September 2018

FORT MCMURRAY RIVER HAZARD STUDY

Channel Stability Investigation Report

Submitted to:
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Report Number: 1662603_R0009, Rev.0

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REPORT

Golder Associates

Classification: Public

Executive Summary

Alberta Environment and Parks (AEP) commissioned Golder Associates Ltd. (Golder) in September 2016 to undertake the Fort McMurray River Hazard Study. The primary purpose of the study was 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 is 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 area is divided into four (4) stream reaches for hydraulic modelling, Athabasca River, Clearwater River, Hangingstone River and Snye River as shown in Table i.

Table i: River Reaches within Study Area

Reach Number	River	Reach Description	Length
1	Athabasca River	From a location 6 km upstream of Highway 63 bridges to a location 8 km downstream of the Clearwater River confluence	15 km
2	Clearwater River	From the confluence with Athabasca River to a location 20 km upstream of the confluence	20 km
3	Hangingstone River	From a location 3 km upstream of Memorial Drive (Highway 63) Bridges to the confluence with Clearwater River	5 km
4	Snye River	Full length from Snye Dyke to the confluence with Clearwater River	1.5 km

The Fort McMurray River Hazard Study includes multiple components and deliverables. This report documents the methodology and results of the channel stability investigation component, including qualitative and limited quantitative information about general channel stability along the study reaches. The Channel Stability Assessment was conducted by completing the following four tasks: channel bank delineation and comparison, cross-section comparison, thalweg comparison and rating curve comparison.

The channel bank delineation and comparison was completed by delineating the banks and mapping river features in both historical and modern imagery datasets. The cross-section and thalweg comparisons to historical datasets could not be completed due to the lack of data. Review of the current cross-section and thalweg data was completed by conducting both qualitative and quantitative analyses. For the rating curve comparison, the historical and current rating curves for the WSC gauge locations within the study area were compared relative to observed changes in the river thalweg and features of the nearest river cross sections. The data collected from the comparison of river geometry (i.e. channel bank delineation) was used to inform the interpretations of changes observed in the rating curves.

Reach 1: Athabasca River

The Athabasca River, Reach 1, is categorized as a straight, single channel river reach confined within a larger incised channel (glacial outwash channel).

Visual evidence in the form of limited occurrence of point and side bars from the aerial imagery suggests that there is limited sediment storage occurring in Athabasca River. The presence of several historical and current forested islands implies some stability within the channel. Due to the confined nature of the channel within this reach, limited lateral migration is occurring. While narrowing of the channel in this reach was observed in the cross-section data, the change is not statistically significant. The thalweg varies with several increases in elevation visible along its length. Based on the straight river channel and visible lack of sediment transport, Athabasca River, is considered to be a non-alluvial channel confined within a geologically historical river valley (e.g. meltwater channel). This observation has been previously documented by others.

Due to the confined nature of the channel and limited lateral migration, this reach is considered stable. Based on the morphological data reviewed, it appears that the capacity of the river to handle discharge has not changed over the extent of historical data reviewed.

Reach 2: Clearwater River

The Clearwater River, Reach 2, is categorized as a sinuous, meandering, single channel river reach confined within a larger incised channel (glacial outwash channel). This reach shows minimal lateral migration of the channel with the main examples of lateral migration occurring along the bends of meanders. Based on the incised meandering channel and limited sediment transport, Clearwater River, is considered to be a sediment-limited alluvial channel confined within a geologically historical river valley (e.g. meltwater channel). This reach is characterized by limited lateral migration, small side bars and stabilization of previous forested islands and side bars.

Due to the confined nature of the channel and limited lateral migration, this reach is considered stable. Based on the morphological data reviewed, it appears that the capacity of the river to handle discharge has not changed over the extent of historical data reviewed.

Reach 3: Hangingstone River

The Hangingstone River, Reach 3, is characterized as a sinuous, meandering and single channel river reach. The upper portion of the reach is characterized by several slightly migrating point and side bars and a slope of -0.005.

The lower portion of the reach is characterized by significantly dynamic side, point and mid-channel bars and a slope of -0.0018. The channel has undergone a significant realignment at the downstream end including migration of the river mouth. The 2016 thalweg shows a concave-upwards profile. The rating curve comparison suggests that at higher discharge volumes, the river can convey more flow within the same channel at the Highway 63 Bridge.

The observed decrease in slope and realignment at the lower portion of the reach suggests that the Hangingstone River at the mouth is a backwater channel to the Clearwater River. As such, it is considered to be unstable at the downstream end and could be susceptible to increased flood hazard due to backwater effects.

Reach 4: Snye River

The Snye River, Reach 4, is characterized as a straight single former secondary river channel with limited sediment transport. No in-channel bars are present along this reach suggesting little to no sediment transport. This reach does not appear to have any obvious surface headwater sources, due to the construction of the road across the mouth at the Athabasca side. Reach 4 has a slope of -0.0008.

As a non-active channel with no in-channel bars, Reach 4 is considered to be stable. However, based on the morphological data reviewed, it appears that the capacity of the river to handle discharge has changed due to the alteration of the channel mouth.

ACKNOWLEDGEMENTS

This component of the Fort McMurray River Hazard Study (i.e., channel stability assessment) was managed by Morgan Tidd and Wolf Ploeger. Overall direction and senior review for this component was provided by Rowland Atkins and Dejiang Long. The channel stability assessment was conducted primarily by Morgan Tidd with support from Gaven Tang, Vanessa Vallis and Peter Thiede.

The authors express their special thanks to Abdullah Mamun, project manager for Alberta Environment and Parks, who provided overall project direction, background data and technical guidance and Patricia Stevenson, (Alberta Environment and Parks), for her support in reviewing the report.

The authors express their thanks to Dennis Lazowski with the Water Survey of Canada for supply of additional background information.

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1.0 INTRODUCTION

1.1 Study Objectives

Alberta Environment and Parks (AEP) commissioned Golder Associates Ltd. (Golder) in September 2016 to undertake 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 is conducted under the provincial Flood Hazard Identification Program (FHIP). The goals of the 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.

The Fort McMurray River Hazard Study includes multiple components and deliverables. This report documents the methodology and results of the channel stability investigation component, including qualitative and limited quantitative information about general channel stability along the study reaches.

1.2 Study Area and Reaches

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

The study area includes the community of Fort McMurray in the Regional District of Wood Buffalo. The study area is divided into four (4) stream reaches for hydraulic modelling, Athabasca River, Clearwater River, Hangingstone River and Snye River as shown in Table 1 and Figure 2a through 2d.

Table 1: River Reaches within Study Area

Reach Number	River	Reach Description	Length
1	Athabasca River	From a location 6 km upstream of Highway 63 bridges to a location 8 km downstream of the Clearwater River confluence	15 km
2	Clearwater River	From the confluence with Athabasca River to a location 20 km upstream of the confluence	20 km
3	Hangingstone River	From a location 3 km upstream of Memorial Drive (Highway 63) Bridges to the confluence with Clearwater River	5 km
4	Snye River	Full length from Snye Dyke to the confluence with Clearwater River	1.5 km

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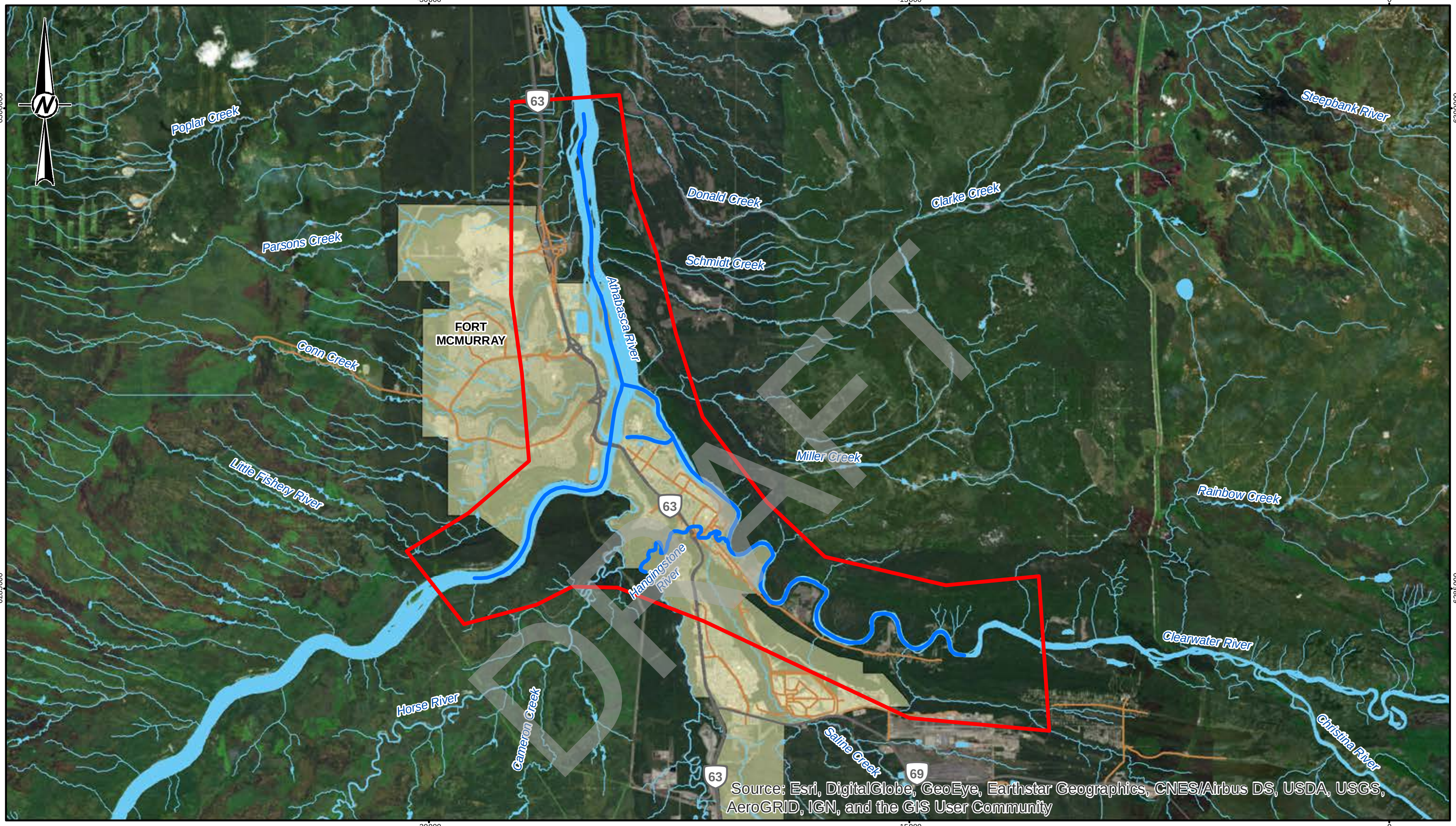

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- POPULATED PLACE
- WATERBODY
- SURVEY REACH
- RIVER HAZARD STUDY AREA

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Alberta Government

CONSULTANT

Golder Associates

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REVIEWED	MT
APPROVED	RA

PROJECT
FORT MCMURRY HAZARD STUDY

TITLE
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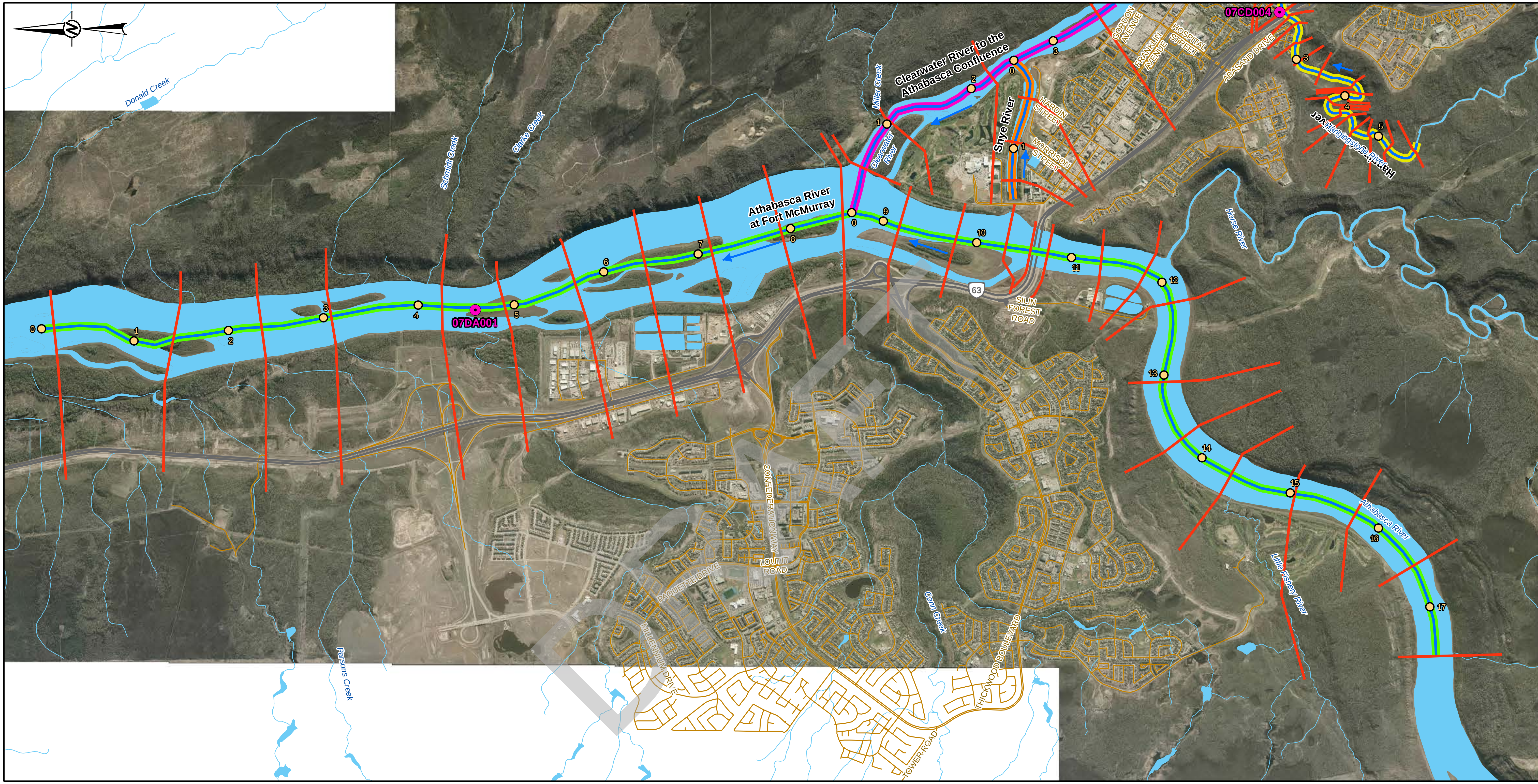

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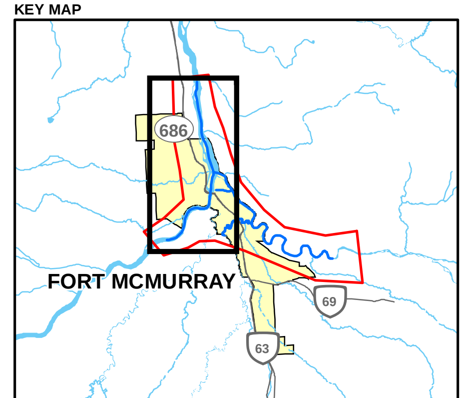
- SECONDARY HIGHWAY
- LOCAL ROAD
- RAILROAD
- WATERCOURSE
- WATERBODY
- FLOW DIRECTION
- RIVER STATION POST
- WATER SURVEY OF CANADA GAUGING STATION
- RIVER CENTRELINE
- CROSS SECTION LOCATION

RIVER REACHES

- ATHABASCA RIVER AT FORT MCMURRAY
- CLEARWATER RIVER TO THE ATHABASCA CONFLUENCE
- HANGINGSTONE RIVER
- SNYE RIVER

KEY MAP



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PROJECT
FORT MCMURRAY HAZARD STUDY

TITLE
ATHABASCA RIVER CROSS-SECTION LOCATIONS AND GAUGING STATIONS

CONSULTANT
Golder Associates

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PREPARED	AL
REVIEWED	MT
APPROVED	RA

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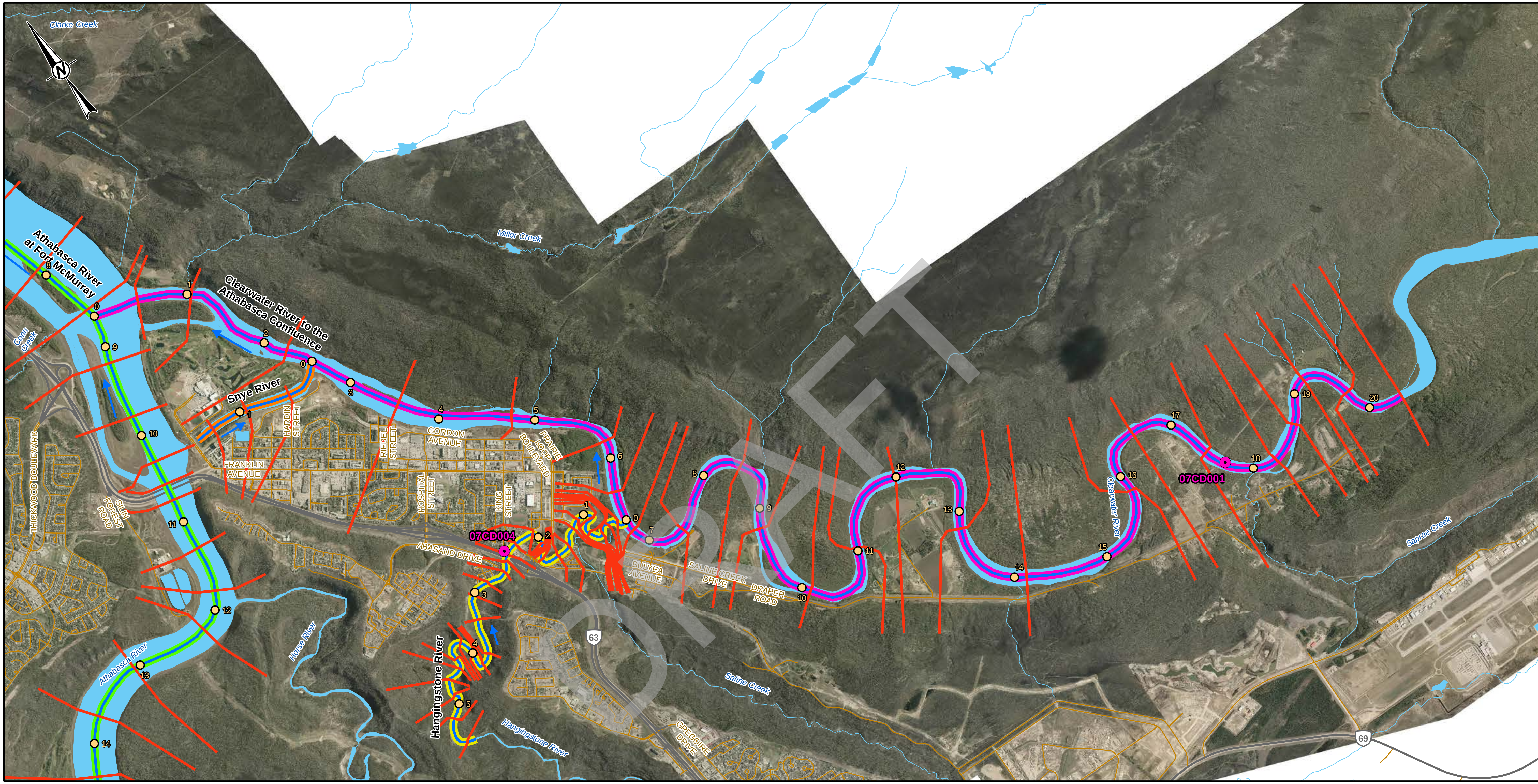

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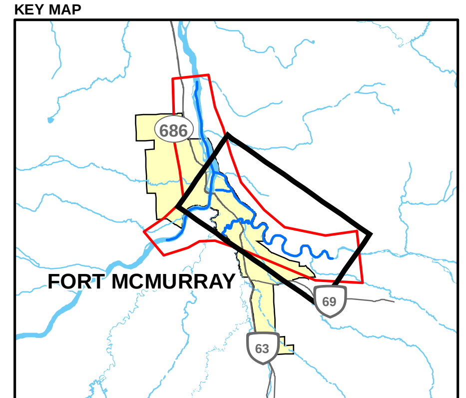
- RAILROAD
- WATERCOURSE
- WATERBODY
- FLOW DIRECTION
- RIVER STATION POST
- WATER SURVEY OF CANADA GAUGING STATION
- RIVER CENTRELINE
- CROSS SECTION LOCATION

RIVER REACHES

- ATHABASCA RIVER AT FORT MCMURRAY
- CLEARWATER RIVER TO THE ATHABASCA CONFLUENCE
- HANGINGSTONE RIVER
- SNYE RIVER

KEY MAP



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PROJECT
FORT MCMURRAY HAZARD STUDY

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CLEARWATER RIVER CROSS-SECTION LOCATIONS AND GAUGING STATIONS

CONSULTANT
Golder Associates

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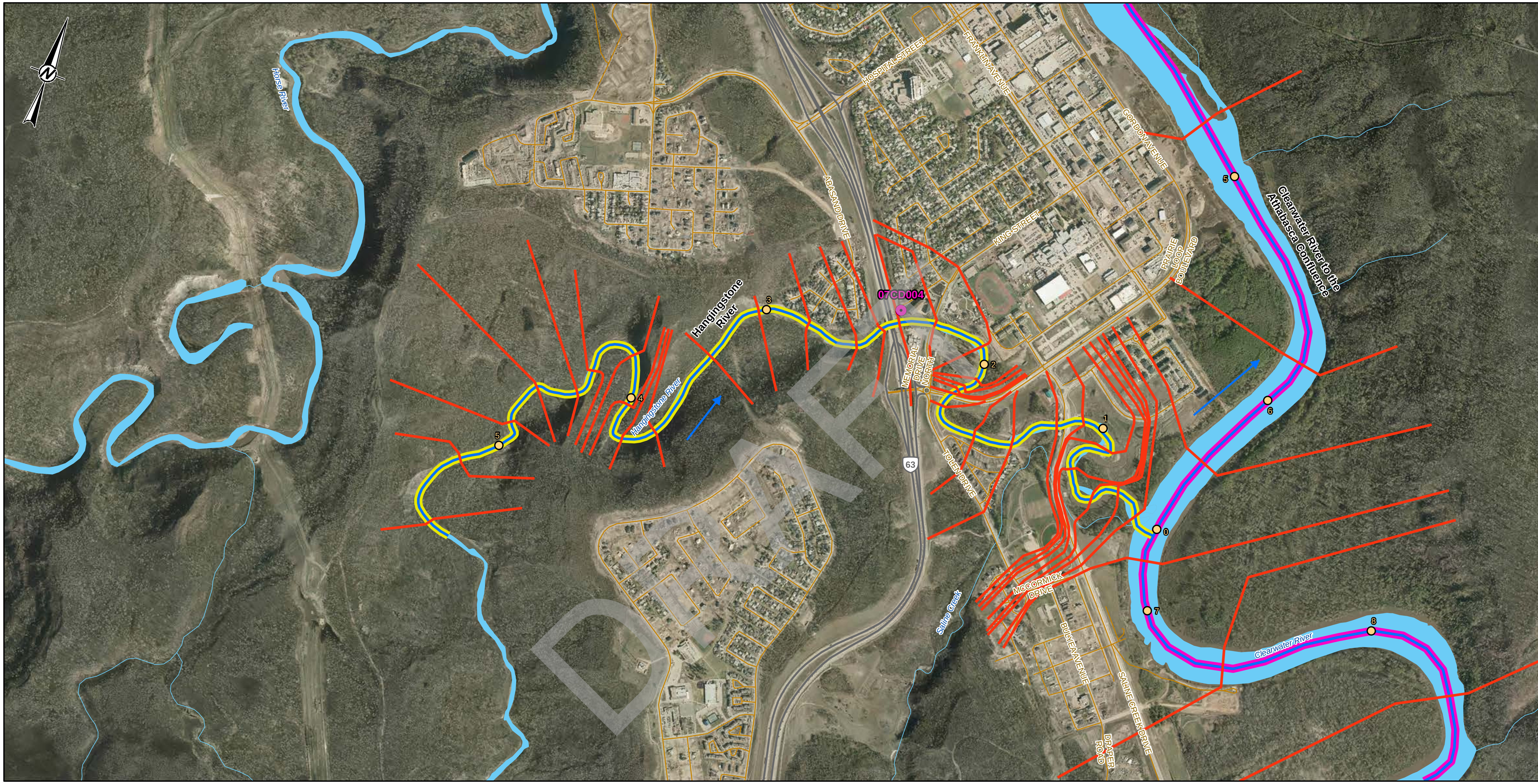

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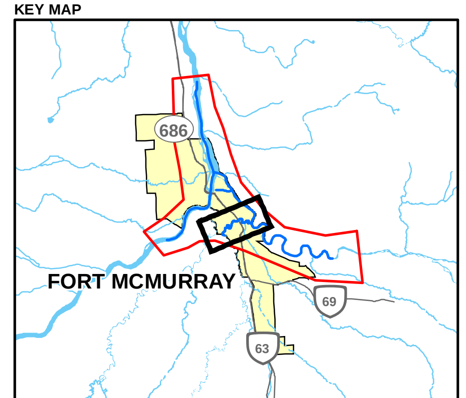
- SECONDARY HIGHWAY
- LOCAL ROAD
- RAILROAD
- WATERCOURSE
- WATERBODY
- FLOW DIRECTION
- RIVER STATION POST
- WATER SURVEY OF CANADA GAUGING STATION
- RIVER CENTRELINE
- CROSS SECTION LOCATION

RIVER REACHES

- ATHABASCA RIVER AT FORT MCMURRAY
- CLEARWATER RIVER TO THE ATHABASCA CONFLUENCE
- HANGINGSTONE RIVER
- SNYE RIVER

KEY MAP



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PROJECT
FORT MCMURRAY HAZARD STUDY

TITLE
HANGINGSTONE RIVER CROSS-SECTION LOCATIONS AND GAUGING STATIONS

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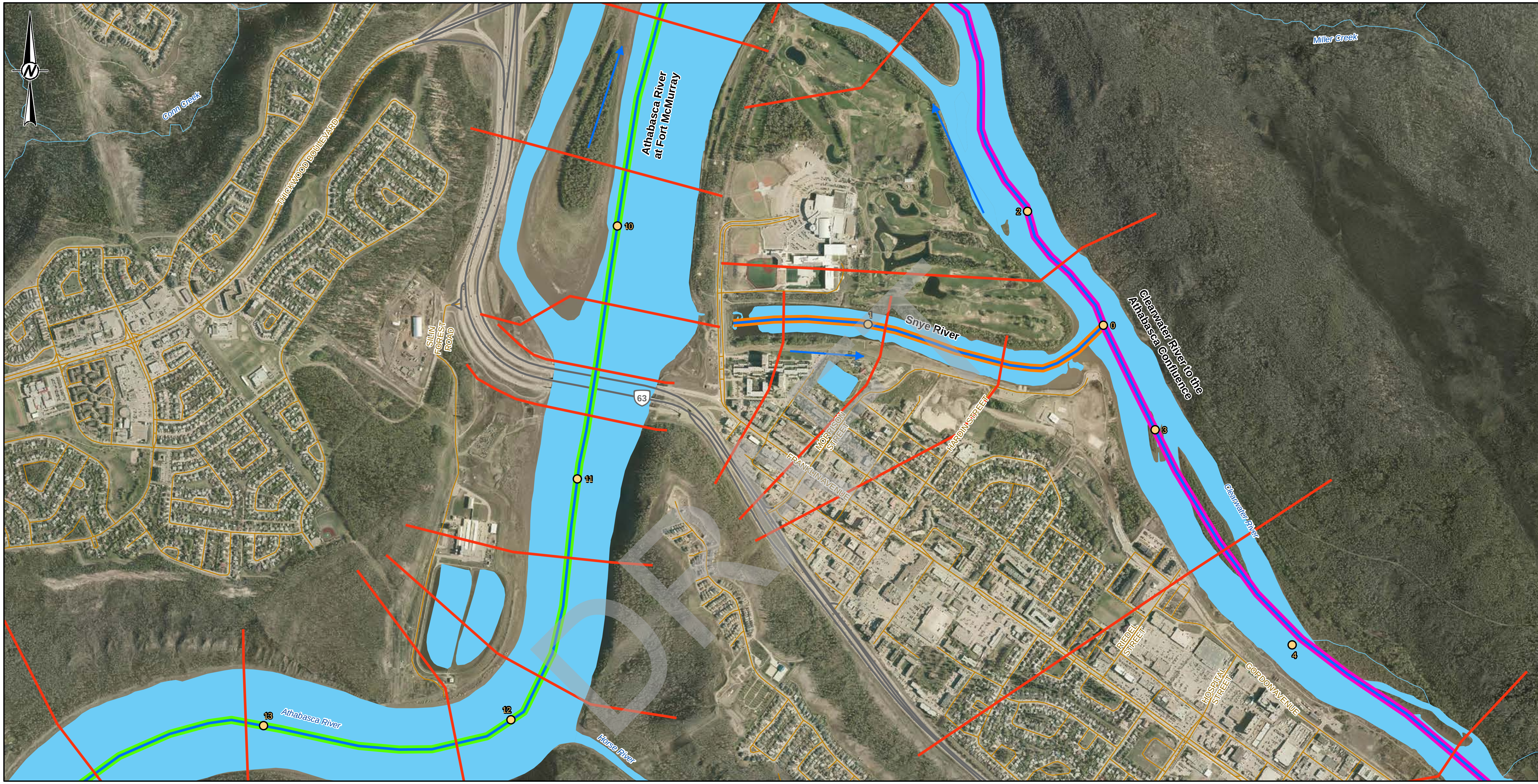

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- LOCAL ROAD
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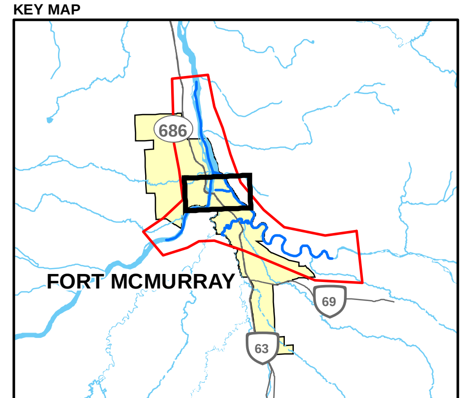
- WATERCOURSE
- WATERBODY
- FLOW DIRECTION
- RIVER STATION POST
- WATER SURVEY OF CANADA GAUGING STATION
- RIVER CENTRELINE
- CROSS SECTION LOCATION

RIVER REACHES

- ATHABASCA RIVER AT FORT MCMURRAY
- CLEARWATER RIVER TO THE ATHABASCA CONFLUENCE
- HANGINGSTONE RIVER
- SNYE RIVER

KEY MAP



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PROJECT
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TITLE
SNYE RIVER CROSS-SECTION LOCATIONS AND GAUGING STATIONS

CONSULTANT
Golder Associates

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PROJECT NO.	CONTROL	REV.	FIGURE
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1.3 Scope of Work

The scope of the channel stability investigation includes the following:

- Historical Aerial Photography Preparation.
- Channel Bank Delineation and Comparison:
  - Identification and comparison of the most recent and historical channel banks to establish representative illustrative bank stability and instability conditions in the study area.
- Current Cross Section Review:
  - Review of the available current channel cross sections along the study reaches.
- Thalweg Profile Review:
  - Review of the most recent thalweg profile.
- Gauge Rating Curve Comparison:
  - Comparison of the river gauge rating curves and evaluation of any rating curve changes.

2.0 AVAILABLE DATA

2.1 Aerial Imagery

Aerial imagery available for this study was from a historical dataset which consisted of 1950 images and a current dataset collected in 2017. Table 2 provides a summary of the dates, scale, resolution, source and accuracy of the aerial imagery datasets used for the channel bank delineation and comparison. Details of the methods and results for the aerial photography preparation are provided in the following technical memorandums:

- 2017 Aerial Imagery Acquisition Memorandum – Fort McMurray River Hazard Study (Golder 2018a); and
- Historical Aerial Imagery Processing - Fort McMurray River Hazard Study (Appendix B).

Table 2: Summary of Aerial Imagery

	Date(s) of Collection	Scale	Resolution	Source	Accuracy
Current	5/18/2017	1:22,000	0.30 m	Geodesy Group Inc. and Golder 2018a	Horizontal = 0.6 m Vertical = 1.0 m
Historical	7/8/1950, 8/01/1950	1:40,000	0.85 m	AEP (see Appendix B)	±5 m

2.2 Cross-Section Data

Cross-section data were only available from the 2016 survey data and 2016 LiDAR data. No historical cross-section data were available. Table 3 provides a summary of the dates, scale, resolution, source and accuracy of the 2016 dataset used for the cross-section review.

Since historical cross-section data were not available for the study area, a comparison could not be conducted. A quantitative review of the available 2016 river geometry (e.g. width and/or depth) was undertaken without comparison to other years.

Table 3: Summary of Cross-Section Data

	Date(s) of Collection	Scale [1]	Resolution	Source	Accuracy
2016 Survey	9/27/2016 to 10/8/2016	--	--	Golder 2018b	RTK = ±0.02 m horizontal and vertical, ADP = ±0.10 m horizontal and vertical.

Note:

1. A map scale is defined as the amount of reduction between the real world and its graphic representation. As LiDAR files are measurements of the real world, they have a scale of 1:1.

2.3 Thalweg Profile Data

Thalweg data were only available from the 2016 survey data. No historical thalweg data were available. The 2017 aerial imagery were used to interpret the location of the thalweg relative to the available 2016 thalweg data and validate the 2016 thalweg profile. Table 4 provides a summary of the dates, scale, resolution, source and accuracy of the datasets used for the thalweg review.

Because historical (pre-2016) thalweg data were not available for any of reaches of the Fort McMurray River study, a comparison could not be conducted. A qualitative review of only 2016 river thalweg data was undertaken. Details of the methods and results of the 2016 survey data are presented in the 2017 Golder Draft Fort McMurray River Hazard Study Survey and Base Data Collection Report (Golder 2018b).

Table 4: Summary of Thalweg Profile Data

	Date(s) of Collection	Scale[1]	Resolution	Source	Accuracy
2016 Survey	9/27/2016 to 10/8/2016	--	--	Golder 2018b	RTK = ±0.02 m horizontal and vertical, ADP = ±0.10 m horizontal and vertical.

Note:

1. A map scale is defined as the amount of reduction between the real world and its graphic representation. As LiDAR files are measurements of the real world, they have a scale of 1:1.

2.4 Rating Curves

Discharge and water level data were provided by the Water Survey of Canada (WSC) (2017) for the following three gauge stations within the study area:

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

Historical datasets were obtained for each station. Hydrometric records obtained extend back to 1957, 1930 and 1965 for Athabasca River below McMurray (WSC Station No. 07DA001), Clearwater River at Draper (WSC Station No. 07CD001), and Hangingstone River at Fort McMurray (WSC Station No. 07CD004), respectively. The gauges at all three stations were moved or replaced resulting in varying survey datums. Varying survey datums between rating curves limit direct interpretation of the relationship between changes in discharge and water level and the channels response to such changes.

The record at Athabasca River below McMurray (WSC Station No. 07DA001) covers the period from 1957 to present. However, the data from prior to 1959 was insufficient to create rating curves. Between 1957 and 1963, the gauge was moved or replaced two times and therefore, consisted of three different survey datums. The data presented for the rating curve at Athabasca River below Fort McMurray include 1959, 1965, 1971, and the most recent dataset from 2010 for comparison and discussion.

The record at Clearwater River at Draper (WSC Station No. 07CD001) covers the period from 1931 to present. However, the data prior to 1959 were insufficient to create rating curves. Between 1957 and 1967, the gauge was moved or replaced two times and therefore, consisted of three different survey datums. The data presented for the rating curve at Clearwater include 1959, 1965, 1971, and the most recent dataset from 1999 for comparison and discussion.

The record at Hangingstone River at Fort McMurray (WSC Station No. 07CD004) covers the period from 1965 to present. However, the data in 1965 were insufficient to create rating curves. Between 1965 and 1985, the gauge was moved or replaced two times and therefore consisted of three different survey datums. The data presented for the rating curve at Clearwater include 1966, 1986, and the most recent dataset from 2013 for comparison and discussion.

3.0 METHODS

3.1 Channel Bank Delineation and Comparison

The channel bank delineation and comparison were conducted in electronic format using ortho-rectified and geo-referenced (triangulated) historical air photos. Historical air photos were reviewed using stereo-pairs for use in mapping software (e.g. PurView™[1]). Coverage, resolution and scale of the imagery are discussed in Section 2.1.

Channel banks were delineated directly onscreen from the historical imagery (1950) and from the most recent aerial imagery (2017). Bank delineation and major river features (e.g. single thread or multi-channel, major islands, sediment bars and/or significant secondary channels) were identified as they pertain to observe channel bank stability or instability. Once mapped in Purview™, the digital channel margins were exported into an ArcGIS 10.3 (ArcMap) database with the geospatial attribute.

A comparison of the historically-imaged and most recently-imaged channel banks was undertaken with both channel bank lines depicted on the most recent photo base provided by AEP. A select set of figures were developed to highlight example areas of general channel stability and instability. These figures are accompanied by a technical summary discussing the general nature of channel stability/instability in the study area (e.g. observations that channel instability is highest on the downstream, outside portion of the major meanders).

3.2 Cross-Section Comparison

Due to the lack of historical cross-section data, only a qualitative and quantitative review could be completed for the current dataset. For the cross-section review, a preliminary analysis was carried out to identify an appropriate number of representative cross sections for review to provide adequate coverage and detail of the Fort McMurray River Study Area. For the cross-section review, a subsample of representative cross sections was selected for review in detail. The selected representative cross sections were compared with estimates of meander spacing to validate coverage of the major river features. A total of 78 representative cross-sections were chosen within the Fort McMurray River study area comprising of the following: 26 from the Athabasca River; 23 from the Clearwater River; 29 from the Hangingstone River; and 4 from Snye River.

Following identification of the representative cross sections, qualitative and quantitative analyses were completed. The qualitative analysis included review and documentation of cross-section features such as right-handedness or left-handedness (i.e. the deepest part being located on the left or right side of the river channel), skewness (i.e. cross section with a uniform geometry or leaning to left or right), single thread or multiple thread channels, and evidence of aggradation or degradation.

The quantitative analysis of channel geometry consisted of the estimation of cross-sectional area, maximum bankfull depth, bankfull width, and average bankfull depth for each cross-section. These parameters were used to determine channel type. As a comparison could not be completed, changes in hydraulic capacity using hydraulic relationships were not assessed nor could a statistical analysis of changes be completed.

[1] Product of I.S.M. International Systemap Corp., distributed by ESRI in Canada. (www.mypurview.com)

3.3 Thalweg Profile Comparison

The river thalweg is the line that passes through the deepest parts of the river in the downstream direction. It links the deepest areas of the river together and a representative feature of channel geometry.

Due to the lack of historical thalweg data for the Fort McMurray River study area, only a qualitative assessment was conducted on the available 2016 river geometry data. The current thalweg profiles were reviewed for general shape and gradient.

Migration of the river channel as documented in the channel bank is deemed to be sufficient to address lateral migration of the river.

3.4 Rating Curve Comparison

Changes in main channel geometry or riverbed elevations result in rating curve changes for a hydrometric gauge. The passage of sediments through the river and the essentially mobile nature of many riverbeds can cause bed levels to increase and decrease in response to natural river changes and flood events.

Available rating curve data was provided by the Water Survey of Canada as described in Section 2.4. The historical and current rating curves were compared, in context with observed changes in the river thalweg and features of nearby river cross sections. Information collected from the comparison and review of channel banks, cross-sections, and the thalweg profile was used to inform the interpretation of changes observed in the rating curves.

4.0 RESULTS

4.1 Channel Bank Comparison

The results of the channel bank delineation and comparison are summarized in Table 5, and the representative sub-reaches are shown in Figure 3 through Figure 6. These results are described below:

- Athabasca River (Reach 1) within the study area is typically defined by a stable planform with limited areas of instability. A representative portion of Reach 1 stable sub-reach is shown in Figure 3. The entire study reach is considered to be stable. An unstable sub-reach has not been included. This sub-reach shows a predominantly straight river within an incised relict pre-glacial valley that has been re-excavated during the post-glacial period. Minimal lateral migration of the channel has occurred with the main examples of lateral migration occurring along the bends of meanders. A lack of historical and current side and mid-channel bars suggest limited sediment storage within the study reach. The presence of several historical and current forested islands implies some stability within the channel. Variation in age of vegetation is visible on several forested islands in both the historical and current imagery with evidence of successive even-aged stands of trees implying occasional ice scour.
- The representative sub-reach along the Clearwater River (Reach 2) is shown in Figure 4. The entire study reach is considered to be stable. An unstable sub-reach has not been included. This sub-reach shows minimal lateral migration of the channel with the main examples of lateral migration occurring along the bends of meanders. The sub-reach from Reach 2 is a meandering sub-reach within an incised relict meltwater channel associated with the draining of Glacial Lake Agassiz (Smith and Fisher 1993). The current river channel is underfit for the valley. This reach is characterized by limited lateral migration, small side bars and stabilization of previous forested islands and side bars.

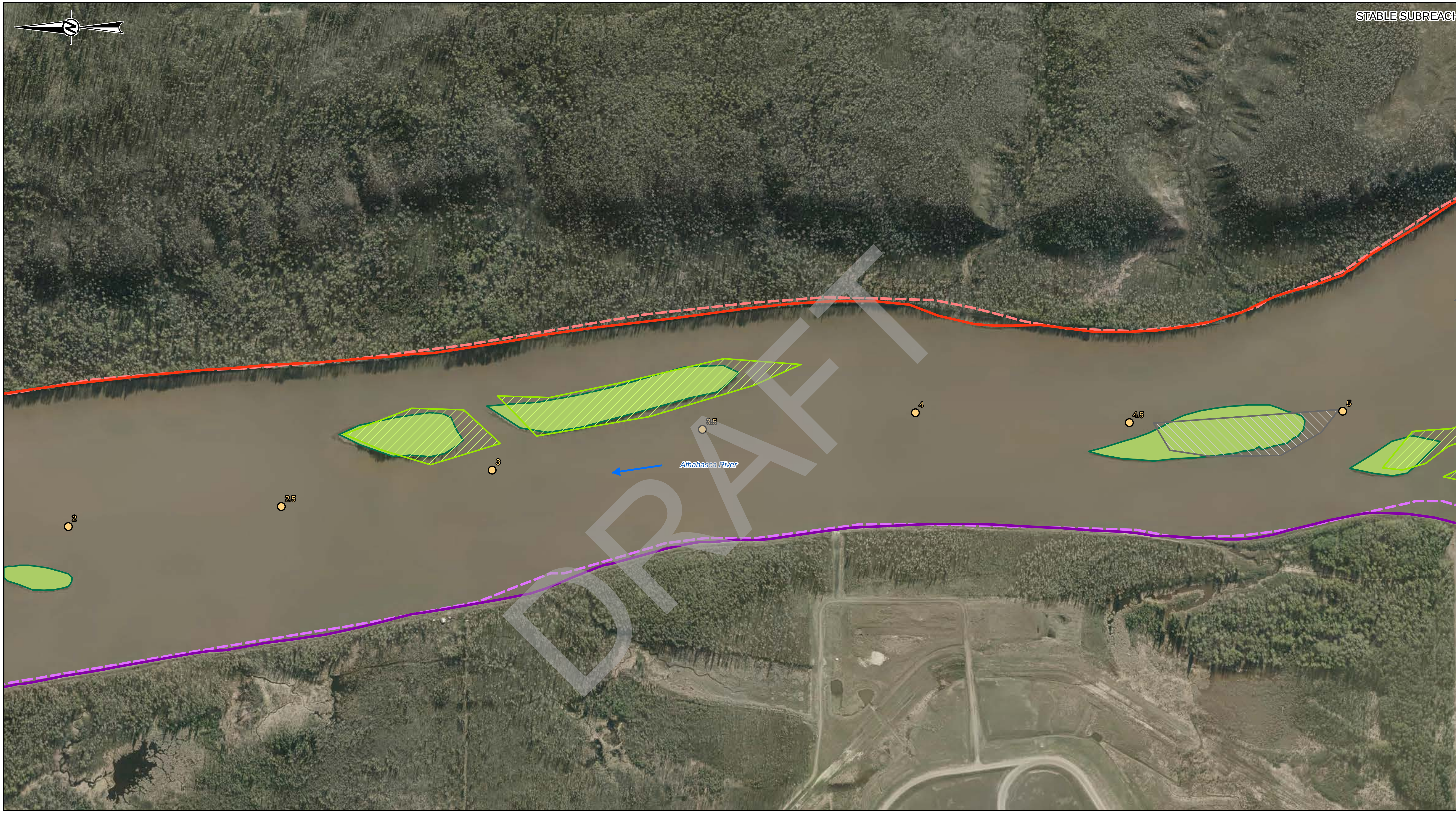
- Representative stable and unstable sub-reaches along the Hangingstone River (Reach 3) are shown in Figure 5. The upper portion of the reach is typically defined by a stable planform incised within a relict channel with limited areas of instability. Several point bars are present in both the historical and current datasets with more side bars present in the 2016 dataset. The observed historical point bars have typically expanded slightly and shifted slightly downstream to their current positions.

  The unstable sub-reach is located near the confluence of the Clearwater River. The lower portion of the reach consists of a sinuous, meandering channel characterized by the presence of side, point and mid-channel bars. The channel has migrated substantially around several meander bends, and possibly undergone avulsion by meander loop cutoff, shifting laterally from the centreline of the river by approximately 50 m to 150 m. Several point and side bars are present in both the historical and current datasets with more side bars present in the 2016 dataset. The mouth of the river has migrated approximately 75 m in the Clearwater downstream direction and channel alignment has been significantly realigned, likely as the result of the rapid drop in stream gradient from the upstream valley, the depositional environment of the river as it approaches the confluence with Clearwater River, and backwater forcing from the Clearwater River causing the channel to shift laterally and realign along this sub-reach.

- The entire Snye River is in Reach 4 (Figure 6) which shows a straight river secondary channel with limited sediment transport. The channel historically connected the Athabasca to the Clearwater River upstream of the main confluence, however the Athabasca side is cut off from the river in the 2016 imagery due to the construction of a man-made causeway in 1966. The 1950 imagery shows the secondary channel diverts flow from Athabasca River to Clearwater River as the mouth (Athabasca side) is oriented upstream and the outlet (Clearwater) is oriented downstream. Minimal lateral migration of the channel has occurred with the main occurrences of lateral migration being co-located at the confluence with the Clearwater River and in the vicinity of man-made structures (i.e. bridges, roadways). The left bank of the Clearwater River where it is connected with the Snye River outlet has migrated approximately 50 m to the west, likely due to the changes in hydraulics when the mouth of Snye River was cut-off from Athabasca River. No active side or point bars are present suggesting low sediment load as expected since the river no longer allows flow.

Table 5: Channel Bank Delineation Comparison

Reach	Representative Subreach (km)	Figure	Description
1 – Athabasca River	2 - 5	Figure 3	■ Confined ■ Incised ■ Limited presence of mid-channel and side bars ■ Mid-channel and side bars have become vegetated ■ Stable
2 - Clearwater River	15 - 18	Figure 4	■ Incised ■ Limited presence of mid-channel and side bars ■ Mid-channel and side bars have become vegetated ■ Stable
3 – Hangingstone River	2.5 – 5.4	Figure 5	■ Confined ■ Incised ■ Limited presence of mid-channel and side bars ■ Stable
	0 – 2.5		■ Presence of point, mid-channel and side bars ■ Significant migration of channel meanders and complete realignment of main channel ■ Unstable
4 - Snye River	0 – 1.6	Figure 6	■ Channel from Athabasca now separated from River ■ Absence of mid-channel and side bars ■ Stable



LEGEND

- RIVER STATION POST (km)
- FLOW DIRECTION
- RIGHT BANK (2017)
- RIGHT BANK HISTORICAL (1950)
- LEFT BANK (2017)
- LEFT BANK HISTORICAL (1950)
- CHANNEL BAR HISTORICAL (1950)
- FORESTED ISLAND (2017)
- FORESTED ISLAND HISTORICAL (1950)

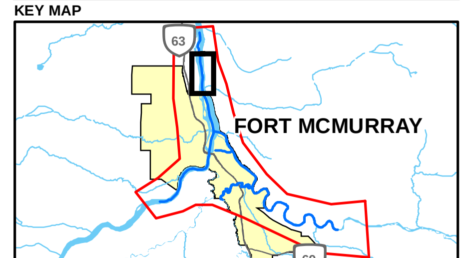
LEGEND KEY MAP

- STABLE SUBREACH

0 250 500

1:8,500 METRES

KEY MAP



PROJECT

FORT MCMURRAY HAZARD STUDY

PROJECT

ATHABASCA RIVER CHANNEL BANK COMPARISON: REPRESENTATIVE SUBREACHES

REFERENCE(S)

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DATUM: NAD 83 CSRS PROJECTION: 3TM 111

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CONSULTANT

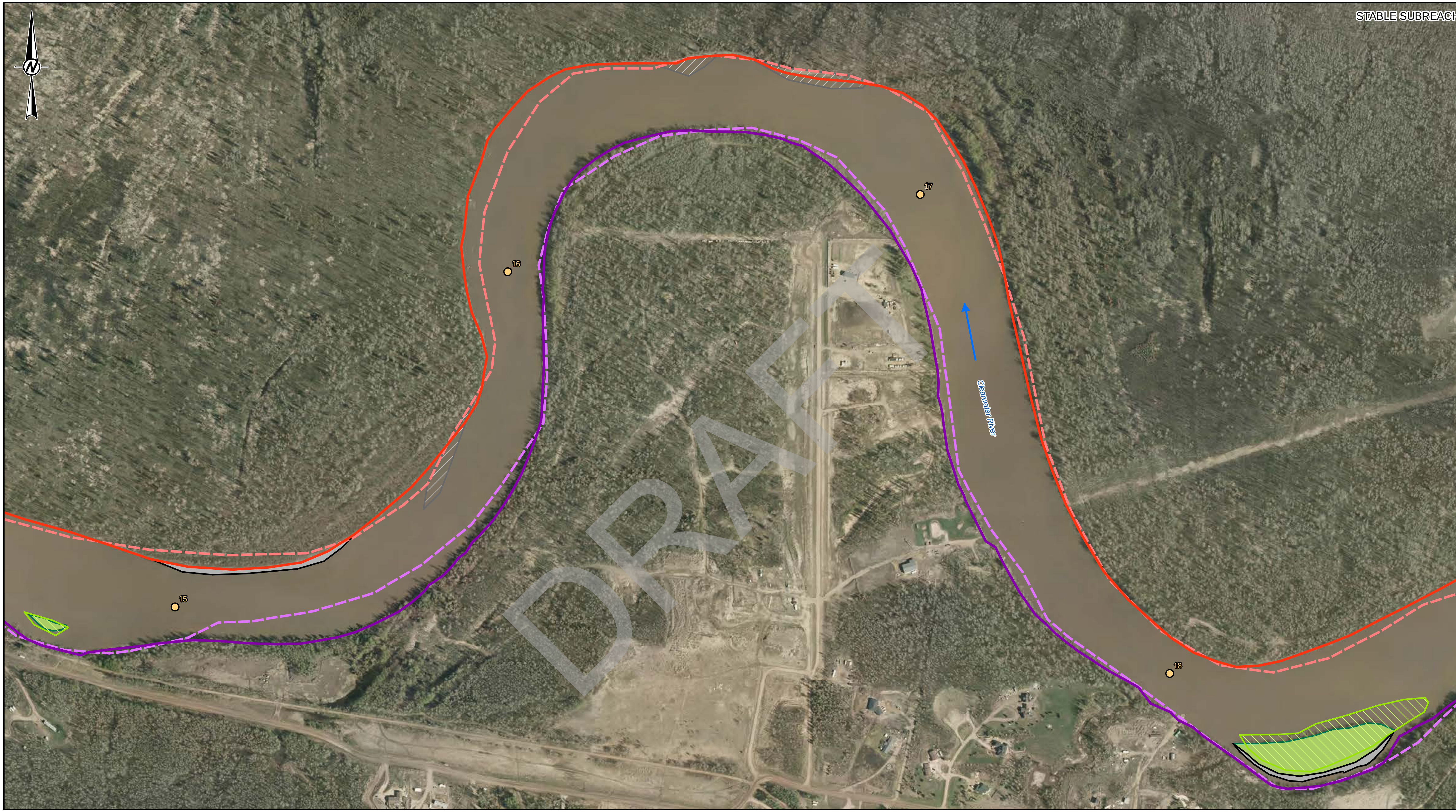
Golder Associates

YYYY-MM-DD	2018-08-28
DESIGNED	MT
PREPARED	AL
REVIEWED	MT
APPROVED	RA

PROJECT NO.	CONTROL	REV.	FIGURE
1662603	9000	0	3

IF THIS MEASUREMENT DOES NOT MATCH WHAT IS SHOWN, THE SHEET SIZE HAS BEEN MODIFIED FROM: ANSI B

25mm



LEGEND

- RIVER STATION POST (km)
- FLOW DIRECTION
- RIGHT BANK (2017)
- RIGHT BANK HISTORICAL (1950)
- LEFT BANK (2017)
- LEFT BANK HISTORICAL (1950)
- CHANNEL BAR (2017)
- CHANNEL BAR HISTORICAL (1950)
- FORESTED ISLAND (2017)
- FORESTED ISLAND HISTORICAL (1950)

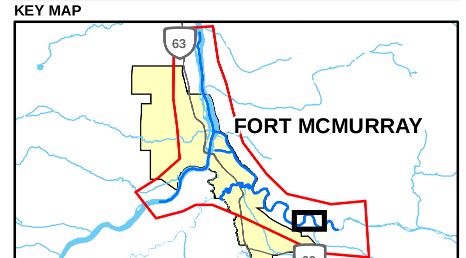
LEGEND KEY MAP

- STABLE SUBREACH

0 200 400

1:6,500 METRES

KEY MAP



PROJECT
FORT MCMURRAY HAZARD STUDY

PROJECT
CLEARWATER RIVER CHANNEL BANK COMPARISON: REPRESENTATIVE SUBREACHES

REFERENCE(S)
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CONSULTANT
Golder Associates

YYYY-MM-DD	2018-08-28
DESIGNED	MT
PREPARED	AL
REVIEWED	MT
APPROVED	RA

PROJECT NO.	CONTROL	REV.	FIGURE
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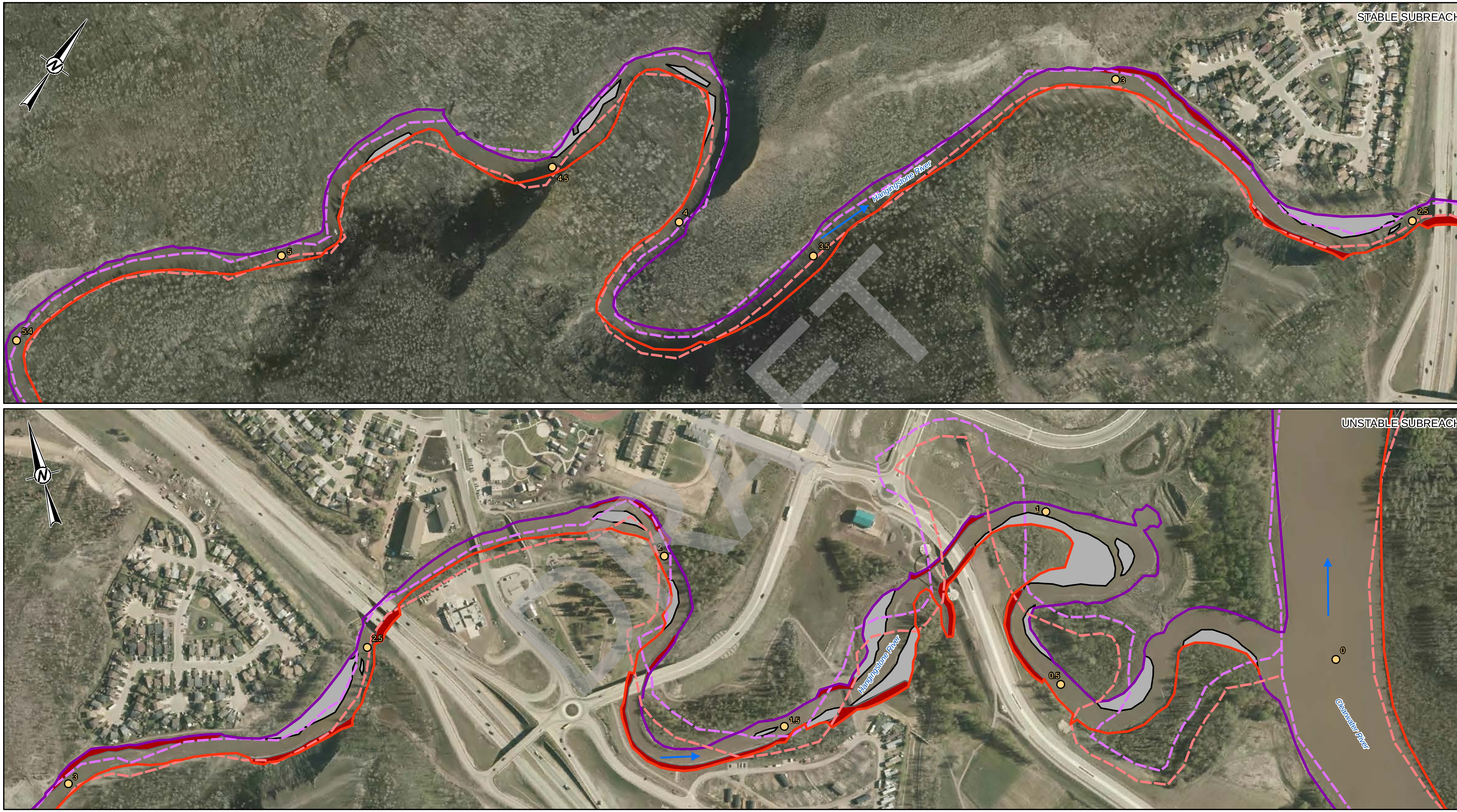
Classification: Public



LEGEND

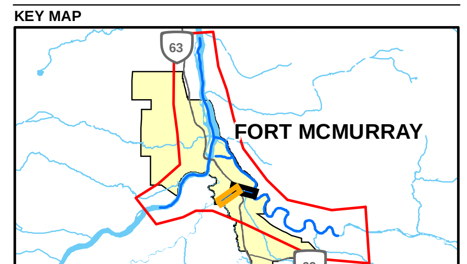
- RIVER STATION POST (km)
- FLOW DIRECTION
- RIGHT BANK (2017)
- RIGHT BANK HISTORICAL (1950)
- LEFT BANK (2017)
- LEFT BANK HISTORICAL (1950)
- PROTECTED BANK (2017)
- CHANNEL BAR (2017)
- CHANNEL BAR HISTORICAL (1950)

LEGEND KEY MAP

- STABLE SUBREACH
- UNSTABLE SUBREACH

0 150 300
1:5,000 METRES

KEY MAP



PROJECT
FORT MCMURRAY HAZARD STUDY

PROJECT
HANGINGSTONE RIVER CHANNEL BANK COMPARISON: REPRESENTATIVE SUBREACHES

REFERENCE(S)
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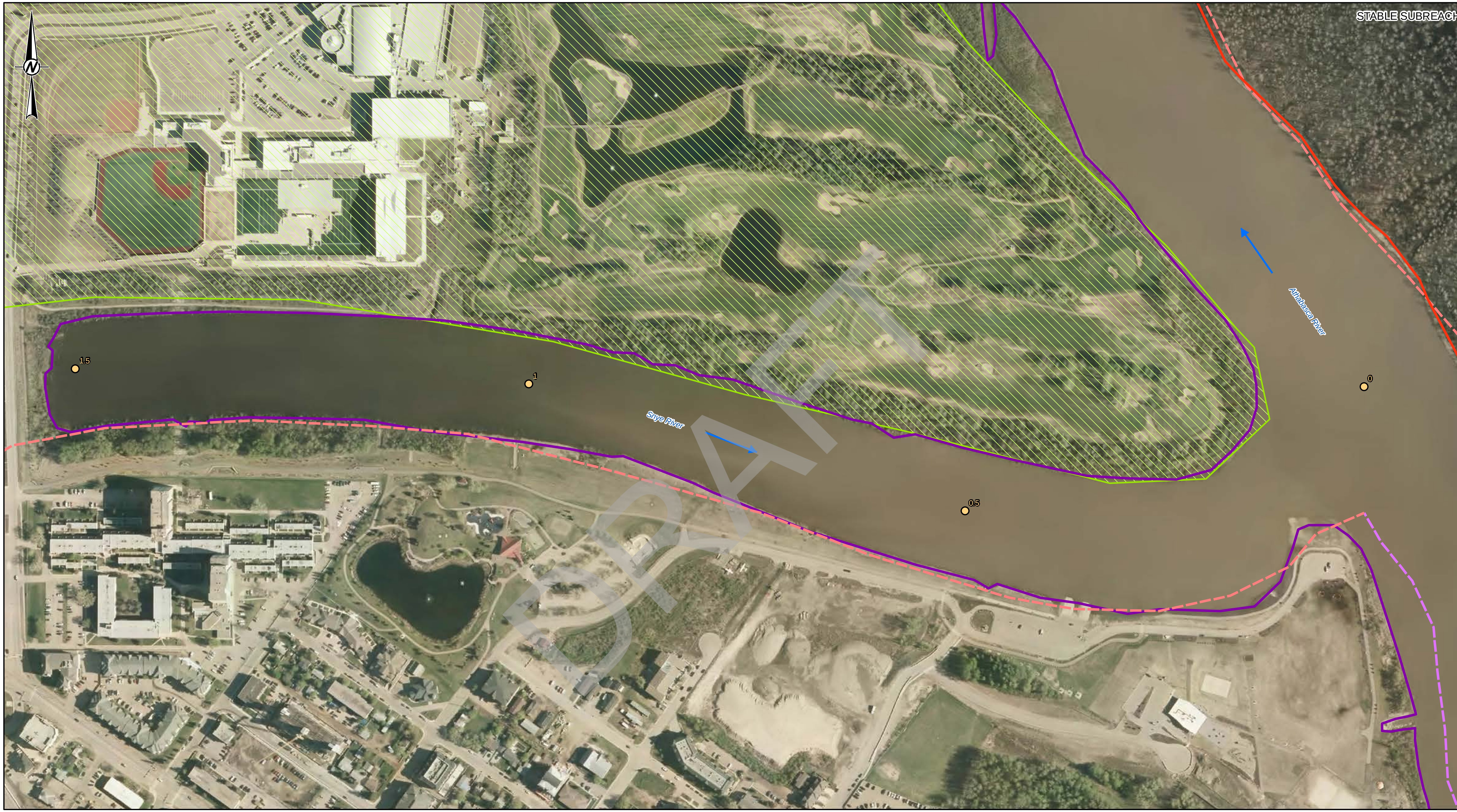
DESIGNED	MT
PREPARED	AL
REVIEWED	MT
APPROVED	RA

PROJECT NO.	CONTROL	REV.	FIGURE
1662603	9000	0	**5**

Classification: Public



LEGEND

- RIVER STATION POST (km)
- FLOW DIRECTION
- RIGHT BANK (2017)
- RIGHT BANK HISTORICAL (1950)
- LEFT BANK (2017)
- LEFT BANK HISTORICAL (1950)
- FORESTED ISLAND HISTORICAL (1950)

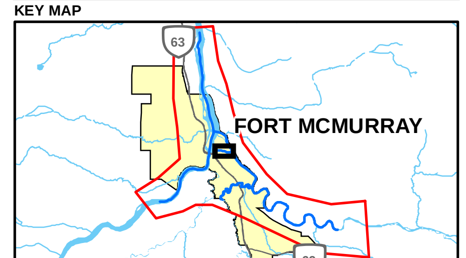
0 100 200

1:4,000 METRES

LEGEND KEY MAP

- STABLE SUBREACH

KEY MAP



PROJECT

FORT MCMURRAY HAZARD STUDY

PROJECT

SNYE RIVER CHANNEL BANK COMPARISON: REPRESENTATIVE SUBREACHES

REFERENCE(S)

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DESIGNED	MT
PREPARED	AL
REVIEWED	MT
APPROVED	RA

PROJECT NO.	CONTROL	REV.	FIGURE
1662603	9000	0	6

Classification: Public

4.2 Cross-Section Comparison

Detailed qualitative and quantitative descriptions for the cross-section review, along with explanations of the descriptors, are presented in Appendix A. Table 6 provides a summary of representative cross-section geometry.

Table 6: Summary of Representative Cross-Section Geometry

Reach	Average Bankfull Width (m)	Maximum Bankfull Depth (m)	Average Bankfull Depth (m)	Cross-Sectional Area (m^2)
1 – Athabasca River	530	4.8	3.0	1535
2 – Clearwater River	150	4.0	2.7	409
3 – Hangingstone River	27	1.7	1.0	27
4 – Snye River	127	3.2	2.2	280

The main quantitative observations indicate average bankfull width for Athabasca, Clearwater, Hangingstone and Snye Rivers were 530 m, 150 m, 27 m, and 127 m, respectively. As a cross-section comparison was not completed, however, observations regarding the differences in channel width were made during the channel bank comparison. For all four reaches, the channel width variation from 1950 to 2016 was within ± 10 m which is within the range of visual error of the historical dataset. Changes in the average bankfull width occurred due to accretion of point bars, erosion of the outer meander bends and stabilization of side and point bars overtime.

4.3 Thalweg Profile Comparison

A thalweg profile comparison could not be conducted for the Fort McMurray Study Area but the 2016 surveyed thalweg profile is shown in Figure 8 through Figure 11, in terms of elevation and distance downstream. Table 7 summarizes, by reach, the average slope calculated from the thalweg profile review.

According to Ritter et al. (1995), thalwegs exhibiting a concave-upward profile shape are typical of an alluvial stream reach in equilibrium. Figure 7 shows an example of a typical concave-upward thalweg representative of an entire stream from its headwaters to its mouth for comparison. The plots for the Athabasca, Clearwater and Snye Rivers exhibit undulating thalweg morphology with an approximately linear (consistent) slope within the study area. For Athabasca and Clearwater Rivers, the study area covers a very small portion of their overall length and therefore the thalwegs presented are only a small representation of the overall thalweg profiles (RAMP 2018). For Athabasca River, the study area is located in the middle to lower course of the thalweg profile (Figure 7) and therefore the portion of the thalweg shown in Figure 8 is representative. For Clearwater River, the study area is located at the mouth of the thalweg profile and the thalweg shown in Figure 9 is therefore representative. Snye River, as previously mentioned, is a secondary channel to Athabasca River that is no longer active. The air photo review indicates the Snye was formerly a channel of Athabasca River. Prior to closing the upstream end by dike, the channel would have behaved similarly to the Athabasca River as a portion of a lower course thalweg channel.

The slopes for the Athabasca, Clearwater and Snye Rivers are -0.0005, -0.0002 and -0.0008, respectively.

Inspection of the thalweg for each of the subreaches suggests that the Hangingstone River, within the study area, follows a general concave-upward trending profile with slopes typically decreasing in steepness from the upstream boundary to the river mouth. The Hangingstone River, at the upstream boundary, has a slope of -0.005, while at the downstream boundary has a slope of -0.0018.

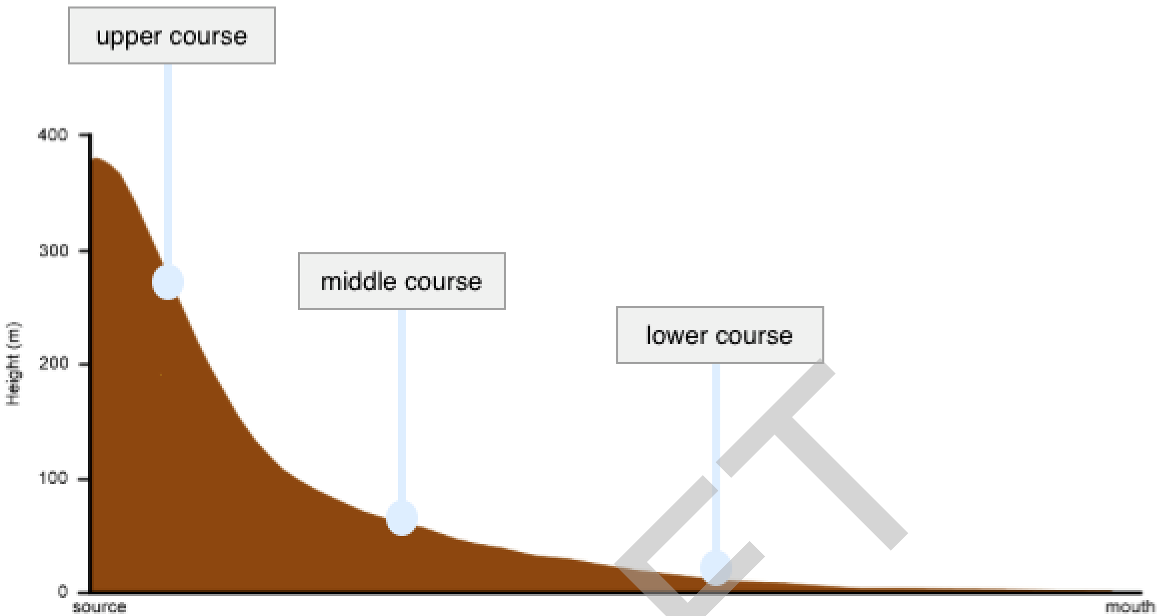

Figure 7: Graded River with a Typical Concave-upward Thalweg Profile
(Source: http://www.geography.learnontheinternet.co.uk/topics/longprofile.html)

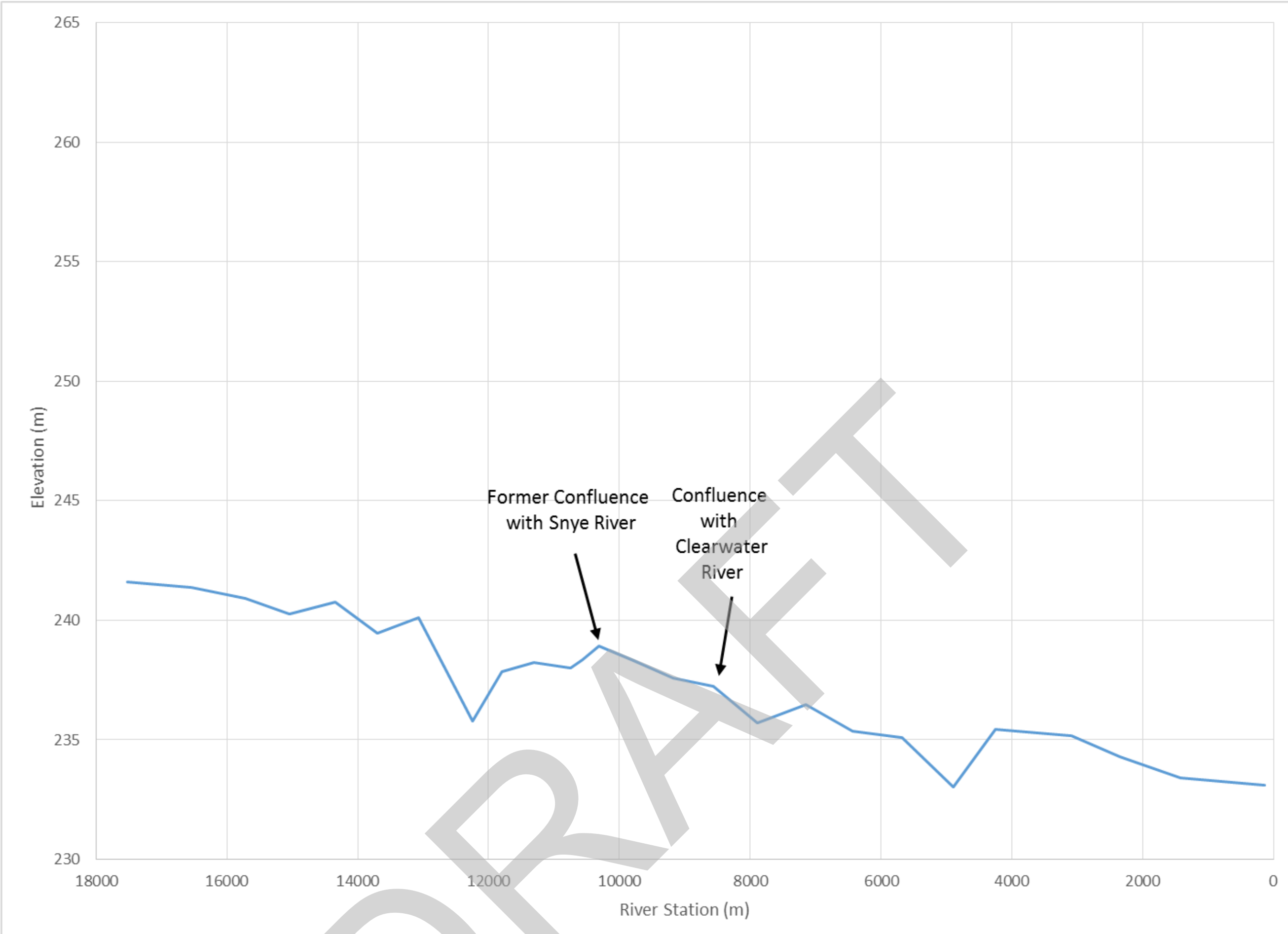

Figure 8: Athabasca River Thalweg (surveyed in 2016)

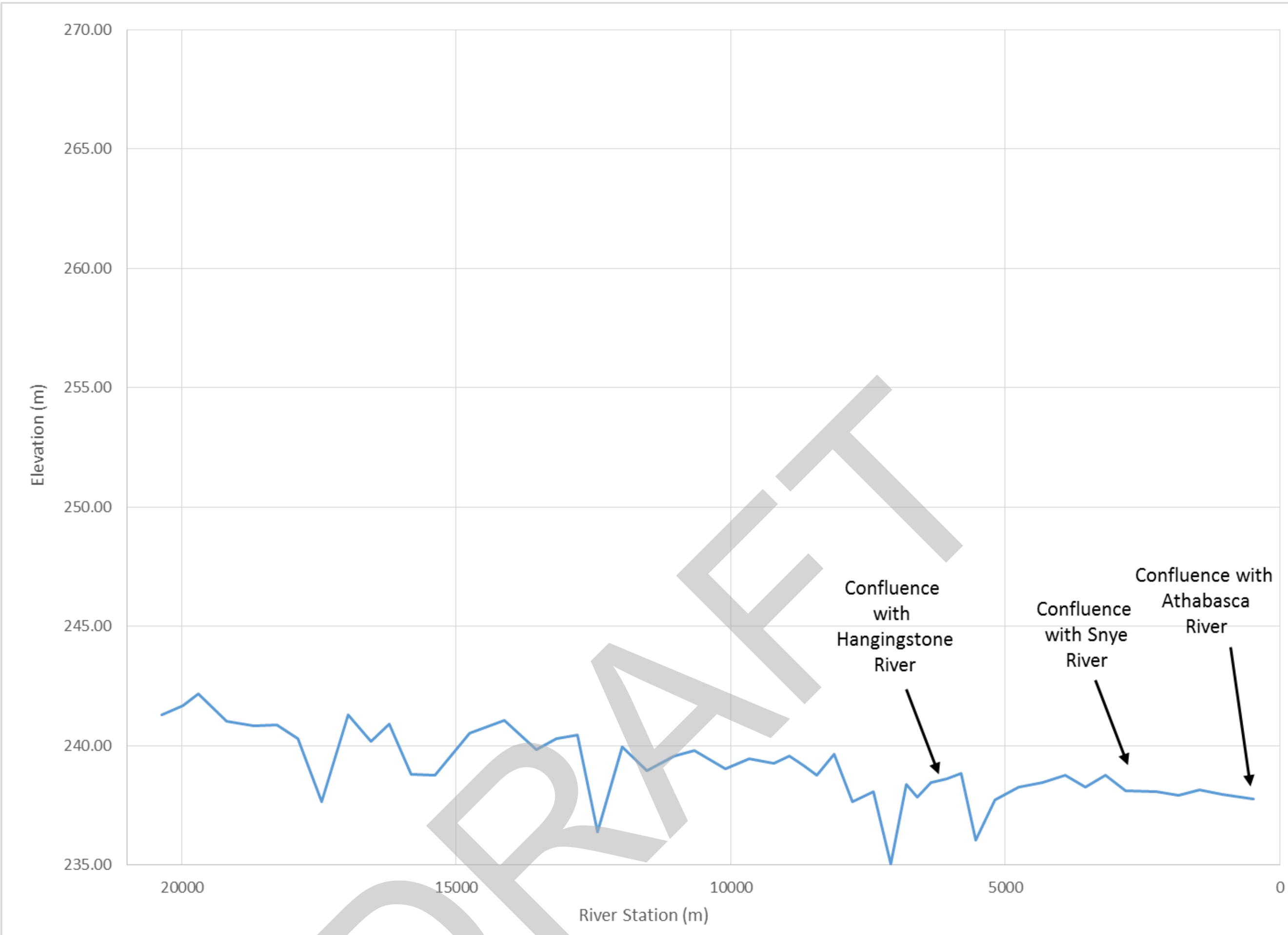

Figure 9: Clearwater River Thalweg (surveyed in 2016)

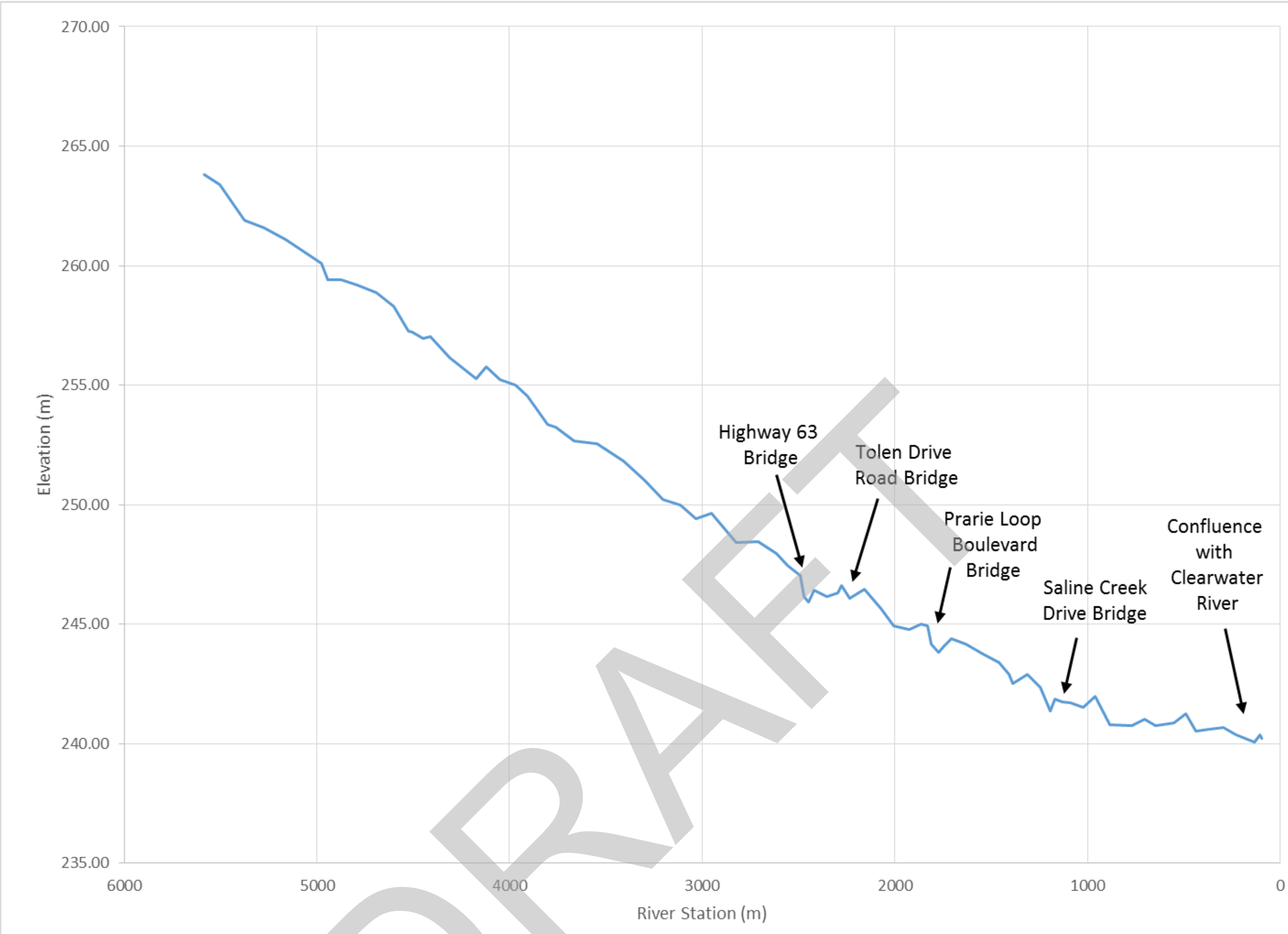

Figure 10: Hangingstone River Thalweg (surveyed in 2016)

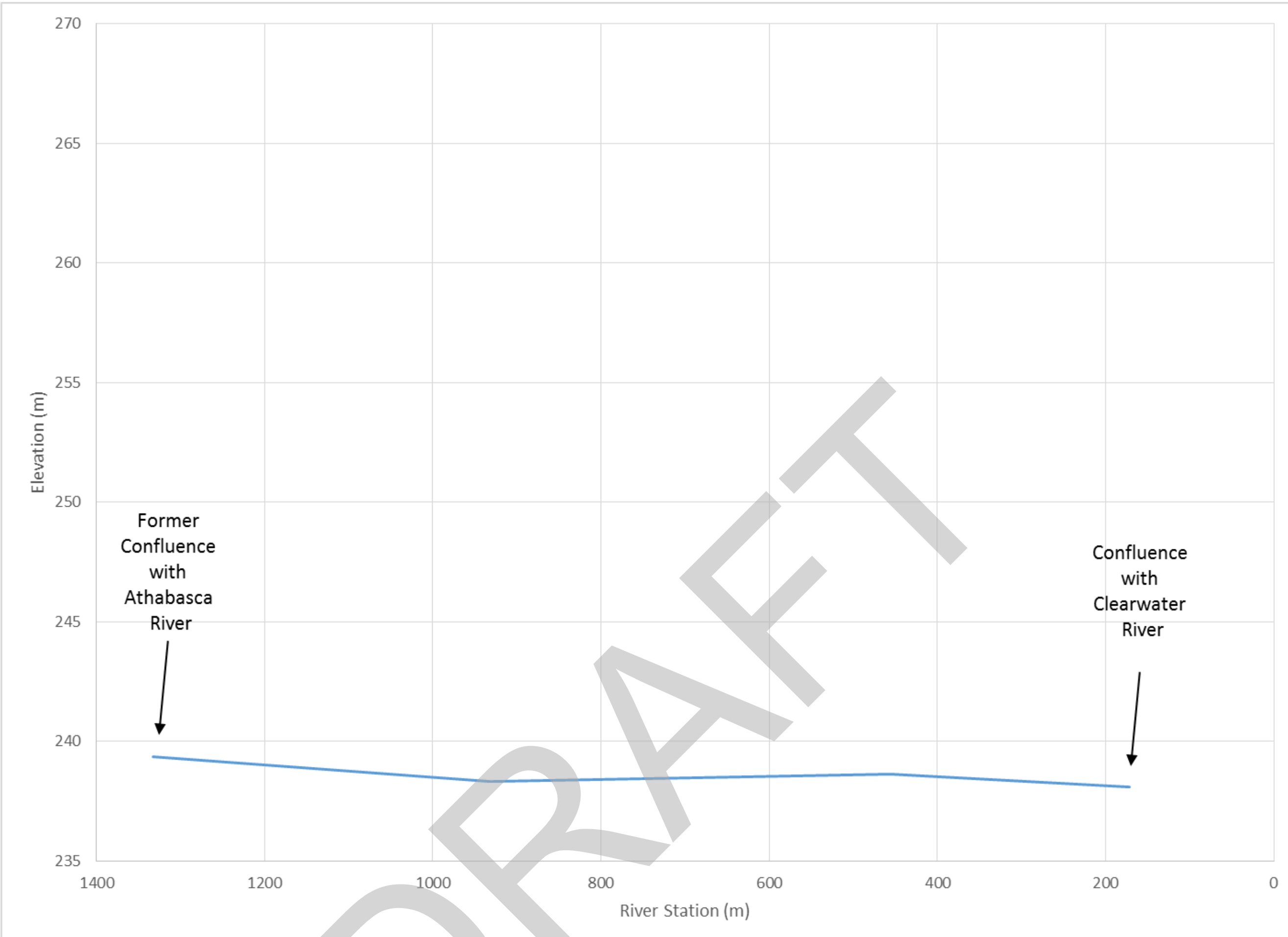

Figure 11: Snye River Thalweg (surveyed in 2016)

4.4 Rating Curve Comparison

The results of the rating curve comparison are shown in Figure 12 through Figure 14.

Athabasca River below McMurray (WSC Station No. 07DA001) is located along Reach 1, approximately 5 km downstream of the confluence with the Clearwater River. The rating curves for this station are shown in Figure 12. The observed change in the rating curve from 1971 to 2010 (Figure 12) suggests the river channel has not changed over the two time periods because the same water surface elevation in 1971 conveys the same discharge in 2016.

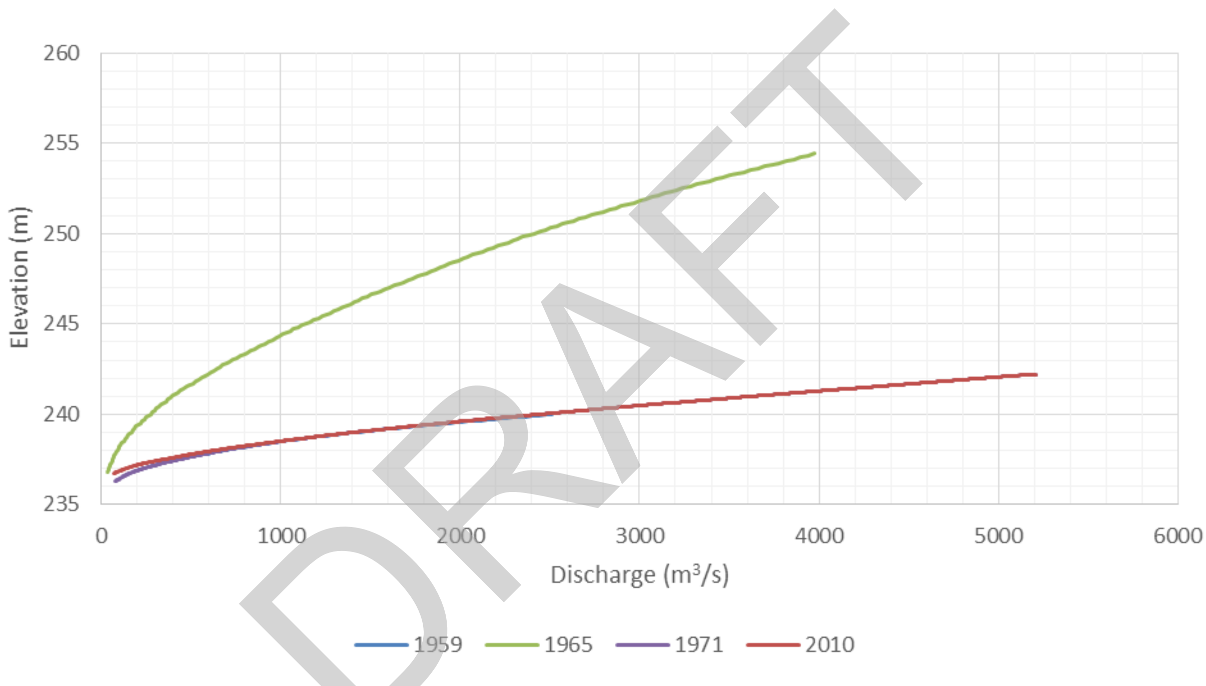

Figure 12: Rating Curve for WSC Station No. 07DA001 (Athabasca River below McMurray)(

Notes: (1) This gauge was moved in 1962 and resurveyed in 1965 which has caused vertical shifts in the datum.
(2) Curves for 1971-1999 and 2010-2016 are on the same datum.

Figure 13 compares select rating curves for the Clearwater River at Draper (WSC Station No. 07CD001). This station is located along Reach 2 approximately 17 km upstream from the confluence with the Athabasca River. The slope for each of the curves is the same for all four years suggesting no change in the morphology of the river. The observed vertical shifts between the curves could be a result of re-surveying. The data from the channel bank comparison also suggests that this reach is stable.

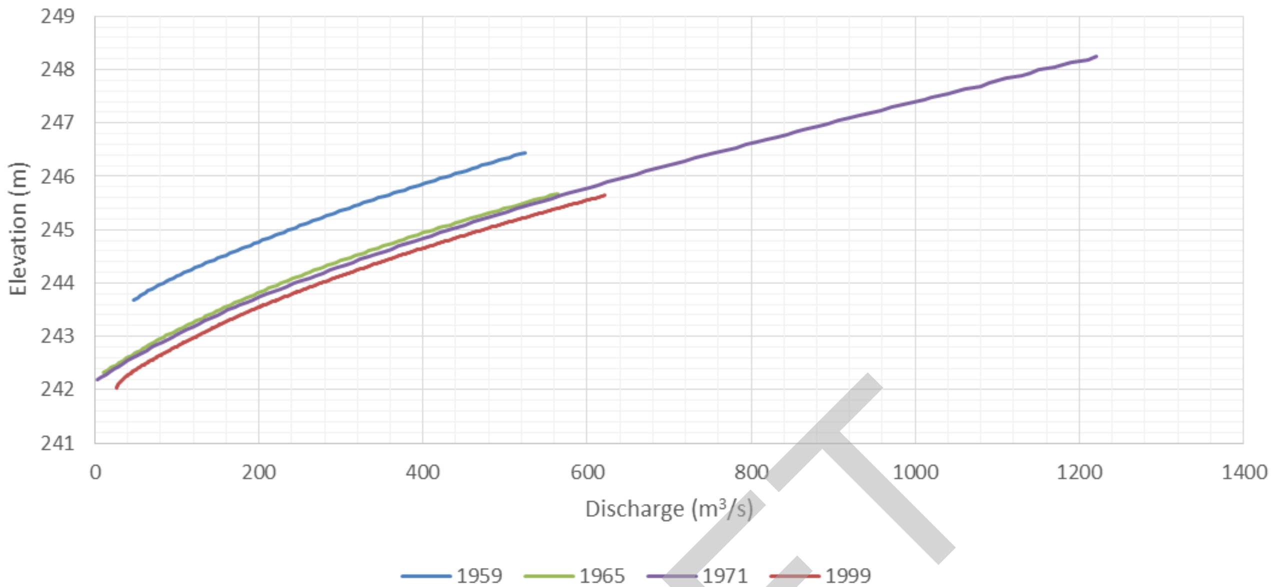

Figure 13: Rating Curves for WSC Station No. 07CD001 (Clearwater River at Draper)

Notes: (1) This gauge was moved in 1957, resurveyed in 1964 and 1967 which has caused vertical shifts in the datum.
(2) Curves for 1971 and 1999 are on the same datum.

Figure 14 shows the rating curves for Hangingstone River at Fort McMurray (WSC Station No. 07CD004), located along reach 3 approximately 2.5 km upstream from the confluence of the Clearwater River, near the Highway 63 bridge. The change in the rating curve at lower discharge levels (<12 m^3/s), as shown in Figure 14, suggests narrowing or shoaling (accretion) of the channel because the same water surface elevation in 1986 and 2013 conveys less discharge in 2013. The loss of conveyance is likely narrowing or shoaling of the channel. At discharges greater than 20 m^3/s, the slight change in rating curve suggests minor widening or increase in average depth of the channel as the same water surface in 1986 and 2013 conveys more discharge in 2013. The increase in conveyance at higher discharges is possibly a result of changes in the channel due to construction of the southbound Highway 63 Bridge. Construction of the bridge may have required widening the bridge span and upper channel banks to allow for channel migration. A widening of the channel of 5 m was observed at the bridge during the channel bank comparison.

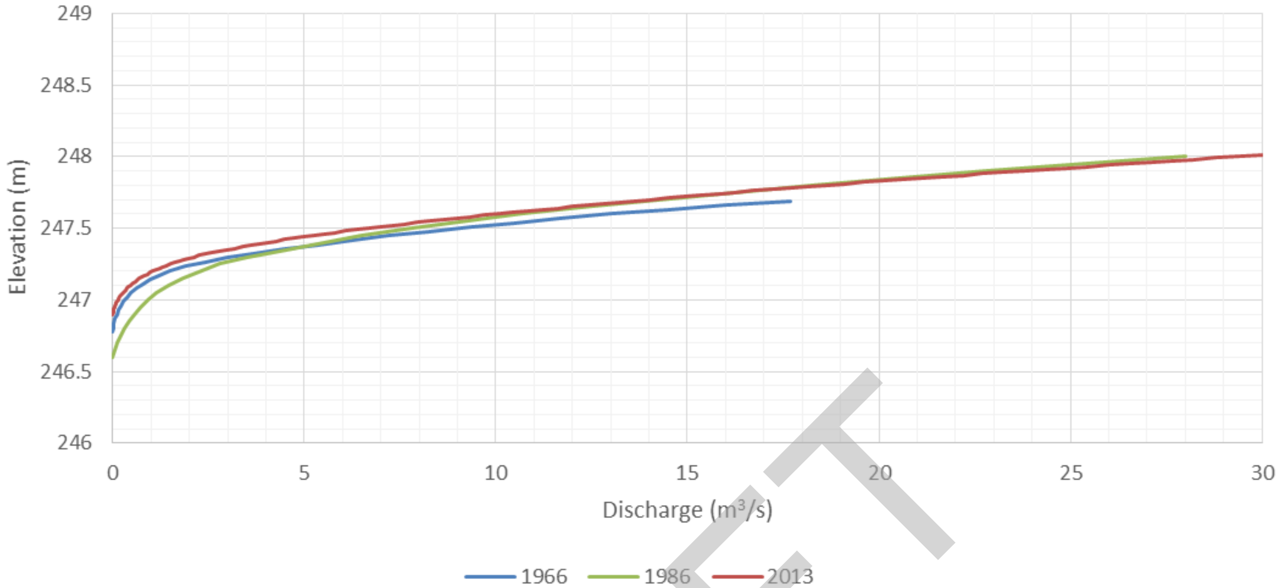

Figure 14: Rating Curves for WSC Station No. 07CD004 (Hangingstone River at Fort McMurray)

Notes: (1) This gauge was moved in 1985 which has caused vertical shifts in the datum.
(2) Curves for 1986 and 2013 are on the same datum.

5.0 CONCLUSIONS

5.1 Athabasca River

The Athabasca River, Reach 1, is categorized as a straight, single channel river reach confined within a larger incised channel (glacial outwash channel).

Visual evidence in the form of limited occurrence of point and side bars from the aerial imagery suggests that there is limited sediment storage occurring in Athabasca River. The presence of several historical and current forested islands implies some stability within the channel. Due to the confined nature of the channel within this reach, limited lateral migration is occurring. While narrowing of the channel in this reach was observed in the cross-section data, the change is not statistically significant. The thalweg varies with several increases in elevation visible along its length. Based on the straight river channel and visible lack of sediment transport, Athabasca River, is considered to be a non-alluvial channel confined within a geologically historical river valley (e.g. meltwater channel). This observation has been previously documented by others.

Due to the confined nature of the channel and limited lateral migration, this reach is considered stable. Based on the morphological data reviewed, it appears that the capacity of the river to handle discharge has not changed over the extent of historical data reviewed.

5.2 Clearwater River

The Clearwater River, Reach 2, is categorized as a sinuous, meandering, single channel river reach confined within a larger incised channel (glacial outwash channel). This reach shows minimal lateral migration of the channel with the main examples of lateral migration occurring along the bends of meanders. Based on the incised meandering channel and limited sediment transport, Clearwater River, is considered to be a sediment-limited alluvial channel confined within a geologically historical river valley (e.g. meltwater channel). This reach is characterized by limited lateral migration, small side bars and stabilization of previous forested islands and side bars.

Due to the confined nature of the channel and limited lateral migration, this reach is considered stable. Based on the morphological data reviewed, it appears that the capacity of the river to handle discharge has not changed over the extent of historical data reviewed.

5.3 Hangingstone River

The Hangingstone River, Reach 3, is characterized as a sinuous, meandering and single channel river reach. The upper portion of the reach is characterized by several slightly migrating point and side bars and a slope of -0.005.

The lower portion of the reach is characterized by significantly dynamic side, point and mid-channel bars and a slope of -0.0018. The channel has undergone a significant realignment at the downstream end including migration of the river mouth. The 2016 thalweg shows a concave-upwards profile. The rating curve comparison suggests that at higher discharge volumes, the river can convey more flow within the same channel at the Highway 63 Bridge.

The observed decrease in slope and realignment at the lower portion of the reach suggests that the Hangingstone River at the mouth is a backwater channel to the Clearwater River. As such, it is considered to be unstable at the downstream end and could be susceptible to increased flood hazard due to backwater effects.

5.4 Snye

The Snye River, Reach 4, is characterized as a straight single former secondary river channel with limited sediment transport. No in-channel bars are present along this reach suggesting little to no sediment transport. This reach does not appear to have any obvious surface headwater sources, due to the construction of the road across the mouth at the Athabasca side. Reach 4 has a slope of -0.0008.

As a non-active channel with no in-channel bars, Reach 4 is considered to be stable. However, based on the morphological data reviewed, it appears that the capacity of the river to handle discharge has changed due to the alteration of the channel mouth.

Table 7: Summary of Qualitative Reach Characteristics

Reach	Current Width to Depth Ratio	Reach Slope (m/m)	Sinuosity (thalweg length/straight valley length)	Summary of observations
1 – Athabasca River	177	-0.0005	1.0	■ Single channel ■ Straight ■ Limited lateral migration ■ Presence of forested bars ■ Incised, confined
2 - Clearwater River	55	-0.0002	1.5	■ Single channel ■ Sinuous/meandering ■ Small side bars ■ Incised ■ Stabilization of forested islands and side bars
3 – Hangingstone River	27	-0.0050 to -0.0018	1.7	■ Single channel ■ Sinuous/meandering ■ Significant lateral migration downstream ■ Point, side and mid-channel bars ■ Incised, confined
4 - Snye River	59	-0.0008	1.0	■ Single channel ■ Straight ■ Limited lateral migration ■ No bars ■ No flow

6.0 CLOSURE

This report is prepared and reviewed by the undersigned.

GOLDER ASSOCIATES LTD.

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https://golderassociates.sharepoint.com/sites/10170g/shared documents/09 channel stability/channel stability report/final - rev0/1662603_r0009_0_report_fort mcmurray channel_stability_20180913.docx

THIRD PARTY DISCLAIMER

REFERENCES

Golder Associates Ltd. (Golder). 2018a. Fort McMurray River Hazard Study - Aerial Imagery Acquisition Memorandum, April 2018.

Golder. 2018b. Fort McMurray River Hazard Study - Survey and Base Data Collection Report, April 2018.

Regional Aquatics Monitoring Program (RAMP). 2018. Hydrology of the Athabasca Oil Sands Region. Retrieved from http://www.ramp-alberta.org/river/hydrology/river+hydrology.aspx. Accessed on January 16, 2018.

Ritter, D.F., Kochel, R.C., Miller, J.R. and Miller, J.R. 1995. Process geomorphology. Dubuque, Iowa: Wm. C. Brown.

Smith, D.G. and Fisher, T.G. 1993. Glacial Lake Agassiz: The northwestern outlet and paleoflood. *Geology* ; 21 (1): 9–12.

Water Survey of Canada (WSC). 2017. Rating Curve Data for WSC Stations Athabasca River below McMurray (WSC Station No. 07DA001); Clearwater River at Draper (WSC Station No. 07CD001); and Hangingstone River at Fort McMurray (WSC Station No. 07CD004). Provided by Dennis Lazowski, Water Survey of Canada division of Environment Canada.

APPENDIX A

2016 Cross-Section Summary

This appendix consists of the qualitative and quantitative analysis of the current cross-section data. The qualitative analysis included review and documentation of cross-section features such as right-handedness or left-handedness (i.e. the deepest part of the channel on the left or right side of the river channel as viewed facing downstream), skewness (i.e. cross section with a uniformly distributed depth profile or a depth distribution that is more deep to left or right when viewed facing downstream), single thread or multiple thread channels, and evidence of aggradation or degradation. The quantitative analysis of channel geometry consisted of the estimation of cross-sectional area, maximum bankfull depth, bankfull width, and average bankfull depth. These parameters were used to determine channel type. As a comparison could not be completed, changes in hydraulic capacity using hydraulic relationships were not assessed nor could a statistical analysis of changes be completed.

	Cross-section ID	River Station (m)	Cross-sectional Area (m^2)	Maximum Bankfull Width (m)	Maximum Bankfull Depth (m)	Average Bankfull Depth (m)	Description
1 – Athabasca River	35	129	1,779	595	5.6	3.0	▪ right-handedness ▪ skewed to right ▪ single channel
	34	1,420	1,926	625	5.7	3.1	▪ right-handedness ▪ skewed to right ▪ dual channel (forested island)
	33	2,347	2,100	650	5.1	3.2	▪ right-handedness ▪ skewed to right ▪ single channel
	32	3,083	1,829	525	4.4	3.5	▪ right-handedness ▪ skewed to right ▪ dual channel (forested island)
	31	4,246	1,600	470	4.4	3.4	▪ central thalweg ▪ skewed to right ▪ single channel
	30	4,899	1,558	530	7.1	2.9	▪ right-handedness ▪ skewed to right ▪ single channel
	29	5,675	2,509	860	5.3	2.9	▪ right-handedness ▪ skewed to right ▪ single channel
	28	6,438	1,905	625	5.2	3.0	▪ left-handedness ▪ skewed to right ▪ multi-channel (forested islands)
	27	7,144	1,867	705	4.3	2.7	▪ right-handedness ▪ skewed to right ▪ multi-channel (forested islands)
	26	7,895	2,138	810	5.4	2.7	▪ right-handedness ▪ skewed to right ▪ dual channel (forested island)
	25	8,559	2,176	880	4.0	2.5	▪ right-handedness ▪ skewed to right ▪ single channel

	Cross-section ID	River Station (m)	Cross-sectional Area (m^2)	Maximum Bankfull Width (m)	Maximum Bankfull Depth (m)	Average Bankfull Depth (m)	Description
1 – Athabasca River	16	9,174	1,357	590	3.9	2.3	▪ right-handedness ▪ skewed to right ▪ dual channel (forested island)
	15	9,779	1,207	470	3.6	2.6	▪ right-handedness ▪ skewed to right ▪ dual channel (forested island)
	14	10,306	1,465	690	3.3	2.1	▪ right-handedness ▪ skewed to right ▪ single channel
	13	10,564	1,163	415	4.0	2.8	▪ right-handedness ▪ skewed to right ▪ single channel
	12	10,747	1,254	410	4.6	3.1	▪ right-handedness ▪ skewed to right ▪ single channel
	11	11,309	1,039	325	4.7	3.2	▪ right-handedness ▪ skewed to right ▪ single channel
	10	11,791	1,315	375	5.4	3.5	▪ left-handedness ▪ skewed to right ▪ single channel
	9	12,237	1,477	385	7.6	3.9	▪ left-handedness ▪ central channel ▪ single channel
	8	13,071	1,140	405	3.6	2.8	▪ central thalweg ▪ skewed to left ▪ single channel
	7	13,706	1,279	445	4.7	2.9	▪ right-handedness ▪ skewed to left ▪ single channel
	6	14,346	1,204	460	3.8	2.6	▪ central thalweg ▪ slightly skewed to right ▪ single channel

	Cross-section ID	River Station (m)	Cross-sectional Area (m^2)	Maximum Bankfull Width (m)	Maximum Bankfull Depth (m)	Average Bankfull Depth (m)	Description
1 – Athabasca River	5	15,048	1142	350	4.7	3.2	▪ right-handedness ▪ skewed to right ▪ single channel
	4	15,716	1148	320	4.4	3.6	▪ central thalweg ▪ skewed to right ▪ single channel
	3	16,535	1152	390	4.5	3.0	▪ central thalweg ▪ skewed to left ▪ single channel
	2	17,519	1172	380	4.8	3.1	▪ left-handedness ▪ skewed to left ▪ single channel
2 – Clearwater River	140	1,043	384	152.3	3.5	2.5	▪ right-handedness ▪ skewed to left ▪ dual channel (forested island)
	137	2,250	483	186.5	3.6	2.6	▪ right-handedness ▪ skewed to right ▪ single channel
	134	3,541	525	204.3	3.6	2.6	▪ left-handedness ▪ skewed to right ▪ single channel
	131	4,760	432	157.2	3.8	2.8	▪ left-handedness ▪ skewed to right ▪ single channel
	128	5,806	463	165.3	3.4	2.8	▪ right-handedness ▪ skewed to right ▪ single channel
	126	6,350	452	159.6	3.9	2.8	▪ right-handedness ▪ skewed to right ▪ single channel
	124	6,802	385	137.1	4.0	2.8	▪ left-handedness ▪ skewed to left ▪ single channel

	Cross-section ID	River Station (m)	Cross-sectional Area (m²)	Maximum Bankfull Width (m)	Maximum Bankfull Depth (m)	Average Bankfull Depth (m)	Description
2 – Clearwater River	122	7,396	414	153.3	4.5	2.7	▪ left-handedness ▪ skewed to left ▪ single channel
	119	8,440	313	120.6	4.1	2.6	▪ right-handedness ▪ skewed to right ▪ single channel
	116	9,210	428	167.8	3.8	2.6	▪ left-handedness ▪ central channel ▪ single channel
	114	10,095	370	112.1	4.2	3.3	▪ left-handedness ▪ skewed to left ▪ single channel
	112	11,033	405	141.7	3.8	2.9	▪ right-handedness ▪ central channel ▪ single channel
	110	11,985	431	152.7	3.6	2.8	▪ right-handedness ▪ skewed to right ▪ single channel
	107	13,179	421	156.4	3.4	2.7	▪ central thalweg ▪ central channel ▪ single channel
	105	14,127	448	185.7	2.9	2.4	▪ left-handedness ▪ skewed to left ▪ single channel
	102	15,826	325	101.2	5.4	3.2	▪ central thalweg ▪ central channel ▪ single channel
	100	16,560	369	132.2	4.2	2.8	▪ right-handedness ▪ skewed to right ▪ single channel
	98	17,460	459	163.8	7.0	2.8	▪ left-handedness ▪ skewed to right ▪ single channel

	Cross-section ID	River Station (m)	Cross-sectional Area (m^2)	Maximum Bankfull Width (m)	Maximum Bankfull Depth (m)	Average Bankfull Depth (m)	Description
2 – Clearwater River	96	18,262	414	160.5	3.9	2.6	▪ left-handedness ▪ skewed to right ▪ single channel
	95	18,685	399	145.6	4.0	2.7	▪ right-handedness ▪ skewed to left ▪ single channel
	94	19,182	447	174.6	4.0	2.6	▪ right-handedness ▪ skewed to right ▪ single channel
	93	19,705	342	143.3	2.9	2.4	▪ right-handedness ▪ skewed to left ▪ single channel
	91	20,359	289	101.9	4.0	2.8	▪ left-handedness ▪ skewed to left ▪ single channel
3 – Hangingstone River	226	92	58	56.5	2.2	1.0	▪ left-handedness ▪ skewed to right ▪ single channel
	223	227	41	30.1	2.2	1.4	▪ left-handedness ▪ skewed to right ▪ single channel
	221	372	41	30.9	2.0	1.3	▪ central thalweg ▪ skewed to right ▪ single channel
	218	549	34	24.8	1.9	1.4	▪ right-handedness ▪ skewed to right ▪ single channel
	215	882	48	56.6	2.4	0.8	▪ central thalweg ▪ skewed to right ▪ single channel
	212	1,088	34	27.2	2.0	1.3	▪ left-handedness ▪ skewed to right ▪ single channel

	Cross-section ID	River Station (m)	Cross-sectional Area (m^2)	Maximum Bankfull Width (m)	Maximum Bankfull Depth (m)	Average Bankfull Depth (m)	Description
3 – Hangingstone River	209	1,193	34	27.3	2.5	1.2	▪ left-handedness ▪ central channel ▪ single channel
	206	1,389	22	23.2	1.8	1.0	▪ central thalweg ▪ central channel ▪ single channel
	203	1,541	26	31.5	1.4	0.8	▪ central thalweg ▪ skewed to right ▪ single channel
	200	1,744	24	19.2	2.0	1.2	▪ right-handedness ▪ skewed to right ▪ single channel
	196	1,861	24	22.9	1.4	1.1	▪ left-handedness ▪ skewed to right ▪ single channel
	193	2,072	28	30.5	1.5	0.9	▪ right-handedness ▪ skewed to right ▪ single channel
	189	2,276	23	27.3	1.2	0.9	▪ central thalweg ▪ skewed to right ▪ single channel
	186	2,418	24	18.2	1.8	1.3	▪ central thalweg ▪ central channel ▪ single channel
	182	2,491	23	22.2	1.4	1.0	▪ central thalweg ▪ central channel ▪ single channel
	180	2,612	17	19.8	1.1	0.9	▪ right-handedness ▪ skewed to right ▪ single channel
	178	2,823	25	22.1	1.7	1.1	▪ right-handedness ▪ skewed to right ▪ single channel

	Cross-section ID	River Station (m)	Cross-sectional Area (m^2)	Maximum Bankfull Width (m)	Maximum Bankfull Depth (m)	Average Bankfull Depth (m)	Description
3 – Hangingstone River	176	3,031	29	23.5	1.8	1.2	▪ left-handedness ▪ skewed to left ▪ single channel
	173	3,298	22	25.7	1.3	0.8	▪ right-handedness ▪ skewed to left ▪ single channel
	170	3,667	20	21.3	1.8	0.9	▪ right-handedness ▪ skewed to right ▪ single channel
	168	3,803	22	18.5	1.8	1.2	▪ right-handedness ▪ skewed to right ▪ single channel
	166	3,971	20	25.8	1.1	0.8	▪ right-handedness ▪ slightly skewed to right ▪ single channel
	163	4,172	21	16.6	2.0	1.3	▪ left-handedness ▪ skewed to left ▪ single channel
	161	4,409	24	32.8	1.5	0.7	▪ right-handedness ▪ slightly skewed to right ▪ single channel
	158	4,525	24	25.2	1.9	1.0	▪ right-handedness ▪ skewed to right ▪ single channel
	156	4,694	23	30.5	1.0	0.8	▪ right-handedness ▪ central channel ▪ single channel
	154	4,874	25	25.1	1.5	1.0	▪ right-handedness ▪ skewed to right ▪ single channel
	150	5,162	18	30.5	1.4	0.6	▪ left-handedness ▪ slightly skewed to left ▪ single channel

	Cross-section ID	River Station (m)	Cross-sectional Area (m^2)	Maximum Bankfull Width (m)	Maximum Bankfull Depth (m)	Average Bankfull Depth (m)	Description
3 – Hangingstone River	147	5,507	24	24.9	1.4	1.0	▪ left-handedness ▪ skewed to left ▪ - single channel
4 – Snye River	145	172	308	119.5	3.6	2.6	▪ right-handedness ▪ skewed to left ▪ single channel
	144	456	346	147.2	3.1	2.4	▪ central thalweg ▪ skewed to left ▪ single channel
	143	932	245	117.4	3.4	2.1	▪ left-handedness ▪ skewed to left ▪ single channel
	142	1,332	219	125.8	2.4	1.7	▪ left-handedness ▪ skewed to left ▪ single channel

APPENDIX B

Historic Imagery Processing Memorandum

TECHNICAL MEMORANDUM

DATE April 23, 2018 **PROJECT No.** 1662603 / 9000

TO Abdullah Mamun
Alberta Environment and Parks (AEP)

CC Wolf Ploeger, Rowland Atkins

FROM Vanessa Vallis, Golder Associates Ltd. (Golder) **EMAIL** vanessa_vallis@golder.com

HISTORICAL AERIAL IMAGERY PROCESSING
FORT MCMURRAY RIVER HAZARD STUDY

1.0 INTRODUCTION

The Channel Stability Component of the Fort McMurray River Hazard Study required the use of historical aerial photography to support project analysis and mapping activities. Golder Associates Ltd. (Golder) worked with Tarin Resource Services Ltd. (Tarin) on the historical aerial imagery processing, with the aerial triangulation, stereo-model creation and orthorectification tasks outsourced to Tarin, while colour balancing, mosaic generation, tiling and review undertaken by Golder. This memorandum provides an overview of the processing methodology, the results of quality assurance checks, and description of historical aerial imagery deliverables.

2.0 METHODOLOGY

The 1950's aerial images selected for the Fort McMurray River Hazard Study were obtained from Alberta Environment and Parks (AEP) in July 2017 and processed according to the specifications as stated in AEP's Terms of Reference (TOR) and the guidelines published in 'General Specifications for Acquiring Aerial Photography (April 2015)'. The photos were chosen to ensure full coverage of the 'Fort McMurray LiDAR Acquisition Area', which was received by Golder on July 20, 2016.

The associated camera calibration reports were requested. However, specific lenses used for the 1950's surveys were unknown (see '1949-Calibration.pdf'). These calibration reports were associated with five lenses used during the same time period. Focal length was estimated as the average calibrated value for the five lenses, i.e., 152.7 mm (also the most frequently noted length) without knowing which lens was used. Image acquisition dates and film rolls used for this project are presented in Table 1.

Table 1: Film Roll Number and Historical Image Acquisition Dates

Photo Scale	Film Roll No.	Photo Year	Acquisition date
1: 40,000	AS0086	1950	07/08/1950
1: 40,000	AS0087	1950	07/08/1950
1: 40,000	AS0088	1950	08/01/1950

The raw images were reviewed for quality assurance and spatial coverage of the project area. Overall, there was some variability in the quality and consistency of the images provided by AEP. The images were provided in a high quality scanned .TIF format with photogrammetric stretches previously applied to most images. Although image artefacts and defects were noted, these were deemed to be acceptable due to the vintage of the project photography.

The aerial triangulation (AT) data processed by Tarin were created using Photomod (version 6 Lite x64) software in conjunction with May 2017 Fort McMurray aerial imagery, which was used to locate suitable photo identifiable GCP locations. The GCPs were identifiable in both modern and historical imagery and were typically located at roads intersections, trail connections and hydrologic feature intersections. In some areas, the absence of anthropogenic features meant that natural terrain features were necessary to use as used as ground control. The GCPs were adjusted to reduce the interior orientation residual values, but one GCP could not be improved because it was situated on the left side of a repaired tear in the image (image ‘5613_181’; film roll AS0087 frame 181). The GCP perimeter fully encompassed photos within the project study area boundary, but did not encompass all of the provided photos, because not all were needed to ensure coverage of the study area.

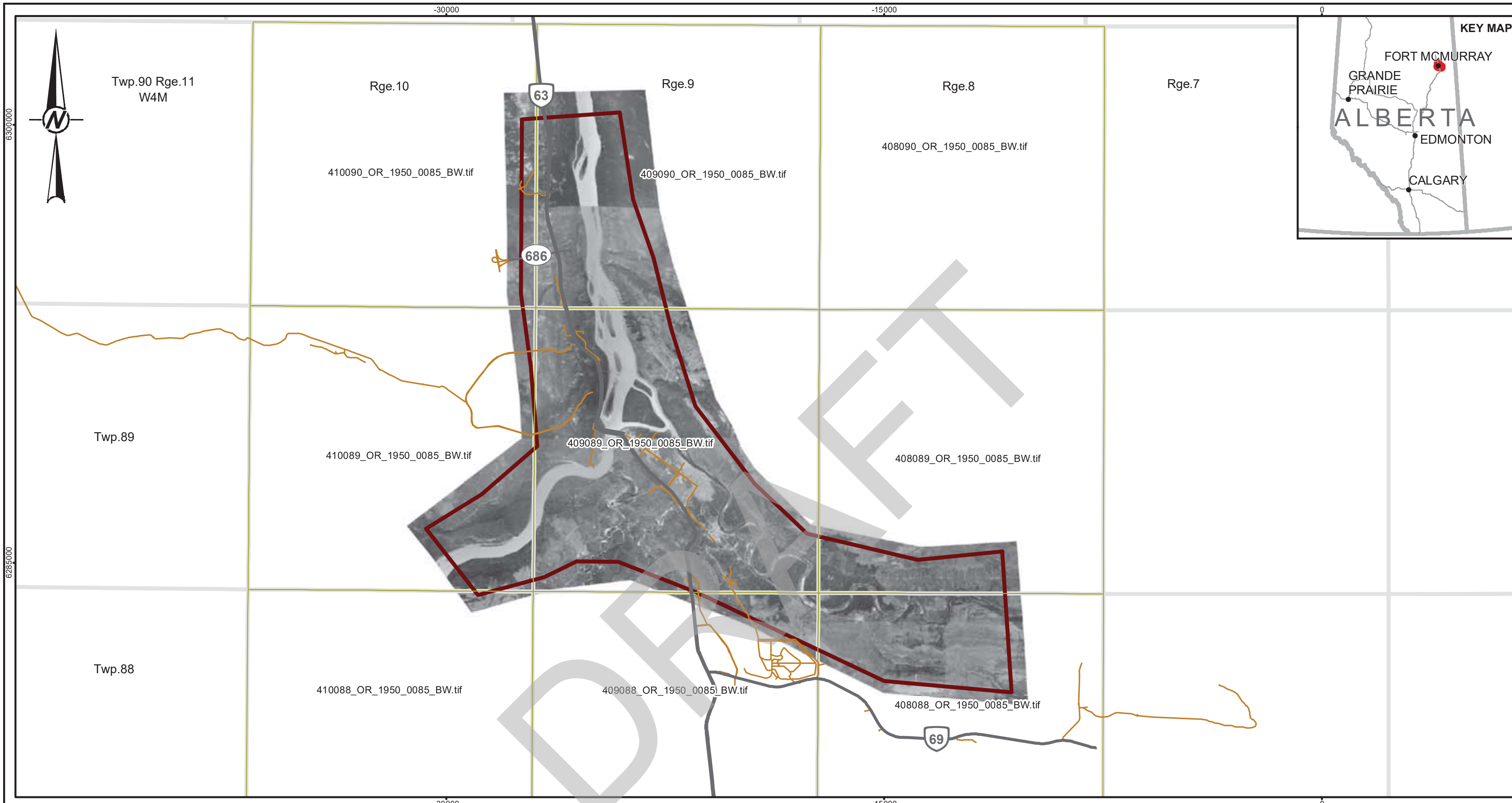
Several thousand automated tie points were generated to cover stereopairs in the bundle block, however, tie points on the left side of the torn image (image ‘5613_181’; film roll AS0087 frame 181) were excluded to improve accuracy. The AT process was completed in one block as the provided photos were acquired with similar specifications during the same season. The bundle adjustment accuracy was set to ‘high accuracy’ which runs up to ten iterations. The AT reports have a comment indicating that residuals flagged with a * symbol are unacceptable; however, this comment should be disregarded because the AT process used a survey grade benchmark of 0.01 metres. The RMSE values as shown in in the AT reports and in Table 2 are a better indicator of the accuracy of this data. The overall accuracy was estimated using the sigma naught value, which was 0.707. The elevation values calculated during the AT process are referenced to the CGVD28 datum. The historic photos and accompanying AT data were then used to create stereomodels using ApplicationMaster (v7.02.49920) within Trimble Inpho software.

Table 2: Summary of Aerial Triangulation Accuracy

	1950			
	X	Y	Z	Exy (m)
Mean GCP RMSE:	0.532	0.467	0.171	0.708
Tie Point RMSE (between stereopairs):	0.418	1.213	1.894	1.283
Tie Point RMSE (on images):	0.009	0.01	N/A	0.013
Sigma naught:	**0.707**			

The historical images were orthorectified using Photomod Software and the AltaLIS 1:20,000 scale digital elevation model (DEM). The resulting greyscale orthophoto chips have a resolution of 85 centimetres and the margins were cropped to remove approximately 20% to 35% of the image margin. The amount of margin cropped from each image was dependant on the amount of image overlap and presence of image artefacts/defects, which were cropped out when possible. Orthorectified chips were reviewed on screen at a scale of 1:10,000 in order to check the positional accuracy, then adjacent images were mosaiced together using ENVI v5.3 software. The 1950 orthomosaic was produced using automated colour balancing to match the colour of adjacent images based on the statistics of the overlapping regions. The historical orthomosaic was produced using a cubic convolution resampling method, an output resolution of 85 cm and a ‘no data value’ of 255. The completed orthomosaic was then split into one township tiles using FME Workbench (version 2017.0) and populated with metadata. An index map of the historical orthomosaic tiles is shown in Figure 1.

PATH: I:\2016\1662603\Mapping\MXD\ImageryProcessing\Historical_Imagery\1662603_1950_Ortho_Index_Rev0.mxd PRINTED ON: 2018-04-20 AT: 3:05:49 PM



LEGEND

- PRIMARY HIGHWAY
- SECONDARY HIGHWAY
- LOCAL ROAD
- ORTHOPHOTO TILE
- IMAGERY ACQUISITION AREA
- PROJECT LOCATION

0 2,500 5,000

1:200,000 METRES

REFERENCE(S)

1. TRANSPORTATION FEATURES OBTAINED FROM GEOGRATIS, © DEPARTMENT OF NATURAL RESOURCES CANADA. ALL RIGHTS RESERVED.
2. TOWNSHIP DATA OBTAINED FROM © GOVERNMENT OF ALBERTA 2015. ALL RIGHTS RESERVED.
3. 85 CM ORTHOPHOTOGRAPHY FLOWN BETWEEN JULY AND AUGUST 1950.
4. COORDINATE SYSTEM: 3TM 111 DATUM: NAD 83 CSRS

CLIENT

ALBERTA ENVIRONMENT AND PARKS

PROJECT

FORT MCMURRAY RIVER HAZARD STUDY

CONSULTANT

Golder Associates

YYYY-MM-DD	2018-04-20
DESIGNED	V. VALLIS
PREPARED	V. VALLIS
REVIEWED	W. PLOEGER
APPROVED	W. PLOEGER

TITLE

HISTORICAL ORTHOPHOTOGRAPHY INDEX MAP

PROJECT NO.	CONTROL	REV.	FIGURE
1662603	9000	0	1

IF THIS MEASUREMENT DOES NOT MATCH WHAT IS SHOWN, THE SHEET HAS BEEN MODIFIED FROM: ANSI A

25mm

0

Classification: Public

3.0 RESULTS

The 1950 tiled orthomosaic was reviewed on-screen at a scale of 1:10,000 with additional spot checks made at a scale of 1:5,000 using ArcGIS version 10.4. The positional accuracy of 1950's imagery was assessed by measuring the positional offset to the same feature as captured in May 2017 Fort McMurray aerial imagery. Continuous features such as roads, railways and streams were checked for continuity between adjacent images. An example is shown in Figure 1. During Golder's check of the orthomosaic, the RMSE was calculated to be 4.02 m (X) and 3.89 m (Y) when 38 check points were considered. All tiles were found to be accurate within 6 m at least 90% of the time, when displacement of both anthropogenic and natural features were measured. Positional errors greater than 6 m may exist in localized areas with steep or complex terrain due to the resolution of the historical DEM used for orthorectification.

The automated colour balancing used to produce the orthomosaic was not able to completely minimize the appearance of seams between adjacent flight lines. Automated colour balancing worked well between adjacent images from the same film roll, however, between different film rolls some differences in image tone remains. Overall, considering the age and variable quality of the provided images, the Fort McMurray historical orthomosaic was assessed to be very good.

Golder undertook a completeness and quality assurance check of the AT data provided by Tarin to ensure that all requested deliverables were received, and that the quality of the deliverables would meet the needs of the project and conform to AEP's general specifications. A visual check was conducted on all stereomodel files (within the project study area) using the Purview Extension for ArcGIS to ensure that the requested models yielded a satisfactory visual effect when viewed in 3D view software. It was not possible to check the stereomodels created in other software specific formats (DATEM, SOCET SET and ZI), but the plain text files were checked for completeness.

The number of aerial triangulation files delivered by Tarin were counted to confirm that they matched the number of processed photos with a few randomly selected files were opened and visually inspected. The spatial reference of the data was also checked to ensure that all data is projected in the local 3-degree Transverse Mercator (3TM) projection using the NAD83 Canadian Spatial Reference System (CSRS) datum. The attributes of the AT photo centres and orthomosaic tile index data were checked to ensure that they contained the correct information and that file naming schemas matched AEP's guidelines. Metadata files for each image were also checked for completeness in ArcCatalog® (v 10.4).

Figure 2: Example of an Orthomosaic Quality Assurance Check at the 1:5,000 Scale.
(The historical orthomosaic (greyscale; at top) is peeled back to reveal the modern landscape (colour image; at bottom). Modern roads from Canvec are overlaid for reference)

4.0 DELIVERABLES

The following files and deliverables are included with this memorandum:

- Tiled historical 1950 orthomosaic of the Athabasca River at Fort McMurray accompanied by metadata;
- Aerial triangulation image adjustment reports for historical images; and
- Aerial triangulation (external orientation) data in plain text format, DATEM, SOCET SET, and Purview compatible file formats.

One digital copies of the above deliverables are being provided on the accompanying USB drive.

5.0 CLOSURE

We trust that the enclosed data meets your present requirements. If you have any questions or require additional details, please contact Wolf Ploeger at (403) 216-8934.

Yours truly,

GOLDER ASSOCIATES LTD.

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ORIGINAL SIGNED

Vanessa Vallis, M.Sc. Remote Sensing / GIS Analyst

Reviewed by:

ORIGINAL SIGNED

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VV/WP/crm

As a global, employee-owned organisation with over 50 years of experience, Golder Associates is driven by our purpose to engineer earth's development while preserving earth's integrity. We deliver solutions that help our clients achieve their sustainable development goals by providing a wide range of independent consulting, design and construction services in our specialist areas of earth, environment and energy.

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