983	2.3	0.0	34	22	63.16
1982	2.2	0.0	34	23	66.08
1978	2.0	0.0	34	24	69.01
2008	2.0	0.0	34	25	71.93
2009	1.7	0.0	34	26	74.85
2006	1.6	0.0	34	27	77.78
1992	1.4	0.0	34	28	80.70
2010	1.4	0.0	34	29	83.63
2012	1.1	0.0	34	30	86.55
2001	0.9	0.0	34	31	89.47
2011	0.7	0.0	34	32	92.40
2000	0.6	0.0	34	33	95.32
1999	0.4	0.0	34	34	98.25

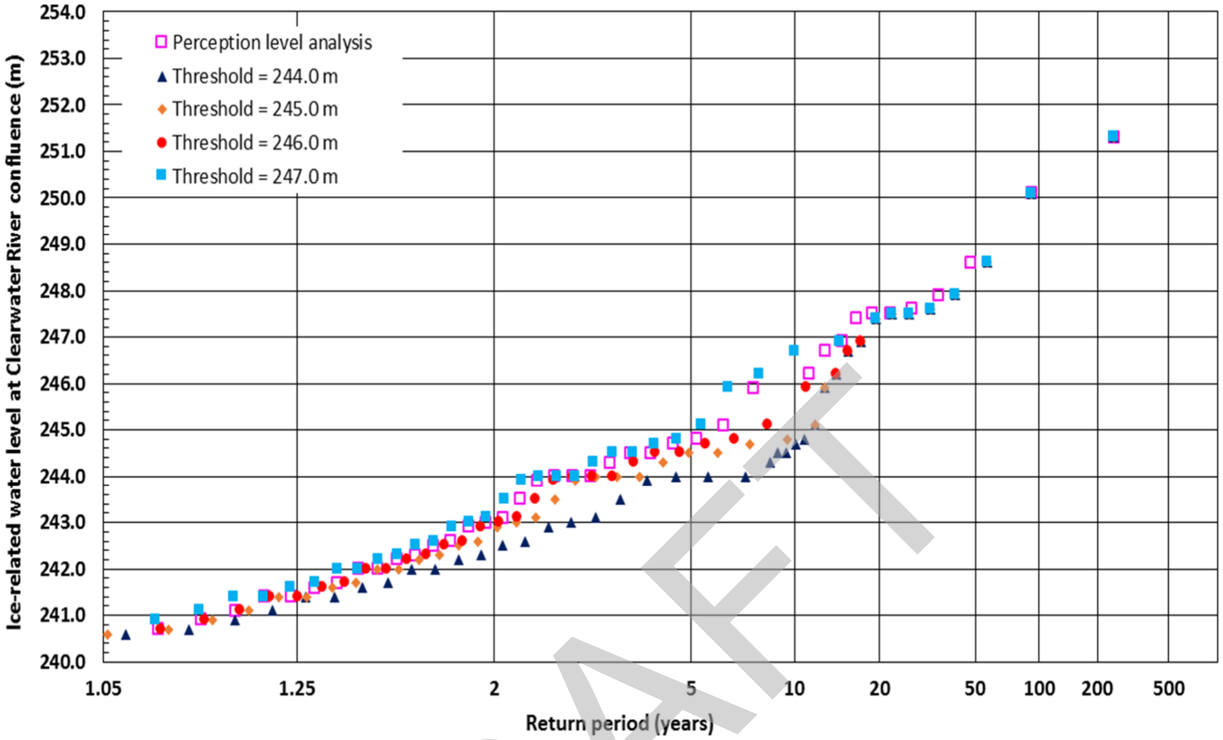

Figure 19: Comparison of Bulletin 17B Plotting Positions to Perception Level Plotting Positions

5.2 Method 2: Bulletin 17B Procedure

The strategy employed in the Bulletin 17B approach was used herein to carry out the frequency analysis of censored ice-related peak water levels using the Pearson III distribution. The procedure is described in Appendix 6 of Bulletin 17B (USGS, 1982) and in the user's manual for the PeakFQ computer program (Flynn et al., 2006). Stedinger and Cohn (1987) and Cohn, Lane, and Baier (1997) also provide a succinct description of the statistical theory that underpins the application of the Bulletin 17B procedures.

For the situation where the flood data contains censored information, the total record would be composed of two periods: (i) a historical record of length N_H in which only the high events above the adopted threshold level T are measured and (ii) a systematic record of length N_S where all events are measured. Missing years in the systematic record would be treated as belonging to the historical period. So, the entire record would consist of four types of data: (i) N_H> documented events above the threshold level in the historical part of the record, (ii) N_H< undocumented events below the threshold level in the historical part of the record, (iii) N_S> documented events above the threshold level in the systematic part of the record, and (iv) N_S< documented events below the threshold level in the systematic part of the record. All would be measured in one way or another, except for the missing years in both the historical and systematic parts of the record.

The challenge is to quantify the statistical characteristics of the unmeasured events in the historical period, which then can be combined with the measured data in both the historical and systematic record periods by applying a weighting factor W = (H-Z)/N to the measured points in the systematic record that are below adopted threshold level. The definitions of H, Z, and N are provided in Table 12, along with the formulae used to determine the plotting positions. The mean, standard deviation, and skew are then calculated in the conventional way using the “method of moments” approach, and any selected reasonable distribution can be adopted to represent the data, although Bulletin 17B suggest either a Pearson III or a log-Pearson III distribution. The Pearson III distribution and the Cunnane plotting positions were adopted herein.

Table 12: Summary of Methods to Compute the Weighting Factor Applied to the Below-Threshold Points in the Systematic Record

Source	Formulation				
	Total Record Length H	**Z**	**N**	**W Weighting Factor**	**m Weighted Rank (1)**
Bulletin 17B, 1982 Cohn et al. Bulletin 17B, 2006	$N_H^> + N_H^< + N_S^> + N_S^<$	$N_H^> + N_S^>$	$N_S^<$	$(N_H^< / N_S^<) + 1$	For $m \leq Z$, $m = r$ For $m > Z$, $m = Z + W (r - Z - 0.50) + 0.5$ $PP = (m - a)/(H + 1 - 2a)$

(1) PP is the plotting position, r is the rank, and a = 0.40 for Cunnane plotting position.

The effects on W vary according to (i) the range of data in the historical and systematic measurement periods and (ii) the choice of the threshold level, since that determines the number of data points in each period, as shown in Table 13. As the threshold level goes up, $N_H>$ and $N_H<$ remain relatively constant but $N_S>$ and $N_S<$ change as events in the systematic record drop out of the above-threshold category and into the below-threshold category. As the threshold level increases, W becomes smaller, which ultimately affects the shape of the frequency curve.

Table 13: Summary of Calculated Weighting Factors

Threshold Level, T (m)	$N_H^>$	$N_H^<$	$N_S^>$	$N_S^<$	W	Source
244.0	7	106	11	23	5.61	Bulletin 17B, 1982
245.0	7	106	6	28	4.79	Bulletin 17B, 1982
246.0	7	106	4	30	4.53	Bulletin 17B, 1982
247.0	6	107	2	32	4.34	Bulletin 17B, 1982

With respect to the calculation of the mean, standard deviation, and skew, Stedinger and Cohn (1986) argue that most of the value in the historical record arises out of knowing the number of events above the threshold level rather than their respective magnitudes. Evidently, using the "method of moments" approach (Tasker and Thomas, 1978) to define the statistics of the composite record does not make full use of the information in the record, and it would be more constructive to use "maximum likelihood" estimates of the statistical parameters. This is computationally difficult, and not used in general practice. As an alternative, Cohn, Lane, and Baier (1997) suggest using the "expected moments algorithm", which is easier to apply than the "maximum likelihood' approach specified in the updated version of Bulletin 17B, yet preserves its attraction.

Clearly, the "maximum likelihood" approach is most rigorous, and it appears that the simpler, but the still complex "expected moments" approach could be a reasonable alternative to be consistent with the Bulletin 17B updates. It is not clear, however, if these more rigorous approaches are warranted, given the long historical period at Fort McMurray and the relatively few historical data that are available. Again, to be consistent with the previous AEP analysis, and without necessarily biasing the frequency analysis, the "method of moments" approach will be used herein to define the statistical parameters of the composite record.

Given the above assumptions, there are three main factors that could bias the results of the threshold-based frequency analysis: (i) the choice of when the systematic record begins, (ii) the length of the historical period, and (iii) the adopted threshold. Contrary to the AEP (1993) analysis, it has been assumed herein that the systematic record begins in 1972, and that any missing data following that could be classified as below threshold and/or very low, so that it does not affect the upper tail of the frequency curve. HBC records indicate that first trading post was constructed in May 1870 on the site. Although the fur trade waxed and waned since then, the area appears to have been continuously occupied after 1870. Records of severe ice-related floods would have been collected from 1871 onward, resulting in a total record length of 147 years.

The threshold applied to any period would depend on the nature of the settlement. In 1875, if the threshold was described by the elevation of the trading post it could have been as high 250 m. In modern times, owing to the development along the Clearwater River, it could have been as low as 245 m – the spill elevation along the Clearwater River. Given the glowing description in the HBC records of the fecundity of the floodplain adjacent to the Clearwater River, it is likely that regardless of the focus on activities at the trading post, any flooding of the Clearwater River floodplain would result in some sort of comment in the days during the transition from the fur trade to more modern times. It would not be inappropriate to test a range of threshold levels between 244 m and 247 m.

The statistical parameters (mean, standard deviation, and skew coefficient) of the four distributions that result from the various threshold levels are summarized in Table 14. As the threshold level increases, the weighting factor decreases as the number of events above the threshold decrease. The weighted mean increases, the standard deviation increases, and the skew coefficient decreases (the curves become flatter). The effect on the frequency distribution is shown in Figure 20**.** The lower threshold levels produce distinctly lower levels in the 2- to 50-year return period range, but due to the higher skew, generally higher levels at return periods greater than about 200 years. However, from a practical perspective, there are minor differences in water levels between the four threshold levels at the 100- and 200-year return periods.

Clearly, the plotted points for the 246.0 and 247.0 m threshold levels reconcile well with the plotted points arising out of perception level analysis (Figure 19). This provides a measure of confidence that either of those two thresholds could be adopted and the two lower levels discounted. After that, the choice becomes somewhat academic. Given that the long return-period floods show a tendency to decrease as more years are added to the analysis, (Figure 20), it is likely that the significance of the large historical floods is diminishing and will continue to do so over time. Furthermore, climate trends and changes in ice conditions downstream of Fort McMurray (more open water and thinner ice covers at breakup due to increasing thermal effects of urban storm water runoff and industrial effluents) will likely reduce the annual likelihood of developing equilibrium jams, thereby on average reducing future breakup levels. So, it is likely prudent to choose a threshold level of 246.0 m to provide at least some recognition of expected future trends. With this in mind, the final frequency curve recommended for the site based on the use of Bulletin 17B is shown in Figure 21.

Table 14: Summary of Statistical Properties and Characteristics of Simulated Frequency Curves for 41 Events Over a Record Length of 147 Years

Threshold Elevation (m)	Number of Events Above Threshold $N_H^{>} + N_S^{>}$	Number of Events Below Threshold $N_H^{<} + N_S^{<}$	Weighting Factor, W	Weighted Mean, M (m)	Weighted Standard Deviation, S (m)	Weighted Skew, G
244.0	18	23	5.61	2.89	1.95	1.47
245.0	13	28	4.79	3.10	1.97	1.22
246.0	11	30	4.53	3.24	2.01	1.04
247.0	8	33	4.34	3.93	2.11	0.89

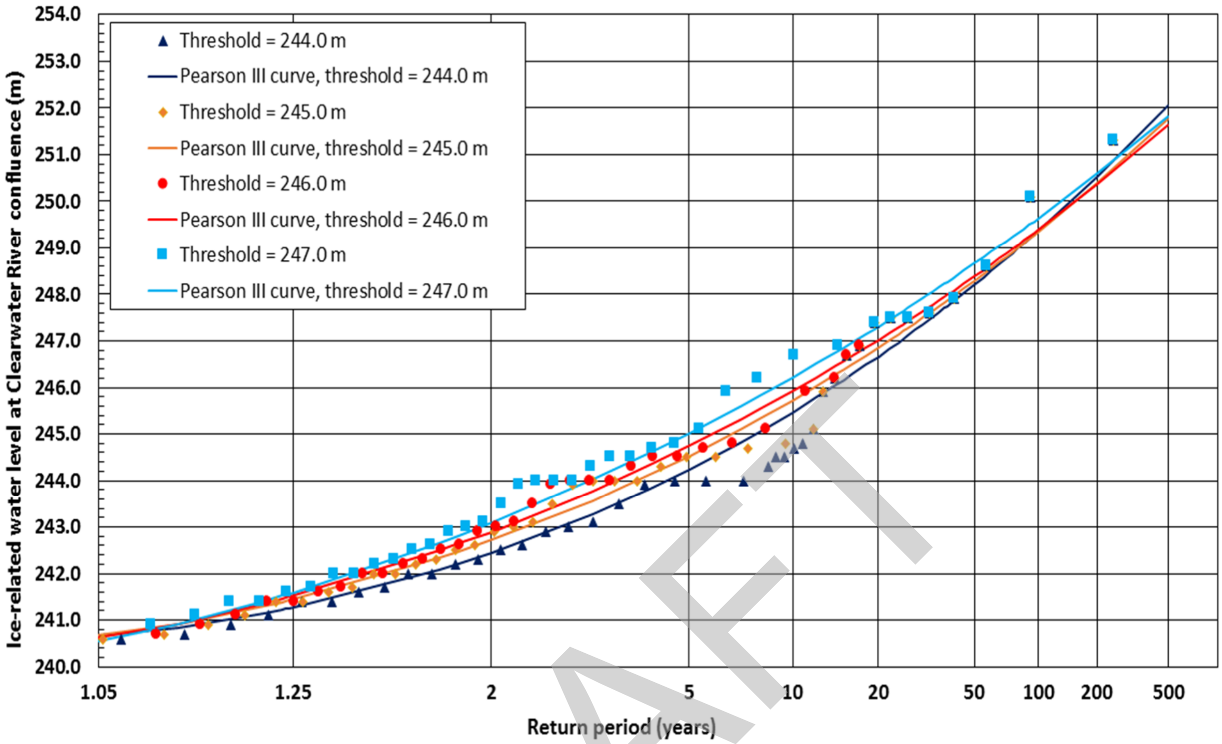

Figure 20: Frequency Curve Comparison of Breakup Water Levels at the Clearwater River Confluence

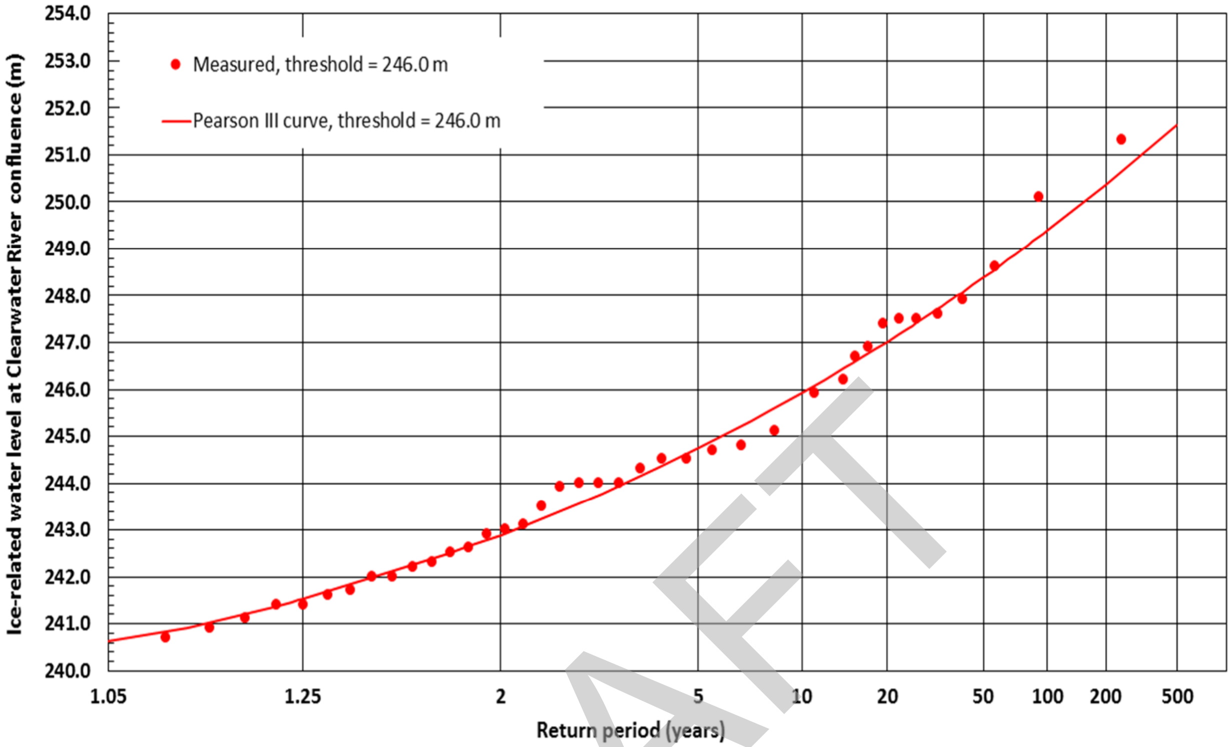

Figure 21: Final Frequency Curve of Breakup Water Levels at the Clearwater River Confluence

5.3 Method 3: Bulletin 17C Procedure

The most current recommendations for the application of the relatively new Bulletin 17C are contained in USGS (2017). Bulletin 17C follows more or less the Bulletin 17B analytical framework, but makes a number of improvements related to the treatment of historical floods, the identification of low outliers, and the calculation of confidence limits. Bulletin 17C also provides of the use of regional skew coefficients, if they are available, and updates the Bureau's understanding of climate variability and climate change.

Given the scope of the analysis described herein, the most germane changes between Bulletins 17B and 17C relate to (i) the use of the expected moments algorithm to define the statistical characteristics of a given flood or water level series and (ii) the ability to include more than one threshold level. Bulletin 17C relies principally on regional skew coefficients but when they are not available it defaults to the station skew. While these features are positive, Bulletin 17C is very much a "black box" with very little user input beyond, for example, inserting the flood data and setting the threshold levels associated with each event. One significant short coming is that only the log-Pearson III distribution is available.

The effects of the multi-threshold capability of the Bulletin 17C statistical approaches are shown in Figure 22, where the Bulletin 17C frequency curve is compared to the results of the perception level analysis, and the Bulletin 17B plotted points, and the Bulletin 17B frequency curve. The Bulletin 17C outcome reconciles reasonably well with the results of the Bulletin 17B analysis for return periods less than about 20 years. However, at the longer and more salient return periods, the Bulletin 17C results deviate significantly from those of Bulletin 17B. At the 100-year return period, the Bulletin 17C result is about two metres higher than the Bulletin 17B result.

The results of the Bulletin 17C analysis are inconsistent with the long historical record at Fort McMurray. A more detailed investigation of the reasons for these inconsistencies is beyond the scope of this project. However, for the case at Fort McMurray, the statistical formulations in Bulletin 17C appear not to assign the correct weights to the historical data and therefore incorrectly calculate both the plotting positions of the data and the distribution skew. It is recommended that the Bulletin 17C results be discounted in favour of those of Bulletin 17B.

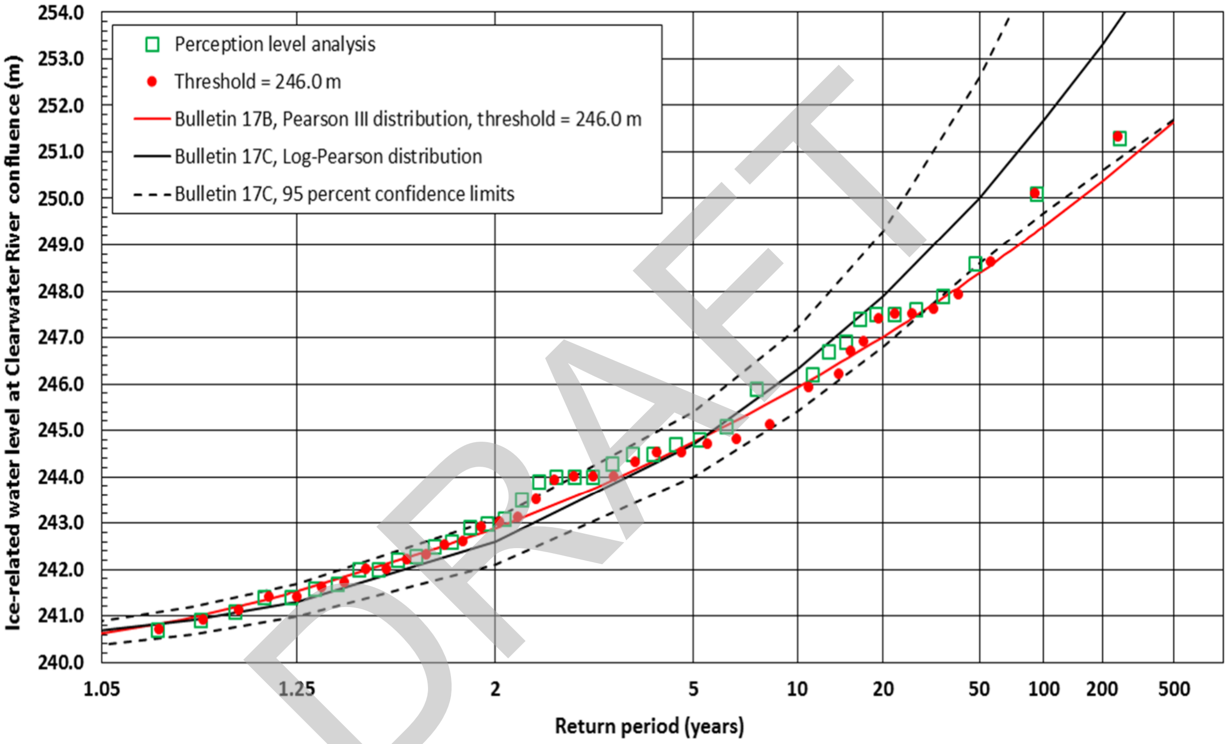

Figure 22: Comparison of Outcomes of the Perception Level, Bulletin 17B, and Bulletin 17C Analyses

5.4 Review of Carrier Discharges

It is expected that the water level frequency distributions summarized above are likely to be relatively closely tied to river discharges in the Athabasca River. Therefore, in order to provide a realistic distribution of flows for each ice jam event, it was necessary to also understand how flows have historically varied on the Athabasca River during spring breakup, and how they may have contributed to the spring breakup levels and processes that have been observed.

Reach 1: Athabasca River Below Confluence

Flows on this river reach were evaluated based on a frequency analysis of WSC data collected at the Athabasca River-Below Fort McMurray Station (WSC Gauge Station No. 07DA001). Flows are recorded continuously at this gauge location, but the carrier discharge that is responsible for a peak ice-related water level during the breakup period is difficult to determine. Even when knowing the exact time of the jam formation or the occurrence of the peak water level it is difficult to estimate the discharge due to substantial day to day changes in the rating curve as the channel transitions from having a stable, solid, and floating ice cover to a fully open water condition. In fact, reasonable estimates of the flows during the breakup period are limited to the period just before breakup when a stable ice cover exists, and the rating curve can be inferred from the winter discharge measurements, and the period after breakup when the open water rating curve would once again apply. Between those dates, the relationship between discharge and water level can vary dramatically, depending on the characteristics of the ice cover and the presence/absence of javes. However, because the discharge increases more or less monotonically as the snowmelt runoff increases, it was considered appropriate to assume a linear variation in discharge between the last ice date and the first open water date, and to discount the unsteady flows that arise from the passage of javes and from the presence of ice jams during that period.

There are various options available to define the representative carrier discharge for a jam event. One option is simply to take the average of the two discharge estimates. This may be appropriate given the vagaries of the discharge during the breakup period. An alternate approach would be to account for the transient nature of the breakup process and how ice-related backwater effects can vary. On the last day of a stable ice cover, the ice cover has yet to be mobilized. With the expectation of a monotonic increase in flow, adoption of the discharge on that day would clearly underestimate the operative carrier discharge, so that would rule out its consideration as the carrier discharge, regardless of the type of breakup that occurs.

For a thermal breakup, one would expect the ice cover to be relatively stable over the breakup period until it simply vanishes, with a somewhat abrupt transition to the open water rating curve from an ice-affected rating curve. For a thermal breakup, the time gap between the last stable ice cover measurement and the first open water measurement is likely to be quite small. This would suggest that the carrier discharge for a thermal event may be close to the discharge on the first day of open water. The same could be said for a jave event. In this case, an ice cover persists until the jave occurs, the ice cover is removed and again there would be a rapid transition to the open water rating curve.

The situation is somewhat different for those years when a stable ice jam forms. A jam could occur anytime between the date of last stable ice cover and first open water, remain in place for a few days while flows increase, and then vanish due to either thermal deterioration or due to the loss of support of the solid ice cover at its toe. Regardless, the operative carrier discharge would be some discharge between that on the day of last stable ice cover and that on the day of first open water.

Some insight into the variability in the definition of the carrier discharge for an ice jam event can be gained by referring to the ice jam calibration exercise described earlier. By iteration, a reasonable estimate of a constant year to year jam roughness was derived so that the adopted carrier discharge for each of the jams would fit within the expected bounds for that year. Table 15 summarizes the expected range of flows and the adopted carrier discharges for the simulated ice jams.

Table 15: Summary of Carrier Discharges Used in the Ice Jam Calibrations

Year	Reported Discharge (m^3/s) at Athabasca River below Fort McMurray WSC Station (07DA001)		Average Discharge (m^3/s)	Adopted Carrier (1) Discharge in Calibration (m^3/s)
	Last Stable Ice Date	First Open Water Date		
1978	309	1560	935	1600
1979	578	1430	1000	1200
1986	485	1070	780	600
1987	910	1550	1230	910
1996	588	1410	1000	1000
Mean			986	1033

(1) *Flows downstream of the Clearwater confluence (includes Clearwater River, Hangingstone River and Snye flows).*

The potential range for the carrier discharge in any given calibration year was judged to be between the flow on the day with the last stable ice cover and the flow on the first day in which the river and returned to a fully open water condition. The carrier discharges were selected within this range. Given the desire to select a single set of ice jam parameters to represent all flow years, (with the exception of the toe location), carrier discharges were then adjusted within this range in order to provide the best match between the simulation results and the observed/ recorded values for water surface elevation or elevation of the top of the ice. In two years the adopted carrier discharge was less than average discharge, in two years it was greater, and in one year it was equal to the average. However, when averaging the results for these five years, the mean “adopted carrier discharge” is only slightly greater than the mean “average discharge” than was calculated for the range. This small sample would suggest that over the long term, adoption of the average discharge in this range is likely a reasonable approach to estimating the carrier discharge for ice jam events.

The annual data summarized in Table 1 above was then used to assess for each year of the series then:

- Discharge on the last day with a stable ice cover for each year
- Discharge on the first day of open water for each year
- The average discharge over the identified breakup period for each year.

A frequency assessment was then performed on the resulting annual series of flows to determine probabilistically derived estimates for each family of flows. The Log Normal distribution was fitted to the data, and it resulted in the estimates for the carrier breakup discharge shown in Table 16 and Figure 23 below. It should be noted that the “average” flows shown in the final column of this Table represent frequency based results of the annual series of average flows – they are not simple averages of the low and high end flows shown for each return period.

Table 16: Breakup Discharge, Athabasca River at Fort McMurray

Return Period (years)	Athabasca River Flow (m^3/s)		
	Low End of Range (Last Stable Ice Cover)	High End of Range (First Day of Open Water)	Frequency Based Assessment of Average Flow
2	400	937	680
5	570	1420	965
10	680	1760	1155
20	780	2110	1340
50	920	2580	1590
100	1025	2950	1770
200	1130	3340	1970

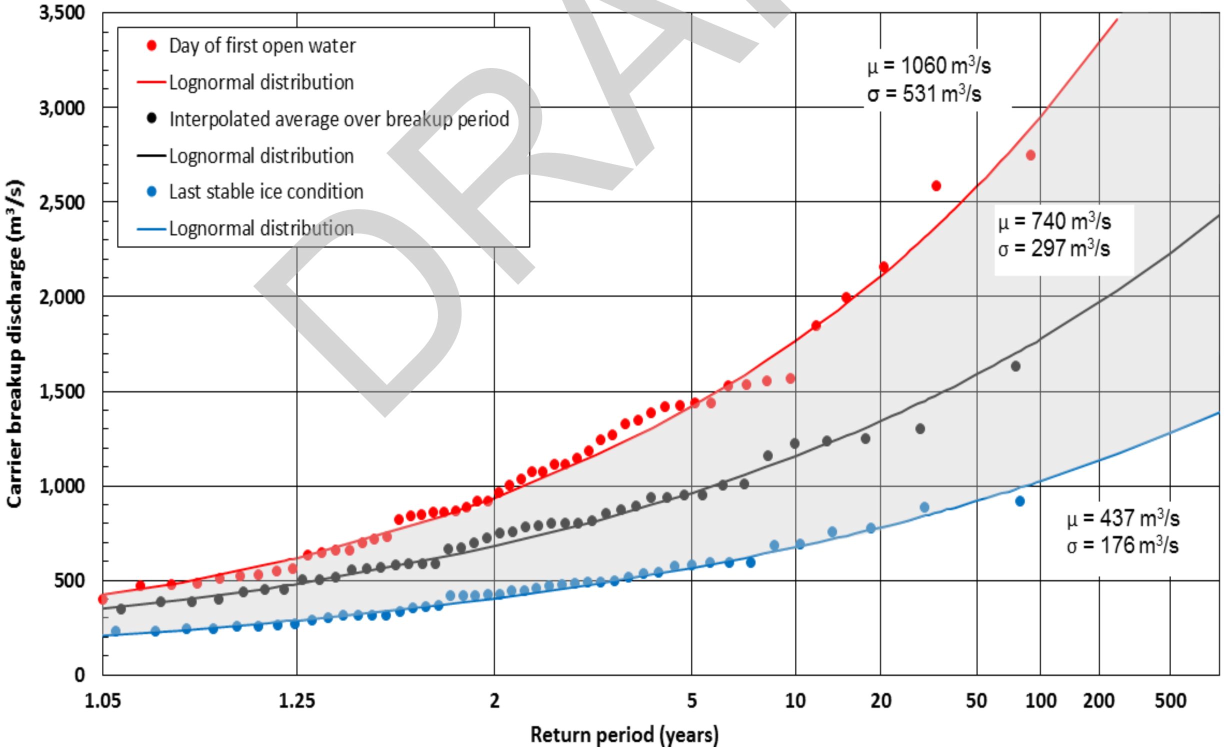

Figure 23: Frequency Curves of Breakup Carrier Discharge, Athabasca River at Fort McMurray

Reach 2: Clearwater River

A similar technique was used to assess the coincident Clearwater River flows expected during the Athabasca River ice jam formation period defined above. An annual series was developed (of the corresponding average Clearwater discharge) using the WSC gauge Clearwater River at Draper (WSC Gauge Station No. 07CD001). Clearwater River flows were estimated on the dates described in Table 1 as representing the beginning and end of the ice jam period on the Athabasca River. The average Clearwater River discharge was then calculated for each year, and frequency analyses were performed on the resulting annual series of average values. The results of the assessment are summarized in Table 17 and Figure 24 below.

Table 17: Coincident Clearwater River Discharges During Athabasca River Breakup

Return Period (years)	Clearwater River Flow (m^3/s)		
	Low End of Range (Last Stable Ice Cover)	High End of Range (First Day of Open Water)	Frequency Based Assessment of Average Flow
2	100	230	170
5	150	350	245
10	185	445	300
20	225	545	350
50	285	690	420
100	335	810	480
200	390	940	540

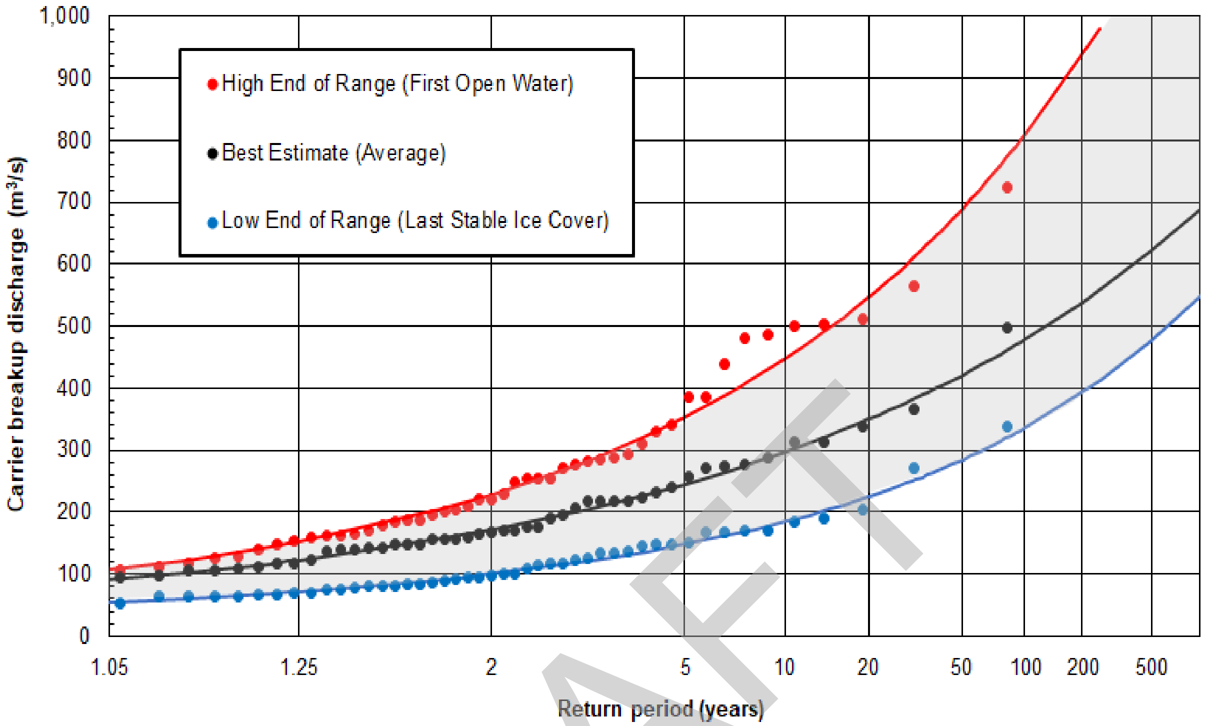

Figure 24: Frequency Curve of Coincident Clearwater River Flow - Athabasca River Breakup

Reach 3: Hangingstone River

A similar technique was used to assess the coincident Hangingstone flows expected during the Athabasca River ice jam formation period defined above. An annual series was developed (of the corresponding average Hangingstone discharge) using records for WSC Gauge Station No. 07CD004. Hangingstone River flows were estimated on the dates described in Table 1 as representing the beginning and end of the ice jam period on the Athabasca River. The average Hangingstone River discharge was then calculated, and frequency analyses were performed on the resulting annual series. The results of the assessment are summarized below.

Table 18: Coincident Hangingstone River Flows During the Athabasca River Breakup

Return Period (years)	Hangingstone River Flow (m^3/s)		
	Low End of Range (Last Stable Ice Cover)	High End of Range (First Day of Open Water)	Frequency Based Assessment of Average Flow
2	2	7	6
5	6	17	13
10	9	26	20
20	13	35	26
50	20	49	36
100	27	60	44
200	36	72	50

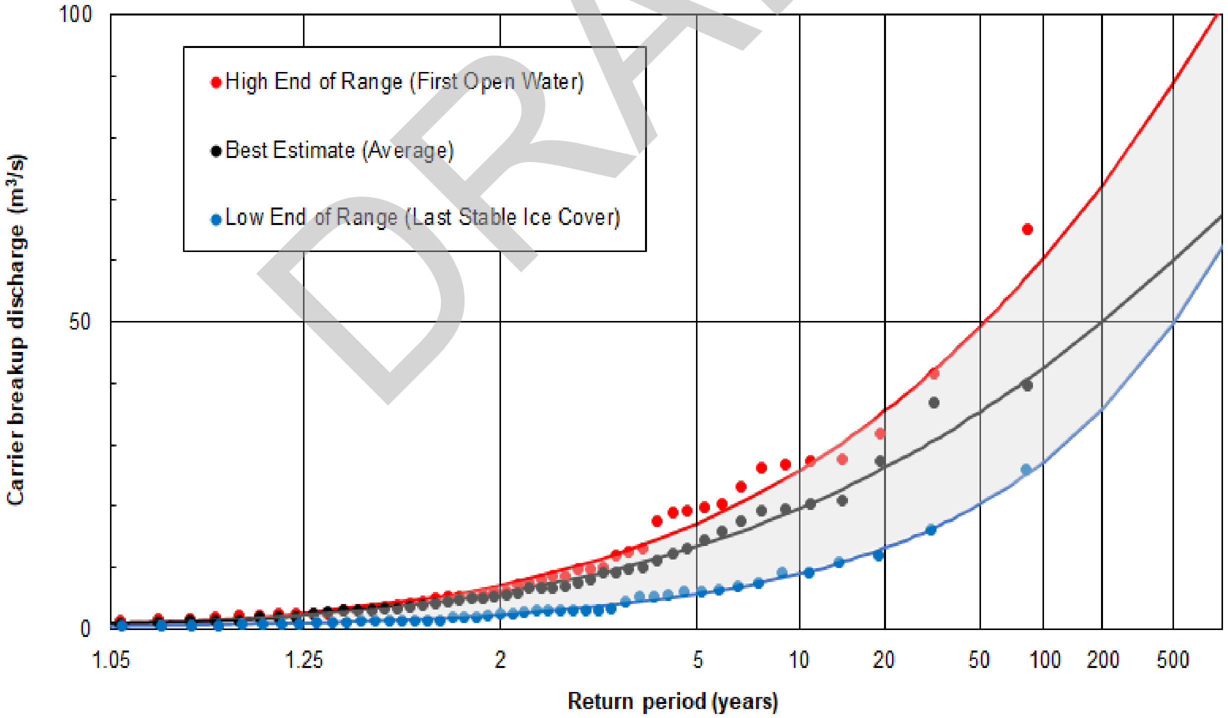

Figure 25: Frequency Curve of Coincident Hangingstone River Flow - Athabasca River Breakup

Reach 4: Athabasca River Above Confluence

The final step in the hydrological assessment was to select a discharge for each flood event for a reach of the Athabasca River upstream of its confluence with the Clearwater River. This could simply be considered to be the carrier discharge estimated in the lower reach of the Athabasca River (and summarized in Table 16) minus the Clearwater River flow presented in Table 17. However, we believe this would underestimate the flood risk for areas on the Athabasca River upstream of the confluence since:

- there is only a weak correlation between the Clearwater River flows and Athabasca River flows at breakup, and to simply assume the two 100 year flows occur coincidentally would underestimate flows (and water levels) on the Athabasca River upstream of the confluence. It is also quite possible that jam events on the Athabasca River could coincide with a period of relatively low flow on the Clearwater River.
- the flows presented in Table 1 for the Clearwater River are likely to be high estimates, considering that the historical Clearwater WSC gauge readings during past events were likely affected by the high backwater created by the Athabasca jam.

Given this uncertainty, it was judged that only the lower end of the Clearwater flow spectrum should be considered when selecting flows in the Athabasca River upstream of the Clearwater River confluence. Figure 24 above shows that Clearwater River flows may be as low as 100 m³/s (or less) at breakup, and therefore it was assumed flows in the Athabasca River upstream of the confluence would only be 100 m³/s less than the downstream carrier flows for these design events. This strategy will result in conservative water level estimates for areas on the Athabasca River upstream of the Clearwater River confluence.

5.5 Summary and Conclusions

Frequency based assessments of ice affected spring water levels on the Athabasca River have been completed. The assessment began with the development of a continuous and consistent water level record at the Clearwater River confluence, and was followed by application of frequency analysis techniques to develop probabilistic estimates of the expected water levels.

The stage frequency analysis suggests that both the Bulletin 17B and perception level analyses produce generally similar shapes of the stage frequency curves. While the Bulletin 17B approach is somewhat more statistically rigorous, the perception level technique has value because it provides information that aids in the selection of the somewhat arbitrary threshold level that is fundamental to the application of the Bulletin 17B technique. From this perspective, the Bulletin 17B technique is recommended, and based on the results of the perception level analysis, a threshold level of 246.0 m is recommended, since it reflects both the shape of the perception level frequency curve and the current floodplain or spill elevation along the Clearwater River. Application of the Bulletin 17C techniques do not appear to provide realistic statistical outcomes.

The recommended historically-based ice affected water level frequencies (using a threshold elevation of 246.0 m, as calculated by Bulletin 17B) are summarized in Table 19. The analysis indicates that the 1875 flood would be about a 300-year event. The next two largest floods – 1928 and 1936 – would have return periods of about 60 and 170 years, respectively. The most recent large floods – 1977 and 1997 – would both be about 30-year events. A comparison of the results of the ice-related water level frequency produced herein with those in earlier studies is provided in Table 20. It is evident that the updated analysis has not resulted in significant changes to the previous ice-related flood frequency estimates at Fort McMurray.

Table 19: Summary of Historically-based Ice-related Water Level Frequencies at the Clearwater River Confluence

Return Period (years)	Annual Probability Being Equalled or Exceeded (percent)	Water Level at Clearwater River Confluence (m)
2	50	242.9
5	20	244.7
10	10	245.9
20	5	247.0
50	2	248.4
100	1	249.4
200	0.5	250.4

Table 20: Comparison of Updated Ice-related Water Level Frequencies with Past Studies

Return Period (years)	Water Level at Clearwater River Confluence (m)				
	NHC (1979)	AEP (1993)	Trillium (2000)	NHC (2014)	Current Study
2	-	243.5	243.2	242.9	242.9
10	244.0	246.0	246.1	246.0	245.9
20	248.0	247.2	247.2	247.1	247.0
50	249.8	248.9	248.7	248.6	248.4
100	250.5	250.0	249.8	249.6	249.4

6.0 ICE JAM FLOOD MODELLING ASSESSMENT

6.1 Computed Ice Jam Flood Frequency Profiles

6.1.1 Athabasca River

Following calibration of the numerical model, and the completion of the water level frequency assessment, additional analyses were undertaken to predict the levels associated with the 50-yr, 100-yr, and 200-yr ice jam flood events. The calibrated model was used in conjunction with the frequency-based water level estimates to simulate a corresponding ice-related water surface profile throughout the study reach for the 50-, 100-, and 200-year ice jam flood events.

The general methodology followed in producing those profiles is as follows.

- Target ice-related Athabasca River water levels at the Clearwater River confluence were selected for each return period based on the results of the water level frequency assessment described in Section 5.5 (Table 19).
- For each event, the toe of the jam was assumed to form approximately 14 km downstream of the McEwan Bridge, at a relative narrow section of the channel. Ice jams have been observed to occur in this area in past years (e.g. 1979). This location is far enough downstream of the flood hazards reach to ensure that an equilibrium ice jam would be produced throughout the entire reach of interest, thereby maximizing the ice jam levels. Toe formation at this site results in maximum water levels throughout the reach - sensitivity runs confirmed that locating the toe any further downstream would not impact the water levels computed at the downstream end of the study reach.
- The input parameters for the development of the ice cover were set to be identical to those used in the model calibration runs. However, in some cases it was necessary to adjust the lateral stress coefficient associated with a cross section. This became necessary if the high stages caused the cover to lift up and over any islands that were in the reach. If the cover did not “ground out” on the island, then the lateral stress coefficient was assumed to revert back to a value of 0.33 – reflective of a wide river jam with only a single set of bank shear lines. Fully dynamic ice covers (i.e. mechanically thickened ice covers) were simulated on the Athabasca River, both upstream and downstream of the Clearwater River confluence.
- The effects of inflows from the Clearwater and Hangingstone Rivers on the spatial distribution of the carrier discharge on the Athabasca River are judged to be minimal. The flows at the Clearwater River at Draper Station (WSC Gauge Station No. 07CD001) during breakup on the Athabasca River are typically 100 - 200 m^3/s and those on the Hangingstone River an order of magnitude less (Figure 24 and Figure 25). The carrier discharge upstream of the Clearwater River confluence was therefore reduced by 100 m^3/s to account for the Clearwater River inflows on the ice jam levels upstream of the confluence. Given the accuracy of both the measured and simulated ice jam levels, deviations from that value would have little meaningful effects on the simulated ice jam levels upstream of the Clearwater River confluence. If anything, this assumption produces conservative estimates of ice jam levels on the Athabasca River upstream of the Clearwater River confluence.

- With the adopted toe location and the carrier discharge defined for the reaches upstream and downstream of the Clearwater confluence, the ice jam profiles were calculated throughout the study reach using the HEC-RAS model. The carrier discharge in the model was adjusted through an iterative process until the calculated water level at the Clearwater Confluence exactly matched the frequency based level summarized in Table 21. This established the event-specific carrier discharge for that portion of the study reach downstream of the Clearwater confluence and, by default, the carrier discharge upstream of the confluence. It was assumed that ice supply would not be a constraint, and that there would be sufficient ice to produce a jam with an equilibrium thickness throughout the entire study reach.

Table 21: Target Water Levels at the Clearwater River Confluence and Corresponding Carrier Discharges

Return Period (years)	Target Water Level at Clearwater River Confluence (m)	Athabasca River Flow (m^3/s)	
		Carrier Discharge Above Confluence	Carrier Discharge Below Confluence
50-yr	248.4	1450	1350
100-yr	249.4	1700	1600
200-yr	250.4	1975	1875

The resulting ice jam profiles are shown in Figure 26, Figure 27, and Figure 28, for the 50-yr, 100-yr, and 200-yr return periods respectively, and represent the best estimate of how ice jam levels vary throughout the reach for each event. A comparison of all three jam profiles is shown in Figure 29. There is not a significant difference in water levels between the jams in the region of the toe, but the longer return period events exhibit greater water levels in the equilibrium portions of the jam, as would be expected. The simulation results for each case are provided in Appendix D for each event.

The final Athabasca river flows needed in the model to match the target levels are summarized in Table 22, and are also compared against the spring frequency based flows. As shown, for all cases, the final modelled flow was actually quite close to the frequency based flow estimate (within 1-8 percent), indicating there is actually a reasonably good correlation between the water level and discharge frequency estimates.

This close match provides confidence in the estimated flood frequency profiles, given that two relatively independent techniques were used to establish ice jam flood potential, and both methods provide very consistent and similar results.

Table 22: Comparison of Flows Needed to Match Target Elevations

Return Period (years)	Frequency Based Breakup Flow (m^3/s)	Adopted Carrier Discharge -Needed to Match Target Water Level (m^3/s)
50-yr	1590	1450
100-yr	1770	1700
200-yr	1970	1975

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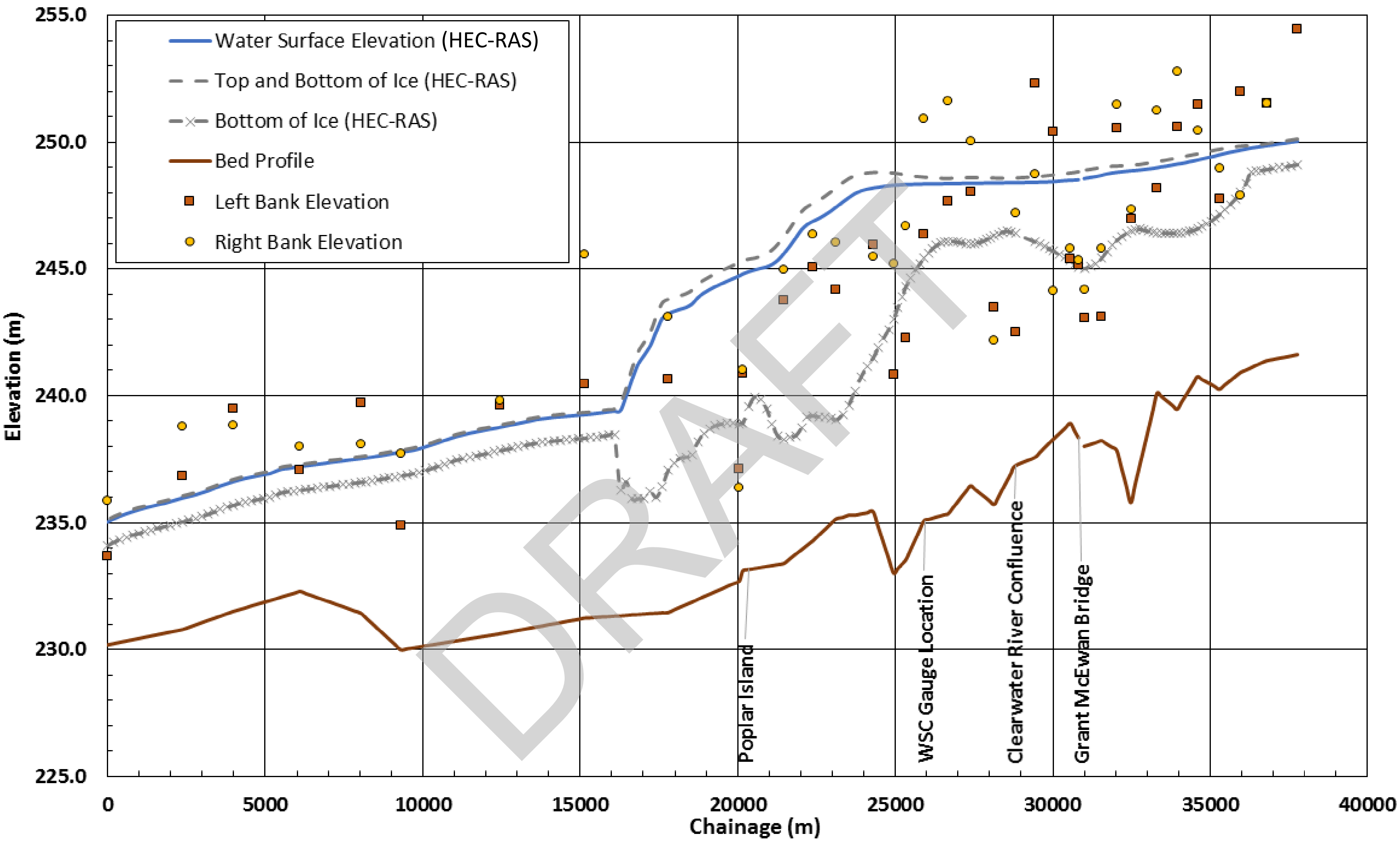

Figure 26: Ice Jam Water Surface Profile: Athabasca River 50-Yr Flood

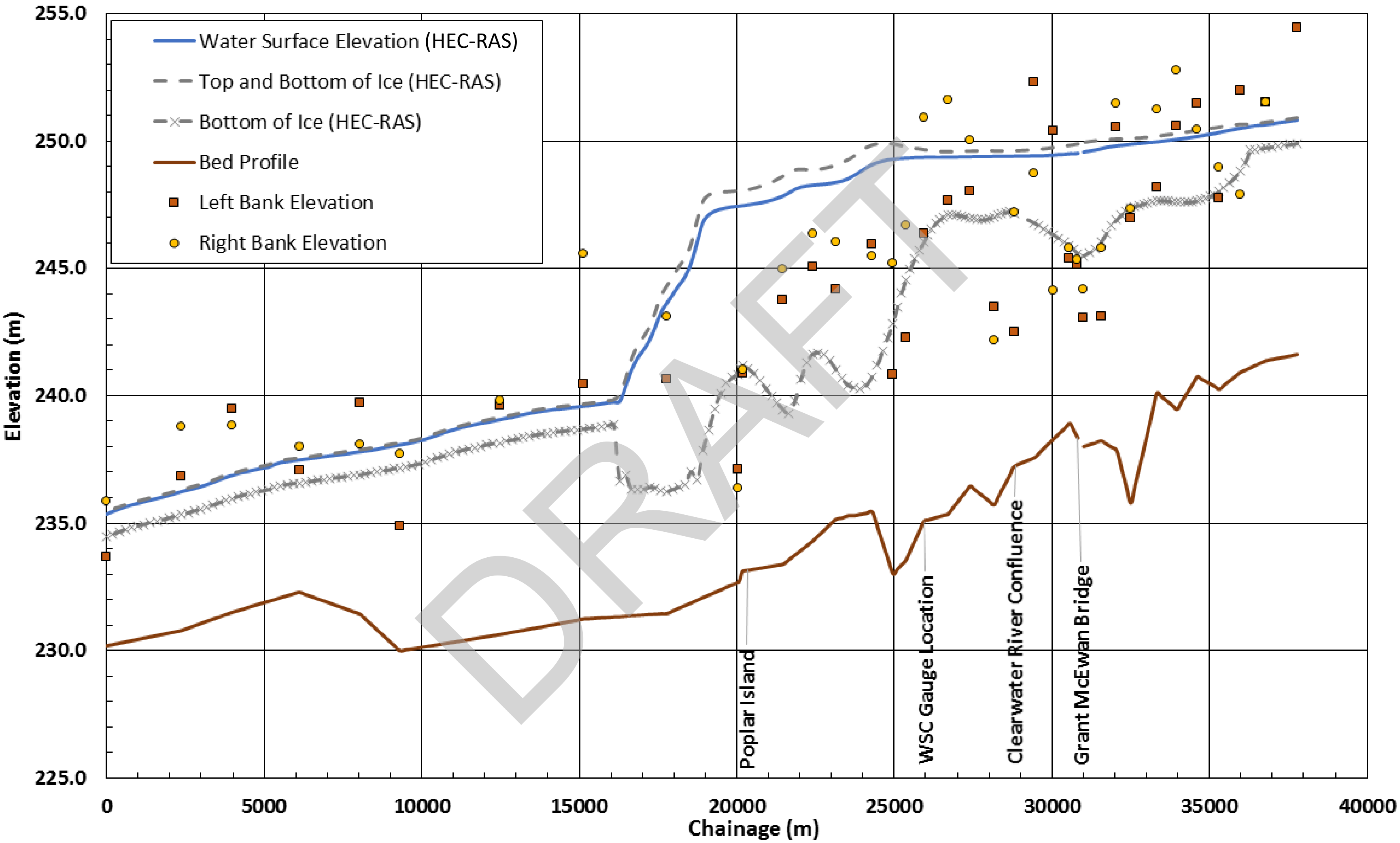

Figure 27: Ice Jam Water Surface Profile: Athabasca River 100-yr Flood

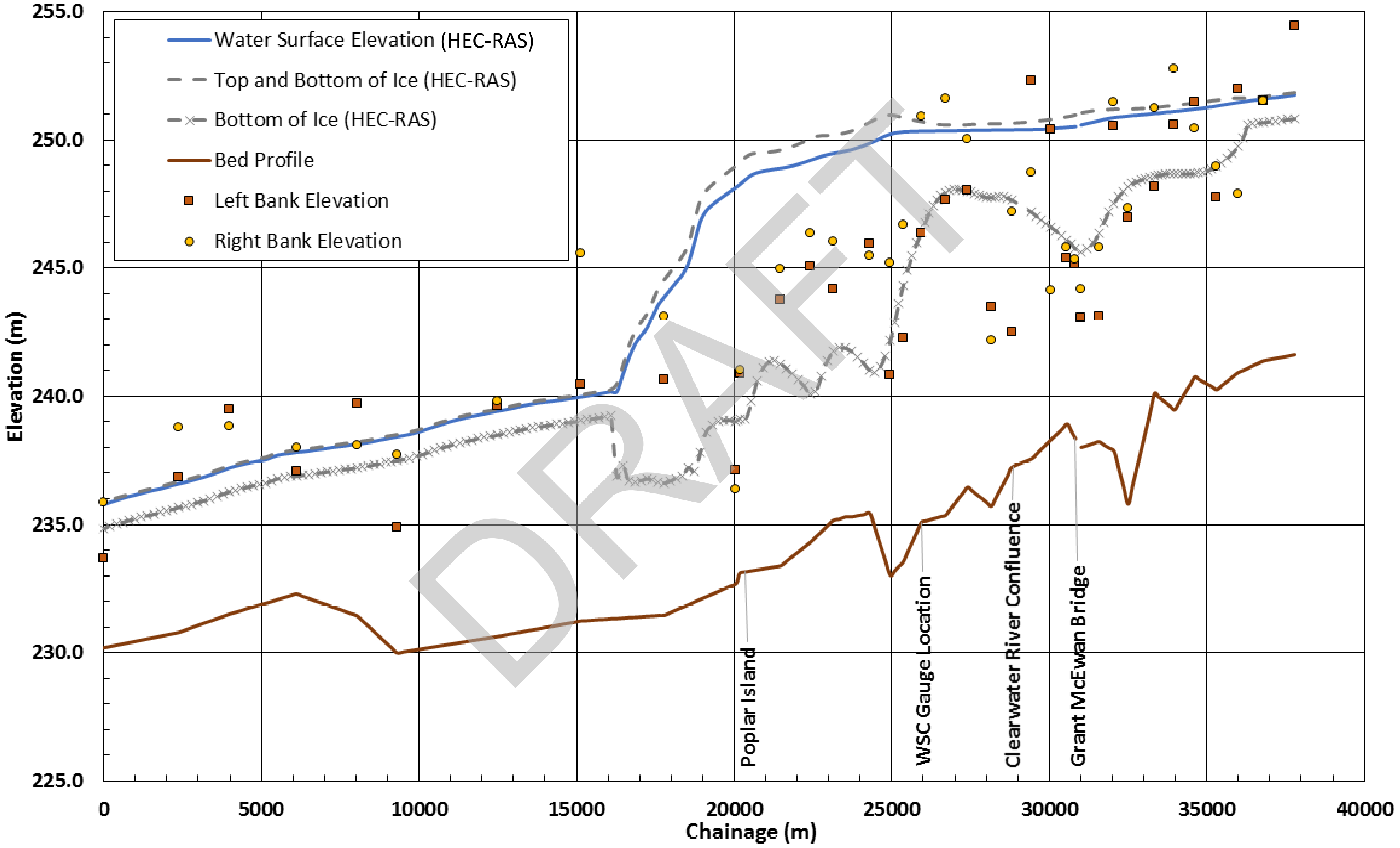

Figure 28: Ice Jam Water Surface Profile: Athabasca River 200-yr Flood

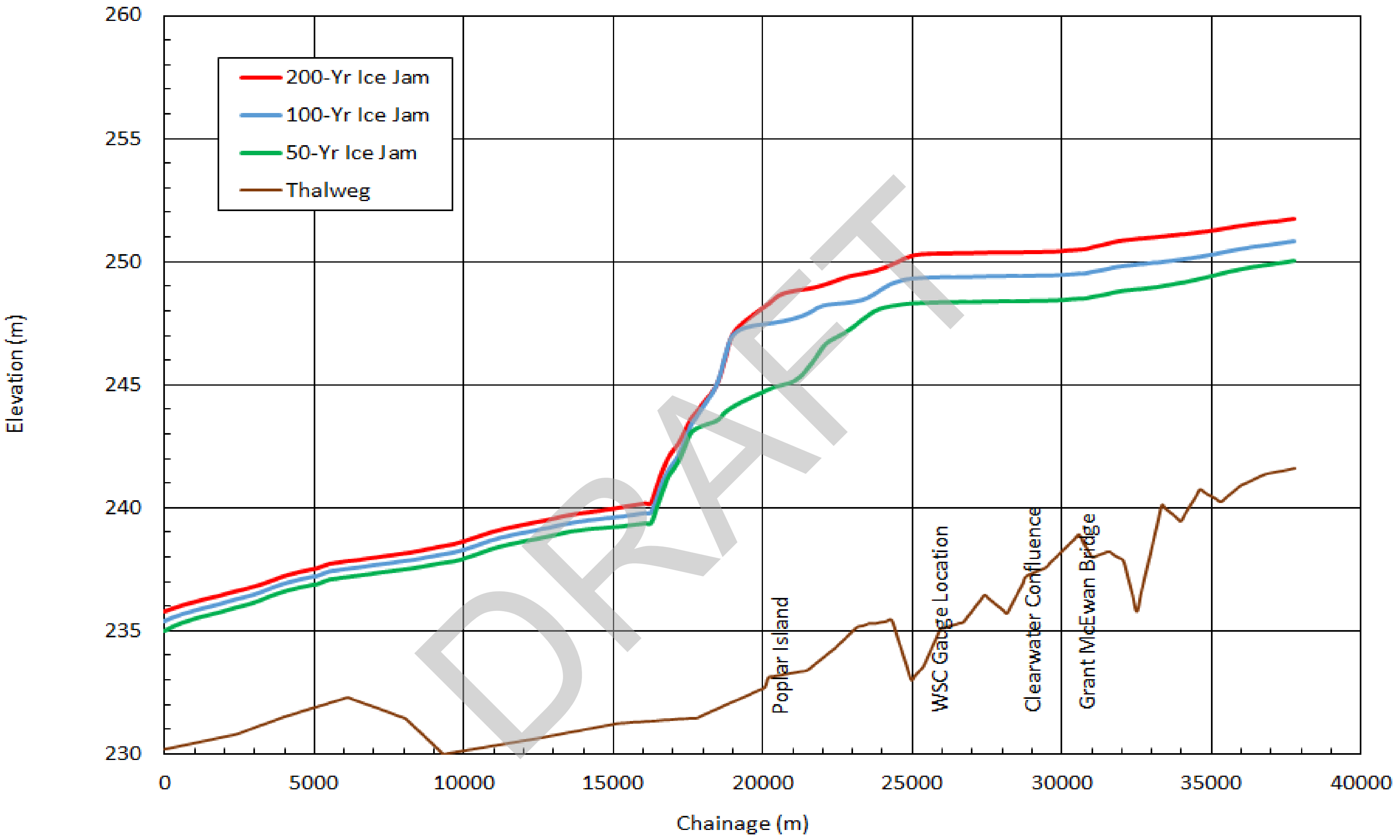

Figure 29: Comparison of Ice Jam Water Surface Profiles: Athabasca River

6.1.2 Clearwater River and Hangingstone River

Ice-related events on both the Clearwater and Hangingstone Rivers are generally decoupled from the those on the Athabasca River. Due to the more northerly and easterly location of its basin, the spring freshet in Clearwater River basin tends to occur later than that in the Athabasca River. Alternatively, because of its small basin size and proximity to the urban area of RMWB, the spring freshet on the Hangingstone River tends to occur before that on the Athabasca River. Furthermore, aufeis tends to dominate the formation of ice in the Hangingstone River, preventing its mobilization during the spring freshet. In many years, the freshet runs on top of the aufeis, melting through the deposits well after the ice has broken up on the Athabasca River.

Nevertheless, there could be the potential for high freshet flows on the Clearwater and Hangingstone Rivers to exacerbate the ice-related backwater levels generated by ice jams on the Athabasca River. Figure 24 and Figure 25, presented earlier, illustrate the range of expected coincident flows that could occur on the Clearwater and Hangingstone Rivers respectively during breakup on the Athabasca River. Table 17 and Table 18 summarize those flows for a range of salient return periods. As for the Athabasca River, the range of flow during breakup in an individual year was based on the WSC flow estimates on the day of last stable ice cover and the first day of open water.

The expected worst-case situation for Fort McMurray would be to experience simultaneous freshet flows on the Clearwater and Hangingstone Rivers with the same return period as the ice event on the Athabasca River. That is, for example,100-yr freshet flows occur simultaneously on the Clearwater and Hangingstone Rivers while a 100-yr jam is in place on the Athabasca River. Clearly, this would be a very severe event but the potential effects on water levels along the Clearwater and Hangingstone Rivers are of interest. Table 23 summarizes the three scenarios that were examined to assess the potential effects on water levels.

Table 23: Flow and Water Level Scenarios Adopted for Clearwater River and Hangingstone River

Return Period of Athabasca River Ice Event (years)	Athabasca River Water Level at Clearwater Confluence (m)	Clearwater River Discharge (m^3/s)	Hangingstone River Discharge (m^3/s)
50-yr	248.4	421	36.0
100-yr	249.4	480	44.0
200-yr	250.4	540	50.0

The Ice enhanced HEC-RAS model was used to assess the water levels along the Clearwater and Hangingstone Rivers for the three scenarios outlined above. Simulations of the Clearwater River water levels that include the presence of both solid and dynamic (i.e. mechanically thickened) ice covers indicates that the presence of either type of ice cover has no effect on water levels. The large backwater effect created on the Clearwater River by the Athabasca River ice jam results in shear stresses and velocities that are so low that a fragmented ice cover would not thicken appreciably should it occur coincidentally with the Athabasca River ice jam. Given these results, and past observations (Andres, personal communication) of unconsolidated broken ice sheets the water level simulations on the Clearwater and Hangingstone Rivers were limited to those representing a solid ice cover.

Figure 30 illustrates the results of the simulations on the Clearwater River. The backwater affects associated with the 50-yr, 100-yr, and 200-yr ice events extend well upstream of Draper without any indication of a transition towards uniform flow conditions. Clearly, the measured water level at the Draper gauge would represent the water level at the Clearwater River confluence for severe ice jam events on the Athabasca River.

Figure 31 shows similar outcomes on the Hangingstone River. However, in this case the backwater effects extend upstream of the Highway 63 bridge and into the Grayling Terrace neighbourhood before transitioning into the uniform flow profile upstream of the backwater area. Clearly, the backwater effects produced by the Athabasca River jams are sufficient to mask any adverse effects on water levels that could result from high flows on either the Clearwater or Hangingstone Rivers. There would be no need to consider the joint probabilities of high ice levels on the Athabasca River and high flows on the Clearwater and Hangingstone Rivers when evaluating the severe ice-related flood hazards.

The simulation results for each case are provided in Tables in Appendix D for each event.

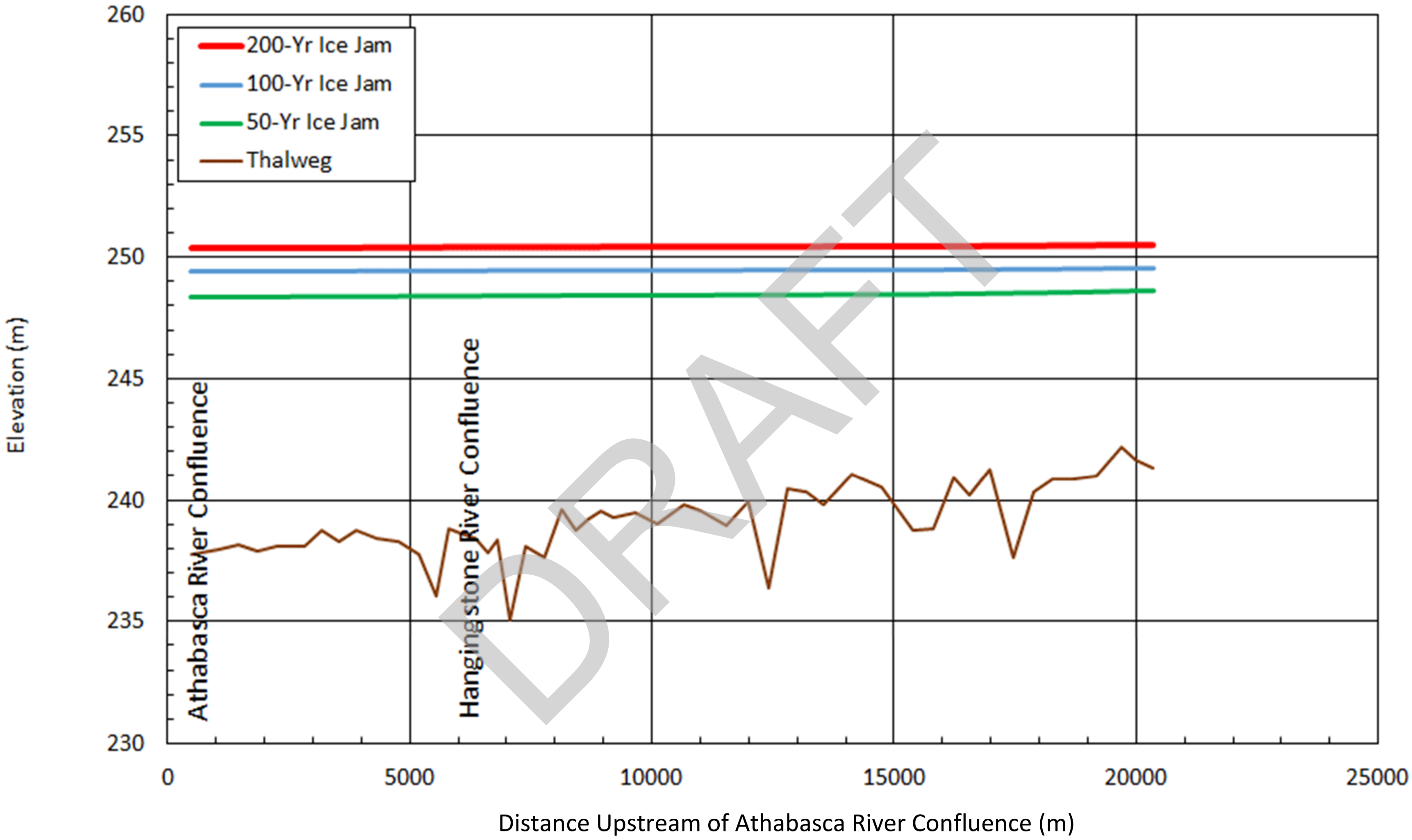

Figure 30: Comparison of Ice Jam Water Surface Profiles: Clearwater River

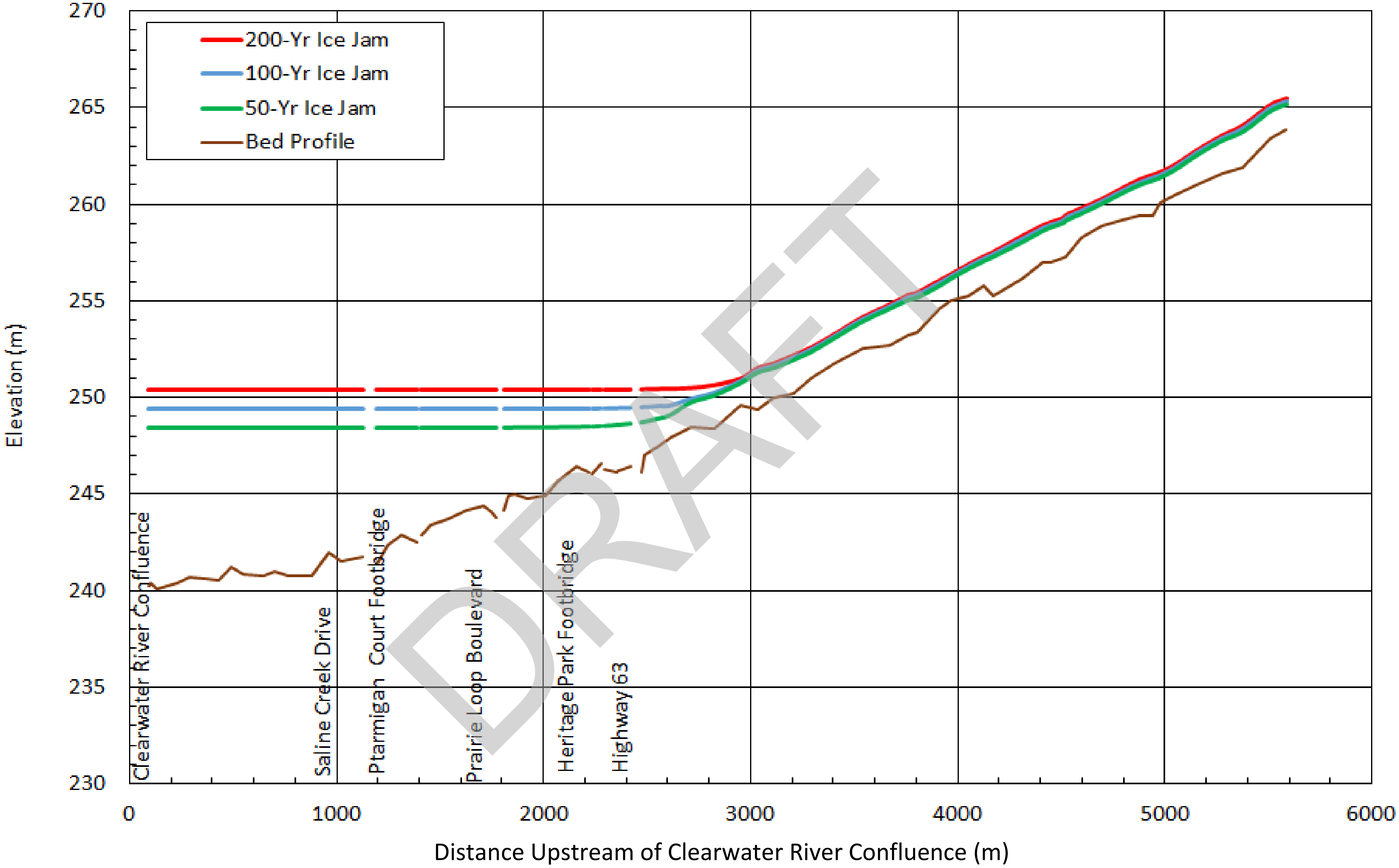

Figure 31: Comparison of Ice Jam Water Surface Profiles: Hangingstone River

6.2 Model Sensitivity Analysis

A number of simulations were undertaken to evaluate the sensitivity of the simulated water levels along the Athabasca, Clearwater, and Hangingstone Rivers to reasonable alternative values of selected ice jam parameters and initial conditions. As discussed earlier, there are three parameters that can affect the configuration (jam thickness and water level) of the ice jam that require definition: (i) bed roughness, (ii) jam roughness, and (iii) the internal strength of the ice cover. Jam characteristics are quite insensitive to changes in the dimensionless coefficient of internal friction, and little insight would be gained by assessing this parameter. Furthermore, given the relative magnitudes of the bed and jam roughness, the flow under the jam is dominated by the ice roughness. Establishing the jam roughness during calibration implicitly accounts for the bed roughness, even though it may be defined a priori on the basis of open water calibrations. From these perspectives, the jam roughness was deemed to be the most critical ice-related parameter to evaluate.

With respect to the initial conditions, the adopted location of the toe is likely the most critical assumption. Clearly, the toe should be located far enough downstream of the study reach so that equilibrium conditions are established throughout the entire reach. However, the adopted toe location should also reflect past experiences and represent the kind of local channel characteristics that could produce lodgement.

A number of sensitivity tests were undertaken to evaluate the impacts of changes in the model setup to computed water levels along the Athabasca and Clearwater Rivers. All tests were based on passage of the 100-yr event, summarized earlier. Flows remained unchanged from those used in the 100-yr jam simulation - that is:

- Athabasca River Flow Upstream of Confluence: 1600 m^3/s
- Athabasca River Flow Downstream of Confluence: 1700 m^3/s
- Clearwater River Flow: 480 m^3/s
- Hangingstone River Flow: 44 m^3/s

In total four sensitivity tests were performed:

Sensitivity Run 1: Decrease in ice cover roughness. For this test case, the ice cover roughness was decreased from the calibrated value of 0.060/0.065 to 0.050/0.055, the low end of the expected range for these types of ice jam events.

Sensitivity Run 2: Increase in ice cover roughness. For this test case, the ice cover roughness was increased from the calibrated value of 0.060/0.065 to 0.080/0.085. This upper limit is near the high end of the expected range for these types of ice jam events.

Sensitivity Run 3: Movement of ice jam toe to downstream location. For this test case, the assumed toe location of the jam was moved to a point that was approximately 3 km downstream of the base case location.

Sensitivity Run 4: Movement of ice jam toe to upstream location. For this test case, the assumed toe location of the jam was moved to a point that was approximately 4 km upstream of the base case location. This would locate the toe of the jam at Poplar Island, which has been a common toe location during past events.

The results of the sensitivity tests are shown in Figure 32 for sensitivity tests 1 and 2, and in Figure 33 for sensitivity tests 3 and 4. These results indicate the following:

- Water levels are most sensitive to the adopted jam roughness. Water levels at the Clearwater River confluence increased by 1.5 m from the calibrated base case when the jam roughness was increased and decreased by 1.0 m when the jam roughness was decreased. At the downstream end of the study domain (Poplar Island), the differences were slightly greater – levels rose by 1.8 m for the case with increased roughness and dropped by 1.1 m for the case with a decreased roughness.
- As would be expected, water levels in the study reach are not significantly affected if the toe is moved downstream because this does not change the extent of the equilibrium portion of the jam within the study reach. The simulation suggests that water levels at the Clearwater River confluence appear to increase by only 0.04 m – an insignificant amount that is most likely related to vagaries in the way the model achieves computational stability. However, water levels at the downstream end of the study domain at Poplar Island increase by about 0.14 m. This may be related to the change in the location of the zone in which the jam profile transitions from the toe region to the equilibrium portion of the jam.
- If the jam toe location is moved 4 km upstream, water levels at the Clearwater River confluence would drop by 0.23 m. However, water levels at the downstream end of the domain would drop by a larger margin – by up to 6.3 m at Poplar Island. In this scenario the toe of the jam is located within the study reach and the lower water levels at Polar Island reflect the truism that while the jam thickness is greatest in the region of the toe, the highest water levels occur within the equilibrium portion of the jam upstream of the toe. Moving the toe of the jam upstream to this location clearly defeats the purpose of the simulations.

Clearly, water levels within the study reach are affected by the adopted location of the jam toe. However, if the toe is located far enough downstream of the study reach so that the jam is at its equilibrium thickness everywhere within the reach, it should not matter where the toe is located. Any subsequent water level discrepancies associated with computational instabilities are too small to significantly affect the modelling results.

The jam roughness significantly affects the simulated water levels simply based on fundamental hydraulics, as would be expected. The adopted calibrated ice roughness still provides the best estimate of ice-related water levels in the study reach and it would be difficult to justify adopting different roughness values. The adopted roughness values have been selected, in tandem with carrier discharges in each calibration year, to best match water levels in the reach. The adoption of higher (or lower) roughness values would invalidate the model calibration results since the relative impact of one parameter (discharge or roughness) relative to the other cannot be separated easily in the field. This would make it difficult to establish a probabilistic definition of ice roughness that could be used in future risk based models.

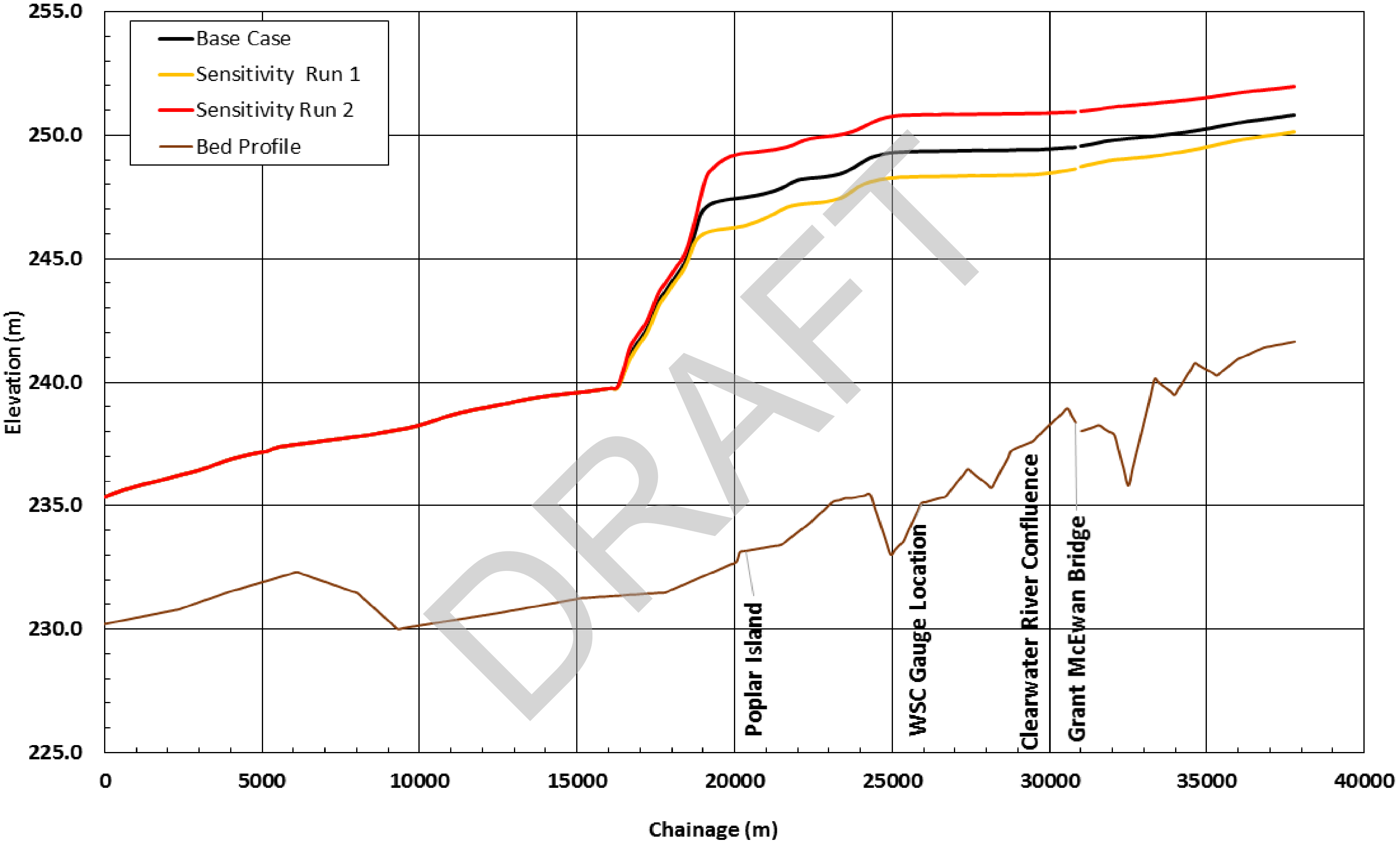

Figure 32: Athabasca River: Sensitivity Analysis- Comparison of Ice Roughness

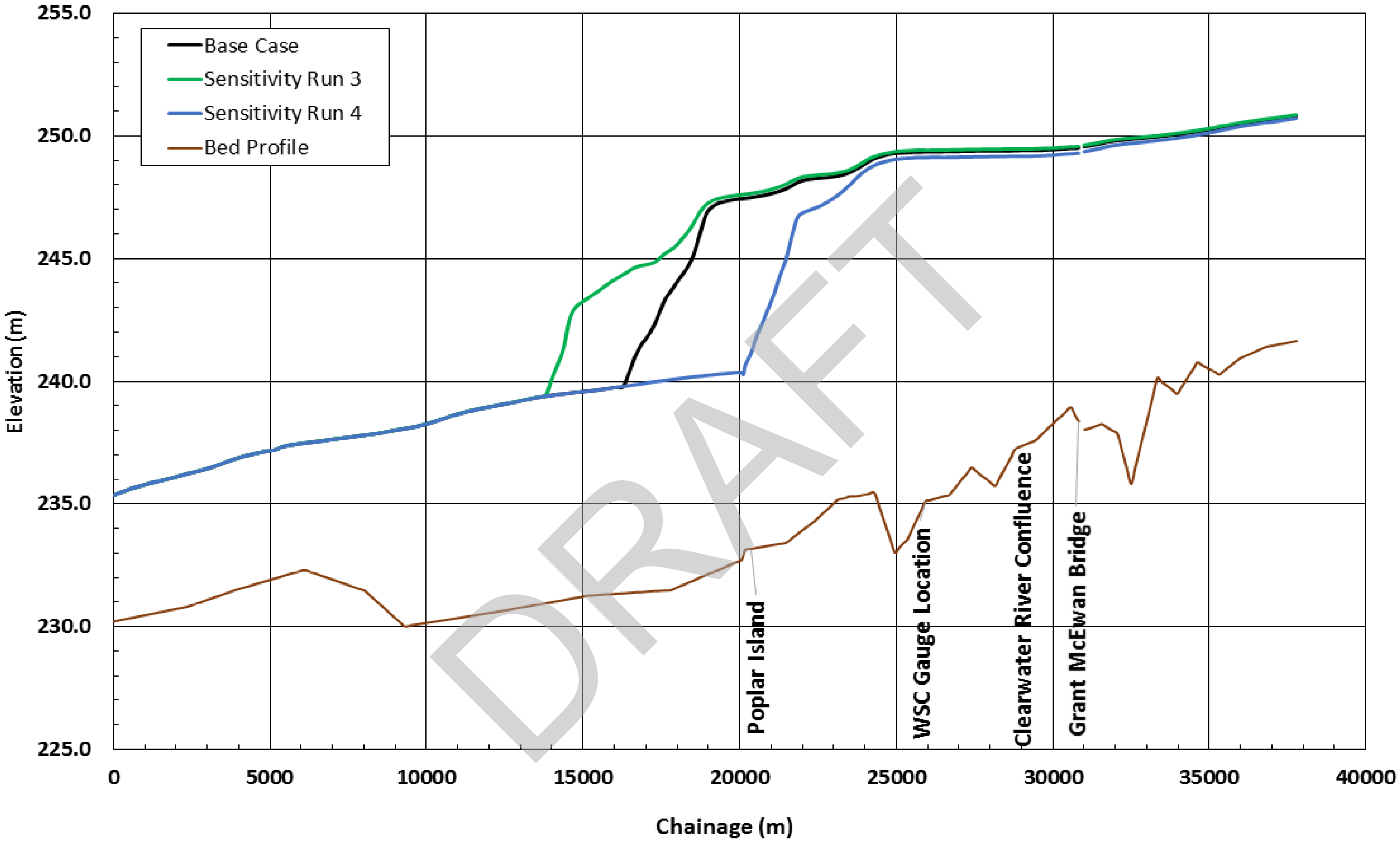

Figure 33: Athabasca River: Sensitivity Analysis-Comparison of Toe Location

7.0 SYNTHETIC ASSESSMENT USING MONTE CARLO ANALYSIS

The statistical analysis of ice-related stages shown in Figure 21 provides a good representation of historical breakup levels within the range of the measured data. Extrapolation beyond the measured range into much longer return period ranges is sometimes difficult without considering process-based arguments, due in part to the role that channel conveyance characteristics can play on limiting ice-related water levels. Furthermore, the frequency curve itself does not provide any insight into the mechanics of breakup and the factors that could contribute to a severe breakup.

However, some process-based generalizations can be made about the shape of the frequency curve. Points in the lower parts of the curve would represent a thermal-type breakup. Points in the upper part of the curve would represent outcomes from mechanical breakups when fully developed equilibrium jams form, or when only javes were experienced because local ice conditions prevented the formation of a stable jam. In other years, a combination of events likely would have produced the peak water level, and it would be difficult to unequivocally characterize the event as belonging to any specific type.

It would be desirable to conduct a fully deterministic analysis to define the expected peak breakup level in each year based on an assemblage of all the known contributing factors, but that would be difficult. However, by invoking a framework that combines considerations of both random and deterministic outcomes it is possible to verify the statistical analysis of measured ice-related water levels, to develop a better understanding of how deterministic factors might affect breakup levels, and perhaps to provide a basis to assess the limitations of the statistical analyses and/or extend it.

The characteristics of an ice jam stage frequency curve at any location along the river (with its unique hydraulic characteristics), depends on the following three main factors, each which have a likelihood of occurring each year.

1. The probability P(Q) of the carrier discharge being equalled or exceeded each year.
2. The probability P(M) of a mechanical breakup occurring each year. This would ultimately lead to an ice run. The probability of a non-mechanical or thermal breakup occurring would be 1-P(M).
3. If breakup is mechanical two outcomes are possible. One outcome, with a probability of occurrence of P(E/M), would be the formation of a fully developed equilibrium jam whose water level would be calculated from equilibrium ice jam theory as a function of the carrier discharge. This the other outcome, with a probability of P(J/M) would be a jave whose water level would reflect a jave that results from the release of an equilibrium jam that is associated with the carrier discharge.

A Monte Carlo analysis is a convenient way to examine the interrelationships between the runoff severity and breakup levels, and to assess how the likelihood of experiencing a given breakup condition affects the breakup severity from a stochastic perspective. The arguments and the analysis may also provide a framework to allow for at least a first-order appreciation of the effects of climate change on the probability of experiencing a severe breakup. The following discussion will describe the application of the Monte Carlo technique, using the historical frequency curve as a calibration tool to determine the appropriate ice state probabilities, to extrapolate the curve to the long return periods that are important in defining overall flood risks. The following ice-related data is required to undertake the analysis.

- A carrier discharge frequency curve based on measured flows at breakup that can be described statistically and that can provide a framework to calculate a long series of individual carrier discharges whose ensemble statistical characteristics match those of the measured carrier discharge.
- Ice-related rating curves that represent the three ice states: (i) thermal breakup, (ii) fully developed equilibrium ice jams, and (iii) javes that result from a release of a fully developed ice jam.
- The definition of the probability of experiencing a given ice state at breakup, that an annual probability of (i) either a thermal or mechanical breakup and (ii) if a mechanical breakup occurs either an equilibrium jam or a jave.

7.1 Carrier Discharge

As noted earlier, the carrier discharge that is responsible for a peak ice-related water level during the breakup period is difficult to determine. Even when knowing the exact time of the jam formation or the occurrence of the peak water level it is difficult to estimate the discharge due to substantial day to day changes in the rating curve as the channel transitions from having a stable, solid, and floating ice cover to a fully open water condition. Reasonable estimates of the flows during the breakup period are limited to the period just before breakup when a stable ice cover exists, and the rating curve can be inferred from the winter discharge measurements, and the period after breakup when the open water rating curve would once again apply. Between those dates, the relationship between discharge and water level can vary dramatically, depending on the characteristics of the ice cover and the presence/absence of javes. However, because the discharge increases more or less monotonically as snowmelt runoff increases, it would likely be appropriate to assume a quasi-linear variation between the last ice date and the first open water date and to discount the unsteady flows that arise from the passage of javes and from the presence of ice jams during that period. As discussed in Section 5.4, for a thermal breakup, one would expect the ice cover to be relatively stable over the breakup period until it simply vanishes, with a rather abrupt transition to the open water rating curve from an ice-affected rating curve. This would suggest that the carrier discharge for a thermal event would be more closely represented by the discharge on the first day of open water. The same could be said for a jave event. The situation is somewhat different for those years when a stable ice jam forms. The ice jam calibration exercise suggested that, on average, the carrier discharge was adequately represented by the average of the measurements taken on the date of the last stable ice cover and the first open water.

Given the intent of the Monte Carlo assessment, and considering the vagaries of ice jam processes at this site, the Monte Carlo assessment was executed based on a carrier discharge estimate represented by the WSC measurement of the discharge on the first day of open water (the upper envelope shown in Figure 23). This is considered to represent the upper limit of this discharge and was adopted to represent what is expected to be a conservatively high estimate of flood potential. Figure 34 shows frequency curves of the minimum, average, and maximum breakup flows on record, the adopted log-normal distribution for each, and a representation of the Monte

Carlo simulations of a 2000-year series of carrier discharges based on the log-normal distribution of discharge on the first day of open water. As shown, the Monte Carlo derived flows follow the traditional frequency distributions quite well. Table 24 summarizes the carrier discharge adopted for various return periods for reaches upstream and downstream of the Clearwater River. The carrier discharges adopted within the Monte Carlo assessment were based on the latter two columns in the table and are considered to represent conservative estimates of the expected carrier discharge.

Table 24: Adopted Frequencies of Carrier Discharge During Breakup at Fort McMurray

Return Period (years)	Annual probability of Exceedance (percent)	Based on First Day of Open Water	
		Flow Downstream of Clearwater River (m^3/s)	Flow Upstream of Clearwater River (m^3/s)
2	50	937	837
5	20	1420	1320
20	5.0	2110	2020
50	2.0	2580	2480
100	1.0	2950	2850
200	0.5	3340	3240

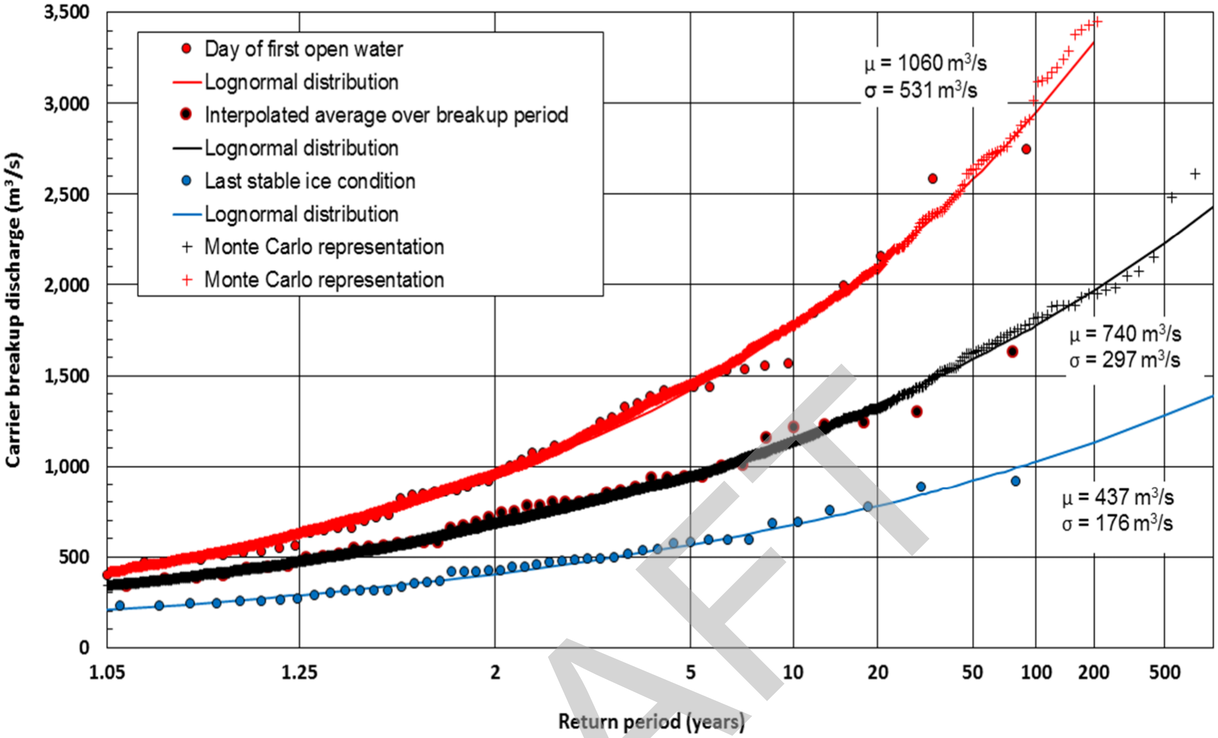

Figure 34: Frequency Curves of Carrier Discharge at Breakup: Athabasca River With Monte Carlo Simulation

7.2 Ice Related Stage-Discharge Rating Curves

As a next step, ice-related rating curves that reflect the ice states at the mouth of the Clearwater River were calculated using the calibrated Ice enhanced HEC-RAS model, and are shown in Figure 35. The calculated late winter rating curve, which represents the water level attained during a thermal breakup, is based on an adopted median late-winter ice thickness of 0.81 m, calibrated bed roughness, and a calibrated under-ice roughness of 0.01, as determined from WSC measurements near the Athabasca River-Below Fort McMurray gauge (WSC Gauge Station No. 07DA001). The equilibrium ice jam rating curve that represents water levels that would occur when a stable jam forms during a mechanical breakup is based upon the calibrated ice jam model as it pertains to the Athabasca River channel at the Clearwater River confluence. The late-winter ice thickness value of 0.81 m was selected based on an average of observations of ice cover thickness summarized in field reports associated with the five calibration/validation years.

While these two curves are relatively straightforward to develop, the procedures for defining the rating curve that is associated with a jave or self-sustaining wave that forms during a mechanical breakup are somewhat more complex. The following procedure has been adopted, using arguments presented Beltaos (2017) about the characteristics of these types of waves.

- The source of the wave is the collapse of an upstream equilibrium ice jam whose characteristics are determined by the carrier discharge and the channel properties of the reach of the Athabasca River between the jam location and the Clearwater River. The height of the equilibrium jam, as defined by the calibrated ice jam model, is related to the carrier discharge upstream of the Clearwater River confluence as shown in Figure 35.
- Upon the collapse of the jam, a self-sustaining breaking front moves downstream with only a slight amount of attenuation due to the support provided by the presence of the intact ice cover downstream of the breaking front. The height of the wave is estimated by two alternative techniques: (i) the equations provided by Henderson and Gerard (1981), as described by Beltaos (1995), whereby the height of the wave is a function of the height of the parent jam and the ratio of the jam height to the downstream depth and (ii) an idealized open water wave that results from the sudden release of a volume of water that corresponds to the profile of the parent jam upstream of MacEwan Bridge. The transient routing of this open water wave was accomplished using the calibrated Ice enhanced HEC-RAS model in a fully dynamic mode.
- The height of the resulting self-sustaining wave is added to the pre-wave water level at the Clearwater River confluence so that the ultimate height of the self-sustaining wave is a function of the height of the upstream jam, which depends solely on the carrier discharge, and the downstream water depth, which also depends on the carrier discharge. Even though the two methods are somewhat similar in that they both reflect open water wave formulations, it is surprising that they produce such similar results given the adjustments made to account for the presence of a downstream ice cover. It is evident that the mobilization of the jam produces a self-sustaining wave that is typically about 50 percent of the difference between the height of the parent jam and the downstream water level (Figure 35).

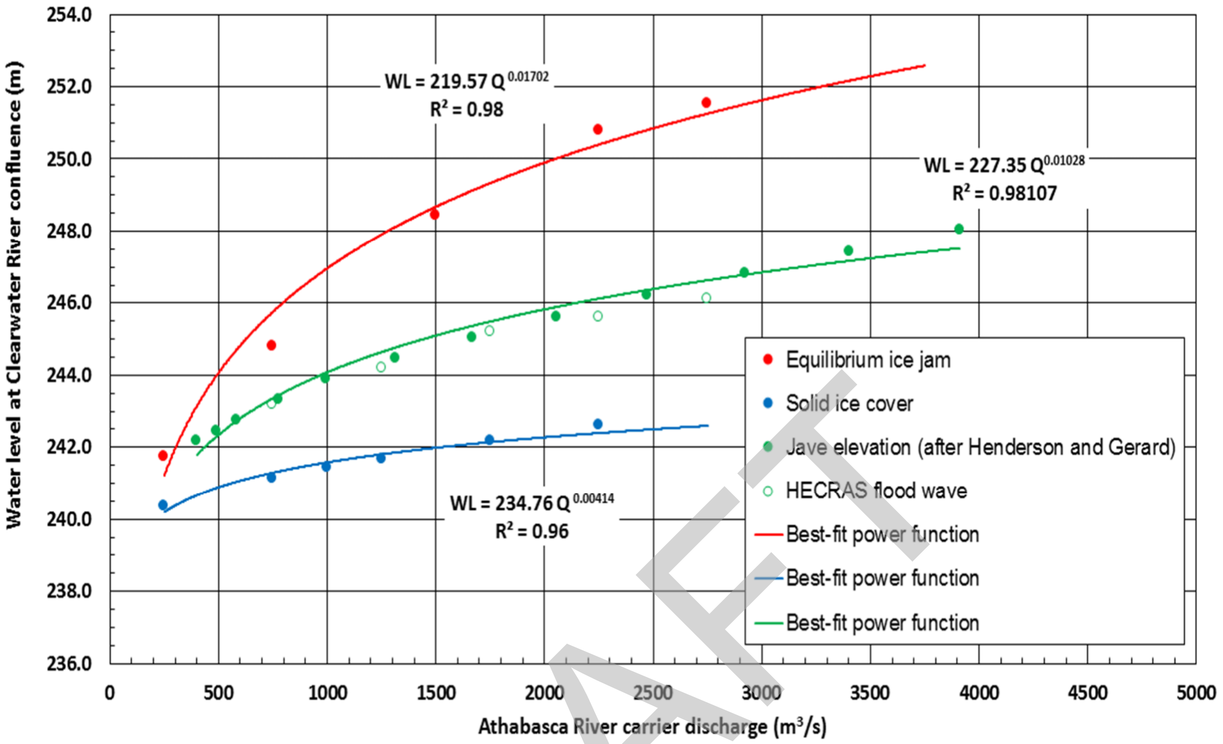

Figure 35: Simulated Rating Curves: Athabasca River at Clearwater River Confluence

7.3 Ice Breakup Type

The probability of occurrence of experiencing a mechanical breakup on the Athabasca River was estimated by interpreting the breakup record at the WSC gauge and classifying each year as either a thermal breakup or a mechanical breakup on the basis of water levels. Breakup would be classified as thermal in those years when gradual and limited water level increases are evident. In years when that is not the case, breakup was estimated as being mechanical in nature. Overall, breakup appeared to be mechanical in 21 out of 36 years of record, suggesting that as a first approximation the annual probability of experiencing a mechanical breakup, P(M) would be close to 60 percent and the probability of seeing a thermal breakup, P(T) would be 40 percent.

One would expect that the likelihood of a mechanical breakup would increase as the carrier discharge increased because higher flows would more readily tend to destabilize the ice cover causing it to fracture and mobilize. When viewed from a logistic regression perspective (Figure 36), it is evident that (i) thermal breakup is more likely to occur at carrier discharges below about 1000 m^3/s, (ii) mechanical breakup can occur at any carrier discharge, and (iii) the probability of a mechanical breakup increases as the carrier discharge increases.

Differentiating between a jave and an equilibrium ice jam situation on the basis of measured water levels when breakup is mechanical is difficult because gauge outages in many of those years prevents classification and, in some years, even stable jams are quite short-lived. In this situation the default method would be to adjust the probabilities of both a mechanical breakup occurring and an equilibrium jam forming until the shape of the observed stage-frequency curve can be reproduced by the Monte Carlo simulation.

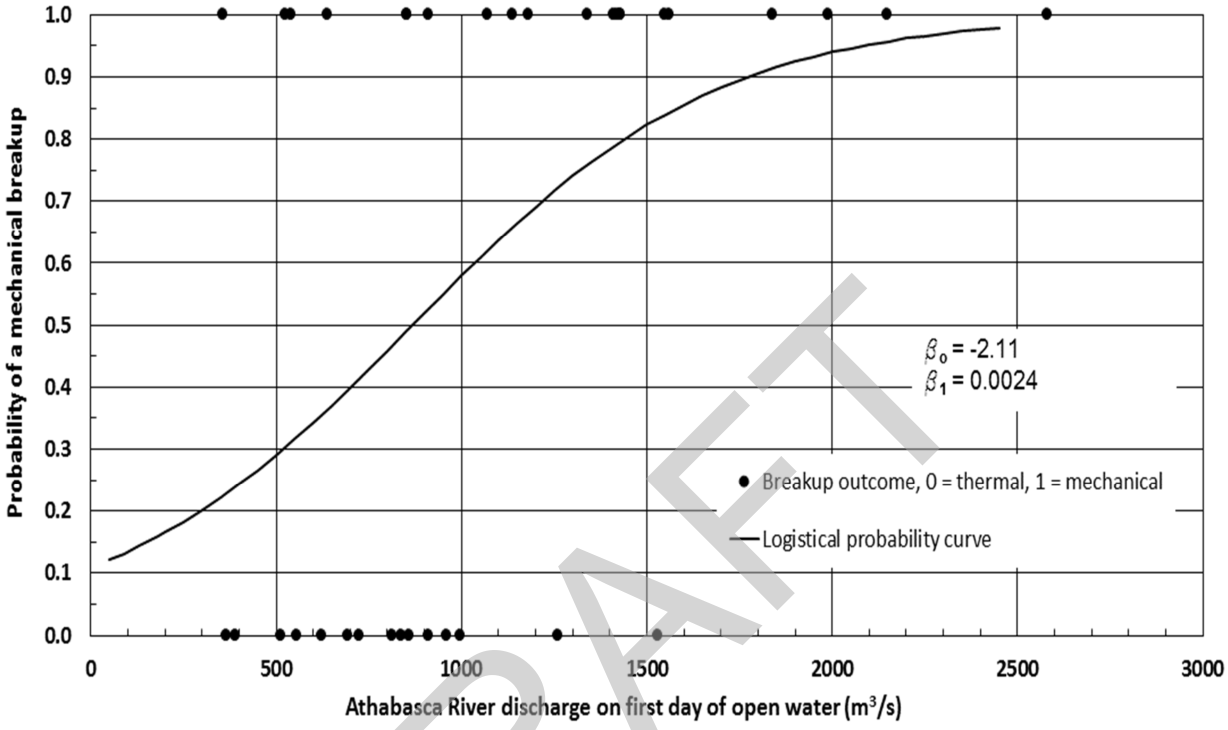

Figure 36: Logistic Regression Curve Defining Probability of Mechanical Breakup Based on Post-Breakup Flow

7.4 Simulated Ice-Related Water Level Frequency Curves

The Monte Carlo representation of the carrier discharge frequency curve shown in Figure 34 is converted into an ice jam stage frequency curve by applying a two-stage Monte Carlo transform. In the first stage, breakup is differentiated between thermal and mechanical by adopting a binomial distribution with an appropriate probability. Either P(T) or P(M) is defined, and if a thermal breakup occurs a mechanical one cannot and vice versa. If the breakup is thermal, the peak level is defined by the late-winter solid ice rating curve. If breakup is mechanical either an equilibrium jam forms or a self-sustaining wave (jave) is experienced. Again, if a jam forms a wave does not and vice versa. If a jam forms, the water level is read off the ice jam rating curve. If a self-sustaining wave occurs, the water level is determined from the jave rating curve. These transforms produce a corresponding data set of 2000 ice-related water levels that are plotted on a frequency curve, which is used directly to define the return periods of various ice-related water levels.

The various ice state probabilities are adjusted in an iterative manner to provide the best fit to the historical frequency curve, focussing on the portions of that curve in which there is the most confidence. The lower portion of the Monte Carlo frequency curve is defined by adjusting the probability of experiencing a thermal/mechanical breakup and the upper part of the curve is defined by adjusting the probability of experiencing either a jave or equilibrium jam if breakup is mechanical in nature.

The final results of the analysis are summarized in Figure 37. The results indicate that at Fort McMurray, at Clearwater River confluence, the historical ice jam frequency curve can be reproduced reasonably well (including extrapolation of the tails) with a Monte Carlo simulation if:

- it is assumed that there is an annual probability of a mechanical breakup of 54 percent (close to the 58 percent suggested by data at the WSC gauge).
- if the breakup is mechanical in nature, the annual probability of experiencing only a jave is 77 percent (probability of a fully developed jam forming would be 23 percent). Over the period of record, this is equivalent to experiencing a thermal breakup in 46 percent of the years, a jave breakup in 41 percent of the years, and a fully developed equilibrium ice jam in 13 percent of the years.

The sensitivity of the shape of the ice-related water level frequency curve to the ice state probabilities is also shown in Figure 37. There is not a significant difference in the Monte Carlo representations when P(M) is in the 0.50 to 0.57 range and P(J/M) is close to 0.77 (with P(E/M) of about 0.24). However, if P(J/M) is reduced to 0.58 and P(E/M) increased to 0.42, for example, the Monte Carlo curve begins to plot well above the historical frequency curve.

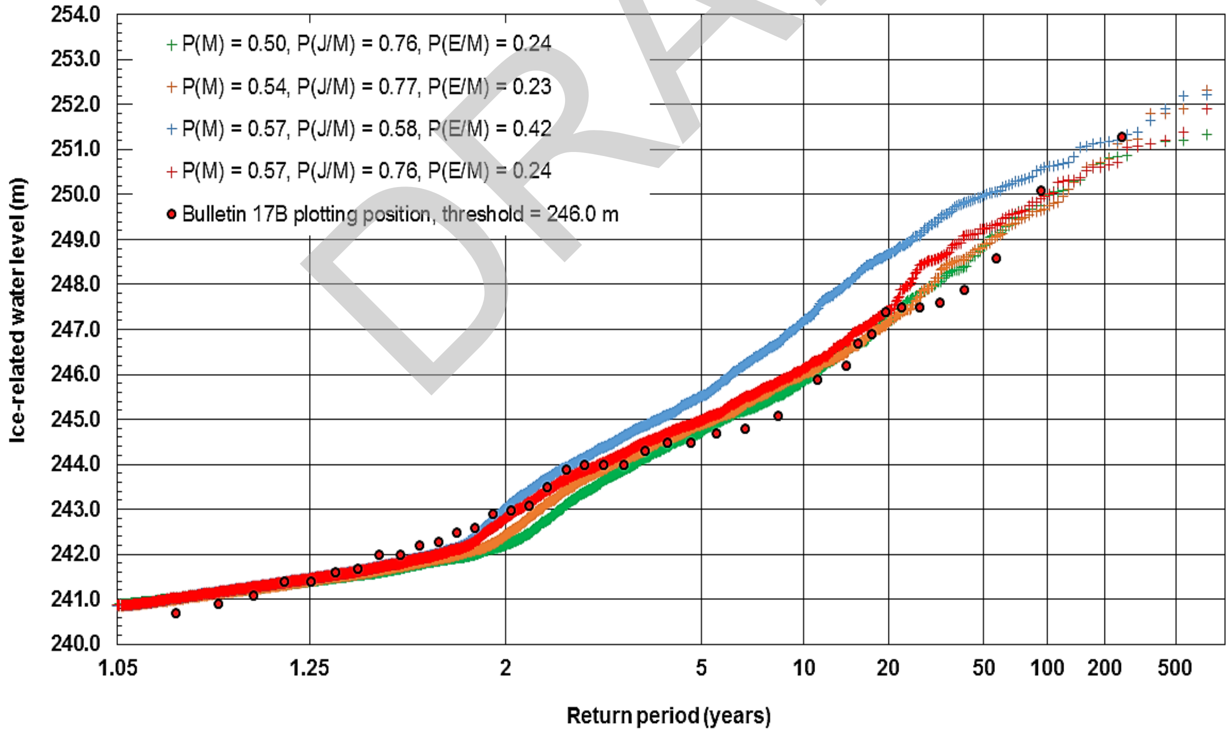

Figure 37: Frequency Curves of Maximum Ice-Related Water Levels, Athabasca River at Clearwater River Confluence

Based purely on considerations of flows at breakup, local hydraulic characteristics, and defined ice jam parameters, the Monte Carlo analysis provides a reasonable representation of the historically-based ice-related frequency curve. This adds credibility to the simple approximations that are necessary to quantify complex physical processes in order to extrapolate into areas beyond those observed in the limited historical record. Most importantly, the analysis appears to support the extrapolation of the historically-based frequency curve into the less well-defined long return periods that are beyond those represented by the bulk of the measured data but that are of most interest from a hazard perspective. Furthermore, the results of the analysis provides a mechanism to quantify how systematic changes in both the hydrologic and ice regimes due to external influences like a changing climate could affect the ice-related hazards.

7.5 Climate Change Implications

Assessing the effects of climate change on breakup severities is a complex and difficult task. The climatic and hydrologic processes that contribute to a given breakup outcome are highly interactive and produce non-linear outcomes. The implementation of the Monte Carlo technique itself requires a great deal of judgement, not to mention the difficulty in prescribing how a changing climate will affect the meteorological characteristics that drive the breakup process.

However, Monte Carlo techniques provide a path towards at least a first order differentiation of the effects that climate change could have if it systematically changes precipitation and temperature patterns. Furthermore, Monte Carlo analysis is a potential tool that can be used to quantify the sensitivity of breakup severity to imposed changes in flows and pre-breakup ice conditions.

For example, with respect to the carrier discharge, arguments could be made that the carrier discharge is related to winter snowfall, and any systematic directional changes in winter snowfall would produce corresponding directional changes in the magnitude of the carrier discharge. All else being equal, a systematic decrease in the carrier discharge would result in a reduced breakup severity, and visa versa. A systematic reduction in snowpack, combined with greater ice deterioration due to warmer spring temperatures may, on average, result in less severe spring runoffs and less ice at breakup. This could increase the likelihood of experiencing a thermal breakup and also contribute to an overall reduction in breakup severity.

Ostensibly, warmer winter temperatures would produce thinner ice covers if not offset by a reduced insulative effects due to reduced snow depths. This would likely result in a reduction in the annual probability of an ice jam forming because of the reduction in the support provided by the solid ice cover at the breaking front. Alternatively, lower flows during breakup could increase the probability of ice jams forming since lower under-ice flow depths at the breaking front would increase the probability of grounding at the breaking front.

On balance, if the consensus is that climate change in the Athabasca River will (i) reduce winter snowfall, (ii) increase winter temperatures, and (iii) increase spring temperatures, it is expected that this would be reflected by the reduction in carrier discharges as defined by P(Q), an decrease in P(M), and a decrease in P(J/M) – all of which suggest a trend towards less severe breakups and a reduction in breakup levels.

8.0 INUNDATION MAPS

8.1 Methodology

Following development of water surface profiles for the 50-yr, 100-yr, and 200-yr ice jam flood events, they were then used to generate inundation maps for these three events. The final ice jam inundation maps are contained in Appendix E of this report. These maps will be used by stakeholders to aid in emergency response planning and preparation, and were developed using the same base maps created for the open water inundation mapping suite.

Inundation maps were prepared with these base maps, which were overlain by inundation polygons that represent the extent of inundation associated with each flood scenario. The inundation limits shown were initially generated automatically using ArcMap (Version 10.3), and following this the maps were edited manually as required to best reflect the expected inundation extent. A unique water surface TIN was generated for each flood profile. This water surface 3D TIN was intersected with the Digital Terrain Model. On each map, the resultant flood inundation polygons are shown as transparent shading with a dark solid outline.

The flood inundation maps were prepared based on:

- Simulated water levels at individual cross sections for the 50-, 100-, and 200- year flood events;
- Locations and extents of individual cross sections;
- LiDAR DTM; and
- Information about permanent flood control structures.

In addition to delineating direct inundation areas, the following special inundation areas were identified for each flood event:

- Scenario 1 – Isolated Areas: These are potentially inundated areas that have no direct hydraulic or overland flow connection to the main channel, but are mapped using main channel water levels. These are typically areas of low ground, and may potentially be inundated due to unidentified culverts, groundwater connection, permeable embankments, or backup from storm sewer systems. These areas have been estimated by projecting main channel water levels into the bank areas. As shown on the mapping series, various areas along the reach are shown as being isolated.
- Scenario 2 – Single Overtopping Point: At locations where inundated areas are connected to the main channel at a single overtopping point (spill point), the inundation extent was re-evaluated using a constant water level which is equal to that at the spill point.
- Scenario 3 – Multiple Overtopping Points: If there are multiple overtopping points related to a single overflow area, the inundation extent was based on the hydraulic gradient in the main channel between the overtopping points. The inundation extent upstream of the most upstream overtopping point and downstream of the most downstream overtopping point, were evaluated using the estimated water level at these bounding spill points.
- Scenario 4 – Single Overtopping Point Causing Overtopping Downstream: Under Scenario 2, if the area behind the single overtopping location would be (after some time) completely inundated and pooled with a

constant surface water elevation similar to the water level at the spill point, this may cause a second overtopping further downstream and flow back into the main channel, because at that point the water level behind the embankment may be higher than that in the main channel. In this case, the inundation extent was re-evaluated using a linear interpolation between the water level at the upstream spill point and the ground elevation at the downstream re-entry point.

- Scenario 5 – Potential Flood Inundation due to Flood Control Structure Failure: In areas where identified flood control structures separate protected areas from the main channel, these areas are mapped and shown as flooded, based on an assumption that the flood control structure may fail. Areas in behind the flood control structure were assumed to be inundated up to the river water level calculated at the flood control structure under a non-failure condition. It should be noted that areas in behind these structures would only be shown as being inundated due to failure of the control structure if river water levels are at or above the base of the control structure (ie. they are actively impounding water).

For ice jam events, in addition to showing areas that would be directly inundated for each event (that is, areas in which the river levels directly overtop natural land), it was necessary to delineate flooding due to Scenarios 1 and 5 above. The tremendous backwater effect created by the ice jam events resulted in only small water level differences in the reach, and therefore Scenarios 2, 3, and 4 were essentially identical and covered by the direct inundation mapping series.

For each flood inundation map, these different areas are shown and differentiated within the legend by using unique shading categories. Three categories of inundation are shown on each for the 50-, 100-, and 200-yr inundation maps: Direct Inundation Extent, Isolated Areas, and Potential Flood Control Structure Failure.

8.2 Direct Flood Inundation Areas

The following general procedure was used in ArcGIS to develop the inundation extent for the three ice jam flood events:

1) Assign water levels at each section for all flood events to the cross section polyline features as attributes. The result is one polyline feature that includes the simulated water levels for all flood events.

2) Create a continuous water level surface using a Triangulated Irregular Network (TIN) between cross sections.

3) Manually adjust the water level surface TIN creation procedure in special areas, as required.

4) Convert the adjusted TIN into a water level raster with the same resolution and cell alignment as the DTM raster.

5) Subtract the DTM from the water level raster.

6) Convert the wet area into a polygon dataset. Features not directly connected to the main river channels were flagged as isolated areas (Scenario 1 above).

Inundation mapping near the mouths of relatively large tributaries was included and projected into the tributary based on the simulated water levels at the locations of the tributary mouths. This applies to Little Fishery Creek (tributary to the Athabasca River at the Fort McMurray Golf Club), Horse River (tributary to the Athabasca River), Conn Creek (tributary to the Athabasca River opposite of the Clearwater River confluence), Saprea Creek (tributary to the Clearwater River), and Saline Creek (tributary to the Hangingstone River).

As noted earlier, water surface elevation TINs for each of the 3 ice jam return period floods were also developed. The TINs were developed using results from the final flood frequency HEC-RAS model for the 50-, 100-, and 200-year floods, and were generated using standard GIS tools. The TINs are three-dimensional flood water surfaces that linearly interpolate computed flood elevations on surfaces between the model cross sections.

8.3 Indirect Flood Inundation Areas

8.3.1 Inundation of Isolated Areas

Isolated areas are potentially inundated areas that have no direct overland connection to the main river channels. These areas may be potentially inundated due to unidentified culverts, groundwater connection, permeable embankments, or backup from storm sewer systems. The extents of isolated areas are identified based on the river main channel water levels.

8.3.2 Inundation Due to Potential Flood Control Structure Failure

Inundation due to potential flood control structure failure is mapped based on main channel water levels. Isolated areas behind flood control structures are only mapped as flood control structure failure if the flood water level in the main river channel is higher than the natural ground or the toe of the control structure as shown in Figure 38.

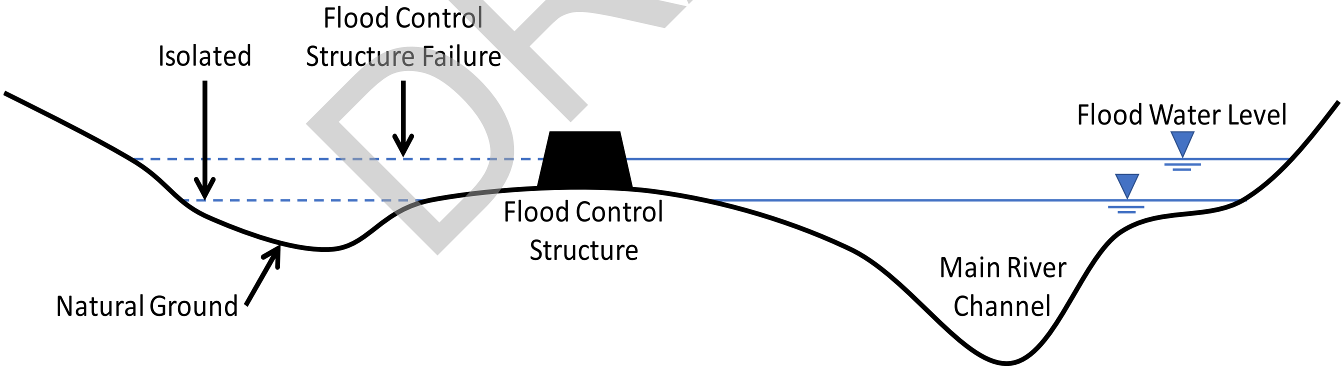

Figure 38: Illustration of Flood Control Structure Failure Inundation and Isolated Area Inundation

8.4 Areas Affected By Flooding

Following development of the inundation maps, the predicted inundation extents were used to estimate the overall impact on developed areas within the study reach for the 50-yr, 100-yr, and 200-yr ice jam flood events. This included potential flood impacts to residential areas, commercial areas, culverts and roads, and area bridges. These impacts are presented in detail in the Risk Assessment Report, but high level summaries are provided below.

8.4.1 Residential Areas Affected By Flooding

Athabasca River

- There would be no residential area affected by flooding along the Athabasca River due to ice jam floods up to the 200-year flood event.

Upper Clearwater River (Draper Area, Upstream of Park Street)

- There would be large portions of the Clearwater River floodplain which are flooded by the ice jam flood events with return periods of 50 years and higher.
- Residential properties along Garden Lane and Riverbend Close would be affected by flooding during the ice jam flood events with return periods of 50 years and higher.

Lower Townsite

- If the flood control structural failure were to occur, residential properties up to Biggs Avenue would experience flooding in the case of an ice jam flood with a return period of 50 years.
- Residential properties up to Ellis Crescent and Bennett Crescent would be flooded in the case of an ice jam flood with a return period of 100 years.
- In the case of an ice jam flood event with a return period of 200 years and higher, residential areas up to Alberta Drive would experience some form of flooding.
- Overtopping of the Hangingstone River bank would occur during ice jam floods with return periods of 50 years and higher.
- Ice jam floods up to 200 year frequency will flood residential areas up to Fraser Avenue.

Ptarmigan Court

- An ice jam flood with a return period of 50 years or higher would inundate Parkview Drive, including the Ptarmigan Trailer Park.

Waterways

- The Waterways community would be flooded past Hughes Avenue due to an ice jam flood event with a return period of 50 years or higher.

8.4.2 Commercial and Industrial Areas Affected By Flooding

Athabasca River

- Partial flooding of the Fort McMurray Golf Club would occur for an ice jam flood with a return period of 50 years and higher.
- Commercial and industrial areas along Highway 63 would experience flooding during a flood with a return period of 50 years and higher.
- Properties in the TaigaNova Eco-Industrial Park would be flooded during ice jam floods with return periods of 50 years and higher.

- Flooding of the Underground Services and Water Metering would occur during ice jam floods with return periods of 50 years and higher.

Clearwater River

- The main building of Dunvegan Gardens on Garden Lane would be inundated during ice jam floods with return periods of 50 years and higher.

Lower Townsite

- For an ice jam flood with a return period of 50 years or higher, flood control structure failure could cause flooding in the commercial and industrial areas between Prairie Loop Boulevard and Franklin Avenue.
- An ice jam flood with a return period of 100 years or higher would cause flooding in the commercial and industrial areas between Prairie Loop Boulevard and Franklin Avenue, also restricting access to the Northern Lights Regional Health Centre.
- An ice jam flood with return period of 200 years or higher will flood the commercial and industrial area up to Highway 63.
- An ice jam flood with a return period of 100 years or higher will flood the commercial and industrial area between Fraser Avenue and Saunderson Avenue.

MacDonald Island Park

- An ice jam flood with a return period of 50 years or higher would cause flooding on MacDonald Island Park.

8.4.3 Culverts and Roads Affected By Flooding

A bridge is considered to be affected by flooding when water reaches its low chord. The three bridges across the Athabasca River, which are included in the HEC-RAS model as one hydraulic structure, have a freeboard of a few meters above the flood levels for all ice jam flood events.

The lower three bridges on the Hangingstone River would be affected during the 100-year flood event. This includes the Ptarmigan Court Footbridge and the Saline Cree Drive bridge and footbridge. Flooding of the Heritage Park Footbridge would occur for return period between the 100 and 200-year ice jam flood events.

Table 25 and Table 26 present summaries of the simulated ice jam flood levels, 100-year flow velocities and clearances for the 100-year flood at the Athabasca River and Hangingstone River bridges (There are no bridges on the Clearwater River or the Snye). Also presented is the estimated flood event for which the lower chord of the bridge deck would first be impacted, creating pressure flow under the deck.

Table 25: Effects On Bridges Along the Athabasca River

Bridge Station (m)	Name	Minimum Deck Elev. (m)	Minimum Low Chord Elev. (m)	Water Level (m)			Average Flow Velocity for the 100-year ice jam flood (m/s)	(Clearance for the 100-year ice jam flood (m)	Flood event with water level exceeding the bridge low chord
				50-yr	100-yr	200-yr			
10675 (Open Water)	Three Athabasca River Bridges	256.6	253.0	248.55	249.57	250.58	0.64	3.4	> 200 years

Table 26: Effects On Bridges Along the Hangingstone River

Bridge Station (m)	Name	Minimum Deck Elev. (m)	Minimum Low Chord Elev. (m)	Water Level (m)			Average Flow Velocity for the 100-year ice jam flood (m/s)	(Clearance for the 100-year ice jam flood (m)	Flood Event with water level exceeding the bridge low chord
				50-yr	100-yr	200-yr			
2,459	Highway 63 (Southbound)	255.3	253.4	248.74	249.54	250.45	0.9	3.9	> 200 years
2,435	Highway 63 (Northbound)	255.4	253.8	248.72	249.53	250.45	0.8	4.3	> 200 years
2,284	Tolen Drive Bridge	251.9	250.6	248.55	249.47	250.43	0.7	1.1	> 200 years
2,227	Heritage Park Footbridge	252.3	250.3	248.51	249.46	250.43	0.6	0.8	100-200 years
1,791	Prairie Loop Boulevard Bridge	259.8	255.7	248.45	249.45	250.43	0.2	6.3	> 200 years
1,399	Ptarmigan Court Footbridge	247.6	247.0	248.44	249.45	250.43	0.1	-2.5	< 50 years
1,181	Saline Creek Drive Footbridge	250.0	249.0	248.44	249.45	250.43	0.2	-0.5	50-100 years
1,149	Saline Creek Drive Bridge	251.2	247.5	248.44	249.45	250.43	0.2	-1.9	<50 years

9.0 ICE JAM FLOOD HAZARD IDENTIFICATION

The ice jam flood hazard area is the area of land that will be flooded during the passage of a 100-year ice jam flood event. This flooded area has been divided into two zones: the floodway and the flood fringe, including high hazard fringe and protected flood fringe sub-zones where appropriate. Flood hazard maps can also show additional flood hazard information, including incremental areas at risk for more severe floods, like the 200-year flood. Flood hazard mapping is typically used for long-term flood hazard area management and land-use planning. The definitions of floodway and flood fringe are as follows:

- 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 areas where the water is 1 m deep or greater and the local velocities are 1 m/s or faster. Typically, the floodway includes the river channel and adjacent overbank areas. 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 land along the edges of the flood hazard area that has relatively shallow water (less than 1 m deep) with lower velocities (less than 1 m/s). 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.

9.1 Ice Jam Design Flood Selection

The ice jam design flood has been selected as the event that generates a spring water level at the Athabasca and Clearwater confluence that has a one percent chance of occurrence or exceedance every year. This is a water level with a statistical return period of 100 years. As noted earlier, the 100-year ice jam level would be generated by a spring breakup carrier discharge of approximately 1700 m^3/s. The derivation of the 100-year ice jam flood profile is described in Section 6.1 above.

9.2 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 and supplemented by the project-specific Terms of Reference, are used to delineate the floodway in such cases:

- The floodway must include the main river channel area.
- Areas where water depths exceed 1 m or flow velocities exceed 1 m/s are typically part of the floodway.
- Exceptions may be made for small backwater areas, ineffective flow areas, or to support creation of a hydraulically smooth floodway.
- 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 can include, but are not limited, to the following circumstances: (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 sub-zones are identified in all areas, whether they are newly-mapped or have a previously-defined or existing floodway. The depth and velocity criteria used to define high hazard flood fringe areas are typically aligned with the 1 m depth and 1 m/s velocity floodway determination criteria for newly-mapped areas.

All areas protected by dedicated flood control structures (e.g., flood berms) that are not overtopped during the design flood are excluded from the floodway. Areas behind flood berms will still be mapped as flooded if they are overtopped, but areas of residual risk of behind flood berms that are not overtopped are mapped as protected flood fringe sub-zones.

9.3 Ice Jam Design Flood Levels

Appendix D summarizes the design water levels for the Athabasca and Clearwater Rivers. The ice jam design levels are summarized for each cross section location, and correspond to the 100-year ice jam levels as described in Section 6.1.

9.4 Ice Jam Floodway Criteria Maps

Floodway criteria maps are a tool for documenting the basis for the location of the boundary between the floodway and flood fringe, and illustrate the following:

- the location and extent of all ice-enhanced hydraulic model cross sections;
- the inundation extent of the design flood, showing areas of dry ground;
- areas where design flood depths are 1 m or greater;
- The locations of the main channel top of bank along each model cross section;
- the proposed floodway boundary, as well as the associated floodway stations corresponding to the floodway determination criteria;
- Background aerial imagery;
- the previous floodway boundary, where it exists; and
- Roads, bridges and flood control structures.

The Floodway criteria maps were developed considering the criteria presented above. The floodway lines were digitized electronically using ArcMap tools, by inspection of the computed flood extents and water depths. It should be noted that delineation of the floodway boundary is not a fully automatic procedure, and in some cases, manual interpretation and judgement was needed to project these water levels onto the surface topography, and to ensure a smooth hydraulic transition between cross sections. In areas with existing previous floodway the existing floodway was not changed in most circumstances as described above.

The ice jam floodway criteria maps are provided in Appendix F of this report. Table 27 and Table 28 summarize the design flood level and design flood extent for the ice jam flooding respectively.

Table 27: Ice Jam Design Flood Level

River	Reach	Cross Section	River Station (Open Water)	River Station (Ice Enhanced)	Ice Jam Design Flood Level
Athabasca	Upper Reach	1	17519	36191.07	250.82
Athabasca	Upper Reach	2	16535	35207.05	250.65
Athabasca	Upper Reach	3	15716	34387.97	250.50
Athabasca	Upper Reach	4	15048	33720.57	250.34
Athabasca	Upper Reach	5	14346	33018.14	250.18
Athabasca	Upper Reach	6	13706	32378.51	250.07
Athabasca	Upper Reach	7	13071	31742.95	249.97
Athabasca	Upper Reach	8	12237	30908.92	249.87
Athabasca	Upper Reach	9	11791	30463.76	249.81
Athabasca	Upper Reach	10	11309	29980.79	249.70
Athabasca	Upper Reach	11	10747	29419.2	249.57
Athabasca	Upper Reach	12	10564	29236.7	249.52
Athabasca	Upper Reach	13	10306	28977.81	249.50
Athabasca	Upper Reach	14	9779	28451.49	249.45
Athabasca	Upper Reach	15	9174	27846.51	249.42
Athabasca	Lower Reach	16	8559	27231.06	249.41
Athabasca	Lower Reach	17	7895	26567.64	249.40
Athabasca	Lower Reach	18	7144	25816.07	249.38
Athabasca	Lower Reach	19	6438	25110.09	249.37
Athabasca	Lower Reach	20	5675	24347.35	249.36
Athabasca	Lower Reach	21	4899	23571.38	249.33
Athabasca	Lower Reach	22	4246	22918.40	249.29
Athabasca	Lower Reach	23	3083	21755.09	249.08
Athabasca	Lower Reach	24	2347	21019.67	248.38
Athabasca	Lower Reach	25	1420	20091.93	248.27
Athabasca	Lower Reach	26	129	18800.79	247.85
Clearwater	Upper Reach	27	20359	20359	249.56
Clearwater	Upper Reach	28	19986	19986	249.55
Clearwater	Upper Reach	29	19705	19705	249.55
Clearwater	Upper Reach	30	19182	19182	249.54

River	Reach	Cross Section	River Station (Open Water)	River Station (Ice Enhanced)	Ice Jam Design Flood Level
Clearwater	Upper Reach	31	18685	18685	249.53
Clearwater	Upper Reach	32	18262	18262	249.52
Clearwater	Upper Reach	33	17883	17883	249.51
Clearwater	Upper Reach	34	17460	17460	249.51
Clearwater	Upper Reach	35	16972	16972	249.50
Clearwater	Upper Reach	36	16560	16560	249.49
Clearwater	Upper Reach	37	16223	16223	249.49
Clearwater	Upper Reach	38	15826	15826	249.48
Clearwater	Upper Reach	39	15382	15382	249.48
Clearwater	Upper Reach	40	14757	14757	249.48
Clearwater	Upper Reach	41	14127	14127	249.47
Clearwater	Upper Reach	42	13537	13537	249.47
Clearwater	Upper Reach	43	13179	13179	249.47
Clearwater	Upper Reach	44	12786	12786	249.47
Clearwater	Upper Reach	45	12424	12424	249.47
Clearwater	Upper Reach	46	11985	11985	249.47
Clearwater	Upper Reach	47	11537	11537	249.46
Clearwater	Upper Reach	48	11033	11033	249.46
Clearwater	Upper Reach	49	10663	10663	249.46
Clearwater	Upper Reach	50	10095	10095	249.46
Clearwater	Upper Reach	51	9674	9674	249.46
Clearwater	Upper Reach	52	9210	9210	249.46
Clearwater	Upper Reach	53	8934	8934	249.45
Clearwater	Upper Reach	54	8679	8679	249.45
Clearwater	Upper Reach	55	8440	8440	249.45
Clearwater	Upper Reach	56	8121	8121	249.45
Clearwater	Upper Reach	57	7780	7780	249.45
Clearwater	Upper Reach	58	7396	7396	249.45
Clearwater	Upper Reach	59	7081	7081	249.45
Clearwater	Upper Reach	60	6802	6802	249.45
Clearwater	Mid Reach	61	6605	6605	249.45

River	Reach	Cross Section	River Station (Open Water)	River Station (Ice Enhanced)	Ice Jam Design Flood Level
Clearwater	Mid Reach	62	6350	6350	249.44
Clearwater	Mid Reach	63	6078	6078	249.44
Clearwater	Mid Reach	64	5806	5806	249.44
Clearwater	Mid Reach	65	5535	5535	249.44
Clearwater	Mid Reach	66	5194	5194	249.43
Clearwater	Mid Reach	67	4760	4760	249.43
Clearwater	Mid Reach	68	4324	4324	249.43
Clearwater	Mid Reach	69	3906	3906	249.43
Clearwater	Mid Reach	70	3541	3541	249.42
Clearwater	Mid Reach	71	3183	3183	249.42
Clearwater	Mid Reach	72	2815	2815	249.42
Clearwater	Lower Reach	73	2250	2250	249.42
Clearwater	Lower Reach	74	1848	1848	249.42
Clearwater	Lower Reach	75	1471	1471	249.41
Clearwater	Lower Reach	76	1043	1043	249.41
Clearwater	Lower Reach	77	480	480	249.41
Snye	Snye	78	1332	1332	249.42
Snye	Snye	79	932	932	249.42
Snye	Snye	80	456	456	249.42
Snye	Snye	81	172	172	249.42
Hangingstone	Hangingstone	82	5586	5586	265.36
Hangingstone	Hangingstone	83	5507	5507	265.01
Hangingstone	Hangingstone	84	5377	5377	263.97
Hangingstone	Hangingstone	85	5278	5278	263.47
Hangingstone	Hangingstone	86	5162	5162	262.77
Hangingstone	Hangingstone	87	5048	5048	261.95
Hangingstone	Hangingstone	88	4975	4975	261.55
Hangingstone	Hangingstone	89	4942	4942	261.42
Hangingstone	Hangingstone	90	4874	4874	261.15
Hangingstone	Hangingstone	91	4788	4788	260.7
Hangingstone	Hangingstone	92	4694	4694	260.18

River	Reach	Cross Section	River Station (Open Water)	River Station (Ice Enhanced)	Ice Jam Design Flood Level
Hangingstone	Hangingstone	93	4600	4600	259.72
Hangingstone	Hangingstone	94	4525	4525	259.36
Hangingstone	Hangingstone	95	4506	4506	259.18
Hangingstone	Hangingstone	96	4449	4449	258.98
Hangingstone	Hangingstone	97	4409	4409	258.8
Hangingstone	Hangingstone	98	4314	4314	258.27
Hangingstone	Hangingstone	99	4172	4172	257.46
Hangingstone	Hangingstone	100	4122	4122	257.21
Hangingstone	Hangingstone	101	4051	4051	256.82
Hangingstone	Hangingstone	102	3971	3971	256.33
Hangingstone	Hangingstone	103	3906	3906	255.94
Hangingstone	Hangingstone	104	3803	3803	255.35
Hangingstone	Hangingstone	105	3759	3759	255.21
Hangingstone	Hangingstone	106	3667	3667	254.73
Hangingstone	Hangingstone	107	3544	3544	254.11
Hangingstone	Hangingstone	108	3410	3410	253.26
Hangingstone	Hangingstone	109	3298	3298	252.56
Hangingstone	Hangingstone	110	3204	3204	252.11
Hangingstone	Hangingstone	111	3112	3112	251.69
Hangingstone	Hangingstone	112	3031	3031	251.44
Hangingstone	Hangingstone	113	2953	2953	250.9
Hangingstone	Hangingstone	114	2823	2823	250.29
Hangingstone	Hangingstone	115	2710	2710	249.97
Hangingstone	Hangingstone	116	2612	2612	249.63
Hangingstone	Hangingstone	117	2557	2557	249.6
Hangingstone	Hangingstone	118	2491	2491	249.55
Hangingstone	Hangingstone	119	2471	2471	249.54
Hangingstone	Hangingstone	120	2448	2448	249.53
Hangingstone	Hangingstone	121	2418	2418	249.5
Hangingstone	Hangingstone	122	2354	2354	249.48
Hangingstone	Hangingstone	123	2294	2294	249.47

River	Reach	Cross Section	River Station (Open Water)	River Station (Ice Enhanced)	Ice Jam Design Flood Level
Hangingstone	Hangingstone	124	2276	2276	249.47
Hangingstone	Hangingstone	125	2236	2236	249.46
Hangingstone	Hangingstone	126	2222	2222	249.46
Hangingstone	Hangingstone	127	2156	2156	249.46
Hangingstone	Hangingstone	128	2072	2072	249.46
Hangingstone	Hangingstone	129	2007	2007	249.46
Hangingstone	Hangingstone	130	1923	1923	249.46
Hangingstone	Hangingstone	131	1861	1861	249.46
Hangingstone	Hangingstone	132	1831	1831	249.45
Hangingstone	Hangingstone	133	1809	1809	249.45
Hangingstone	Hangingstone	134	1771	1771	249.45
Hangingstone	Hangingstone	135	1744	1744	249.45
Hangingstone	Hangingstone	136	1707	1707	249.45
Hangingstone	Hangingstone	137	1631	1631	249.45
Hangingstone	Hangingstone	138	1541	1541	249.45
Hangingstone	Hangingstone	139	1460	1460	249.45
Hangingstone	Hangingstone	140	1408	1408	249.45
Hangingstone	Hangingstone	141	1389	1389	249.45
Hangingstone	Hangingstone	142	1314	1314	249.45
Hangingstone	Hangingstone	143	1243	1243	249.45
Hangingstone	Hangingstone	144	1193	1193	249.45
Hangingstone	Hangingstone	145	1171	1171	249.45
Hangingstone	Hangingstone	146	1130	1130	249.45
Hangingstone	Hangingstone	147	1088	1088	249.45
Hangingstone	Hangingstone	148	1023	1023	249.45
Hangingstone	Hangingstone	149	960	960	249.45
Hangingstone	Hangingstone	150	882	882	249.45
Hangingstone	Hangingstone	151	769	769	249.45
Hangingstone	Hangingstone	152	701	701	249.45
Hangingstone	Hangingstone	153	648	648	249.45
Hangingstone	Hangingstone	154	549	549	249.45

River	Reach	Cross Section	River Station (Open Water)	River Station (Ice Enhanced)	Ice Jam Design Flood Level
Hangingstone	Hangingstone	155	490	490	249.45
Hangingstone	Hangingstone	156	435	435	249.45
Hangingstone	Hangingstone	157	372	372	249.45
Hangingstone	Hangingstone	158	293	293	249.45
Hangingstone	Hangingstone	159	227	227	249.45
Hangingstone	Hangingstone	160	134	134	249.45
Hangingstone	Hangingstone	161	106	106	249.45
Hangingstone	Hangingstone	162	92	92	249.45

Table 28: Ice Jam Floodway Determination Criteria and Details

River	Reach	Cross Section	River Station (Open Water)	River Station (Ice Enhanced)	Ice Jam Design Flood Level (m)	Floodway Extents		Description	
						Left Station (m)	Right Station (m)	Left Station	Right Station
Athabasca	Upper Reach	1	17519	36191.07	250.82	193.63	585.23	Inundation Extent (1)	Inundation Extent (1)
Athabasca	Upper Reach	2	16535	35207.05	250.65	185.04	613.14	Inundation Extent (1)	Inundation Extent (1)
Athabasca	Upper Reach	3	15716	34387.97	250.50	657.45	1025.15	Inundation Extent (1)	Inundation Extent (1)
Athabasca	Upper Reach	4	15048	33720.57	250.34	1737.91	2156.79	1 m Depth	Inundation Extent (1)
Athabasca	Upper Reach	5	14346	33018.14	250.18	706.34	1200.05	Inundation Extent (1)	Inundation Extent (1)
Athabasca	Upper Reach	6	13706	32378.51	250.07	453.08	928.05	Inundation Extent (2)	Inundation Extent (1)
Athabasca	Upper Reach	7	13071	31742.95	249.97	119.71	568.66	Inundation Extent (1)	Inundation Extent (1)
Athabasca	Upper Reach	8	12237	30908.92	249.87	579.06	1076.38	1 m Depth	1 m Depth
Athabasca	Upper Reach	9	11791	30463.76	249.81	583.16	996.08	Inundation Extent (2)	Inundation Extent (1)
Athabasca	Upper Reach	10	11309	29980.79	249.70	384.56	816.45	1 m Depth	Inundation Extent (1)
Athabasca	Upper Reach	11	10747	29419.2	249.57	29.87	777.51	Inundation Extent (1)	Inundation Extent (1)
Athabasca	Upper Reach	12	10564	29236.7	249.52	248.53	701.49	Inundation Extent (1)	Inundation Extent (1)
Athabasca	Upper Reach	13	10306	28977.81	249.50	936.62	936.62	Inundation Extent (1)	Inundation Extent (1)
Athabasca	Upper Reach	14	9779	28451.49	249.45	207.84	960.16	Inundation Extent (1)	Inundation Extent (1)
Athabasca	Upper Reach	15	9174	27846.51	249.42	614.12	1393.97	Inundation Extent (1)	Previous Floodway
Athabasca	Lower Reach	16	8559	27231.06	249.41	658.19	1950.00	Inundation Extent (1)	Inundation Extent (1)
Athabasca	Lower Reach	17	7895	26567.64	249.40	750.72	1959.52	1 m Depth	Inundation Extent (1)
Athabasca	Lower Reach	18	7144	25816.07	249.38	559.88	2045.64	Inundation Extent (1)	Inundation Extent (1)
Athabasca	Lower Reach	19	6438	25110.1	249.37	331.66	2156.14	1 m Depth	Inundation Extent (1)
Athabasca	Lower Reach	20	5675	24347.35	249.36	524.91	2112.28	Mixed	Inundation Extent (1)
Athabasca	Lower Reach	21	4899	23571.39	249.29	587.15	1939.86	1 m Depth	1 m Depth
Athabasca	Lower Reach	22	4246	22918.41	249.08	1058.28	2181.17	1 m Depth	1 m Depth
Athabasca	Lower Reach	23	3083	21755.1	248.38	886.81	2071.37	1 m Depth	1 m Depth

River	Reach	Cross Section	River Station (Open Water)	River Station (Ice Enhanced)	Ice Jam Design Flood Level (m)	Floodway Extents		Description	
						Left Station (m)	Right Station (m)	Left Station	Right Station
Athabasca	Lower Reach	24	2347	21019.68	248.27	795.66	2073.47	1 m Depth	1 m Depth
Athabasca	Lower Reach	25	1420	20091.93	247.85	363.77	1893.92	1 m Depth	1 m Depth
Athabasca	Lower Reach	26	129	18800.79	247.47	354.21	1927.04	1 m Depth	Inundation Extent (1)
Clearwater	Upper Reach	27	20359	20359	249.56	524.64	1003.76	1 m Depth	1 m Depth
Clearwater	Upper Reach	28	19986	19986	249.55	460.06	1102.32	1 m Depth	1 m Depth
Clearwater	Upper Reach	29	19705	19705	249.55	377.38	1243.68	1 m Depth	1 m Depth
Clearwater	Upper Reach	30	19182	19182	249.54	423.28	1385.72	1 m Depth	1 m Depth
Clearwater	Upper Reach	31	18685	18685	249.53	353.99	1519.68	1 m Depth	1 m Depth
Clearwater	Upper Reach	32	18262	18262	249.52	434.40	1718.02	1 m Depth	1 m Depth
Clearwater	Upper Reach	33	17883	17883	249.51	590.18	1813.84	1 m Depth	1 m Depth
Clearwater	Upper Reach	34	17460	17460	249.51	965.66	2114.82	1 m Depth	1 m Depth
Clearwater	Upper Reach	35	16972	16972	249.50	861.72	1984.20	Mixed	1 m Depth
Clearwater	Upper Reach	36	16560	16560	249.49	769.10	1740.90	1 m Depth	1 m Depth
Clearwater	Upper Reach	37	16223	16223	249.49	695.86	1886.95	1 m Depth	1 m Depth
Clearwater	Upper Reach	38	15826	15826	249.48	450.29	2052.52	1 m Depth	1 m Depth
Clearwater	Upper Reach	39	15382	15382	249.48	438.25	2026.73	1 m Depth	1 m Depth
Clearwater	Upper Reach	40	14757	14757	249.48	570.22	1905.05	1 m Depth	1 m Depth
Clearwater	Upper Reach	41	14127	14127	249.47	435.53	1835.00	1 m Depth	Inundation Extent (1)
Clearwater	Upper Reach	42	13537	13537	249.47	352.54	1905.40	1 m Depth	Inundation Extent (1)
Clearwater	Upper Reach	43	13179	13179	249.47	313.55	2027.79	1 m Depth	Inundation Extent (1)
Clearwater	Upper Reach	44	12786	12786	249.47	311.45	2119.69	1 m Depth	Inundation Extent (1)
Clearwater	Upper Reach	45	12424	12424	249.47	304.24	1800.77	1 m Depth	Inundation Extent (1)
Clearwater	Upper Reach	46	11985	11985	249.47	267.72	1727.00	1 m Depth	1 m Depth
Clearwater	Upper Reach	47	11537	11537	249.46	276.05	1724.48	1 m Depth	1 m Depth

River	Reach	Cross Section	River Station (Open Water)	River Station (Ice Enhanced)	Ice Jam Design Flood Level (m)	Floodway Extents		Description	
						Left Station (m)	Right Station (m)	Left Station	Right Station
Clearwater	Upper Reach	48	11033	11033	249.46	336.06	2033.08	1 m Depth	1 m Depth
Clearwater	Upper Reach	49	10663	10663	249.46	367.21	1781.01	1 m Depth	1 m Depth
Clearwater	Upper Reach	50	10095	10095	249.46	346.48	1597.60	1 m Depth	1 m Depth
Clearwater	Upper Reach	51	9674	9674	249.46	213.32	1680.01	Previous Floodway	1 m Depth
Clearwater	Upper Reach	52	9210	9210	249.46	168.27	1735.43	Previous Floodway	Inundation Extent (1)
Clearwater	Upper Reach	53	8934	8934	249.45	179.12	1841.83	Previous Floodway	Inundation Extent (1)
Clearwater	Upper Reach	54	8679	8679	249.45	202.10	1736.41	Previous Floodway	Inundation Extent (1)
Clearwater	Upper Reach	55	8440	8440	249.45	207.03	1588.89	Previous Floodway	Inundation Extent (1)
Clearwater	Upper Reach	56	8121	8121	249.45	214.47	1711.98	Inundation Extent (1)	Inundation Extent (1)
Clearwater	Upper Reach	57	7780	7780	249.45	212.73	1835.72	Inundation Extent (1)	Inundation Extent (1)
Clearwater	Upper Reach	58	7396	7396	249.45	187.33	1806.24	Previous Floodway	Inundation Extent (1)
Clearwater	Upper Reach	59	7081	7081	249.45	161.42	1675.81	Previous Floodway	Inundation Extent (1)
Clearwater	Upper Reach	60	6802	6802	249.45	484.49	1677.76	Inundation Extent (1)	Inundation Extent (1)
Clearwater	Mid Reach	61	6605	6605	249.45	451.21	1683.15	Previous Floodway	Inundation Extent (1)
Clearwater	Mid Reach	62	6350	6350	249.44	433.57	1273.82	Previous Floodway	Inundation Extent (1)
Clearwater	Mid Reach	63	6078	6078	249.44	478.76	985.60	Previous Floodway	Inundation Extent (1)
Clearwater	Mid Reach	64	5806	5806	249.44	545.72	755.56	Previous Floodway	Inundation Extent (1)
Clearwater	Mid Reach	65	5535	5535	249.44	563.71	569.90	Previous Floodway	Inundation Extent (1)
Clearwater	Mid Reach	66	5194	5194	249.43	432.38	374.69	Previous Floodway	Inundation Extent (1)
Clearwater	Mid Reach	67	4760	4760	249.43	404.61	422.33	Previous Floodway	Inundation Extent (1)
Clearwater	Mid Reach	68	4324	4324	249.43	240.36	511.90	Previous Floodway	Inundation Extent (1)
Clearwater	Mid Reach	69	3906	3906	249.43	546.49	1570.28	Previous Floodway	Inundation Extent (1)
Clearwater	Mid Reach	70	3541	3541	249.42	488.56	1656.53	Previous Floodway	Inundation Extent (1)
Clearwater	Mid Reach	71	3183	3183	249.42	988.91	1691.57	Previous Floodway	Inundation Extent (1)

River	Reach	Cross Section	River Station (Open Water)	River Station (Ice Enhanced)	Ice Jam Design Flood Level (m)	Floodway Extents		Description	
						Left Station (m)	Right Station (m)	Left Station	Right Station
Clearwater	Mid Reach	72	2815	2815	249.42	813.29	1709.53	Previous Floodway	Inundation Extent (1)
Clearwater	Lower Reach	73	2250	2250	249.42	574.23	1457.64	Previous Floodway	Inundation Extent (1)
Clearwater	Lower Reach	74	1848	1848	249.42	529.20	1289.54	Previous Floodway	Inundation Extent (1)
Clearwater	Lower Reach	75	1471	1471	249.41	187.77	1149.15	Previous Floodway	Inundation Extent (1)
Clearwater	Lower Reach	76	1043	1043	249.41	68.55	1085.08	Previous Floodway	Inundation Extent (1)
Clearwater	Lower Reach	77	480	480	249.41	n/a	688.86	No Floodway (3)	Inundation Extent (1)
Snye	Snye	78	1332	1332	249.42	35.33	360.56	Previous Floodway	Inundation Extent (1)
Snye	Snye	79	932	932	249.42	n/a	266.47	No Floodway (3)	Inundation Extent (1)
Snye	Snye	80	456	456	249.42	n/a	586.65	No Floodway (3)	Inundation Extent (1)
Snye	Snye	81	172	172	249.42	n/a	n/a	No Floodway (3)	Inundation Extent (1)
Hangingstone	Hangingstone	82	5586	5586	265.36	n/a	n/a	No Floodway (4)	No Floodway (4)
Hangingstone	Hangingstone	83	5507	5507	265.01	n/a	n/a	No Floodway (4)	No Floodway (4)
Hangingstone	Hangingstone	84	5377	5377	263.97	n/a	n/a	No Floodway (4)	No Floodway (4)
Hangingstone	Hangingstone	85	5278	5278	263.47	n/a	n/a	No Floodway (4)	No Floodway (4)
Hangingstone	Hangingstone	86	5162	5162	262.77	n/a	n/a	No Floodway (4)	No Floodway (4)
Hangingstone	Hangingstone	87	5048	5048	261.95	n/a	n/a	No Floodway (4)	No Floodway (4)
Hangingstone	Hangingstone	88	4975	4975	261.55	n/a	n/a	No Floodway (4)	No Floodway (4)
Hangingstone	Hangingstone	89	4942	4942	261.42	n/a	n/a	No Floodway (4)	No Floodway (4)
Hangingstone	Hangingstone	90	4874	4874	261.15	n/a	n/a	No Floodway (4)	No Floodway (4)
Hangingstone	Hangingstone	91	4788	4788	260.70	n/a	n/a	No Floodway (4)	No Floodway (4)
Hangingstone	Hangingstone	92	4694	4694	260.18	n/a	n/a	No Floodway (4)	No Floodway (4)
Hangingstone	Hangingstone	93	4600	4600	259.72	n/a	n/a	No Floodway (4)	No Floodway (4)
Hangingstone	Hangingstone	94	4525	4525	259.36	n/a	n/a	No Floodway (4)	No Floodway (4)
Hangingstone	Hangingstone	95	4506	4506	259.18	n/a	n/a	No Floodway (4)	No Floodway (4)

River	Reach	Cross Section	River Station (Open Water)	River Station (Ice Enhanced)	Ice Jam Design Flood Level (m)	Floodway Extents		Description	
						Left Station (m)	Right Station (m)	Left Station	Right Station
Hangingstone	Hangingstone	96	4449	4449	258.98	n/a	n/a	No Floodway (4)	No Floodway (4)
Hangingstone	Hangingstone	97	4409	4409	258.80	n/a	n/a	No Floodway (4)	No Floodway (4)
Hangingstone	Hangingstone	98	4314	4314	258.27	n/a	n/a	No Floodway (4)	No Floodway (4)
Hangingstone	Hangingstone	99	4172	4172	257.46	n/a	n/a	No Floodway (4)	No Floodway (4)
Hangingstone	Hangingstone	100	4122	4122	257.21	n/a	n/a	No Floodway (4)	No Floodway (4)
Hangingstone	Hangingstone	101	4051	4051	256.82	n/a	n/a	No Floodway (4)	No Floodway (4)
Hangingstone	Hangingstone	102	3971	3971	256.33	n/a	n/a	No Floodway (4)	No Floodway (4)
Hangingstone	Hangingstone	103	3906	3906	255.94	n/a	n/a	No Floodway (4)	No Floodway (4)
Hangingstone	Hangingstone	104	3803	3803	255.35	n/a	n/a	No Floodway (4)	No Floodway (4)
Hangingstone	Hangingstone	105	3759	3759	255.21	n/a	n/a	No Floodway (4)	No Floodway (4)
Hangingstone	Hangingstone	106	3667	3667	254.73	n/a	n/a	No Floodway (4)	No Floodway (4)
Hangingstone	Hangingstone	107	3544	3544	254.11	n/a	n/a	No Floodway (4)	No Floodway (4)
Hangingstone	Hangingstone	108	3410	3410	253.26	n/a	n/a	No Floodway (4)	No Floodway (4)
Hangingstone	Hangingstone	109	3298	3298	252.56	n/a	n/a	No Floodway (4)	No Floodway (4)
Hangingstone	Hangingstone	110	3204	3204	252.11	n/a	n/a	No Floodway (4)	No Floodway (4)
Hangingstone	Hangingstone	111	3112	3112	251.69	n/a	n/a	No Floodway (4)	No Floodway (4)
Hangingstone	Hangingstone	112	3031	3031	251.44	n/a	n/a	No Floodway (4)	No Floodway (4)
Hangingstone	Hangingstone	113	2953	2953	250.90	n/a	n/a	No Floodway (4)	No Floodway (4)
Hangingstone	Hangingstone	114	2823	2823	250.29	n/a	n/a	No Floodway (4)	No Floodway (4)
Hangingstone	Hangingstone	115	2710	2710	249.97	360.29	385.29	Inundation Extent (1)	Inundation Extent (1)
Hangingstone	Hangingstone	116	2612	2612	249.63	378.07	423.06	Inundation Extent (1)	Inundation Extent (1)
Hangingstone	Hangingstone	117	2557	2557	249.60	355.62	400.76	Inundation Extent (1)	Inundation Extent (1)
Hangingstone	Hangingstone	118	2491	2491	249.55	363.58	390.65	Inundation Extent (1)	Inundation Extent (1)
Hangingstone	Hangingstone	119	2471	2471	249.54	364.84	390.40	Inundation Extent (1)	Inundation Extent (1)

River	Reach	Cross Section	River Station (Open Water)	River Station (Ice Enhanced)	Ice Jam Design Flood Level (m)	Floodway Extents		Description	
						Left Station (m)	Right Station (m)	Left Station	Right Station
Hangingstone	Hangingstone	120	2448	2448	249.53	350.45	375.34	Inundation Extent (1)	Inundation Extent (1)
Hangingstone	Hangingstone	121	2418	2418	249.50	345.85	369.27	Inundation Extent (1)	Inundation Extent (1)
Hangingstone	Hangingstone	122	2354	2354	249.48	354.37	384.79	Inundation Extent (1)	Inundation Extent (1)
Hangingstone	Hangingstone	123	2294	2294	249.47	410.91	441.49	Inundation Extent (1)	Inundation Extent (1)
Hangingstone	Hangingstone	124	2276	2276	249.47	439.15	474.03	Inundation Extent (1)	Inundation Extent (1)
Hangingstone	Hangingstone	125	2236	2236	249.46	473.88	529.97	Inundation Extent (1)	Inundation Extent (1)
Hangingstone	Hangingstone	126	2222	2222	249.46	493.71	540.95	Inundation Extent (1)	Inundation Extent (1)
Hangingstone	Hangingstone	127	2156	2156	249.46	571.01	730.55	Inundation Extent (2)	Inundation Extent (2)
Hangingstone	Hangingstone	128	2072	2072	249.46	435.89	913.19	Previous Floodway	Inundation Extent (2)
Hangingstone	Hangingstone	129	2007	2007	249.46	474.54	256.14	Previous Floodway	Inundation Extent (2)
Hangingstone	Hangingstone	130	1923	1923	249.46	479.74	337.56	Previous Floodway	Inundation Extent (2)
Hangingstone	Hangingstone	131	1861	1861	249.46	478.23	383.64	Previous Floodway	Inundation Extent (1)
Hangingstone	Hangingstone	132	1831	1831	249.45	467.41	394.63	Previous Floodway	Inundation Extent (1)
Hangingstone	Hangingstone	133	1809	1809	249.45	471.46	386.80	Previous Floodway	Inundation Extent (1)
Hangingstone	Hangingstone	134	1771	1771	249.45	467.12	194.20	Previous Floodway	Inundation Extent (1)
Hangingstone	Hangingstone	135	1744	1744	249.45	466.01	213.10	Previous Floodway	Inundation Extent (1)
Hangingstone	Hangingstone	136	1707	1707	249.45	471.31	235.72	Previous Floodway	Previous Floodway
Hangingstone	Hangingstone	137	1631	1631	249.45	470.18	247.75	Previous Floodway	Previous Floodway
Hangingstone	Hangingstone	138	1541	1541	249.45	473.13	364.79	Previous Floodway	Previous Floodway
Hangingstone	Hangingstone	139	1460	1460	249.45	472.21	346.48	Previous Floodway	Previous Floodway
Hangingstone	Hangingstone	140	1408	1408	249.45	472.67	405.38	Previous Floodway	Previous Floodway
Hangingstone	Hangingstone	141	1389	1389	249.45	468.05	398.60	Previous Floodway	Previous Floodway
Hangingstone	Hangingstone	142	1314	1314	249.45	468.41	595.29	Previous Floodway	Inundation Extent (1)
Hangingstone	Hangingstone	143	1243	1243	249.45	467.42	565.10	Previous Floodway	Inundation Extent (1)

River	Reach	Cross Section	River Station (Open Water)	River Station (Ice Enhanced)	Ice Jam Design Flood Level (m)	Floodway Extents		Description	
						Left Station (m)	Right Station (m)	Left Station	Right Station
Hangingstone	Hangingstone	144	1193	1193	249.45	466.65	673.82	Previous Floodway	Inundation Extent (1)
Hangingstone	Hangingstone	145	1171	1171	249.45	457.40	687.01	Previous Floodway	Inundation Extent (1)
Hangingstone	Hangingstone	146	1130	1130	249.45	465.45	736.47	Previous Floodway	Inundation Extent (1)
Hangingstone	Hangingstone	147	1088	1088	249.45	481.93	780.78	Previous Floodway	Inundation Extent (1)
Hangingstone	Hangingstone	148	1023	1023	249.45	489.35	899.90	Inundation Extent (1)	Inundation Extent (1)
Hangingstone	Hangingstone	149	960	960	249.45	491.83	935.74	Inundation Extent (1)	Inundation Extent (1)
Hangingstone	Hangingstone	150	882	882	249.45	495.39	1077.27	Inundation Extent (1)	Inundation Extent (1)
Hangingstone	Hangingstone	151	769	769	249.45	492.61	1298.90	Inundation Extent (1)	Inundation Extent (1)
Hangingstone	Hangingstone	152	701	701	249.45	494.64	1296.91	Inundation Extent (1)	Inundation Extent (1)
Hangingstone	Hangingstone	153	648	648	249.45	500.32	1273.84	Inundation Extent (1)	Inundation Extent (1)
Hangingstone	Hangingstone	154	549	549	249.45	495.76	1133.57	Inundation Extent (1)	Inundation Extent (1)
Hangingstone	Hangingstone	155	490	490	249.45	492.69	1070.49	Inundation Extent (1)	Previous Floodway
Hangingstone	Hangingstone	156	435	435	249.45	487.35	1005.26	Inundation Extent (1)	Previous Floodway
Hangingstone	Hangingstone	157	372	372	249.45	485.09	970.73	Inundation Extent (1)	Previous Floodway
Hangingstone	Hangingstone	158	293	293	249.45	486.14	1024.80	Inundation Extent (1)	Previous Floodway
Hangingstone	Hangingstone	159	227	227	249.45	483.53	979.07	Previous Floodway	Inundation Extent (1)
Hangingstone	Hangingstone	160	134	134	249.45	452.17	977.47	Previous Floodway	Inundation Extent (1)
Hangingstone	Hangingstone	161	106	106	249.45	492.44	1001.72	Previous Floodway	Inundation Extent (1)
Hangingstone	Hangingstone	162	92	92	249.45	467.18	1023.44	Inundation Extent (1)	Inundation Extent (1)

Notes:

1) *No viable flood fringe*
2) *Floodway set at interior inundation extent, no viable interior flood fringe*
3) *No floodway station because edge of inundation is outside of cross section extent*
4) *No floodway station because ice jam is not applicable for the upstream reach of the Hangingstone River*

9.5 Areas in the Floodway

The following areas are in the floodway:

- The main channels of the Athabasca, Clearwater and Hangingstone Rivers and the Snye.
- Approximately 2.8 km of the downstream end of the main channel of the Horse River.
- All islands in the Athabasca River main channel.
- Major parts of the undeveloped low-lying Clearwater River floodplains on the right (north-east) side of the river.
- Major parts of the low lying Clearwater River floodplains on the left (south-west) side of the river upstream of the Hangingstone confluence.
- Areas beyond the flood control structure, between Saline Creek Drive and Cliff Avenue (Clearwater River)
- The confluence area of the Hangingstone River.
- Fort McMurray Lower Townsite Area between the Prairie Loop Boulevard and Franklin Avenue.

9.6 Areas in the Flood Fringe

The following areas are identified to be in the flood fringe:

- Limited low-lying floodplain areas along the Athabasca River.
- Parts of the Clearwater River floodplain on both sides of the river including large portions of the properties along Garden Lane.
- Large portions of downtown Fort McMurray near the Hangingstone and Clearwater confluence (Lower Townsite), between Franklin Avenue and Tolen Drive. Portions of the Fort McMurray Heritage Village lie within the high hazard flood fringe, along with the Syncrude Sport and Wellness centre.
- Areas of downtown Fort McMurray, between Gordon Avenue and Fraser Avenue.
- Major parts of the McDonald Island and its facilities. Portions of Shell Place lie within the high hazard flood fringe.
- Limited low-lying floodplain areas along the Hangingstone River upstream of the Memorial Drive Bridges (Highway 63).
- Heritage Park.

10.0 ICE JAM FLOOD ELEVATION GRIDS

Water surface elevation grids and flood depth grids were also prepared for each flood event and provided with the GIS deliverables. For each of the flood events the following GIS data has been provided:

- Inundation polygons;
- Flood water level triangulated irregular network;
- Flood water level raster; and
- Flood water depths raster.

These products are a convenient and effective tool for communicating flood severity. They are commonly used by the United States Federal Emergency Management Agency (FEMA) to identify flood risk and provide additional information that can be used to visualize, understand, and communicate the depth of flooding within a study area. They can also provide valuable input to comprehensive risk assessments. Model results were post processed to define inundation elements such as extent, elevation and flood depth.

In order to do so, model geometry (cross sections, levees, etc.) was imported into ArcGIS and using the water surface elevation associated with each cross section, a Triangulated Irregular Network (TIN) surface of the flood level was created. The flood depth grid dataset was created using tools available within ArcMap to (1) convert flood water surface elevation TINs into a raster format which led to the production of a water surface grid and (2) "subtract" the DTM raster from these water surface rasters to estimate a resulting flood depth grid raster.

Separate ArcGIS 10.3 compatible raster files were completed for each of the 50-, 100- and 200-yr ice jam events.

The final grid cell size (resolution) for these plots was set to be identical to that of the DTM, and has an estimated 0.50 m pixel size. This size was selected to ensure that all grids have a consistent cell size and orientation.

11.0 SUMMARY AND CONCLUSIONS

Ice jam analyses have been completed for the Fort McMurray River Hazard Study. The primary purpose of this component of the study has been to assess and identify ice jam related river and flood hazards along the Athabasca River, the Clearwater River (including the Snye), and the Hangingstone River through Fort McMurray. The study results and conclusions are summarized below:

- The study began with a review and assessment of past historical ice events. The review showed that ice related events have long been a part of the flood history in Fort McMurray, with major events occurring in 1875, 1885, 1928, 1936, 1977, 1978, 1987, 1996, and 1997 to name a few. A specialized review was conducted of the 1875 event, the largest ice related event to have occurred since records were kept. The review concluded that the recorded descriptions of the 1875 event were believable and that estimated water levels were credible. It has therefore been included in all frequency based estimates performed in the current study.

- Frequency based assessments of ice affected spring water levels on the Athabasca River were also completed. The assessment began with the development of a continuous and consistent water level record at the Clearwater River confluence, and was followed by application of frequency analysis techniques to develop probabilistic estimates of the expected water levels. Available water level data in the reach is summarized in Table 1 of this report. This table gathers and summarizes measured and estimated water levels in the reach from years as early as 1875, and as recent as 2017. Table 19 provides a summary of the frequency based results, and shows recommended water levels for ice related events with various return periods. Of significant note, the analysis indicates that the 1875 flood would be about a 300-year event, and that the most recent large floods – 1977 and 1997 – would both be about 30-year events. The 100 year event would result in a water level of elevation 249.4 m at the confluence of the Athabasca and Clearwater Rivers.
    - A frequency based assessment was also performed on estimated river flows at the time of breakup on the Athabasca River. The review noted that there is considerable uncertainty in the determination of a carrier discharge at breakup since reasonable estimates of the flows during the breakup period are limited to the period just before breakup when a stable ice cover exists, and the period after breakup when the open water rating curve would once again apply. Using insight gathered during the calibration phase of the ice enhanced HEC-RAS model, it was judged that use of an average of these two flows would provide the best estimate of the spring breakup discharge. Table 29 below summarizes the resulting frequency based estimate of spring breakup discharge.

Table 29: Summary of Breakup Discharge

Return Period (years)	River Flow (m^3/s)		
	Athabasca River below Clearwater Confluence	Clearwater River	Hangingstone River
2	680	170	6
5	965	245	13
10	1155	300	20
20	1340	350	26
50	1590	420	36
100	1770	480	44
200	1970	540	50

- The open water HEC-RAS model was enhanced to simulate ice conditions within the study reach, and subsequently calibrated to three recent ice events for which suitable historical data exists (1986, 1987, and 1996). The model was then successfully validated against two additional ice events in 1978 and 1979. The calibrated model was considered suitable and ready for use in simulating a range of ice jam events.

- Following calibration of the numerical model, and the completion of the water level frequency assessment, additional analyses were undertaken to predict the levels associated with the 50-yr, 100-yr, and 200-yr ice jam flood events. The calibrated model was used in conjunction with the frequency-based water level estimates to simulate a corresponding ice-related water surface profile throughout the study reach for the 50-, 100-, and 200-year ice jam flood events. To do so, the carrier discharge in the model was adjusted through an iterative process until the calculated water level at the Clearwater Confluence exactly matched the frequency based levels. This provided a realistic ice profile for each event that also matched the frequency based water level estimate at the Athabasca/Clearwater confluence. It was interesting to note that for all cases, the final flow needed in the HEC-RAS model to match the confluence water level was actually within 1 to 8 percent of the independently calculated frequency based flow estimates summarized in Table 22 above. This close match provides confidence in the estimated flood frequency profiles, given that two relatively independent techniques were used to establish ice jam flood potential, and both methods provide very consistent and similar results.
- Sensitivity tests were performed to evaluate the impact on simulated water levels along the Athabasca, Clearwater, and Hangingstone Rivers if reasonable alternative values of ice jam parameters and initial conditions were selected. The results found that the ice impacted water levels were most sensitive to changes in the adopted roughness parameter. Water levels at the Clearwater River confluence increased by 1.5 m from the calibrated base case when the jam roughness was increased and decreased by 1.0 m when the jam roughness was decreased. At the downstream end of the study domain (Poplar Island), the differences were slightly greater – levels rose by 1.8 m for the case with increased roughness and dropped by 1.1 m for the case with a decreased roughness.
- The calibrated ice enhanced HEC-RAS model and the LiDAR DTM provided a good basis for simulating the flood levels and preparing inundation maps for the 3 ice related flood events (i.e., 50-, 100-, and 200-year floods), including direct flood inundation areas and other indirect flood inundation areas. Based on the simulation results, the main areas to be affected by ice affected flooding have been identified as follows:
    - There would be no residential flooding along the Athabasca River. However, there would be large portions of the Clearwater River floodplain affected by ice jam flood events with return periods of 50 years or higher, leading to significant residential flooding;
    - For the case of an ice jam flood event with a return period of 200 years (the largest return period considered in this study), residential areas up to Alberta Drive would experience some form of flooding in the Lower Townsite.
    - An ice jam flood event with a return period of 50 years or higher would result in flooding of commercial and industrial areas along Highway 63, properties in the TaigaNova Eco-Industrial Park, and flooding of the Underground Services and Water Metering.
    - An ice jam flood with a return period of 100 years or higher would cause flooding in the commercial and industrial areas between Prairie Loop Boulevard and Franklin Avenue, also restricting access to the Northern Lights Regional Health Centre in the Old Townsite. An ice jam flood with return period of 200 years or higher will flood the commercial and industrial area up to Highway 63 in this area.

  - Bridges on the Athabasca River are high enough that their bridge decks would not be impacted by ice events with a return period of 200 years. However, a number of bridges on the lower Hangingstone River would begin to experience pressurized flow for ice jam related events with return periods of 50 years or higher.

- Finally, floodway criteria maps were prepared for the study reach in accordance with all Provincial standards. The maps illustrate the location of the floodway boundaries corresponding to the 100-year ice jam event. The floodway criteria maps were developed considering two main criteria: areas in which flow depths exceed 1 m and the location of the previous floodway.

Report Signature Page

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APPENDIX A

1875 ICE JAM FLOOD ASSESSMENT REPORT

Golder Associates Ltd.

Fort McMurray River Hazard Study

Report on 1875 Ice Jam Flood Assessment

04-08-2017	D	Final	S. Zare	J. Groeneveld D. Andres	B. Alinejad	
Date	**Rev.**	**Status**	**Prepared By**	**Checked By**	**Approved By**	**Approved By**
HATCH						**Client**

Executive Summary:

The 1875 flood event is the largest ice event in recorded history on the Athabasca River at Fort McMurray. The event was noted to have occurred in late April, and produced a peak water level at the Hudson's Bay Company (HBC) post that has been estimated to be between el. 251.5 m (825 ft.) and 253.0 m (830 ft.) (Blench, 1964). Given the considerable influence that this event can have on flood frequency estimates for the long return periods, this review was undertaken to look more closely into this event to better understand the context for this flood, to assess the overall plausibility of an ice jam producing these high levels, and to provide a best estimate of the resulting water level at the confluence of the Athabasca and Clearwater Rivers using independent and modern analyses.

The review was conducted based on available historical documentation, and through application of the HEC-RAS model to simulate the physical processes associated with a flood of this magnitude. The findings included:

- The HBC post in 1875 was likely located near the right abutment of the current McEwan Bridge.
- The 1875 flood event is indeed plausible and should not be discounted. It is estimated that the level was likely to be el. 252.5 m at the Fort location. Water levels at the Clearwater confluence were likely to be approximately 0.5 m lower than this, or el. 252.0 m.
- A numerical ice model (HEC-RAS) was applied to determine if the river bathymetry/geometry, and present day ice mechanics, would support observations of such high ice driven levels. The results suggest that flows of 2500 m^3/s with an ice roughness of 0.085 would be sufficient to create the levels estimated for the 1875 event.

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1. Introduction

1.1 General

Alberta Environment and Parks (AEP) retained Golder Associates Ltd. (Golder), in collaboration with SG1 Water Consulting Ltd. (SG1) and Hatch Ltd. (Hatch), in September 2016 to conduct the Fort McMurray River Hazard Study. The primary purpose of the study is to assess and identify river and flood hazards along the Athabasca River, the Clearwater River (including the Snye), and the Hangingstone River through Fort McMurray, AB in the Regional Municipality of Wood Buffalo (RMWB).

The study is being completed under the provincial Flood Hazard Identification Program (FHIP). The goals of this program include enhancement of public safety and reduction of future flood damages through the identification of river and flood hazards. Project stakeholders include the Government of Alberta, the RMWB, and the public.

This memorandum report documents the methodology and results of the 1875 Ice Jam Flood Assessment, which is part of the ice jam flood assessment component of the study. The assessment was conducted in consultation with Mr. David Andres, who provided invaluable guidance and input to the assessment.

1.2 Context

The 1875 flood event is the largest ice event in recorded history on the Athabasca River at Fort McMurray. The event was noted to have occurred in late April, and produced a peak water level at the Hudson's Bay Company (HBC) post that has been estimated to be between el. 251.5 m (825 ft.) and 253.0 m (830 ft.) (Blench, 1964). Given the considerable influence that this event can have on flood frequency estimates for the long return periods, it was necessary to look more closely into this event to better understand the context for this flood, to assess the overall plausibility of an ice jam producing these high levels, and to provide a best estimate of the resulting water level at the confluence of the Athabasca and Clearwater Rivers using independent and modern analyses. This was done through a two-step process:

- A review of historical and archival documents.
- A forensic assessment using the HEC-RAS computer model to simulate ice jam levels for a range of plausible flows during breakup.

The results of each step are briefly summarized below.

2. Historical Review

As a first step in the assessment, the team reviewed existing anecdotal observations and quantitative information on the flood event. Between the dates of February 16 and 17, 2017, a literature and archival review was performed at the HBC Archives in Winnipeg, Manitoba to search for anecdotal evidence supporting claims of ice jam floods at Fort McMurray in 1875. Results of a literature and archival review performed previously are contained in Appendix A of the 1964 Blench report. Portions of this appendix are reproduced in Appendix B of this report.

The objectives of the current review were to:

- Better understand the antecedent conditions that preceded the flood event, including any information on any significant meteorological events that may have contributed both to spring flows and strength/thickness of the ice floes that comprised the jam;
- Decipher the important causes or contributing factors to the actual event, like the nature of the winter ice cover, the breakup process upstream, and the extent of the ice jam (toe location, etc.);
- Determine/confirm the location of the HBC trading post in 1875;
- Produce an independent estimate of the peak elevation of the flood within the context of the available information, and compare this to previous estimates that have established the elevation of that flood event to be between el. 251.5 m and 253.0 m.

The two best sources of data for the actual event were found to be the 1964 Blench report and the records held at the HBC Archives in Winnipeg. The results of this literature review are summarized below.

2.1 Location of HBC Post in 1875

Over the course of its existence, the HBC post at Fort McMurray has been built and rebuilt in several different locations. According to the Fort McMurray Heritage Society, the original location of the post in 1870 was on the north/east side of the Clearwater River at its confluence with the Athabasca River opposite of MacDonald Island on a point referred to today as Peden's Point. It is understood that after flooding in the first year after being built, the post was moved to what is now the base of Highway 63/Memorial Drive Bridge on the east side of the Athabasca River, where it operated until 1898. The land sat vacant from 1898 to 1907; in 1907 new buildings were built at this location when the HBC returned to Fort McMurray. These buildings were used until 1921 when a new store was built on Franklin Avenue; this store was used until 1945. The different locations of the post are shown in Figure 2-1: Location 1 is the original post location at Peden's Point, Location 2 is at the base of Highway 63/Memorial Drive Bridge, and Location 3 is the most recent location on Franklin Avenue.

An 1876 map (HBC Arch. G.1/246) that shows the location of the second post on the south side of the confluence of the Clearwater and Athabasca Rivers is shown in Figure 2-2. The 1876 map is relatively coarse in its depiction of the location of the post, but the map shows the post to be located on the right bank of the river between what is now River View Heights and the Snye (Clearwater River). The map also appears to identify the Horse River and Hangingstone River, but does not identify them as such. This location fits well with the descriptions provided by H. J. Moberly in his journal entries. Of note:

- The post was located at a point on the Athabasca with a large prairie area located to the rear of the main structure (termed fort in the archives) along the Clearwater River.
- The post had a high ridge of land immediately to the south of the fort. This high ridge of land is specifically noted in Mr. Moberly's letter to have helped protect the fort from the velocities and ice forces associated with the jam by creating an eddy, or shadow in the flow.
- Mr. Moberly notes having to traverse a distance of approximately 100 yards to reach the higher ground of the above mentioned spur once water levels had risen to the point of flooding the post's buildings. In fact, Mr. Moberly reached safety by half wading and half swimming across this gap in the ice filled water.
- The archives also contain a sketch made by Mr. Moberly in 1877 showing the overall layout of the Fort (archive item 11M2, G.1/333). This sketch is shown in Figure 2-2. As shown, the fort was located just to the west of what is shown as a branch of the Clearwater River. This was most likely the Snye channel.

This evidence would place the post at approximately Location 2 as shown in Figure 2-1.

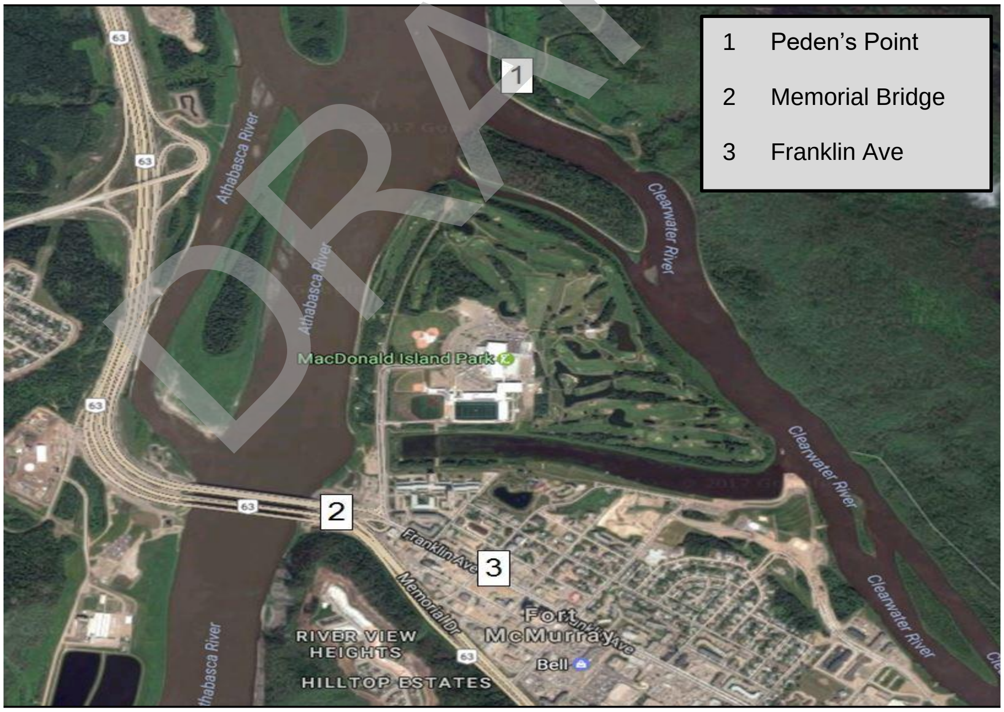


Figure 2-1: Historical HBC Post Locations **(map: Google Earth)**

The team was able to obtain a telling photo of the HBC post (circa 1920's) from the University of Alberta archives, taken from a vantage point on the Athabasca River as a boat approached the post from downstream. This photo is shown in Figure 2-4. The high ridge immediately behind (and south of) the post is evident – consistent with what is there today. For comparison, an image of that area from a similar vantage point in the DTM developed for this project (collected in 2016) is shown in Figure 2-5. The DTM shown in this image was developed based on the current survey data, but major man made features (such as the Memorial Bridge abutments) have been removed to better represent the topography in 1875. The view is very similar, providing further evidence that Location 2 was the very likely position of the HBC post at the time of the flood.

As part of the review, we also assessed the likely floodplain elevations in this area based on the latest digital terrain models. Although construction of the bridge in the early 60's likely altered local topography, large tracts of land adjacent to the bridge show the floodplain to be quite flat, as it extended upstream along the Clearwater River. This was likely the case even at the turn of the century. The latest DTM data indicates the elevations in this area vary between el. 251.0 m and 252.0 m – very similar to the el. 250.85 m (823 ft.) identified in the Blench (1964) report. To provide further confirmation on these elevations, digital copies of historical construction drawings for the Memorial Drive bridge were obtained, and these drawings show bore holes and bank elevations in this area circa 1964. These drawings have been included in Appendix C of this document. The bank elevations discussed above are very consistent with the data shown on these drawings.

Therefore, in summary, the HBC post was likely located at Location 2 shown in Figure 2-1. The ground elevation of the post was likely close to the level reported in the Blench study, and for the purpose of this assessment can be assumed to have been el. 250.85 m in 1875.

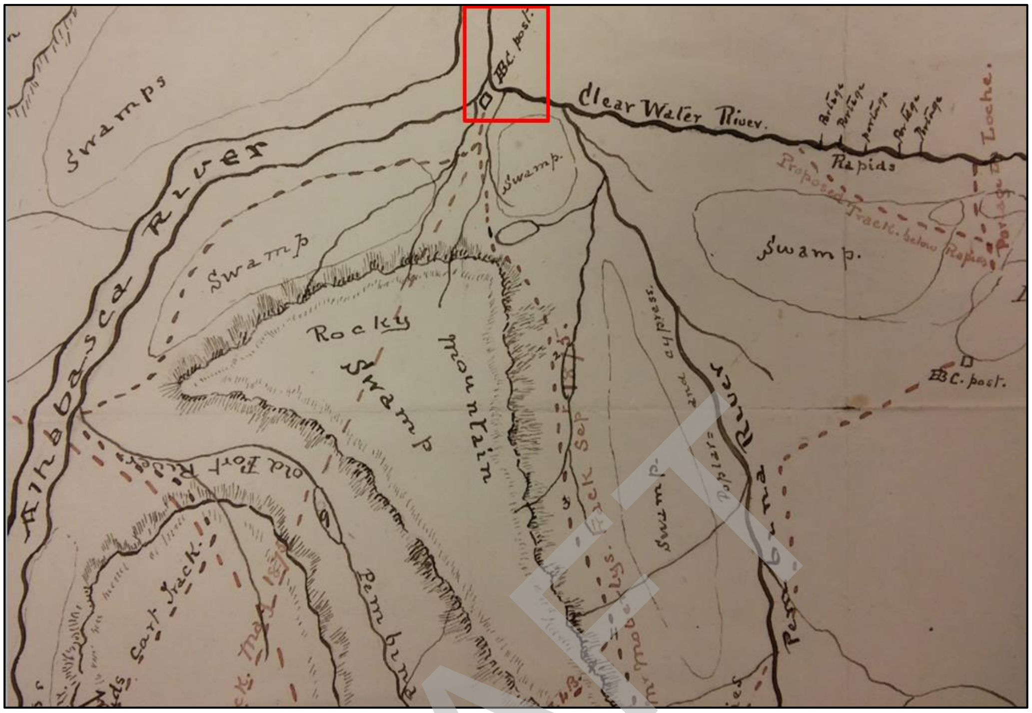


Figure 2-2: Map of HBC Post circa 1876 (HBC Arch. G.1/246)

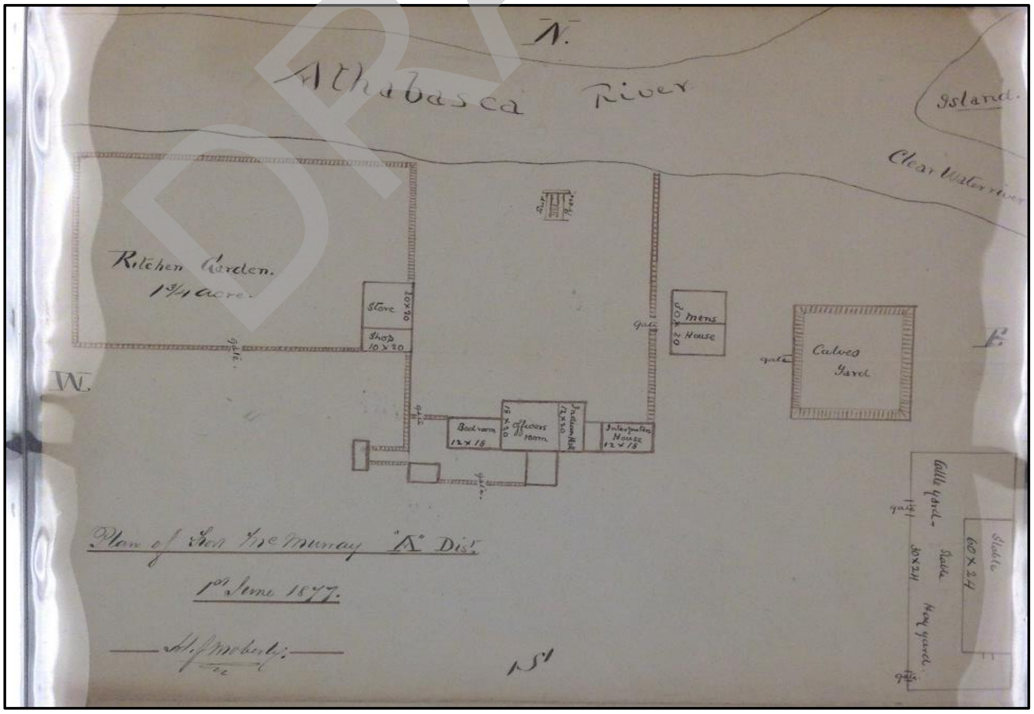


Figure 2-3: Layout of HBC Post circa 1877 (HBC Arch. G.1/333)

Figure 2-4: **Photo of HBC Post in early 1920s (U of A Archives)**

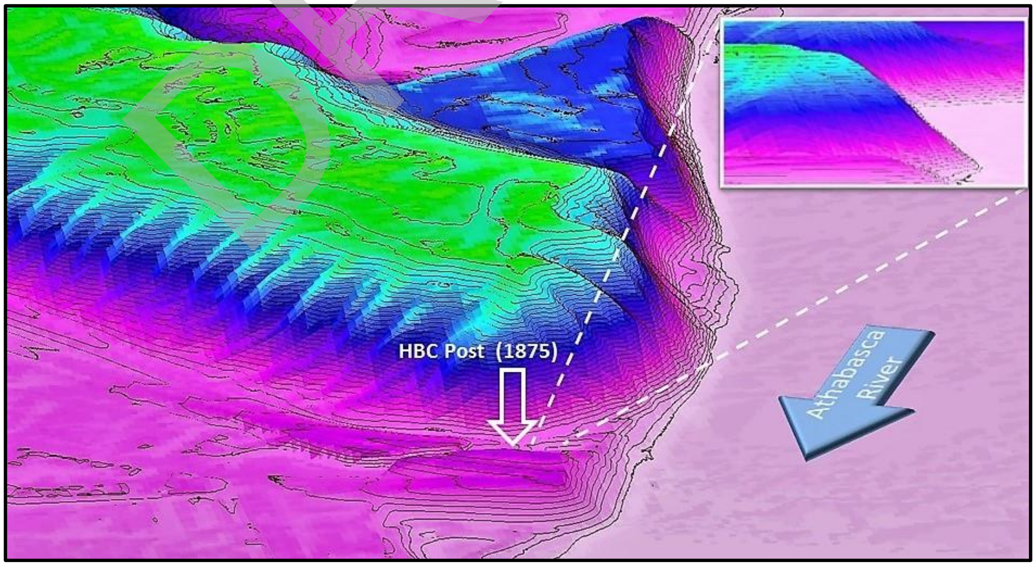


Figure 2-5: **DTM Image From Similar Vantage Point as Photo. Note the flat plain and high ridge in behind the post location.**

2.2 1875 Flood Event

The majority of details associated with the 1875 ice jam event were contained in three short letters that were previously reviewed and reported on in the 1964 Blench report. For convenience, excerpts from these letters have been included in Appendix A of this report. A further search of records at the archives did not reveal any additional information or correspondence related to the flood. Daily journals from the post for the 1875 period do not exist, either having never been written or not surviving to present day.

Daily journals from the HBC post at Fort Chipewyan were reviewed to get a sense of the 1874-75 winter severity. Fort Chipewyan was situated downstream of Fort McMurray at Lake Athabasca. Although ice conditions at Fort Chipewyan would not mirror those at Fort McMurray, weather conditions could likely be similar at the two posts. Excerpts from the daily journals at Fort Chipewyan from the fall of 1874 through to the spring of 1875 describing weather and ice conditions are provided in Appendix B.

Based on these descriptions, the following can be inferred.

- The winter preceding the 1875 flood event was quite cold. There were some short periods of warm temperatures, but overall, it was characterized as a long, bitter winter. Temperatures remained cool until mid-April. The Fort Chipewyan records indicate temperatures increased quite significantly around April 16th – just days before the ice jam occurred.
- Snow depths seemed to be quite large based on Mr. Moberly's descriptions. This, combined with the cool spring prior to the ice jam event, could indicate that spring runoff was more concentrated in 1875, resulting in unusually large flows during the spring freshet.
- The ice sheets on the Athabasca River were likely quite thick and competent prior to breakup. Because of the cold winter, and late spring, this river ice would likely have remained quite strong with little deterioration prior to the arrival of the spring freshet.
- Mr. Moberly reports that at least an 85 mile stretch of the Athabasca River suddenly broke up upstream of Fort McMurray. The volume of ice within this length of river would be more than enough to form a severe jam at Fort McMurray that could attain an equilibrium condition over a considerable length.
- It is noted that on the morning of April 20th, the river ice first broke up and began to run, but then a jam quickly formed with the influx of upstream ice. The jam is noted to have occurred just downstream of the Athabasca and Clearwater confluence, where the river becomes more braided and begins to narrow. This is a typical jam formation point on the Athabasca River.
- Water levels rose quickly, forcing immediate evacuations of the HBC post. Mr. Moberly reports that the water level rose almost 57 ft. (17.4 m) at its peak. Quite literally, this would have resulted in a water level higher than 256.0 m at the post. However, we agree

with the Blench report that this level may have been exaggerated. As noted in the Blench report, it is unlikely that the water level would have been more than 7 ft. (2.1 m) above the floor elevation of the Fort – higher levels would have resulted in considerable damage and/or removal of the Post. As shown in Figure 2-4, the Post infrastructure was not likely particularly robust. As well, Mr. Moberly reports that in escaping the flood, he had to partially wade and partially swim from the Post to the nearby ridge. If the ground elevation was 250.85 m as reported in the Blench report, the peak water level likely would not have been more than 1.5 m higher than this. Considering this, our best estimate of the peak level reached in 1875 was approximately el. 252.5 m.

3. Application of HEC-RAS Model

Following the confirmation of the HBC Post location, and the review of anecdotal data on the flood, the next step in the assessment involved the set up and use of the HEC-RAS hydraulic model to assess the conditions that may have led to the high levels associated with the jam event. This was done to establish the plausibility of reaching these high levels, and to provide a best estimate of what this level may have been not only at the Fort location, but also at the confluence of the Clearwater and Athabasca Rivers.

The assessment involved the following steps:

- An open water, HEC-RAS model for the Athabasca and Clearwater Rivers at Fort McMurray was created from river survey data collected in October 2016 and 2016 LiDAR data. The model was calibrated for the low-flow, open water condition and is considered to be appropriate for this assessment. Based on the composition of the bed in this area, it is unlikely that the bed geometry of the river has changed significantly since 1875, and it is therefore a good representation of the river's bathymetric character. The Manning's bed roughness (n) in the model was 0.030 for the Athabasca River main channel, and it varied spatially between 0.050 and 0.150 on the floodplain. It should be noted that the model was not calibrated against historical ice jam events, but is considered sufficient for a forensic analysis of the 1875 ice jam level.
- The model was then modified to try to emulate conditions as they would have been during the 1875 jam event. To do this, all obvious dikes, bridge abutments, and other features that may have been added to the local topography since then were eliminated from the dataset. However, the bathymetry was assumed to remain unchanged, as noted earlier.
- Ice parameters were then added to the model. Parameters to be entered included the initial sheet ice thickness, the roughness of the cover (main channel and floodplains), the porosity of the jam, the internal strength of the jam, the longitudinal to lateral ratio of internal forces, the maximum velocity under the jam, and the nature of the cover (jam vs ice sheet). Of these, most parameters were initially assigned values based on the judgement of our modellers, and on the experience gained from past model applications

on the river. However, a range of key parameters was also selected for testing. The key parameters tested included:

- Location of jam toe: Two locations were tested: one located approximately 9.5 Km downstream of the proposed for location- 7.5 km downstream of the Clearwater confluence (Toe Location 1), and the other located approximately 5.5 km downstream of the proposed fort location - 3.5 km downstream of the confluence (Toe Location 2). Ice jams occur at various locations within this reach given the braided nature of the channel. These two locations were selected to test the sensitivity in water level at the Fort location to the toe location of the jam. The further downstream the toe is, the more likely the jam would have reached an equilibrium thickness at the Fort location.
- Discharge: Steady state discharges ranging from 2500 m^3/s to 4000 m^3/s were tested. This range of discharges represents an extreme upper end of the expected the spring freshet hydrology. Steady state discharges were utilized since the shape and nature of the incoming hydrograph would be almost impossible to predict. This is standard practice for most ice jam assessments.
- Roughness of ice cover: Ice roughness values ranging from 0.065 up to 0.085 were tested. These values were selected based on the findings of past investigations on the Athabasca River (Andres, 1977-1979, 1983-1986). It is expected that the actual value would likely lie between these ranges. The composite roughness is then calculated for each simulation cross section within the model based on the Belkon-Sabaneev equation.

- Following this, a series of runs were undertaken in which different combinations of these key parameters were tested.

The results were then plotted on a series of profiles and rating curves to assess the likely water levels that may have occurred at the HBC location. Figure 3-1 to Figure 3-10 summarize the results of these runs.

Figure 3-1, Figure 3-2, Figure 3-3 and Figure 3-4 illustrate the resulting water surface profiles for flows of 2500 m^3/s, 3000 m^3/s, 3500 m^3/s, and 4000 m^3/s respectively for a case in which the toe of the jam is at the most downstream location. In each Figure, for context, the red box shown represents the range in water levels previously estimated in the Blench report.

Figure 3-5, Figure 3-6, Figure 3-7 and Figure 3-8 illustrate the resulting water surface profiles for flows of 2500 m^3/s, 3000 m^3/s 3500 m^3/s, and 4000 m^3/s respectively for a case in which the toe of the jam is at the more upstream location (3 km downstream of the confluence).

Figure 3-9 illustrates the stage-discharge rating curve at the HBC location for the most downstream toe location, while Figure 3-10 illustrates the stage-discharge rating curve at the HBC location for the second, more upstream toe location.

In reviewing these charts, the ice jam appears to have reached an equilibrium thickness at the post location for either of the assumed jam initiation points. The equilibrium jam thickness for these runs was approximately 5 m. Where the jam covered areas of the floodplain, the thickness of the jam restricted flow movement on the floodplains, and therefore almost all conveyance continued to be in the main channel of the river. The findings of this preliminary study indicate that the model predictions are consistent with the water surface elevation range established through our review of the archival record. Ice jam formation at either toe location could have led to these types of levels for various combinations of assumed ice jam roughness and river flows.

However, it is our opinion that the most probable combination of parameters creating the 1875 event would involve a scenario involving higher than normal river flows, the higher end of the roughness range (based on an assumption that the ice was not significantly deteriorated at breakup), and formation at a downstream toe location (resulting in an equilibrium thickness and water surface profile at both the Fort location and the Clearwater confluence). Considering a “best estimate” water level at the Fort location of approximately el. 252.5 m (based on historical data), this would mean that flows at the time of the event may have been approximately 2500 m^3/s at the peak of the event (based on Figure 3-9). Given the expected slope of the ice jam, the water level at the Athabasca-Clearwater confluence would be approximately 0.5 m lower, at el. 252.0 m.

It should be noted that these estimates of the 1875 event have been based on the team’s best judgment in terms of ice parameters and driving mechanisms.

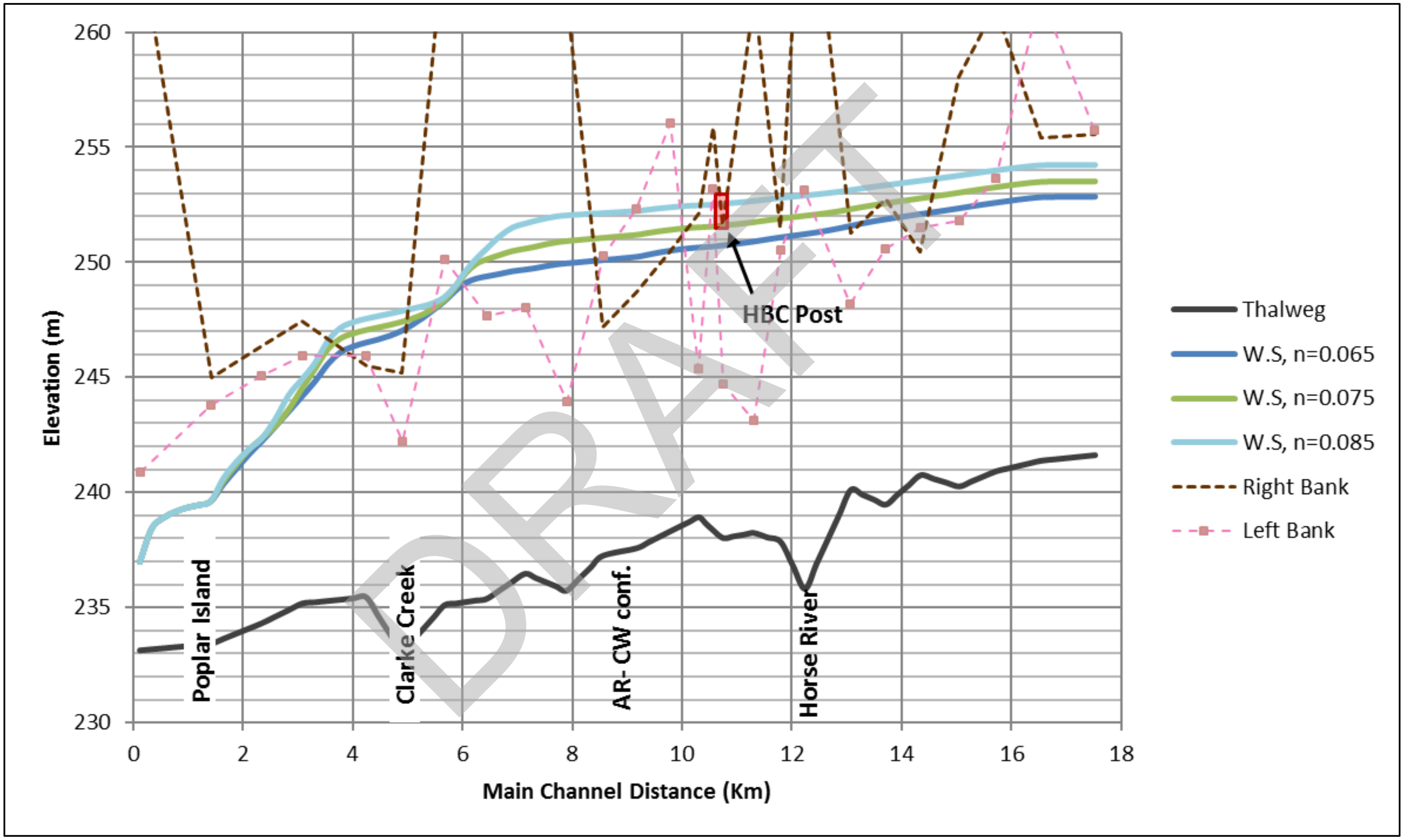


Figure 3-1: WSE Profile for Toe Location 1 (9.5 km downstream of fort location), Q = 2500 m^3/s

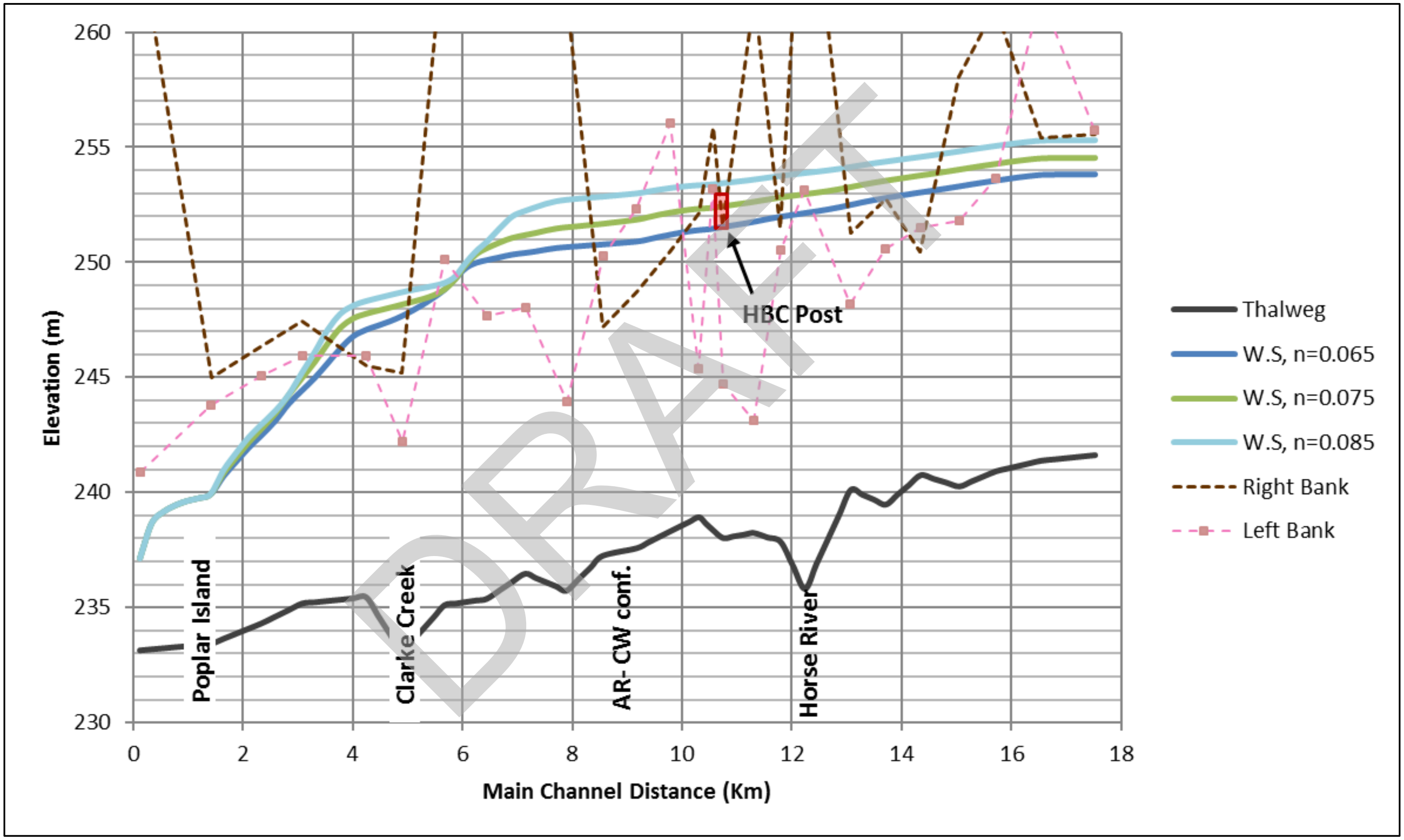


Figure 3-2: WSE Profile for Toe Location 1 (9.5 km downstream of fort location), Q = 3000 m^3/s

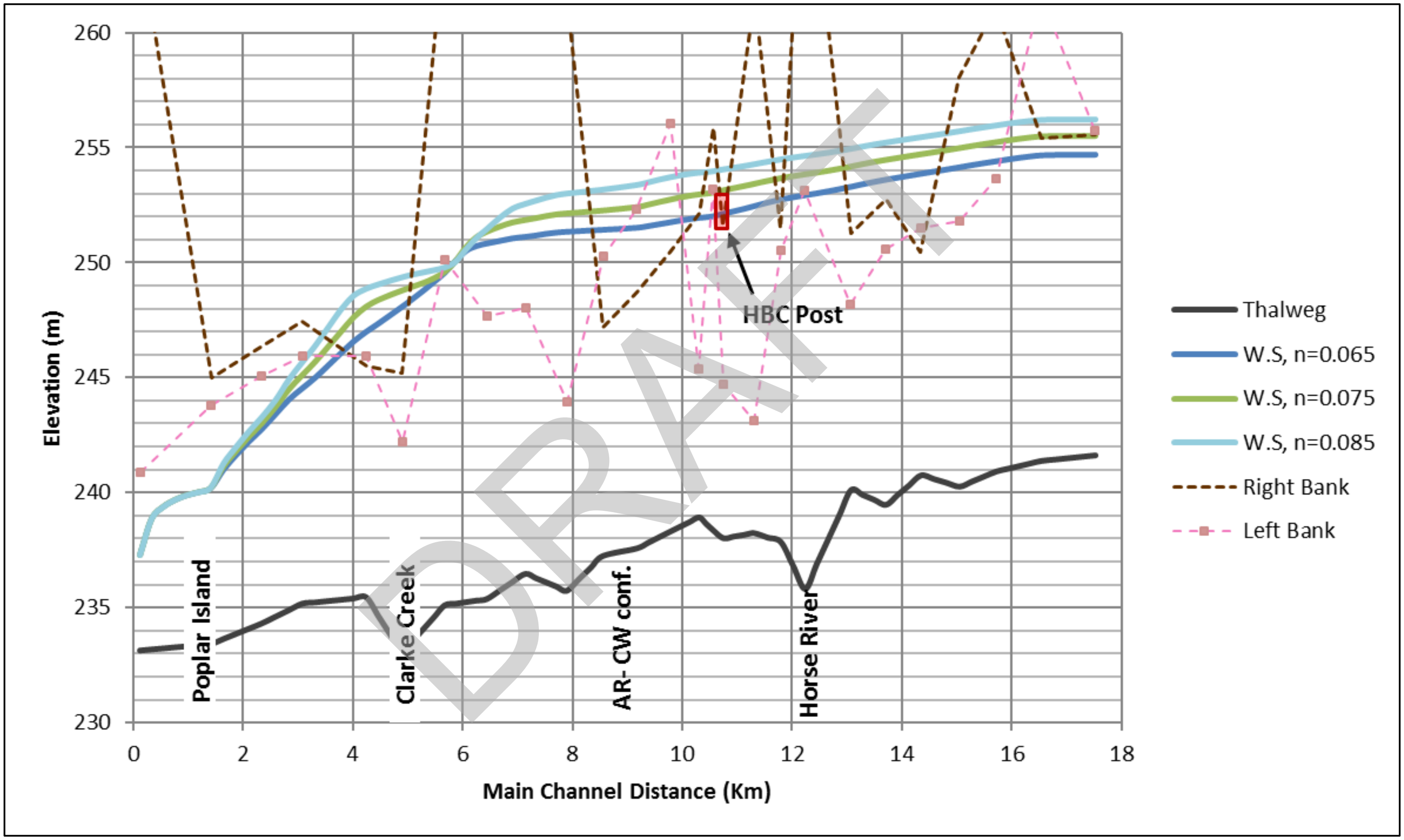


Figure 3-3: WSE Profile for Toe Location 1 (9.5 km downstream of fort location), Q = 3500 m^3/s

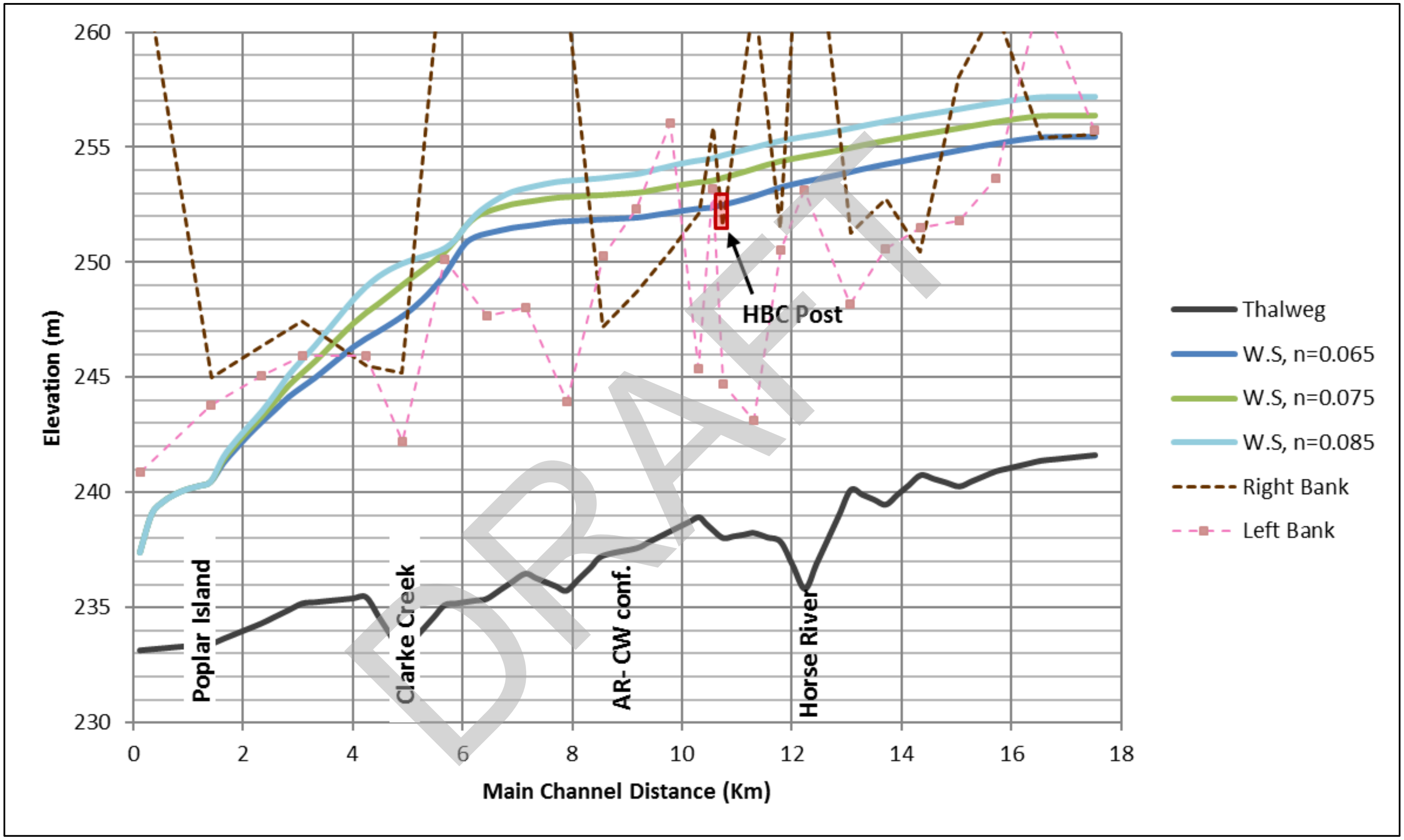


Figure 3-4: WSE Profile for Toe Location 1 (9.5 km downstream of fort location), Q = 4000 m^3/s

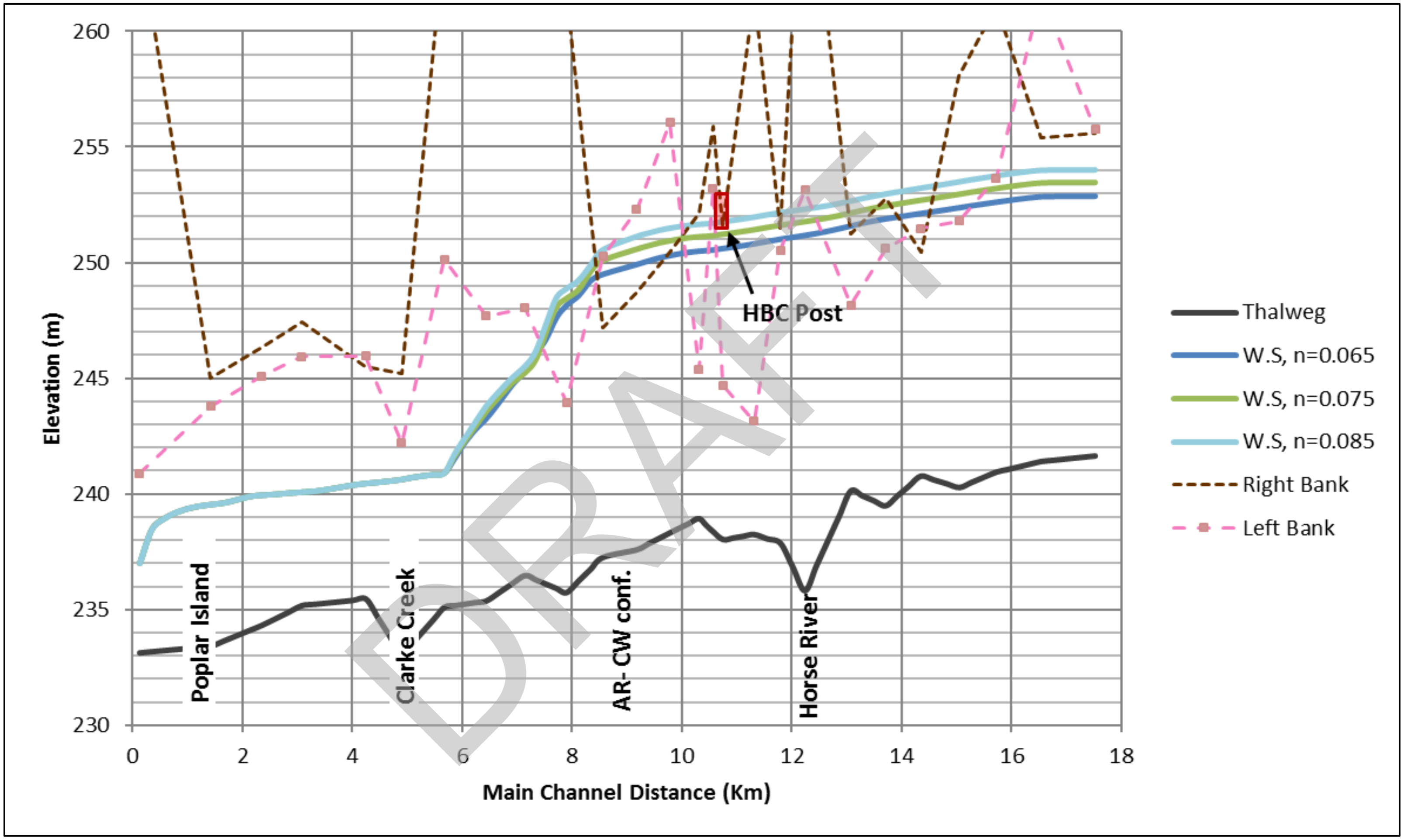


Figure 3-5: Toe Location 2 (5.5 km downstream of fort location), Q = 2500 m^3/s

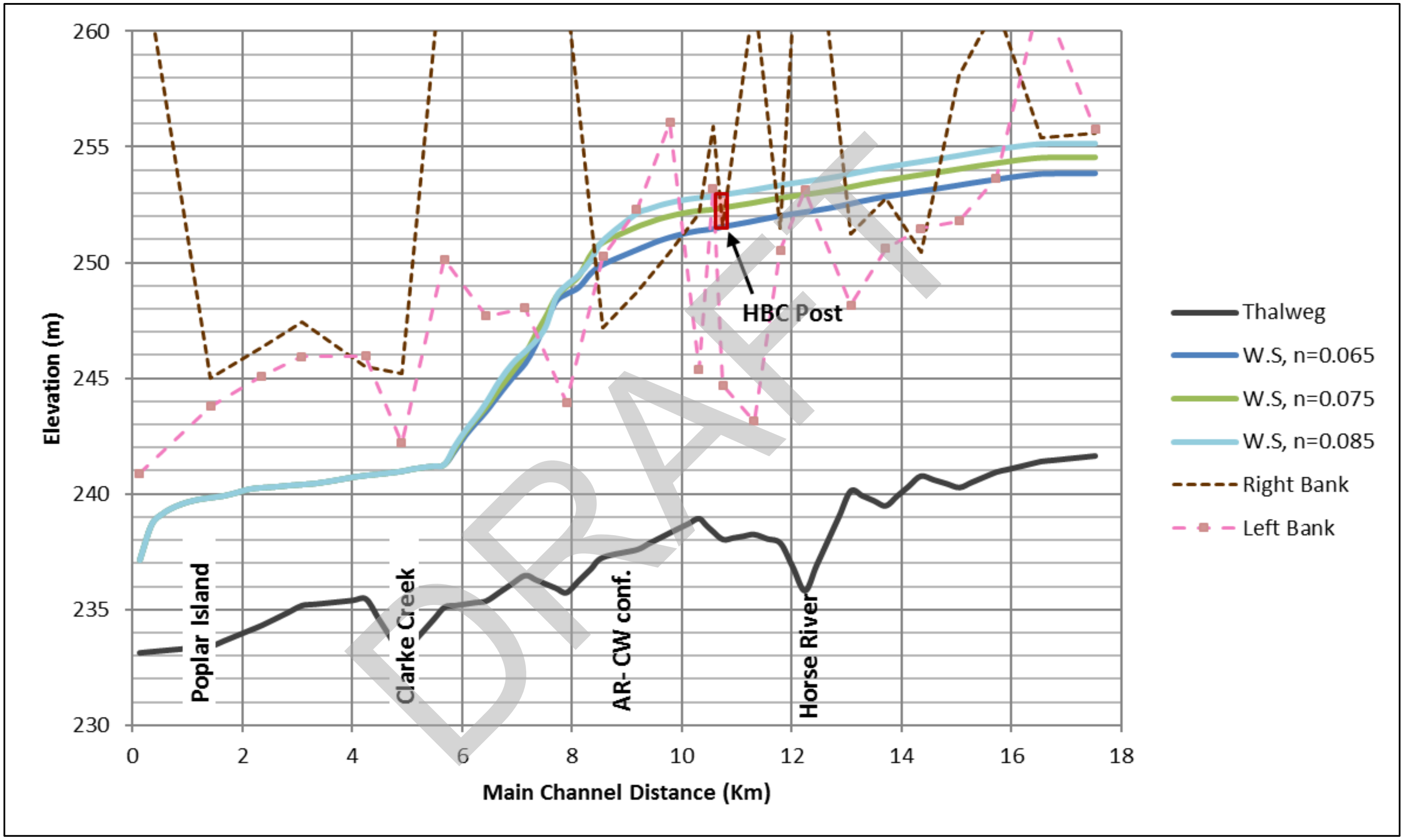


Figure 3-6 : Toe Location 2 (5.5 km downstream of fort location), Q = 3000 m^3/s

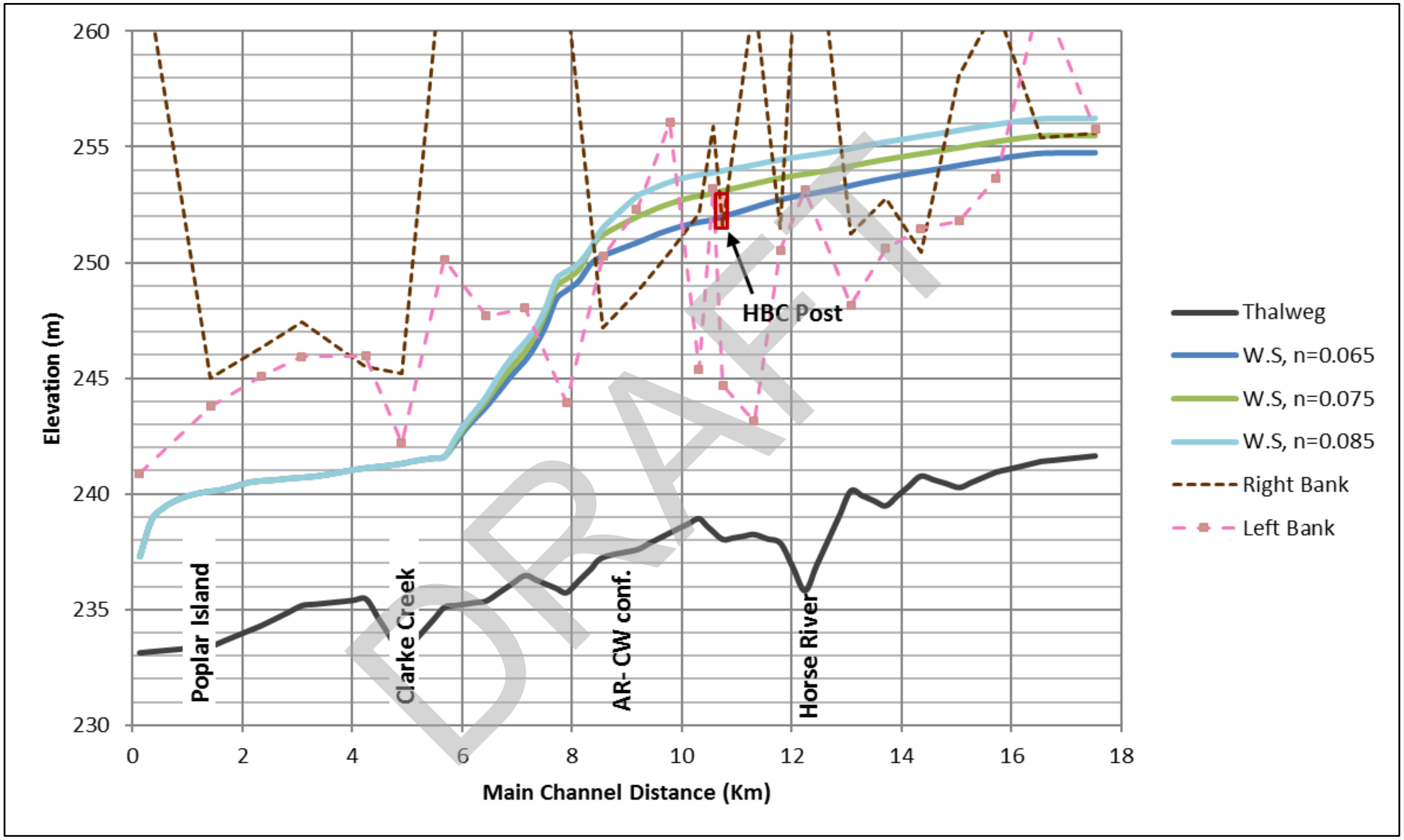


Figure 3-7: Toe Location 2 (5.5 km downstream of fort location), Q = 3500 m^3/s

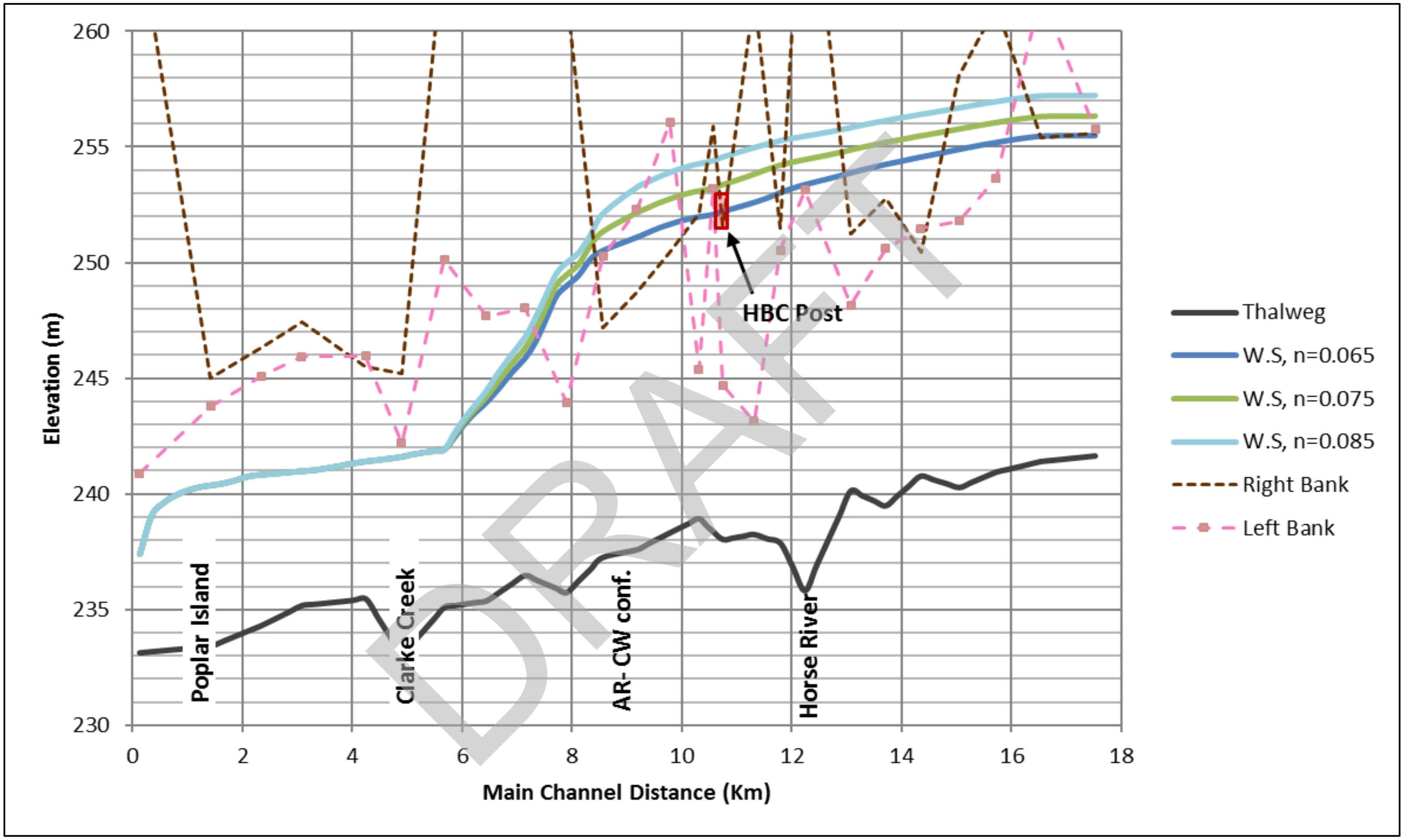


Figure 3-8: **Toe Location 2 (5.5 km downstream of fort location), Q = 4000 m^3/s**

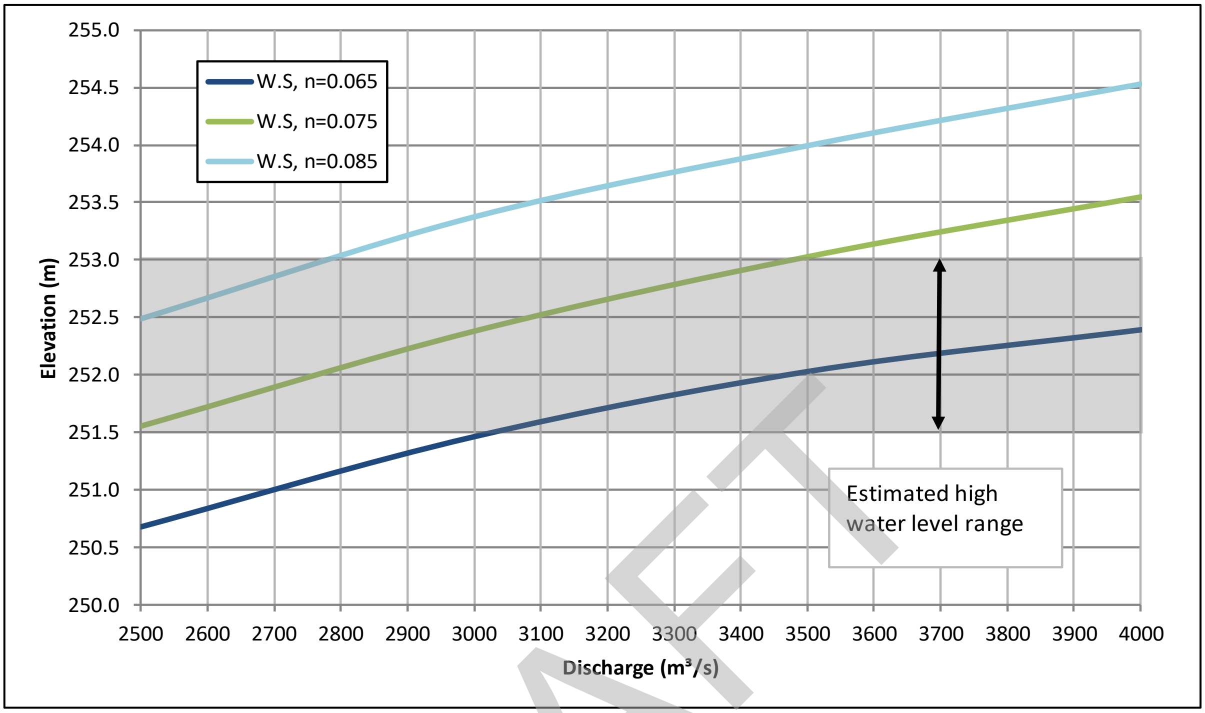


Figure 3-9: Stage-Discharge Rating Curve at HBC Location 2 – Toe Location 1 (9.5 km downstream)

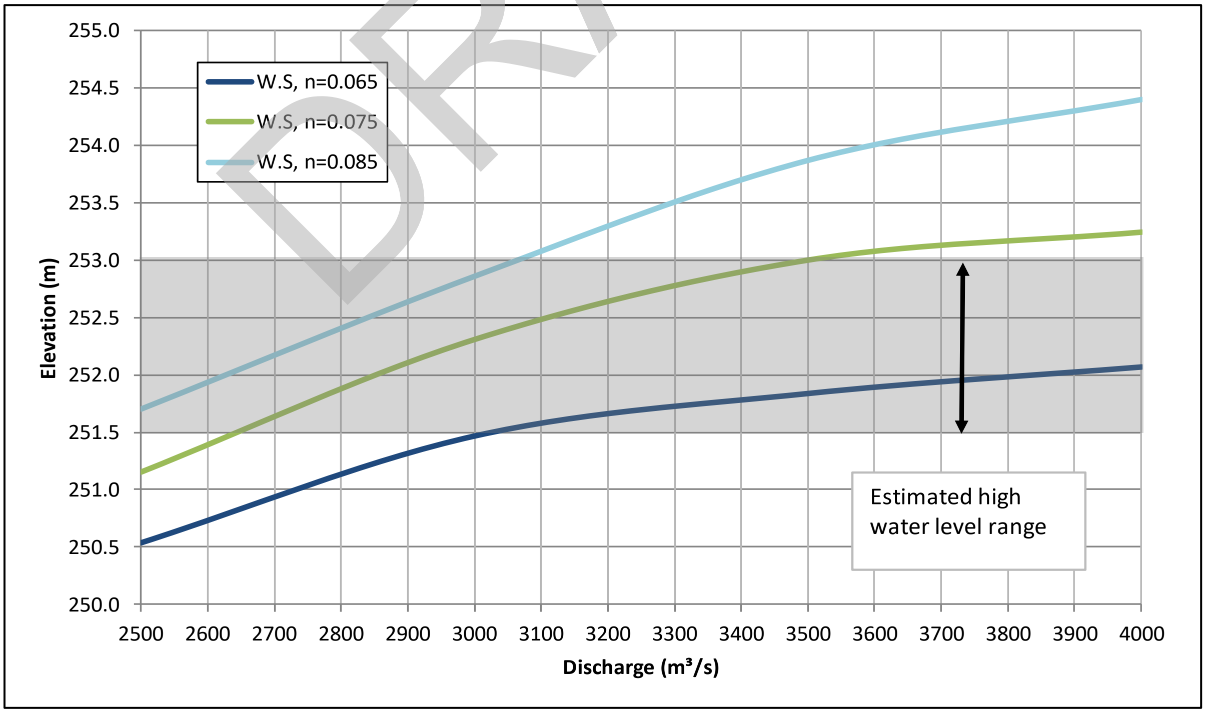


Figure 3-10: Stage-Discharge Rating Curve at HBC Location 2 – Toe Location 2 (5.5 km downstream)

4. Summary

The 1875 flood event has been reviewed based on available historical documentation, and through application of the HEC-RAS model. The assessment has resulted in the following findings:

- The HBC post was likely located at Location 2 of Figure 2-1 in 1875. This position has been established independently through a review of Mr. Moberly's letters, discussions with staff at the Fort McMurray Heritage Society and the staff at the HBC Archives, an archived map showing the post location, and an historical photo of the post.
- The conclusion of this assessment is that the peak water level during the 1875 ice jam event was likely to be at el. 252.5 m at the HBC Fort location. Water levels at the Clearwater confluence were likely to be approximately 0.5 m lower than this, or el. 252.0 m. This independent assessment therefore suggests that the levels reported in the 1964 Blench report are reasonable estimates of the peak levels reached - historical estimates of the peak level reached range between the elevations of el. 251.5 m and el. 253.0 m.
- Anecdotal information suggests that conditions were favorable for the development of a more severe than usual ice run that year. Snowpacks were characterized as being high, the winter was described as being bitterly cold, and extending into mid April before temperatures began to rise.
- A numerical ice model was applied to determine if the river bathymetry/geometry, and present day ice mechanics, would support observations of such high ice driven levels. The results of this modelling exercise suggests that ice jam formation, with a toe that is within 5 km downstream of the post location, could have led to these types of levels for various combinations of assumed ice jam roughness and river flow. The results suggest that flows of 2500 m^3/s with an ice roughness of 0.085 would be sufficient to create the levels estimated for the 1875 event.

It should be noted that these estimates of the 1875 event have been based on the team's best judgment in terms of ice parameters and driving mechanisms.

Appendix A: Excerpts from 1964 Blench Report on 1875 Ice Jam Flood

APPENDIX A

ICE JAM FLOOD DATA

1875 Flood.

The following is a quotation from page 151, H.J. Moberly's account of this flood (Ref. 2):

"The winter of 1874-75 was a bitter one, with deep snow and never a thaw until April. On the 2nd or 3rd of that month, however, a further heavy fall of snow was followed by a sudden rise in temperature. The change of weather and weight of the melting snow caused the ice for the eighty-five-mile stretch of rapids above the fort to break up, and it came down the Athabasca with terrific force. On striking the turn in the stream at the post it blocked the river and drove the ice two miles up the Clearwater in piles forty or fifty feet high. In less than an hour the water rose fifty-seven feet, flooding the whole flat and mowing down trees, some three feet in diameter, like grass.

Fortunately, the spur of the hill just above the fort sloped to the river, forming an eddy. The flood caught only one of the houses, but this was at once swept away. When the water had mounted almost to the bank I ordered everyone back to the high ground, but fearing that if the rise reached the house its contents would be damaged, I stayed behind and, shutting the doors, commenced to carry what articles I could to the upper rooms.

Presently I noticed water trickling in under the doors. I was too much occupied, however, to take the time to look out, until a large tree dashed in at the window. I knew now that I was in for a cold bath.

After I had with great difficulty got out of the trap a hundred yards of water five to ten feet deep still separated me from dry land. When, at times wading and again swimming, I at length reach it and safety no one with ague ever shook harder than did I after my ducking.

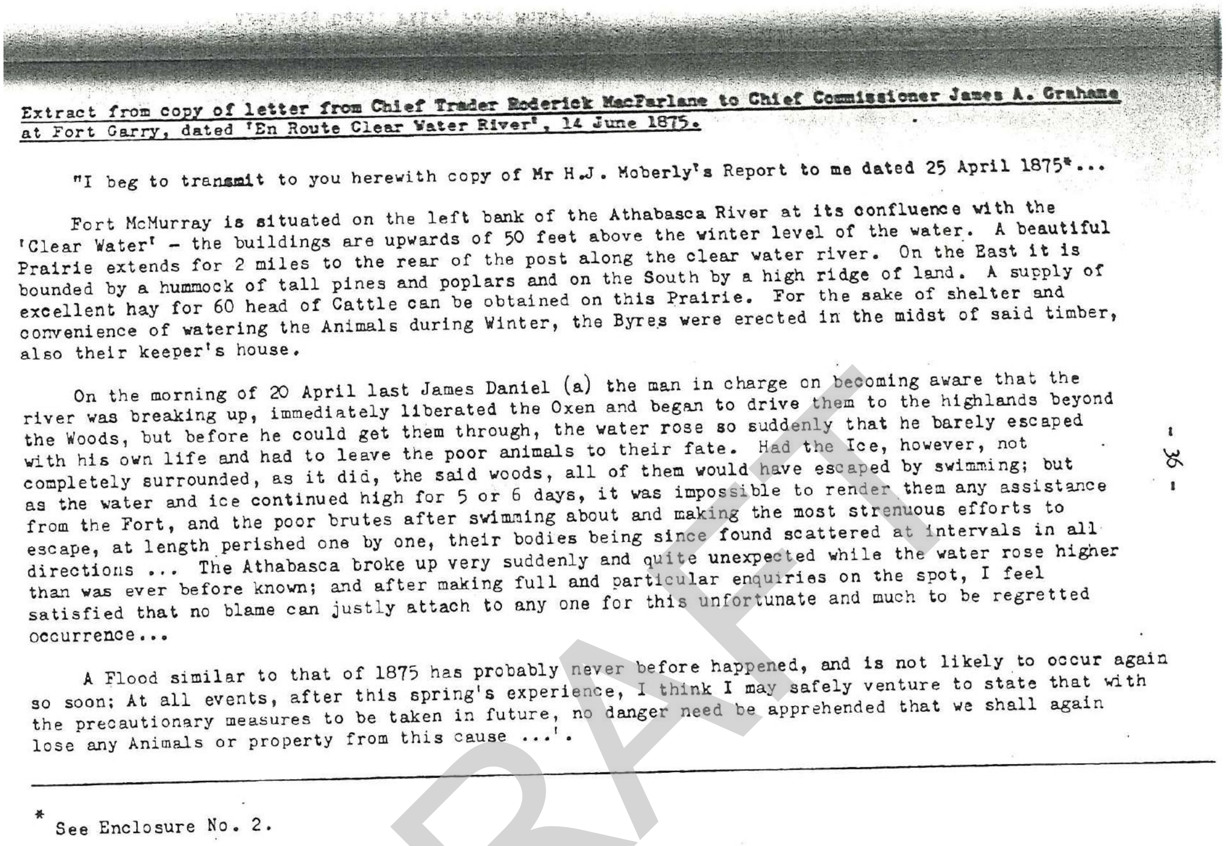
We cleared away the snow and made a comfortable camp, and here we remained for five days before we could re-occupy the houses. Out of thirty-seven oxen for the transport service one only escaped. The rest were drowned".

On April 1st, 1964, Mr. Joseph Shott, age 78, pointed out the site of the original Hudson's Bay Co. post located as shown on Fig. 14. The elevation of the ground surface at this point is about 823. The site is about 100 yards from a steep rise or terrace in the ground roughly parallel to the 825 contour at the west end of Franklin Avenue. The post was a log structure and would have been carried away had the water risen 57 ft. (to about elev. 847 or 24 ft. above the ground) as stated in the above quotation. While the dimensions of the buildings are not available, it is likely that they would have floated had the water depth reached more than about 7 feet. The maximum water level must therefore have been no more than 830. The lowest possible maximum level was about 2 ft. above the ground or elevation 825.

Mr. Shott's comments on his father's stories of the "big flood" in which many cattle died in the "Prairies" area, were in agreement with other available accounts of the incident.

Extracts from the Hudson's Bay Co. files, included in this Appendix, provide further details of this flood. The second paragraph of Enclosure 1 locates the fort on the left bank of the Athabasca. Since the location described, "A beautiful Prairie .....", exists only near the right bank, it would appear that Mr. Moberly was facing upstream when he gave the description.

It should be noted that the above quotation states the flood occurred on the 2 or 3rd of the month whereas Moberly's report to the Hudson's Bay Co. gives the date as April 20.



Extract from copy of letter from Chief Trader Roderick MacFarlane to Chief Commissioner James A. Grahame at Fort Garry, dated 'En Route Clear Water River', 14 June 1875.

"I beg to transmit to you herewith copy of Mr H.J. Moberly's Report to me dated 25 April 1875*...

Fort McMurray is situated on the left bank of the Athabasca River at its confluence with the 'Clear Water' – the buildings are upwards of 50 feet above the winter level of the water. A beautiful Prairie extends for 2 miles to the rear of the post along the clear water river. On the East it is bounded by a hummock of tall pines and poplars and on the South by a high ridge of land. A supply of excellent hay for 60 head of Cattle can be obtained on this Prairie. For the sake of shelter and convenience of watering the Animals during Winter, the Byres were erected in the midst of said timber, also their keeper's house.

On the morning of 20 April last James Daniel (a) the man in charge on becoming aware that the river was breaking up, immediately liberated the Oxen and began to drive them to the highlands beyond the Woods, but before he could get them through, the water rose so suddenly that he barely escaped with his own life and had to leave the poor animals to their fate. Had the Ice, however, not completely surrounded, as it did, the said woods, all of them would have escaped by swimming; but as the water and ice continued high for 5 or 6 days, it was impossible to render them any assistance from the Fort, and the poor brutes after swimming about and making the most strenuous efforts to escape, at length perished one by one, their bodies being since found scattered at intervals in all directions ... The Athabasca broke up very suddenly and quite unexpected while the water rose higher than was ever before known; and after making full and particular enquiries on the spot, I feel satisfied that no blame can justly attach to any one for this unfortunate and much to be regretted occurrence...

A Flood similar to that of 1875 has probably never before happened, and is not likely to occur again so soon; At all events, after this spring's experience, I think I may safely venture to state that with the precautionary measures to be taken in future, no danger need be apprehended that we shall again lose any Animals or property from this cause ...'.

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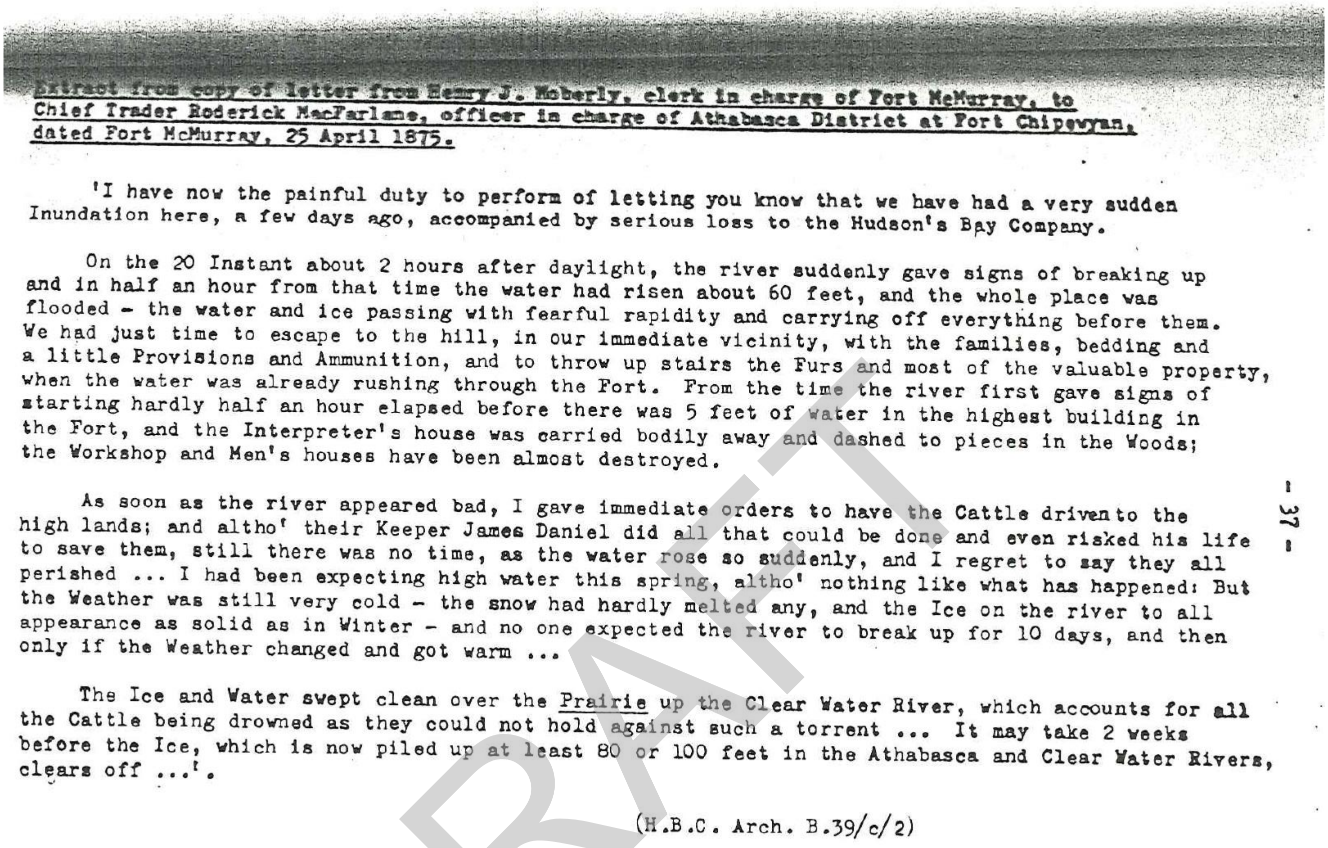
* See Enclosure No. 2.



<u>Extract from copy of letter from Henry J. Moberly, clerk in charge of Fort McMurray, to Chief Trader Roderick MacFarlane, officer in charge of Athabasca District at Fort Chipewyan, dated Fort McMurray, 25 April 1875.</u>

'I have now the painful duty to perform of letting you know that we have had a very sudden Inundation here, a few days ago, accompanied by serious loss to the Hudson's Bay Company.

On the 20 Instant about 2 hours after daylight, the river suddenly gave signs of breaking up and in half an hour from that time the water had risen about 60 feet, and the whole place was flooded – the water and ice passing with fearful rapidity and carrying off everything before them. We had just time to escape to the hill, in our immediate vicinity, with the families, bedding and a little Provisions and Ammunition, and to throw up stairs the Furs and most of the valuable property, when the water was already rushing through the Fort. From the time the river first gave signs of starting hardly half an hour elapsed before there was 5 feet of water in the highest building in the Fort, and the Interpreter's house was carried bodily away and dashed to pieces in the Woods; the Workshop and Men's houses have been almost destroyed.

As soon as the river appeared bad, I gave immediate orders to have the Cattle driven to the high lands; and altho' their Keeper James Daniel did all that could be done and even risked his life to save them, still there was no time, as the water rose so suddenly, and I regret to say they all perished ... I had been expecting high water this spring, altho' nothing like what has happened: But the Weather was still very cold – the snow had hardly melted any, and the Ice on the river to all appearance as solid as in Winter – and no one expected the river to break up for 10 days, and then only if the Weather changed and got warm ...

The Ice and Water swept clean over the <u>Prairie</u> up the Clear Water River, which accounts for all the Cattle being drowned as they could not hold against such a torrent ... It may take 2 weeks before the Ice, which is now piled up at least 80 or 100 feet in the Athabasca and Clear Water Rivers, clears off ...'.

(H.B.C. Arch. B.39/c/2)

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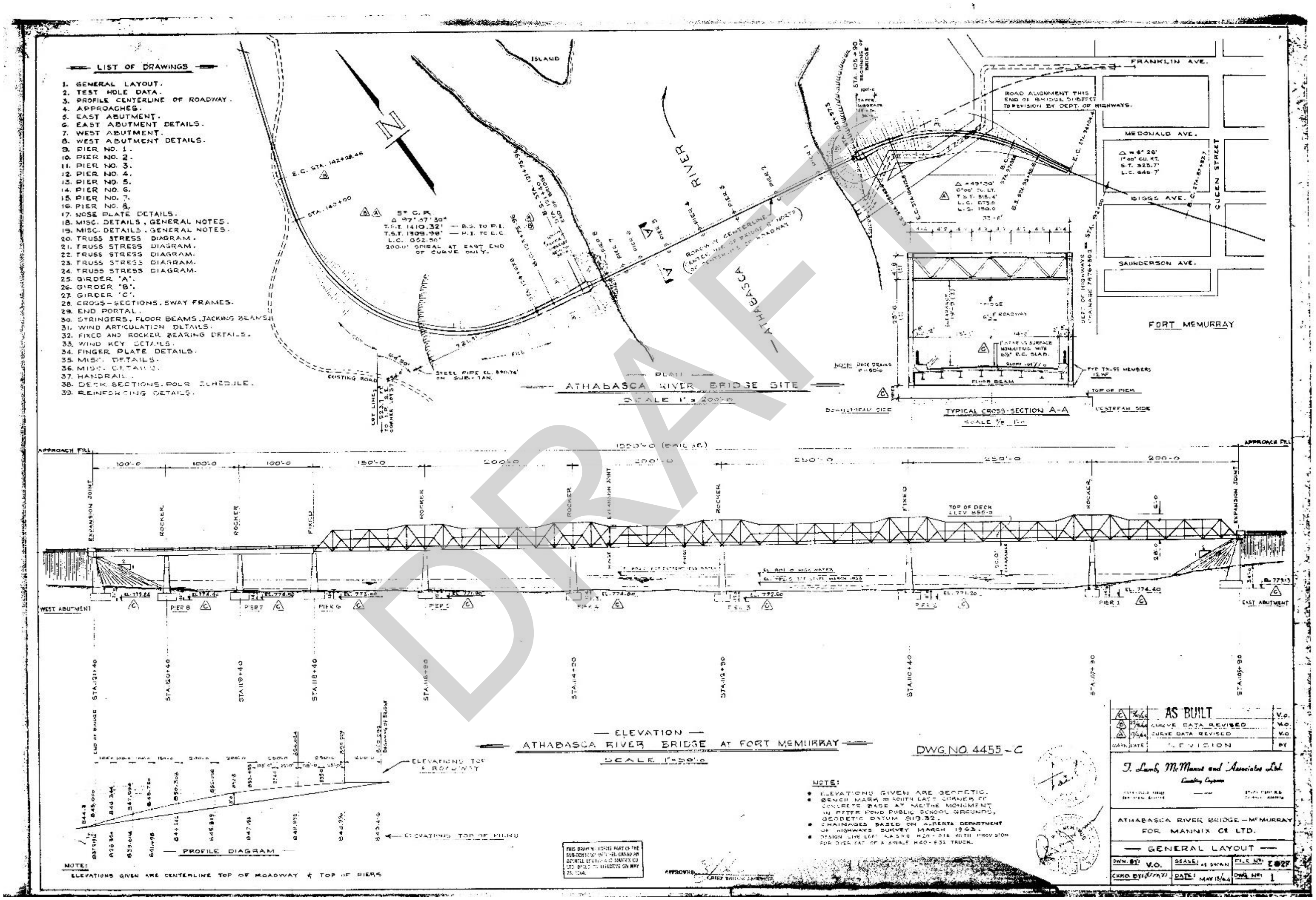
Appendix B: Daily Meteorological Observations, Winter of 1874/75

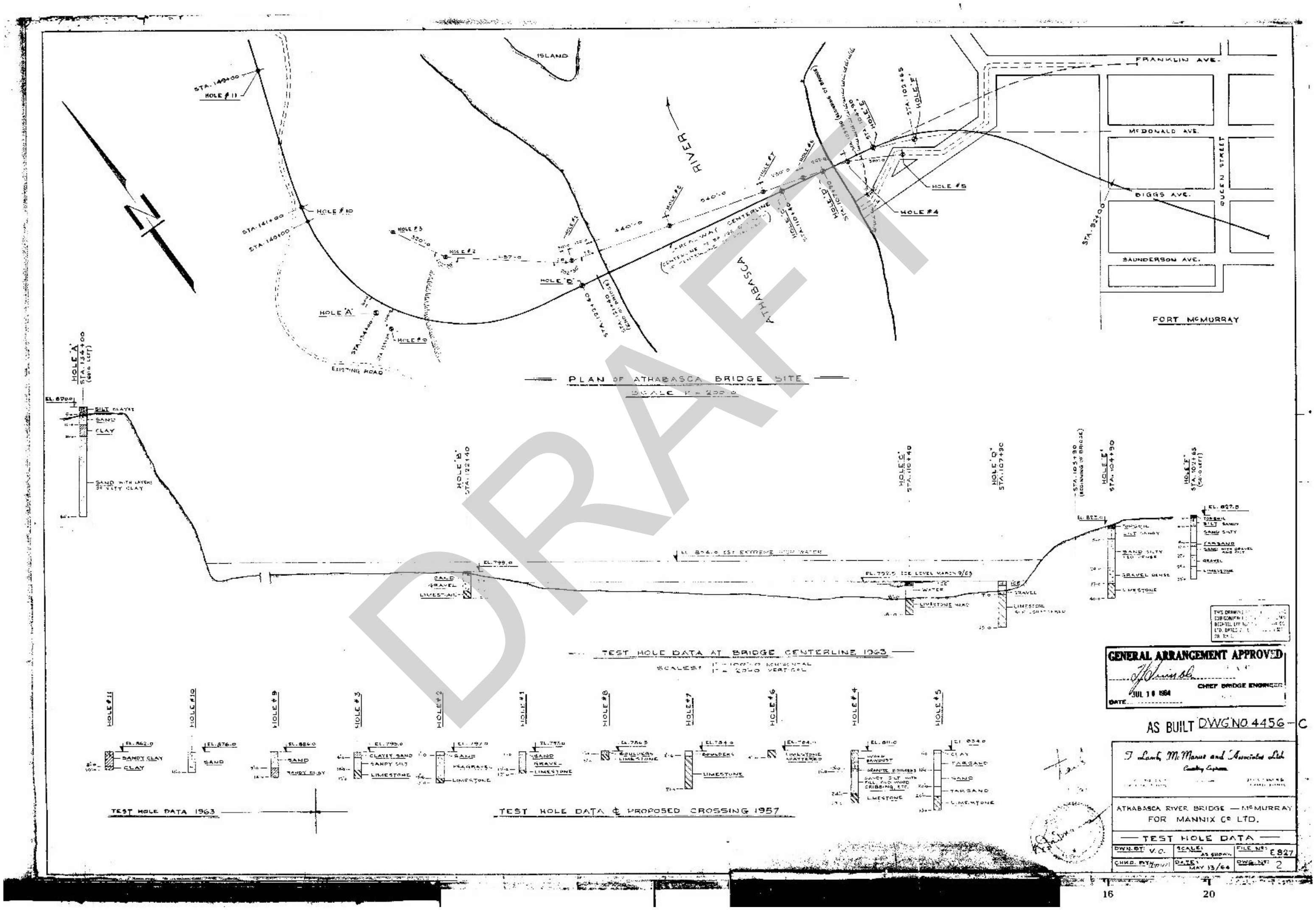
Excerpts from Daily Journals at Fort Chipewyan Describing Weather and Ice Conditions (HBC Arch. B.39/a/50)

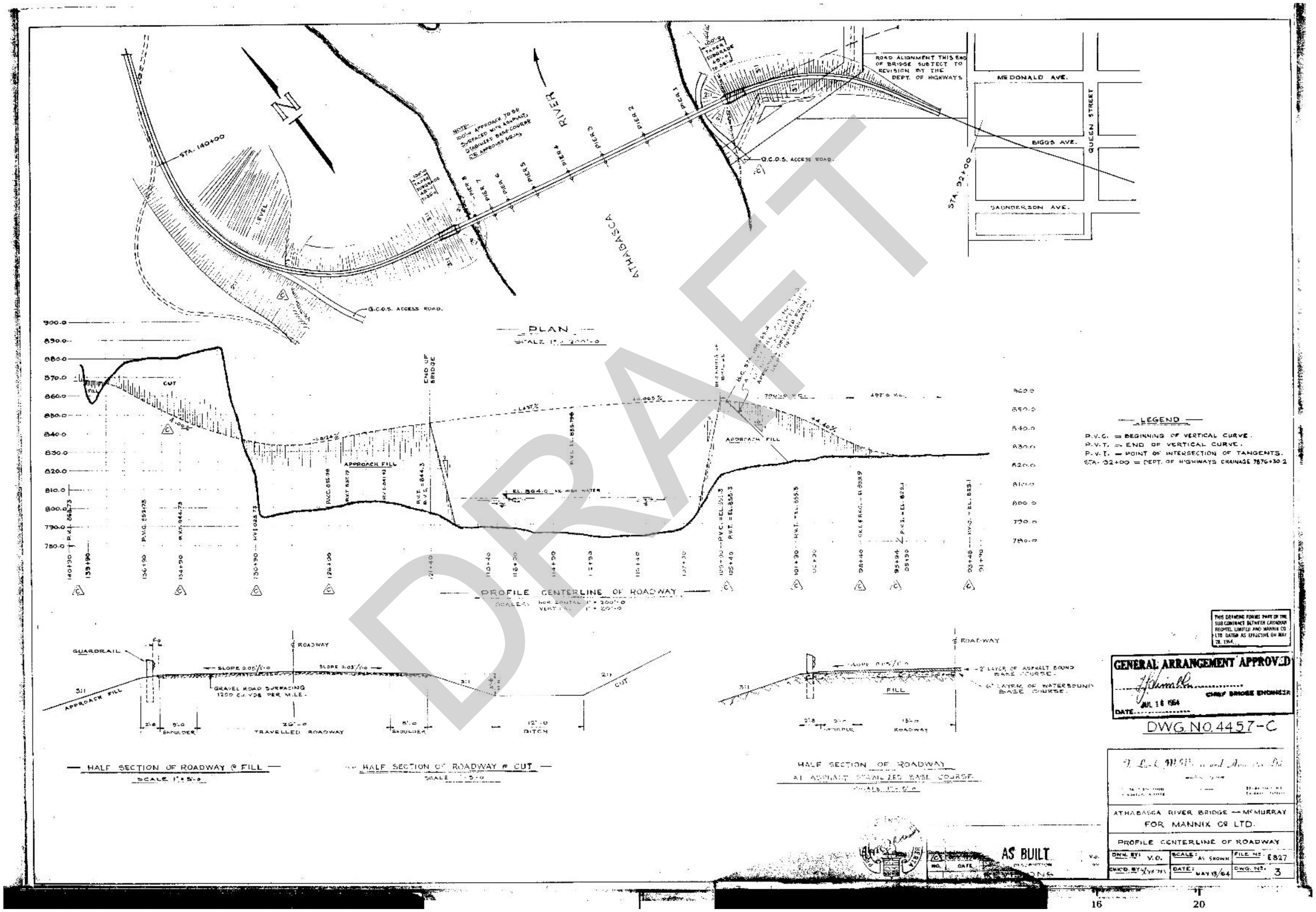
Date	Comment
2-6 Oct 1874	Fine and calm.
7-8 Oct 1874	Cloudy and colder than usual.
9-18 Oct 1784	Fine day.
22 Oct 1874	Clouds and wind.
24 Oct 1874	Cold with showers of snow and ice.
27 Oct 1874	Wind north, slight fall of snow, William Charles came back owing to ice drifting.
28 Oct 1874	Weather overcast, Willian Charles gathering up hay on the land.
30-31 Oct 1874	Weather fine, no appearance of cold weather.
2 Nov 1874	Wind, overcast, slight fall of snow.
3-9 Nov 1874	Wind, no appearance of cold.
10 Nov 1874	Wind, small cold, slight fall of snow.
12 Nov 1874	Cold, the weather has now changed.
13-15 Nov 1874	Cold weather, wind.
16 Nov 1874	Clear weather, small cold.
19 Nov 1874	Weather milder than usual, slight fall of snow.
20-21 Nov 1874	Weather overcast.
22 Nov 1874	Weather cold.
23 Nov 1874	Clear weather.
24 Nov 1874	Nice weather.
28-29 Nov 1874	Clear cold weather.
30 Nov 1874	Slight fall of snow.
1 Dec 1874	Fine clear weather.
2-5 Dec 1874	Mild weather.
7 Dec 1874	Shower of rain last night, by the afternoon blowing storm and snowing, ice dangerous, horses unfit to cross to the fishery owing to the weather being so mild.
10 Dec 1874	Coldest day this winter, clear weather.
11-12 Dec 1874	Weather cold.
13 Dec 1874	Overcast, weather mild.
14 Dec 1874	Snowing and drifting.
17-18 Dec 1874	Weather much milder.
21 Dec 1874	Beautiful clear day.
22-23 Dec 1874	Mild weather, beautiful.
24 Dec 1874	Overcast, snowing.
25 Dec 1874	Overcast.
26-28 Dec 1874	Weather cold.
1 Jan 1875	Weather milder than usual.
7 Jan 1875	Clear, cold.
8 Jan 1875	Clear.
9 Jan 1875	34 below zero at sunrise, clear.
12 Jan 1875	Weather cold.
13 Jan 1875	Weather much milder than usual.
15-19 Jan 1875	Weather not so cold.

20 Jan 1875	Strong wind from north. Snowing and drifting. MacKlin, McKay, Flett, and Beechaw commenced to chop ice for summer's use.
21 Jan 1875	Strong wind from north. Snowing and drifting.
22-25 Jan 1875	Weather much milder.
26 Jan 1875	Weather clear and bright.
27 Jan 1875	Clear cold day.
28-30 Jan 1875	Mild weather.
1-2 Feb 1875	Fine clear day, but cold.
3-4 Feb 1875	Weather cold.
6 Feb 1875	A beautiful day.
8 Feb 1875	Mild weather.
10 Feb 1875	29 below zero, rather cold and clear.
11 Feb 1875	Rather cold, weather clear.
12-14 Feb 1875	Fine clear day.
15 Feb 1875	Storming in first part of day then clear.
16-20 Feb 1875	Mild weather.
21 Feb 1875	Weather cold.
22 Feb 1875	Clear cold day, 35 below zero.
23-26 Feb 1875	Weather cold.
1 Mar 1875	First part of the day mild, but after dark blowing, snowing, and drifting.
4-6 Mar 1875	Snow.
8 Mar 1875	Weather mild.
11 Mar 1875	Snowing and drifting.
13-14 Mar 1875	Weather cold for this time of the season.
19 Mar 1875	Weather mild, snowing.
20 Mar 1875	Mild weather.
21-22 Mar 1875	Weather cold.
23-24 Mar 1875	Much milder today.
27 Mar 1875	Blowing and drifting.
28 Mar 1875	Mild, blowing slightly.
29 Mar 1875	Overcast, mild.
30-31 Mar 1875	First mild day of the season.
1 Apr 1875	A beautiful day, thawing slightly.
3 Apr 1875	Weather clear.
4 Apr 1875	Weather clear, but cold.
6 Apr 1875	Weather mild.
8 Apr 1875	Appearance of spring, thawing slightly.
10 Apr 1875	Slight fall of snow toward sundown, fine and clear.
13 Apr 1875	A beautiful day, thawing.
16 Apr 1875	Warmest day of the season.
22 Apr 1875	Thawing but little.
23-26 Apr 1875	Thawing a great deal today.
27-29 Apr 1875	Weather cold, thawing but little.
3 May 1875	Water commencing to make its appearance on the ice.

Appendix C: McEwan Bridge Drawings


LIST OF DRAWINGS
1. GENERAL LAYOUT.
2. TEST HOLE DATA.
3. PROFILE CENTERLINE OF ROADWAY.
4. APPROACHES.
5. EAST ABUTMENT.
6. EAST ABUTMENT DETAILS.
7. WEST ABUTMENT.
8. WEST ABUTMENT DETAILS.
9. PIER NO. 1.
10. PIER NO. 2.
11. PIER NO. 3.
12. PIER NO. 4.
13. PIER NO. 5.
14. PIER NO. 6.
15. PIER NO. 7.
16. PIER NO. 8.
17. NOSE PLATE DETAILS.
18. MISC. DETAILS, GENERAL NOTES.
19. MISC. DETAILS, GENERAL NOTES.
20. TRUSS STRESS DIAGRAM.
21. TRUSS STRESS DIAGRAM.
22. TRUSS STRESS DIAGRAM.
23. TRUSS STRESS DIAGRAM.
24. TRUSS STRESS DIAGRAM.
25. GIRDER 'A'.
26. GIRDER 'B'.
27. GIRDER 'C'.
28. CROSS-SECTIONS, SWAY FRAMES.
29. END PORTAL.
30. STRINGERS, FLOOR BEAMS, JACKING BEAMS.
31. WIND ARTICULATION DETAILS.
32. FIXED AND ROCKER BEARING DETAILS.
33. WIND KEY DETAILS.
34. FINGER PLATE DETAILS.
35. MISC. DETAILS.
36. MISC. DETAILS.
37. HANDRAIL.
38. DECK SECTIONS, POUR SCHEDULE.
39. REINFORCING DETAILS.
ISLAND
N
RIVER
ATHABASCA
FRANKLIN AVE.
McDONALD AVE.
BIGGS AVE.
SAUNDERSON AVE.
QUEEN STREET
FORT McMURRAY
EXISTING ROAD
PLAN
ATHABASCA RIVER BRIDGE SITE
SCALE 1" = 200'-0
TYPICAL CROSS-SECTION A-A
APPROACH FILL
100'-0
100'-0
100'-0
150'-0
200'-0
200'-0
250'-0
250'-0
200'-0
EXPANSION JOINT
ROCKER
FIXED
TOP OF DECK
WEST ABUTMENT
PIER 8
PIER 7
PIER 6
PIER 5
PIER 4
PIER 3
PIER 2
PIER 1
EAST ABUTMENT
ELEVATION
ATHABASCA RIVER BRIDGE AT FORT McMURRAY
SCALE 1" = 50'-0
DWG. NO. 4455 – C
PROFILE DIAGRAM
ELEVATIONS TOP OF ROADWAY
ELEVATIONS TOP OF PIERS
NOTE:
ELEVATIONS GIVEN ARE CENTERLINE TOP OF ROADWAY & TOP OF PIERS
NOTE:
ELEVATIONS GIVEN ARE GEODETIC.
BENCH MARK = SOUTH EAST CORNER OF CONCRETE BASE AT METRE MONUMENT IN PETER POND PUBLIC SCHOOL GROUNDS, GEODETIC DATUM 819.32.
CHAINAGES BASED ON ALBERTA DEPARTMENT OF HIGHWAYS SURVEY MARCH 1963.
DESIGN LIVE LOAD A.A.S.H.O. H20-S16 WITH PROVISION FOR OVERLOAD OF A SINGLE H40-S32 TRUCK.
APPROVED
C 12/10/65 AS BUILT V.O.
B 22/6/64 CURVE DATA REVISED V.O.
A 17/6/64 CURVE DATA REVISED V.O.
MARK DATE REVISION BY
T. Lamb, McManus and Associates Ltd.
Consulting Engineers
ATHABASCA RIVER BRIDGE – McMURRAY
FOR MANNIX Co LTD.
GENERAL LAYOUT
DWN. BY: V.O.
SCALE: AS SHOWN
FILE No: E027
CKD. BY:
DATE: MAY 13/64
DWG. No: 1


ISLAND
RIVER
ATHABASCA
FRANKLIN AVE.
McDONALD AVE.
DIGGS AVE.
SAUNDERSON AVE.
QUEEN STREET
FORT McMURRAY
HOLE #11
HOLE #10
HOLE #3
HOLE #2
HOLE #9
HOLE 'A'
HOLE 'B'
HOLE 'C'
HOLE 'D'
HOLE 'E'
HOLE #4
HOLE #5
STA. 140+00
STA. 141+00
STA. 122+40
EXISTING ROAD
PLAN OF ATHABASCA BRIDGE SITE
SCALE 1" = 200'-0
EL. 854.0 EST. EXTREME HIGH WATER
EL. 799.0
EL. 792.5 ICE LEVEL MARCH 9/63
ICE
WATER
LIMESTONE
SAND
GRAVEL
CLAY
SILT
TAR SAND
TEST HOLE DATA AT BRIDGE CENTERLINE 1963
SCALES: 1" = 100'-0 HORIZONTAL 1" = 20'-0 VERTICAL
HOLE #11
HOLE #10
HOLE #9
HOLE #3
HOLE #2
HOLE #1
HOLE #8
HOLE #7
HOLE #6
HOLE #4
HOLE #5
TEST HOLE DATA 1963
TEST HOLE DATA & PROPOSED CROSSING 1957
GENERAL ARRANGEMENT APPROVED
CHIEF BRIDGE ENGINEER
JUL 10 1964
DATE
AS BUILT DWG NO 4456 - C
T. Lamb, McManus and Associates Ltd.
Consulting Engineers
ATHABASCA RIVER BRIDGE — McMURRAY
FOR MANNIX Co LTD.
TEST HOLE DATA
DWN. BY: V.C.
SCALE: AS SHOWN
FILE No: E827
CHKD. BY:
DATE: MAY 13/64
DWG. No: 2
16
20


N
ATHABASCA RIVER
STA. 140+00
STA. 92+00
PIER 1
PIER 2
PIER 3
PIER 4
PIER 5
PIER 6
PIER 7
PIER 8
G.C.O.S. ACCESS ROAD
ROAD ALIGNMENT THIS END OF BRIDGE SUBJECT TO REVISION BY THE DEPT. OF HIGHWAYS
MCDONALD AVE.
BIGGS AVE.
SAUNDERSON AVE.
QUEEN STREET
PLAN
SCALE 1" = 200'-0
END OF BRIDGE
CUT
APPROACH FILL
EL. 804.0 ± HIGH WATER
PROFILE CENTERLINE OF ROADWAY
SCALES: HORIZONTAL 1" = 200'-0 VERT. 1" = 20'-0
LEGEND
P.V.C. = BEGINNING OF VERTICAL CURVE.
P.V.T. = END OF VERTICAL CURVE.
P.V.I. = POINT OF INTERSECTION OF TANGENTS.
STA. 92+00 = DEPT. OF HIGHWAYS CHAINAGE 7876+30.2
GUARDRAIL
SLOPE 0.03'/1'-0
GRAVEL ROAD SURFACING 1200 CU. YDS. PER MILE
20'-0 TRAVELLED ROADWAY
SHOULDER
DITCH
HALF SECTION OF ROADWAY @ FILL
SCALE 1" = 5'-0
HALF SECTION OF ROADWAY @ CUT
SCALE 1" = 5'-0
2" LAYER OF ASPHALT BOUND BASE COURSE
6" LAYER OF WATERBOUND BASE COURSE
HALF SECTION OF ROADWAY AT ASPHALT STABILIZED BASE COURSE
SCALE 1" = 5'-0
THIS DRAWING FORMS PART OF THE SUB-CONTRACT BETWEEN CANADIAN BECHTEL LIMITED AND MANNIX CO LTD DATED AS EFFECTIVE ON MAY 28, 1964.
GENERAL ARRANGEMENT APPROVED
CHIEF BRIDGE ENGINEER
DATE JUL 16 1964
DWG. NO. 4457-C
AS BUILT
ATHABASCA RIVER BRIDGE — McMURRAY
FOR MANNIX CO LTD.
PROFILE CENTERLINE OF ROADWAY
DWN. BY: V.O.
SCALE: AS SHOWN
FILE No. E827
DATE: MAY 13/64
DWG. No. 3
16
20

Appendix C

APPENDIX B

BIBLIOGRAPHY OF HISTORICAL ICE STUDY REPORTS

Salient Ice-Related Reports Documenting Breakup Processes and Water Levels on the Athabasca River at Fort McMurray

Existing reports and/or documents that address ice-related concerns on the Athabasca River at Fort McMurray were identified and their titles are summarized herein. There are many reports in the literature that cover a wide range of ice-related topics at Fort McMurray. The reports were placed into two categories – primary sources and secondary sources. Those reports that contain the following information were considered as primary data sources.

1. Observed/measured ice-related annual peak water levels.
2. Descriptions of the characteristics/mechanics of the breakup process, including factors that affect the timing and severity of breakup and the ice condition (sate) that produces the peak ice-related water level – thermal breakup, ice surge (jave), and/or fully developed equilibrium ice jam within the context of the flow at breakup.
3. Descriptions of statistical techniques used to develop stage frequency curves from the historical data, including the perception stage method, the historical data adjustment approach outlined in Bulletin 17B, and Monte Carlo simulations.
4. Frequency estimates of ice-related water levels.

Each of the primary data resources have been tagged below regarding which of the four information classes they are likely to contain – the bold numbers shown in parentheses at the end of each reference represent the type of data contained in each reference.

The remaining reports, which (i) discuss flood mitigation issues at a management level, (ii) are previous iterations or draft reports that contribute to a subsequent final report, or (iii) are theses upon which a journal article is based, are relegated to secondary status.

Primary Sources (Described by Relevant Topic):

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Andres D. D. and Rickert, H.A., 1985. Observations of the 1985 breakup in the Athabasca River basin upstream of Fort McMurray, Alberta. Alberta Research Council Report No. SWE-85/10. Edmonton, Alberta. **(1)**

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Mahabir, C. and Garner, L., 2007. Athabasca River ice observations 2006–2007. Report of River Ice Engineering Team, Water Management Operations. Alberta Environment, Edmonton, AB. **(1)**

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Northwest Hydraulic Consultants Ltd. (NHC), 1979. A study of flood levels and impacts of dikes along the Clearwater River at Fort McMurray. Report prepared for Alberta Environmental Protection. **(1,3,4)**

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APPENDIX C

ALBERTA ENVIRONMENT AND PARKS ICE-RELATED WATER LEVEL DATA

Year	Breakup Date		Peak Breakup Water Levels in m (H_B)						Adjusted to G70 by:	Thermal breakup or original ice jam location?	Comment on WL's
	Day (dd-mm)	Source	G90	G85	G80	G75	G70	G55			
			Intake 1	Intake 2	Bridges	Mc I	Clearwater	WSC			
1875	20-Apr	HBC			253.0		252.0		NHC (1978)	G75-G80	G80 estimated, flood
1881	21-Apr	HBC			< 250		249.0		NHC (1978)	G75-G80	flood
1885	9-Apr	HBC			249.0		248.1		NHC (1978)	G70-G80	flood
1925							247.4 [a]				flood
1928							248.6 [a]				flood
1936	21-Apr	NARC					250.1				flood
1938	27-Apr	DOT									
1939	21-Apr	DOT									
1940	25-Apr	DOT									
1941	14-Apr	DOT									
1948	1-May	DOT									
1949	15-Apr	DOT									
1950	28-Apr	DOT									
1953	21-Apr	DOT									
1954	9-May	DOT									breakup date questionable
1955	17-Apr	DOT									
1956	20-Apr	DOT									
1957	before 3-May	DOT									

	Breakup Date		Peak Breakup Water Levels in m (H_B)						Adjusted to G70 by:	Thermal breakup or original ice jam location?	Comment on WL's
Year	Day (dd-mm)	Source	G90	G85	G80	G75	G70	G55			
			Intake 1	Intake 2	Bridges	Mc I	Clearwater	WSC			
1958	15-Apr	DOT						244.9 [b]			no flood damage
1959	13-Apr	DOT									
1960	15-Apr	WSC									
1961	28-Apr	WSC									
1962	17-Apr	WSC					246.2 [b]	242.7			Doyle (1987); flood; G70 questionable
1963	20-Apr	DOT			247.5 [b]		247.5 [b]	*244*		G75-G80 [l]	Doyle (1987); *gauge malfunctioned*; flood
1964	21-Apr	WSC									flood not severe
1965	14-Apr	WSC									
1966	15-Apr	WSC						239.6			Doyle (1987)
1967	28-Apr	WSC						*239*			Doyle (1987); *gauge malfunctioned*
1968	27-Apr	WSC						238.4		thermal breakup	Doyle (1987)
1969	14-Apr	WSC						*239.0*			Doyle (1987); *gauge malfunctioned*
1970	7-Apr	WSC						238.4			Doyle (1987)
1971	20-Apr	WSC						239.0			Doyle (1987)
1972	22-Apr	WSC			245.3 [c]		244.3	244.7	NHC (1978)	ice jam [c]	Doyle (1987); G70 questionable
1973	18-Apr	WSC						240.5			
1974	19-Apr	WSC			247.2 [j]		246.7 [j]	*241.4*		uneventful breakup [j]	*gauge malfunctioned*
1975	25-Apr	WSC						*239.7*			*gauge malfunctioned*

	Breakup Date		Peak Breakup Water Levels in m (H_B)								
Year	**Day (dd-mm)**	**Source**	**G90**	**G85**	**G80**	**G75**	**G70**	**G55**	**Adjusted to G70 by:**	**Thermal breakup or original ice jam location?**	**Comment on WL's**
			Intake 1	**Intake 2**	**Bridges**	**Mc I**	**Clearwater**	**WSC**			
1976	13-Apr	WSC						*242.4*			ARC; *gauge malfunctioned*
1977	14-Apr	WSC			248.7		247.6	*244.2*		G45-G50 to G125	ARC; *gauge malfunctioned;* flood
1978	19-Apr	WSC					242.0	240.6		G80 to G130-G135	ARC
1979	28-Apr	WSC			247.5		246.9	*244.9*		G35-G40 to G110-G115	ARC; *gauge malfunctioned*; flood
1980	15-Apr	WSC						240.7			
1981	10-Apr	WSC					244.0$_g$	*240.7*			ARC; *gauge malfunctioned*
1982	26-Apr	AE			246.8		242.2	*238.9*		G70 to G90-G95	ARC; *gauge malfunctioned*
1983	18-Apr	WSC			242.0		242.3	239.6		uneventful breakup	G70 questionable; ARC
1984	10-Apr	WSC			244.5		243.5	240.9	AE (1993)	G85-G90 to G110-G115	G70 questionable; ARC
1985	18-Apr	ARC					243.5	*241.2*		uneventful breakup	ARC; *gauge malfunctioned*
1986	19-Apr	WSC					244.0	240.9		G50 to G115	ARC
1987	16-Apr	WSC			246.5$_e$		245.1$_e$	*241*		G45 to G115$_e$	*gauge malfunctioned*
1988	16-Apr	WSC			244.8$_k$		244.5$_k$	*241*		G45-G50 to G115$_k$	*gauge malfunctioned*
1989	22-Apr	WSC					243.1$_f$	*238*			*gauge malfunctioned*
1990	20-Apr	WSC					243.0$_f$	*239*			*gauge malfunctioned*
1991	13-Apr	WSC						*240*		uneventful breakup$_g$	*gauge malfunctioned*

	Breakup Date		Peak Breakup Water Levels in m (H_B)								
Year	Day (dd-mm)	Source	G90	G85	G80	G75	G70	G55	Adjusted to G70 by:	Thermal breakup or original ice jam location?	Comment on WL's
			Intake 1	Intake 2	Bridges	Mc I	Clearwater	WSC			
1992	3-Apr	WSC					241.4 [g]	239.5		uneventful breakup [g]	
1993	19-Apr	WSC						*239*		uneventful breakup [g]	*gauge malfunctioned*
1994	11-Apr	WSC					244.0 [g]	242.8		uneventful breakup [g]	
1995	22-Apr	WSC						239.0		uneventful breakup [g]	
1996	16-Apr	WSC					245.9 [g]	243.2		ice jam [g]	
1997	20-Apr	RMWB					247.0 [g]			ice jam [g]	large ice jam; G70 questionable
1998	9-Apr	WSC	243.0 [h]					239.0		uneventful breakup [g]	
1999	14-Apr	WSC	242.0 [i]	242.1 [i]	241.2 [i]	240.8 [i]	240.4 [i]	238.5		thermal breakup [i]	
2000	23-Apr	WSC	241.9 [h]				240.6 [i]	238.6		uneventful breakup [i]	
2001	25-Apr	UA	243.2	242.7	242.1		240.9			small ice run	
2002											
2003											242.1 in Clearwater River Critical River Elevations
2004											
2005	21-Apr	AE					242.5				
2006	19-Apr	AE					241.62				
2007	19-Apr	AE					244.27				April 19 (?), 245.7 at Water Treatment Plant in Clearwater River Critical River Elevations

	Breakup Date		Peak Breakup Water Levels in m (H_B)						Adjusted to G70 by:	Thermal breakup or original ice jam location?	Comment on WL's
Year	Day (dd-mm)	Source	G90	G85	G80	G75	G70	G55			
			Intake 1	Intake 2	Bridges	Mc I	Clearwater	WSC			
2008	2-May	AE					242				(+/- 0.5m), 243.5 at Waterways in Clearwater River Critical River Elevations,
2009	18-Apr	AE					241.7				(+/- 0.5m)
2010	15-Apr	AE					241.38				(+/- 0.5m) HWM also available at the Water Treatment Plant & Fort McMurray Golf Course
2011	23-Apr	AE					240.655				HWM also available at the Water Treatment Plant & Fort McMurray Golf Course
2012	22-Apr	AE					241.093				HWM also available at the Water Treatment Plant & Fort McMurray Golf Course
2013	29-Apr	AE					244.497				HWM also available at the Water Treatment Plant & Fort McMurray Golf Course
2014	27-Apr	AE									No AEP info available, RMWB might have supporting information.
2015	7-Apr	AE					244.794			ice jam formed through town on breakup date	HWM also available at the Water Treatment Plant & Fort McMurray Golf Course, flooding of low lying areas

Year	Breakup Date		Peak Breakup Water Levels in m (H_B)						Adjusted to G70 by:	Thermal breakup or original ice jam location?	Comment on WL's
	Day (dd-mm)	Source	G90	G85	G80	G75	G70	G55			
			Intake 1	Intake 2	Bridges	Mc I	Clearwater	WSC			
2016	10-Apr	AE					243.91			ice jam formed through town on breakup date	HWM also available at the Water Treatment Plant & Fort McMurray Golf Course, some low lying areas affected
2017	25-Apr	AE					242.89			ice jam formed just upstream of bridges on April 12, ice remained in town until April 25 when the jam released (breakup date).	HWM also available at the Water Treatment Plant & Fort McMurray Golf Course

[a] *Northern Alberta Railways Co. as referred to in Blench and Associates Ltd. (1964)*

[b] *Department of Northern Affairs and National Resources as referred to in Blench and Associates Ltd. (1964)*

[c] *Northwest Hydraulic Consultants Ltd. (1978)*

[d] *Strip chart from WSC gauge below Fort McMurray on the Athabasca River*

[e] *Alberta Environment (1988)*

[f] *City of Fort McMurray as referred to in Alberta Environmental Protection (1993)*

[g] *Alberta Environment (personal communication)*

[h] *Regional Municipality of Wood Buffalo (2002)*

[i] *University of Alberta*

[j] *Northwest Hydraulic Consultants Ltd. (1974)*

[k] *Alberta Environment (1989): Draft*

[l] *Blench and Associates Ltd. (1964)*

HBC = Hudson's Bay Co.

NHC = Northwest Hydraulic Consultant Ltd.

NARC = Northern Alberta Railways Co.

DOT = Department of Transportation, Canada

WSC = Water Survey of Canada

ARC = Alberta Research Council

AE = Alberta Environment

RMWB = Regional Municipality of Wood Buffalo

UA = University of Alberta

Note: *Green cells represent years, which no ice jam occurred between the Golf Course and D/S of the Clearwater River Confluence where it affects the Clearwater River water level. Gauge malfunctioned was only documented for H_B. When the source for H_B and the ice jam locations was different from the breakup date source, a comment was added*

APPENDIX D

WATER SURFACE PROFILES 50-YR, 100-YR AND 200-YR ICE JAM EVENT

					50 Year Flood		100 Year Flood		200 Year Flood	
River	River Station (Open Water)	Description	River Station (Ice Enhanced)	Thalweg Elevation (m)	Flow (m^3/s)	Water Surface (m)	Flow (m^3/s)	Water Surface (m)	Flow (m^3/s)	Water Surface (m)
Athabasca	36191.07	Upper end of reach	17518.78	241.62	1350	250.02	1600	250.82	1875	251.75
Athabasca	35207.05		16534.76	241.38	1350	249.84	1600	250.65	1875	251.60
Athabasca	34387.97		15715.68	240.92	1350	249.67	1600	250.50	1875	251.46
Athabasca	33720.57		15048.28	240.26	1350	249.49	1600	250.34	1875	251.32
Athabasca	33018.14		14345.85	240.75	1350	249.28	1600	250.18	1875	251.20
Athabasca	32378.51		13706.22	239.47	1350	249.12	1600	250.07	1875	251.11
Athabasca	31742.95		13070.66	240.11	1350	248.98	1600	249.97	1875	251.03
Athabasca	30908.92		12236.63	235.8	1350	248.86	1600	249.87	1875	250.93
Athabasca	30463.76		11791.47	237.85	1350	248.80	1600	249.81	1875	250.87
Athabasca	29980.79		11308.5	238.23	1350	248.68	1600	249.70	1875	250.75
Athabasca	29419.2		10746.91	238.01	1350	248.55	1600	249.57	1875	250.58
Athabasca	29347.21	Grant McEwan Bridge	10674.92	-	-	-	-	-	-	-
Athabasca	29236.7		10564.41	238.35	1350	248.50	1600	249.52	1875	250.52
Athabasca	28977.81		10305.52	238.92	1350	248.48	1600	249.50	1875	250.49
Athabasca	28451.49		9779.201	238.30	1350	248.43	1600	249.45	1875	250.44
Athabasca	27846.51	Clearwater Confluence	9174.223	237.57	1450	248.40	1700	249.42	1975	250.40
Athabasca	27231.06		8558.773	237.24	1450	248.39	1700	249.41	1975	250.39
Athabasca	26567.64		7895.353	235.72	1450	248.38	1700	249.40	1975	250.38
Athabasca	25816.07		7143.78	236.46	1450	248.37	1700	249.38	1975	250.36
Athabasca	25110.09	WSC Gauge Location	6437.807	235.36	1450	248.35	1700	249.37	1975	250.35
Athabasca	24347.35		5675.062	235.09	1450	248.34	1700	249.36	1975	250.34
Athabasca	23775.79		n/a	233.56	1450	248.32	1700	249.33	1975	250.31
Athabasca	23571.38		4899.097	233.02	1450	248.29	1700	249.29	1975	250.22
Athabasca	22918.4		4246.117	235.44	1450	248.18	1700	249.08	1975	249.87

					50 Year Flood		100 Year Flood		200 Year Flood	
River	River Station (Open Water)	Description	River Station (Ice Enhanced)	Thalweg Elevation (m)	Flow (m^3/s)	Water Surface (m)	Flow (m^3/s)	Water Surface (m)	Flow (m^3/s)	Water Surface (m)
Athabasca	21755.09		3082.808	235.16	1450	247.43	1700	248.38	1975	249.47
Athabasca	21019.67	Poplar Island	2347.389	234.30	1450	246.87	1700	248.27	1975	249.20
Athabasca	20091.93		1419.641	233.40	1450	245.59	1700	247.85	1975	248.89
Athabasca	18800.79		128.5046	233.12	1450	244.79	1700	247.47	1975	248.27
Athabasca	18402.34		n/a	232.70	1450	244.71	1700	247.45	1975	248.15
Athabasca	16145.39		n/a	231.47	1450	243.22	1700	243.68	1975	243.89
Athabasca	15245.39		n/a	231.25	1450	239.24	1700	239.61	1975	239.97
Athabasca	13485.84		n/a	230.64	1450	238.75	1700	239.08	1975	239.41
Athabasca	10317.84		n/a	230.00	1450	237.77	1700	238.09	1975	238.42
Athabasca	9042.438		n/a	231.45	1450	237.51	1700	237.82	1975	238.13
Athabasca	7123.497		n/a	232.30	1450	237.20	1700	237.50	1975	237.81
Athabasca	4986.258		n/a	231.51	1450	236.60	1700	236.89	1975	237.19
Athabasca	3393.253		n/a	230.80	1450	235.96	1700	236.26	1975	236.58
Athabasca	1010.78		n/a	230.20	1450	235.01	1700	235.37	1975	235.76
Clearwater	20359.02	Upper end of reach	20359.02	241.31	385	248.63	436	249.56	488	250.49
Clearwater	19986.30		19986.30	241.67	385	248.62	436	249.55	488	250.49
Clearwater	19705.16		19705.16	242.18	385	248.61	436	249.55	488	250.48
Clearwater	19181.71		19181.71	241.03	385	248.59	436	249.54	488	250.48
Clearwater	18685.47		18685.47	240.85	385	248.57	436	249.53	488	250.47
Clearwater	18261.58		18261.58	240.87	385	248.56	436	249.52	488	250.47
Clearwater	17882.61		17882.61	240.31	385	248.55	436	249.51	488	250.46
Clearwater	17460.42		17460.42	237.64	385	248.54	436	249.51	488	250.46
Clearwater	16972.25		16972.25	241.28	385	248.53	436	249.50	488	250.46
Clearwater	16560.32		16560.32	240.18	385	248.52	436	249.49	488	250.45

					50 Year Flood		100 Year Flood		200 Year Flood	
River	River Station (Open Water)	Description	River Station (Ice Enhanced)	Thalweg Elevation (m)	Flow (m^3/s)	Water Surface (m)	Flow (m^3/s)	Water Surface (m)	Flow (m^3/s)	Water Surface (m)
Clearwater	16222.89		16222.89	240.91	385	248.51	436	249.49	488	250.45
Clearwater	15826.04		15826.04	238.81	385	248.50	436	249.48	488	250.44
Clearwater	15382.20		15382.20	238.75	385	248.49	436	249.48	488	250.44
Clearwater	14757.45		14757.45	240.54	385	248.49	436	249.48	488	250.44
Clearwater	14127.07		14127.07	241.05	385	248.48	436	249.47	488	250.44
Clearwater	13537.46		13537.46	239.82	385	248.48	436	249.47	488	250.44
Clearwater	13178.92		13178.92	240.31	385	248.47	436	249.47	488	250.43
Clearwater	12785.95		12785.96	240.44	385	248.47	436	249.47	488	250.43
Clearwater	12424.12		12424.13	236.37	385	248.47	436	249.47	488	250.43
Clearwater	11984.90		11984.91	239.96	385	248.47	436	249.47	488	250.43
Clearwater	11537.24		11537.25	238.96	385	248.47	436	249.46	488	250.43
Clearwater	11033.47		11033.48	239.56	385	248.46	436	249.46	488	250.43
Clearwater	10662.83		10662.84	239.81	385	248.46	436	249.46	488	250.43
Clearwater	10095.14		10095.15	239.03	385	248.46	436	249.46	488	250.43
Clearwater	9673.80		9673.81	239.46	385	248.46	436	249.46	488	250.43
Clearwater	9209.62		9209.63	239.27	385	248.45	436	249.46	488	250.43
Clearwater	8934.32		8934.33	239.56	385	248.45	436	249.45	488	250.43
Clearwater	8679.21		8679.22	239.19	385	248.45	436	249.45	488	250.42
Clearwater	8439.88		8439.89	238.76	385	248.45	436	249.45	488	250.42
Clearwater	8120.88		8120.88	239.63	385	248.45	436	249.45	488	250.42
Clearwater	7779.76		7779.77	237.66	385	248.44	436	249.45	488	250.42
Clearwater	7396.45		7396.45	238.07	385	248.44	436	249.45	488	250.42
Clearwater	7080.89		7080.89	235.03	385	248.44	436	249.45	488	250.42
Clearwater	6802.13		6802.13	238.39	385	248.44	436	249.45	488	250.42

					50 Year Flood		100 Year Flood		200 Year Flood	
River	**River Station (Open Water)**	**Description**	**River Station (Ice Enhanced)**	**Thalweg Elevation (m)**	**Flow (m^3/s)**	**Water Surface (m)**	**Flow (m^3/s)**	**Water Surface (m)**	**Flow (m^3/s)**	**Water Surface (m)**
Clearwater	6604.86	Confluence with Hangingstone	6604.85	237.84	421	248.44	480	249.45	538	250.42
Clearwater	6350.50		6350.49	238.45	421	248.43	480	249.44	538	250.42
Clearwater	6078.46		6078.45	238.61	421	248.43	480	249.44	538	250.42
Clearwater	5805.90		5805.89	238.84	421	248.43	480	249.44	538	250.42
Clearwater	5535.46		5535.45	236.06	421	248.42	480	249.44	538	250.41
Clearwater	5194.11		5194.10	237.74	421	248.42	480	249.43	538	250.41
Clearwater	4759.93		4759.93	238.27	421	248.42	480	249.43	538	250.41
Clearwater	4324.20		4324.20	238.45	421	248.41	480	249.43	538	250.41
Clearwater	3906.22		3906.22	238.76	421	248.41	480	249.43	538	250.40
Clearwater	3541.04		3541.04	238.27	421	248.41	480	249.42	538	250.40
Clearwater	3182.93		3182.93	238.76	421	248.41	480	249.42	538	250.40
Clearwater	2815.17		2815.17	238.10	421	248.41	480	249.42	538	250.40
Clearwater	2250.47	Confluence with Snye	2250.47	238.07	421	248.40	480	249.42	538	250.40
Clearwater	1847.55		1847.54	237.92	421	248.40	480	249.42	538	250.40
Clearwater	1470.96		1470.96	238.15	421	248.40	480	249.41	538	250.40
Clearwater	1043.02		1043.02	237.96	421	248.39	480	249.41	538	250.39
Clearwater	479.82	Athabasca Confluence	479.82	237.78	421	248.39	480	249.41	538	250.39
Hangingstone	5585.59		5585.61	263.83	36	265.21	44	265.36	50	265.46
Hangingstone	5506.66		5506.68	263.40	36	264.85	44	265.01	50	265.12
Hangingstone	5376.60		5376.62	261.90	36	263.80	44	263.97	50	264.08
Hangingstone	5277.66		5277.68	261.59	36	263.34	44	263.47	50	263.56
Hangingstone	5161.99		5162.01	261.10	36	262.64	44	262.77	50	262.85
Hangingstone	5048.18		5048.2	260.47	36	261.82	44	261.95	50	262.05
Hangingstone	4975.22		4975.24	260.09	36	261.41	44	261.55	50	261.66

					50 Year Flood		100 Year Flood		200 Year Flood	
River	**River Station (Open Water)**	**Description**	**River Station (Ice Enhanced)**	**Thalweg Elevation (m)**	**Flow (m^3/s)**	**Water Surface (m)**	**Flow (m^3/s)**	**Water Surface (m)**	**Flow (m^3/s)**	**Water Surface (m)**
Hangingstone	4941.60		4941.62	259.42	36	261.27	44	261.42	50	261.53
Hangingstone	4874.37		4874.39	259.41	36	261.02	44	261.15	50	261.27
Hangingstone	4787.70		4787.72	259.19	36	260.58	44	260.70	50	260.80
Hangingstone	4693.74		4693.76	258.87	36	260.05	44	260.18	50	260.27
Hangingstone	4600.28		4600.30	258.28	36	259.57	44	259.72	50	259.82
Hangingstone	4524.80		4524.82	257.26	36	259.21	44	259.36	50	259.47
Hangingstone	4505.95		4505.97	257.21	36	259.05	44	259.18	50	259.29
Hangingstone	4449.33		4449.35	256.96	36	258.84	44	258.98	50	259.08
Hangingstone	4408.84		4408.86	257.03	36	258.65	44	258.80	50	258.91
Hangingstone	4313.53		4313.55	256.15	36	258.09	44	258.27	50	258.39
Hangingstone	4172.10		4172.12	255.28	36	257.32	44	257.46	50	257.55
Hangingstone	4122.04		4122.06	255.77	36	257.07	44	257.21	50	257.30
Hangingstone	4051.34		4051.36	255.25	36	256.69	44	256.82	50	256.91
Hangingstone	3971.19		3971.21	255.01	36	256.21	44	256.33	50	256.42
Hangingstone	3906.40		3906.42	254.55	36	255.78	44	255.94	50	256.05
Hangingstone	3803.12		3803.14	253.36	36	255.20	44	255.35	50	255.45
Hangingstone	3759.01		3759.03	253.25	36	255.06	44	255.21	50	255.32
Hangingstone	3667.13		3667.15	252.66	36	254.60	44	254.73	50	254.81
Hangingstone	3543.80		3543.82	252.55	36	253.98	44	254.11	50	254.20
Hangingstone	3410.36		3410.37	251.82	36	253.14	44	253.26	50	253.34
Hangingstone	3297.98		3297.99	251.00	36	252.42	44	252.56	50	252.65
Hangingstone	3204.18		3204.19	250.21	36	251.96	44	252.11	50	252.21
Hangingstone	3112.05		3112.06	250.00	36	251.55	44	251.69	50	251.80
Hangingstone	3031.11		3031.12	249.41	36	251.30	44	251.44	50	251.54

					50 Year Flood		100 Year Flood		200 Year Flood	
River	**River Station (Open Water)**	**Description**	**River Station (Ice Enhanced)**	**Thalweg Elevation (m)**	**Flow (m^3/s)**	**Water Surface (m)**	**Flow (m^3/s)**	**Water Surface (m)**	**Flow (m^3/s)**	**Water Surface (m)**
Hangingstone	2952.68		2952.69	249.63	36	250.78	44	250.90	50	251.02
Hangingstone	2822.85		2822.86	248.43	36	250.12	44	250.29	50	250.67
Hangingstone	2710.26		2710.27	248.47	36	249.76	44	249.97	50	250.53
Hangingstone	2611.93		2611.94	247.97	36	249.11	44	249.63	50	250.49
Hangingstone	2557.02		2557.03	247.46	36	248.93	44	249.60	50	250.48
Hangingstone	2490.55		2490.56	247.05	36	248.77	44	249.55	50	250.46
Hangingstone	2471.19		2471.2	246.14	36	248.74	44	249.54	50	250.45
Hangingstone	2459.802	Upstream Highway 63	-	-	-	-	-	-	-	-
Hangingstone	2448.20		2448.21	245.93	36	248.72	44	249.53	50	250.45
Hangingstone	2435.36		-	-	-	-	-	-	-	-
Hangingstone	2417.89		2417.90	246.43	36	248.66	44	249.50	50	250.44
Hangingstone	2360.00*		2360.02	246.17	36	248.60	44	249.49	50	250.43
Hangingstone	2353.99		2354.00	246.14	36	248.60	44	249.48	50	250.43
Hangingstone	2323.76*		2323.78	246.22	36	248.57	44	249.48	50	250.43
Hangingstone	2293.53		2293.55	246.30	36	248.55	44	249.47	50	250.43
Hangingstone	2284.351	Tolen Drive	-	-	-	-	-	-	-	-
Hangingstone	2276.29		2276.31	246.60	36	248.54	44	249.47	50	250.43
Hangingstone	2235.72		2235.74	246.06	36	248.51	44	249.46	50	250.43
Hangingstone	2227.861	Heritage Park Footbridge	-	-	-	-	-	-	-	-
Hangingstone	2221.77		2221.79	246.14	36	248.51	44	249.46	50	250.43
Hangingstone	2156.10		2156.12	246.45	36	248.49	44	249.46	50	250.43
Hangingstone	2071.51		2071.52	245.66	36	248.48	44	249.46	50	250.43
Hangingstone	2007.20		2007.22	244.91	36	248.46	44	249.46	50	250.43
Hangingstone	1923.40		1923.41	244.79	36	248.46	44	249.46	50	250.43

					50 Year Flood		100 Year Flood		200 Year Flood	
River	River Station (Open Water)	Description	River Station (Ice Enhanced)	Thalweg Elevation (m)	Flow (m^3/s)	Water Surface (m)	Flow (m^3/s)	Water Surface (m)	Flow (m^3/s)	Water Surface (m)
Hangingstone	1860.69		1860.70	245.00	36	248.46	44	249.46	50	250.43
Hangingstone	1831.47		1831.48	244.92	36	248.45	44	249.45	50	250.43
Hangingstone	1809.22		1809.23	244.15	36	248.45	44	249.45	50	250.43
Hangingstone	1791.239	Prairie Loop Boulevard	-	-	-	-	-	-	-	-
Hangingstone	1771.25		1771.27	243.80	36	248.45	44	249.45	50	250.43
Hangingstone	1744.08		1744.10	244.07	36	248.45	44	249.45	50	250.43
Hangingstone	1706.85		1706.87	244.41	36	248.45	44	249.45	50	250.43
Hangingstone	1630.86		1630.88	244.15	36	248.44	44	249.45	50	250.43
Hangingstone	1541.09		1541.11	243.74	36	248.44	44	249.45	50	250.43
Hangingstone	1459.56		1459.59	243.38	36	248.44	44	249.45	50	250.43
Hangingstone	1408.07		1408.10	242.89	36	248.44	44	249.45	50	250.43
Hangingstone	1399.323	Ptarmigan Court Footbridge	-	-	-	-	-	-	-	-
Hangingstone	1389.48		1389.51	242.51	36	248.44	44	249.45	50	250.43
Hangingstone	1313.77		1313.80	242.89	36	248.44	44	249.45	50	250.43
Hangingstone	1242.93		1242.96	242.36	36	248.44	44	249.45	50	250.43
Hangingstone	1193.16		1193.18	241.37	36	248.44	44	249.45	50	250.43
Hangingstone	1181.222	Saline Creek Footbridge	-	-	-	-	-	-	-	-
Hangingstone	1171.26		1171.28	241.88	36	248.44	44	249.45	50	250.43
Hangingstone	1149.126	Saline Creek Drive	-	-	-	-	-	-	-	-
Hangingstone	1129.93		1129.95	241.74	36	248.44	44	249.45	50	250.42
Hangingstone	1087.97		1087.99	241.71	36	248.44	44	249.45	50	250.42
Hangingstone	1022.87		1022.88	241.52	36	248.44	44	249.45	50	250.42
Hangingstone	960.05		960.06	241.96	36	248.44	44	249.45	50	250.42
Hangingstone	882.28		882.28	240.8	36	248.44	44	249.45	50	250.42

					50 Year Flood		100 Year Flood		200 Year Flood	
River	River Station (Open Water)	Description	River Station (Ice Enhanced)	Thalweg Elevation (m)	Flow (m^3/s)	Water Surface (m)	Flow (m^3/s)	Water Surface (m)	Flow (m^3/s)	Water Surface (m)
Hangingstone	769.00		769.00	240.77	36	248.44	44	249.45	50	250.42
Hangingstone	700.75		700.75	241.01	36	248.44	44	249.45	50	250.42
Hangingstone	648.16		648.16	240.74	36	248.44	44	249.45	50	250.42
Hangingstone	548.93		548.94	240.88	36	248.44	44	249.45	50	250.42
Hangingstone	489.79		489.80	241.24	36	248.44	44	249.45	50	250.42
Hangingstone	434.94		434.94	240.54	36	248.44	44	249.45	50	250.42
Hangingstone	372.11		372.11	240.61	36	248.44	44	249.45	50	250.42
Hangingstone	292.77		292.77	240.69	36	248.44	44	249.45	50	250.42
Hangingstone	226.84		226.84	240.37	36	248.44	44	249.45	50	250.42
Hangingstone	133.86		133.86	240.06	36	248.44	44	249.45	50	250.42
Hangingstone	106.21		106.21	240.37	36	248.44	44	249.45	50	250.42
Hangingstone	92.31		92.31	240.21	36	248.44	44	249.45	50	250.42

APPENDIX E

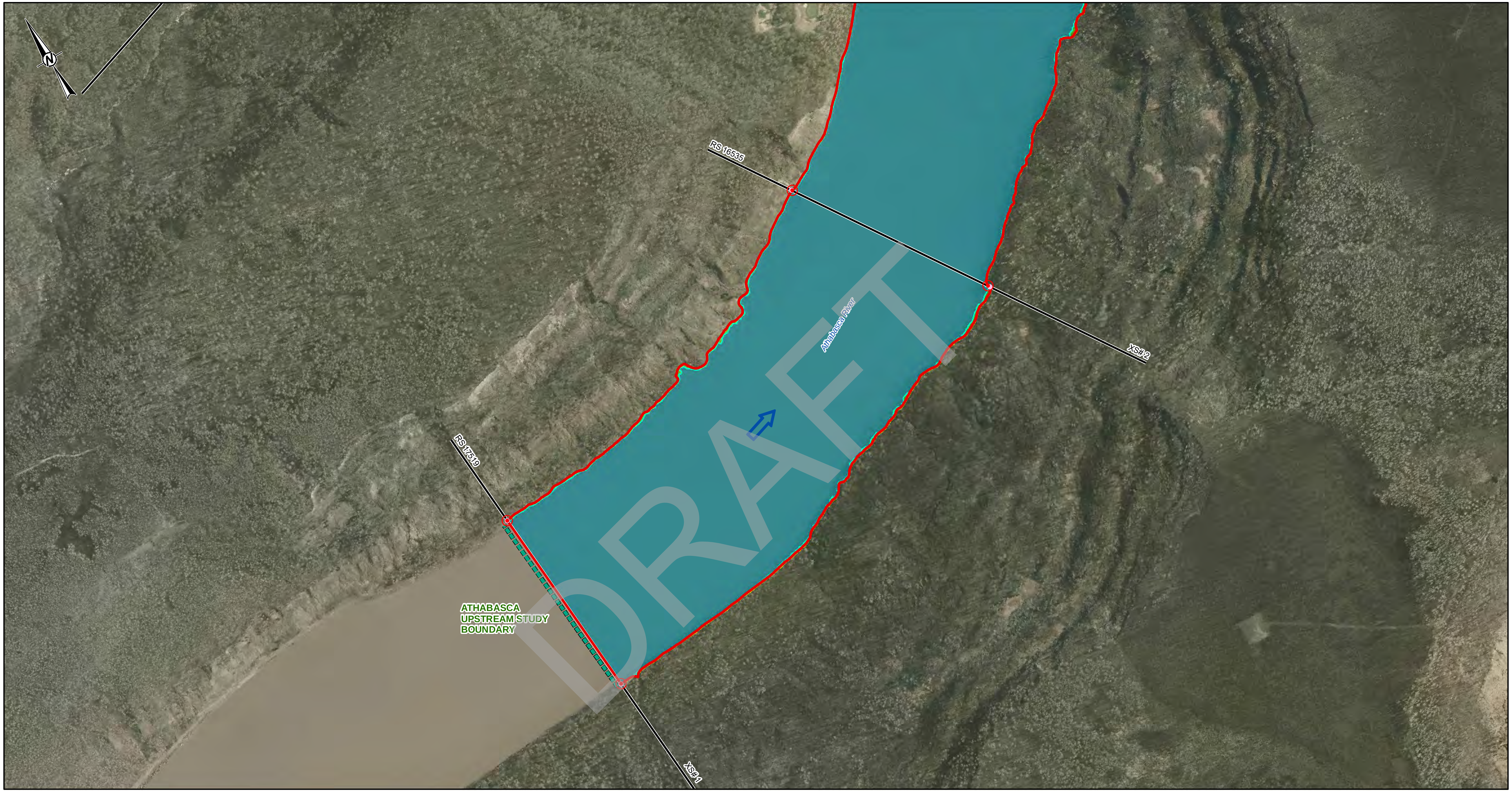
ICE JAM FLOOD INUNDATION MAPS

Inundation mapping is provided in a separate Map Book

APPENDIX F

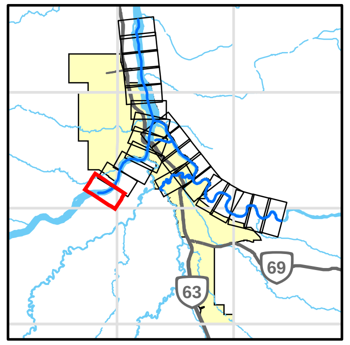
ICE JAM FLOODWAY CRITERIA MAPS

SHEET 2 ↑



LEGEND

- CROSS SECTION
- XS#110 CROSS SECTION NUMBER
- *RS57085* RIVER STATION
- ⇨ FLOW DIRECTION
- BRIDGE
- LOCAL ROAD
- PRIMARY HIGHWAY
- STUDY BOUNDARY
- FLOOD CONTROL STRUCTURE
- 🟥 PROPOSED FLOODWAY BOUNDARY
- ● BANK STATION
- ◉ PROPOSED ICE JAM FLOODWAY STATION
- PREVIOUS FLOODWAY
- 🟦 DEPTH ≥ 1 M
- 🟩 100-YEAR ICE JAM FLOOD EXTENT



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PROJECT
FORT McMURRAY RIVER HAZARD STUDY

CONSULTANT
GOLDER
MEMBER OF WSP

YYYY-MM-DD	2022-07-19
DESIGNED	NG
PREPARED	PT
REVIEWED	WP
APPROVED	WP

TITLE
ICE JAM FLOODWAY CRITERIA MAP

PROJECT NO.	CONTROL	REV.	FIGURE
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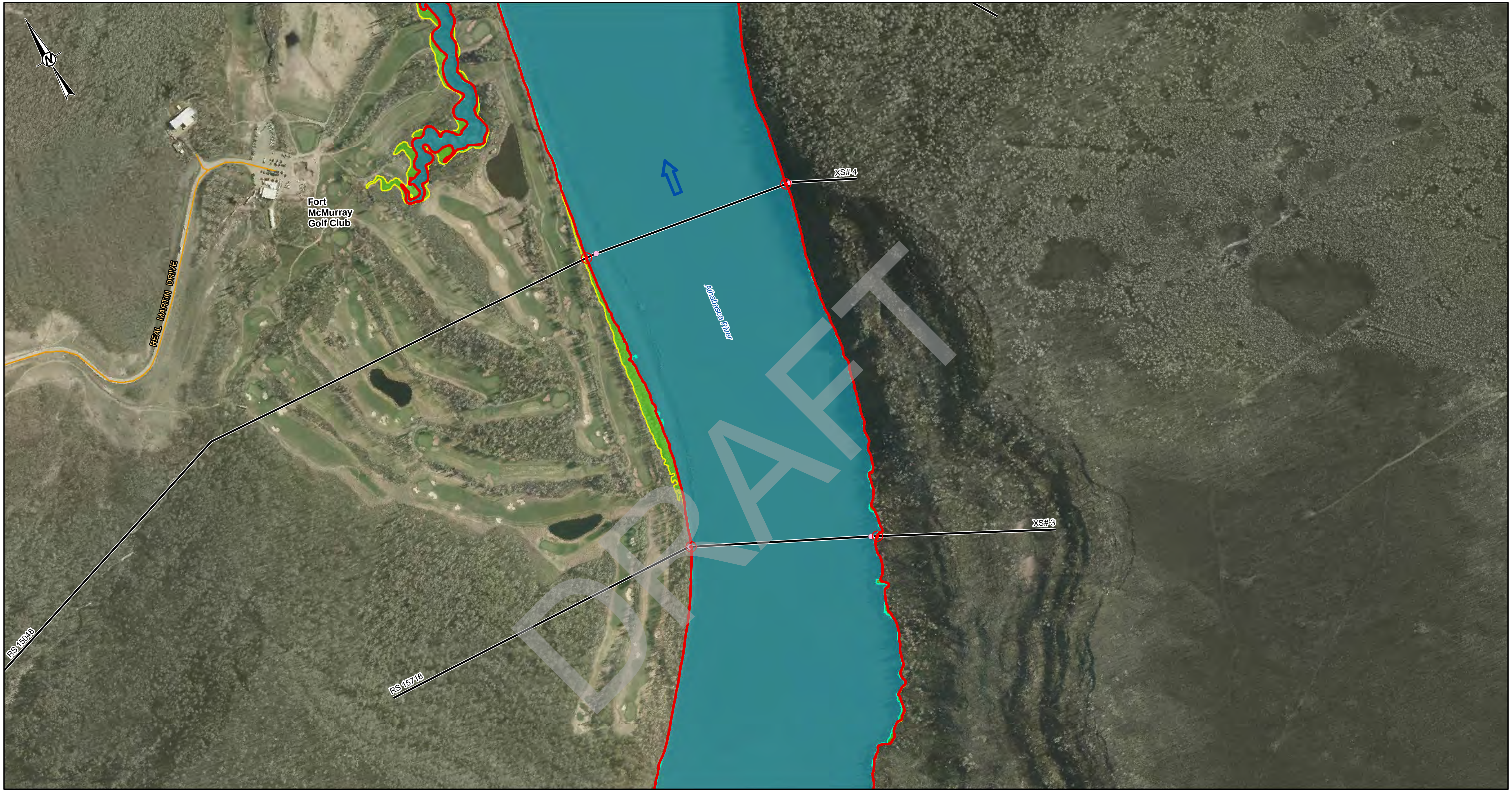

SHEET 1 ↓

LEGEND

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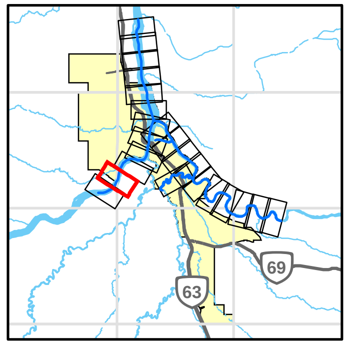
XS#110	CROSS SECTION NUMBER
RS57085	RIVER STATION
⇨	FLOW DIRECTION
⌶	BRIDGE
─	LOCAL ROAD
▬	PRIMARY HIGHWAY
■■■	STUDY BOUNDARY
▮▮▮▮	FLOOD CONTROL STRUCTURE
🟥	PROPOSED FLOODWAY BOUNDARY
●	BANK STATION
⊙	PROPOSED ICE JAM FLOODWAY STATION
⬚	PREVIOUS FLOODWAY
🟦	DEPTH ≥ 1 M
🟩	100-YEAR ICE JAM FLOOD EXTENT



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PROJECT
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TITLE
ICE JAM FLOODWAY CRITERIA MAP

PROJECT NO.	CONTROL	REV.	FIGURE
1662603	7000	0	Sheet 2 of 23

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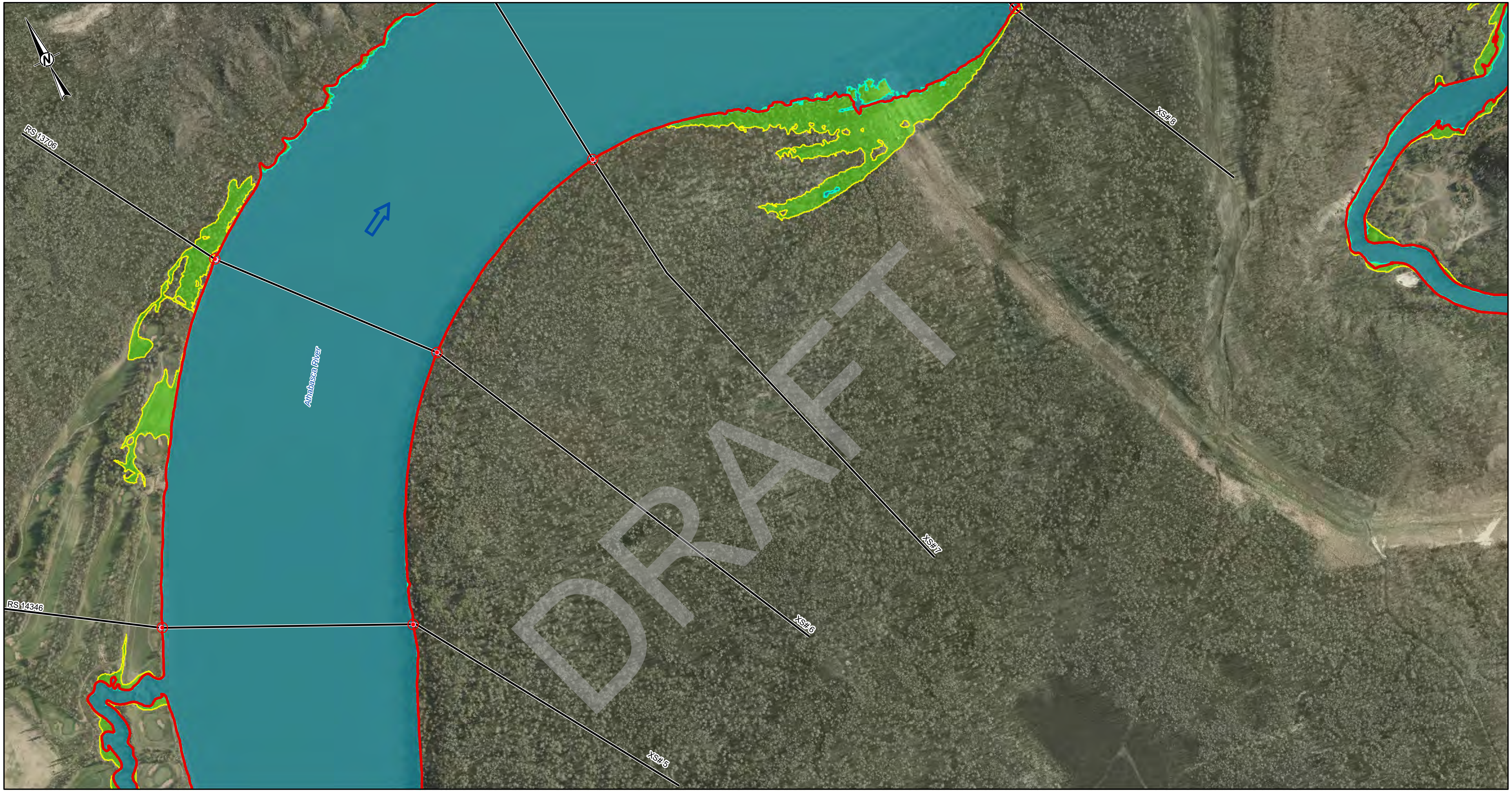
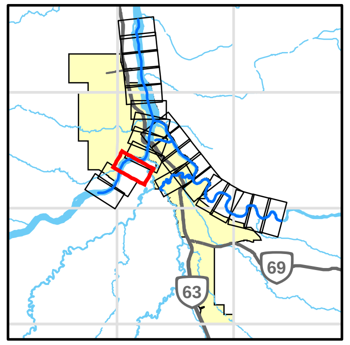


SHEET 2 ↓

LEGEND

- CROSS SECTION
- XS#110 CROSS SECTION NUMBER
- *RS57085* RIVER STATION
- ⇨ FLOW DIRECTION
- BRIDGE
- LOCAL ROAD
- PRIMARY HIGHWAY
- STUDY BOUNDARY
- FLOOD CONTROL STRUCTURE
- 🟥 PROPOSED FLOODWAY BOUNDARY
- ● BANK STATION
- ⦿ PROPOSED ICE JAM FLOODWAY STATION
- PREVIOUS FLOODWAY
- 🟦 DEPTH ≥ 1 M
- 🟩 100-YEAR ICE JAM FLOOD EXTENT



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TITLE
ICE JAM FLOODWAY CRITERIA MAP

PROJECT NO.	CONTROL	REV.	FIGURE
1662603	7000	0	Sheet 3 of 23

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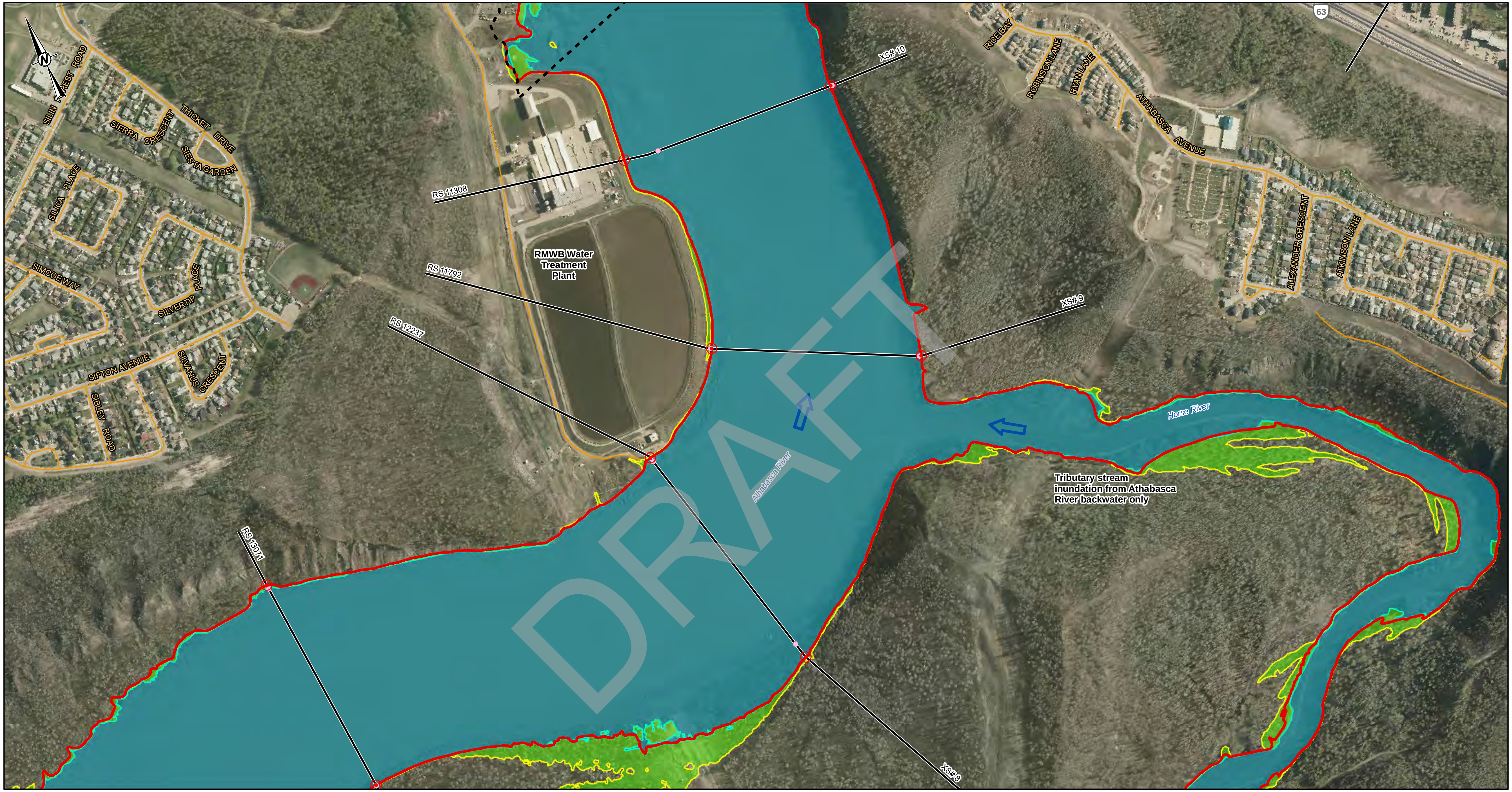

SHEET 3 ↓

LEGEND

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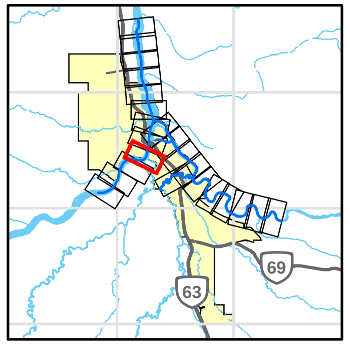
XS#110	CROSS SECTION NUMBER
RS57085	RIVER STATION
⇨	FLOW DIRECTION
⌶	BRIDGE
─	LOCAL ROAD
▬	PRIMARY HIGHWAY
▪▪▪	STUDY BOUNDARY
⦙⦙⦙	FLOOD CONTROL STRUCTURE
▭	PROPOSED FLOODWAY BOUNDARY
●	BANK STATION
⊙	PROPOSED ICE JAM FLOODWAY STATION
⬚	PREVIOUS FLOODWAY
🟦	DEPTH ≥ 1 M
🟩	100-YEAR ICE JAM FLOOD EXTENT



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TITLE
ICE JAM FLOODWAY CRITERIA MAP

PROJECT NO.	CONTROL	REV.	FIGURE
1662603	7000	0	Sheet 4 of 23

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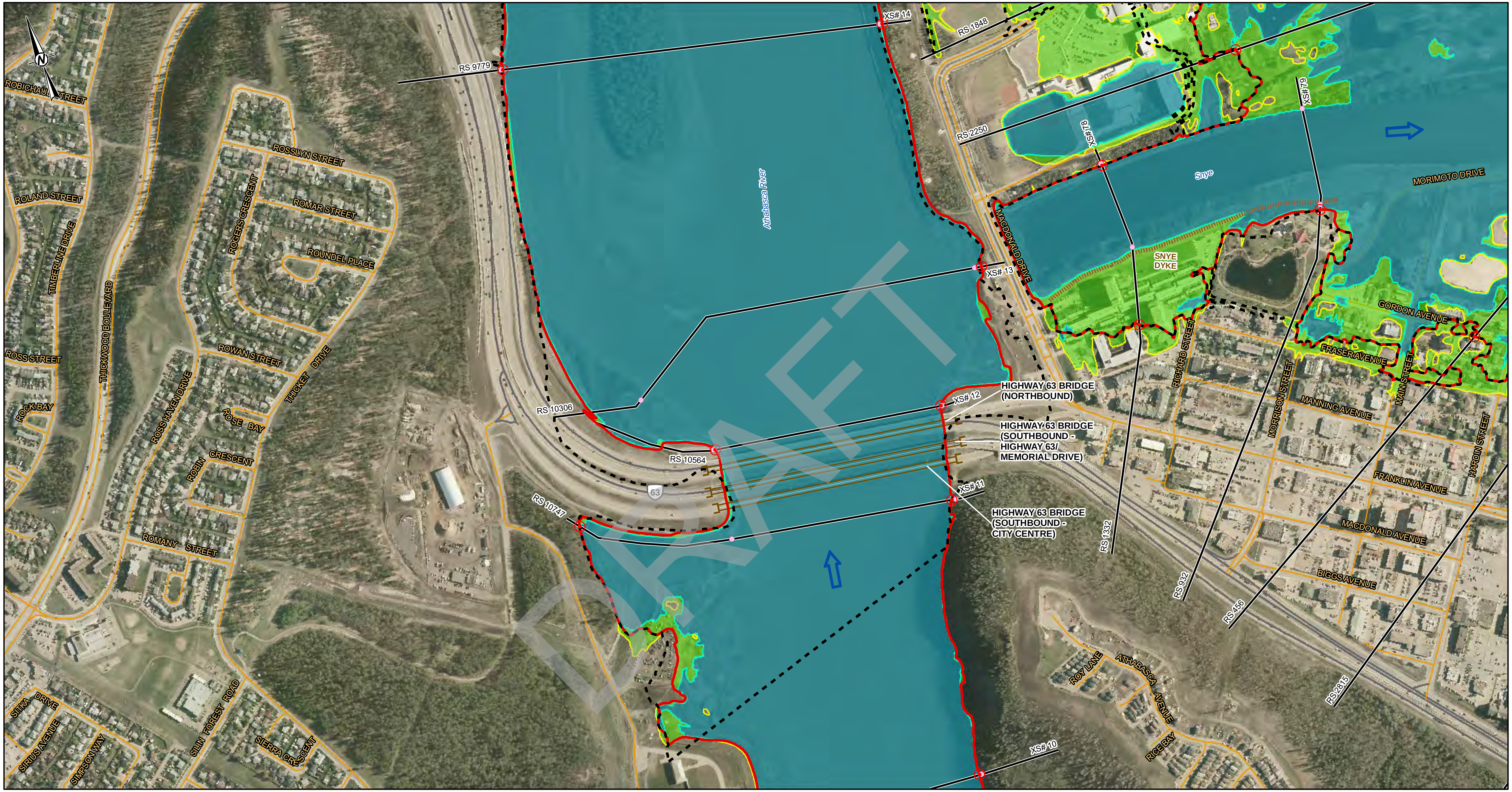
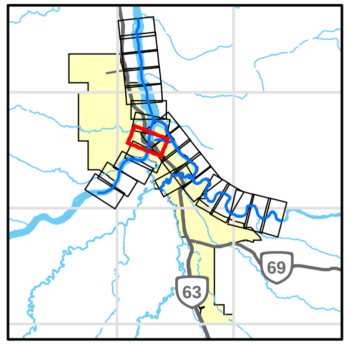


SHEET 21 ↓

SHEET 4 ↓

LEGEND

▬	CROSS SECTION
XS#110	CROSS SECTION NUMBER
RS57085	RIVER STATION
⇨	FLOW DIRECTION
⊢⊣	BRIDGE
—	LOCAL ROAD
▬	PRIMARY HIGHWAY
▪▪▪	STUDY BOUNDARY
▮▮▮	FLOOD CONTROL STRUCTURE
▭	PROPOSED FLOODWAY BOUNDARY
●	BANK STATION
◉	PROPOSED ICE JAM FLOODWAY STATION
⬚	PREVIOUS FLOODWAY
🟦	DEPTH ≥ 1 M
🟩	100-YEAR ICE JAM FLOOD EXTENT



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APPROVED	WP

TITLE
ICE JAM FLOODWAY CRITERIA MAP

PROJECT NO.	CONTROL	REV.	FIGURE
1662603	7000	0	Sheet 5 of 23

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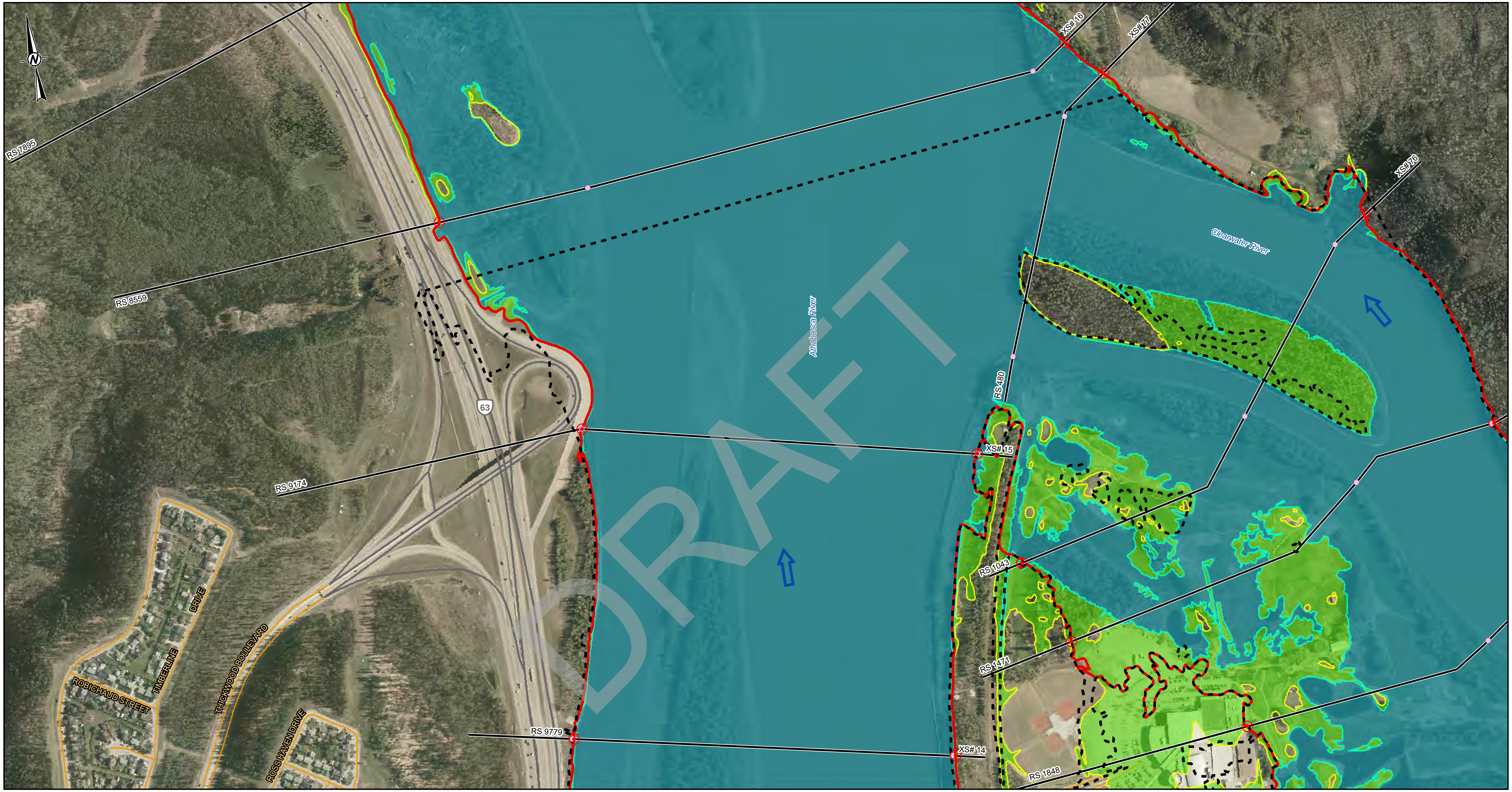
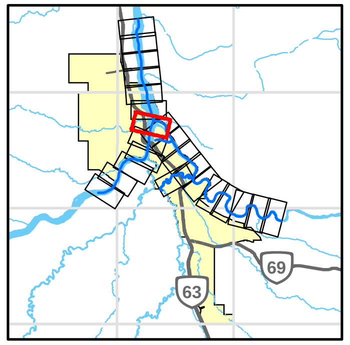


SHEET 22 ↓

SHEET 5 ↓

LEGEND

▬	CROSS SECTION	🟥	PROPOSED FLOODWAY BOUNDARY
XS#110	CROSS SECTION NUMBER	●	BANK STATION
RS57085	RIVER STATION	⦿	PROPOSED ICE JAM FLOODWAY STATION
⇨	FLOW DIRECTION	⬚	PREVIOUS FLOODWAY
⊐⊏	BRIDGE	🟦	DEPTH ≥ 1 M
─	LOCAL ROAD	🟩	100-YEAR ICE JAM FLOOD EXTENT
─	PRIMARY HIGHWAY		
▪▪▪	STUDY BOUNDARY		
▮▮▮	FLOOD CONTROL STRUCTURE		



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DATUM: NAD 83 CSRS PROJECTION: 3TM 111

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PREPARED	PT
REVIEWED	WP
APPROVED	WP

PROJECT

FORT McMURRAY RIVER HAZARD STUDY

TITLE

ICE JAM FLOODWAY CRITERIA MAP

PROJECT NO.	CONTROL	REV.	FIGURE
1662603	7000	0	Sheet 6 of 23

PATH: I:\CLIENTS\GOVERNMENT_OF_ALBERTA\21452576\Fort McMurray\Mapping\Products\Hydrology\05_Design Flood Hazard Mapping\Rev0\1662603_Floodway_Criteria-Ice-Jam_Rev0.mxd PRINTED ON: 2022-07-29 AT: 8:04:33 AM

25mm

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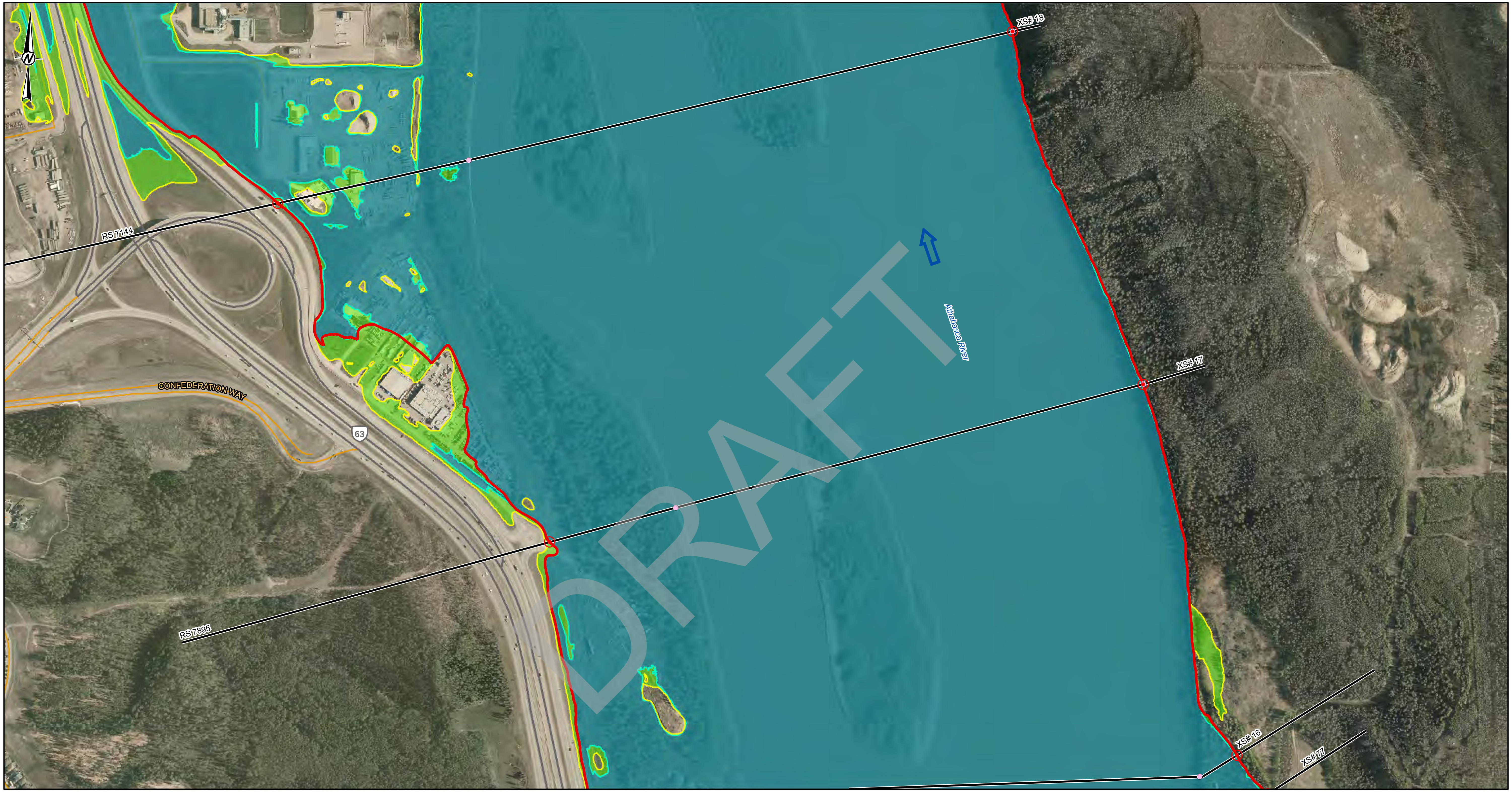
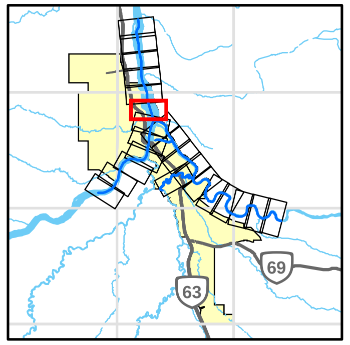
SHEET 8 ↑



SHEET 6 ↓

LEGEND

—	CROSS SECTION
XS#110	CROSS SECTION NUMBER
RS57085	RIVER STATION
⇨	FLOW DIRECTION
⊢⊣	BRIDGE
—	LOCAL ROAD
—	PRIMARY HIGHWAY
■■■	STUDY BOUNDARY
▮▮▮	FLOOD CONTROL STRUCTURE
▭	PROPOSED FLOODWAY BOUNDARY
●	BANK STATION
⊙	PROPOSED ICE JAM FLOODWAY STATION
⌐ ¬	PREVIOUS FLOODWAY
🟦	DEPTH ≥ 1 M
🟩	100-YEAR ICE JAM FLOOD EXTENT



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CONSULTANT
GOLDER
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DESIGNED	NG
PREPARED	PT
REVIEWED	WP
APPROVED	WP

TITLE
ICE JAM FLOODWAY CRITERIA MAP

PROJECT NO.	CONTROL	REV.	FIGURE
1662603	7000	0	Sheet 7 of 23

PATH: I:\CLIENTS\GOVERNMENT_OF_ALBERTA\21452576\Fort McMurray\Mapping\Products\Hydrology\05_Design Flood Hazard Mapping\Rev0\1662603_Floodway_Criteria-Ice-Jam_Rev0.mxd PRINTED ON: 2022-07-29 AT: 8:04:47 AM

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25mm

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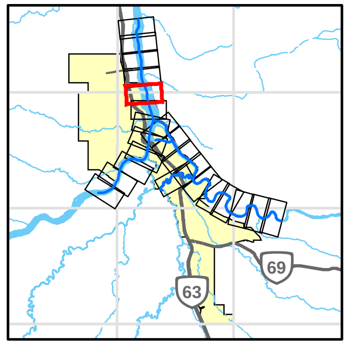
Classification: Public

SHEET 9 ↑

SHEET 7 ↓

LEGEND

—	CROSS SECTION	🟥	PROPOSED FLOODWAY BOUNDARY
XS#110	CROSS SECTION NUMBER	●	BANK STATION
RS57085	RIVER STATION	⊙	PROPOSED ICE JAM FLOODWAY STATION
⇨	FLOW DIRECTION	⬚	PREVIOUS FLOODWAY
⊏⊐	BRIDGE	🟦	DEPTH ≥ 1 M
—	LOCAL ROAD	🟩	100-YEAR ICE JAM FLOOD EXTENT
—	PRIMARY HIGHWAY		
▪▪▪	STUDY BOUNDARY		
⦀	FLOOD CONTROL STRUCTURE		



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PREPARED	PT
REVIEWED	WP
APPROVED	WP

TITLE
ICE JAM FLOODWAY CRITERIA MAP

PROJECT NO.	CONTROL	REV.	FIGURE
1662603	7000	0	Sheet 8 of 23

PATH: I:\CLIENTS\GOVERNMENT_OF_ALBERTA\21452576\Fort McMurray\Mapping\Products\Hydrology\05_Design Flood Hazard Mapping\Rev0\1662603_Floodway_Criteria-Ice-Jam_Rev0.mxd PRINTED ON: 2022-07-29 AT: 8:05:00 AM

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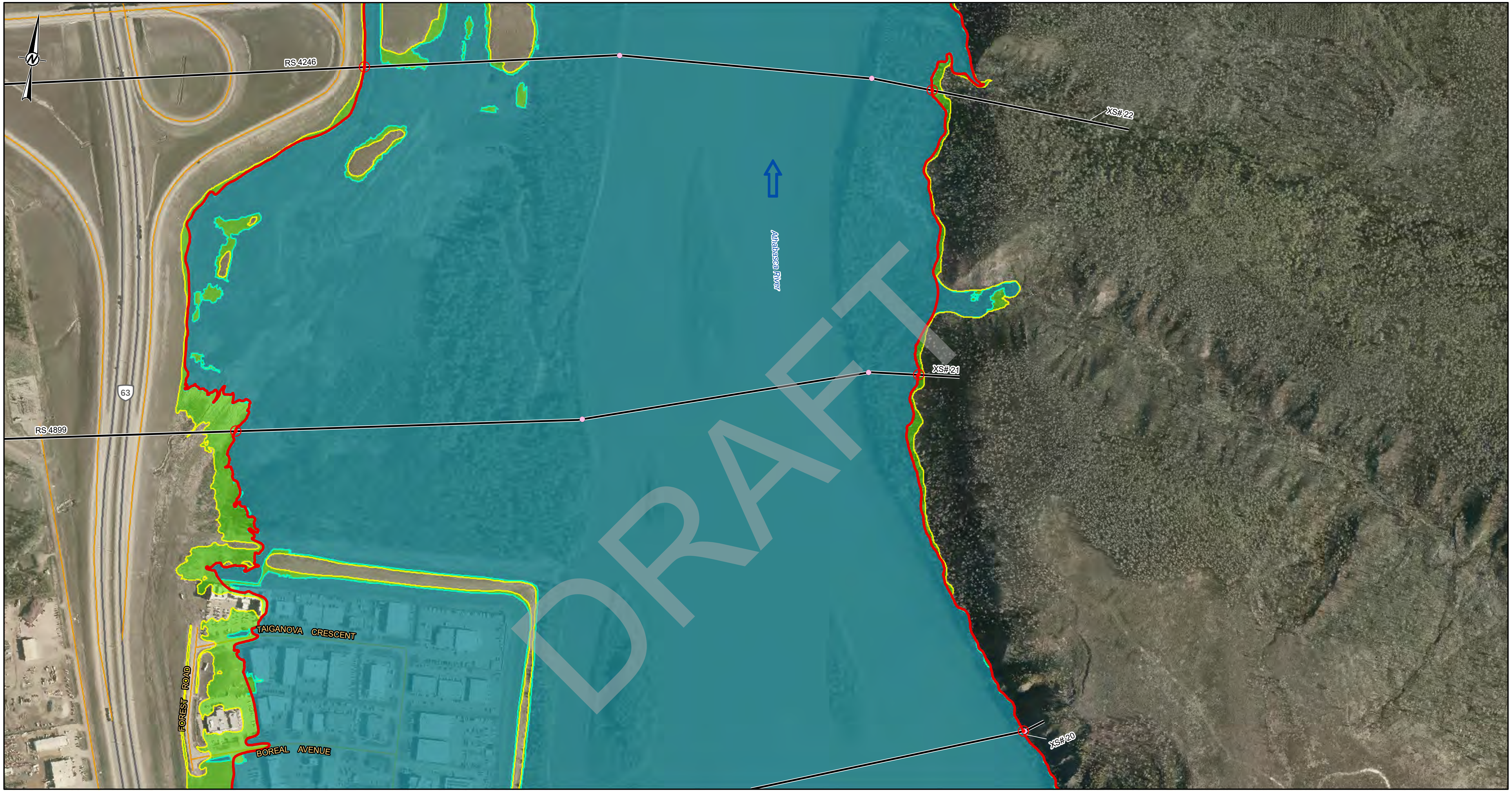
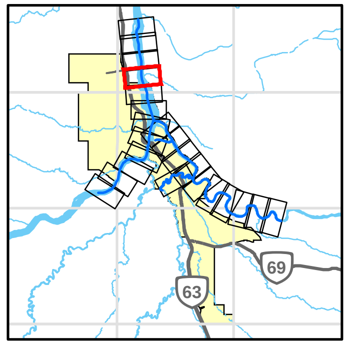
SHEET 10 ↑



SHEET 8 ↓

LEGEND

- ▬ CROSS SECTION
- XS#110 CROSS SECTION NUMBER
- *RS57085* RIVER STATION
- ⇨ FLOW DIRECTION
- BRIDGE
- ― LOCAL ROAD
- ▬ PRIMARY HIGHWAY
- ▪▪▪ STUDY BOUNDARY
- ▮▮▮ FLOOD CONTROL STRUCTURE
- 🟥 PROPOSED FLOODWAY BOUNDARY
- ● BANK STATION
- ◉ PROPOSED ICE JAM FLOODWAY STATION
- ⬚ PREVIOUS FLOODWAY
- 🟦 DEPTH ≥ 1 M
- 🟩 100-YEAR ICE JAM FLOOD EXTENT



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APPROVED	WP

TITLE

ICE JAM FLOODWAY CRITERIA MAP

PROJECT NO.	CONTROL	REV.	FIGURE
1662603	7000	0	Sheet 9 of 23

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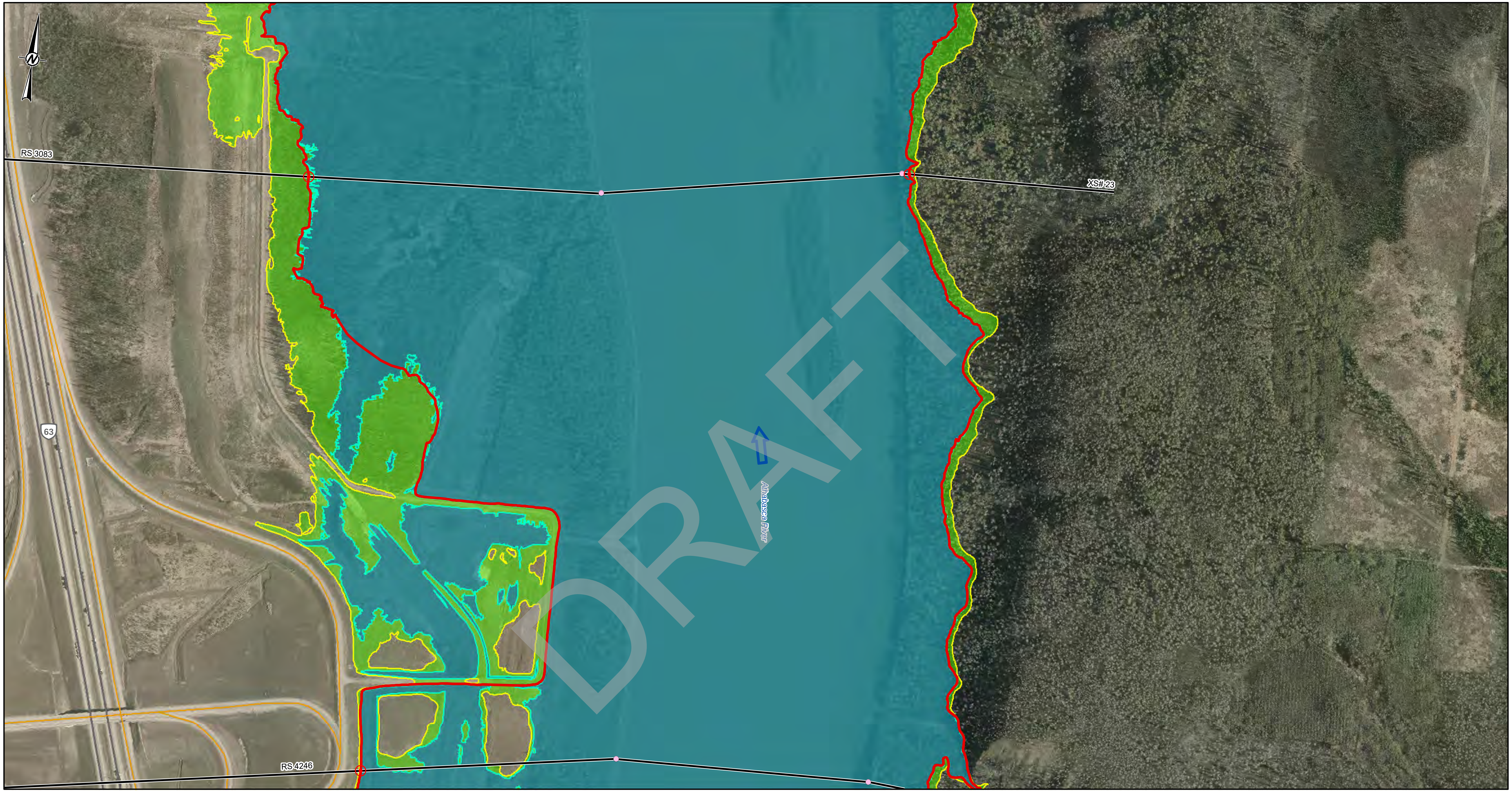
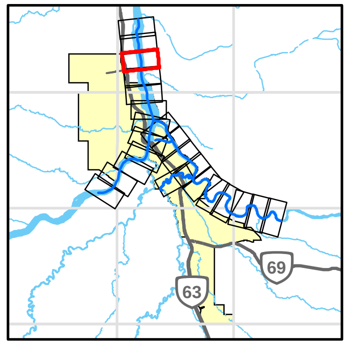
SHEET 11 ↑



SHEET 9 ↓

LEGEND

▬	CROSS SECTION
XS#110	CROSS SECTION NUMBER
RS57085	RIVER STATION
⇨	FLOW DIRECTION
⊢⊣	BRIDGE
—	LOCAL ROAD
—	PRIMARY HIGHWAY
▪▪▪	STUDY BOUNDARY
⦙⦙⦙	FLOOD CONTROL STRUCTURE
🟥	PROPOSED FLOODWAY BOUNDARY
●	BANK STATION
⊙	PROPOSED ICE JAM FLOODWAY STATION
▭	PREVIOUS FLOODWAY
🟦	DEPTH ≥ 1 M
🟩	100-YEAR ICE JAM FLOOD EXTENT



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PROJECT
FORT McMURRAY RIVER HAZARD STUDY

TITLE
ICE JAM FLOODWAY CRITERIA MAP

PROJECT NO.	CONTROL	REV.	FIGURE
1662603	7000	0	Sheet 10 of 23

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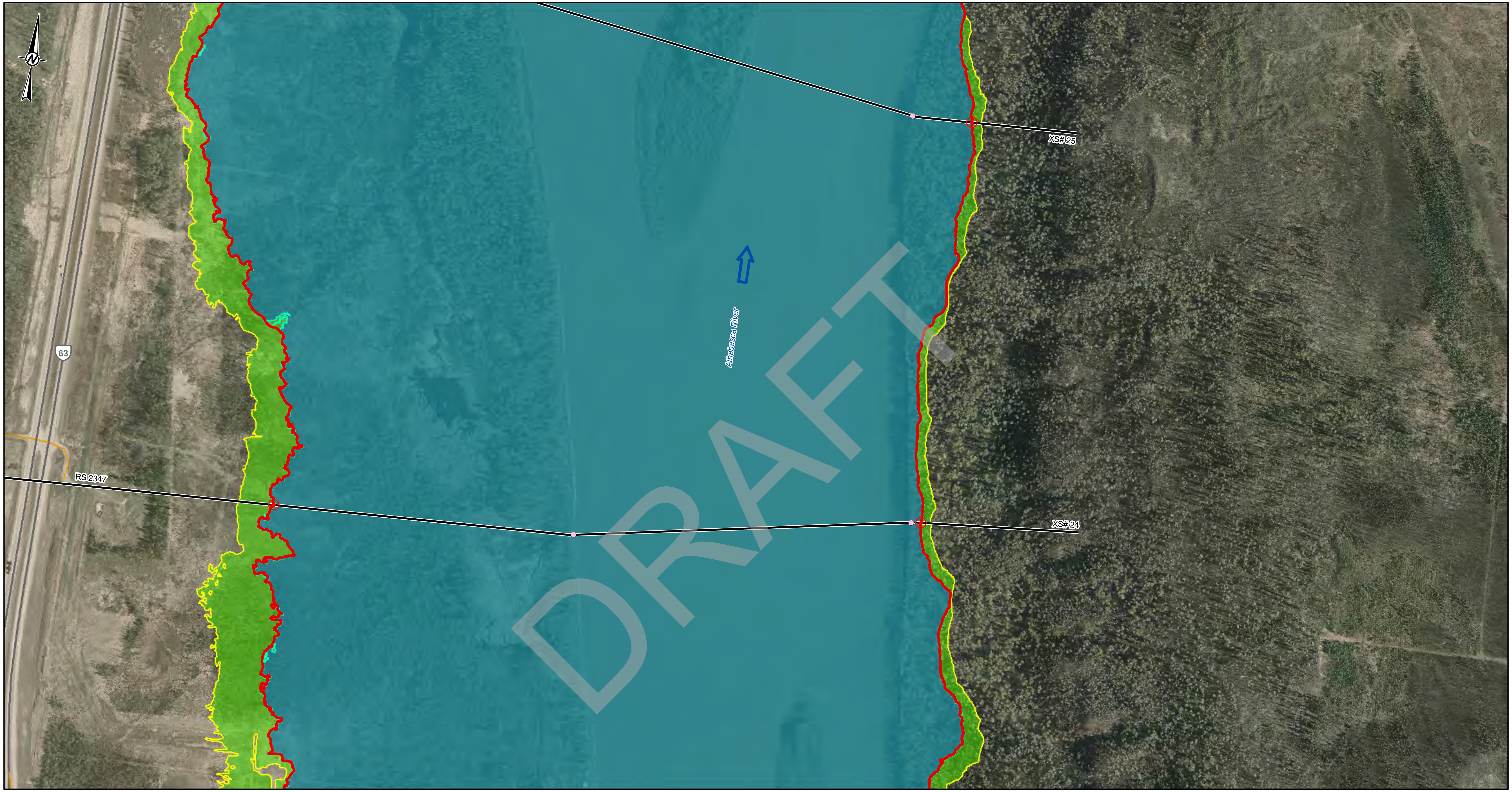
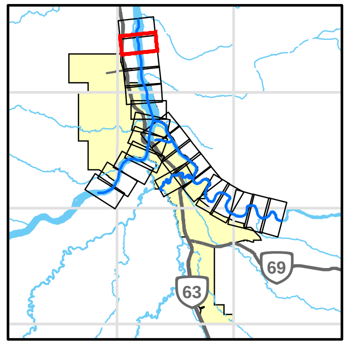
SHEET 12 ↑



SHEET 10 ↓

LEGEND

▬	CROSS SECTION	🟥	PROPOSED FLOODWAY BOUNDARY
XS#110	CROSS SECTION NUMBER	●	BANK STATION
RS57085	RIVER STATION	⊙	PROPOSED ICE JAM FLOODWAY STATION
⇨	FLOW DIRECTION	▭	PREVIOUS FLOODWAY
⊐	BRIDGE	🟦	DEPTH ≥ 1 M
—	LOCAL ROAD	🟩	100-YEAR ICE JAM FLOOD EXTENT
—	PRIMARY HIGHWAY		
▪▪▪	STUDY BOUNDARY		
▮▮▮	FLOOD CONTROL STRUCTURE		



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PROJECT
FORT McMURRAY RIVER HAZARD STUDY

TITLE
ICE JAM FLOODWAY CRITERIA MAP

PROJECT NO.	CONTROL	REV.	FIGURE
1662603	7000	0	Sheet 11 of 23

PATH: I:\CLIENTS\GOVERNMENT_OF_ALBERTA\21452576\Fort McMurray\Mapping\Products\Hydrology\05_Design Flood Hazard Mapping\Rev0\1662603_Floodway_Criteria-Ice-Jam_Rev0.mxd PRINTED ON: 2022-07-29 AT: 8:05:39 AM

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25mm

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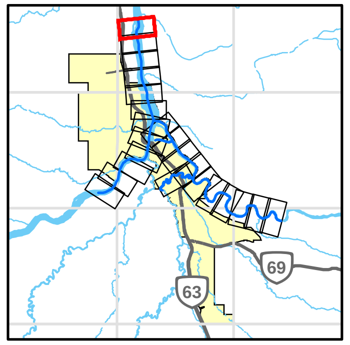
LEGEND

▬	CROSS SECTION
XS#110	CROSS SECTION NUMBER
RS57085	RIVER STATION
⇨	FLOW DIRECTION
⌶	BRIDGE
—	LOCAL ROAD
▬	PRIMARY HIGHWAY
▪▪▪	STUDY BOUNDARY
⦙⦙⦙	FLOOD CONTROL STRUCTURE
🟥	PROPOSED FLOODWAY BOUNDARY
●	BANK STATION
⦿	PROPOSED ICE JAM FLOODWAY STATION
⬚	PREVIOUS FLOODWAY
🟦	DEPTH ≥ 1 M
🟩	100-YEAR ICE JAM FLOOD EXTENT

SHEET 11 ↓



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TITLE
ICE JAM FLOODWAY CRITERIA MAP

PROJECT NO.	CONTROL	REV.	FIGURE
1662603	7000	0	Sheet 12 of 23

PATH: I:\CLIENTS\GOVERNMENT_OF_ALBERTA\21452576\Fort McMurray\Mapping\Products\Hydrology\05_Design Flood Hazard Mapping\Rev0\1662603_Floodway_Criteria-Ice-Jam_Rev0.mxd PRINTED ON: 2022-07-29 AT: 8:05:52 AM

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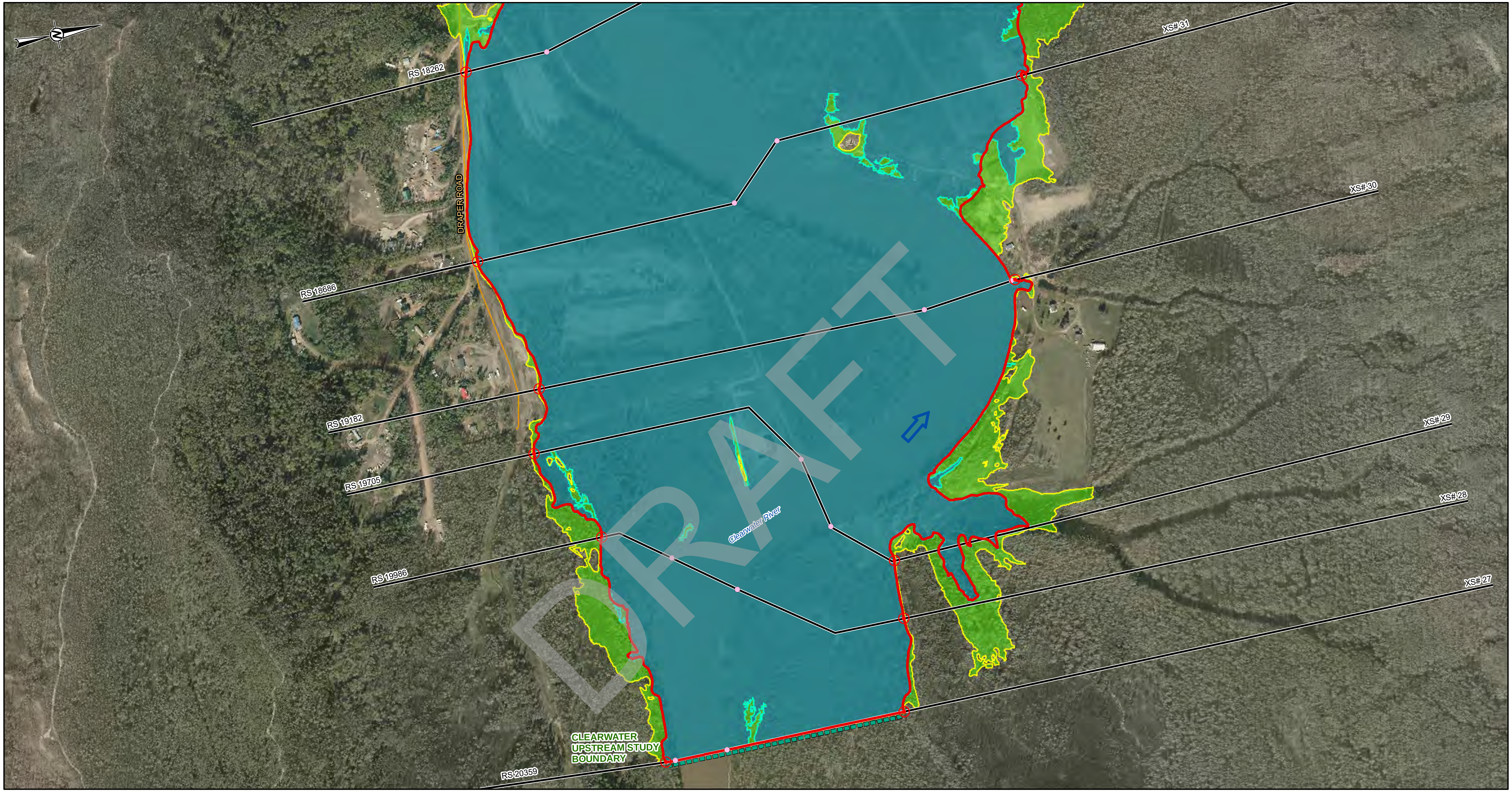
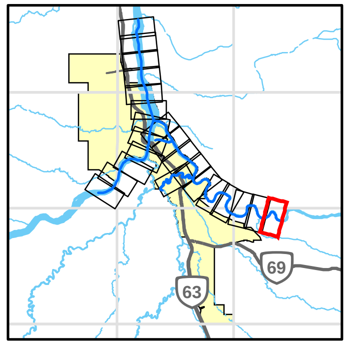


LEGEND

━	CROSS SECTION	🟥	PROPOSED FLOODWAY BOUNDARY
XS#110	CROSS SECTION NUMBER	●	BANK STATION
RS57085	RIVER STATION	⊙	PROPOSED ICE JAM FLOODWAY STATION
⇨	FLOW DIRECTION	▭	PREVIOUS FLOODWAY
⊏⊐	BRIDGE	🟦	DEPTH ≥ 1 M
─	LOCAL ROAD	🟩	100-YEAR ICE JAM FLOOD EXTENT
─	PRIMARY HIGHWAY		
▬▬▬	STUDY BOUNDARY		
┃┃┃┃	FLOOD CONTROL STRUCTURE		



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REVIEWED	WP
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TITLE
ICE JAM FLOODWAY CRITERIA MAP

PROJECT NO.	CONTROL	REV.	FIGURE
1662603	7000	0	Sheet 13 of 23

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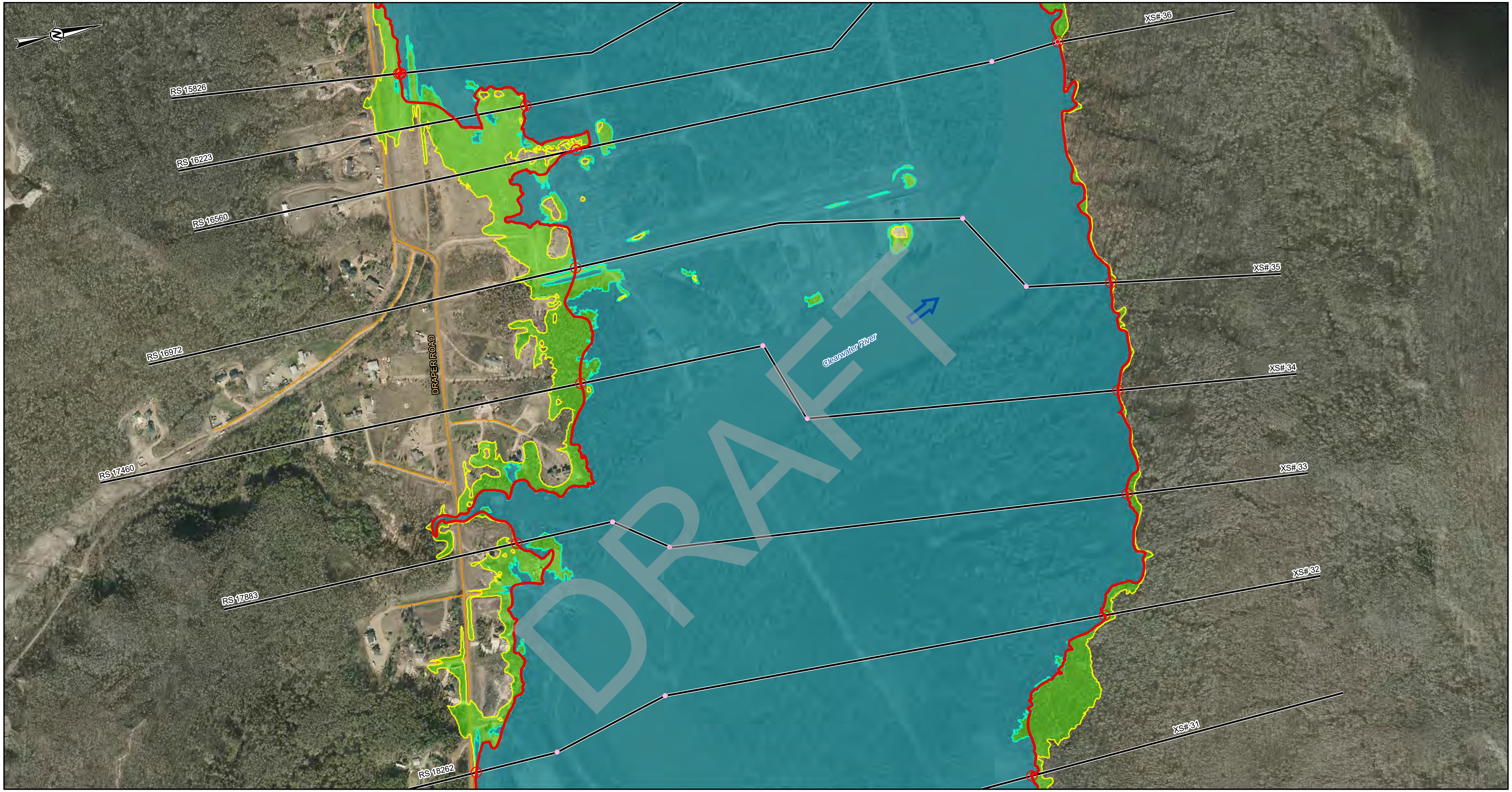
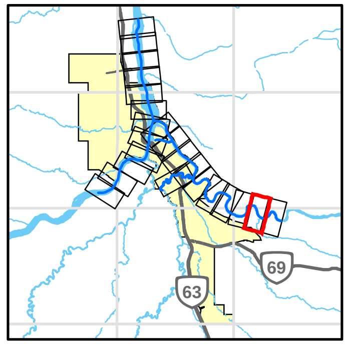


SHEET 13 ↓

LEGEND

- ▬ CROSS SECTION
- XS#110 CROSS SECTION NUMBER
- *RS57085* RIVER STATION
- ⇨ FLOW DIRECTION
- BRIDGE
- LOCAL ROAD
- PRIMARY HIGHWAY
- ▪▪▪ STUDY BOUNDARY
- FLOOD CONTROL STRUCTURE
- 🟥 PROPOSED FLOODWAY BOUNDARY
- ● BANK STATION
- ⊙ PROPOSED ICE JAM FLOODWAY STATION
- PREVIOUS FLOODWAY
- 🟦 DEPTH ≥ 1 M
- 🟩 100-YEAR ICE JAM FLOOD EXTENT



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PROJECT
FORT McMURRAY RIVER HAZARD STUDY

TITLE
ICE JAM FLOODWAY CRITERIA MAP

PROJECT NO.	CONTROL	REV.	FIGURE
1662603	7000	0	Sheet 14 of 23

25mm
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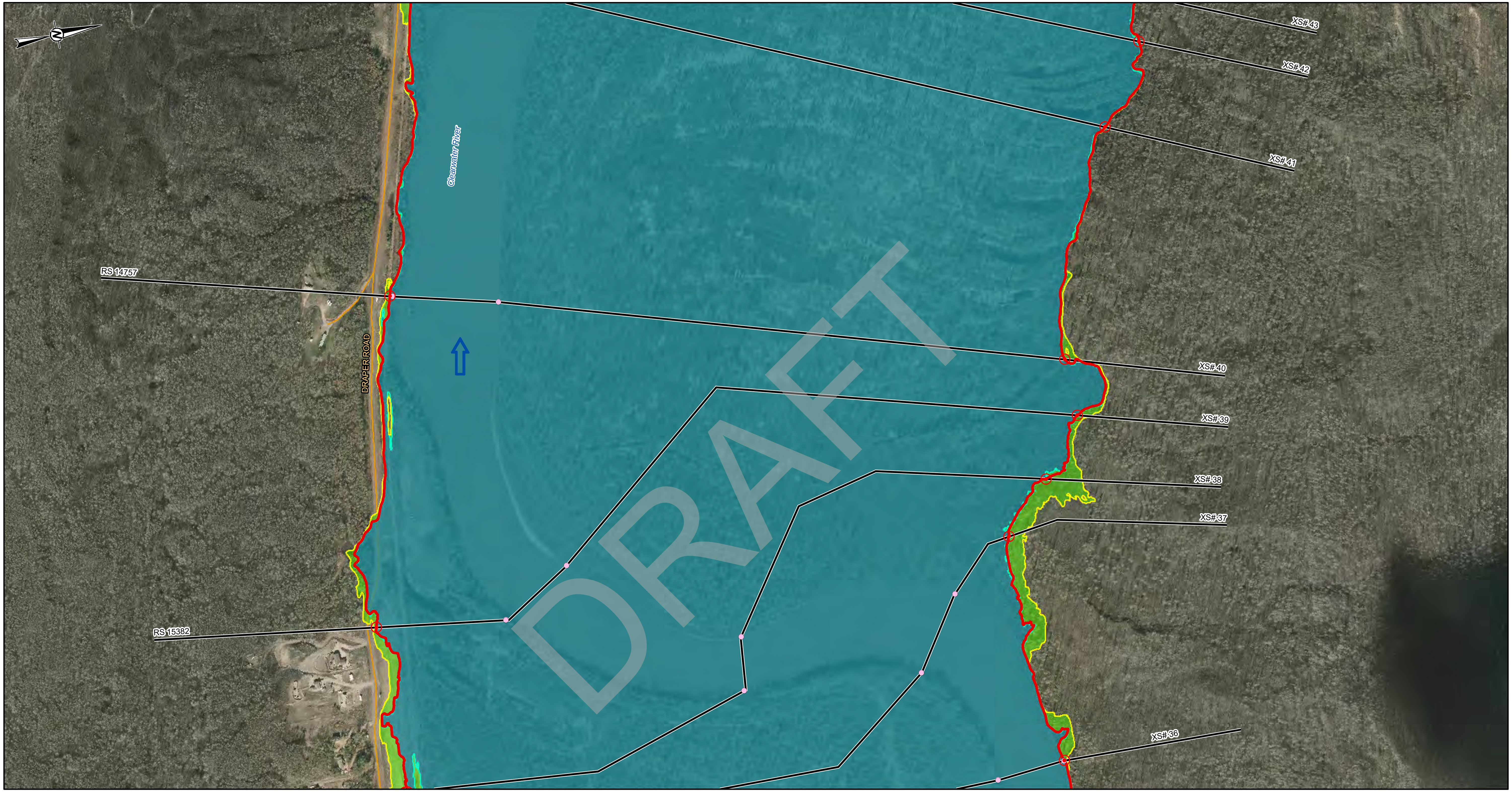
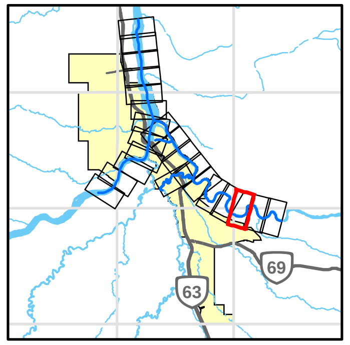
SHEET 16 ↑



SHEET 14 ↓

LEGEND

━━	CROSS SECTION
XS#110	CROSS SECTION NUMBER
RS57085	RIVER STATION
⇨	FLOW DIRECTION
⊐⊏	BRIDGE
──	LOCAL ROAD
──	PRIMARY HIGHWAY
▪▪▪	STUDY BOUNDARY
▮▮▮	FLOOD CONTROL STRUCTURE
🟥	PROPOSED FLOODWAY BOUNDARY
●	BANK STATION
⊙	PROPOSED ICE JAM FLOODWAY STATION
▭	PREVIOUS FLOODWAY
🟦	DEPTH ≥ 1 M
🟩	100-YEAR ICE JAM FLOOD EXTENT



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DESIGNED	NG
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REVIEWED	WP
APPROVED	WP

TITLE
ICE JAM FLOODWAY CRITERIA MAP

PROJECT NO.	CONTROL	REV.	FIGURE
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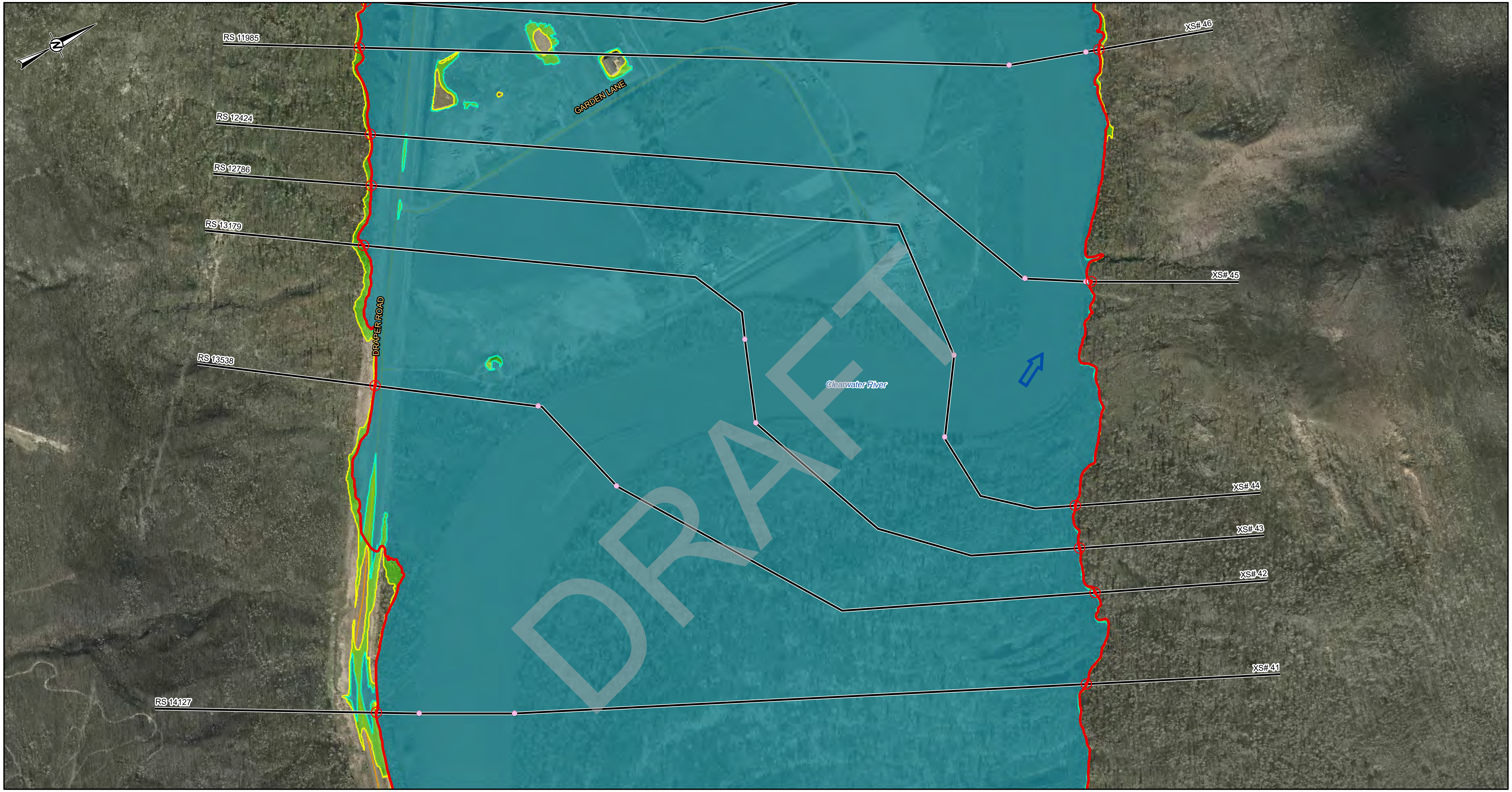
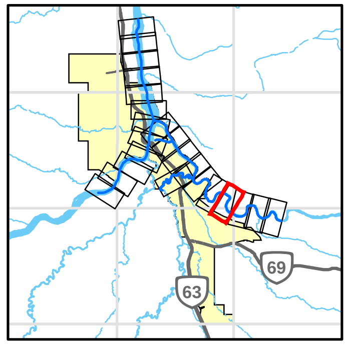


SHEET 15 ↓

LEGEND

▬	CROSS SECTION	▭	PROPOSED FLOODWAY BOUNDARY
XS#110	CROSS SECTION NUMBER	●	BANK STATION
RS57085	RIVER STATION	◉	PROPOSED ICE JAM FLOODWAY STATION
⇨	FLOW DIRECTION	⬚	PREVIOUS FLOODWAY
⊢⊣	BRIDGE	🟦	DEPTH ≥ 1 M
—	LOCAL ROAD	🟩	100-YEAR ICE JAM FLOOD EXTENT
—	PRIMARY HIGHWAY		
■■■	STUDY BOUNDARY		
▮▮▮	FLOOD CONTROL STRUCTURE		



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0 150 300
1:7,500 METRES

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PROJECT
FORT McMURRAY RIVER HAZARD STUDY

TITLE
ICE JAM FLOODWAY CRITERIA MAP

PROJECT NO.	CONTROL	REV.	FIGURE
1662603	7000	0	Sheet 16 of 23

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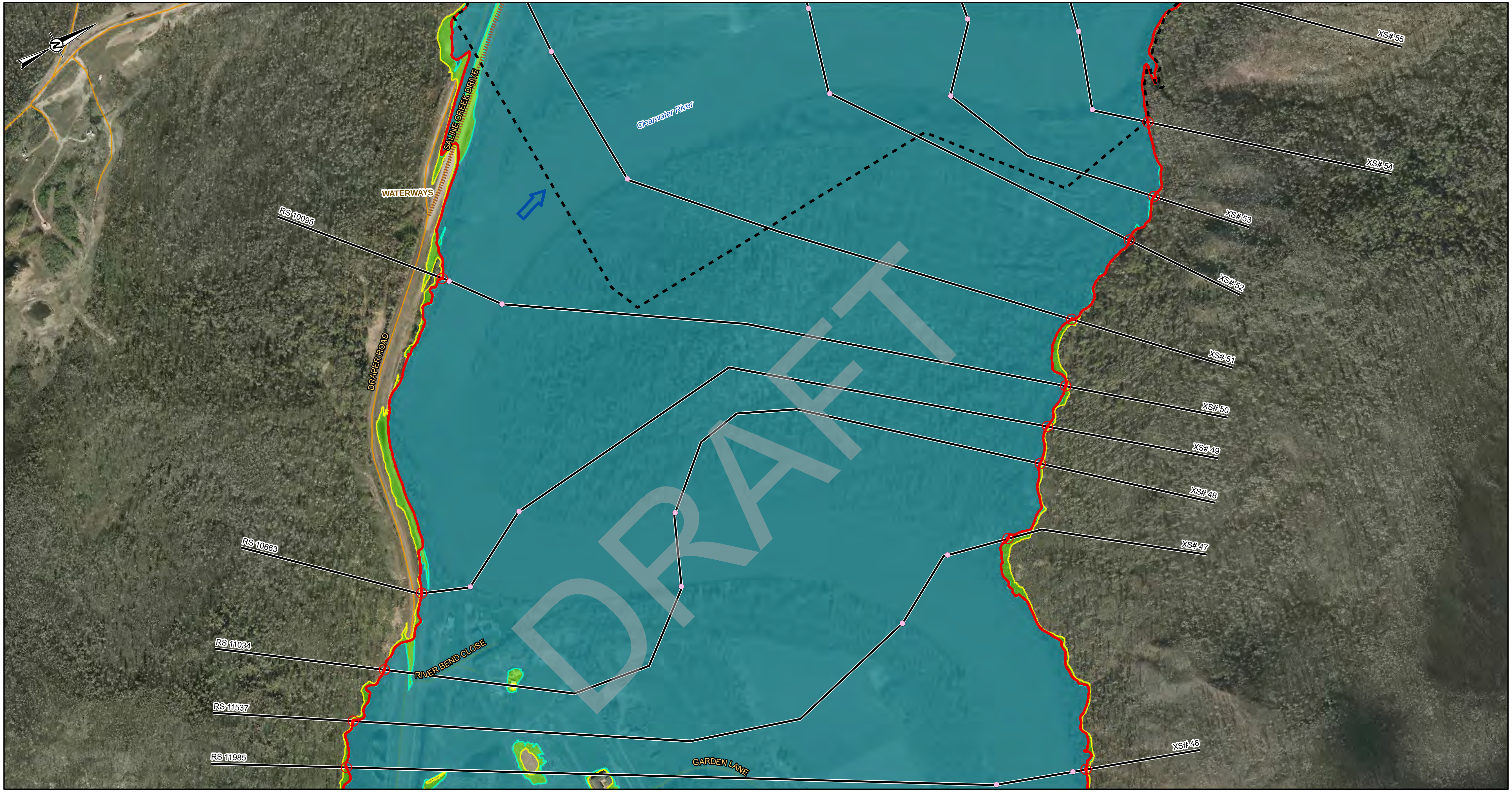

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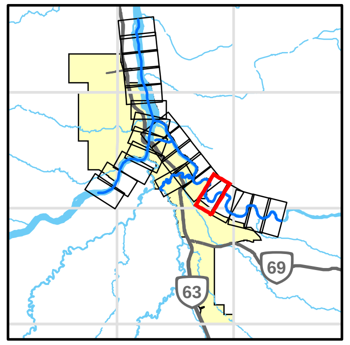
LEGEND

—	CROSS SECTION
XS#110	CROSS SECTION NUMBER
RS57085	RIVER STATION
⇨	FLOW DIRECTION
⊢⊣	BRIDGE
—	LOCAL ROAD
—	PRIMARY HIGHWAY
▬▬▬	STUDY BOUNDARY
▮▮▮▮▮	FLOOD CONTROL STRUCTURE
☐	PROPOSED FLOODWAY BOUNDARY
●	BANK STATION
⊙	PROPOSED ICE JAM FLOODWAY STATION
▭	PREVIOUS FLOODWAY
🟦	DEPTH ≥ 1 M
🟩	100-YEAR ICE JAM FLOOD EXTENT



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GOLDER
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1662603	7000	0	Sheet 17 of 23

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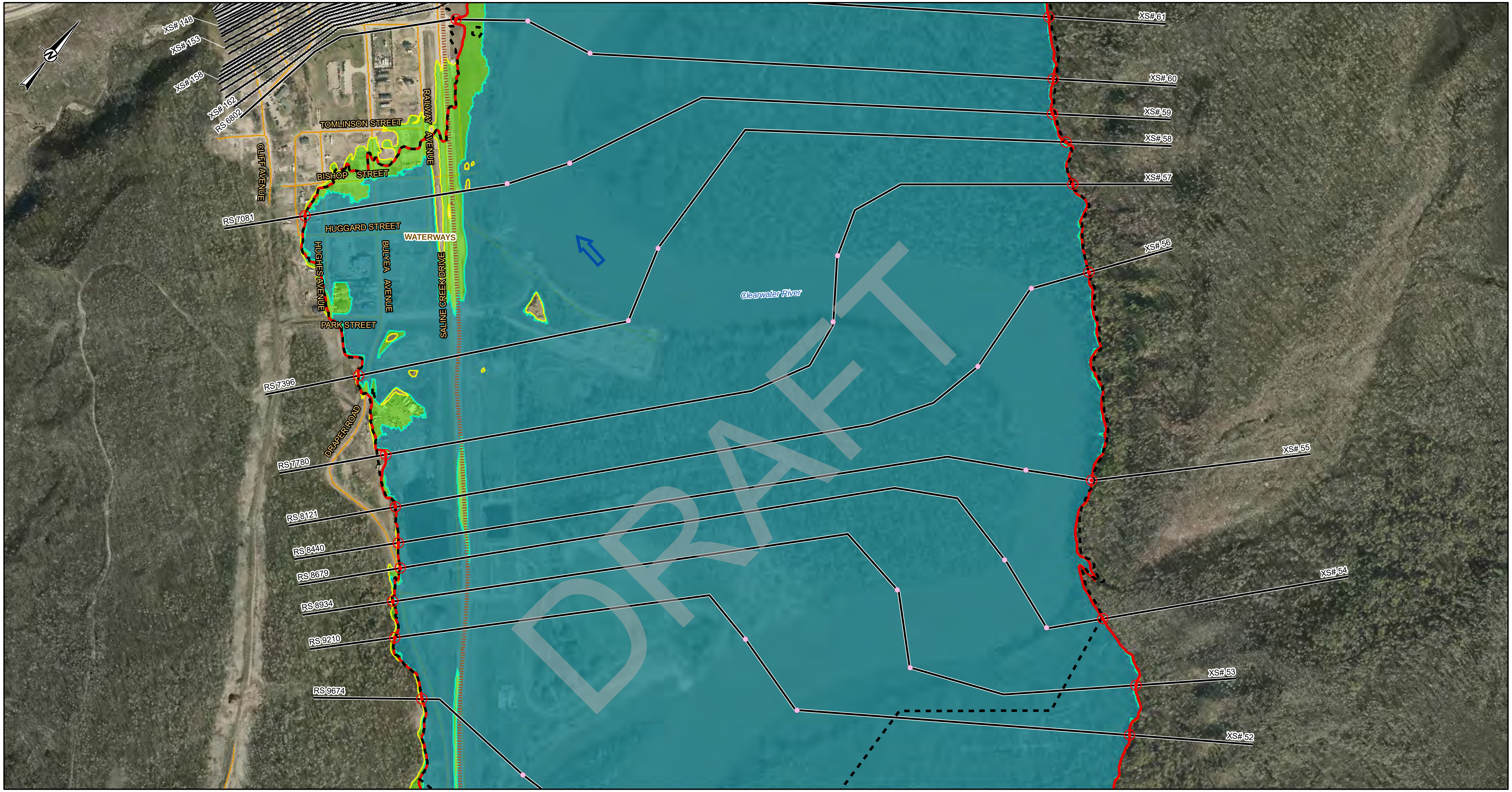

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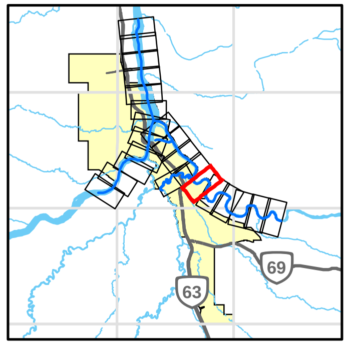
LEGEND

- ▬ CROSS SECTION
- XS#110 CROSS SECTION NUMBER
- *RS57085* RIVER STATION
- ⇨ FLOW DIRECTION
- BRIDGE
- LOCAL ROAD
- PRIMARY HIGHWAY
- ▪▪▪ STUDY BOUNDARY
- FLOOD CONTROL STRUCTURE
- 🟥 PROPOSED FLOODWAY BOUNDARY
- ● BANK STATION
- ⊙ PROPOSED ICE JAM FLOODWAY STATION
- PREVIOUS FLOODWAY
- 🟦 DEPTH ≥ 1 M
- 🟩 100-YEAR ICE JAM FLOOD EXTENT



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PROJECT NO.	CONTROL	REV.	FIGURE
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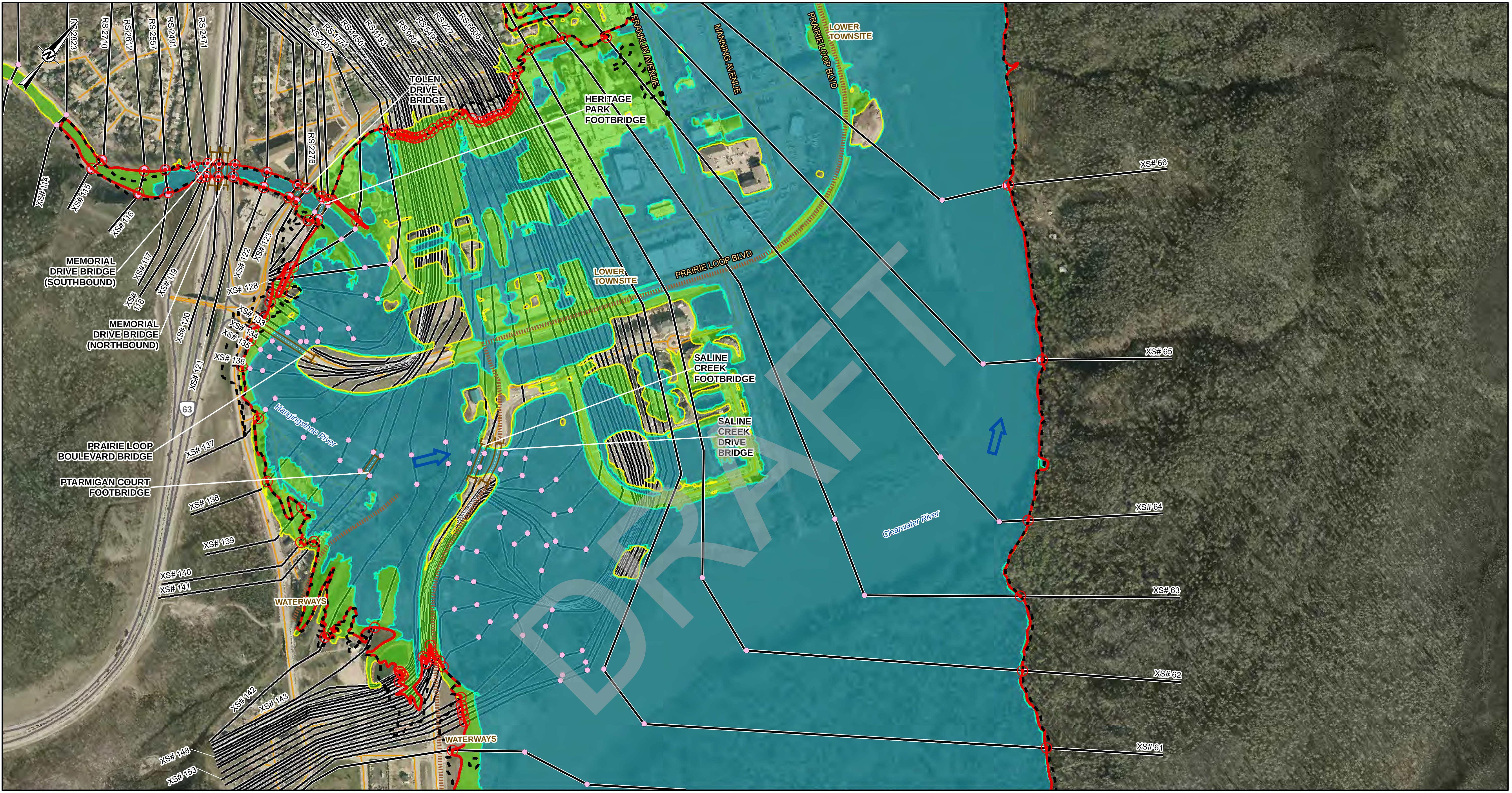

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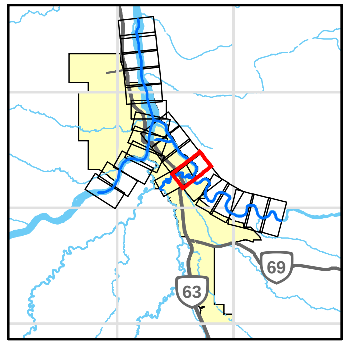
LEGEND

▬	CROSS SECTION
XS#110	CROSS SECTION NUMBER
RS57085	RIVER STATION
⇨	FLOW DIRECTION
╪	BRIDGE
─	LOCAL ROAD
─	PRIMARY HIGHWAY
■■■	STUDY BOUNDARY
▮▮▮▮	FLOOD CONTROL STRUCTURE
▭	PROPOSED FLOODWAY BOUNDARY
●	BANK STATION
◉	PROPOSED ICE JAM FLOODWAY STATION
╍	PREVIOUS FLOODWAY
🟦	DEPTH ≥ 1 M
🟩	100-YEAR ICE JAM FLOOD EXTENT



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PROJECT NO.	CONTROL	REV.	FIGURE
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PATH: I:\CLIENTS\GOVERNMENT_OF_ALBERTA\21452576\Fort McMurray\Mapping\Products\Hydrology\05_Design Flood Hazard Mapping\Rev0\1662603_Floodway_Criteria-Ice-Jam_Rev0.mxd PRINTED ON: 2022-07-29 AT: 8:07:33 AM

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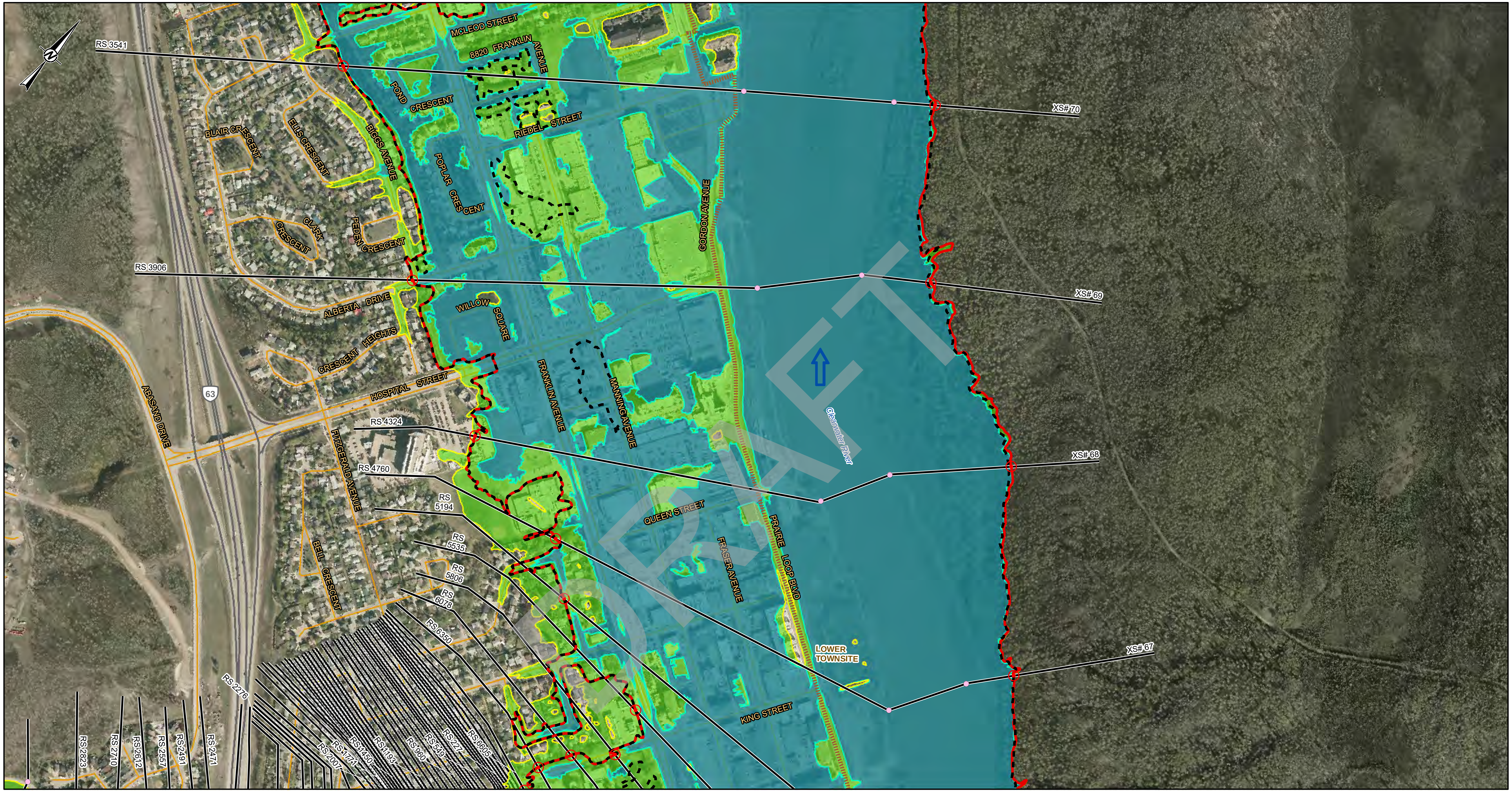

SHEET 19 ↓

LEGEND

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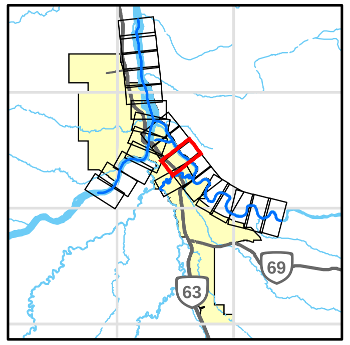
- XS#110 CROSS SECTION NUMBER
- *RS57085* RIVER STATION
- FLOW DIRECTION
- BRIDGE
- LOCAL ROAD
- PRIMARY HIGHWAY
- STUDY BOUNDARY
- FLOOD CONTROL STRUCTURE
- 🟥 PROPOSED FLOODWAY BOUNDARY
- ● BANK STATION
- ⊙ PROPOSED ICE JAM FLOODWAY STATION
- PREVIOUS FLOODWAY
- 🟦 DEPTH ≥ 1 M
- 🟩 100-YEAR ICE JAM FLOOD EXTENT



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TITLE
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PROJECT NO.	CONTROL	REV.	FIGURE
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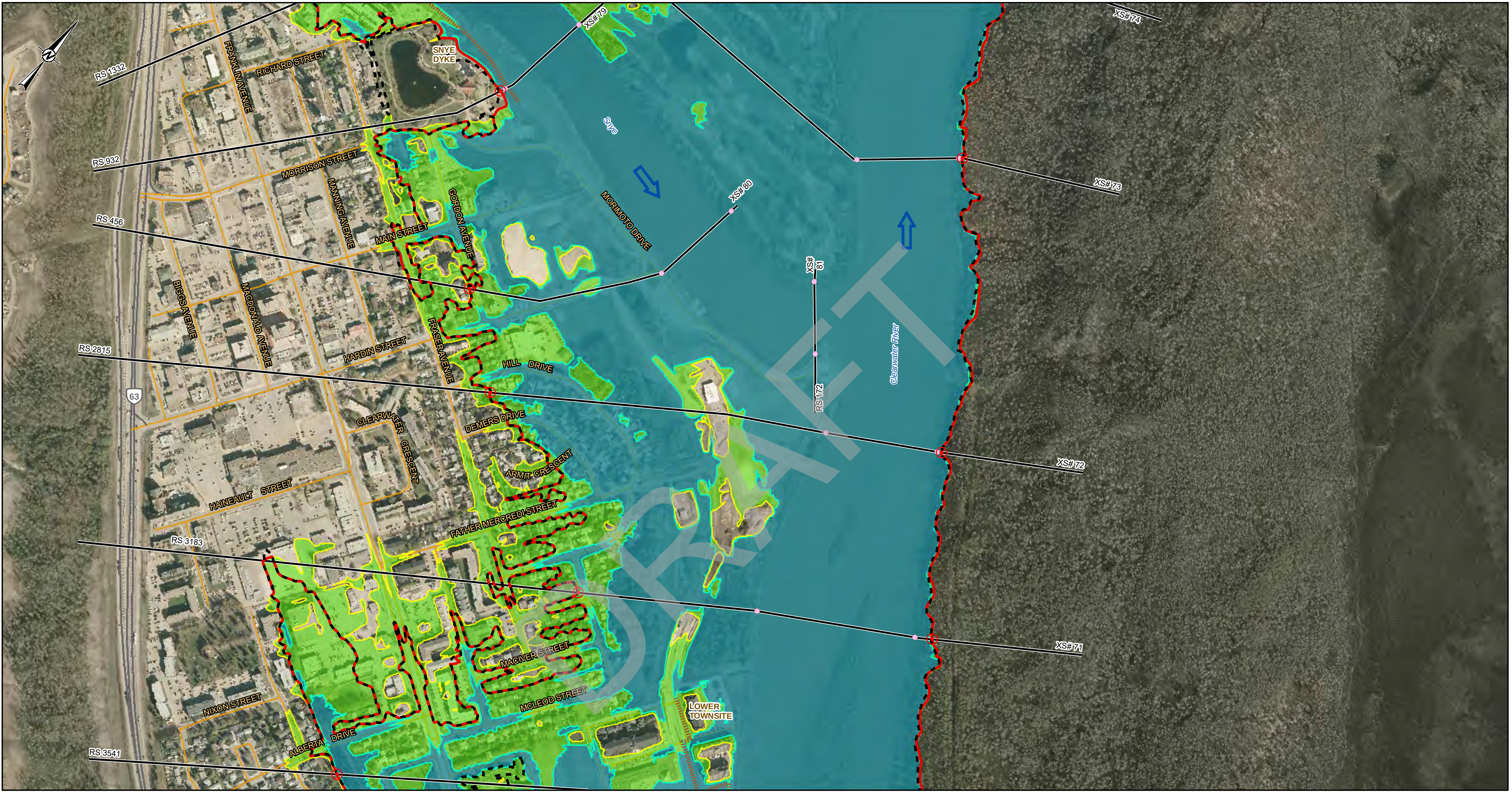
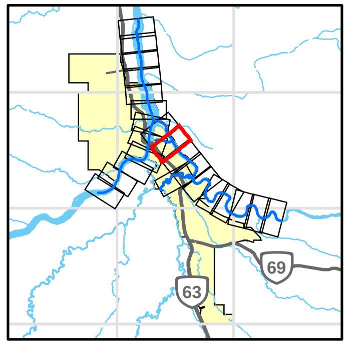


SHEET 20↓

LEGEND

▬	CROSS SECTION	🟥	PROPOSED FLOODWAY BOUNDARY
XS#110	CROSS SECTION NUMBER	●	BANK STATION
RS57085	RIVER STATION	⊙	PROPOSED ICE JAM FLOODWAY STATION
⇨	FLOW DIRECTION	▭	PREVIOUS FLOODWAY
⊢⊣	BRIDGE	🟦	DEPTH ≥ 1 M
—	LOCAL ROAD	🟩	100-YEAR ICE JAM FLOOD EXTENT
—	PRIMARY HIGHWAY		
▬ ▬ ▬	STUDY BOUNDARY		
▮▮▮▮▮	FLOOD CONTROL STRUCTURE		



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1662603	7000	0	Sheet 21 of 23

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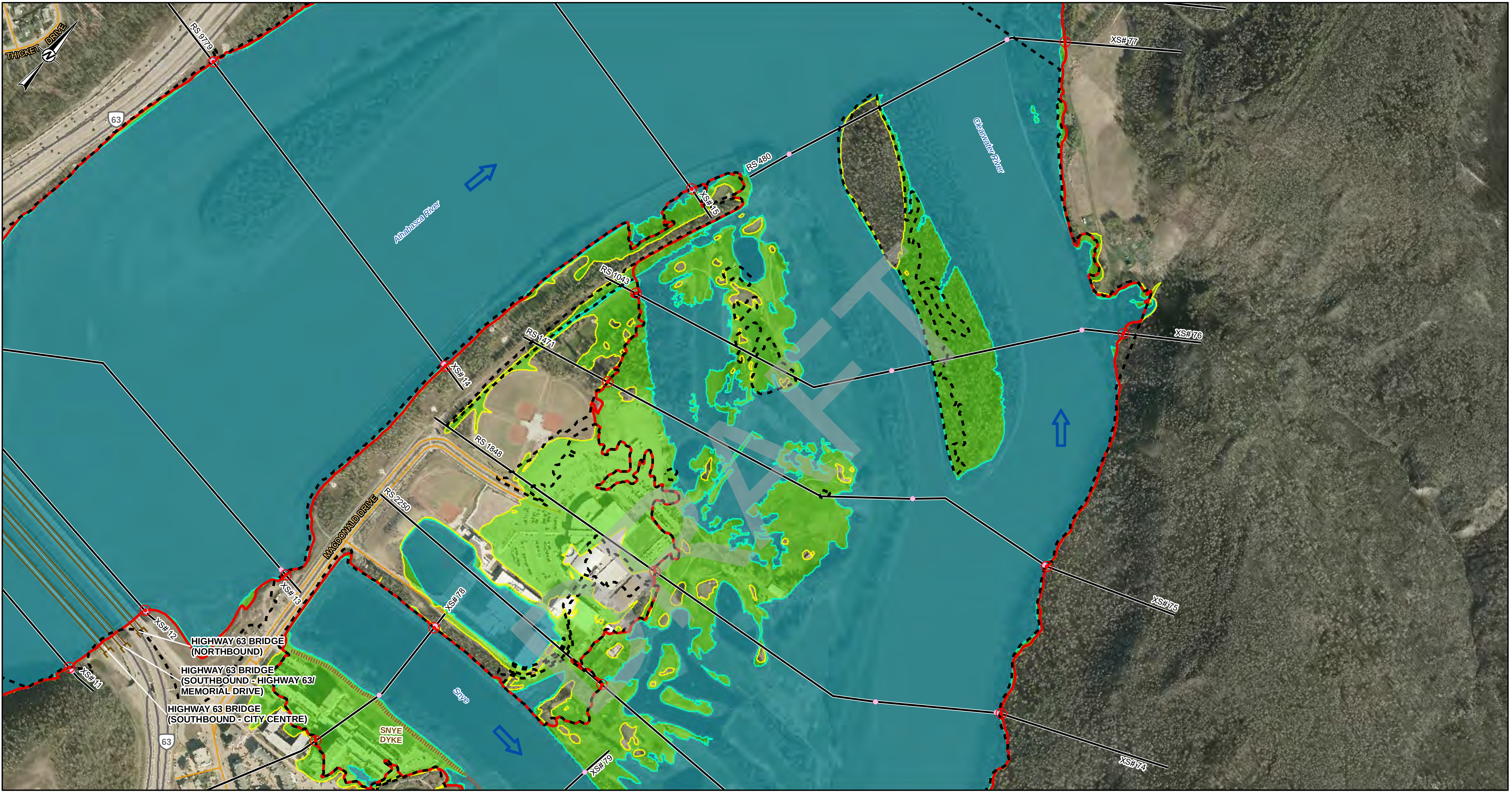

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LEGEND

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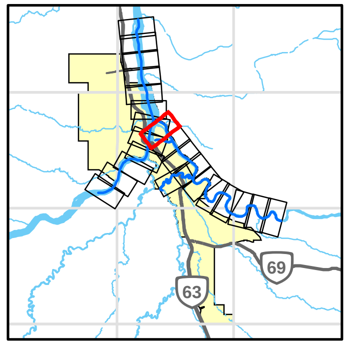
RS57085	RIVER STATION
⇨	FLOW DIRECTION
⊏⊐	BRIDGE
—	LOCAL ROAD
—	PRIMARY HIGHWAY
▬▬▬	STUDY BOUNDARY
▮▮▮▮	FLOOD CONTROL STRUCTURE
🟥	PROPOSED FLOODWAY BOUNDARY
●	BANK STATION
⊙	PROPOSED ICE JAM FLOODWAY STATION
⬚	PREVIOUS FLOODWAY
🟦	DEPTH ≥ 1 M
🟩	100-YEAR ICE JAM FLOOD EXTENT



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PROJECT NO.	CONTROL	REV.	FIGURE
1662603	7000	0	Sheet 22 of 23

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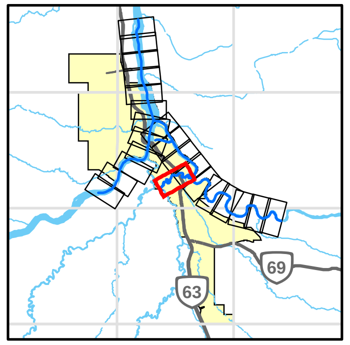
- *RS57085* RIVER STATION
- FLOW DIRECTION
- BRIDGE
- LOCAL ROAD
- PRIMARY HIGHWAY
- STUDY BOUNDARY
- FLOOD CONTROL STRUCTURE
- PROPOSED FLOODWAY BOUNDARY
- BANK STATION
- PROPOSED ICE JAM FLOODWAY STATION
- PREVIOUS FLOODWAY
- DEPTH ≥ 1 M
- 🟩 100-YEAR ICE JAM FLOOD EXTENT



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TITLE
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PROJECT NO.	CONTROL	REV.	FIGURE
1662603	7000	0	Sheet 23 of 23

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APPENDIX G

VALIDATION OF MODEL TO 2020 ICE JAM EVENT

1.0 INTRODUCTION

Alberta Environment and Parks (AEP) retained Golder Associates Ltd. (Golder), in collaboration with SG1 Water Consulting Ltd. (SG1) and Hatch Ltd. (Hatch), to assess the implications of the severe 2020 ice jam event on the ice-related flood hazard at Fort McMurray, Alberta. The original assessment study was completed in 2018, and the results of that study are presented in “Fort McMurray River Hazard Study, Ice Jam Modelling and Flood Hazard Identification Report”, November, 2018”. The work summarized in this appendix includes an update to the results of the operative ice-related water level frequency curve that was derived in the original assessment study and provides verification of the HEC-RAS ice jam model predictions as it pertains to the 2020 ice jam event. This is followed up with an assessment of the need for remapping the ice-related flood hazard zones along the Athabasca River, the Clearwater River, and the Hangingstone River within the study area.

Within this context, the following work was undertaken:

- The documented ice jam flood history was extended to 2020, and salient background data were provided for each additional year added to the original assessment data set.
- The ice jam flood frequency analysis was updated, the updated frequency curve was compared to the one previously produced, and ice-related water levels at the Clearwater-Athabasca confluence were updated for salient return periods.
- The 2020 ice jam event was described from the perspective of simulating the ice-related water levels within the jam using the HEC-RAS modelling framework.
- The robustness of the existing HEC-RAS ice jam model was assessed in terms of its ability to simulate the 2020 event.
- Recommendations were made regarding whether it is necessary to update the existing flood hazard mapping.

2.0 REVIEW OF STAGE-FREQUENCY ASSESSMENT

2.1 Peak Ice-Related Water Levels at the Clearwater-Athabasca Confluence

The updated water level frequency analysis is based on three additional years of data: 2018, 2019, and 2020. These data are summarized in Table 1, along with background information at the Water Survey of Canada (WSC) Athabasca River below Fort McMurray gauge (WSC Station No. 07DA001) that provides updated hydrologic context for the 2016 and 2017 events and for the measured peak water levels at the confluence for the 2018 to 2020 period. As in the main report, the data are described as follows:

1) Breakup year.
2) Last date of stable ice cover when the late-winter, ice-related rating curve is assumed to apply. This parameter is deduced from the water level trends, and represents the day before the ice cover appears to destabilize and significant shifts from the winter curve start to occur. In some years, this appears to occur well before breakup due to gauge malfunction. The data are disregarded in these cases.
3) Water level on date of last stable ice cover.

4) Reported discharge on date of last stable ice cover, based on WSC extrapolations of the winter rating curve. This provides an estimate of the minimum flow that could have occurred during breakup. Even though the ice cover is relatively stable and the year-to-year ice thickness is not that variable, the technique adopted by WSC to estimate the discharge based on water level is quite coarse.

5) Date of peak daily water level during the breakup period.

6) Peak daily water level during the breakup period.

7) Peak instantaneous water level, derived from the gauge data or from high water marks.

8) Date of instantaneous peak water level, if available.

9) First date of open water when ice effects have vanished, and the open water rating curve would apply. In some years, the record indicates that this occurs well after breakup because of gauge malfunction.

10) Water level on first date of open water.

11) Reported discharge on first date of open water. This provides an estimate of the maximum flow that may have occurred during breakup.

12) Periods of missing data at the WSC Station No. 07DA001 gauge during the breakup period.

13) Breakup type, either thermal or mechanical, as inferred from the gauge record or from observations.

14) Salient notes about the quality of the data and the breakup characteristics at the Fort McMurray gauge.

15) Date of the peak water/ice level at the RMWB gauge “Athabasca River at Highway 63” Note this is a downward facing sonar gauge, and measures the top of the water surface under open water conditions, and ice cover under winter conditions.

16) Peak water/ice level measured by the RMWB gauge “Athabasca River at Highway 63” . Note this gauge is a downward-facing sonar, so it measures the top of the water or ice.

17) Date of the peak water level at the RMWB gauge “Clearwater River at NTCL” at the old Northern Transport Company Limited (NTCL) dock, which is located on the Clearwater River approximately 120 m downstream of the intersection of Hospital Street and Prairie Loop Boulevard.

18) Peak water level measured by the RMWB gauge “Clearwater River at NTCL”.

19) Adopted ice-related water level at the Athabasca-Clearwater confluence, which served as the basis for the frequency analysis of historical ice-related flood peaks. This water level is either a direct measurement or inferred from data obtained at the Highway 63 Bridge gauge.

illustrates the year-to-year variation in the peak ice-related water levels for the period of record on the Athabasca River at the confluence of the Clearwater River. The 2020 event is the third largest on record, exceeded only by the 1875 and 1936 events by 3.1 m and 1.2 m, respectively. In terms of more recent large events, the 2020 ice jam level was approximately 1.0 m higher than that of the 1977 event and 1.4 m higher than that of the 1997 event.

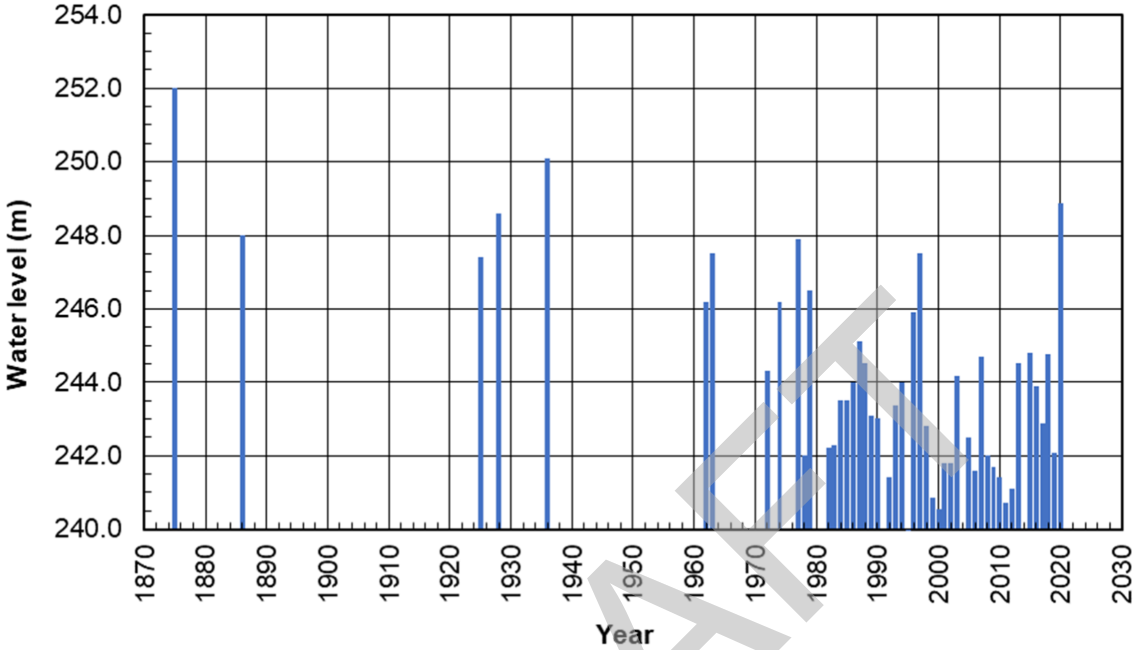

Figure 1: Historical Breakup Levels at Athabasca-Clearwater River Confluence

Table 1: Summary of Breakup-related Flows and Water Levels at WSC Station No. 07DA001 and within Fort McMurray

Year	Last Stable Ice Condition			Peak Daily Water Level		Peak Instantaneous Water Level		First Open Water			Dates of Missing Gauge Readings	Breakup Type (1)	Notes for WSC Gauge	Peak Ice/Water Level at Hwy 63 Bridge		Peak Water Level at Clearwater River at NTCL		Peak Water Level at Athabasca/ Clearwater Confluence (m)
	Date	Water Level (m)	Discharge (m³/s)	Date	Water Level (m)	Water Level (m)	Date	Date	Water Level (m)	Discharge (m³/s)				Date	Water Level (m)	Date	Water Level (m)	
[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]	[14]	[15]	[16]	[17]	[18]	[19]
2016	Apr 10	238.135	423					Apr 26	237.740	474	Apr 11 - Apr 17	M	Missing breakup data					243.9
2017	Apr 07	237.971	268					May 01	238.557	1030	Apr 09 – Apr 25 (2)	T	Missing breakup data	Apr 12 Apr 25	243.4 243.2	Apr 25	242.7	242.9
2018	Apr 24	238.850	376					May 03	240.044	2580	Apr 25 - Apr 29	M/S	Missing breakup data	Apr 26	245.4	Apr 26	244.9	NA(6)
2019	Apr 08	239.190	1110					May 13	237.973	946	Apr 10 - May 12	T	Missing breakup data	Apr 21	243.2	Apr 12 Apr 21	241.9 (3) 241.5	242.1
2020	Apr 25	241.170	1060			248.50 (4)		May 04	239.573	1940	Apr 26 - May 03	M	Missing breakup data	Apr 26 Apr 27	250.3 249.7	Apr 28/29	248.8	248.9 (5)

Notes:

(1) Breakup is classified into three basic types: thermal (T), mechanical, (M), and if mechanical either a jam forms or a surge passes through the reach (S).

(2) The stage record on the AEP website indicates that the WSC gauge was inoperative between April 9 and April 26, inclusive. However, the daily record published by WSC contains both daily water levels and discharges for that period. It appears that this record was infilled based on other information not available to the authors. The RWMB gauge at the Highway 63 Bridge indicates water levels fluctuating between 242.0 m and 243.5 m during the period April 12 to 17. On April 12, an ice jam formed just upstream of the Highway 63 bridge. This is followed by a period of steady water levels at an elevation of 242.5 m until the eventual thermal release of the ice jam on April 25. On that day, water levels rose slightly to elevation 243.2 m followed by a rapid water level decrease to 241.6 m as the ice went out.

(3) There were two distinct peaks at this location: the April 12 peak was the result of the escaped water wave the occurred when the ice jam near Crooked Rapids released and re-formed further downstream. The April 21 peak resulted from the eventual thermal release of the remains of the final ice jam..

(4) This elevation is based on an interpolation of the AEP high water marks measured after the event.

(5) In 2020, all gauges in the vicinity of the Athabasca-Clearwater confluence remained at peak levels for a period of about three to four days. During this time, water levels fluctuated by ±0.2 m. The peak water level at the confluence is based on post-flood highwater mark surveys. The relationship of this water level to a particular jam configuration is difficult to determine.

(6) WSC gauge data is unreliable - reading appears to be over-estimated and inconsistent with other readings in the area

2.2 Stage Frequency Analysis at the Clearwater River Confluence

The water level frequency analysis carried out in the original assessment was undertaken using two techniques: (i) the standardized frequency assessment of water levels using the threshold approach described in USGS Bulletin 17B (1982) and (ii) the perception level method that was first applied to the analysis of ice-related water level by Gerard and Karpuk (1979). Definitions of perception, or threshold levels, are required in both techniques to identify critical elevations above which events would have likely been noted (and below which events would have gone unnoticed). The perception level method allows for changing perception levels in the historical period, based on perceived changes in the degree of local interest in flood events. The Bulletin 17B technique adopts one threshold level that is used throughout the historical period. The two approaches were reconciled in the 2017 analysis by adopting a threshold level of 246.0 m – the nominal top of bank and/or top of rail elevation along the Clearwater River – in the Bulletin 17B technique. The Bulletin 17B technique was then adopted because of its more general usage throughout North America for a wide range of flood types.

This update defers to the outcomes of the previous analysis, whereby the Bulletin 17B technique with a threshold level of 246.0 m is used to analyze the updated data set. A complete description of the Bulletin 17B technique is provided in the main report; it will not be described herein other than to reiterate the parameters embedded in the technique.

In applying the Bulletin 17B technique, the total record is assumed to be composed of two periods: (i) a historical record of length N_H in which only the high events above the adopted threshold level T are measured and (ii) a systematic record of length N_S where all events are measured. Missing years in the systematic record are treated as belonging to the historical period. Therefore, the entire record would consist of four types of data: (i) $N_H^>$ documented events above the threshold level in the historical part of the record, (ii) $N_H^<$ undocumented events below the threshold level in the historical part of the record, (iii) $N_S^>$ documented events above the threshold level in the systematic part of the record, and (iv) $N_S^<$ documented events below the threshold level in the systematic part of the record. All would be measured in one way or another, except for the missing years in both the historical and systematic parts of the record. The statistical parameters that are calculated from the lengths of the various record types are summarized in Table 2.

Table 2: Statistical Parameters for Bulletin 17B Technique

Parameter	Formulation
Total record length, H	$N_H^> + N_H^< + N_S^> + N_S^<$
Total number of observed events, Z	$N_H^> + N_S^>$
Number of observed events below the threshold level in systematic period, N	$N_S^<$
Weighting factor, W	$(N_H^< / N_S^<) + 1$
Weighted rank, m, of observed events ranked from largest to smallest, where r is the rank	*For* $m \le Z$: $m = r$ *For* $m > Z$: $m = Z + W(r - Z - 0.50) + 0.5$
Plotting position, PP, where a = 0.4 for the Cunnane plotting formulae	$(m - a) / (H + 1 - 2a)$

The updated record extends the original assessment record by three events, all of which contribute to increasing the number of events that are contained in the systematic record. Within that record, the 2018 and 2019 events fall below the adopted threshold level and the 2020 event falls above the threshold level. A comparison of the statistical parameters of the 2017 record and the updated record is shown in Table 3. The addition of the three most recent years of data reduces the weighting factor and increases the weighted mean, but decreases the weighted standard deviation and the weighted skew coefficient. This as the overall effect of slightly flattening the frequency curve.

Table 3: Summary of Event Numbers and Calculated Weighting Factors (Threshold Level of 246.0 m)

Parameter	Analysis to 2017 (1870-2017)	Analysis to 2020 (1870-2020)
$N_H^>$	7	7
$N_H^<$	106	106
$N_S^>$	4	5
$N_S^<$	30	32
W	4.53	4.31
Weighted mean, M	3.24	3.30
Weighted standard deviation, S	2.01	1.99
Weighted skew coefficient, G	1.04	0.967

The two frequency curves are shown for comparison in Figure 2, with the 2020 data set plotted for context. The 2020 frequency curve plots slightly below the 2017 curve at the longer return periods, and slightly above the 2017 curve for the shorter return periods. The 2020 curve should not be viewed as being significantly different from the 2017 curve (Table 4) given the accuracies in measuring water levels within the severe jams, like those that form at Fort McMurray, and the tolerances in statistical analysis as a result of the weighting process. It is therefore recommended that no changes be made to the adopted frequency curve in the original assessment.

Table 4: Comparison of Historical Ice-Related Water Level Frequencies at the Athabasca-Clearwater Confluence

Return Period (years)	Annual Probability Being Equalled or Exceeded (percent)	Water Level at Athabasca-Clearwater Confluence (m)		
		2017 Analysis (1870- 2017)	Current Analysis (1870-2020)	Difference w.r.t. 2017 Analysis
2	50	242.9	243.0	0.1
5	20	244.7	244.8	0.1
10	10	245.9	246.0	0.1
20	5	247.0	247.0	0
50	2	248.4	248.3	-0.1
100	1	249.4	249.3	-0.1
200	0.5	250.4	250.2	-0.2

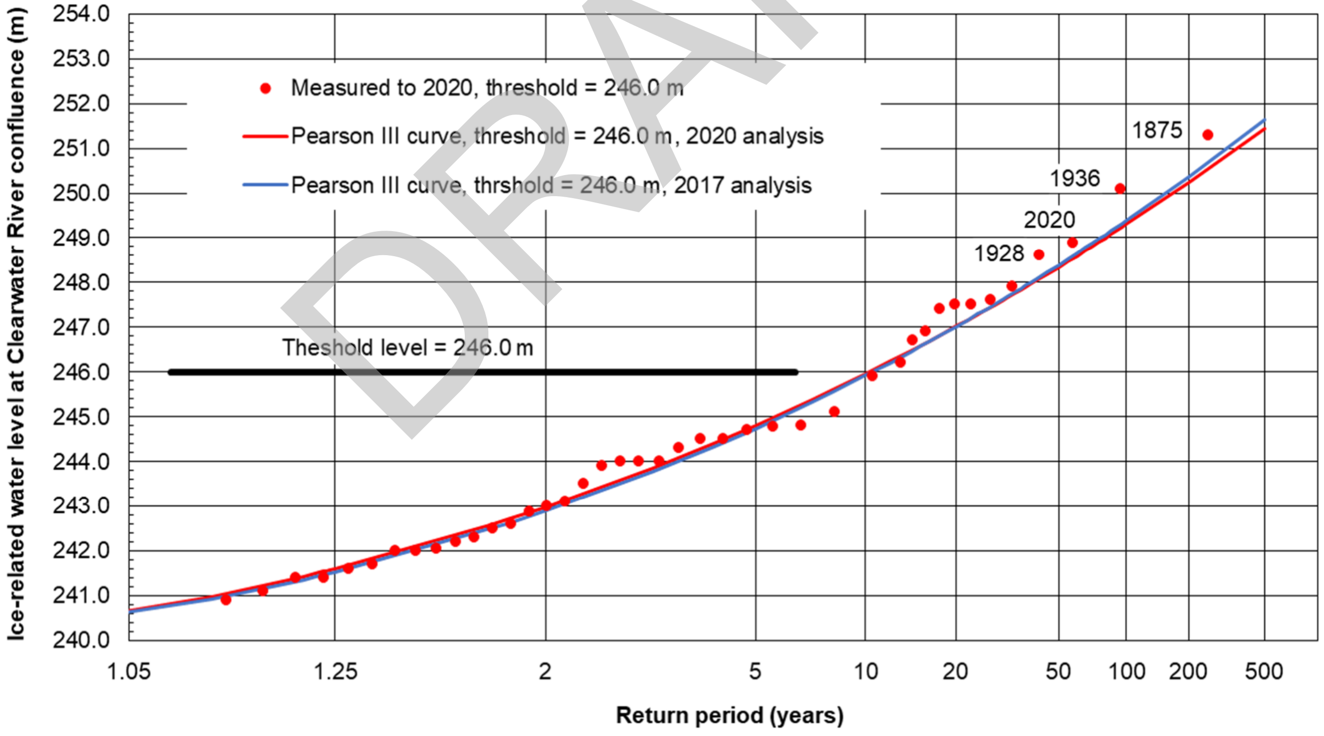

Figure 2: Frequency Curve of Historical Breakup Levels at Athabasca-Clearwater Confluence

3.0 MODEL SIMULATION OF 2020 ICE JAM EVENT

The next step of the assessment involved re-mobilization of the ice enhanced HEC-RAS model and its application to simulate peak water levels associated with the 2020 event. As noted earlier, several well-documented historical ice jam events were previously used to calibrate, and then validate, the model. The 2020 event provides an additional data point to evaluate the model's ability to replicate the complex hydraulic conditions that can occur in this reach during an ice jam event. The approach to this assessment was based on the following steps:

- Review of the event and measured water levels
- Review of the event hydrology to estimate the operative carrier discharge
- Re-mobilization of the numerical model to simulate the 2020 ice jam event

For this assessment, available river flows were initially reviewed to provide a best estimate of the likely carrier discharge for the 2020 ice jam event. Using this discharge, the model was then run using the ice parameter sets developed in the original assessment (i.e., ice specific gravity, porosity, internal friction angle and stress ratio) to assess their ability to reproduce 2020 levels.

3.1 Event Observations

The 2020 spring ice jam event, which occurred in late April / early May, resulted in the flooding of a significant number of areas in Fort McMurray along both the Athabasca and Clearwater River. The breakup period lasted for approximately one week, from April 26 to May 1. Data available for the event was quite extensive, and included the following:

- Aerial imagery of the ice jam, acquired while it was at or near to its peak level (Figure 5).
- High water levels, recorded at 24 locations along both the Athabasca and Clearwater Rivers at the locations shown in
- Figure 6. Peak levels measured by AEP at each of these locations are summarized in Table 6.
- WSC gauge information from several tributary gauges. Unfortunately, the hydrometric gauge "Athabasca River below Fort McMurray" (WSC Station No. 07DA001) stopped operating on April 25 as the river levels began to rise sharply, and did not begin operating again until May 4 when the gauge was serviced and put back into commission.
- Continuous water level hydrographs at a select number of sites in the Fort McMurray area, as shown in Figure 4. The data are currently provisional and considered to be preliminary in nature and may be subject to change when manually reviewed and corrected by WSC and/or AEP. Note that the level data provided by the "Athabasca River at Highway 63 Bridge" was measured with a downward-facing sonar instrument, so the levels provided are the elevation of the water surface (if ice were not present) or the elevation top of the ice (if ice were present).
- Aerial imagery (photos and video footage) of the 2020 ice jam event acquired by AEP and numerous citizens at various times during the event.

In reviewing this data, and available observation reports, details on the event were as follows:

- AEP began their usual observation program for ice jam activity on the Athabasca River in April 2020, and on April 20 noted that the ice cover on the Athabasca River was largely intact but with short sections of open water and leads evident within the rapid areas upstream of Fort McMurray. With continuing warm weather, it was noted on April 22 that, although the cover still was largely intact, it was deteriorating quickly in upstream reaches. Ice runs were noted to be passing through the Town of Athabasca late on April 22, raising water levels at the town.
- On April 24, an ice jam formed upstream of Fort McMurray. The toe of the jam was located between Little Cascade Rapids and Cascade Rapids (26 km upstream of the Highway 63 Bridge). The head of the ice jam was located 46 km upstream of the bridge.
- The ice jam released early in the morning on April 26, and the breaking ice front pushed into the reach downstream of the Clearwater River confluence, causing water levels in Fort McMurray to rise and forcing Athabasca River ice to flow up the Clearwater River. This occurred over the course of the morning as the movement of this ice slowed and eventually lodged. The toe of the resulting ice jam was observed to be 14 km downstream of the Highway 63 Bridge and the head of the jam was located10 km upstream of the bridge – a jam length of approximately 24 km. Figure 3, taken on April 28 (date of peak water levels in downtown Fort McMurray), provides an aerial view of ice conditions along the Clearwater River.
- The ice jam ultimately caused water levels along the Athabasca and Clearwater Rivers to rise more than 6 m at Fort McMurray, with Athabasca River ice being pushed about 7 km up into the Clearwater River. The jam remained in place but began melting due to the influx of warmer flows associated with spring runoff so that it had shortened to 20 km in length by April 28. By April 29, the jam had shortened to 15 km, and levels had begun falling in the Athabasca River, as shown in Figure 4.
- By April 29, the head of the jam had melted to the Athabasca-Clearwater confluence, while the toe remained in its original location.
- By May 1, the jam had melted out and water levels fell. An ice plug remained in place at the mouth of the Clearwater River. The plug slowed the release of water from the Clearwater River and melted out on May 2.

Figure 3: View of Clearwater River and Athabasca River (Morning of April 29, 2020, AEP Ice Observation Report No.8)

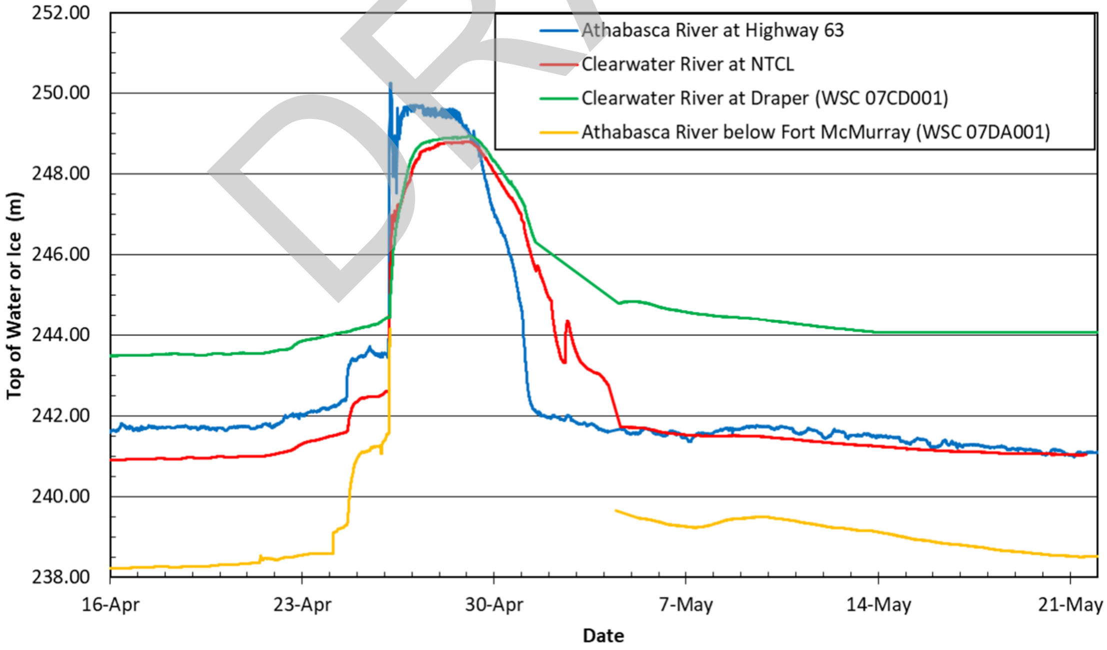

Figure 4: Ice-Related Water Levels in Vicinity of Fort McMurray during 2020 Ice Jam Event

Figure 5: Aerial Imagery of Flood Extent in Fort McMurray (April 28, 2020)

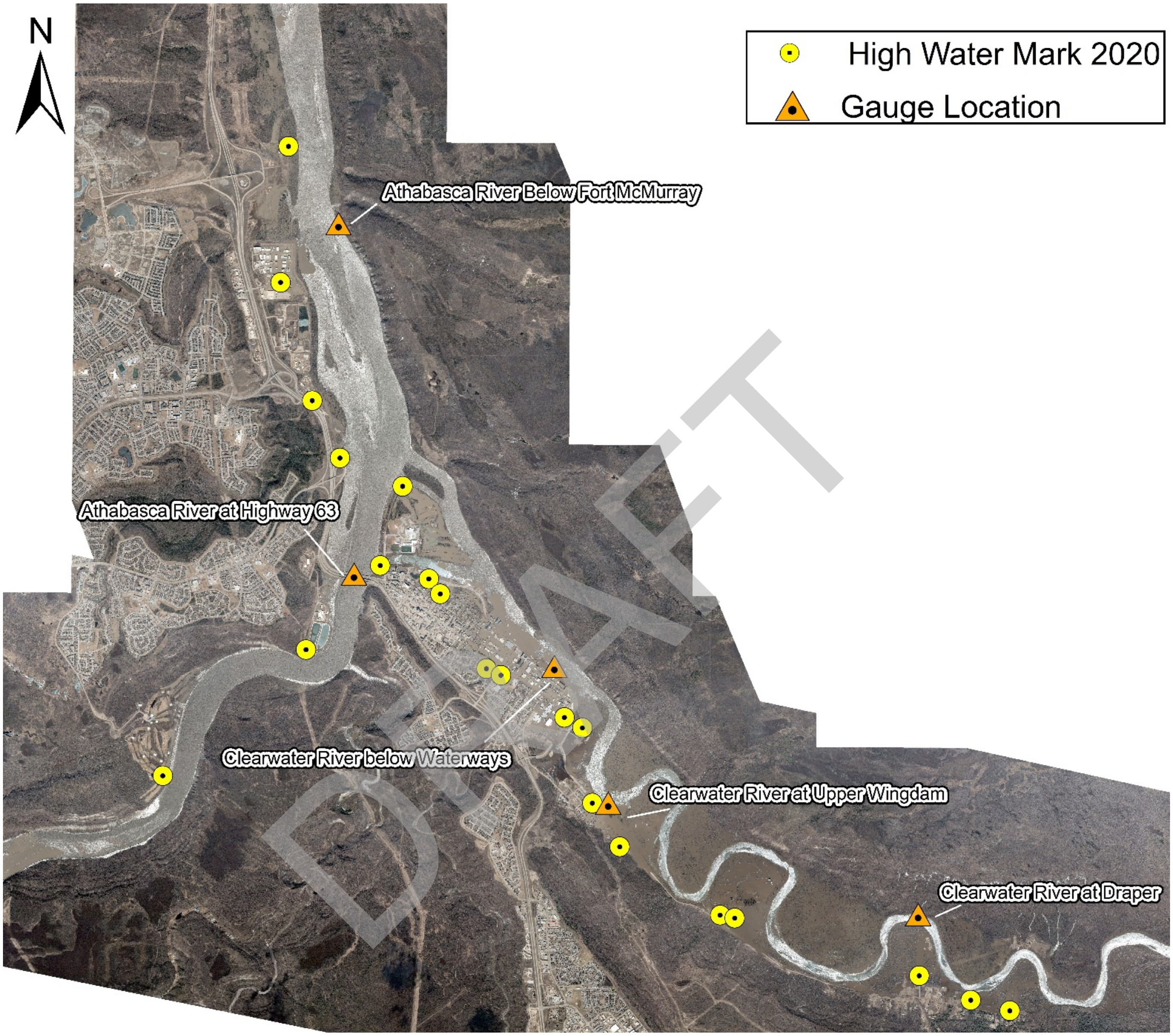

Figure 6: Location of Surveyed High Water Marks

3.2 Review of Event Hydrology

Discharge can be highly variable during the breakup period and the WSC gauges provide imperfect estimates of flows at that time. Gauges often become inoperative and usually the effects of ice on the rating curve are unknown. In 2020, WSC gauges in the vicinity of Fort McMurray, from which a carrier discharge could be determined, were damaged due to the severity of the breakup event. However, the hydrometric gauge Athabasca River at Athabasca (WSC Station No. 07BE001), located at the Town of Athabasca, operated throughout the breakup event, and data from there provides insight into the day-to-day variability of Athabasca River flows upstream of Fort McMurray. Consistent with archived observation reports, it appears that breakup occurred on April 22 in Athabasca, and a large surge of ice and water passed through Athabasca early on April 23. From April 24 onward, the open water rating curve would have been only marginally, or not at all, affected by ice on this gauge. Figure 7 shows the provisional streamflow data available at these two Athabasca River gauges.

Breakup in the reaches just upstream of Fort McMurray began on or about April 26 and, given a time lag of approximately two days for the flows at Athabasca to reach Fort McMurray, the contributing flows on the Athabasca River from upstream of Athabasca on April 24 and April 25 are estimated as being 1500 m^3/s and 2000 m^3/s, respectively. These flows would have been augmented by local tributary flow entering the river between Athabasca and Fort McMurray. Regionalizing the concurrent tributary inflows downstream of Athabasca (about 10 m^3/s from the Wandering River and 25 m^3/s from the House River) suggests that local inflows from the basin between Athabasca and Fort McMurray would have been in the order of 250 m^3/s. This suggests the carrier discharge for this jam event would have been between 1730 m^3/s and 2250 m^3/s upstream of Fort McMurray. It is also possible that the surge of ice and water experienced at Athabasca could have further increased the carrier discharge in Fort McMurray as the jave could have caught up and augmented the natural river flows in the Athabasca.

Downstream of the Athabasca-Clearwater confluence, discharge on the Athabasca River would have been higher due to flow contributions from the Clearwater River. In reviewing the Clearwater River discharge data and recognizing that they were significantly affected by backwater from the Athabasca River stages, it appears that peak flows during the ice jam event were likely in the 200 m^3/s range (Figure 8). Therefore, it is surmised that flows on the Athabasca River below the confluence were likely between 1930 m^3/s and 2500 m^3/s. Taking all this information into consideration, Figure 9 provides an estimate of flows on the Athabasca River during the 2020 ice jam event. The period shaded in blue indicates the approximate period when the jam was in place in Fort McMurray. Based on observation reports, peak water levels on the Clearwater River occurred overnight on April 28-29, which corresponds with the expected peak flows.

The final flows selected for modelling of this event included an adopted carrier discharge (formative flow) of 2300 m^3/s in the upper Athabasca reach, 200 m^3/s in the Clearwater River, and 2500 m^3/s in the lower Athabasca reach. This is discussed in the sections below.

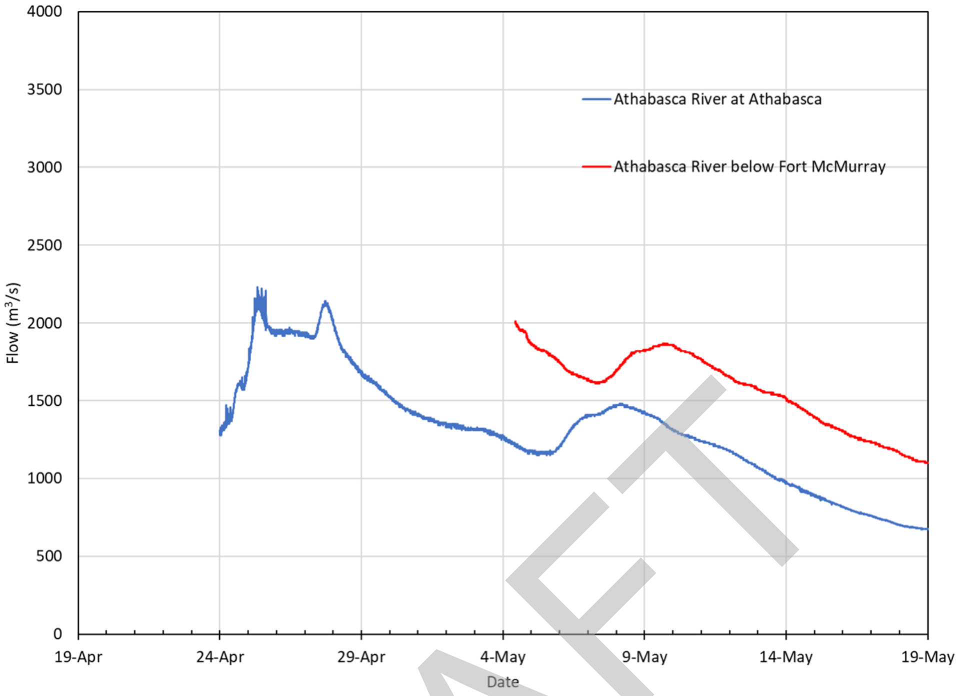

Figure 7: Recorded Flows on Athabasca River at Athabasca (07BE001) and Fort McMurray (07DA001) – Spring 2020

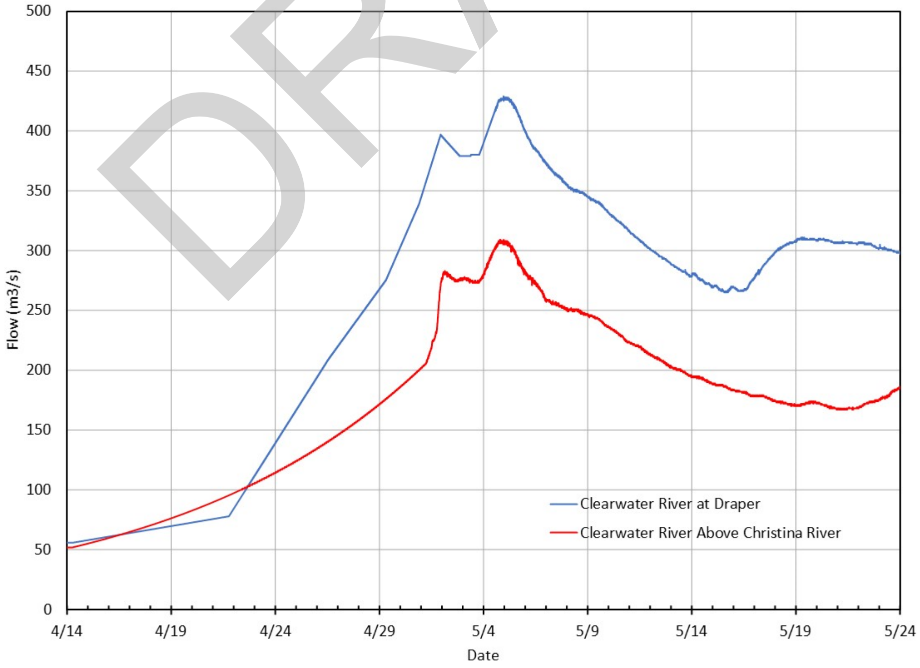

Figure 8: Recorded Flows on Clearwater River at Draper (07CD001) and above Christina River (07CD005) – Spring 2020

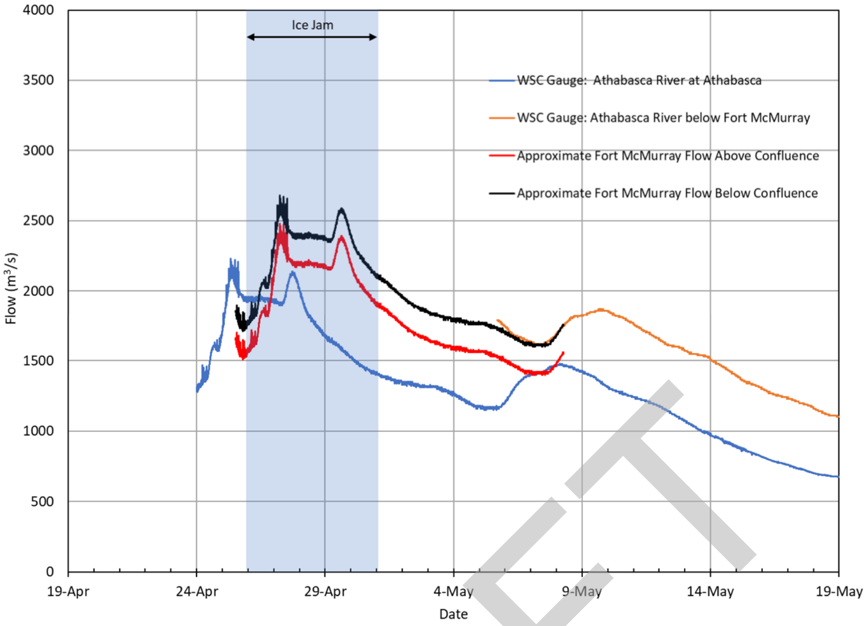

Figure 9: Estimated Flows on Athabasca River at Various Locations – Spring 2020

3.3 Model Setup

The model was setup using the hydraulic parameters (Table 5) adopted in the calibration and validation analysis undertaken in the original assessment, and the following work was carried out.

Table 5: Ice Jam Parameters Used in the 2017 Simulations

Manning's Coefficient, n		Ice specific gravity	Friction angle, ϕ	Ice jam porosity	Lateral stress coefficient of ice jam, K1	Approx. Ice jam strength parameter, μ	Maximum water velocity at toe	Ice jam cohesion
(solid ice cover)	(ice jam)		(degrees)				(m/s)	(Pa)
0.01	0.060-0.065	0.916	45	0.4	0.33-0.825	1.7	2	0

- The recorded field data were reviewed and the location of the jam toe was translated into relative model stationing and applied to the appropriate cross section.
- An initial sheet ice thickness of 1.0 m was adopted for the model run. This provides the initial ice thickness for the model to start the ice jam calculations and is close to the solid ice cover thickness expected at the site at the end of winter.
- The model was set to compute a dynamic ice jam in both the channel and overbank areas for all cross sections located at and upstream of the toe. Although 1.0 m was specified as the initial ice thickness along

the length of the jam, the model iterated to determine the stable ice thickness at each cross section location. At the Grant McEwan Bridge, the model was set to allow a dynamic ice computation (wide river ice jam) to proceed through the bridge cross section.

- The roughness of the ice cover was set as a fixed variable for the simulation. The ice cover roughness for each jam varied from 0.060 to 0.065 for areas located upstream of the McEwan bridge where covers tend to be thicker, and rougher. The bed roughness was based on the calibrated bed roughness for the open channel model.
- Internal strength of the ice jam is represented by μ, which is a dimensionless coefficient. The coefficient μ scales with the internal friction angle, φ, and the longitudinal-to-lateral stress transformation coefficient within the jam. A value of 45 degrees was selected for the internal friction angle whereas the stress ratio value was selected from a range between 0.33 to 0.825. The equation to compute μ is presented below:

$$\mu = \kappa_1 \tan(\varphi)\tan^2(\pi/_4 + \varphi/_2)$$

- Ice jam profiles were simulated for an adopted carrier discharge (formative flow) of 2300 m^3/s in the upper Athabasca reach, 200 m^3/s in the Clearwater River, and 2500 m^3/s in the lower Athabasca reach.

3.4 Model Results

The ice enhanced HEC-RAS model, as calibrated in the original assessment, accurately simulates the measured ice jam profile as defined by the highwater marks that were produced by the 2020 breakup event. However, two modifications were required to account for ice-related conditions associated with the 2020 event.

- Site observations and drone video footage collected following breakup show that ice from the Athabasca River had been pushed into the Clearwater River for a distance of several kilometres. Therefore, the ice thickness in the Clearwater River reach between the mouth and the upstream end of MacDonald Island was increased to match the thickness of the cover computed by HEC-RAS in the Athabasca River. The ice cover in this reach was given a roughness equivalent to that of the Athabasca River ice jam. This modification allowed the model to better match the high water levels measured on the Clearwater River.
- At the upstream end of the Athabasca River model, initial validation simulations showed that the model underpredicted water levels in the vicinity of the golf course by approximately 1 m.. It was judged that the measured high water marks were partly a result of the initial breaking front, before the main jam stabilized, and they would not have been related to its post-formation characteristics. As well, the head of the jam was identified at a location upstream of our model extent, and the HEC-RAS model did not directly account for ice located upstream of the upstream model boundary. This would cause the model to asymptote to a thinner ice cover thereby producing a lower water level than what would have been produced by the longer ice cover, and the passage of the surge. To compensate for this, the model thicknesses were increased in the upper reach to match the equilibrium thickness calculated by the model at the location of the Fort McMurray Water Treatment Plant, which is situated on the left floodplain within 1.5 km of the highway bridges. This considerably improved the goodness of fit in the upper reaches and was considered to be justifiable since the actual jam extended upstream of the model extents.

Final model results for the 2020 ice jam event are summarized in Figure 10 for the Athabasca River, and in Figure 11 for a combined profile that includes the Clearwater River and a short reach of the Athabasca River below it's confluence. Detailed tabular results are provided for the full reach in Appendix G1. Table 6 summarizes the difference between simulated results and recorded water levels at high water mark locations throughout the modelling domain. The comparison includes all observation points in the reach, except for the data collected at highwater mark AthMcM-4, which is located downstream of the Clearwater confluence, in the Taiga Nova area. The surveyed data at this location was flagged as being unreliable given its inconsistency with other upstream and downstream measurements.

As shown in Table 6, the average deviation between the computed and observed profiles is approximately 0.03 m, with maximum positive and negative deviations of approximately -0.52 m and +0.39 m at the AthMcm-6 and AthMcm-9 high water marks, respectively. This is considered to be a satisfactory match.

Given its good performance in matching the 2020 ice jam event, as well as the five other historical events previously tested, the ice enhanced HEC-RAS model remains current. No further updates to the model are required at this time.

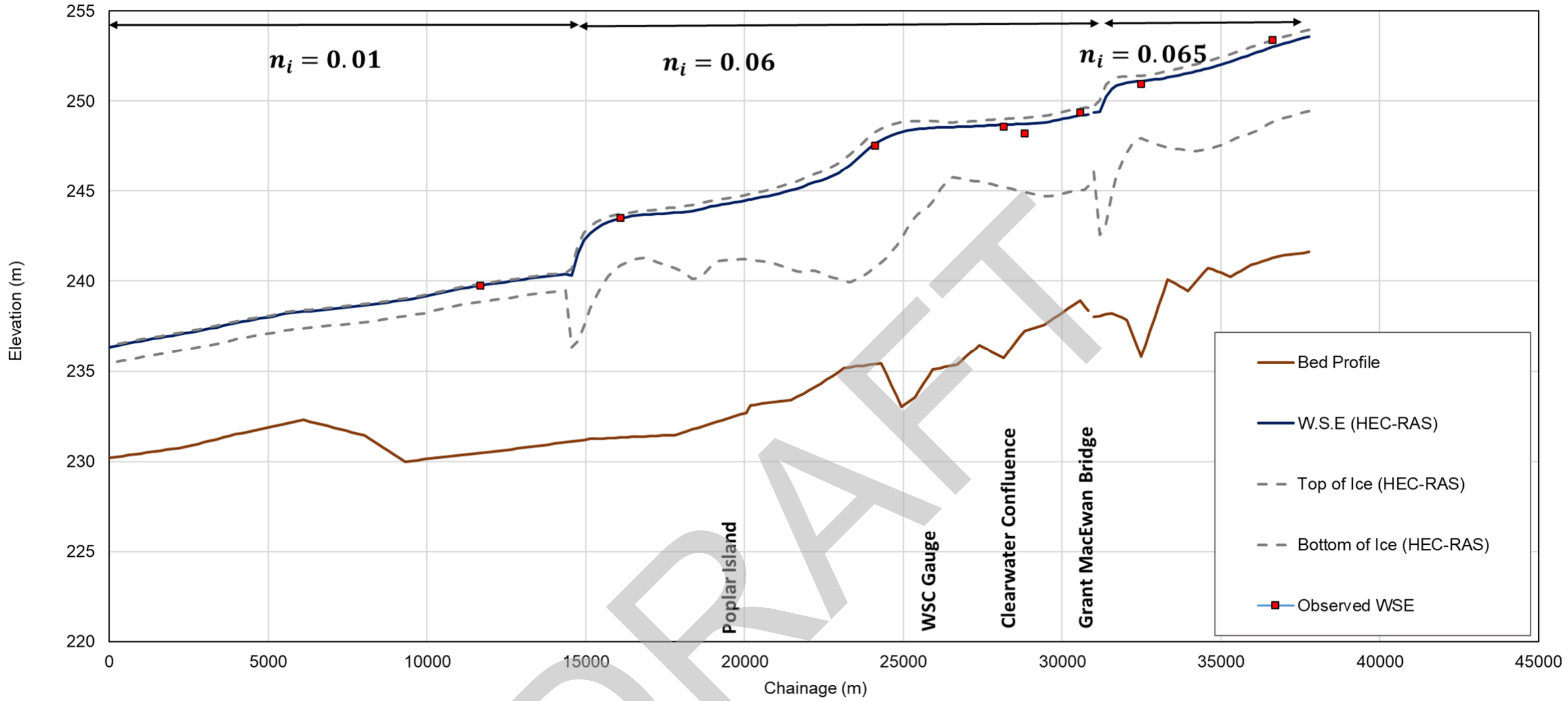

Figure 10: Calibration Results for 2020 Ice Jam on Athabasca River

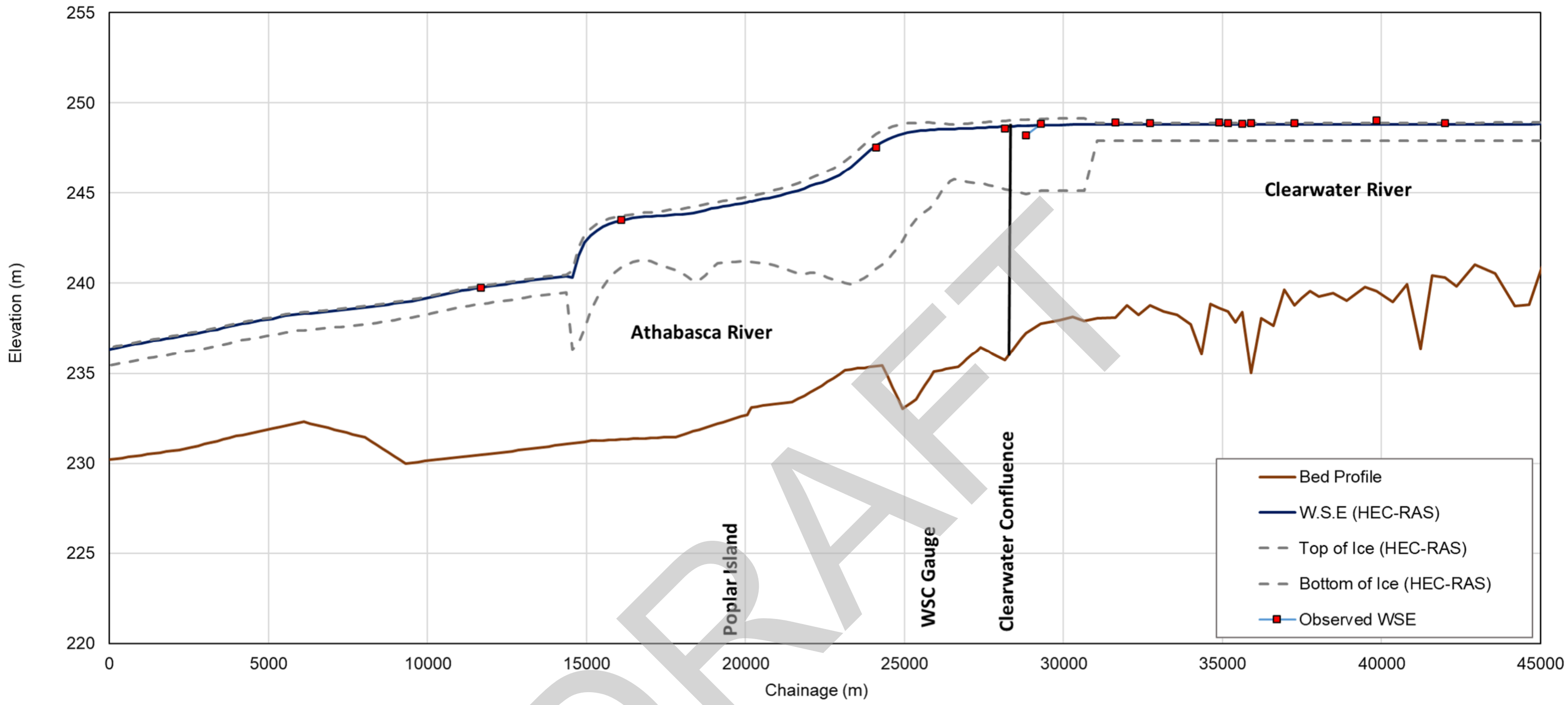

Figure 11: Calibration Results for 2020 Ice Jam on Athabasca and Clearwater Rivers

Table 6: Comparison of Simulated and Observed Water Levels for 2020 Ice Jam Event

HWM No.	River Reach	River Station (Ice Enhanced)	River Station (Open Water)	Observed HWM (m)	Simulated Level (m)	Difference (m)
AthMcM-1	Athabasca Lower	12693.8	n/a	239.753	239.83	-0.077
AthMcM-2	Athabasca Lower	15759.6	n/a	243.502	243.51	-0.008
AthMcM-3	Athabasca Lower	22724.5	4051	247.34	247.72	-0.38
AthMcM-4	Athabasca Lower	24347.35	5675	Disregarded	248.53	-
AthMcM-5	Athabasca Lower	26567.64	7895	248.603	248.7	-0.097
AthMcM-6	Athabasca Lower	27231	8559	248.238	248.76	-0.522
AthMcM-7	Athabasca Lower	24419	5746	249.368	249.23	0.138
AthMcM-8	Athabasca Upper	30908	12235	250.942	251.14	-0.198
AthMcM-9	Athabasca Upper	35043	16371	253.448	253.06	0.388
CLR5D-1	Clearwater Lower	490	490	248.818	248.79	0.028
CLR5D-2	Clearwater Lower	2815	2815	248.907	248.81	0.097
CLR5D-3	Clearwater Lower	2815	2815	248.909	248.81	0.099
CLR5D-4	Clearwater Middle	3906	3906	248.901	248.81	0.091
CLR5D-5	Clearwater Middle	3906	3906	248.9	248.81	0.09
CLR5D-6	Clearwater Middle	6078	6078	248.916	248.81	0.106
CLR5D-7	Clearwater Middle	6350	6350	248.875	248.81	0.065
CLR5D-8	Clearwater Middle	6800	6800	248.844	248.81	0.034
CLR5D-9	Clearwater Upper	7080	7080	248.897	248.81	0.087
CLR5D-10	Clearwater Upper	8439	8439	248.875	248.81	0.065
CLR5D-11	Clearwater Upper	11033	11033	249.022	248.82	0.202
CLR5D-12	Clearwater Upper	13178	13178	248.905	248.82	0.085
CLR5D-13	Clearwater Upper	16698	16698	248.946	248.83	0.116
CLR5D-14	Clearwater Upper	18261	18261	248.915	248.84	0.075
CLR5D-15	Clearwater Upper	19181	19181	249.052	248.85	0.202
					Average	**0.03**

4.0 SUMMARY AND CONCLUSIONS

The ice-related water level frequency analysis for the Athabasca River at Fort McMurray was updated to include additional breakup data collected since completing the original assessment. The 2020 frequency curve should not be viewed as being significantly different from the original assessment curve (Figure 2; Table 2) given the accuracies in measuring water levels within the severe jams (like those that form at Fort McMurray) and the tolerances in statistical analysis as a result of the weighting process. It is therefore recommended that no changes be made to the adopted original assessment frequency curve.

The ice enhanced HEC-RAS model developed as part of the original assessment was utilized once again to assess and evaluate the recent 2020 ice jam event. Using identical model parameters to those used in previous validation/calibration runs, the model was able to successfully replicate the 2020 event, with an average deviation of only 0.03 m from surveyed measurement points.

Given its good performance in matching the 2020 ice jam event, as well as the five other historical events previously tested, the ice enhanced HEC-RAS model remains current. Therefore, no further updates to the model are required at this time, nor is there a need to update the existing flood hazard mapping.

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Gerard, R. and E. Karpuk, 1979. *Probability analysis of historical flood data.* J. of the Hydr. Div., ASCE, 105(HY9), 1153-1165.

United States Geological Survey (USGS), 1982. *Guidelines for determining flood flow frequency, Bulletin #17B of the Hydrology Subcommittee.* Interagency Advisory Committee on Water Data. U.S. Department of the Interior, Office of Water Data Coordination, Reston, Virginia, USA.

APPENDIX G1

DETAILED TABLE OF RESULTS

Project: Fort McMurray Ice Study
Description: Summary of 2020 Ice Validation Event Results

River	Reach	River Sta (Ice Model)	River Sta (Open Water)	Cum Ch Len (m)	Q Total (m3/s)	Min Ch El (m)	W.S. Elev (m)	Ice Vol Total (m3)	Ice Thick Chan (m)	Ice Top Chan (m)	Ice Btm Chan (m)	Obs WS (m)
Snye	Snye	1332.108	1332.108	1332.1	0.1	239.34	248.81					
Snye	Snye	931.9456	931.9456	931.94	0.1	238.31	248.81					
Snye	Snye	455.9648	455.9648	455.96	0.1	238.63	248.81					
Snye	Snye	171.6331	171.6331	171.63	0.1	238.11	248.81					
Hangingstone	Hangingstone	5585.592	5585.592	5585.61	20	263.83	264.88					
Hangingstone	Hangingstone	5506.659	5506.659	5506.68	20	263.4	264.5					
Hangingstone	Hangingstone	5376.601	5376.601	5376.62	20	261.9	263.41					
Hangingstone	Hangingstone	5277.659	5277.659	5277.68	20	261.59	263.03					
Hangingstone	Hangingstone	5161.992	5161.992	5162.01	20	261.1	262.36					
Hangingstone	Hangingstone	5048.179	5048.179	5048.2	20	260.47	261.49					
Hangingstone	Hangingstone	4975.215	4975.215	4975.24	20	260.09	261.07					
Hangingstone	Hangingstone	4941.598	4941.598	4941.62	20	259.42	260.91					
Hangingstone	Hangingstone	4874.372	4874.372	4874.39	20	259.41	260.67					
Hangingstone	Hangingstone	4787.698	4787.698	4787.72	20	259.19	260.27					
Hangingstone	Hangingstone	4693.74	4693.74	4693.76	20	258.87	259.75					
Hangingstone	Hangingstone	4600.277	4600.277	4600.3	20	258.28	259.22					
Hangingstone	Hangingstone	4524.798	4524.798	4524.82	20	257.26	258.83					
Hangingstone	Hangingstone	4505.953	4505.953	4505.97	20	257.21	258.69					
Hangingstone	Hangingstone	4449.333	4449.333	4449.35	20	256.96	258.5					
Hangingstone	Hangingstone	4408.838	4408.838	4408.86	20	257.03	258.31					
Hangingstone	Hangingstone	4313.529	4313.529	4313.55	20	256.15	257.58					
Hangingstone	Hangingstone	4172.101	4172.101	4172.12	20	255.28	256.97					
Hangingstone	Hangingstone	4122.038	4122.038	4122.06	20	255.77	256.74					
Hangingstone	Hangingstone	4051.339	4051.339	4051.36	20	255.25	256.37					
Hangingstone	Hangingstone	3971.188	3971.188	3971.21	20	255.01	255.94					
Hangingstone	Hangingstone	3906.399	3906.399	3906.42	20	254.55	255.43					
Hangingstone	Hangingstone	3803.124	3803.124	3803.14	20	253.36	254.84					
Hangingstone	Hangingstone	3759.014	3759.014	3759.03	20	253.25	254.69					
Hangingstone	Hangingstone	3667.133	3667.133	3667.15	20	252.66	254.28					
Hangingstone	Hangingstone	3543.804	3543.804	3543.82	20	252.55	253.68					
Hangingstone	Hangingstone	3410.358	3410.358	3410.37	20	251.82	252.85					
Hangingstone	Hangingstone	3297.98	3297.98	3297.99	20	251	252.12					
Hangingstone	Hangingstone	3204.177	3204.177	3204.19	20	250.21	251.62					
Hangingstone	Hangingstone	3112.05	3112.05	3112.06	20	250	251.16					
Hangingstone	Hangingstone	3031.108	3031.108	3031.12	20	249.41	250.95					
Hangingstone	Hangingstone	2952.679	2952.679	2952.69	20	249.63	250.46					
Hangingstone	Hangingstone	2822.849	2822.849	2822.86	20	248.43	249.78					
Hangingstone	Hangingstone	2710.264	2710.264	2710.27	20	248.47	249.41					
Hangingstone	Hangingstone	2611.931	2611.931	2611.94	20	247.97	248.98					

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Hangingstone	Hangingstone	2557.02	2557.02	2557.03	20	247.46	248.92					
Hangingstone	Hangingstone	2490.552	2490.552	2490.56	20	247.05	248.87					
Hangingstone	Hangingstone	2471.188	2471.188	2471.2	20	246.14	248.87					
Hangingstone	Hangingstone	2459.802 BRIDGE 1		Mult Open								
Hangingstone	Hangingstone	2448.198	2448.198	2448.21	20	245.93	248.86					
Hangingstone	Hangingstone	2435.36 BRIDGE 2		Mult Open								
Hangingstone	Hangingstone	2417.885	2417.885	2417.9	20	246.43	248.85					
Hangingstone	Hangingstone	2360.00*		2360.02	20	246.17	248.84					
Hangingstone	Hangingstone	2353.985	2353.985	2354	20	246.14	248.84					
Hangingstone	Hangingstone	2323.76*		2323.78	20	246.22	248.83					
Hangingstone	Hangingstone	2293.532	2293.532	2293.55	20	246.3	248.83					
Hangingstone	Hangingstone	2284.351 BRIDGE 3		Mult Open								
Hangingstone	Hangingstone	2276.289	2276.289	2276.31	20	246.6	248.83					
Hangingstone	Hangingstone	2235.721	2235.721	2235.74	20	246.06	248.82					
Hangingstone	Hangingstone	2227.861 BRIDGE 4		Mult Open								
Hangingstone	Hangingstone	2221.769	2221.769	2221.79	20	246.14	248.82					
Hangingstone	Hangingstone	2156.103	2156.103	2156.12	20	246.45	248.82					
Hangingstone	Hangingstone	2071.505	2071.505	2071.52	20	245.66	248.82					
Hangingstone	Hangingstone	2007.202	2007.202	2007.22	20	244.91	248.82					
Hangingstone	Hangingstone	1923.395	1923.395	1923.41	20	244.79	248.82					
Hangingstone	Hangingstone	1860.687	1860.687	1860.7	20	245	248.82					
Hangingstone	Hangingstone	1831.466	1831.466	1831.48	20	244.92	248.81					
Hangingstone	Hangingstone	1809.216	1809.216	1809.23	20	244.15	248.81					
Hangingstone	Hangingstone	1791.239 BRIDGE 5		Mult Open								
Hangingstone	Hangingstone	1771.252	1771.252	1771.27	20	243.8	248.81					
Hangingstone	Hangingstone	1744.084	1744.084	1744.1	20	244.07	248.81					
Hangingstone	Hangingstone	1706.852	1706.852	1706.87	20	244.41	248.81					
Hangingstone	Hangingstone	1630.86	1630.86	1630.88	20	244.15	248.81					
Hangingstone	Hangingstone	1541.086	1541.086	1541.11	20	243.74	248.81					
Hangingstone	Hangingstone	1459.563	1459.563	1459.59	20	243.38	248.81					
Hangingstone	Hangingstone	1408.073	1408.073	1408.1	20	242.89	248.81					
Hangingstone	Hangingstone	1399.323 BRIDGE 6		Mult Open								
Hangingstone	Hangingstone	1389.484	1389.484	1389.51	20	242.51	248.81					
Hangingstone	Hangingstone	1313.773	1313.773	1313.8	20	242.89	248.81					
Hangingstone	Hangingstone	1242.932	1242.932	1242.96	20	242.36	248.81					
Hangingstone	Hangingstone	1193.156	1193.156	1193.18	20	241.37	248.81					
Hangingstone	Hangingstone	1181.222 BRIDGE 7		Mult Open								
Hangingstone	Hangingstone	1171.259	1171.259	1171.28	20	241.88	248.81					
Hangingstone	Hangingstone	1149.126 BRIDGE 8		Mult Open								

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Hangingstone	Hangingstone	1129.931	1129.931	1129.95	20	241.74	248.81					
Hangingstone	Hangingstone	1087.974	1087.974	1087.99	20	241.71	248.81					
Hangingstone	Hangingstone	1022.868	1022.868	1022.88	20	241.52	248.81					
Hangingstone	Hangingstone	960.0525	960.0525	960.06	20	241.96	248.81					
Hangingstone	Hangingstone	882.2751	882.2751	882.28	20	240.8	248.81					
Hangingstone	Hangingstone	768.9972	768.9972	769	20	240.77	248.81					
Hangingstone	Hangingstone	700.7451	700.7451	700.75	20	241.01	248.81					
Hangingstone	Hangingstone	648.1558	648.1558	648.16	20	240.74	248.81					
Hangingstone	Hangingstone	548.9328	548.9328	548.94	20	240.88	248.81					
Hangingstone	Hangingstone	489.7931	489.7931	489.8	20	241.24	248.81					
Hangingstone	Hangingstone	434.9363	434.9363	434.94	20	240.54	248.81					
Hangingstone	Hangingstone	372.1107	372.1107	372.11	20	240.61	248.81					
Hangingstone	Hangingstone	292.7723	292.7723	292.77	20	240.69	248.81					
Hangingstone	Hangingstone	226.8436	226.8436	226.84	20	240.37	248.81					
Hangingstone	Hangingstone	133.8605	133.8605	133.86	20	240.06	248.81					
Hangingstone	Hangingstone	106.2144	106.2144	106.21	20	240.37	248.81					
Hangingstone	Hangingstone	92.31356	92.31356	92.31	20	240.21	248.81					
Clearwater	Upper Reach	20359.02	20359.02	13754.17	180	241.31	248.85	9153763	1	248.93	247.93	
Clearwater	Upper Reach	19986.3	19986.3	13381.45	180	241.67	248.84	9013376	1	248.93	247.93	
Clearwater	Upper Reach	19705.16	19705.16	13100.31	180	242.18	248.84	8866767	1	248.92	247.92	
Clearwater	Upper Reach	19181.71	19181.71	12576.86	180	241.03	248.84	8646865	1	248.92	247.92	249.05
Clearwater	Upper Reach	18685.47	18685.47	12080.62	180	240.85	248.83	8299013	1	248.92	247.92	
Clearwater	Upper Reach	18261.58	18261.58	11656.73	180	240.87	248.83	7905582	1	248.92	247.92	248.91
Clearwater	Upper Reach	17882.61	17882.61	11277.76	180	240.31	248.83	7542919	1	248.91	247.91	
Clearwater	Upper Reach	17460.42	17460.42	10855.57	180	237.64	248.83	7190213	1	248.91	247.91	
Clearwater	Upper Reach	16972.25	16972.25	10367.4	180	241.28	248.83	6930585	1	248.91	247.91	
Clearwater	Upper Reach	16698.2*		10093.4	180	240.55	248.83	6769681	1	248.91	247.91	248.95
Clearwater	Upper Reach	16560.32	16560.32	9955.47	180	240.18	248.83	6703611	1	248.91	247.91	
Clearwater	Upper Reach	16222.89	16222.89	9618.04	180	240.91	248.82	6572483	1	248.91	247.91	
Clearwater	Upper Reach	15826.04	15826.04	9221.19	180	238.81	248.82	6404857	1	248.91	247.91	
Clearwater	Upper Reach	15382.2	15382.2	8777.35	180	238.75	248.82	6055392	1	248.91	247.91	
Clearwater	Upper Reach	14757.45	14757.45	8152.6	180	240.54	248.82	5713181	1	248.9	247.9	
Clearwater	Upper Reach	14127.07	14127.07	7522.22	180	241.05	248.82	4972447	1	248.9	247.9	
Clearwater	Upper Reach	13537.46	13537.46	6932.61	180	239.82	248.82	4498654	1	248.9	247.9	
Clearwater	Upper Reach	13178.92	13178.92	6574.07	180	240.31	248.82	4178976	1	248.9	247.9	248.9
Clearwater	Upper Reach	12785.95	12785.95	6181.11	180	240.44	248.82	3932247	1	248.9	247.9	
Clearwater	Upper Reach	12424.12	12424.12	5819.28	180	236.37	248.82	3668699	1	248.9	247.9	
Clearwater	Upper Reach	11984.9	11984.9	5380.06	180	239.96	248.82	3383379	1	248.9	247.9	
Clearwater	Upper Reach	11537.24	11537.24	4932.4	180	238.96	248.82	3169097	1	248.9	247.9	

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Clearwater	Upper Reach	11033.47	11033.47	4428.63	180	239.56	248.82	2884469	1	248.9	247.9	249.02
Clearwater	Upper Reach	10662.83	10662.83	4057.99	180	239.81	248.82	2686616	1	248.9	247.9	
Clearwater	Upper Reach	10095.14	10095.14	3490.3	180	239.03	248.81	2469015	1	248.9	247.9	
Clearwater	Upper Reach	9673.802	9673.802	3068.96	180	239.46	248.81	2143320	1	248.9	247.9	
Clearwater	Upper Reach	9209.617	9209.617	2604.78	180	239.27	248.81	1708523	1	248.9	247.9	
Clearwater	Upper Reach	8934.315	8934.315	2329.48	180	239.56	248.81	1550099	1	248.9	247.9	
Clearwater	Upper Reach	8679.208	8679.208	2074.37	180	239.19	248.81	1390697	1	248.9	247.9	
Clearwater	Upper Reach	8439.882	8439.882	1835.04	180	238.76	248.81	1279917	1	248.9	247.9	248.88
Clearwater	Upper Reach	8120.876	8120.876	1516.03	180	239.63	248.81	1115376	1	248.9	247.9	
Clearwater	Upper Reach	7779.764	7779.764	1174.92	180	237.66	248.81	841786.6	1	248.9	247.9	
Clearwater	Upper Reach	7396.448	7396.448	791.6	180	238.07	248.81	584112.8	1	248.9	247.9	
Clearwater	Upper Reach	7080.891	7080.891	476.04	180	235.03	248.81	381227.5	1	248.9	247.9	248.9
Clearwater	Upper Reach	6802.133	6802.133	197.28	180	238.39	248.81	237245.3	1	248.9	247.9	248.84
Clearwater	Mid Reach	6604.857	6604.857	4354.38	200	237.84	248.81	2760301	1	248.9	247.9	
Clearwater	Mid Reach	6350.496	6350.496	4100.02	200	238.45	248.81	2592054	1	248.9	247.9	248.88
Clearwater	Mid Reach	6078.455	6078.455	3827.98	200	238.61	248.81	2392465	1	248.89	247.89	248.92
Clearwater	Mid Reach	5805.896	5805.896	3555.42	200	238.84	248.81	2189980	1	248.89	247.89	
Clearwater	Mid Reach	5535.46	5535.46	3284.98	200	236.06	248.81	2050845	1	248.89	247.89	
Clearwater	Mid Reach	5194.108	5194.108	2943.63	200	237.74	248.81	1969933	1	248.89	247.89	
Clearwater	Mid Reach	4759.934	4759.934	2509.46	200	238.27	248.81	1803052	1	248.89	247.89	
Clearwater	Mid Reach	4324.203	4324.203	2073.73	200	238.45	248.81	1537030	1	248.89	247.89	
Clearwater	Mid Reach	3906.219	3906.219	1655.75	200	238.76	248.81	1297463	1	248.89	247.89	248.9
Clearwater	Mid Reach	3541.042	3541.042	1290.57	200	238.27	248.81	1059696	1	248.89	247.89	
Clearwater	Mid Reach	3182.93	3182.93	932.46	200	238.76	248.81	781777.4	1	248.89	247.89	
Clearwater	Mid Reach	2815.173	2815.173	564.7	200	238.1	248.81	515083	1	248.89	247.89	248.91
Clearwater	Lower Reach	2250.473	2250.473	2250.47	200	238.07	248.81	3904753	1	248.89	247.89	
Clearwater	Lower Reach	1847.547	1847.547	1847.54	200	237.92	248.8	3392129	4	249.14	245.14	
Clearwater	Lower Reach	1470.964	1470.964	1470.96	200	238.15	248.8	2728099	4	249.14	245.14	
Clearwater	Lower Reach	1043.023	1043.023	1043.02	200	237.96	248.79	2122099	4	249.13	245.13	
Clearwater	Lower Reach	479.8225	479.8225	479.82	200	237.78	248.79	1178024	4	249.12	245.12	248.85
Athabasca	Upper Reach	36191.07	17519	8960.03	2300	241.62	253.59	12364670	4.5	253.96	249.46	
Athabasca	Upper Reach	35994.1*		8763.23	2300	241.57	253.49	12152710	4.5	253.87	249.37	
Athabasca	Upper Reach	35797.3*		8566.42	2300	241.52	253.39	11937010	4.5	253.77	249.27	
Athabasca	Upper Reach	35600.5*		8369.62	2300	241.48	253.29	11717220	4.51	253.67	249.16	
Athabasca	Upper Reach	35403.7*		8172.82	2300	241.43	253.19	11493330	4.51	253.57	249.06	
Athabasca	Upper Reach	35207.05	16535	7976.01	2300	241.38	253.1	11265700	4.52	253.48	248.96	
Athabasca	Upper Reach	35043.1*		7812.2	2300	241.29	253.01	11077140	4.55	253.39	248.84	253.4
Athabasca	Upper Reach	34879.3*		7648.38	2300	241.2	252.91	10892960	4.62	253.3	248.68	
Athabasca	Upper Reach	34715.5*		7484.56	2300	241.1	252.81	10712670	4.7	253.2	248.51	

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Athabasca	Upper Reach	34551.7*		7320.75	2300	241.01	252.7	10536800	4.75	253.1	248.35	
Athabasca	Upper Reach	34387.97	15716	7156.93	2300	240.92	252.6	10366750	4.77	253	248.23	
Athabasca	Upper Reach	34221.0*		6990.08	2300	240.76	252.51	10194630	4.76	252.91	248.14	
Athabasca	Upper Reach	34054.1*		6823.23	2300	240.59	252.41	10017710	4.76	252.81	248.05	
Athabasca	Upper Reach	33887.3*		6656.38	2300	240.43	252.31	9835564	4.78	252.71	247.93	
Athabasca	Upper Reach	33720.57	15048	6489.53	2300	240.26	252.21	9647472	4.81	252.61	247.8	
Athabasca	Upper Reach	33580.0*		6349.05	2300	240.36	252.12	9481893	4.85	252.53	247.68	
Athabasca	Upper Reach	33439.6*		6208.56	2300	240.46	252.04	9307317	4.88	252.45	247.58	
Athabasca	Upper Reach	33299.1*		6068.08	2300	240.55	251.97	9124048	4.89	252.38	247.49	
Athabasca	Upper Reach	33158.6*		5927.59	2300	240.65	251.89	8932518	4.89	252.31	247.41	
Athabasca	Upper Reach	33018.14	14346	5787.1	2300	240.75	251.82	8733097	4.89	252.23	247.34	
Athabasca	Upper Reach	32890.2*		5659.18	2300	240.49	251.76	8548936	4.88	252.17	247.29	
Athabasca	Upper Reach	32762.2*		5531.25	2300	240.24	251.7	8367044	4.85	252.11	247.26	
Athabasca	Upper Reach	32634.3*		5403.32	2300	239.98	251.65	8188077	4.8	252.05	247.25	
Athabasca	Upper Reach	32506.4*		5275.4	2300	239.73	251.59	8012634	4.74	251.99	247.25	
Athabasca	Upper Reach	32378.51	13706	5147.47	2300	239.47	251.54	7841181	4.66	251.93	247.27	
Athabasca	Upper Reach	32251.4*		5020.36	2300	239.6	251.5	7675835	4.58	251.88	247.3	
Athabasca	Upper Reach	32124.2*		4893.25	2300	239.73	251.45	7516359	4.49	251.83	247.33	
Athabasca	Upper Reach	31997.1*		4766.14	2300	239.85	251.4	7362692	4.41	251.77	247.36	
Athabasca	Upper Reach	31870.0*		4639.02	2300	239.98	251.36	7214730	4.33	251.72	247.4	
Athabasca	Upper Reach	31742.95	13071	4511.91	2300	240.11	251.31	7072423	4.24	251.67	247.43	
Athabasca	Upper Reach	31603.9*		4372.91	2300	239.39	251.27	6921082	4.13	251.62	247.48	
Athabasca	Upper Reach	31464.9*		4233.9	2300	238.67	251.23	6772424	4.01	251.57	247.56	
Athabasca	Upper Reach	31325.9*		4094.89	2300	237.95	251.2	6627021	3.88	251.52	247.64	
Athabasca	Upper Reach	31186.9*		3955.88	2300	237.24	251.17	6480647	3.74	251.48	247.74	
Athabasca	Upper Reach	31047.9*		3816.88	2300	236.52	251.14	6338991	3.6	251.44	247.84	
Athabasca	Upper Reach	30908.92	12237	3677.87	2300	235.8	251.12	6201459	3.48	251.41	247.93	250.94
Athabasca	Upper Reach	30760.5*		3529.48	2300	236.48	251.09	6061234	3.53	251.39	247.86	
Athabasca	Upper Reach	30612.1*		3381.1	2300	237.17	251.06	5918900	3.82	251.38	247.56	
Athabasca	Upper Reach	30463.76	11791	3232.71	2300	237.85	251.02	5769035	4.2	251.37	247.17	
Athabasca	Upper Reach	30302.6*		3071.72	2300	237.98	250.95	5597561	4.71	251.35	246.64	
Athabasca	Upper Reach	30141.6*		2910.73	2300	238.1	250.86	5416551	5.4	251.31	245.91	
Athabasca	Upper Reach	29980.79	11309	2749.74	2300	238.23	250.69	5189608	6.38	251.23	244.85	
Athabasca	Upper Reach	29793.5*		2562.54	2300	238.16	250.25	4828143	7.74	250.9	243.16	
Athabasca	Upper Reach	29606.3*		2375.34	2300	238.08	249.43	4509335	7.47	250.06	242.59	
Athabasca	Upper Reach	29419.2	10747	2188.14	2300	238.01	249.39	4260561	3.63	249.7	246.07	
Athabasca	Upper Reach	29347.21 BRIDGE 1		Mult Open								
Athabasca	Upper Reach	29236.7	10564	2005.64	2300	238.35	249.28	4016223	4.37	249.65	245.28	
Athabasca	Upper Reach	29107.1*		1876.2	2300	238.63	249.24	3841174	4.58	249.63	245.05	

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River	Reach	River Sta (Ice Model)	River Sta (Open Water)	Cum Ch Len (m)	Q Total (m3/s)	Min Ch El (m)	W.S. Elev (m)	Ice Vol Total (m3)	Ice Thick Chan (m)	Ice Top Chan (m)	Ice Btm Chan (m)	Obs WS (m)
Athabasca	Upper Reach	28977.81	10306	1746.75	2300	238.92	249.21	3610881	4.53	249.59	245.06	249.37
Athabasca	Upper Reach	28802.2*		1571.31	2300	238.71	249.15	3265832	4.51	249.53	245.02	
Athabasca	Upper Reach	28626.9*		1395.87	2300	238.51	249.09	2922839	4.52	249.47	244.95	
Athabasca	Upper Reach	28451.49	9779	1220.43	2300	238.3	249.02	2578715	4.55	249.4	244.85	
Athabasca	Upper Reach	28300.2*		1069.19	2300	238.12	248.96	2289955	4.55	249.35	244.79	
Athabasca	Upper Reach	28149*		917.94	2300	237.94	248.91	1985908	4.55	249.29	244.74	
Athabasca	Upper Reach	27997.7*		766.7	2300	237.75	248.86	1672125	4.54	249.24	244.7	
Athabasca	Upper Reach	27846.51	9174	615.45	2300	237.57	248.82	1355822	4.48	249.2	244.72	
Athabasca	Lower Reach	27231.06	8559	28813.79	2500	237.24	248.75	40785990	4.15	249.09	244.95	248.2
Athabasca	Lower Reach	27098.3*		28681.11	2500	236.94	248.73	40395340	4.08	249.08	245	
Athabasca	Lower Reach	26965.6*		28548.42	2500	236.63	248.72	40012880	4	249.06	245.06	
Athabasca	Lower Reach	26833.0*		28415.74	2500	236.33	248.71	39639930	3.93	249.04	245.12	
Athabasca	Lower Reach	26700.3*		28283.06	2500	236.02	248.7	39275730	3.86	249.03	245.17	
Athabasca	Lower Reach	26567.64	7895	28150.37	2500	235.72	248.69	38920870	3.79	249.01	245.22	248.6
Athabasca	Lower Reach	26442.3*		28025.11	2500	235.84	248.68	38579360	3.72	248.99	245.27	
Athabasca	Lower Reach	26317.1*		27899.85	2500	235.97	248.67	38241610	3.65	248.98	245.32	
Athabasca	Lower Reach	26191.8*		27774.58	2500	236.09	248.66	37909870	3.58	248.96	245.38	
Athabasca	Lower Reach	26066.5*		27649.32	2500	236.21	248.65	37632730	3.51	248.95	245.44	
Athabasca	Lower Reach	25941.3*		27524.06	2500	236.34	248.64	37355200	3.44	248.93	245.49	
Athabasca	Lower Reach	25816.07	7144	27398.79	2500	236.46	248.63	37076400	3.39	248.92	245.53	
Athabasca	Lower Reach	25674.8*		27257.6	2500	236.24	248.62	36767410	3.34	248.9	245.56	
Athabasca	Lower Reach	25533.6*		27116.41	2500	236.03	248.6	36471560	3.28	248.88	245.59	
Athabasca	Lower Reach	25392.4*		26975.21	2500	235.8	248.59	36188500	3.23	248.86	245.63	
Athabasca	Lower Reach	25251.2*		26834.02	2500	235.58	248.58	35843720	3.17	248.84	245.68	
Athabasca	Lower Reach	25110.09	6438	26692.82	2500	235.36	248.57	35464790	3.11	248.83	245.72	
Athabasca	Lower Reach	24982.9*		26565.7	2500	235.32	248.56	35117510	3.06	248.82	245.76	
Athabasca	Lower Reach	24855.8*		26438.57	2500	235.27	248.55	34770790	3.16	248.82	245.66	
Athabasca	Lower Reach	24728.7*		26311.45	2500	235.23	248.54	34409880	3.42	248.83	245.41	
Athabasca	Lower Reach	24601.6*		26184.32	2500	235.18	248.54	34024110	3.73	248.85	245.12	
Athabasca	Lower Reach	24474.4*		26057.2	2500	235.13	248.53	33607160	4.1	248.87	244.77	
Athabasca	Lower Reach	24347.35	5675	25930.07	2500	235.09	248.52	33154650	4.49	248.9	244.41	245.7
Athabasca	Lower Reach	24204.4*		25787.06	2500	234.71	248.51	32592050	4.77	248.91	244.14	
Athabasca	Lower Reach	24061.5*		25644.04	2500	234.33	248.49	32022900	4.94	248.91	243.97	
Athabasca	Lower Reach	23918.6*		25501.03	2500	233.95	248.47	31453810	5.12	248.9	243.78	
Athabasca	Lower Reach	23775.79	5103	25358.01	2500	233.56	248.44	30887140	5.34	248.89	243.55	
Athabasca	Lower Reach	23707.6*		25222.08	2500	233.38	248.41	30345540	5.66	248.89	243.23	
Athabasca	Lower Reach	23639.5*		25086.14	2500	233.2	248.37	29793690	6.06	248.88	242.82	
Athabasca	Lower Reach	23571.38	4899	24950.21	2500	233.02	248.3	29230500	6.52	248.85	242.33	
Athabasca	Lower Reach	23408.1*		24786.96	2500	233.62	248.21	28583910	6.82	248.79	241.97	

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Athabasca	Lower Reach	23244.9*		24623.72	2500	234.23	248.11	28224360	7.08	248.71	241.63	
Athabasca	Lower Reach	23081.6*		24460.48	2500	234.84	247.99	27860480	7.29	248.6	241.31	
Athabasca	Lower Reach	22918.4	4246	24297.23	2500	235.44	247.85	27495930	7.42	248.47	241.05	
Athabasca	Lower Reach	22724.5*		24103.35	2500	235.39	247.65	27056370	7.45	248.27	240.82	247.53
Athabasca	Lower Reach	22530.6*		23909.46	2500	235.35	247.39	26600390	7.54	248.03	240.49	
Athabasca	Lower Reach	22336.7*		23715.57	2500	235.3	247.07	26132950	7.41	247.69	240.28	
Athabasca	Lower Reach	22142.8*		23521.69	2500	235.3	246.74	25661280	7.26	247.35	240.09	
Athabasca	Lower Reach	21948.9*		23327.8	2500	235.21	246.44	25187240	7.08	247.04	239.96	
Athabasca	Lower Reach	21755.09	3083	23133.92	2500	235.16	246.21	24717670	6.74	246.77	240.03	
Athabasca	Lower Reach	21571.2*		22950.06	2500	234.95	246.01	24279820	6.43	246.55	240.12	
Athabasca	Lower Reach	21387.3*		22766.21	2500	234.73	245.84	23847570	6.17	246.36	240.19	
Athabasca	Lower Reach	21203.5*		22582.35	2500	234.52	245.7	23422550	5.89	246.2	240.31	
Athabasca	Lower Reach	21019.67	2347	22398.5	2500	234.3	245.59	23007250	5.59	246.06	240.47	
Athabasca	Lower Reach	20834.1*		22212.95	2500	234.12	245.49	22591460	5.36	245.94	240.58	
Athabasca	Lower Reach	20648.5*		22027.4	2500	233.94	245.38	22167130	5.25	245.82	240.57	
Athabasca	Lower Reach	20463.0*		21841.85	2500	233.76	245.25	21729670	5.16	245.68	240.52	
Athabasca	Lower Reach	20277.4*		21656.3	2500	233.58	245.13	21286270	5	245.55	240.55	
Athabasca	Lower Reach	20091.93	1420	21470.75	2500	233.4	245.04	20849010	4.79	245.44	240.65	
Athabasca	Lower Reach	19907.4*		21286.3	2500	233.36	244.96	20432840	4.56	245.34	240.78	
Athabasca	Lower Reach	19723.0*		21101.85	2500	233.32	244.88	20042820	4.35	245.24	240.89	
Athabasca	Lower Reach	19538.5*		20917.4	2500	233.28	244.8	19680430	4.16	245.15	240.99	
Athabasca	Lower Reach	19354.1*		20732.96	2500	233.24	244.73	19346610	4	245.06	241.06	
Athabasca	Lower Reach	19169.6*		20548.51	2500	233.2	244.66	18875040	3.87	244.98	241.11	
Athabasca	Lower Reach	18985.2*		20364.06	2500	233.16	244.59	18407780	3.75	244.9	241.15	
Athabasca	Lower Reach	18800.79	129	20179.61	2500	233.12	244.53	17943290	3.64	244.83	241.19	
Athabasca	Lower Reach	18601.5*		20115.36	2500	232.91	244.51	17795620	3.59	244.81	241.22	
Athabasca	Lower Reach	18402.34		20051.11	2500	232.7	244.49	17651750	3.56	244.79	241.23	
Athabasca	Lower Reach	18214.2*		19863.03	2500	232.6	244.43	17131370	3.52	244.73	241.21	
Athabasca	Lower Reach	18026.1*		19674.95	2500	232.5	244.38	16619120	3.47	244.67	241.2	
Athabasca	Lower Reach	17838.1*		19486.87	2500	232.39	244.32	16116760	3.42	244.61	241.19	
Athabasca	Lower Reach	17650.0*		19298.79	2500	232.29	244.26	15623920	3.39	244.55	241.16	
Athabasca	Lower Reach	17461.9*		19110.71	2500	232.19	244.2	15138180	3.39	244.49	241.1	
Athabasca	Lower Reach	17273.8*		18922.63	2500	232.09	244.14	14645820	3.65	244.44	240.79	
Athabasca	Lower Reach	17085.7*		18734.55	2500	231.99	244.05	14136590	3.93	244.38	240.45	
Athabasca	Lower Reach	16897.7*		18546.47	2500	231.88	243.95	13617420	4.13	244.3	240.17	
Athabasca	Lower Reach	16709.6*		18358.39	2500	231.78	243.89	13100800	4.09	244.23	240.14	
Athabasca	Lower Reach	16521.5*		18170.31	2500	231.68	243.86	12604960	3.81	244.18	240.37	
Athabasca	Lower Reach	16333.4*		17982.24	2500	231.58	243.83	12140240	3.54	244.13	240.59	
Athabasca	Lower Reach	16145.39		17794.16	2500	231.47	243.81	11705580	3.34	244.09	240.75	

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Athabasca	Lower Reach	16081.1*		17604.19	2500	231.46	243.79	11277460	3.21	244.06	240.85	
Athabasca	Lower Reach	16016.8*		17414.22	2500	231.44	243.75	10873730	3.07	244.01	240.94	
Athabasca	Lower Reach	15952.5*		17224.25	2500	231.43	243.72	10497350	2.89	243.97	241.07	
Athabasca	Lower Reach	15888.2*		17034.29	2500	231.41	243.71	10150030	2.72	243.93	241.21	
Athabasca	Lower Reach	15823.9*		16844.32	2500	231.39	243.69	9826775	2.63	243.91	241.28	
Athabasca	Lower Reach	15759.6*		16654.35	2500	231.38	243.66	9519825	2.61	243.88	241.27	
Athabasca	Lower Reach	15695.3*		16464.38	2500	231.36	243.61	9223246	2.64	243.83	241.19	
Athabasca	Lower Reach	15631.1*		16274.41	2500	231.34	243.55	8931297	2.73	243.78	241.05	
Athabasca	Lower Reach	15566.8*		16084.45	2500	231.33	243.48	8638864	2.85	243.72	240.87	243.5
Athabasca	Lower Reach	15502.5*		15894.48	2500	231.31	243.4	8341879	3.02	243.65	240.63	
Athabasca	Lower Reach	15438.2*		15704.51	2500	231.3	243.29	8033719	3.28	243.57	240.29	
Athabasca	Lower Reach	15373.9*		15514.54	2500	231.28	243.15	7705976	3.65	243.45	239.8	
Athabasca	Lower Reach	15309.6*		15324.58	2500	231.26	242.92	7438485	4.1	243.27	239.16	
Athabasca	Lower Reach	15245.39		15134.61	2500	231.25	242.64	7147159	4.54	243.02	238.49	
Athabasca	Lower Reach	15119.7*		14944.64	2500	231.2	242.26	6834249	5.21	242.7	237.49	
Athabasca	Lower Reach	14994.0*		14754.67	2500	231.16	241.53	6513230	5.28	241.97	236.69	
Athabasca	Lower Reach	14868.3*		14564.7	2500	231.12	240.33	6230789	4.36	240.7	236.34	
Athabasca	Lower Reach	14742.6*		14374.74	2500	231.07	240.4	6070553	1	240.48	239.48	
Athabasca	Lower Reach	14616.9*		14184.77	2500	231.03	240.36	5997943	1	240.45	239.45	
Athabasca	Lower Reach	14491.3*		13994.8	2500	230.99	240.33	5923787	1	240.41	239.41	
Athabasca	Lower Reach	14365.6*		13804.83	2500	230.94	240.29	5847275	1	240.38	239.38	
Athabasca	Lower Reach	14239.9*		13614.87	2500	230.9	240.26	5767672	1	240.34	239.34	
Athabasca	Lower Reach	14114.2*		13424.9	2500	230.86	240.21	5684950	1	240.3	239.3	
Athabasca	Lower Reach	13988.5*		13234.93	2500	230.81	240.17	5599697	1	240.25	239.25	
Athabasca	Lower Reach	13862.8*		13044.96	2500	230.77	240.11	5512375	1	240.2	239.2	
Athabasca	Lower Reach	13737.2*		12854.99	2500	230.73	240.06	5424710	1	240.14	239.14	
Athabasca	Lower Reach	13611.5*		12665.03	2500	230.68	240.01	5340460	1	240.09	239.09	
Athabasca	Lower Reach	13485.84		12475.06	2500	230.64	239.96	5260349	1	240.05	239.05	
Athabasca	Lower Reach	13287.8*		12277.06	2500	230.6	239.92	5178216	1	240	239	
Athabasca	Lower Reach	13089.8*		12079.06	2500	230.56	239.87	5095136	1	239.96	238.96	
Athabasca	Lower Reach	12891.8*		11881.06	2500	230.52	239.82	5010385	1	239.91	238.91	
Athabasca	Lower Reach	12693.8*		11683.06	2500	230.48	239.77	4924824	1	239.86	238.86	239.75
Athabasca	Lower Reach	12495.8*		11485.06	2500	230.44	239.72	4841186	1	239.8	238.8	
Athabasca	Lower Reach	12297.8*		11287.06	2500	230.4	239.66	4760796	1	239.75	238.75	
Athabasca	Lower Reach	12099.8*		11089.06	2500	230.36	239.6	4683656	1	239.69	238.69	
Athabasca	Lower Reach	11901.8*		10891.06	2500	230.32	239.53	4609705	1	239.62	238.62	
Athabasca	Lower Reach	11703.8*		10693.06	2500	230.28	239.46	4538944	1	239.54	238.54	
Athabasca	Lower Reach	11505.8*		10495.06	2500	230.24	239.38	4471436	1	239.47	238.47	
Athabasca	Lower Reach	11307.8*		10297.06	2500	230.2	239.3	4407180	1	239.39	238.39	

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Athabasca	Lower Reach	11109.8*		10099.06	2500	230.16	239.22	4345895	1	239.31	238.31	
Athabasca	Lower Reach	10911.8*		9901.06	2500	230.12	239.15	4287810	1	239.23	238.23	
Athabasca	Lower Reach	10713.8*		9703.06	2500	230.08	239.08	4232896	1	239.16	238.16	
Athabasca	Lower Reach	10515.8*		9505.06	2500	230.04	239.02	4181152	1	239.11	238.11	
Athabasca	Lower Reach	10317.84		9307.06	2500	230	238.98	4132552	1	239.06	238.06	
Athabasca	Lower Reach	10135.6*		9124.86	2500	230.21	238.93	4089360	1	239.01	238.01	
Athabasca	Lower Reach	9953.44*		8942.66	2500	230.41	238.88	4046398	1	238.96	237.96	
Athabasca	Lower Reach	9771.24*		8760.46	2500	230.62	238.83	4003535	1	238.91	237.91	
Athabasca	Lower Reach	9589.04*		8578.26	2500	230.83	238.78	3960922	1	238.86	237.86	
Athabasca	Lower Reach	9406.84*		8396.06	2500	231.04	238.73	3918582	1	238.82	237.82	
Athabasca	Lower Reach	9224.64*		8213.86	2500	231.24	238.69	3876219	1	238.77	237.77	
Athabasca	Lower Reach	9042.438		8031.66	2500	231.45	238.65	3833832	1	238.73	237.73	
Athabasca	Lower Reach	8850.54*		7839.77	2500	231.53	238.62	3786768	1	238.7	237.7	
Athabasca	Lower Reach	8658.65*		7647.87	2500	231.62	238.58	3734953	1	238.66	237.66	
Athabasca	Lower Reach	8466.76*		7455.98	2500	231.71	238.54	3678379	1	238.63	237.63	
Athabasca	Lower Reach	8274.86*		7264.09	2500	231.79	238.51	3617078	1	238.59	237.59	
Athabasca	Lower Reach	8082.97*		7072.19	2500	231.88	238.48	3551082	1	238.56	237.56	
Athabasca	Lower Reach	7891.07*		6880.3	2500	231.96	238.44	3480396	1	238.53	237.53	
Athabasca	Lower Reach	7699.18*		6688.41	2500	232.04	238.41	3395755	1	238.49	237.49	
Athabasca	Lower Reach	7507.29*		6496.51	2500	232.13	238.37	3301874	1	238.46	237.46	
Athabasca	Lower Reach	7315.39*		6304.62	2500	232.21	238.34	3202944	1	238.42	237.42	
Athabasca	Lower Reach	7123.497		6112.72	2500	232.3	238.31	3099035	1	238.4	237.4	
Athabasca	Lower Reach	6929.20*		5918.43	2500	232.23	238.28	2990161	1	238.37	237.37	
Athabasca	Lower Reach	6734.91*		5724.13	2500	232.16	238.25	2880889	1	238.33	237.33	
Athabasca	Lower Reach	6540.61*		5529.84	2500	232.09	238.21	2771439	1	238.29	237.29	
Athabasca	Lower Reach	6346.32*		5335.54	2500	232.01	238.13	2662593	1	238.21	237.21	
Athabasca	Lower Reach	6152.03*		5141.25	2500	231.94	238.03	2555677	1	238.12	237.12	
Athabasca	Lower Reach	5957.73*		4946.95	2500	231.87	237.99	2451546	1	238.07	237.07	
Athabasca	Lower Reach	5763.44*		4752.66	2500	231.8	237.94	2356014	1	238.02	237.02	
Athabasca	Lower Reach	5569.14*		4558.36	2500	231.73	237.88	2260103	1	237.97	236.97	
Athabasca	Lower Reach	5374.85*		4364.07	2500	231.65	237.82	2163929	1	237.91	236.91	
Athabasca	Lower Reach	5180.55*		4169.77	2500	231.58	237.76	2068070	1	237.85	236.85	
Athabasca	Lower Reach	4986.258		3975.48	2500	231.51	237.69	1973731	1	237.77	236.77	
Athabasca	Lower Reach	4787.13*		3776.35	2500	231.42	237.6	1879187	1	237.69	236.69	
Athabasca	Lower Reach	4588.01*		3577.23	2500	231.33	237.52	1787958	1	237.6	236.6	
Athabasca	Lower Reach	4388.88*		3378.1	2500	231.24	237.44	1701411	1	237.53	236.53	
Athabasca	Lower Reach	4189.76*		3178.97	2500	231.16	237.37	1619604	1	237.45	236.45	
Athabasca	Lower Reach	3990.63*		2979.85	2500	231.07	237.3	1542550	1	237.39	236.39	
Athabasca	Lower Reach	3791.50*		2780.72	2500	230.98	237.24	1452400	1	237.32	236.32	

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Description: Summary of 2020 Ice Validation Event Results

River	Reach	River Sta (Ice Model)	River Sta (Open Water)	Cum Ch Len (m)	Q Total (m3/s)	Min Ch El (m)	W.S. Elev (m)	Ice Vol Total (m3)	Ice Thick Chan (m)	Ice Top Chan (m)	Ice Btm Chan (m)	Obs WS (m)
Athabasca	Lower Reach	3592.38*		2581.6	2500	230.89	237.18	1346401	1	237.26	236.26	
Athabasca	Lower Reach	3393.253		2382.47	2500	230.8	237.12	1209081	1	237.21	236.21	
Athabasca	Lower Reach	3194.71*		2183.93	2500	230.75	237.06	1074688	1	237.14	236.14	
Athabasca	Lower Reach	2996.17*		1985.39	2500	230.7	236.98	964376.9	1	237.07	236.07	
Athabasca	Lower Reach	2797.64*		1786.85	2500	230.65	236.92	862587.3	1	237	236	
Athabasca	Lower Reach	2599.10*		1588.31	2500	230.6	236.86	759267.7	1	236.95	235.95	
Athabasca	Lower Reach	2400.56*		1389.77	2500	230.55	236.81	655988.9	1	236.89	235.89	
Athabasca	Lower Reach	2202.02*		1191.24	2500	230.5	236.75	554801.3	1	236.83	235.83	
Athabasca	Lower Reach	2003.48*		992.7	2500	230.45	236.69	456523.8	1	236.77	235.77	
Athabasca	Lower Reach	1804.94*		794.16	2500	230.4	236.62	361242.4	1	236.71	235.71	
Athabasca	Lower Reach	1606.40*		595.62	2500	230.35	236.56	268897.2	1	236.64	235.64	
Athabasca	Lower Reach	1407.86*		397.08	2500	230.3	236.49	178771.5	1	236.58	235.58	
Athabasca	Lower Reach	1209.32*		198.54	2500	230.25	236.42	89529.49	1	236.51	235.51	
Athabasca	Lower Reach	1010.78			2500	230.2	236.35		1	236.43	235.43	