May 2018

FORT MCMURRAY RIVER HAZARD STUDY

Hydraulic Model Creation and Calibration Report

Submitted to:
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2013 Flood on the Hangingstone River (Courtesy of Regional Municipality of Wood Buffalo)

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REPORT

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 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 includes the river reaches listed in Table i.

Table i: River Reaches in the Study Area

River	Reach Description	Length
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
Clearwater River	20 km river reach upstream of the confluence with Athabasca River	20 km
Hangingstone River	From a location 3 km upstream of Memorial Drive (Highway 63) Bridges to the confluence with Clearwater River	5 km
The Snye	Full length from Snye Dike 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 hydraulic model creation and calibration component, which will support future flood mapping and flood risk assessment. The tasks associated with this component include pertinent flood history documentation, description of river and valley features, model setup, model calibration, sensitivity analysis and generation of open water flood frequency profiles.

All river reaches in the study area are integrated into one HEC-RAS model. The model was calibrated for:

- low flow conditions based on water levels and discharges measured in September 2016;
- high flow conditions based on high water marks and high water levels collected by AEP and RMWB during and after the June 2013 flood; and
- the flow-stage rating curves for the Water Survey of Canada (WSC) gauging stations in the study area.

The calibrated main channel Manning's *n* values for high flow conditions are listed in Table ii.

Table ii: Calibrated River Channel Roughness Values for High Flow Conditions

River	Calibrated Manning's *n* Value
Athabasca River	0.030
Clearwater River	0.030 – 0.032
Hangingstone River	0.038 – 0.040
The Snye	0.030

The calibrated model was used to simulate the open water surface profiles for the 2-, 5-, 10-, 20-, 35-, 50-, 75-, 100-, 200-, 350-, 500-, 750-, and 1,000-year flood events in the study area.

A model sensitivity was evaluated using the 100-year flood simulation results. The results of the sensitivity analysis show that variation of the river channel roughness values has a much higher influence on the simulated flood levels than variation of the floodplain roughness values. The variation is, on average, estimated to be within a range of ±0.34 m of the simulated values along the Athabasca River, ±0.30 m along the Clearwater River, ±0.29 m along the Hangingstone River, and ±0.28 m in the Snye.

Acknowledgements

This component of the Fort McMurray River Hazard Study was managed by Dr. Wolf Ploeger. Overall direction and senior review for this component was provided by Dr. Dejiang Long. The hydraulic modelling was performed by Gaven Tang, Hossein Kheirkhah and Wolf Ploeger.

The authors express their special thanks to Abdullah Mamun, Project Manager for Alberta Environment and Parks (AEP), who provided overall study management, background data, and technical guidance.

The authors also express their gratitude to Patricia Stevenson, Jim Choles, and Peter Onyshko of AEP for their support and for providing background information.

The authors express their thanks to Maureen Nakonechny, Project Manager in the Engineering Department of the Regional Municipality of Wood Buffalo, for providing available information.

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1.0 INTRODUCTION

1.1 Study Objectives

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).

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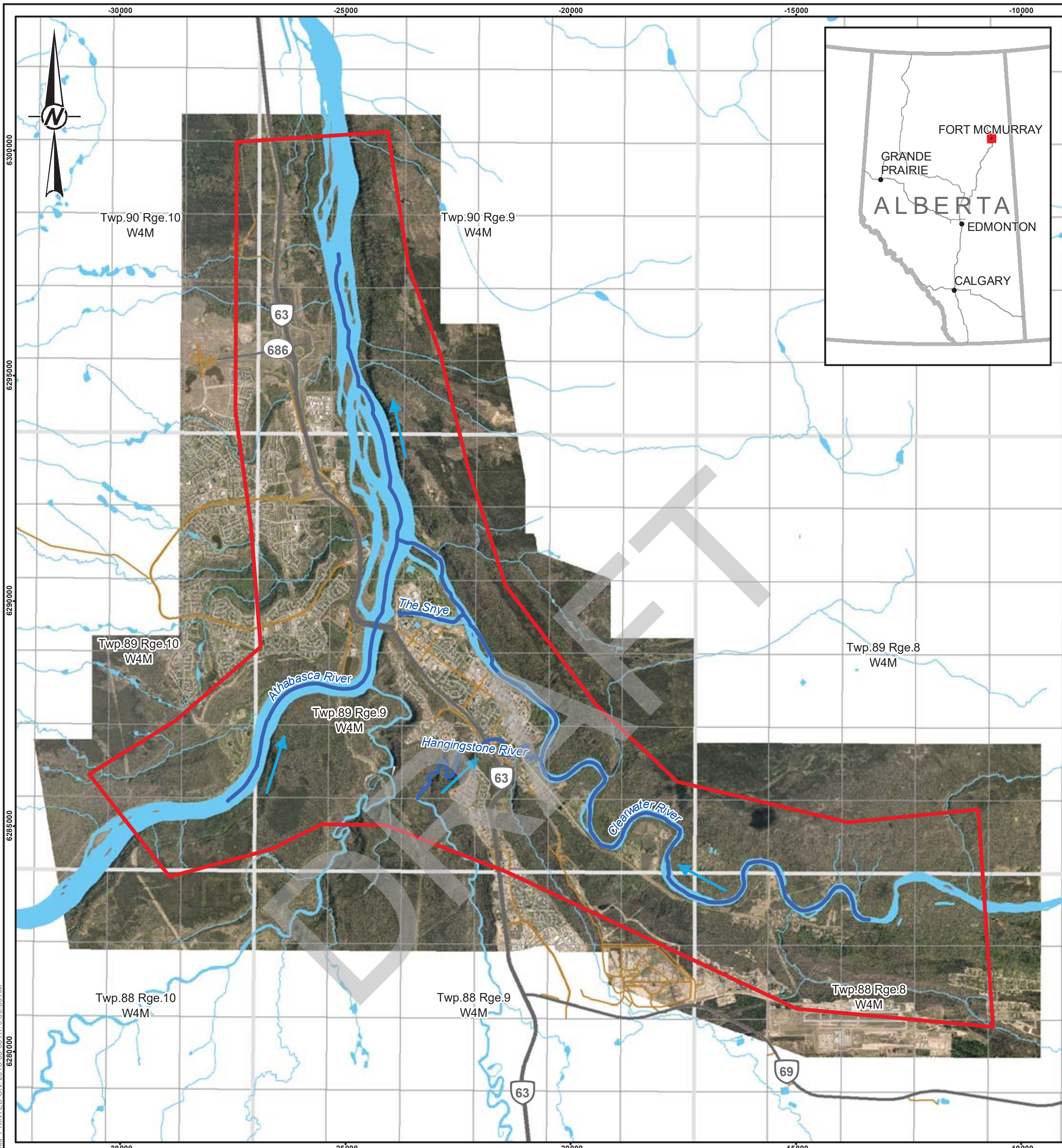
1.2 Study Reaches

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 reaches are summarized in Table 1.

Table 1: River Reaches in the Study Area

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



LEGEND

- STUDY REACH
- STUDY AREA
- FLOW DIRECTION
- WATERCOURSE
- WATERBODY

TRANSPORTATION FEATURES

- PRIMARY HIGHWAY
- SECONDARY HIGHWAY
- LOCAL ROAD

0 2 4
1:125,000 KILOMETRES

REFERENCE(S)

IMAGERY CAPTURED MAY 2017 BY GEODESY GROUP INC. FOR THE GOVERNMENT OF ALBERTA.
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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

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PREPARED	SK
REVIEWED	WP
APPROVED	DL

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1.3 Work Scope

The scope of the Hydraulic Model Creation and Calibration component of the study includes the following:

- Documentation of Flooding History;
- Summary of Available Data;
- Documentation of River and Valley Features;
- Model Setup;
- Model Calibration;
- Generation of Open-Water Flood Frequency Profiles; and
- Model Sensitivity Analysis.

2.0 FLOODING HISTORY

2.1 General Information

Fort McMurray is located at the confluence of the Athabasca and Clearwater Rivers, and has a history of ice jam flooding. In the spring, the ice cover on the Athabasca River can break up dynamically, and large ice runs are not uncommon. When an ice jam forms on the Athabasca River at or downstream of the Clearwater River confluence, it can cause significant flooding in downtown Fort McMurray. Additionally, the presence of a competent ice cover on the Athabasca River when the Clearwater River is undergoing breakup can also lead to ice jams and significant flooding.

Open water floods along the Athabasca River and Clearwater River typically result in lower water levels than ice jam floods. However, open water flood levels along the Hangingstone River can be higher than ice jam flood levels, especially in the reach upstream of Saline Creek Drive. The following sections describe the historic and recent floods in the study area.

2.2 Open Water Floods

2.2.1 Historic and Observed Floods

There is no record of severe historic open water flooding in the study area before systematic flood level recording.

2.2.2 Recent and Recorded Floods

The flood of June 2013 is the only recent and recorded open water flood within the study area with High Water Marks (HWMs) available for the Hangingstone River and associated water levels on the Clearwater River. The following description of this event was provided by TetraTech (2015) and is quoted below:

> *"A major open water flood occurred on the Hangingstone River in June 2013, resulting in damage in the lower reaches due to both channel erosion and high water conditions which overtopped the river bank in places (…) The flood event resulted in the evacuation of over 400 people, with flood damage to basements in the Graying Terrace area, Heritage Park and the Syncrude Centre for Sport and Wellness. Keyano College was flooded when river water flowed straight down the road after storm sewers filled to capacity, and there was also flood damage to the Home Hardware store."*

The 2013 flood on the Hangingstone River is the largest recorded open water flood in recent history. The flooding is shown in the photographs in Figures 2 to 5, which were provided by the RMWB.

2.3 Ice Jam Floods

Fort McMurray has a history of ice jam flooding. Historic records of ice jamming dated back to 1875 with several observed and recorded significant ice jam events since then. It is generally understood that ice jam flooding is the main source of flooding along the Athabasca and Clearwater Rivers and Fort McMurray's lower townsite and waterways communities. A detailed description of historic and recent ice jam flooding is provided in a separate report entitled "Fort McMurray River Hazard Study – Ice Jam Modelling Assessment and Flood Hazard Identification".

Figure 2: Aerial View of Inundation along the Lower Hangingstone during the 2013 Flood

Figure 3: Aerial View showing the Hangingstone Confluence and Saline Creek Drive during the 2013 Flood

Figure 4: Fort McMurray Heritage Village during the 2013 Flood

Figure 5: Fort McMurray Tarsands Lions Club during the 2013 Flood

3.0 AVAILABLE DOCUMENTS AND DATA

3.1 Hydrology Summary

The Athabasca River starts in the Rocky Mountains near Mount Columbia (elevation 3,747 m and flows northeast for 1,300 km before discharging through the Peace-Athabasca Delta and emptying into Lake Athabasca (elevation 208 m) (RAMP 2016a). The river drains an area of approximately 133,000 km² at the gauging station downstream of Fort McMurray (i.e., Athabasca River below McMurray, WSC Station No. 07DA001).

As a major river system, the Athabasca River is influenced by a variety of climate, terrain and landscape characteristics within its basin. The seasonality of climatic conditions is a major factor affecting river flow conditions. Cold winters, when most of the seasonal precipitation falls as snow, are typically followed by warm summers, when snow and glacial melt waters from the river's headwaters combine with runoff from localized snowmelt and rainfall events throughout the basin. As the river flows north toward Lake Athabasca, water is contributed to the river from individual sub-basins including the Clearwater River.

The Clearwater River at Draper (i.e., WSC Station No. 07CD001) drains an area of approximately 30,800 km². Broach Lake in northwestern Saskatchewan, at an elevation of 460 m, forms the headwaters of the Clearwater River. From its headwaters in Broach Lake, the river flows through Saskatchewan and Alberta and joins the Athabasca River at Fort McMurray. High flows often occur in spring as snowmelt combined with spring rainfall results in seasonal high (peak) flows. Floods have also been recorded in the summer months due to extreme rainfall events within the drainage area.

The Hangingstone River originates in a set of low hills, and flows northward into the Clearwater River in Fort McMurray, approximately 65 km from its origin. The river basin has a total drainage area of 1,105 km². Saline Creek is a major tributary which joins the Hangingstone River one kilometre downstream of the WSC gauge in Fort McMurray. The creek has a drainage area of approximately 137 km² above Tolen Drive near its mouth.

The Snye is considered a part of the Clearwater River with no significant local inflow.

The flood flow frequency estimates for the Athabasca River, Clearwater River and Hangingstone River are documented in a separate report entitled "Fort McMurray River Hazard Study - Open Water Hydrology Assessment Report" (Golder 2017). The flood flow frequency estimates at key locations in the study area are summarized in Table 2.

3.2 DTM Data

The detailed Digital Terrain Model (DTM) for the study area was provided by AEP. It was developed from a 2016 LiDAR survey and is available as gridded raster with 0.5 m resolution, ESRI Terrain and triangulated irregular network (TIN). The DTM was delivered in the local study coordinate system and datum (3TM 111°, NAD83 CSRS).

3.3 Survey Data

A detailed description of the survey data is provided in a separate report entitled "Fort McMurray River Hazard Study – Survey and Base Data Collection Report" (Golder 2018a).

Table 2: Summary of Flood Flow Frequency Estimates

Location	Flood Peak Discharges of Various Return Periods (m^3/s)												
	2-Year	5-Year	10-Year	20-Year	35-Year	50-Year	75-Year	100-Year	200-Year	350-Year	500-Year	750-Year	1,000-Year
Athabasca River above Clearwater River Confluence	2,030	2,800	3,360	3,950	4.460	4,790	5,190	5,480	6,230	6,870	7,310	7,820	8,200
Athabasca River below Clearwater River Confluence	2,290	3,110	3,710	4,330	4.860	5,210	5,620	5,920	6,680	7,340	7,780	8,300	8,680
Clearwater River at Draper (upstream of Hangingstone River Confluence)	366	513	609	699	770	814	864	900	983	1,050	1,090	1,140	1,170
Clearwater River below Hangingstone River Confluence	385	540	641	737	812	859	911	949	1,040	1,110	1,150	1,200	1,240
Hangingstone River above Saline Creek Confluence	35.8	63.5	87.4	116	143	162	187	206	260	312	349	397	434
Hangingstone River below Saline Creek Confluence	35.8	63.5	87.4	116	143	162	187	206	260	312	349	397	434

3.4 Existing Models

The existing hydraulic models for the study area were listed in Table 3.

Table 3: Existing Hydraulic Models for the Study Area

No.	Report	Program Used	Date	Author or Source
1	Fort McMurray Flood Protection Conceptual Design	HEC-RAS	2014	Northwest Hydraulic Consultants (NHC)

3.5 High Water Marks

The available high water mark reports and data for open water flooding are listed in Table 4. Additional data related to ice jam flooding is listed in the separate report entitled "Fort McMurray River Hazard Study – Ice Jam Modelling Assessment and Flood Hazard Identification" (Golder 2018b).

Table 4: Available High Water Mark Reports and Data

No.	Report	Flood Event	Author or Source
1	High Water Mark Report - Hangingstone River, Saline Creek and Morris Creek at Fort McMurray	2013	Alberta Environment and Sustainable Resource Development (ESRD)
2	Water Level Report – Clearwater River at Fort McMurray	2013	Alberta Environment and Sustainable Resource Development (ESRD)
3	Fort McMurray Flood Protection Conceptual Design	2014	Northwest Hydraulic Consultants (NHC)

3.6 Gauging Station Data and Rating Curves

The following active Water Survey of Canada (WSC) gauging stations are located within the study area:

- 07DA001 – Athabasca River below McMurray;
- 07CD001 – Clearwater River at Draper; and
- 07CD004 – Hangingstone River at Fort McMurray.

3.7 Flood Photography

Table 5 lists the available flood photography for open water flooding in the study area.

Table 5: Available Flood Photography for Open Water Flooding in the Study Area

No.	Report/Description	Flood Event	Author or Source
1	Hangingstone River Basin Study	2013	Tetra Tech EBA Inc.
2	Hangingstone River Flooding	2013	RMWB

4.0 RIVER AND VALLEY FEATURES

4.1 General Description

The Athabasca River, Clearwater River and Hangingstone River are the primary water courses in Fort McMurray. The Athabasca River starts in the Rocky Mountains and flows northeast for 1,300 km before discharging through the Peace-Athabasca Delta and emptying into Lake Athabasca. In the study area, the Athabasca River flows northward from a location approximately 6 km upstream of Highway 63 bridges to a location approximately 8 km downstream of the Clearwater River confluence.

The Clearwater River originates from Broach Lake in Saskatchewan and flows mostly in southwest direction for approximately 250 km before discharging into the Athabasca River in Fort McMurray. The upstream end of the Clearwater River study reach is located approximately 20 km upstream of the confluence with the Athabasca River in Fort McMurray or 3 km upstream of WSC Station No. 07CD001 (Clearwater River at Draper).

The Hangingstone River originates in a set of low hills south of Fort McMurray and flows northward into the Clearwater River in Fort McMurray, approximately 65 km from its origin. Saline Creek is a major tributary which joins the Hangingstone River at a location approximately one kilometre downstream of the WSC Station No. 07CD004 (Hangingstone River at Fort McMurray). The study reach starts from a location of approximately 3 km upstream of the Memorial Drive Bridges (Highway 63) to the confluence with the Clearwater River.

The Snye channel used to be an open connection between the Athabasca and Clearwater Rivers. The Snye cut-off dike was constructed in the mid 1960s along the Athabasca River bank in an effort to move the ice jam location further downstream for reducing the ice jam water levels backing into the Clearwater River (Blench 1964).

4.2 Channel and Floodplain Characteristics

4.2.1 Athabasca River

Channel Characteristics

The Athabasca River study reach upstream of the Clearwater River confluence is situated in a pre-glacial valley structure that was filled with glacial sediments during the glacial period and the re-excavated by the river during the post glacial period. Currently the valley has a top width of about 1,000 m and a wetted width of about 350 m upstream of the Highway 63 bridges, and a top width of about 500 to 700 m downstream of the bridges.

The channel pattern upstream of the Clearwater River confluence is straight to slightly sinuous inside clearly defined banks with an average slope of 0.0005 (0.05%). Upstream of the Highway 63 bridges the width to depth ratio is approximately 230. Downstream of the Highway 63 bridges the width to depth ratio increases to approximately 420. There is a rapids section near the water treatment plant upstream of the Horse River confluence.

Downstream of the Highway 63 bridges the Athabasca River joins the larger Clearwater River glacial valley with top width of approximately 2,500 m. The channel pattern changes noticeably from single-channel meandering to multi-channel with several islands and sand bars. The channel slope decreases to approximately 0.0003 (0.03%).

The Horse River is the only major tributary to the Athabasca River (other than the Clearwater River) within the study area. It discharges into the Athabasca River at a location of approximately 1 km upstream of the Highway 63 bridges.

Floodplain Characteristics

The floodplain along the Athabasca River upstream of the Highway 63 bridges is typically less than 100 m wide beyond both river banks. The banks are heavily vegetated or relatively steep in most areas. The floodplain is undeveloped except for the Fort McMurray Golf Club on the left bank (west) at the upstream end of the study area and the waste water treatment plant upstream of the Highway 63 bridges. The river is incised within the relatively steep valley walls.

Downstream of the Highway 63 bridges, the Athabasca River valley widens into the confluence with Clearwater River. However, the channel banks beyond the confluence are relatively high with limited floodplain area, indicating that the river channel remains incised within the river valley. On the right bank (east) downstream of the Highway 63 bridges the Snye dike separates the Athabasca River from the Snye. The valley wall is located along the right (east) bank of the Clearwater River resulting in relatively high banks bounding the east side of the confluence. There are distributary mouth islands of Clearwater River at the confluence with Athabasca River that have been modified by human development. Downstream of the confluence with Clearwater River the channel on the right side is confined by a relatively steep valley wall with limited floodplain area.

On the left (west) bank of Athabasca River upstream of the Highway 63 bridges, there is a small section of a 200 m wide floodplain area between the wastewater treatment plant and the Highway 63 bridges. Downstream of the Highway 63 bridges the channel is confined by the relatively high highway embankment with limited floodplain area.

A commercial development is situated on the floodplain of Athabasca River on the left (west) bank between the highway intersection (Confederation Way) for the communities of Timberlea and Eagle Ridge, located approximately 3 km downstream of the highway 63 bridges, and the new highway intersection (Parsons Access Road) located approximately 6.5 km downstream of the Highway 63 bridges. Accessed by Taiga Nova Crescent, the commercial development is partly protected from flooding by a berm. From the northern end of this development to the downstream end of the study reach, the floodplain on the left bank is approximately 1 km wide with dense vegetation in most areas.

4.2.2 Clearwater River

Channel Characteristics

The study reach of the Clearwater River is situated in a glacial outwash valley with a relatively uniform top width of about 1,500 m and steep valley walls. The width between the valley wall toes across the river is approximately 1,300 m. The Clearwater River is underfit within the valley. The river has a channel width of approximately 150 m and a prominent meandering planform that extends from valley wall to valley wall.

The river has a sinuosity ratio of approximately 1.6. The downstream migration of the meanders over the historical period is inferred from the observable meander scroll patterns on the valley floor. The channel has an average slope of 0.0002 (0.02%) with little variation within the study area. The river channel has a typical width to depth ratio of 100.

There are some localized medial and longitudinal sand bars within the channel and point-bars situated along the insides of the river bends. Both riverbanks upstream of Fort McMurray's Lower Townsite are densely vegetated. Along the Lower Townsite on the left bank (west) there are some old docks constructed with steel sheet piles.

Floodplain Characteristics

The Clearwater River floodplain is mostly located in the loops between the meander bends. Along the right (east) bank these floodplain areas are heavily vegetated and not accessible from the left side. The floodplains have typical widths of 700 m to 900 m. Upstream of the Lower Townsite the left (west) floodplain has been partially developed. The left bank (west) floodplain also occurs in the loops between meander bends.

The Lower Townsite and the Waterways community are situated partly within the left (west) floodplain of the Clearwater River and are prone to ice jam flooding. Flood control structures are currently being constructed in Fort McMurray along the Clearwater River to reduce the risk of ice jam flooding in these communities. Downstream of the confluence with the Snye, the floodplain of Clearwater River includes MacDonald Island which has been developed into a Golf Course and Recreation Centre.

4.2.3 Hangingstone River

Channel Characteristics

Upstream of Memorial Drive (Highway 63) the Hangingstone River is situated in a valley of approximately 80 m deep and 500 m wide. Hangingstone River has a typical channel width to depth ratio of approximately of 36 within the study area. Within the sinuous valley the channel is relatively straight and well defined. The channel is approximately 30 m wide and has a slope of 0.005 (0.5%). The channel bed materials consist of cobbles and gravel. The banks are heavily vegetated in most areas. In some areas, the channel banks are located at the toes of the valley walls with active or historical landslides.

Downstream of Memorial Drive the Hangingstone River enters the much larger Clearwater River valley, and the river channel slope decreases to 0.003 (0.3%). The river planform becomes meandering with a sinuosity ratio of 1.6. Along this lower Hangingstone River reach there are large bank protection areas and several bridges. The channel bed materials consist of gravels and cobbles.

Floodplain Characteristics

The floodplain upstream of Memorial Drive is mostly occupied by undisturbed, vegetated wetlands. The floodplain is limited by the relatively steep valley walls. The community of Grayling Terrace immediately upstream of Memorial Drive on the left floodplain is prone to flooding. The floodplain areas downstream of Memorial Drive are highly urbanized. Currently there are various levels of flood protection provided along this reach of Hangingstone River.

Some low-lying areas along the Hangingstone River are currently designated as parkland (Fort McMurray Lions Club at Tolen Drive). Between the Saline Creek Drive Bridge and the confluence with the Clearwater River, the floodplains immediately along the Hangingstone River are undeveloped. However, there is recent development on low lying areas of the Clearwater River and Hangingstone River floodplains along Fontaine Avenue.

The lower Hangingstone River is subject to backwater flooding from Clearwater River during ice jam events.

4.2.4 The Snye

Channel Characteristics

The Snye channel is the remainder of a channel connection between the Athabasca River and the Clearwater River before construction of the Snye dike (i.e., C. A. Knight Way). The Snye Dike now connects MacDonald Island with the Lower Townsite. There is a culvert underneath the Snye Dike that was installed to enable episodic flushing of the Snye when water levels in the Athabasca River are higher than those of the Clearwater River. However, the culvert outlet couldn't be located during a site reconnaissance.

The lack of flow or water exchange has likely contributed to sedimentation in the Snye. At the east end of the Snye water depth are shallow, and there is vegetation growth in the channel. There is a noticeable sand bar at the confluence with the Clearwater River due to sedimentation from the Clearwater River.

Floodplain Characteristics

The Snye floodplain is part of the larger Clearwater River floodplain which includes large areas of Fort McMurray's Lower Townsite. Along the south side of the Snye, flood control structures are currently being constructed to reduce the risk of flooding during ice jam events.

4.3 Large Tributaries

The Horse River enters the Athabasca River at a location approximately 1 km upstream of the Highway 63 Bridges opposite from the Fort McMurray waste water treatment plant. The Horse River has a catchment area of approximately 2,130 km^2 according to the discontinued WSC gauge 07CC001 (Horse River at Abasands Park).

Saline Creek enters the Hangingstone River at a location immediately upstream of the Saline Creek Drive Footbridge. The catchment area of Saline Creek was estimated to be approximately 117 km^2 based on a LiDAR DTM in Fort McMurray and USGS 20 m raster DEM outside the Town.

4.4 Bridges, Culverts and Weirs

There are three bridges along the Athabasca River study reach and eight bridges along the Hangingstone River study reach (see Table 6). There are no bridges along the Clearwater River study reach.

Table 6: List of Bridges within the Study Reach

No.	River	River Station (m)	Name	Description	Type
1	Athabasca River	10681	Grant MacEwan Bridge	Highway 63 (Off-ramp to Franklin Avenue)	7-Span
2	Athabasca River	10650	Steinhauer Bridge (Southbound)	Highway 63 (Memorial Drive)	7-Span
3	Athabasca River	10608	Athabasca River Bridge (Northbound)	Highway 63 (Memorial Drive)	7-Span
4	Hangingstone River	2,425	Highway 63 (Southbound)	Memorial Drive	3-Span
5	Hangingstone River	2,403	Highway 63 (Northbound)	Memorial Drive	3-Span
6	Hangingstone River	2,245	Tolen Drive Bridge	Tolen Drive	Clear-Span
7	Hangingstone River	2,188	Heritage Park Footbridge	Below Tolen Drive	Clear-Span
8	Hangingstone River	1,763	Prairie Loop Boulevard Bridge	Prairie Loop Boulevard	4-Span
9	Hangingstone River	1,373	Ptarmigan Court Footbridge	Below Prairie Loop Boulevard	Clear-Span
10	Hangingstone River	1,142	Saline Creek Drive Footbridge	Saline Creek Drive	Clear-Span
11	Hangingstone River	1,109	Saline Creek Drive Bridge	Saline Creek Drive	Clear-Span

The three Bridges over the Athabasca River have identical pier positions, very similar opening widths, and bridge deck elevations much higher than the peak ice jam flood levels. Therefore, these three bridges were modelled as one integrated bridge in the hydraulic model setup.

There is a culvert underneath the Snye Dike between the Athabasca River and the Snye. This culvert is only open for flushing the Snye. Therefore, the culvert was not included in the hydraulic model setup.

4.5 Flood Control Structures

There is one flood control structure along the right (south) bank of the Snye River. There are continuous flood control structures along the left bank of the Clearwater River that tie in with flood control structures on the Hangingstone River within the study area.

A summary of flood control structures within the study area is provided in Table 7. The locations of the flood control structures and summary datasheets for the various flood control structures are provided in a separate report entitled "Survey and Base Data Collection Report" (Golder 2018).

Table 7: Flood Control Structures within the Study Area

Waterbody	Description	Name / Identifier	Approximate Length (m)	Side of River[a]	Type
The Snye	Elevated pathway between MacDonald Drive and Borealis Park	Reach 1 (Snye Dyke)	635	Right	Pathway
Clearwater River	Prairie Loop Boulevard between McLeod Street and Riedel Street (Riverwalk Villas)	Reach 5 (Lower Townsite)	210	Left	Road
Clearwater River	Prairie Loop Boulevard between Riedel Street and Franklin Avenue	Reach 6 (Lower Townsite)	1945	Left	Road
Clearwater River	Prairie Loop Boulevard between Franklin Avenue and Saline Creek Drive intersection	Augment to Reach 7 (Lower Townsite)	465	Left	Road
Clearwater and Hangingstone Rivers	Saline Creek Drive between Saline Creek Drive Bridge and Park Street	Reach 10 (Waterways)	1450	Right (Hangingstone); Left (Clearwater)	Road
Clearwater and Hangingstone Rivers	Saline Creek Drive between Saline Creek turnaround and Prairie Loop Boulevard	Reach 10 (Waterways)	95	Left (Hangingstone); Left (Clearwater)	Road
Clearwater River	Saline Creek Drive between Park Street and junction with Draper Road	Reach 11 (Waterways)	1125	Left	Road
Saline Creek	Retaining structure – gabion basket	Reach 10 (Waterways)	210	Left	Retaining Structure

(a) Left or right refer to directions as seen by an observer looking downstream.

4.6 Other Features

There is a culvert through the Snye Dyke (i.e., MacDonald Drive culvert). This culvert has a gatewell chamber installed near its upstream (west) end to regulate the amount of flow that passes between the Athabasca River and the Snye. Flow in the Snye culvert can be in either direction depending on water levels within the Athabasca and Clearwater rivers. The MacDonald Drive culvert is operated and maintained by the RMWB. The gate is closed during flood conditions.

5.0 MODEL CONSTRUCTION

5.1 HEC-RAS Program

5.1.1 Description

The HEC-RAS program (Version 5.0.3) was used as the software platform for developing the one-dimensional (1D) hydraulic models in the study area. The HEC-RAS program was developed by the Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers (USACE). The River Analysis System (RAS) software has a graphical user interface, separate hydraulic analysis components, data storage and management capabilities, and graphics and reporting facilities. HEC-RAS is a commonly-used program in North America and around the world. (USACE 2016).

The HEC-RAS program was designed to perform one-dimensional hydraulic calculations for a full network of natural and constructed channels. HEC-RAS is capable of simulating steady and unsteady flow conditions. The program can be used to calculate water surface profiles for gradually varied flow. The program is capable of calculating the water surface profiles associated with subcritical, supercritical and mixed flow regimes. In this study, the program is used in steady-state mode.

The basic computational procedure for steady-state simulation is based on the solution of the one-dimensional energy equation. Energy losses are evaluated by friction (Manning's equation) and contraction/expansion. The momentum equation is utilized in situation where the water surface profile is rapidly varied. The program can be used to simulate the effects of various obstructions such as bridges, culverts, weirs, spillways and other structures in the floodplain.

The main assumptions in 1D modelling are listed below:

- The variation of the river channel and floodplain geometries is represented by a series of cross sections;
- The water level is constant at each cross section; and
- The flow is perpendicular to the cross section alignment.

The HEC-GeoRAS module (Version 10.2) is used to prepare cross section data based on the LiDAR DEM and river survey data (Golder 2018). HEC-GeoRAS is an ArcGIS extension tool specifically designed to create a HEC-RAS import file from geospatial data.

5.1.2 General Model Setup

Reaches

All reaches in the study area are included into one integrated model setup. The model consists of seven reaches as shown in Table 8.

Table 8: Reaches in the Hydraulic Model

River	Reach	Length (km)
Athabasca River	Upper Reach	8.9
Athabasca River	Lower Reach	8.7
Clearwater River	Upper Reach	13.7
Clearwater River	Middle Reach	4.1
Clearwater River	Lower Reach	2.5
Hangingstone River	Whole Reach	5.6
The Snye	Whole Reach	1.6

Cross Sections

The cross section alignment and extent were selected following the general approach listed below:

- The cross sections should be approximately perpendicular to the flow direction both in the main channel and the floodplains. This resulted in some cross sections bended using multiple vertices.
- The cross sections must not cross each other.
- The cross sections should have sufficient lengths on the floodplains to extend beyond the limits of all simulated open-water and ice jam floods.

A conceptual two-dimensional hydraulic analysis was performed for the lower reach of the Hangingstone River to understand the possible flood flow paths on the floodplains for extreme events when Hangingstone River flows would overtop its banks. This analysis was used to inform the selection of the cross section alignments on the floodplains in that area.

Boundary Conditions

The HEC-RAS model requires specification of boundary conditions at all open and internal boundaries. The open boundaries specified in the hydraulic models are listed below:

- Discharge at the upstream end of the Athabasca River study reach;
- Discharge at the upstream end of the Clearwater River study reach;
- Discharge at the upstream end of the Hangingstone River study reach;
- Discharge at the upstream end of the Snye study reach; and
- Normal flow condition at the downstream end of the Athabasca River study reach.

A schematic of the model setup is shown in Figure 6.

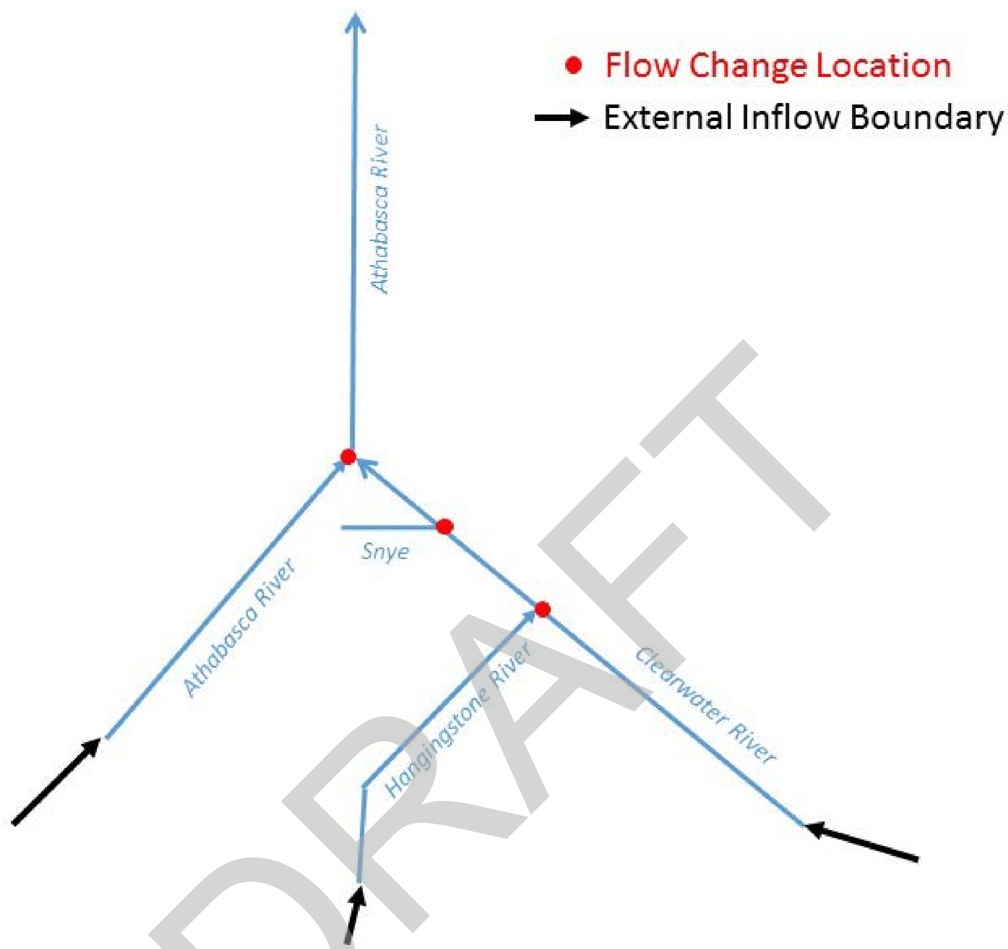


Figure 6: Flow Change Locations Used in the Model Setup

5.2 Geometric Data Base

5.2.1 Cross Section Data

Locations of the cross sections included in the model were selected based on the locations of surveyed cross sections and modelling requirements. The cross section data were extracted from the following sources:

- River survey data collected in 2016 (Golder 2018); and
- 2016 LiDAR data provided by AEP.

The alignments of the cross sections on the floodplains were selected based an examination of the topography and professional judgement. HEC-GeoRAS was used to define the main channels, overbank flow paths, bank stations, and cross section river stations.

Table 9 and 10 provide summaries of the river reaches and the number of cross sections in each reach.

Table 9: Number of Cross Sections in Model Reaches

River Name in HEC-RAS	Reach Name In HEC-RAS	Description of Reach	From River Station (m)	To River Station (m)	Length (m)	Number of Cross Sections
Athabasca	Upper Reach	Upstream study end to Clearwater River confluence	8,660	17,525	8,865	15
Athabasca	Lower Reach	Clearwater River confluence to downstream study end	0	8,660	8,660	11
Clearwater	Upper Reach	Upstream study reach to Hangingstone River confluence	6,669	20,369	13,700	30
Clearwater	Mid Reach	Hangingstone River confluence to Snye confluence	2,544	6,669	4,125	12
Clearwater	Lower Reach	Snye confluence to confluence with Athabasca River	0	2,544	2,544	5
Hangingstone	Hangingstone	Upstream study end to confluence with Clearwater River	0	5,604	5,604	81
Snye	Snye	Upstream study end to confluence with Clearwater River	0	1,569	1,569	4
					TOTAL	**158**

Table 10: Summary of Study Reaches

Study Reach	Reach Length (km)	Number of Cross Sections	Average Cross Section Spacing (m)
Athabasca River	17.5	26	670
Clearwater River	20.3	47	430
Hangingstone River	5.6	81	69
Snye	1.6	4	390

5.2.1.1 Roughness Distribution

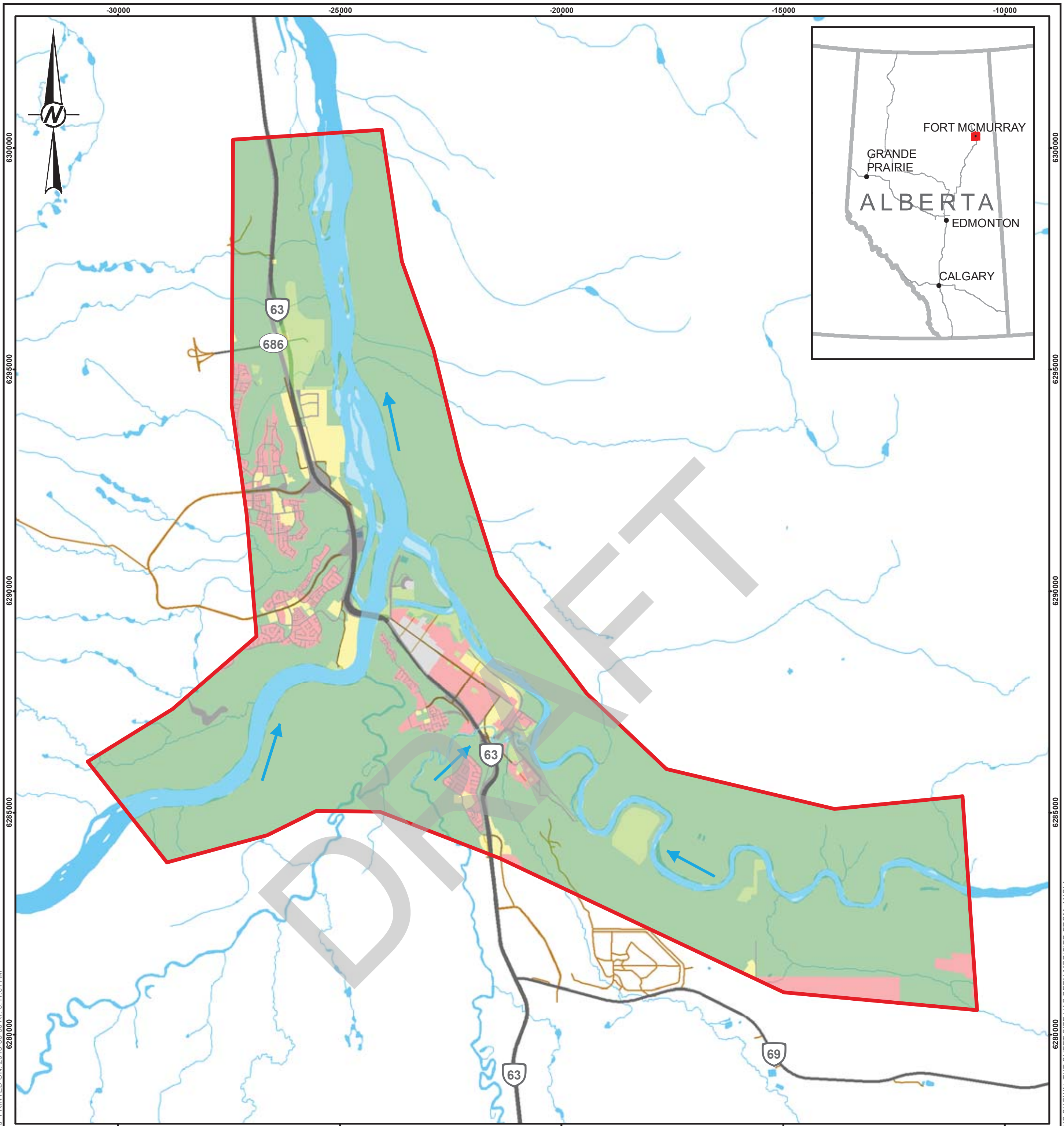
The left and right bank stations defining the main channel were determined using HEC-GeoRAS based on the 2016 LiDAR data, 2013 aerial imagery and survey data. Manning's *n* roughness values were specified using the distributed roughness approach, which allows for multiple, varying roughness values within each cross section. The initial roughness distribution was specified based on the following data:

- Bank lines established from the LiDAR data, aerial imagery and surveyed data to identify the main channels;
- Land use information provided by the RMWB; and
- Information collected during the site reconnaissance in October 2016.

These data sources were used to define seven roughness classes. The initial roughness values (Manning's *n*) assigned to the classes are provided in Table 11. These initial values were selected based on literature and professional judgement. The roughness values were applied to the cross sections using HEC-GeoRAS and modified at some locations during the model calibration process (see Section 5.6.3.2). The roughness distribution is shown in Figure 7.

Table 11: Roughness Classes and Initial Manning's *n* Values

Number	Description	Initial Manning's *n*
1	Rivers	0.030
2	Urban Mixture (Residential))	0.080
3	Urban Mixture (Industrial)	0.060
4	Urban Mixture (Downtown)	0.070
5	Streets	0.030
6	Grassland and Open Space	0.050
7	Dense Vegetation	0.150



LEGEND

- STUDY AREA
- FLOW DIRECTION
- WATERCOURSE
- WATERBODY

TRANSPORTATION FEATURES

- PRIMARY HIGHWAY
- SECONDARY HIGHWAY
- LOCAL ROAD

LAND USE CLASSES

- DENSE VEGETATION
- GRASSLAND AND OPEN SPACE
- RIVER
- STREET
- URBAN MIXTURE (DOWNTOWN)
- URBAN MIXTURE (INDUSTRIAL)
- URBAN MIXTURE (RESIDENTIAL)

0 2 4

1:125,000 KILOMETRES

REFERENCE(S)

ALBERTA DIGITAL BASE DATA OBTAINED FROM ALTALIS LTD. © GOVERNMENT OF ALBERTA 2014. ALL RIGHTS RESERVED, CANVEC, GEOGRATIS, IHS ENERGY INC. REGIONAL MUNICIPALITY OF WOOD BUFFALO.
PROJECTION: 3TM 111° DATUM: NAD 83 CSRS

CLIENT

Alberta Government

PROJECT

FORT MCMURRAY RIVER HAZARD STUDY

TITLE

ROUGHNESS CLASS DISTRIBUTION

CONSULTANT

Golder Associates

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

PROJECT NO.	CONTROL	REV.	FIGURE
1662603	3000	0	7

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25mm

Classification: Public

5.2.2 Bridges, Culverts, Weirs and Dams

Bridges

The bridge geometries used in the HEC-RAS model were defined based on the following data:

- River and bridge surveys completed in 2016 (Golder 2018); and
- As-built drawings provided by Alberta Transportation.

All existing bridges are represented in the HEC-RAS model. They include those which may not affect water levels during floods (e.g., clear span bridges with sufficient freeboards). Losses through bridges are calculated in the model using the energy equation (i.e., standard step method).

Bridges are modelled using upstream and downstream cross sections. Internal cross sections cut along the centerlines of the bridges are not used. This is because the lengths of upstream and downstream cross sections are different in some cases, which would result in levees and ineffective flow areas being misplaced along the bridge cross sections.

The cross sections that cover the lower Hangingstone River tend to have large lengths. To properly model overland flows that can bypass bridges, the multiple flow analysis is implemented. This allows the HEC-RAS model to calculate a distribution of flows that are conveyed through the bridge openings and bypassed around the bridges. Not using the multiple flow analysis would result in bypassed flows being treated as flows over a broad-crested weir.

There are variations of bridge types, abutments, approaches and embankments within the study area. For each bridge ineffective areas upstream and downstream of the bridges were carefully selected on a case-by-case basis including the selection of permanent and non-permanent ineffective areas where appropriate.

All bridges within the study area are approximately perpendicular to the main channel flow direction, so that it was not necessary to include any skew in the model.

The initial values of the contraction and expansion coefficients at the bridges were selected to be 0.3 and 0.5, respectively. These are typical values listed in the HEC-RAS user manual.

The total number of bridges included in the model is summarized in Table 12.

Table 12: Number of Hydraulic Structures Included in the Hydraulic Model

	Bridges	Culverts	Weirs and Dams	Other Features
Athabasca River	1[(a)]	None	None	None
Clearwater River	None	None	None	None
Hangingstone River	8	None	None	None
The Snye	None	None	None	None

(a) The three bridges on the Athabasca River are modelled as one bridge in the hydraulic model.

Culvert

There is no culvert included in the model setup.

Weir and Dam

There is no weir or dam included in the model setup.

5.2.3 Flood Control Structures

Flood control structures considered in this study were based on feedback from the stakeholders. Only structures that are regularly maintained by the stakeholders and designed to provide a certain level of protection were included in this study. This does not include private flood protection berms.

Flood control structures are represented in the HEC-RAS model using one (or a combination) of the two methods listed below:

- Levees; and
- Ineffective flow areas.

Method selection was based on professional judgement and suitability of use for the particular cross section. If one method was selected for a particular flood control structure, it was consistently used for the entire length of that flood control structure.

The total number of flood control structures included in the hydraulic model is provided in Table 13.

Table 13: Flood Control Structures within Study Area

Waterbody	Description	Name / Identifier	Approximate Length (m)	Side of River[(a)]	Type
The Snye	Elevated pathway between MacDonald Drive and Borealis Park	Reach 1 (Snye Dyke)	635	Right	Pathway
Clearwater River	Prairie Loop Boulevard between McLeod Street and Riedel Street (Riverwalk Villas)	Reach 5 (Lower Townsite)	210	Left	Road
Clearwater River	Prairie Loop Boulevard between Riedel Street and Franklin Avenue	Reach 6 (Lower Townsite)	1945	Left	Road
Clearwater River	Prairie Loop Boulevard between Franklin Avenue and Saline Creek Drive intersection	Augment to Reach 7 (Lower Townsite)	465	Left	Road
Clearwater and Hangingstone Rivers	Saline Creek Drive between Saline Creek Drive Bridge and Park Street	Reach 10 (Waterways)	1450	Right (Hangingstone); Left (Clearwater)	Road
Clearwater and Hangingstone Rivers	Saline Creek Drive between Saline Creek turnaround and Prairie Loop Boulevard	Reach 10 (Waterways)	95	Left (Hangingstone); Left (Clearwater)	Road

Table 13: Flood Control Structures within Study Area

Waterbody	Description	Name / Identifier	Approximate Length (m)	Side of River[a]	Type
Clearwater River	Saline Creek Drive between Park Street and junction with Draper Road	Reach 11 (Waterways)	1125	Left	Road
Saline Creek	Retaining structure – gabion basket	Reach 10 (Waterways)	210	Left	Retaining Structure

(a) Left or right refer to directions as seen by an observer looking downstream.

5.2.4 Other Features

There are no other hydraulically relevant features included in the model setup.

5.3 Model Calibration and Validation

5.3.1 Methodology

The Manning's roughness *n* value and the bridge contraction/expansion coefficients are the two primary model parameters used in calibrating the HEC-RAS model. Selection of initial Manning's *n* values included consideration of river bed/bank materials, vegetation cover, site information collected during the field inspection, and Golder's experience with previous hydraulic modelling studies of the Athabasca River.

Manning's *n* value may reduce with increased stage. However, in the case of sand bed rivers, higher flows may result in increased bed load transport and bed form sizes (e.g., dunes and ripples) that would increase the effective roughness. Model calibration was conducted based on the pertinent flow and water level information of the low flow and high flow conditions, and the WSC gauging station rating curves to determine appropriate roughness values across a wide range of flows, as described below:

- <u>Low Flow Calibration:</u> The surveyed water levels and measured flows during the river surveys were used for the low flow calibration.
- <u>High Flow Calibration:</u> Available high water marks on the Hangingstone River, high water level measurements on the Clearwater River and peak flow estimates for the 2013 flood event were used for high flow calibration. The 2013 flood was the only open-water flood event for which high water mark measurements were available to this study.
- <u>Rating Curve Calibration:</u> The flow-stage rating curves for the three WSC gauging stations within the study area were used in the model calibration to understand and quantify the potential variation of effective roughness at various water stages.

The model calibration process involved multiple iterations to adjust the model parameter values, conduct simulations, and compare the simulated water levels with the high water marks (for high flow calibration), surveyed water levels (for low flow calibration), and gauging station rating curve data. The objective of the model calibration was to achieve good matches between the simulated water levels and the high water marks, surveyed water levels and gauged water levels.

For the study area there was no additional surveyed high water mark for other open-water flood event. Therefore, no model validation based on other open water flood events was performed.

The results of the model calibration are described in the following sections.

5.3.2 Low Flow Calibration

5.3.2.1 Boundary Conditions

The water level and discharge measurements on the Athabasca River, Clearwater River and Hangingstone River were conducted on September 29 and 30, 2017. The measured flows used in the model calibration are listed in Table 14.

Table 14: Measured Discharges and Corresponding WSC Gauge Data

Waterbody	Date	WSC Gauging Station	Discharge (m^3/s)		Difference	
			WSC Gauge	Survey Measurement	(m^3/s)	(%)
Athabasca River	September 30, 2016	Athabasca River below McMurray (07DA001)	602	571	31	5
Clearwater River	September 30, 2016	Clearwater River at Draper (07CD001)	166	159	7	4
Hangingstone River	September 29, 2016	Hangingstone River at Fort McMurray (07CD004)	3.6	3.3	0.3	9

Notes:
1. Discharge on the Hangingstone River was measured using an ADV.
2. Discharge on the Athabasca and Clearwater Rivers was measured using an ADP.
3. Discharge values for the WSC gauge reading were based on real-time data posted online by AEP. Data obtained from AEP are provisional and preliminary in nature and may be subject to change when manually reviewed and corrected.

5.3.2.2 Athabasca River

The Athabasca River channel roughness values were calibrated based on the measured discharge and water level data collected during the low flow conditions on September 30, 2016. The surveyed river discharge on that day was 571 m^3/s downstream of the Clearwater River confluence, which is approximately 25% of the 2-year flood peak flow. The measured water level at the downstream study boundary was used as the downstream boundary condition.

Figure 8 shows a comparison between the simulated water surface profile and measured water levels for the low flow conditions. Table A.1 in Appendix A lists the differences between the simulated and measured water levels.

The average difference between the simulated and measured water levels is 0.00 m (excluding one outlier), with individual differences ranging from -0.18 m to +0.14 m (excluding one outlier) (see Figure 9).

The calibrated channel Manning's *n* value for the low flow conditions is 0.029, which is within the typical range of roughness for large sand and gravel bed rivers (Chow 1959).

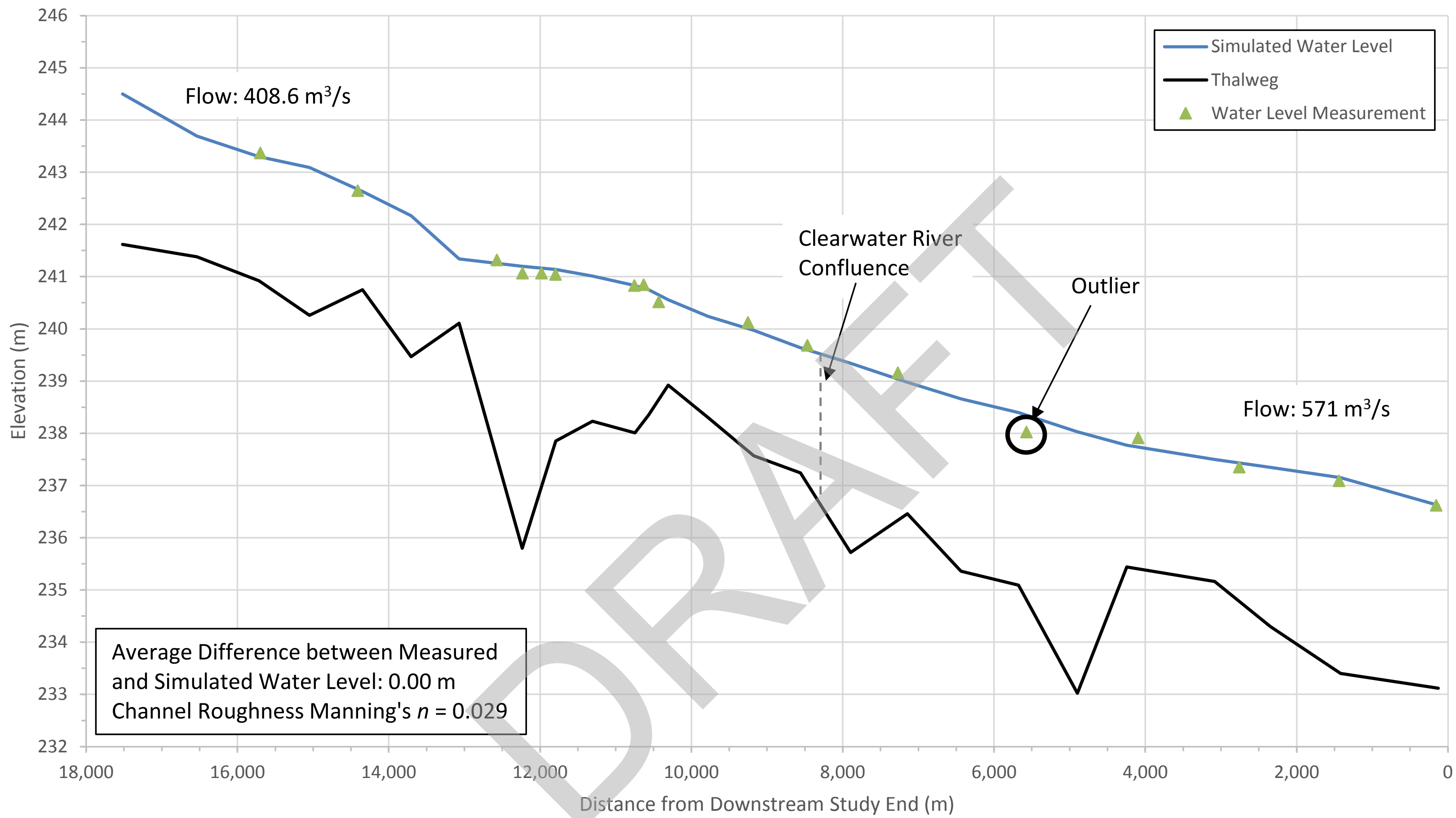


Figure 8: Comparison of Simulated Athabasca River Water Surface Profile with Surveyed Water Levels for Low Flow Conditions

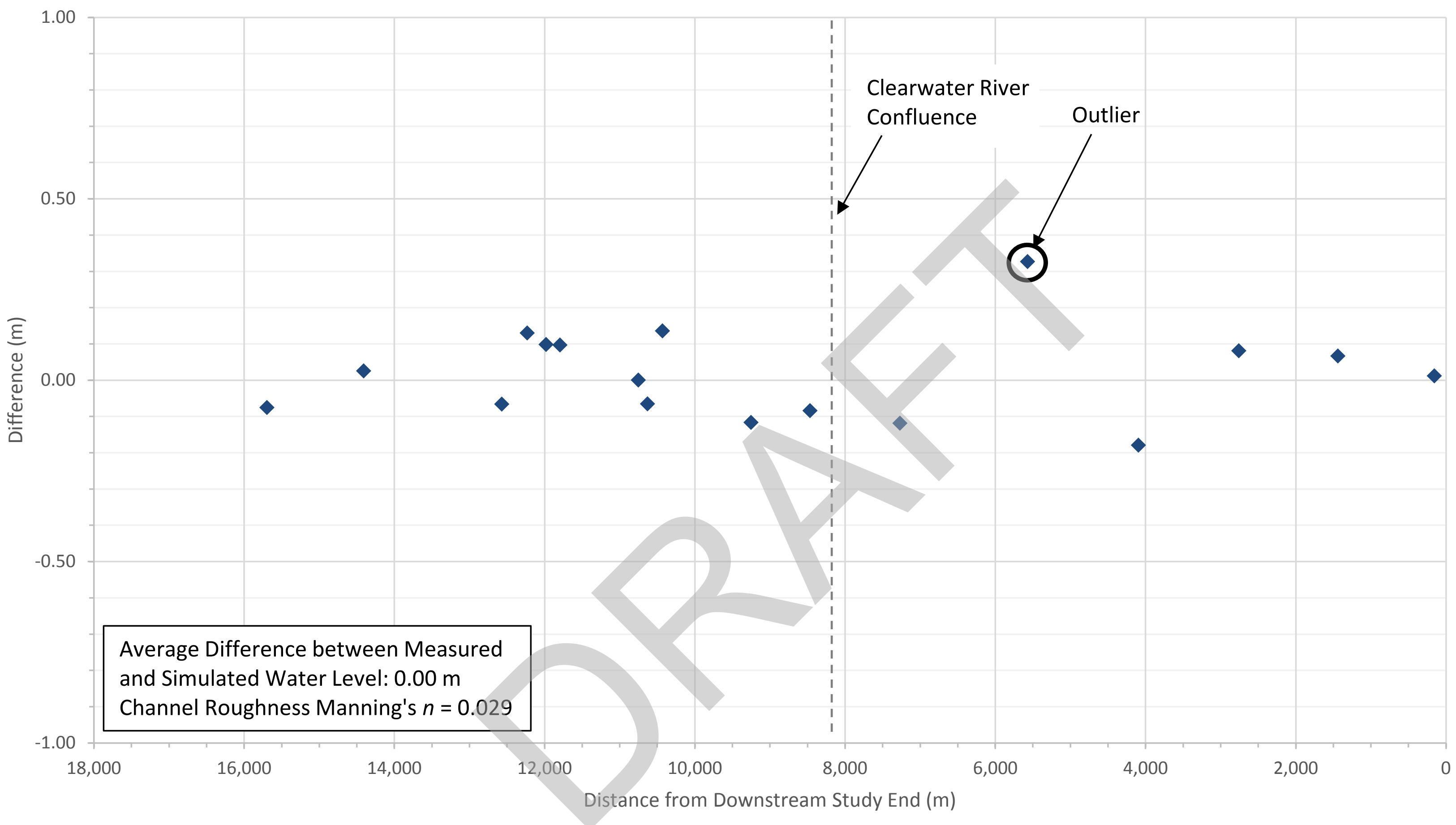


Figure 9: Difference of Simulated and Surveyed Athabasca River Water Levels for Low Flow Conditions

5.3.2.3 Clearwater River

The Clearwater River channel roughness values were calibrated based on the measured discharge and water level data collected during the low flow conditions on September 30, 2016. The surveyed river discharge on that day was 159 m^3/s in the upper reach (upstream of the Hangingstone River confluence), which is approximately 43% of the 2-year flood peak flow. The simulated water level in the Athabasca River at the confluence was used as the downstream boundary condition.

Figure 10 shows a comparison between the simulated water surface profile and measured water levels for the low flow conditions. Table A.2 in Appendix A lists the differences between the simulated and measured water levels.

The average difference between the simulated and measured water levels is 0.01 m, with individual differences ranging from -0.19 m to +0.10 m (see Figure 11).

The calibrated channel Manning's *n* value for low flow conditions is 0.027, which is within the typical range of roughness for large sand bed rivers (Chow 1959).

5.3.2.4 Hangingstone River

The Hangingstone River channel roughness values were calibrated based on the measured discharge and water level data collected during the low flow conditions on September 29, 2016. The surveyed river discharge on that day was 3.3 m^3/s, which is approximately 9% of the 2-year flood peak flow. The simulated water level in the Clearwater River at the confluence was used as the downstream boundary condition.

Figure 12 shows a comparison between the simulated water surface profile and measured water levels for the low flow conditions. Table A.3 in Appendix A lists the differences between the simulated and measured water levels.

The average difference between the simulated and measured water levels is as follows (see Figure 13):

- 0.00 m for the lower reach (below Memorial Drive Bridges) with individual differences ranging from -0.15 m to +0.14 m; and
- -0.04 m for the upper reach (upstream of Memorial Drive Bridges) with individual difference ranging from -0.22 m to +0.14 m.

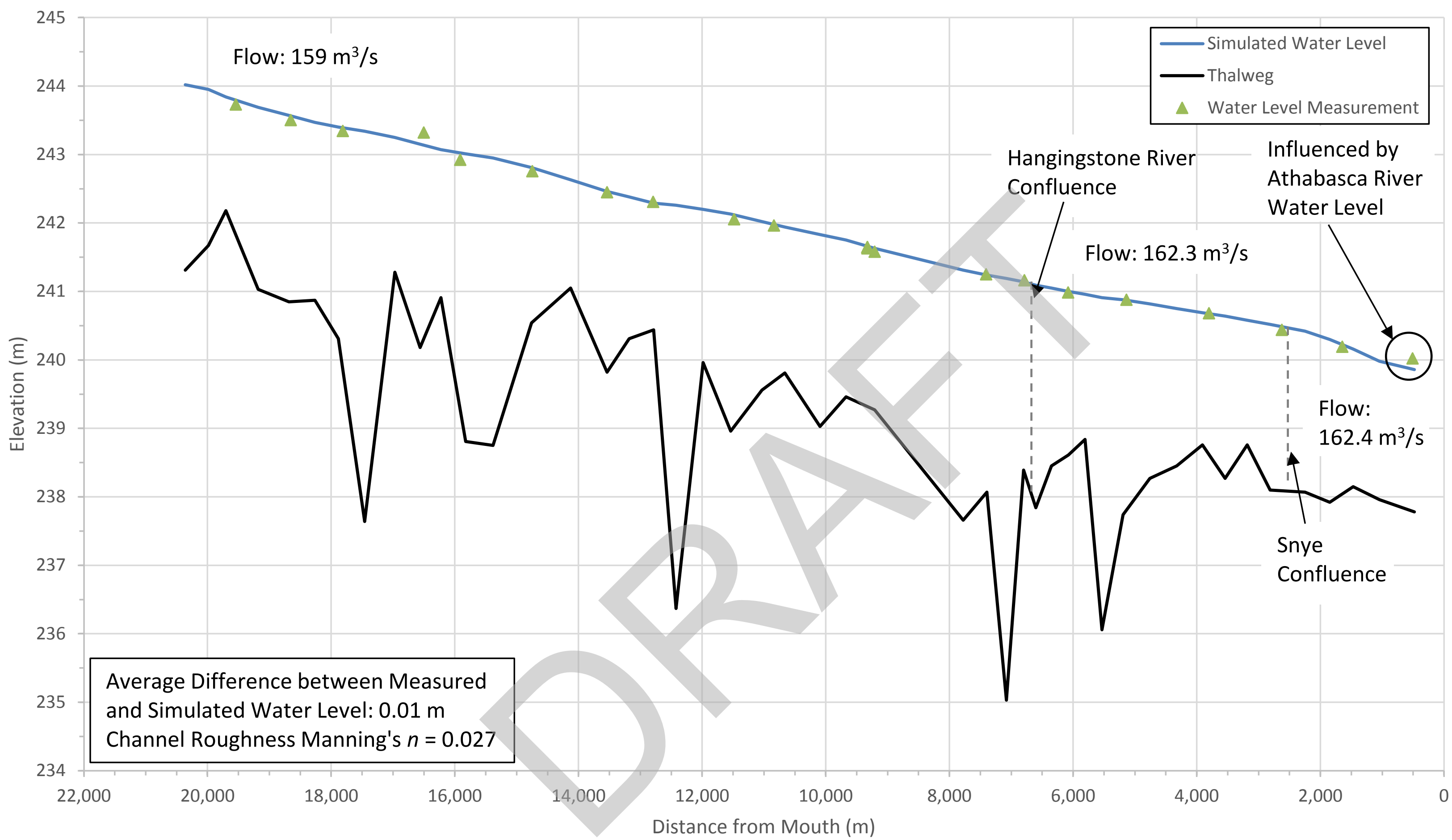


Figure 10: Comparison of Simulated Clearwater River Water Surface Profile with Surveyed Water Levels for Low Flow Conditions

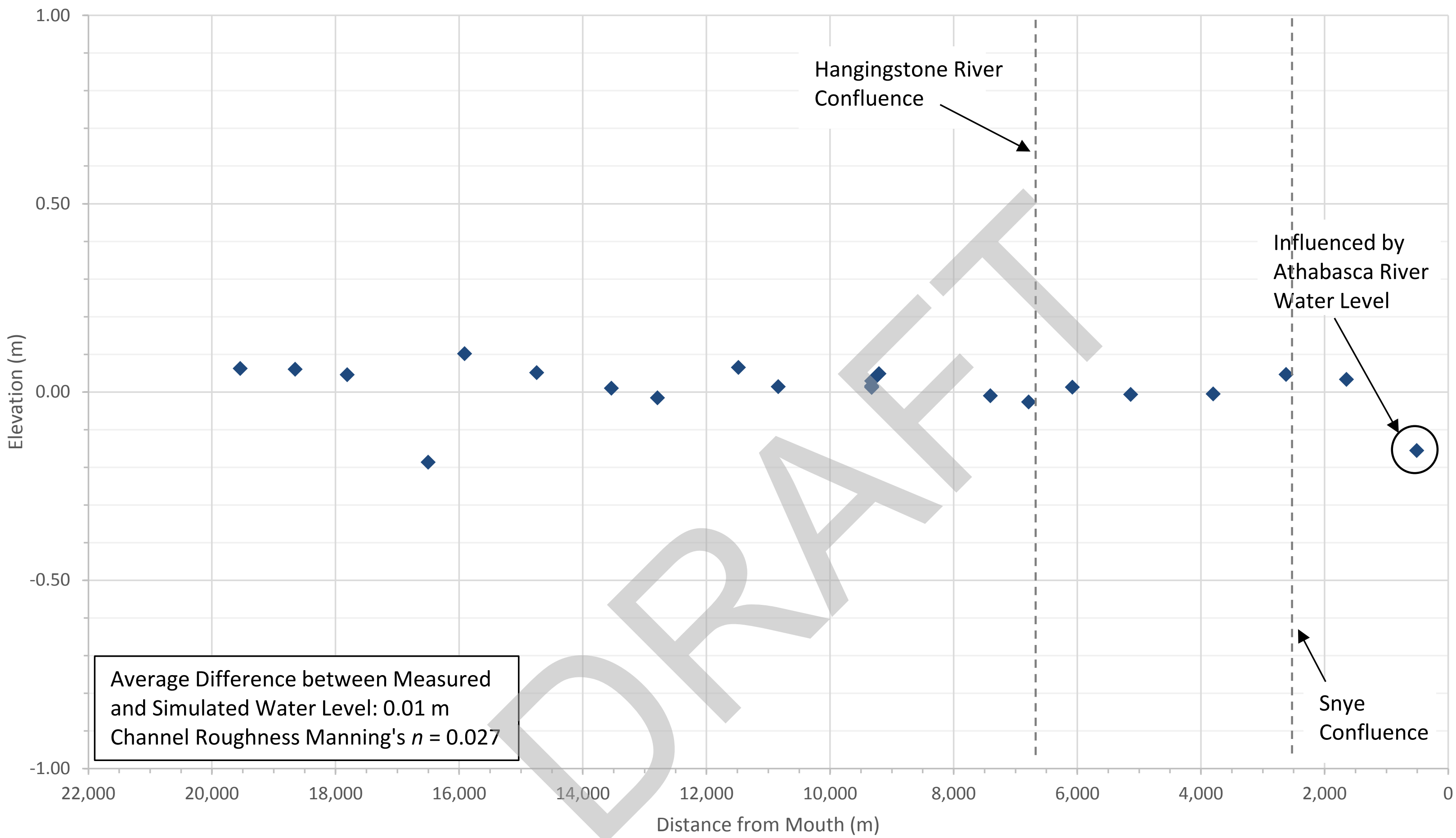


Figure 11: Difference of Simulated and Surveyed Clearwater River Water Levels for Low Flow Conditions

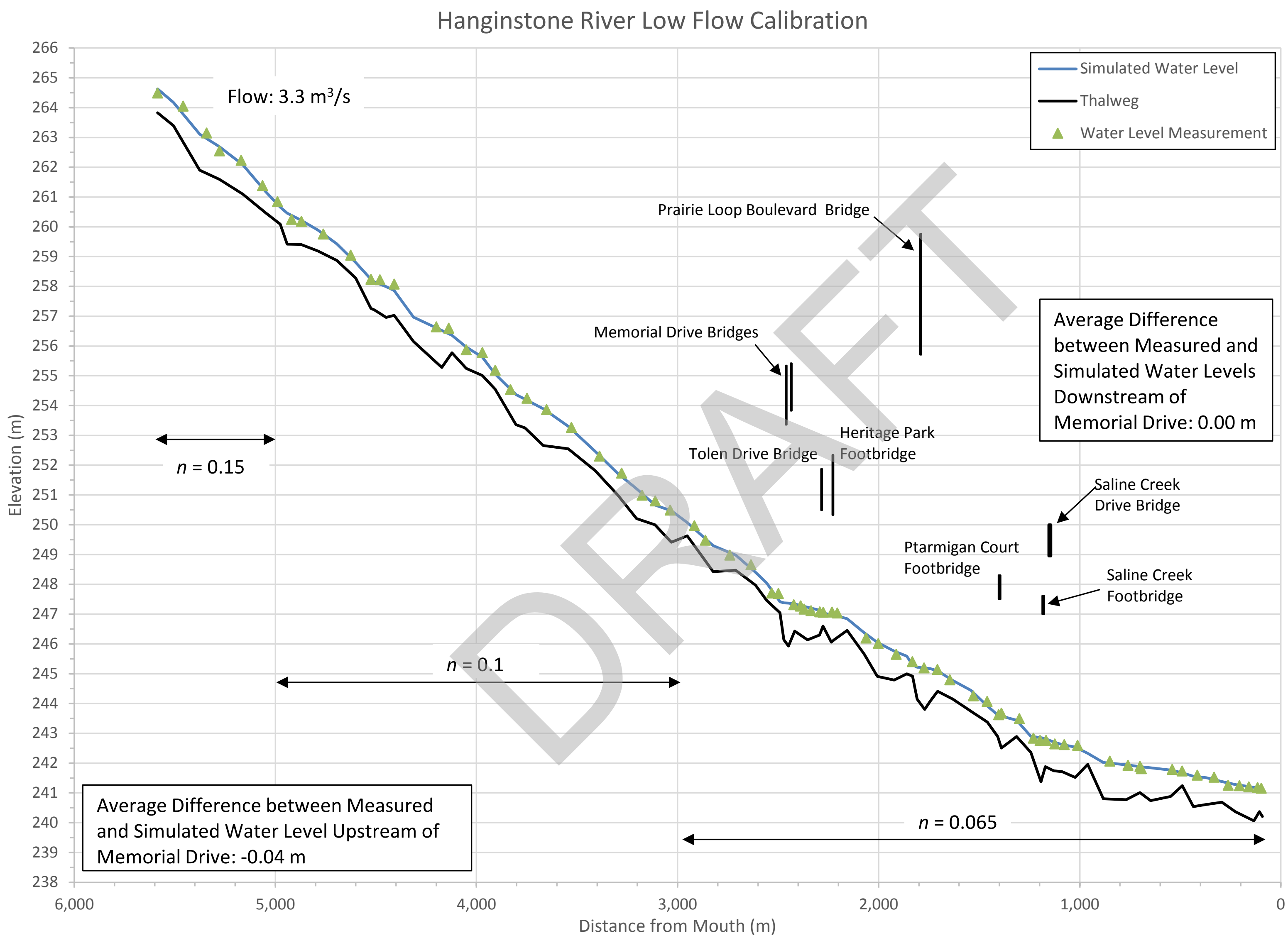


Figure 12: Comparison of Simulated Hangingstone River Water Surface Profile with Surveyed Water Levels for Low Flow Conditions

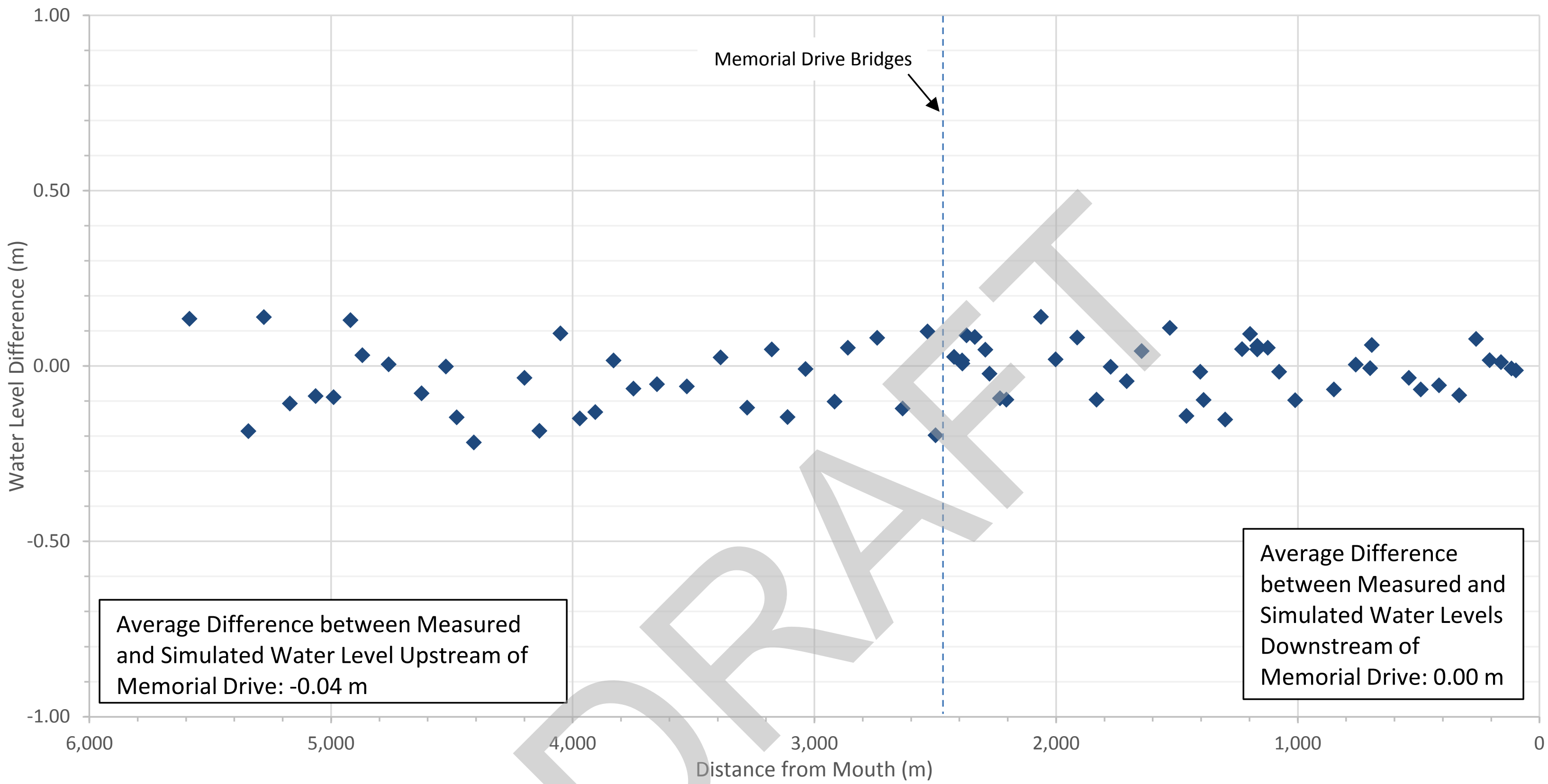


Figure 13: Difference of Simulated and Surveyed Hangingstone River Water Levels for Low Flow Conditions

The low flow calibration results show that the Hangingstone River channel Manning's *n* values for low flow conditions varies along the study reach. The lower river reach (downstream of Memorial Drive bridges) generally has milder bed slopes and larger water depths than the upstream river reach. The river reach upstream of the Memorial Drive bridges has more pronounced riffle and pool sequences than the downstream river reach. The calibrated river channel Manning's *n* roughness values for low flow conditions are listed in Table 15.

Table 15: Calibrated Manning's n Values for Low Flow Conditions on the Hangingstone River

No	From Station (m)	To Station (m)	Main Channel Manning's *n*	Note
1	5,585	5,048	0.150	Most upstream reach with high channel variability
2	4,975	2,952	0.100	Upstream of Grayling Terrace
3	2,822	92	0.065	Downstream of Grayling Terrace

The calibrated Manning's *n* values for the lower reach are within the typical range of roughness for small and steep gravel bed rivers (Chow 1959). The relatively high roughness upstream of Grayling Terrace is likely caused by additional roughness due to local effects such as pool and riffle sequences, sharp meander bends or other local features that affect the hydraulic conditions during low flows.

5.3.2.5 The Snye

The main channel roughness value in the Snye was not calibrated. The Manning's n value of 0.027 was assumed based on the calibrated value for the Clearwater River. The Snye is considered a standing water body with its water levels affected by the water levels in the Clearwater River at the Snye confluence.

5.3.3 High Flow Calibration

5.3.3.1 Athabasca River

There are no open water high water marks available along the Athabasca River study reach. The Manning's *n* values for high flow conditions were calibrated based on the flow-stage rating curve for the WSC gauging station 07DA001 (Athabasca River below McMurray) (see Section 5.3.4).

5.3.3.2 Clearwater River

There are no open water flood high water mark available along the Clearwater River study reach. The HEC-RAS model for the Clearwater River is calibrated based on the revised 2013 water level report (AEP 2017) and supplementary water levels for the 2013 high flow event provided by the RMWB (NHC 2014).

There was limited overland flooding along the Clearwater River during the 2013 high flow event. Therefore, the overland roughness values have little effect on the simulated water levels for that event and no adjustment was made to the initial roughness estimates for the floodplain areas. The model calibration was achieved by adjusting the main channel Manning's *n* values so that the simulated water levels were in good match with the 2013 high water levels.

The Clearwater River model calibration is based on the discharge on the day of the water level measurements (June 13, 2013) as listed in Table 16. The downstream end of the Clearwater River is coupled to the Athabasca River. A normal depth boundary with a slope of 0.0035 is applied at the downstream end of the Athabasca River model reach.

Table 16: River Discharges on June 13, 2013 used for the Clearwater River Model Calibration

River Reach	Flood Peak Discharge (m^3/s)
Athabasca River below Clearwater Confluence	2,790
Clearwater River upstream of Hangingstone River Confluence	666
Hangingstone River	97

Figure 14 shows a comparison between the simulated water surface profile and reported water levels for the 2013 high flow event.

Table A.4 in Appendix A lists the differences between the simulated and reported water levels. The average difference between the simulated and reported water levels is 0.17 m, with individual differences ranging from 0.00 m to +0.40 m (see Figure 15).

Based on the reported water levels for the 2013 event, the Manning's *n* value for the lower Clearwater River channel would be slightly lower than 0.03. However, slightly more conservative Manning's *n* values of 0.030 to 0.032 were selected for high flow conditions along the Clearwater River reach, based on the results of the rating curve calibration (see Section 5.3.4). The selected Manning's *n* values are within the typical range of roughness values for sand bed rivers during high flow conditions (Chow 1959).

5.3.3.3 Hangingstone River

The Hangingstone River in Fort McMurray experienced a large flood event in June 2013 with an estimated return period of approximately 100 years. The HEC-RAS model for the Hangingstone River was calibrated based on the revised 2013 water level report (AEP 2017) and supplementary water levels for the 2013 high flow event provided by the RMWB (NHC 2014).

Even though there was local overland flooding and locally severe bank erosion during the 2013 flood, the flooded overland area was relatively small, and the available information was not sufficient to calibrate the overland Manning's *n* values. The overland Manning's *n* values were estimated to have little effects on the simulated water level for that event. Therefore, no adjustment was made to the initial estimates of Manning's *n* values for the floodplain areas. The model calibration was achieved by adjusting the river channel Manning's *n* values so that the simulated water levels were in good match with the reported 2013 high water levels.

The Hangingstone River model calibration was based on the estimated flood peak discharge on June 11, 2013 (see Table 17). The downstream end of the Hangingstone River is connected to the Clearwater River which is connected to the Athabasca River. A normal depth boundary with a slope of 0.0035 is applied at the downstream end of the Athabasca River model reach.

Table 17: River Discharges on June 11, 2013 used for the Hangingstone River Model Calibration

River Reach	Flood Peak Discharge (m^3/s)
Athabasca River below Clearwater Confluence	2,680
Clearwater River upstream of Hangingstone River Confluence	569
Hangingstone River	200

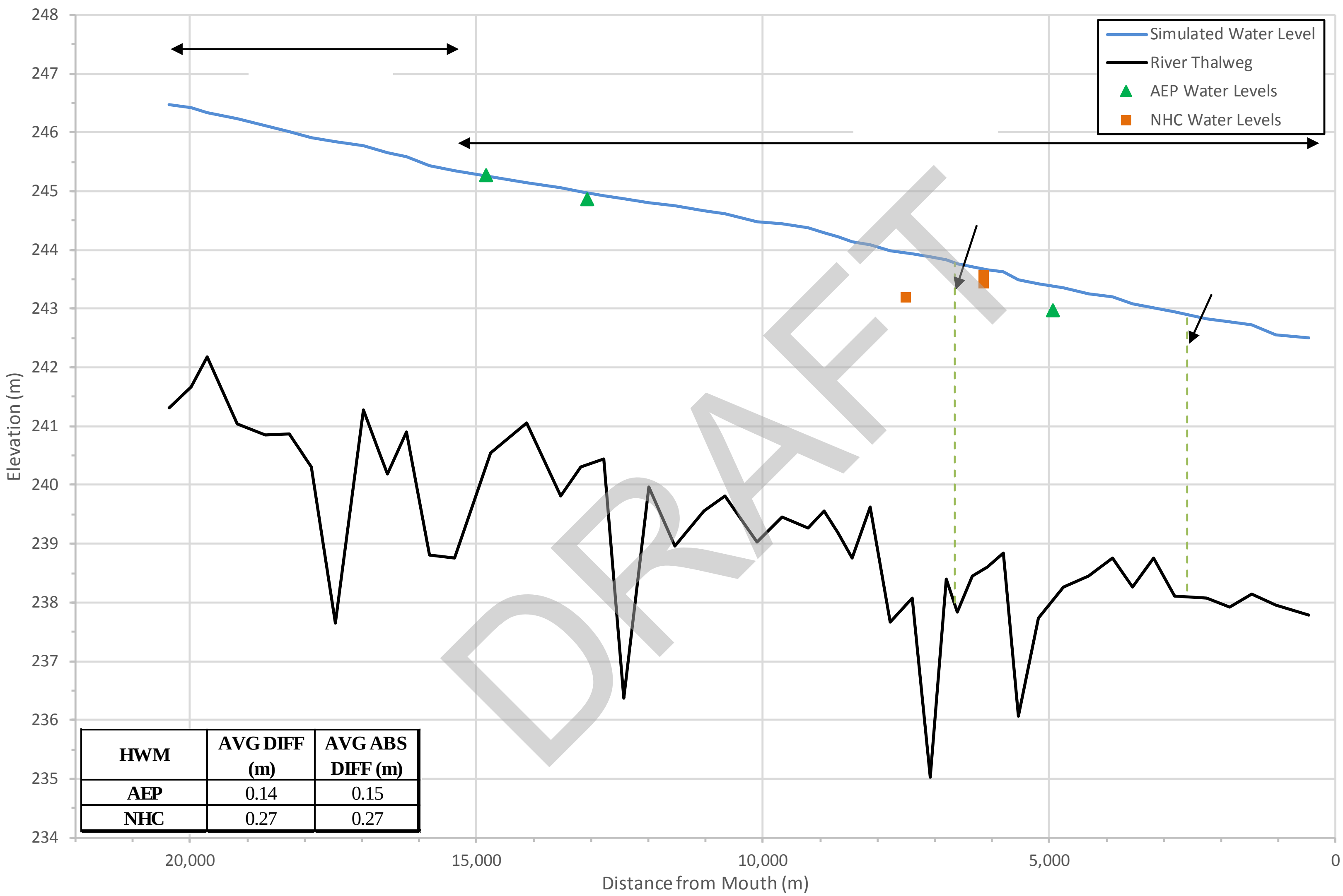
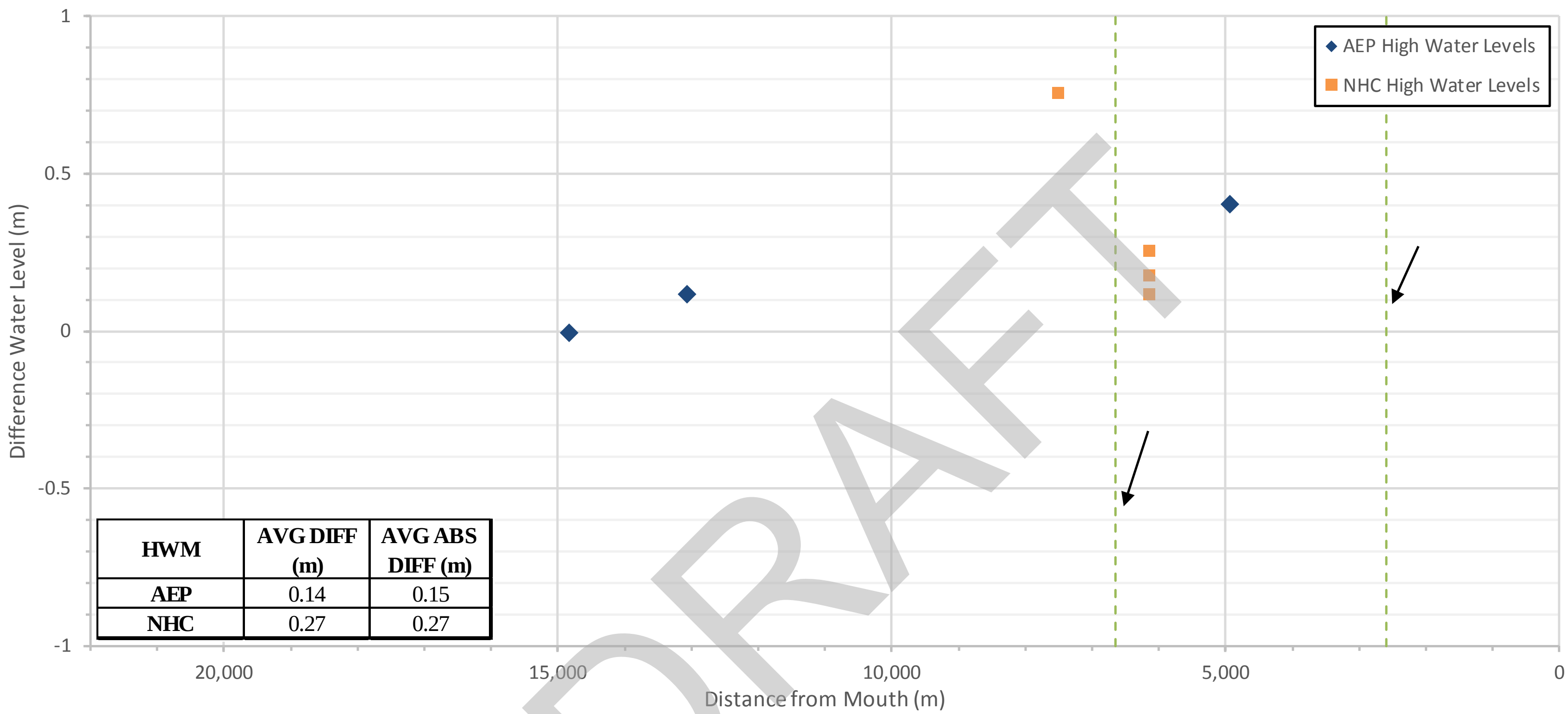


Figure 14: Comparison of Simulated Clearwater River Water Surface Profile and Reported Water Levels for the 2013 High Flow Event



HWM	AVG DIFF (m)	AVG ABS DIFF (m)
AEP	0.14	0.15
NHC	0.27	0.27

Figure 15: Difference of Simulated Clearwater River Water Levels and Reported Water Levels for the 2013 High Flow Event

Figure 16 shows a comparison between the simulated water surface profile and reported high water levels for the 2013 flood event.

Table A.5 in Appendix A lists the differences between the simulated and reported high water levels. The average difference between the simulated and AEP high water levels is 0.02 m, with individual differences ranging from -0.42 m to +0.20 m. The average difference between the simulated and NHC high water levels is 0.07 m, with individual differences ranging from -0.60 m to + 0.42 m (see Figure 17).

5.3.3.4 The Snye

There was no data for calibrating the Snye main channel Manning's *n* value.

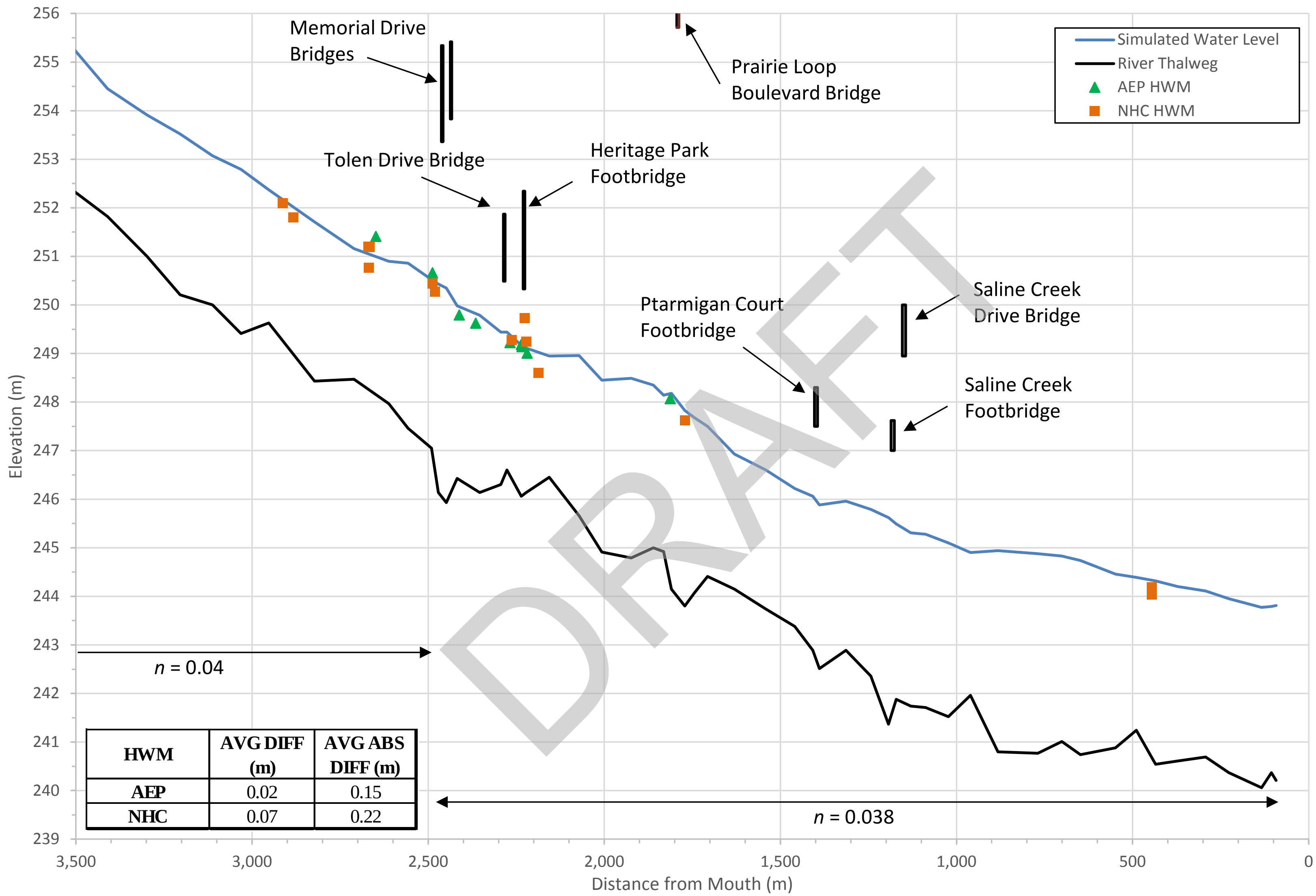
5.3.4 Gauge Data and Rating Curves

The data available at the following WSC gauging stations were used to support the high flow model calibration and to quantify the variability of the main channel roughness over a range of flows:

- 07DA001 – Athabasca River below McMurray;
- 07CD001 – Clearwater River at Draper; and
- 07CD004 – Hangingstone River at Fort McMurray.

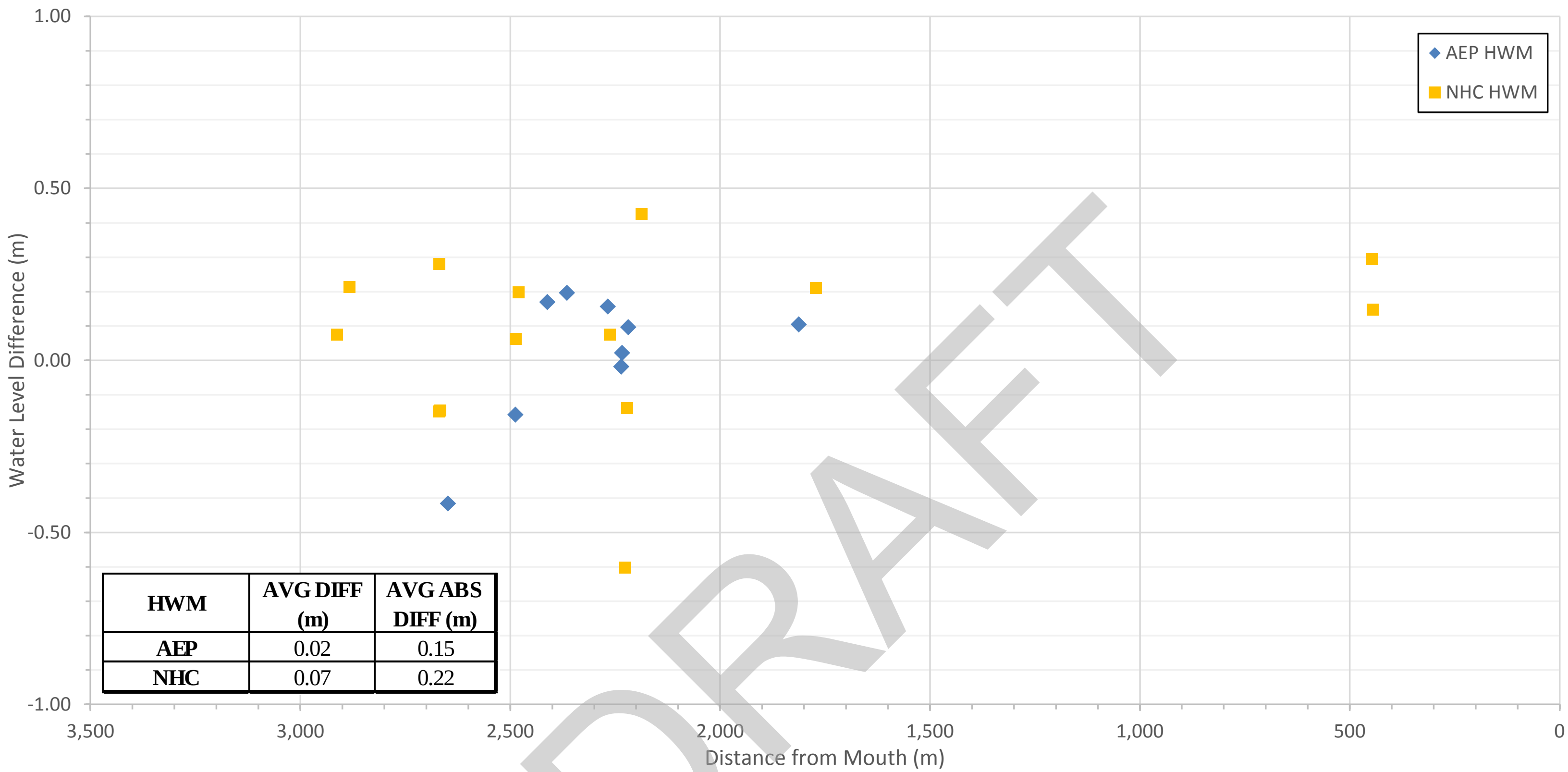
Additional cross sections were interpolated in HEC-RAS to simulate the hydraulic conditions at the exact gauge locations. The model was calibrated based on the flow-stage rating curves for these stations. The calibration results are shown in Figure 18 to Figure 20. The results are summarized below:

- Athabasca River: The Manning's *n* value increases from 0.024 for low flows to 0.03 for high flows. This is likely caused by increased form roughness (ripples and dunes) during high flows.
- Clearwater River: The Manning's *n* value increases from 0.027 for low flows to 0.032 for high flows. This is likely caused by increased form roughness (ripples and dunes) during higher flows.
- Hangingstone River: The Manning's *n* value decreases from 0.065 for low flows to 0.038 for high flows which is expected for a relatively steep gravel and cobble bed river.



HWM	AVG DIFF (m)	AVG ABS DIFF (m)
AEP	0.02	0.15
NHC	0.07	0.22

Figure 16: Comparison of Simulated Hangingstone River Water Surface Profile with Reported High Water Levels for the 2013 Flood Event



HWM	AVG DIFF (m)	AVG ABS DIFF (m)
AEP	0.02	0.15
NHC	0.07	0.22

Figure 17: Difference of Simulated Hangingstone River Water Levels and Reported High Water Levels for the 2013 Flood Event

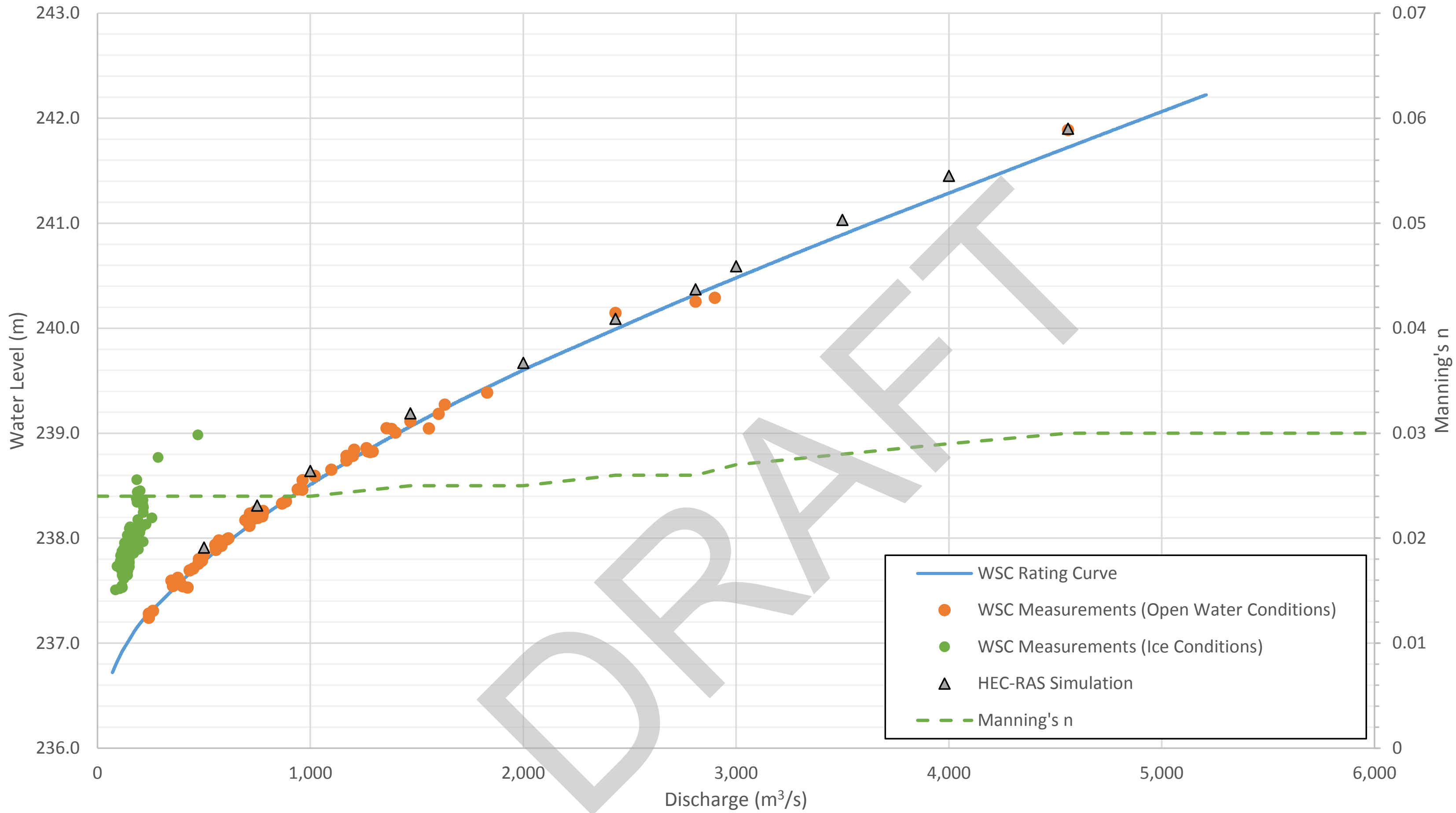


Figure 18: Calibration Results based on the Athabasca River below McMurray (07DA001) Rating Curve

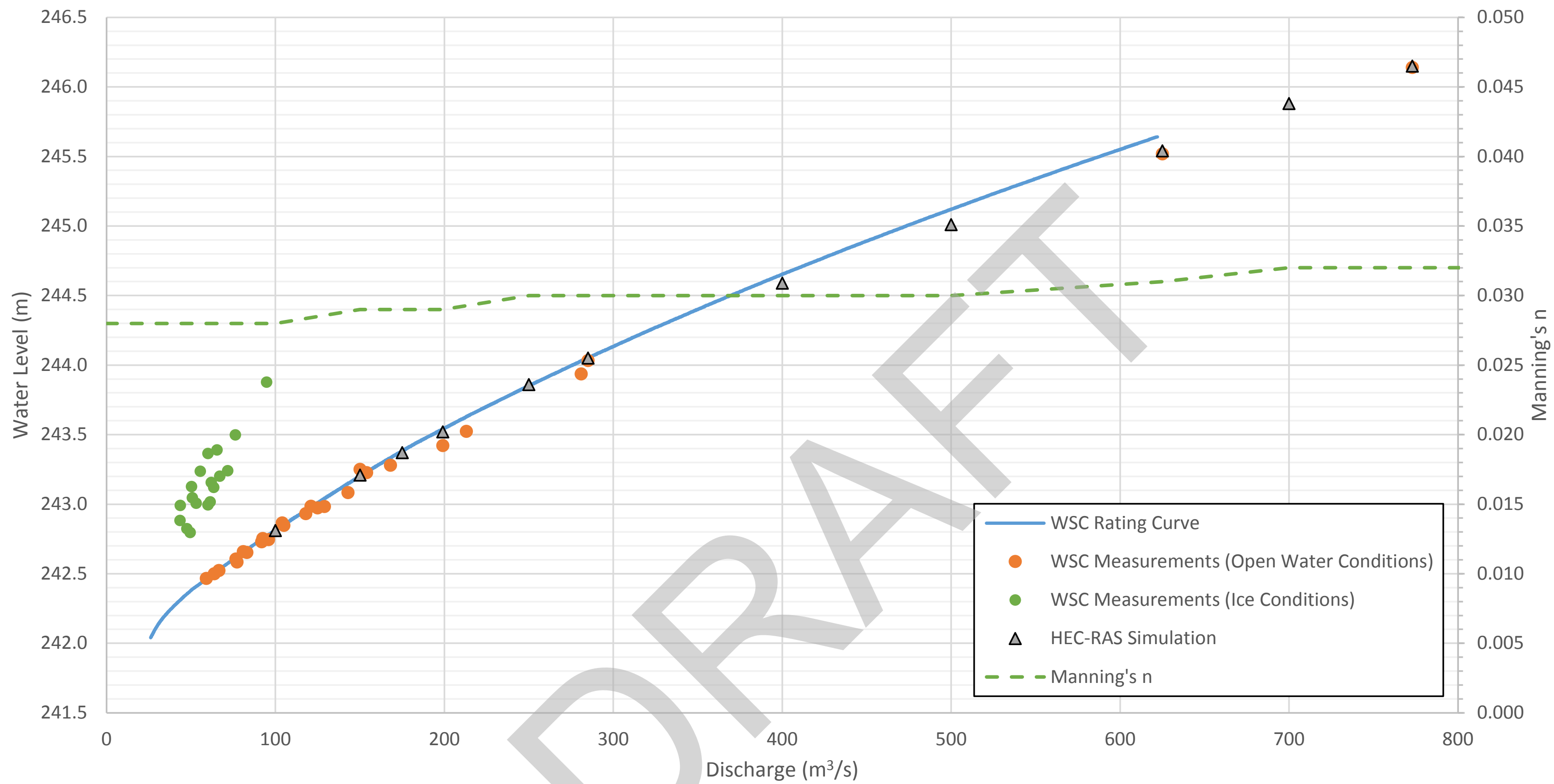


Figure 19: Calibration Results based on the Clearwater River at Draper (07CD001) Rating Curve

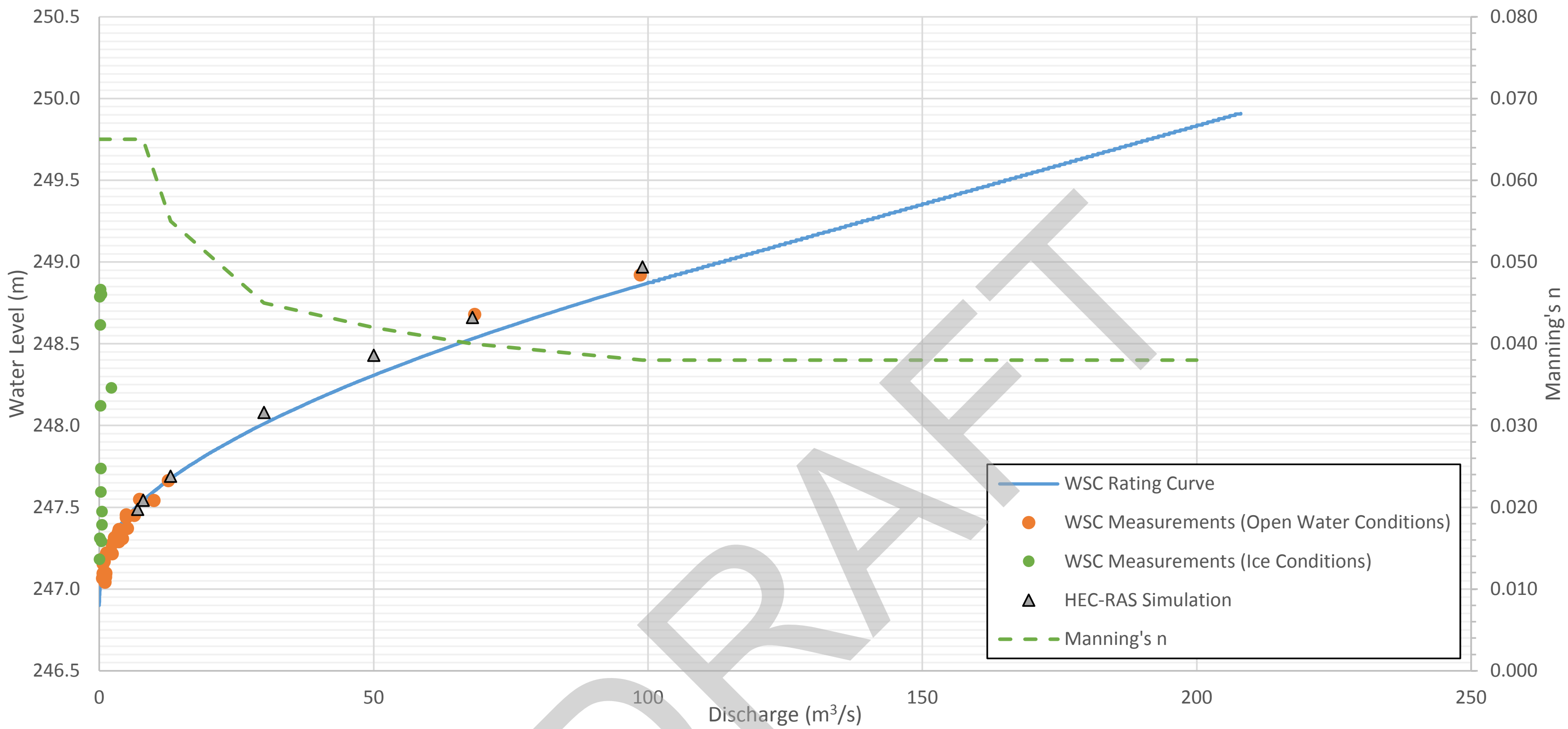


Figure 20: Calibration Results based on the Hangingstone River at Fort McMurray (07CD004) Rating Curve

5.3.5 Summary of Calibration Results

The main purpose of this study is the identification of river and flood hazards. Therefore, the focus of model calibration was to determine appropriate Manning's *n* values for high flow conditions.

Athabasca River

There were no open water high water marks available for the Athabasca River. Therefore, the results from the gauge rating curve calibration were used to determine the high flow Manning's *n* value.

Clearwater River

Water level measurements on the Clearwater River were available for the June 2013 open water flood event. The Manning's *n* values for the upper Clearwater River study reach were based on the gauge rating curve calibration results, and for the lower Clearwater River study reach were based on the measured water levels. However, conservative Manning's *n* values were selected for the lower Clearwater River reach so that the values are similar to those for the comparable Athabasca River reaches, to account for the uncertainty associated with the measured water levels.

The differences between the simulated and measured water levels during the June 2013 flood event are summarized in Table 18.

Table 18: Clearwater River High Flow Calibration Results

Parameter	Water Level Difference (m)
Mean difference between simulated and AEP reported water levels	0.14
Mean absolute difference between simulated and AEP reported water levels	0.15
Mean difference between simulated and NHC reported water levels	0.27
Mean absolute difference between simulated and NHC reported water levels	0.27

Hangingstone River

High water marks were available for the June 2013 flood event on the Hangingstone River in Fort McMurray. The high water level data were used to calibrate the main channel Manning's *n* values. The results show that the simulated water levels are in good agreement with the reported water levels.

The differences between the simulated and reported water levels for the June 2013 flood event are summarized in Table 19.

Table 19: Hangingstone River High Flow Calibration Results

Parameter	Water Level Difference (m)
Mean difference between simulated water levels and AEP high water marks	0.02
Mean absolute difference between simulated water levels and AEP high water marks	0.15
Mean difference between simulated water levels and RMWB high water marks	0.07
Mean absolute difference between simulated water levels and RMWB high water marks	0.22

The Snye

The main channel roughness value in the Snye was not calibrated. The Manning's *n* value was assumed to be the same as for the Clearwater River.

5.4 Model Parameters

5.4.1 Manning Roughness

5.4.1.1 Channel Roughness

The calibrated river channel Manning's *n* values are summarized in Table 20. The longitudinal variations of the Manning's *n* values along the rivers are shown in Figure 14 (Clearwater River) and Figure 16 (Hangingstone River).

Table 20: Calibrated Channel Roughness Values for High Flow Conditions

Stream	Calibrated Manning's *n* Value
Athabasca River	0.030
Clearwater River	0.030 – 0.032
Hangingstone River	0.038 – 0.040
The Snye	0.030

5.4.1.2 Overbank Roughness

There was insufficient data available to calibrate the overbank roughness values for open water flood conditions. Therefore, no adjustment to the initially estimated Manning's *n* values for the overbank areas was made during the calibration process.

Table 21: Estimated Overbank Roughness Values

Number	Description	Estimated Manning's *n* Value
1	Rivers	See above (Table 20)
2	Urban Mixture (Residential)	0.080
3	Urban Mixture (Industrial)	0.060
4	Urban Mixture (Downtown)	0.070
5	Streets	0.030
6	Grassland and Open Space	0.050
7	Dense Vegetation	0.150

5.4.2 Expansion and Contraction Coefficients

The calibrated contraction and expansion coefficients for all bridges are 0.1 and 0.3, respectively. These values were applied to all cross sections.

5.4.3 Obstructions and Ineffective Flow Areas

The following three types of ineffective flow areas were implemented in the model setup:

- <u>Topographical low areas in which standing water may occur:</u> Permanent ineffective flow areas were specified to block off low-lying areas that do not effectively convey flow.

- Topographical low areas that can be activated: Non-permanent ineffective flow areas were specified to block off low-lying areas that can become active after the water level is above a certain elevation.
- Bridge decks and embankments: Permanent ineffective flow areas were specified to block off flow through bridge embankments.

Small residential buildings and houses are not specified as building blockage, because their effects on the hydraulic conditions in the overbank areas are represented by the composite or apparent Manning's value for residential areas.

5.4.4 Flow Split, Island and Diversion

There is no flow split, island or diversion included in the HEC-RAS model setup.

5.5 Open Water Flood Frequency Profiles

5.5.1 Hydrology Summary

Surface water profiles were simulated for the 2-, 5-, 10-, 20-, 35-, 50-, 75-, 100-, 200-, 350-, 500-, 750- and 1,000-year flood events using the calibrated HEC-RAS model. The estimated peak discharges for these flood events were determined in the hydrology analysis (Golder 2017).

The boundary condition at the downstream end of the Athabasca River study reach was estimated based on normal flow depth with an energy slope of 0.035% for all flood discharges. The flood peak discharges for the study reaches are summarized in Table 22.

Table 22: Flood Peak Discharges along the Study Reaches

Flood Event	Flood Peak Discharges (m^3/s)						
	Athabasca River		Clearwater River			Hangingstone River	Snye[(a)]
	Upstream of Clearwater River Confluence	Downstream of Clearwater River Confluence	Upstream of Hangingstone River Confluence	Downstream of Hangingstone River Confluence	Downstream of the Snye		
2-Year	2,030	2,290	366	385	385	35.8	1
5-Year	2,800	3,110	513	540	540	63.5	1
10-Year	3,360	3,710	609	641	641	87.4	1
20-Year	3,950	4,330	699	737	737	116	1
35-Year	4,460	4,860	770	812	812	143	1
50-Year	4,790	5,210	814	859	859	162	1
75-Year	5,190	5,620	864	911	911	187	1
100-Year	5,480	5,920	900	949	949	206	1
200-Year	6,230	6,680	983	1,040	1,040	260	1
350-Year	6,870	7,340	1,050	1,110	1,110	312	1
500-Year	7,310	7,780	1,090	1,150	1,150	349	1
750-Year	7,820	8,300	1,140	1,200	1,200	397	1
1,000-Year	8,200	8,680	1,170	1,240	1,240	434	1

(a) The small discharge in the Snye was assumed to facilitate numerical simulation.

5.5.2 Athabasca River

The simulated open water flood profiles of the various return periods for the Athabasca River are shown in Figure 21. The open water flood water levels for individual cross sections are listed in Table B1 in Appendix B.

5.5.3 Clearwater River

The simulated open water flood profiles of the various return periods for the Clearwater River are shown in Figure 22. The open water flood water levels for individual cross sections are listed in Table B2 in Appendix B.

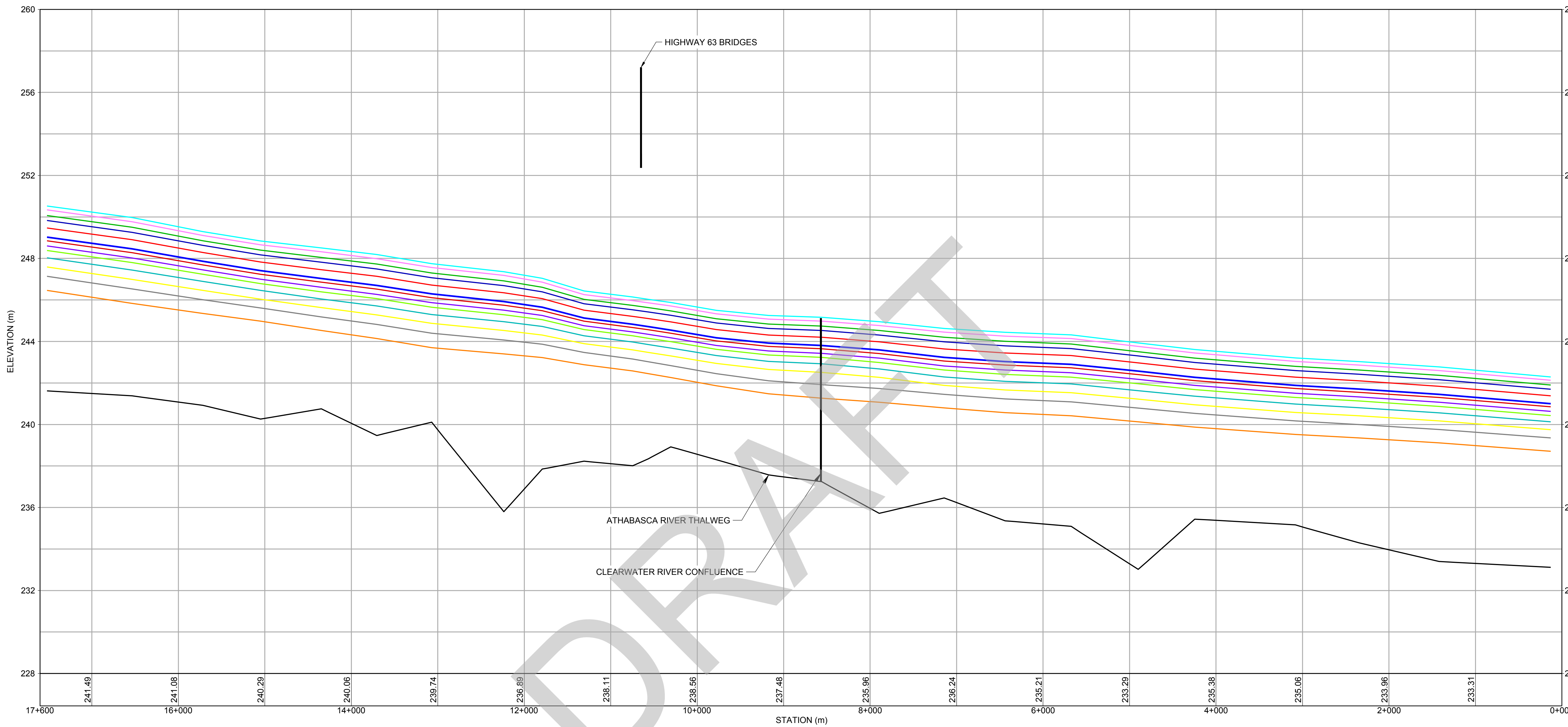
5.5.4 Hangingstone River

The simulated open water flood profiles of the various return periods for the Hangingstone River are shown in Figure 23. The open water flood water levels for individual cross sections are listed in Table B3 in Appendix B.

Along the Hangingstone River there were nine cross sections at which the simulated water levels were lower than those at the downstream cross sections for some flood profiles. In most locations such conditions occur at sharp meander bends where the cross section geometries change from relatively wide and shallow sections to narrow and deep sections. Local minor losses at these locations were introduced in the model to account for the additional head losses based on empirical formulas (Montes 1998).

5.5.5 Snye

The simulated open water flood profiles of the various return periods for the Snye are shown in Figure 24. The simulated open water flood water levels for individual cross sections are listed in Table B4 in Appendix B.



LEGEND

- DESIGN FLOOD PROFILE - 2 YEAR
- DESIGN FLOOD PROFILE - 5 YEAR
- DESIGN FLOOD PROFILE - 10 YEAR
- DESIGN FLOOD PROFILE - 20 YEAR
- DESIGN FLOOD PROFILE - 35 YEAR
- DESIGN FLOOD PROFILE - 50 YEAR
- DESIGN FLOOD PROFILE - 75 YEAR
- DESIGN FLOOD PROFILE - 100 YEAR
- DESIGN FLOOD PROFILE - 200 YEAR
- DESIGN FLOOD PROFILE - 350 YEAR
- DESIGN FLOOD PROFILE - 500 YEAR
- DESIGN FLOOD PROFILE - 750 YEAR
- DESIGN FLOOD PROFILE - 1000 YEAR

REFERENCE

FLOOD PROFILES FROM HEC-RAS MODELLING, RIVER THALWEG FROM SURVEY DATA COLLECTED BY GOLDER FROM SEPTEMBER 27 TO OCTOBER 6, 2016.

0 1,000 2,000

HORIZONTAL SCALE 1:50,000 METRES

VERTICAL EXAGGERATION = 240X

CLIENT

ALBERTA ENVIRONMENT AND PARKS

PROJECT

FORT McMURRAY HAZARD STUDY

TITLE

OPEN WATER FLOOD PROFILES - ATHABASCA RIVER REACH

CONSULTANT

Golder Associates

YYYY-MM-DD	2018-05-28
PREPARED	JDS
DESIGN	WP
REVIEW	WP
APPROVED	DL

PROJECT No.	PHASE	Rev.	FIGURE
1662603	3000	0	21

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25 mm

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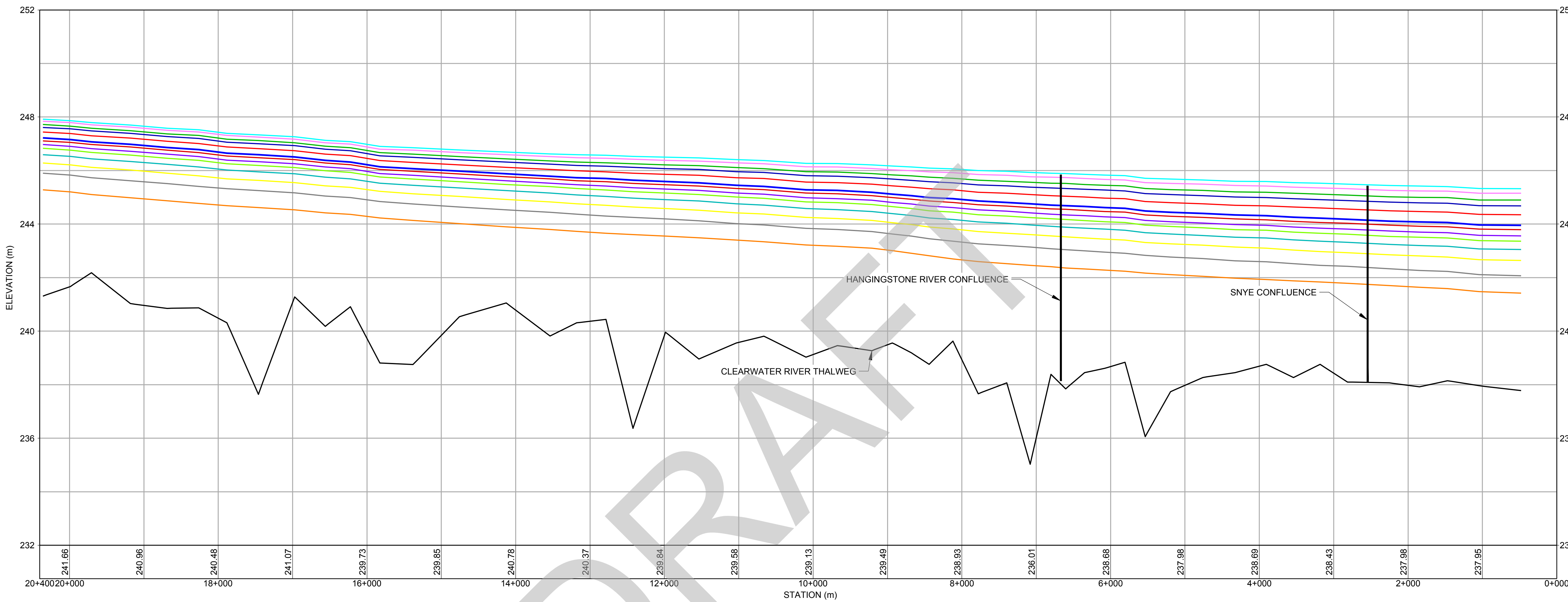

DRAFT

LEGEND

- DESIGN FLOOD PROFILE - 2 YEAR
- DESIGN FLOOD PROFILE - 5 YEAR
- DESIGN FLOOD PROFILE - 10 YEAR
- DESIGN FLOOD PROFILE - 20 YEAR
- DESIGN FLOOD PROFILE - 35 YEAR
- DESIGN FLOOD PROFILE - 50 YEAR
- DESIGN FLOOD PROFILE - 75 YEAR
- DESIGN FLOOD PROFILE - 100 YEAR
- DESIGN FLOOD PROFILE - 200 YEAR
- DESIGN FLOOD PROFILE - 350 YEAR
- DESIGN FLOOD PROFILE - 500 YEAR
- DESIGN FLOOD PROFILE - 750 YEAR
- DESIGN FLOOD PROFILE - 1000 YEAR

REFERENCE

FLOOD PROFILES FROM HEC-RAS MODELLING, RIVER THALWEG FROM SURVEY DATA COLLECTED BY GOLDER FROM SEPTEMBER 27 TO OCTOBER 6, 2016.

0 1,000 2,000

HORIZONTAL SCALE 1:60,000 METRES
VERTICAL EXAGGERATION = 360X

CLIENT
ALBERTA ENVIRONMENT AND PARKS

PROJECT
FORT McMURRAY HAZARD STUDY

TITLE
OPEN WATER FLOOD PROFILES - CLEARWATER RIVER REACH

CONSULTANT

Golder Associates

YYYY-MM-DD	2018-05-28
PREPARED	JDS
DESIGN	WP
REVIEW	WP
APPROVED	DL

PROJECT No.	PHASE	Rev.	FIGURE
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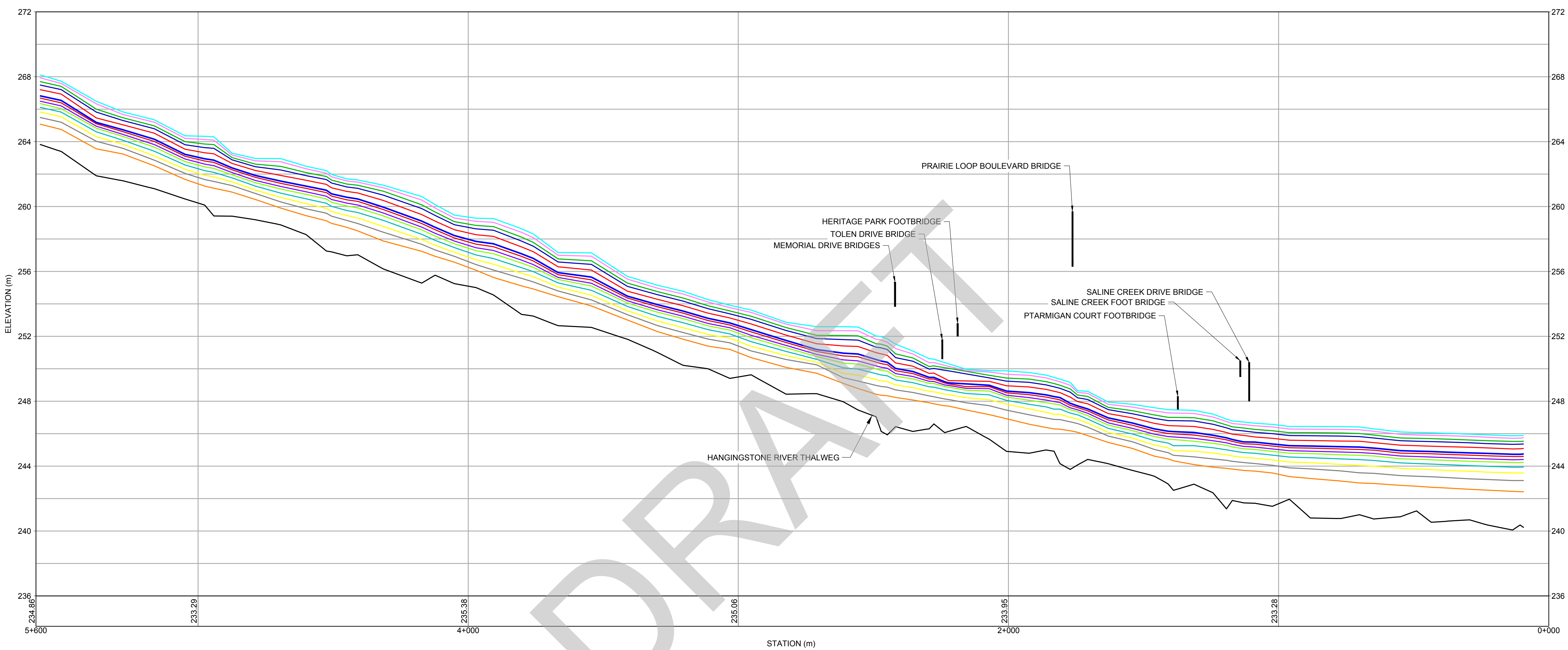

LEGEND

- DESIGN FLOOD PROFILE - 2 YEAR
- DESIGN FLOOD PROFILE - 5 YEAR
- DESIGN FLOOD PROFILE - 10 YEAR
- DESIGN FLOOD PROFILE - 20 YEAR
- DESIGN FLOOD PROFILE - 35 YEAR
- DESIGN FLOOD PROFILE - 50 YEAR
- DESIGN FLOOD PROFILE - 75 YEAR
- DESIGN FLOOD PROFILE - 100 YEAR
- DESIGN FLOOD PROFILE - 200 YEAR
- DESIGN FLOOD PROFILE - 350 YEAR
- DESIGN FLOOD PROFILE - 500 YEAR
- DESIGN FLOOD PROFILE - 750 YEAR
- DESIGN FLOOD PROFILE - 1000 YEAR

REFERENCE

FLOOD PROFILES FROM HEC-RAS MODELLING, RIVER THALWEG FROM SURVEY DATA COLLECTED BY GOLDER FROM SEPTEMBER 27 TO OCTOBER 6, 2016.

0 250 500

HORIZONTAL SCALE 1:15,000 METRES
VERTICAL EXAGGERATION = 60X

CLIENT
ALBERTA ENVIRONMENT AND PARKS

PROJECT
FORT McMURRAY HAZARD STUDY

TITLE
OPEN WATER FLOOD PROFILES - HANGINGSTONE RIVER REACH

CONSULTANT

Golder Associates

YYYY-MM-DD	2018-05-28
PREPARED	JDS
DESIGN	WP
REVIEW	WP
APPROVED	DL

PROJECT No.	PHASE	Rev.	FIGURE
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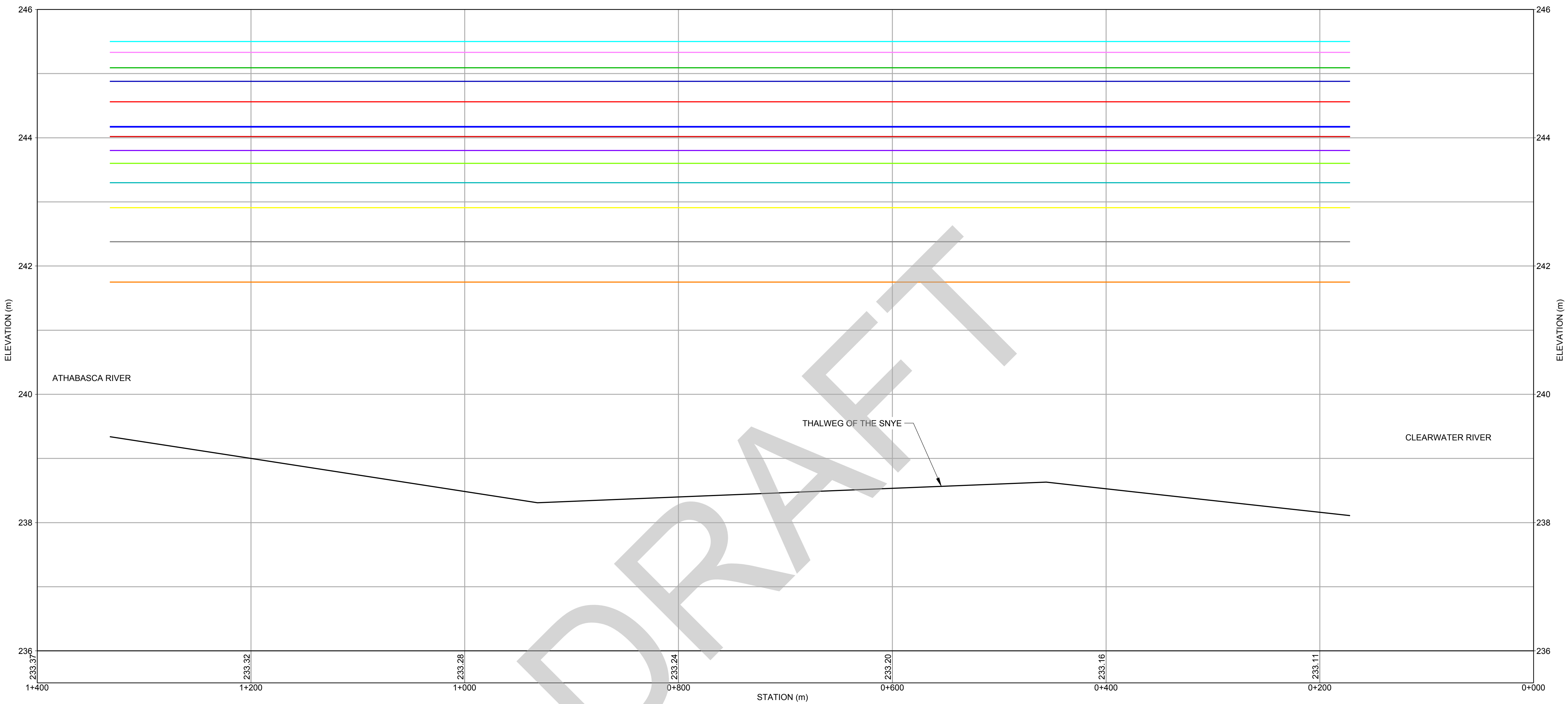
25 mm

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



LEGEND

- DESIGN FLOOD PROFILE - 2 YEAR
- DESIGN FLOOD PROFILE - 5 YEAR
- DESIGN FLOOD PROFILE - 10 YEAR
- DESIGN FLOOD PROFILE - 20 YEAR
- DESIGN FLOOD PROFILE - 35 YEAR
- DESIGN FLOOD PROFILE - 50 YEAR
- DESIGN FLOOD PROFILE - 75 YEAR
- DESIGN FLOOD PROFILE - 100 YEAR
- DESIGN FLOOD PROFILE - 200 YEAR
- DESIGN FLOOD PROFILE - 350 YEAR
- DESIGN FLOOD PROFILE - 500 YEAR
- DESIGN FLOOD PROFILE - 750 YEAR
- DESIGN FLOOD PROFILE - 1000 YEAR

REFERENCE

FLOOD PROFILES FROM HEC-RAS MODELLING, RIVER THALWEG FROM SURVEY DATA COLLECTED BY GOLDER FROM SEPTEMBER 27 TO OCTOBER 6, 2016.

0 100 200

HORIZONTAL SCALE 1:4,000 METRES
VERTICAL EXAGGERATION = 60X

CLIENT
ALBERTA ENVIRONMENT AND PARKS

PROJECT
FORT McMURRAY HAZARD STUDY

TITLE
OPEN WATER FLOOD PROFILES - SNYE REACH

CONSULTANT

Golder Associates

YYYY-MM-DD	2018-05-28
PREPARED	JDS
DESIGN	WP
REVIEW	WP
APPROVED	DL

PROJECT No.	PHASE	Rev.	FIGURE
1662603	3000	0	24

5.6 Model Sensitivity

5.6.1 Summary

Sensitivity analyses were conducted to evaluate the effects of changing model parameters on the simulated 100-year flood water levels. The model parameters included in the sensitivity analyses are the downstream boundary condition and Manning's *n* values for channels and floodplains. The results of the sensitivity analyses are used to quantify the level of uncertainty associated with the simulated 100-year flood levels. The sensitivity analysis results are summarized in Table 23.

Table 23: Summary of Sensitivity Analysis Results

Water Body	Parameter	Absolute Water Level Difference due to Various Percent Changes from the Base Values (m)							
		Channel Manning's *n*		Floodplain Manning's *n*		Channel and Floodplain Manning's *n*		Downstream Boundary Energy Slope	
		+10%	-10%	+10%	-10%	+10%	-10%	+10%	-10%
Athabasca River	Maximum	0.32	0.34	0.01	0	0.32	0.34	0.14	0.17
	Minimum	0.28	0.29	0	0	0.28	0.29	0	0
	Average	0.30	0.31	0	0	0.30	0.31	0	0
Clearwater River	Maximum	0.29	0.3	0.02	0.02	0.29	0.3	0.02	0.03
	Minimum	0.2	0.22	0	0	0.21	0.23	0	0
	Average	0.25	0.26	0.01	0.01	0.25	0.27	0.01	0.01
Hangingstone River	Maximum	0.28	0.29	0.02	0.02	0.28	0.29	0.01	0.02
	Minimum	0.02	0.02	0	0	0.04	0.04	0	0
	Average	0.13	0.14	0.00	0.01	0.14	0.14	0	0
Snye River	Maximum	0.28	0.28	0.01	0	0.28	0.28	0.01	0.03
	Minimum	0.28	0.28	0.01	0	0.28	0.28	0.01	0.03
	Average	0.28	0.28	0.01	0	0.28	0.28	0.01	0.03

5.6.2 Boundary Conditions

The normal flow condition was assumed as the downstream boundary condition in the HEC-RAS model. A sensitivity analysis was performed to assess the effects of varying the assumed downstream boundary slope on the upstream water levels. The downstream boundary energy slope was varied by ±10% from the base value of 0.00035.

The results of the sensitivity analysis of the downstream boundary condition are presented in Figure C.4, Figure C.8, Figure C.12 and Figure C.16 in Appendix C.

The water level at the downstream boundary increased by 0.17 m for decreasing the slope by 10% and reduced by 0.14 m by increasing the slope by 10%. Due to the relatively gentle slope of the Athabasca River, the energy slope change at the downstream model boundary has small effects (i.e., between -0.02 m and +0.03 m) on the water levels near the Clearwater River confluence which is located 8.7 km upstream of the downstream model boundary.

5.6.3 Manning Roughness

5.6.3.1 Channel Roughness

The results of the sensitivity analysis of the channel Manning's *n* values are presented in Figure C.1, Figure C.5, Figure C.9 and Figure C.13 in Appendix C.

5.6.3.2 Overbank Roughness

The results of the sensitivity analysis of the overbank Manning's *n* values are presented in Figure C.2, Figure C.6, Figure C.10 and Figure C.14 in Appendix C.

5.6.3.3 Combined Roughness

The results of the sensitivity analysis of the combined channel and overbank Manning's *n* values are presented in Figure C.3, Figure C.7, Figure C.11 and Figure C.15 in Appendix C.

6.0 CONCLUSIONS

6.1 Model Calibration

The HEC-RAS model set up for the study reaches of the Athabasca River, Clearwater River, Hangingstone River and the Snye, was calibrated based on the available low flow, high flow, and rating curve data. The calibrated HEC-RAS model can be reliably used in this study for simulating various flood events with return periods ranging from 2 to 1,000 years.

River channel Manning's n roughness coefficient is the main model parameter used in calibrating the HEC-RAS model. The calibrated river channel Manning's n values for the low flow conditions on the Athabasca River and Clearwater River are generally lower than those for the high flow conditions. The calibrated river channel Manning's n values for the low flow conditions on the Hangingstone River are generally higher than those for the high flow conditions.

The calibrated channel Manning's n values for the high flow conditions is 0.030 along the Athabasca River study reach, range from 0.030 to 0.032 along the Clearwater River study reach, and from 0.038 to 0.040 along the Hangingstone River study reach. These Manning's n values are within the typical range of roughness values for similar rivers (Chow 1959).

6.2 Model Sensitivity

A model sensitivity was evaluated using the 100-year flood simulation results. The results of the sensitivity analysis show that variation of the river channel roughness values has a much higher influence on the simulated flood levels than variation of the floodplain roughness values, and that on average, the 100-year flood levels are estimated to be within a range of ±0.34 m of the simulated values along the Athabasca River, ±0.30 m along the Clearwater River, ±0.29 m along the Hangingstone River, and ±0.28 m in the Snye.

6.3 Flood Profiles

The calibrated HEC-RAS model provides a reliable tool for simulating the flood profiles of the 2-, 5-, 10-, 20-, 35-, 50-, 75-, 100-, 200-, 350-, 500-, 750- and 1,000-year flood events in the study area.

Report Signature Page

This report was prepared and reviewed by the undersigned.

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https://golderassociates.sharepoint.com/sites/10170g/shared documents/03 hydraulic modelling/report/final rev0/1662603_r0003_0_modelling_report_20180527.docx

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APPENDIX A

Model Calibration Results

Table A.1: Comparison of Simulated and Surveyed Water Levels along the Athabasca River during the 2016 Survey

No	River Station (m)	Surveyed Water Level (m)	Simulated Water Level (Interpolated from Cross Sections) (m)	Difference (Simulated – Surveyed) (m)	Measured Discharge (m^3/s)	Survey Date	Notes
1	15697	243.37	243.29	-0.07	408.6[(a)]	9/30/2016	
2	14411	242.65	242.67	0.03	408.6[(a)]	9/30/2016	
3	12572	241.32	241.26	-0.07	408.6[(a)]	9/30/2016	
4	12231	241.07	241.20	0.13	408.6[(a)]	9/30/2016	
5	11982	241.07	241.17	0.10	408.6[(a)]	9/30/2016	
6	11794	241.04	241.14	0.10	408.6[(a)]	9/30/2016	
7	10754	240.83	240.83	0.00	408.6[(a)]	9/30/2016	
8	10632	240.85	240.78	-0.07	408.6[(a)]	9/30/2016	
9	10432	240.52	240.65	0.14	408.6[(a)]	9/30/2016	
10	9254	240.12	240.01	-0.12	408.6[(a)]	9/30/2016	
11	8469	239.68	239.60	-0.08	571	9/30/2016	
12	7269	239.16	239.04	-0.12	571	9/30/2016	
13	5573	238.02	238.35	0.33	571	9/30/2016	considered Outlier
14	4095	237.91	237.73	-0.18	571	9/30/2016	
15	2760	237.35	237.43	0.08	571	9/30/2016	
16	1442	237.09	237.15	0.07	571	9/30/2016	
17	157	236.62	236.63	0.01	571	9/30/2016	

(a) Discharges upstream of the Clearwater River confluence calculated by subtracting the measured discharge in the Clearwater River on the same day.

Table A.2: Comparison of Simulated and Surveyed Water Levels along the Clearwater River during the 2016 Survey

No	River Station (m)	Surveyed Water Level (m)	Simulated Water Level (Interpolated from Cross Sections) (m)	Difference (Simulated – Surveyed) (m)	Measured Discharge (m^3/s)	Survey Date	Notes
1	19543	243.73	243.79	0.06	159	9/30/2016	
2	18654	243.50	243.56	0.06	159	9/30/2016	
3	17814	243.34	243.39	0.05	159	9/30/2016	
4	16502	243.32	243.14	-0.19	159	9/30/2016	
5	15915	242.92	243.02	0.10	159	9/30/2016	
6	14746	242.76	242.81	0.05	159	9/30/2016	
7	13537	242.45	242.46	0.01	159	9/30/2016	
8	12792	242.31	242.29	-0.02	159	9/30/2016	
9	11484	242.05	242.12	0.07	159	9/30/2016	
10	10838	241.96	241.98	0.01	159	9/30/2016	
11	9326	241.63	241.66	0.03	159	9/30/2016	
12	9326	241.65	241.66	0.01	159	9/30/2016	
13	9326	241.65	241.66	0.01	159	9/30/2016	
14	9326	241.64	241.66	0.02	159	9/30/2016	
15	9210	241.58	241.63	0.05	159	9/30/2016	
16	7409	241.25	241.24	-0.01	159	9/30/2016	
17	6789	241.16	241.14	-0.03	159	9/30/2016	
18	6079	240.987	241.00	0.01	162.3[(a)]	9/30/2016	D/S of Hangingstone River confluence
19	5138	240.879	240.87	-0.01	162.3[(a)]	9/30/2016	
20	3802	240.681	240.68	-0.01	162.3[(a)]	9/30/2016	
21	2622	240.439	240.49	0.05	162.3[(a)]	9/30/2016	
22	1647	240.192	240.23	0.03	162.4[(b)]	9/30/2016	D/S of the Snye confluence
23	510	240.022	239.87	-0.16	162.4[(b)]	9/30/2016	Influenced by simulated water level in Athabasca River

(a) Discharges downstream of Hangingstone River confluence calculated by adding the measured discharge in the Hangingstone River on the same day.

(b) Assumed 0.1 m^3/s as additional inflow from the Snye

Table A.3: Comparison of Simulated and Surveyed Water Levels along the Hangingstone River during the 2016 Survey

No	River Station (m)	Surveyed Water Level (m)	Simulated Water Level (Interpolated from Cross Sections) (m)	Difference (Simulated – Surveyed) (m)	Measured Discharge (m^3/s)	Survey Date	Notes
1	5586	264.50	264.63	0.13	3.3	9/29/2016	
2	5342	263.15	262.96	-0.19	3.3	9/29/2016	
3	5278	262.55	262.69	0.14	3.3	9/29/2016	
4	5170	262.24	262.13	-0.11	3.3	9/29/2016	
5	5064	261.39	261.30	-0.09	3.3	9/29/2016	
6	4989	260.85	260.76	-0.09	3.3	9/29/2016	
7	4920	260.25	260.38	0.13	3.3	9/29/2016	
8	4871	260.19	260.22	0.03	3.3	9/29/2016	
9	4762	259.76	259.76	0.00	3.3	9/29/2016	
10	4626	259.05	258.97	-0.08	3.3	9/29/2016	
11	4525	258.24	258.24	0.00	3.3	9/29/2016	
12	4480	258.22	258.08	-0.15	3.3	9/29/2016	
13	4409	258.08	257.86	-0.22	3.3	9/29/2016	
14	4200	256.64	256.61	-0.03	3.3	9/29/2016	
15	4138	256.60	256.41	-0.19	3.3	9/29/2016	
16	4051	255.88	255.97	0.09	3.3	9/29/2016	
17	3971	255.78	255.63	-0.15	3.3	9/29/2016	
18	3906	255.19	255.06	-0.13	3.3	9/29/2016	
19	3831	254.54	254.56	0.02	3.3	9/29/2016	
20	3748	254.25	254.18	-0.06	3.3	9/29/2016	
21	3651	253.87	253.82	-0.05	3.3	9/29/2016	
22	3528	253.27	253.21	-0.06	3.3	9/29/2016	
23	3389	252.30	252.33	0.02	3.3	9/29/2016	
24	3278	251.74	251.62	-0.12	3.3	9/29/2016	
25	3176	251.00	251.04	0.05	3.3	9/29/2016	
26	3111	250.80	250.66	-0.15	3.3	9/29/2016	
27	3036	250.49	250.48	-0.01	3.3	9/29/2016	
28	2917	249.97	249.87	-0.10	3.3	9/29/2016	
29	2862	249.48	249.54	0.05	3.3	9/29/2016	
30	2740	248.99	249.07	0.08	3.3	9/29/2016	
31	2635	248.66	248.53	-0.12	3.3	9/29/2016	
32	2532	247.71	247.81	0.10	3.3	9/29/2016	
33	2498	247.69	247.49	-0.20	3.3	9/29/2016	
34	2422	247.32	247.34	0.03	3.3	9/29/2016	
35	2389	247.27	247.29	0.02	3.3	9/29/2016	
36	2388	247.28	247.29	0.01	3.3	9/29/2016	
37	2371	247.17	247.26	0.09	3.3	9/29/2016	
38	2337	247.12	247.20	0.08	3.3	9/29/2016	
39	2293	247.08	247.13	0.05	3.3	9/29/2016	
40	2276	247.06	247.04	-0.02	3.3	9/29/2016	
41	2232	247.07	246.98	-0.09	3.3	9/29/2016	
42	2206	247.04	246.94	-0.10	3.3	9/29/2016	

Table A.3: Comparison of Simulated and Surveyed Water Levels along the Hangingstone River during the 2016 Survey

No	River Station (m)	Surveyed Water Level (m)	Simulated Water Level (Interpolated from Cross Sections) (m)	Difference (Simulated – Surveyed) (m)	Measured Discharge (m^3/s)	Survey Date	Notes
43	2063	246.20	246.34	0.14	3.3	9/29/2016	
44	2002	246.01	246.03	0.02	3.3	9/29/2016	
45	1913	245.65	245.73	0.08	3.3	9/29/2016	
46	1832	245.40	245.31	-0.10	3.3	9/29/2016	
47	1775	245.19	245.19	0.00	3.3	9/29/2016	
48	1708	245.15	245.10	-0.04	3.3	9/29/2016	
49	1646	244.79	244.84	0.04	3.3	9/29/2016	
50	1530	244.26	244.37	0.11	3.3	9/29/2016	
51	1460	244.07	243.93	-0.14	3.3	9/29/2016	
52	1404	243.63	243.61	-0.02	3.3	9/29/2016	
53	1390	243.68	243.58	-0.10	3.3	9/29/2016	
54	1300	243.49	243.34	-0.15	3.3	9/29/2016	
55	1230	242.84	242.89	0.05	3.3	9/29/2016	
56	1198	242.76	242.85	0.09	3.3	9/29/2016	
57	1168	242.75	242.81	0.06	3.3	9/29/2016	
58	1168	242.76	242.81	0.05	3.3	9/29/2016	
59	1124	242.65	242.70	0.05	3.3	9/29/2016	
60	1077	242.62	242.61	-0.02	3.3	9/29/2016	
61	1011	242.60	242.50	-0.10	3.3	9/29/2016	
62	850	242.06	242.00	-0.07	3.3	9/29/2016	
63	760	241.93	241.93	0.00	3.3	9/29/2016	
64	701	241.89	241.88	-0.01	3.3	9/29/2016	
65	693	241.81	241.87	0.06	3.3	9/29/2016	
66	541	241.79	241.76	-0.03	3.3	9/29/2016	
67	491	241.74	241.67	-0.07	3.3	9/29/2016	
68	416	241.60	241.55	-0.05	3.3	9/29/2016	
69	332	241.53	241.44	-0.08	3.3	9/29/2016	
70	262	241.26	241.33	0.08	3.3	9/29/2016	
71	207	241.24	241.26	0.02	3.3	9/29/2016	
72	160	241.20	241.22	0.01	3.3	9/29/2016	
73	116	241.18	241.17	-0.01	3.3	9/29/2016	
74	97	241.16	241.15	-0.01	3.3	9/29/2016	

Table A.4: Comparison of Simulated water levels and Surveyed High Water Marks along the Clearwater River for High Flow Calibration

No	River Station (m)	Surveyed High Water Marks (m)	Simulated Water Level (Interpolated from Cross Sections) (m)	Difference (Simulated – Surveyed) (m)	Measured Discharge (m^3/s)	Survey Date	Notes
1	7515	243.19	243.95	0.76	666	6/13/2013	
2	6138	243.56	243.68	0.12	666	6/13/2013	
3	6139	243.50	243.68	0.18	666	6/13/2013	
4	6148	243.43	243.68	0.26	666	6/13/2013	
5	4930	242.98	243.38	0.40	666	6/13/2013	
6	13068	244.86	244.97	0.12	666	6/13/2013	
7	14840	245.27	245.26	0.00	666	6/13/2013	

Table A.5: Comparison of Simulated Water Levels and Surveyed High Water Marks along the Hangingstone River for High Flow Calibration

No	River Station (m)	Surveyed High Water Marks (m)	Simulated Water Level (Interpolated from Cross Sections) (m)	Difference (Simulated – Surveyed) (m)	Measured Discharge (m3/s)	Survey Date	Notes
1	2648	251.41	251.00	-0.42	200	6/11/2013	
2	2488	250.66	250.51	-0.16	200	6/11/2013	
3	2412	249.79	249.96	0.17	200	6/11/2013	
4	2365	249.63	249.82	0.20	200	6/11/2013	
5	2268	249.22	249.38	0.16	200	6/11/2013	
6	2236	249.19	249.17	-0.02	200	6/11/2013	
7	2234	249.14	249.16	0.02	200	6/11/2013	
8	2219	249.01	249.10	0.10	200	6/11/2013	
9	1813	248.07	248.17	0.10	200	6/11/2013	
10	2914	252.10	252.17	0.07	200	6/11/2013	
11	2883	251.80	252.01	0.21	200	6/11/2013	
12	2670	251.20	251.05	-0.15	200	6/11/2013	
13	2668	250.77	251.05	0.28	200	6/11/2013	
14	2666	251.19	251.04	-0.15	200	6/11/2013	
15	2487	250.44	250.50	0.06	200	6/11/2013	
16	2480	250.27	250.47	0.20	200	6/11/2013	
17	2263	249.28	249.35	0.08	200	6/11/2013	
18	2226	249.73	249.13	-0.60	200	6/11/2013	
19	2221	249.25	249.11	-0.14	200	6/11/2013	
20	2187	248.60	249.02	0.43	200	6/11/2013	
21	1772	247.62	247.83	0.21	200	6/11/2013	
22	445.9	244.04	244.33	0.29	200	6/11/2013	
23	445.6	244.19	244.33	0.15	200	6/11/2013	

APPENDIX B

Flood Profiles

Table B.1: Athabasca River Flood Profile

River	Reach	River Sta.	Min Ch. El	2-year	5-year	10-year	20-year	35-year	50-year	75-year	100-year	200-year	350-year	500-year	750-year	1000-year
Athabasca	Upper Reach	17518.78	241.62	246.46	247.14	247.59	248.03	248.38	248.60	248.85	249.03	249.47	249.83	250.07	250.34	250.53
Athabasca	Upper Reach	16534.76	241.38	245.83	246.53	246.99	247.44	247.80	248.02	248.28	248.46	248.90	249.26	249.50	249.77	249.97
Athabasca	Upper Reach	15715.68	240.92	245.35	246.01	246.46	246.89	247.24	247.45	247.69	247.86	248.29	248.63	248.85	249.11	249.29
Athabasca	Upper Reach	15048.28	240.26	244.98	245.61	246.04	246.46	246.79	247.00	247.24	247.41	247.83	248.17	248.40	248.66	248.84
Athabasca	Upper Reach	14345.85	240.75	244.53	245.18	245.63	246.05	246.39	246.61	246.86	247.03	247.46	247.82	248.05	248.32	248.51
Athabasca	Upper Reach	13706.22	239.47	244.14	244.82	245.28	245.71	246.06	246.27	246.52	246.70	247.14	247.49	247.73	247.99	248.19
Athabasca	Upper Reach	13070.66	240.11	243.70	244.40	244.87	245.30	245.65	245.87	246.11	246.29	246.72	247.07	247.30	247.56	247.75
Athabasca	Upper Reach	12236.63	235.8	243.40	244.07	244.53	244.95	245.29	245.51	245.75	245.92	246.35	246.69	246.92	247.18	247.36
Athabasca	Upper Reach	11791.47	237.85	243.22	243.87	244.31	244.72	245.05	245.25	245.48	245.65	246.06	246.39	246.61	246.86	247.04
Athabasca	Upper Reach	11308.5	238.23	242.88	243.47	243.89	244.27	244.57	244.76	244.98	245.13	245.51	245.82	246.03	246.26	246.43
Athabasca	Upper Reach	10746.91	238.01	242.58	243.15	243.59	243.97	244.27	244.46	244.67	244.83	245.21	245.53	245.74	245.97	246.14
Athabasca	Upper Reach	10564.41	238.35	242.45[a]	243.02[a]	243.47[a]	243.85[a]	244.15[a]	244.34[a]	244.56[a]	244.71[a]	245.10[a]	245.42[a]	245.63[a]	245.86[a]	246.03[a]
Athabasca	Upper Reach	10305.52	238.92	242.26	242.84	243.30	243.68	243.99	244.18	244.40	244.55	244.94	245.26	245.47	245.71	245.88
Athabasca	Upper Reach	9779.201	238.3	241.87	242.45	242.94	243.32	243.62	243.81	244.03	244.18	244.57	244.89	245.09	245.33	245.50
Athabasca	Upper Reach	9174.223	237.57	241.48	242.10	242.65	243.04	243.35	243.54	243.76	243.92	244.31	244.63	244.84	245.08	245.25
Athabasca	Lower Reach	8558.773	237.24	241.27	241.92	242.51	242.92	243.23	243.43	243.65	243.81	244.20	244.53	244.74	244.98	245.16
Athabasca	Lower Reach	7895.353	235.72	241.07	241.73	242.27	242.68	242.99	243.20	243.42	243.59	243.98	244.31	244.53	244.77	244.95
Athabasca	Lower Reach	7143.78	236.46	240.80	241.45	241.88	242.29	242.62	242.82	243.06	243.23	243.64	243.98	244.20	244.45	244.63
Athabasca	Lower Reach	6437.807	235.36	240.57	241.23	241.66	242.08	242.41	242.62	242.86	243.03	243.44	243.79	244.01	244.26	244.44
Athabasca	Lower Reach	5675.062	235.09	240.42	241.09	241.53	241.95	242.28	242.49	242.73	242.90	243.32	243.66	243.88	244.14	244.32
Athabasca	Lower Reach	4899.097	233.02	240.13	240.79	241.22	241.63	241.96	242.17	242.40	242.57	242.97	243.30	243.51	243.76	243.93
Athabasca	Lower Reach	4246.117	235.44	239.87	240.53	240.95	241.36	241.68	241.88	242.11	242.27	242.67	242.99	243.20	243.44	243.61
Athabasca	Lower Reach	3082.808	235.16	239.52	240.17	240.58	240.98	241.30	241.50	241.73	241.88	242.28	242.60	242.80	243.04	243.21
Athabasca	Lower Reach	2347.389	234.3	239.35	240.00	240.42	240.81	241.13	241.33	241.55	241.71	242.10	242.42	242.62	242.86	243.03
Athabasca	Lower Reach	1419.641	233.4	239.11	239.76	240.17	240.56	240.87	241.07	241.30	241.45	241.84	242.16	242.37	242.60	242.77
Athabasca	Lower Reach	128.5046	233.12	238.71	239.35	239.75	240.13	240.43	240.63	240.85	241.00	241.38	241.70	241.90	242.13	242.29

(a) Linear Interpolation between upstream and downstream water levels to remove dip at bridge.

Table B.2: Clearwater River Flood Profile

River	Reach	River Sta.	Min Ch. El	2-year	5-year	10-year	20-year	35-year	50-year	75-year	100-year	200-year	350-year	500-year	750-year	1000-year
Clearwater	Upper Reach	20359.02	241.31	245.28	245.91	246.28	246.60	246.83	246.97	247.12	247.22	247.45	247.62	247.72	247.85	247.92
Clearwater	Upper Reach	19986.3	241.67	245.20	245.83	246.21	246.53	246.77	246.91	247.06	247.16	247.39	247.57	247.67	247.79	247.87
Clearwater	Upper Reach	19705.16	242.18	245.11	245.74	246.12	246.44	246.68	246.82	246.98	247.08	247.31	247.48	247.59	247.72	247.80
Clearwater	Upper Reach	19181.71	241.03	244.99	245.63	246.02	246.35	246.59	246.73	246.88	246.99	247.22	247.40	247.50	247.63	247.71
Clearwater	Upper Reach	18685.47	240.85	244.87	245.51	245.91	246.23	246.47	246.61	246.77	246.87	247.10	247.28	247.38	247.51	247.59
Clearwater	Upper Reach	18261.58	240.87	244.78	245.42	245.81	246.14	246.38	246.53	246.68	246.79	247.02	247.21	247.32	247.45	247.54
Clearwater	Upper Reach	17882.61	240.31	244.69	245.32	245.70	246.03	246.26	246.40	246.55	246.66	246.89	247.07	247.18	247.32	247.40
Clearwater	Upper Reach	17460.42	237.64	244.62	245.26	245.64	245.96	246.20	246.34	246.49	246.60	246.83	247.02	247.13	247.26	247.35
Clearwater	Upper Reach	16972.25	241.28	244.54	245.18	245.56	245.89	246.12	246.26	246.42	246.52	246.76	246.94	247.05	247.18	247.27
Clearwater	Upper Reach	16560.32	240.18	244.43	245.06	245.44	245.76	246.00	246.14	246.29	246.39	246.62	246.81	246.92	247.06	247.15
Clearwater	Upper Reach	16222.89	240.91	244.36	245.00	245.38	245.71	245.94	246.08	246.23	246.34	246.57	246.76	246.87	247.01	247.10
Clearwater	Upper Reach	15826.04	238.81	244.24	244.85	245.23	245.54	245.77	245.91	246.05	246.16	246.38	246.57	246.68	246.82	246.92
Clearwater	Upper Reach	15382.2	238.75	244.15	244.76	245.14	245.46	245.70	245.83	245.98	246.09	246.32	246.51	246.63	246.77	246.87
Clearwater	Upper Reach	14757.45	240.54	244.03	244.65	245.04	245.37	245.60	245.74	245.89	245.99	246.23	246.42	246.54	246.69	246.79
Clearwater	Upper Reach	14127.07	241.05	243.91	244.55	244.94	245.27	245.50	245.64	245.79	245.90	246.14	246.34	246.46	246.61	246.72
Clearwater	Upper Reach	13537.46	239.82	243.81	244.45	244.85	245.18	245.41	245.55	245.71	245.81	246.06	246.26	246.38	246.54	246.65
Clearwater	Upper Reach	13178.92	240.31	243.74	244.38	244.78	245.11	245.35	245.49	245.64	245.75	246.01	246.21	246.34	246.50	246.62
Clearwater	Upper Reach	12785.95	240.44	243.67	244.32	244.72	245.05	245.30	245.44	245.60	245.72	245.98	246.19	246.32	246.48	246.59
Clearwater	Upper Reach	12424.12	236.37	243.63	244.27	244.66	244.99	245.24	245.38	245.55	245.66	245.93	246.14	246.28	246.44	246.56
Clearwater	Upper Reach	11984.9	239.96	243.57	244.21	244.60	244.94	245.18	245.33	245.50	245.61	245.88	246.10	246.24	246.41	246.53
Clearwater	Upper Reach	11537.24	238.96	243.50	244.14	244.54	244.88	245.13	245.28	245.45	245.57	245.84	246.06	246.21	246.38	246.50
Clearwater	Upper Reach	11033.47	239.56	243.41	244.05	244.45	244.78	245.03	245.19	245.36	245.48	245.77	245.99	246.14	246.31	246.44
Clearwater	Upper Reach	10662.83	239.81	243.36	243.99	244.40	244.74	244.99	245.15	245.32	245.44	245.73	245.96	246.10	246.28	246.41
Clearwater	Upper Reach	10095.14	239.03	243.24	243.87	244.27	244.61	244.86	245.02	245.19	245.31	245.60	245.84	245.99	246.17	246.30
Clearwater	Upper Reach	9673.802	239.46	243.19	243.82	244.24	244.57	244.83	244.99	245.16	245.29	245.58	245.82	245.98	246.16	246.30
Clearwater	Upper Reach	9209.617	239.27	243.12	243.75	244.17	244.51	244.76	244.92	245.10	245.23	245.53	245.77	245.92	246.11	246.25
Clearwater	Upper Reach	8934.315	239.56	243.03	243.66	244.08	244.43	244.69	244.85	245.03	245.16	245.47	245.72	245.88	246.07	246.21
Clearwater	Upper Reach	8679.208	239.19	242.94	243.58	244.01	244.36	244.62	244.79	244.97	245.10	245.42	245.67	245.83	246.03	246.17
Clearwater	Upper Reach	8439.882	238.76	242.85	243.49	243.93	244.28	244.55	244.71	244.90	245.04	245.36	245.62	245.79	245.99	246.13
Clearwater	Upper Reach	8120.876	239.63	242.74	243.41	243.86	244.22	244.49	244.66	244.86	244.99	245.32	245.59	245.76	245.96	246.10
Clearwater	Upper Reach	7779.764	237.66	242.64	243.31	243.77	244.13	244.40	244.58	244.77	244.91	245.24	245.51	245.68	245.89	246.04
Clearwater	Upper Reach	7396.448	238.07	242.57	243.25	243.71	244.08	244.35	244.53	244.72	244.86	245.20	245.47	245.65	245.86	246.01
Clearwater	Upper Reach	7080.891	235.03	242.51	243.19	243.66	244.02	244.30	244.47	244.67	244.81	245.15	245.43	245.61	245.82	245.97
Clearwater	Upper Reach	6802.133	238.39	242.46	243.14	243.61	243.97	244.25	244.43	244.62	244.77	245.11	245.40	245.58	245.79	245.95
Clearwater	Mid Reach	6604.857	237.84	242.41	243.09	243.57	243.93	244.22	244.39	244.59	244.74	245.09	245.38	245.56	245.77	245.93
Clearwater	Mid Reach	6350.496	238.45	242.37	243.05	243.53	243.90	244.18	244.36	244.56	244.70	245.05	245.34	245.52	245.74	245.90
Clearwater	Mid Reach	6078.455	238.61	242.32	243.00	243.48	243.85	244.14	244.32	244.52	244.66	245.02	245.31	245.49	245.71	245.87
Clearwater	Mid Reach	5805.896	238.84	242.28	242.96	243.45	243.82	244.10	244.28	244.49	244.63	244.99	245.28	245.46	245.68	245.84
Clearwater	Mid Reach	5535.46	236.06	242.20	242.87	243.35	243.71	243.99	244.17	244.37	244.51	244.87	245.16	245.35	245.57	245.74
Clearwater	Mid Reach	5194.108	237.74	242.14	242.81	243.29	243.66	243.94	244.12	244.32	244.47	244.82	245.12	245.31	245.53	245.70
Clearwater	Mid Reach	4759.934	238.27	242.07	242.74	243.23	243.60	243.88	244.07	244.27	244.42	244.78	245.08	245.27	245.50	245.67
Clearwater	Mid Reach	4324.203	238.45	242.00	242.66	243.16	243.53	243.81	243.99	244.20	244.35	244.72	245.02	245.22	245.45	245.61
Clearwater	Mid Reach	3906.219	238.76	241.94	242.61	243.12	243.49	243.78	243.97	244.18	244.33	244.70	245.00	245.20	245.43	245.60

Table B.2: Clearwater River Flood Profile

River	Reach	River Sta.	Min Ch. El	2-year	5-year	10-year	20-year	35-year	50-year	75-year	100-year	200-year	350-year	500-year	750-year	1000-year
Clearwater	Mid Reach	3541.042	238.27	241.88	242.53	243.04	243.42	243.71	243.90	244.11	244.27	244.64	244.95	245.15	245.39	245.56
Clearwater	Mid Reach	3182.93	238.76	241.84	242.47	242.98	243.36	243.66	243.85	244.07	244.22	244.60	244.92	245.12	245.36	245.53
Clearwater	Mid Reach	2815.173	238.10	241.79	242.42	242.93	243.32	243.62	243.81	244.03	244.18	244.56	244.88	245.08	245.32	245.49
Clearwater	Lower Reach	2250.473	238.07	241.70	242.33	242.85	243.24	243.54	243.74	243.96	244.11	244.50	244.82	245.02	245.26	245.44
Clearwater	Lower Reach	1847.547	237.92	241.64	242.27	242.81	243.20	243.51	243.70	243.92	244.08	244.47	244.79	245.00	245.24	245.42
Clearwater	Lower Reach	1470.964	238.15	241.59	242.23	242.77	243.17	243.48	243.68	243.90	244.06	244.45	244.78	244.99	245.23	245.40
Clearwater	Lower Reach	1043.023	237.96	241.48	242.11	242.67	243.07	243.38	243.58	243.81	243.97	244.36	244.69	244.90	245.15	245.33
Clearwater	Lower Reach	479.8225	237.78	241.42	242.07	242.64	243.05	243.36	243.56	243.79	243.95	244.35	244.68	244.90	245.15	245.32

Table B.3: Hangingstone River Flood Profile

River	Reach	River Sta.	Min Ch. El	2-year	5-year	10-year	20-year	35-year	50-year	75-year	100-year	200-year	350-year	500-year	750-year	1000-year
Hangingstone	Hangingstone	5585.592	263.83	265.08	265.49	265.83	266.12	266.35	266.50	266.69	266.83	267.21	267.50	267.71	267.94	268.12
Hangingstone	Hangingstone	5506.659	263.40	264.75	265.20	265.54	265.82	266.04	266.20	266.39	266.54	266.93	267.21	267.41	267.59	267.73
Hangingstone	Hangingstone	5376.601	261.90	263.56	264.02	264.31	264.61	264.83	264.96	265.10	265.19	265.46	265.82	266.00	266.33	266.49
Hangingstone	Hangingstone	5277.659	261.59	263.24	263.59	263.84	264.09	264.32	264.45	264.62	264.73	265.04	265.30	265.47	265.68	265.83
Hangingstone	Hangingstone	5161.992	261.10	262.51	262.86	263.12	263.41	263.66	263.82	264.01	264.15	264.52	264.80	264.98	265.20	265.35
Hangingstone	Hangingstone	5048.179	260.47	261.67	262.05	262.30	262.56	262.78	262.93	263.10	263.22	263.54	263.81	264.00	264.20	264.36
Hangingstone	Hangingstone	4975.215	260.09	261.26	261.66	261.93	262.21	262.45	262.62	262.81	262.94	263.31	263.63	263.86	264.13	264.33
Hangingstone	Hangingstone	4941.598	259.42	261.13	261.55	261.83	262.11	262.35	262.52	262.72	262.86	263.25	263.59	263.82	264.10	264.30
Hangingstone	Hangingstone	4874.372	259.41	260.89	261.29	261.53	261.77	261.96	262.10	262.27	262.38	262.66	262.88	263.02	263.18	263.29
Hangingstone	Hangingstone	4787.698	259.19	260.44	260.81	261.02	261.26	261.47	261.61	261.80	261.92	262.22	262.46	262.62	262.82	262.97
Hangingstone	Hangingstone	4693.74	258.87	259.91	260.29	260.56	260.83	261.08	261.24	261.43	261.57	261.92	262.26	262.48	262.76	262.95
Hangingstone	Hangingstone	4600.277	258.28	259.44	259.87	260.18	260.48	260.75	260.91	261.12	261.26	261.62	261.91	262.10	262.33	262.49
Hangingstone	Hangingstone	4524.798	257.26	259.12	259.59	259.89	260.20	260.47	260.64	260.86	261.01	261.37	261.66	261.85	262.06	262.21
Hangingstone	Hangingstone	4505.953	257.21	258.97	259.41	259.70	260.01	260.27	260.44	260.65	260.79	261.16	261.45	261.63	261.83	261.98
Hangingstone	Hangingstone	4449.333	256.96	258.72	259.14	259.45	259.76	260.03	260.21	260.42	260.57	260.93	261.21	261.39	261.58	261.71
Hangingstone	Hangingstone	4408.838	257.03	258.50	258.95	259.29	259.63	259.92	260.10	260.32	260.47	260.84	261.12	261.31	261.50	261.64
Hangingstone	Hangingstone	4313.529	256.15	257.87	258.42	258.77	259.14	259.42	259.60	259.81	259.96	260.37	260.70	260.94	261.16	261.32
Hangingstone	Hangingstone	4172.101	255.28	257.24	257.67	257.97	258.29	258.56	258.73	258.95	259.10	259.51	259.88	260.11	260.40	260.62
Hangingstone	Hangingstone	4122.038	255.77	256.93	257.32	257.61	257.92	258.18	258.35	258.57	258.72	259.10	259.45	259.66	259.91	260.12
Hangingstone	Hangingstone	4051.339	255.25	256.57	256.93	257.19	257.47	257.71	257.87	258.07	258.21	258.57	258.88	259.07	259.29	259.47
Hangingstone	Hangingstone	3971.188	255.01	256.08	256.43	256.72	257.02	257.28	257.46	257.68	257.85	258.27	258.63	258.84	259.09	259.28
Hangingstone	Hangingstone	3906.399	254.55	255.63	256.09	256.45	256.80	257.09	257.29	257.53	257.71	258.16	258.54	258.76	259.03	259.26
Hangingstone	Hangingstone	3803.124	253.36	255.11	255.58	255.90	256.24	256.52	256.70	256.93	257.09	257.52	257.88	258.12	258.42	258.64
Hangingstone	Hangingstone	3759.014	253.25	254.92	255.36	255.67	255.99	256.26	256.43	256.65	256.81	257.22	257.56	257.79	258.09	258.31
Hangingstone	Hangingstone	3667.133	252.66	254.45	254.80	255.04	255.29	255.50	255.63	255.80	255.93	256.29	256.58	256.77	257.00	257.17
Hangingstone	Hangingstone	3543.804	252.55	253.87	254.25	254.53	254.84	255.10	255.27	255.48	255.65	256.09	256.44	256.66	256.94	257.15
Hangingstone	Hangingstone	3410.358	251.82	253.01	253.34	253.58	253.84	254.05	254.19	254.36	254.48	254.79	255.08	255.28	255.53	255.70
Hangingstone	Hangingstone	3297.98	251.00	252.29	252.66	252.94	253.23	253.48	253.63	253.82	253.95	254.28	254.56	254.75	254.97	255.14
Hangingstone	Hangingstone	3204.177	250.21	251.82	252.23	252.53	252.84	253.09	253.24	253.43	253.56	253.89	254.17	254.36	254.60	254.77
Hangingstone	Hangingstone	3112.05	250.00	251.40	251.83	252.12	252.41	252.65	252.80	252.98	253.11	253.43	253.71	253.89	254.12	254.27
Hangingstone	Hangingstone	3031.108	249.41	251.20	251.60	251.88	252.15	252.38	252.53	252.70	252.83	253.13	253.39	253.57	253.77	253.92
Hangingstone	Hangingstone	2952.679	249.63	250.69	251.10	251.39	251.67	251.92	252.07	252.28	252.41	252.76	253.05	253.24	253.47	253.62
Hangingstone	Hangingstone	2822.849	248.43	250.09	250.57	250.82	251.07	251.29	251.44	251.62	251.75	252.08	252.36	252.54	252.75	252.87
Hangingstone	Hangingstone	2710.264	248.47	249.73	250.24	250.40	250.58	250.76	250.89	251.07	251.19	251.55	251.86	252.07	252.35	252.59
Hangingstone	Hangingstone	2611.931	247.97	249.10	249.45	249.72	250.06	250.35	250.55	250.79	250.96	251.41	251.80	252.05	252.35	252.59
Hangingstone	Hangingstone	2557.02	247.46	248.78	249.25	249.61	249.98	250.29	250.49	250.74	250.91	251.38	251.77	252.03	252.34	252.57
Hangingstone	Hangingstone	2490.552	247.05	248.43	248.97	249.33	249.70	249.99	250.18	250.41	250.57	251.00	251.34	251.55	251.82	252.02
Hangingstone	Hangingstone	2471.188	246.14	248.37	248.91	249.26	249.62	249.91	250.10	250.32	250.48	250.92	251.29	251.51	251.78	251.99
Hangingstone	Hangingstone	2448.198	245.93	248.34	248.87	249.22	249.57	249.85	250.03	250.25	250.40	250.83	251.19	251.40	251.64	251.84
Hangingstone	Hangingstone	2417.885	246.43	248.23	248.70	249.01	249.31	249.55	249.71	249.89	250.02	250.36	250.69	250.92	251.25	251.52
Hangingstone	Hangingstone	2353.985	246.14	248.07	248.54	248.84	249.14	249.38	249.52	249.70	249.83	250.16	250.47	250.67	250.91	251.09
Hangingstone	Hangingstone	2293.532	246.30	247.91	248.33	248.62	248.89	249.10	249.23	249.37	249.47	249.72	249.98	250.14	250.37	250.63
Hangingstone	Hangingstone	2276.289	246.60	247.84	248.28	248.58	248.87	249.09	249.22	249.37	249.47	249.74	250.02	250.18	250.38	250.59

Table B.3: Hangingstone River Flood Profile

River	Reach	River Sta.	Min Ch. El	2-year	5-year	10-year	20-year	35-year	50-year	75-year	100-year	200-year	350-year	500-year	750-year	1000-year
Hangingstone	Hangingstone	2235.721	246.06	247.72	248.14	248.44	248.71	248.9	249.01	249.12	249.20	249.40	249.91[a]	250.06[a]	250.21[a]	250.47[a]
Hangingstone	Hangingstone	2221.769	246.14	247.70	248.11	248.40	248.67	248.86	248.97	249.06	249.13	249.27	249.87[a]	250.02[a]	250.15[a]	250.43[a]
Hangingstone	Hangingstone	2156.103	246.45	247.46	247.91	248.22	248.48	248.68	248.79	248.90	249.07[a]	249.25[a]	249.68[a]	249.83[a]	249.88	250.23[a]
Hangingstone	Hangingstone	2071.505	245.66	247.18	247.73	248.10	248.39	248.63	248.77	248.90	248.99	249.22	249.44	249.59	249.78	249.98
Hangingstone	Hangingstone	2007.202	244.91	246.92	247.45	247.81	248.04	248.25	248.36	248.51	248.62	248.93	249.22	249.41	249.64	249.81
Hangingstone	Hangingstone	1923.395	244.79	246.58	247.16	247.53	247.8	248.05	248.21	248.39	248.52	248.86	249.15	249.35	249.57	249.74
Hangingstone	Hangingstone	1860.687	245.00	246.38	246.95	247.31	247.64	247.9	248.06	248.24	248.37	248.7	248.99	249.18	249.41	249.58
Hangingstone	Hangingstone	1831.466	244.92	246.30	246.88	247.20	247.51	247.81[a]	247.97[a]	248.14[a]	248.27[a]	248.59[a]	248.87[a]	249.05[a]	249.27[a]	249.43[a]
Hangingstone	Hangingstone	1809.216	244.15	246.28	246.86	247.19	247.5	247.75	247.9	248.07	248.19	248.5	248.77	248.95	249.16	249.32
Hangingstone	Hangingstone	1771.252	243.80	246.18	246.73	247	247.27	247.47	247.6	247.75	247.87	248.25	248.56	248.76	248.99	249.16
Hangingstone	Hangingstone	1744.084	244.07	246.09	246.63	246.9	247.16	247.36	247.47	247.61	247.71	247.98	248.21	248.38	248.54	248.65
Hangingstone	Hangingstone	1706.852	244.41	245.88	246.4	246.65	246.9	247.11	247.26	247.41	247.53	247.84	248.11	248.3	248.49	248.61
Hangingstone	Hangingstone	1630.86	244.15	245.46	245.85	246.09	246.33	246.53	246.67	246.85	246.97	247.24	247.48	247.62	247.81	247.95
Hangingstone	Hangingstone	1541.086	243.74	245.09	245.5	245.73	245.98	246.19	246.33	246.52	246.66	246.97	247.24	247.42	247.64	247.81
Hangingstone	Hangingstone	1459.563	243.38	244.61	245.03	245.3	245.59	245.82	245.98	246.16	246.3	246.64	246.94	247.15	247.41	247.61
Hangingstone	Hangingstone	1408.073	242.89	244.45	244.84	245.12	245.42	245.67	245.83	246.02	246.16	246.51	246.81	247.02	247.28	247.48
Hangingstone	Hangingstone	1389.484	242.51	244.33	244.67	244.95	245.26	245.65[a]	245.81[a]	246.00[a]	246.14[a]	246.50[a]	246.80[a]	247.02[a]	247.28[a]	247.47[a]
Hangingstone	Hangingstone	1313.773	242.89	244.1	244.57	244.92	245.26	245.55	245.72	245.93	246.08	246.46	246.78	247	247.26	247.45
Hangingstone	Hangingstone	1242.932	242.36	243.94	244.45	244.8	245.14	245.41	245.58	245.78	245.92	246.28	246.59	246.79	247.04	247.21
Hangingstone	Hangingstone	1193.156	241.37	243.86	244.36	244.7	245.02	245.29	245.44	245.63	245.76	246.09	246.37	246.55	246.76	246.91
Hangingstone	Hangingstone	1171.259	241.88	243.82	244.31	244.64	244.95	245.2	245.35	245.53	245.66	245.98	246.25	246.43	246.64	246.79
Hangingstone	Hangingstone	1129.931	241.74	243.74	244.22	244.55	244.85	245.08	245.23	245.39	245.51	245.90[a]	246.18[a]	246.36[a]	246.58[a]	246.73[a]
Hangingstone	Hangingstone	1087.974	241.71	243.69	244.17	244.5	244.8	245.04	245.19	245.37	245.49	245.82	246.11	246.29	246.51	246.67
Hangingstone	Hangingstone	1022.868	241.52	243.58	244.06	244.39	244.69	244.93	245.08	245.26	245.39	245.73	246.02	246.21	246.43	246.59
Hangingstone	Hangingstone	960.0525	241.96	243.36	243.9	244.27	244.57	244.81	244.97	245.15	245.29	245.62	245.91	246.09	246.31	246.48
Hangingstone	Hangingstone	882.2751	240.80	243.25	243.85	244.23	244.54	244.79	244.94	245.13	245.27	245.61	245.9	246.08	246.31	246.47
Hangingstone	Hangingstone	768.9972	240.77	243.09	243.72	244.13	244.46	244.73	244.9	245.09	245.23	245.58	245.88	246.07	246.29	246.46
Hangingstone	Hangingstone	700.7451	241.01	242.98	243.62	244.06	244.43	244.7	244.87	245.06	245.21	245.56	245.85	246.04	246.27	246.44
Hangingstone	Hangingstone	648.1558	240.74	242.94	243.58	244.03	244.38	244.65	244.81	245.01	245.15	245.49	245.77	245.96	246.17	246.33
Hangingstone	Hangingstone	548.9328	240.88	242.83	243.45	243.89	244.23	244.49	244.66	244.85	244.99	245.33	245.61	245.78	245.99	246.15
Hangingstone	Hangingstone	489.7931	241.24	242.78	243.42	243.85	244.2	244.46	244.63	244.83	244.96	245.3	245.58	245.75	245.96	246.11
Hangingstone	Hangingstone	434.9363	240.54	242.73	243.38	243.82	244.17	244.44	244.61	244.8	244.94	245.28	245.55	245.73	245.94	246.09
Hangingstone	Hangingstone	372.1107	240.61	242.68	243.33	243.77	244.12	244.4	244.57	244.77	244.91	245.25	245.53	245.7	245.91	246.07
Hangingstone	Hangingstone	292.7723	240.69	242.61	243.27	243.73	244.08	244.35	244.53	244.73	244.87	245.21	245.48	245.66	245.87	246.02
Hangingstone	Hangingstone	226.8436	240.37	242.56	243.22	243.68	244.04	244.32	244.49	244.69	244.83	245.17	245.44	245.62	245.82	245.98
Hangingstone	Hangingstone	133.8605	240.06	242.49	243.17	243.63	244	244.27	244.45	244.64	244.78	245.12	245.39	245.57	245.77	245.92
Hangingstone	Hangingstone	106.2144	240.37	242.48	243.17	243.64	244	244.28	244.45	244.65	244.79	245.13	245.4	245.57	245.78	245.93
Hangingstone	Hangingstone	92.31356	240.21	242.47	243.17	243.64	244.01	244.29	244.46	244.66	244.8	245.14	245.42	245.59	245.8	245.95

(a) Linear Interpolation between upstream and downstream water levels to remove dip at bridge.

Table B.4: Snye River Flood Profile

River	Reach	River Sta.	Min Ch. El	2-year	5-year	10-year	20-year	35-year	50-year	75-year	100-year	200-year	350-year	500-year	750-year	1000-year
Snye	Snye	1332.108	239.34	241.75	242.38	242.91	243.3	243.6	243.8	244.02	244.17	244.56	244.88	245.09	245.33	245.5
Snye	Snye	931.9456	238.31	241.75	242.38	242.91	243.3	243.6	243.8	244.02	244.17	244.56	244.88	245.09	245.33	245.5
Snye	Snye	455.9648	238.63	241.75	242.38	242.91	243.3	243.6	243.8	244.02	244.17	244.56	244.88	245.09	245.33	245.5
Snye	Snye	171.6331	238.11	241.75	242.38	242.91	243.3	243.6	243.8	244.02	244.17	244.56	244.88	245.09	245.33	245.5

APPENDIX C

Model Sensitivity Analysis

Figure C.1: Channel Roughness Sensitivity Analysis for Athabasca River

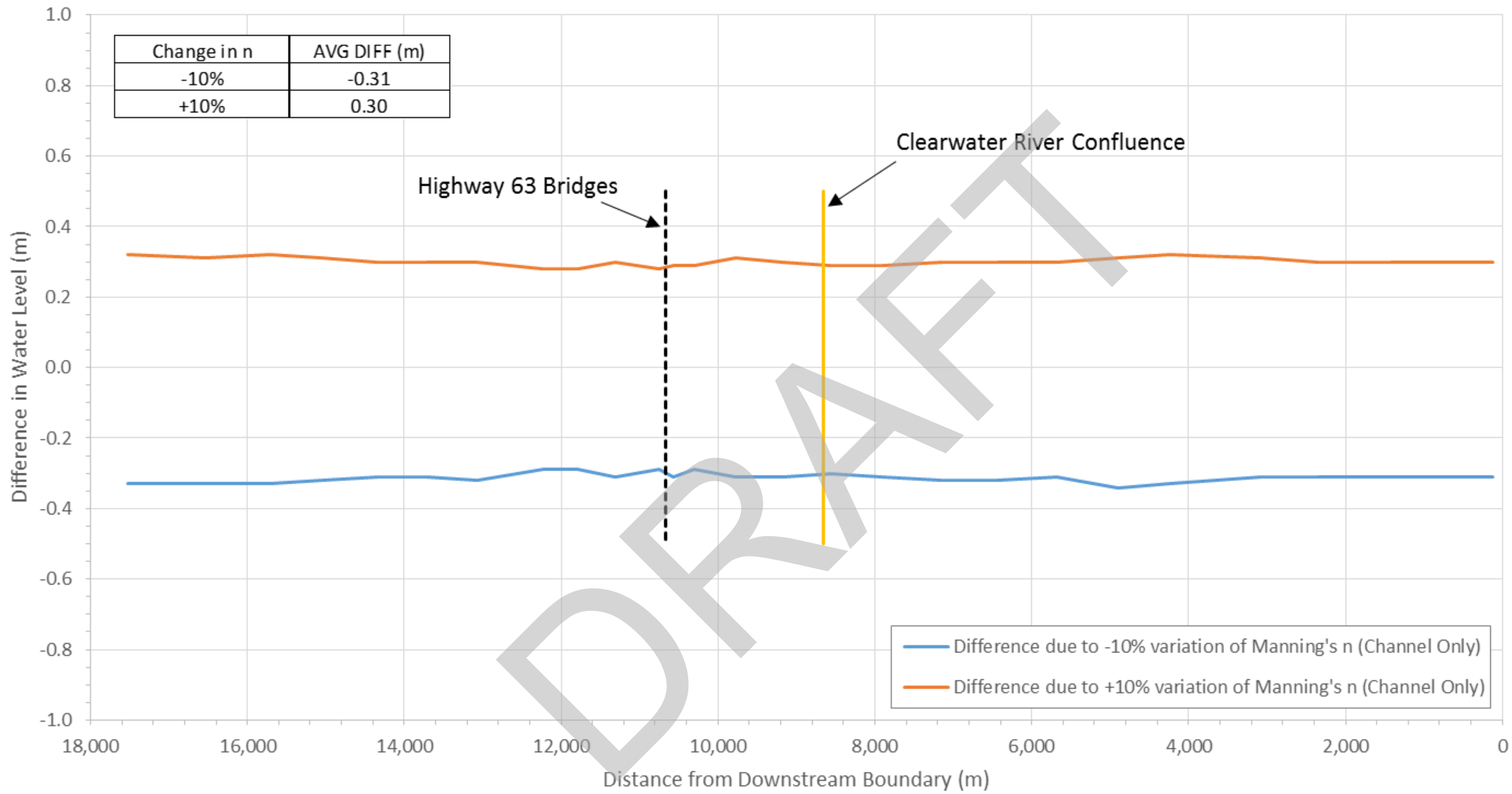
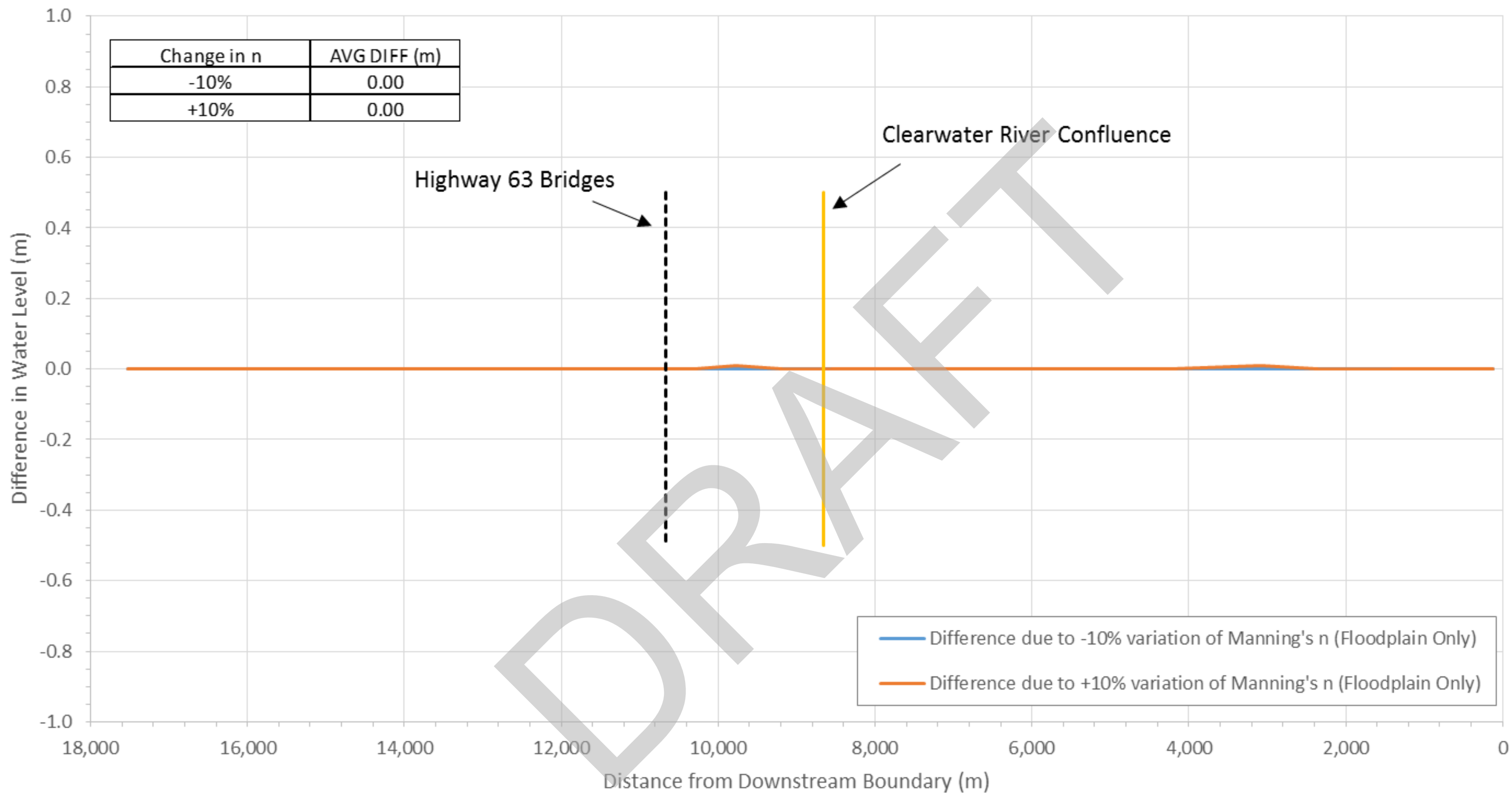


Figure C.2: Floodplain Roughness Sensitivity Analysis for Athabasca River



Change in n	AVG DIFF (m)
-10%	0.00
+10%	0.00

Figure C.3: Channel and Floodplain Roughness Sensitivity Analysis for Athabasca River

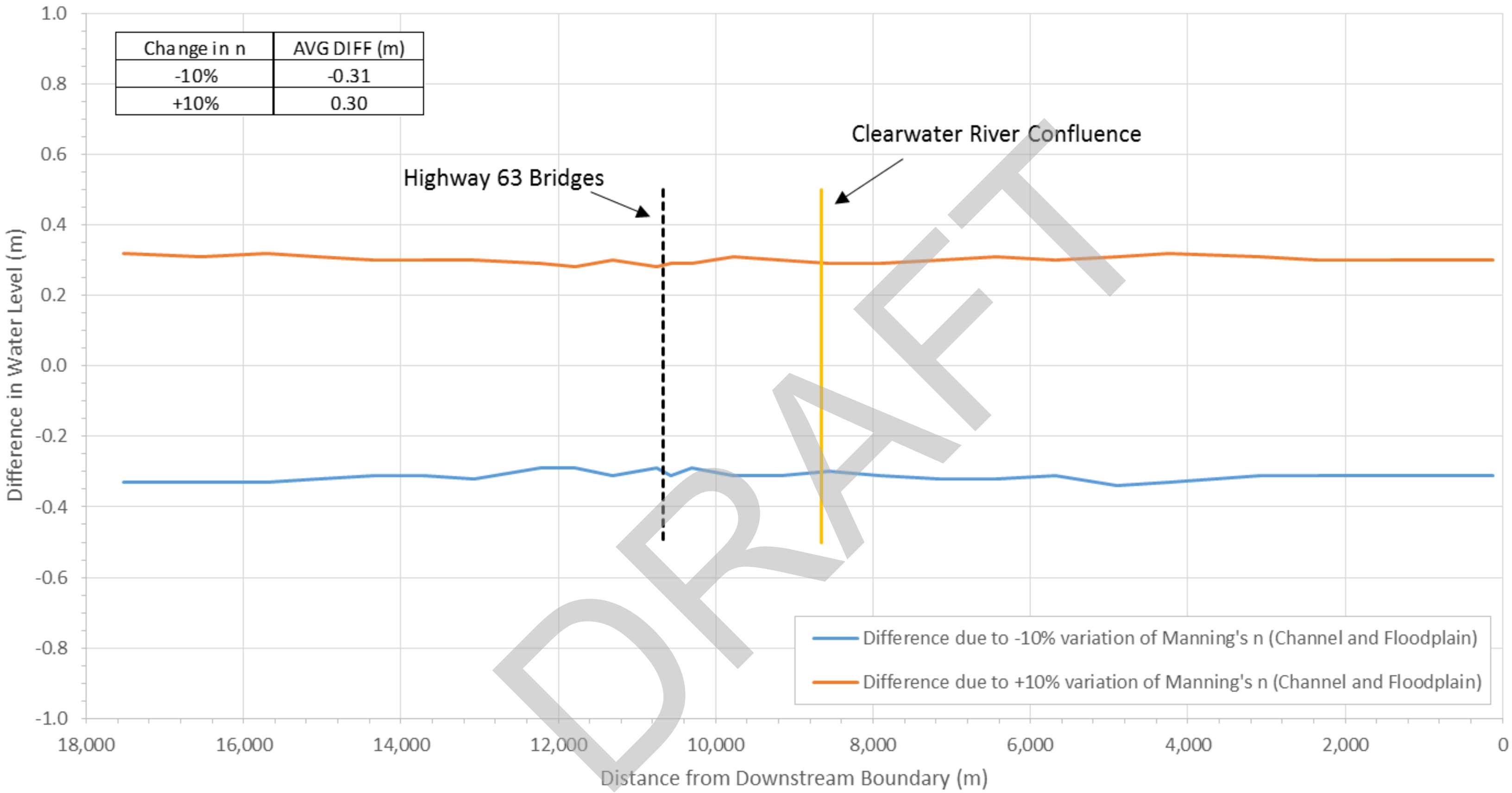


Figure C.4: Downstream Boundary Condition Sensitivity Analysis for Athabasca River

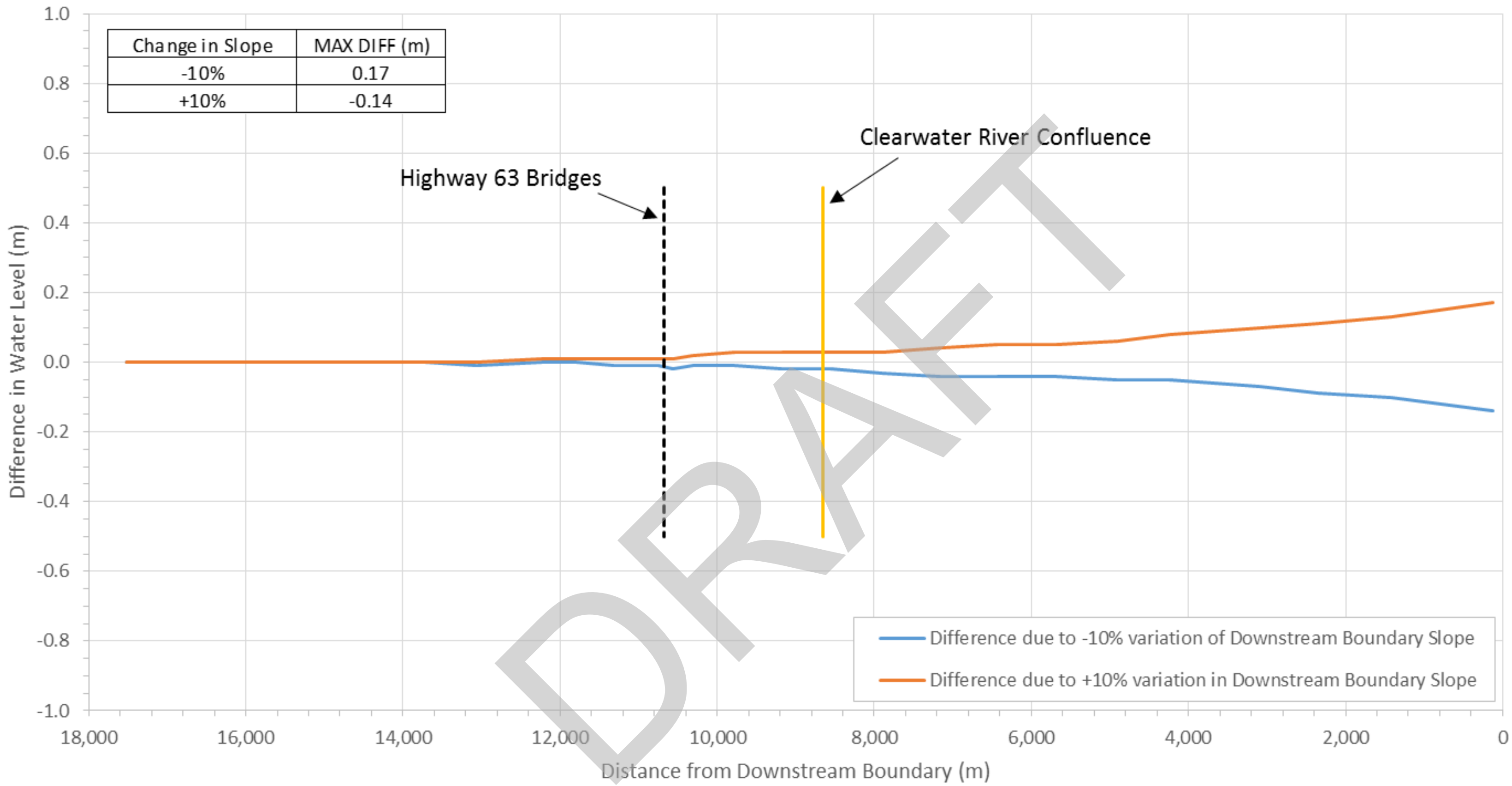


Figure C.5: Channel Roughness Sensitivity Analysis for Hangingstone River

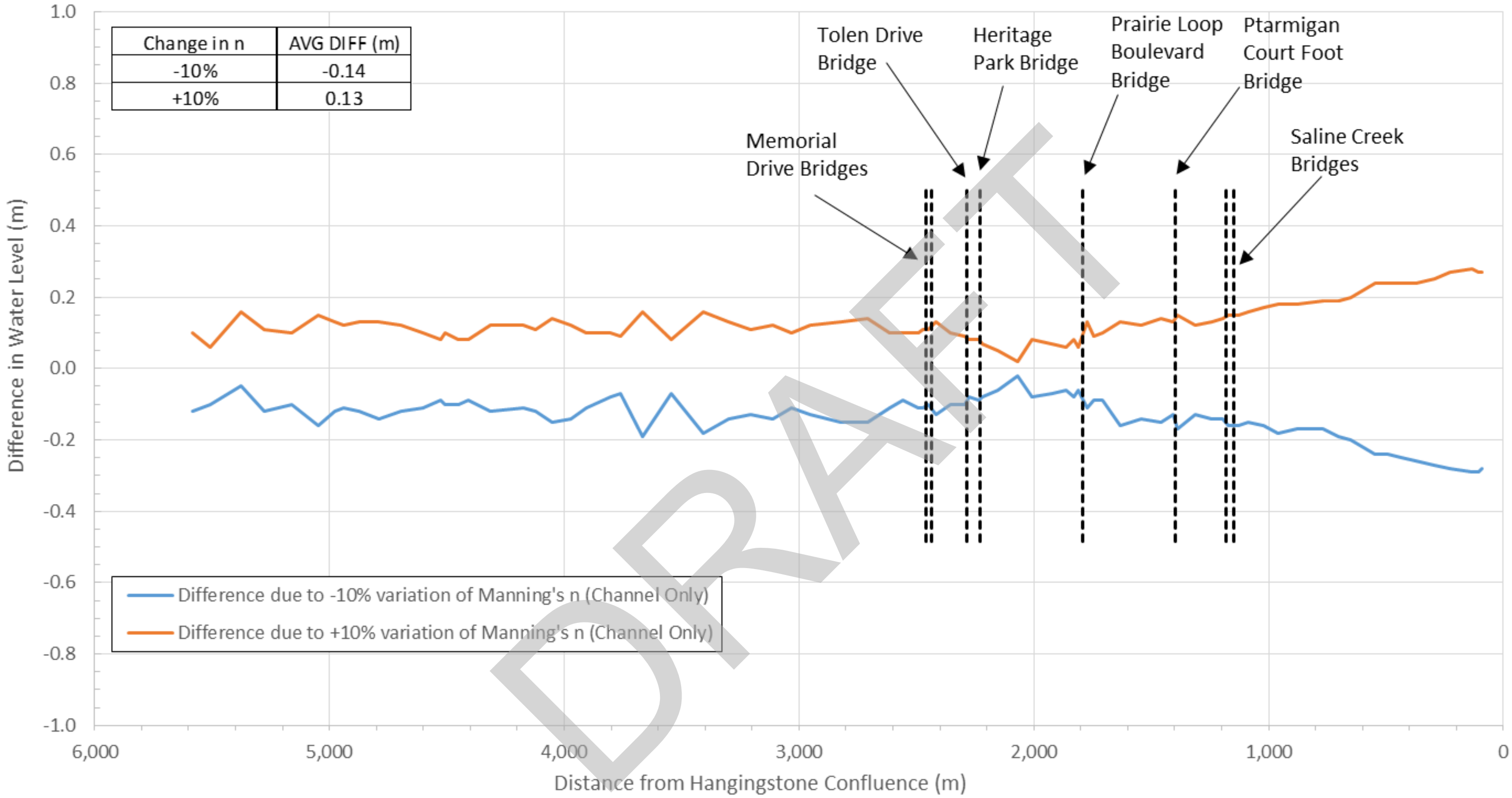


Figure C.6: Floodplain Roughness Sensitivity Analysis for Hangingstone River

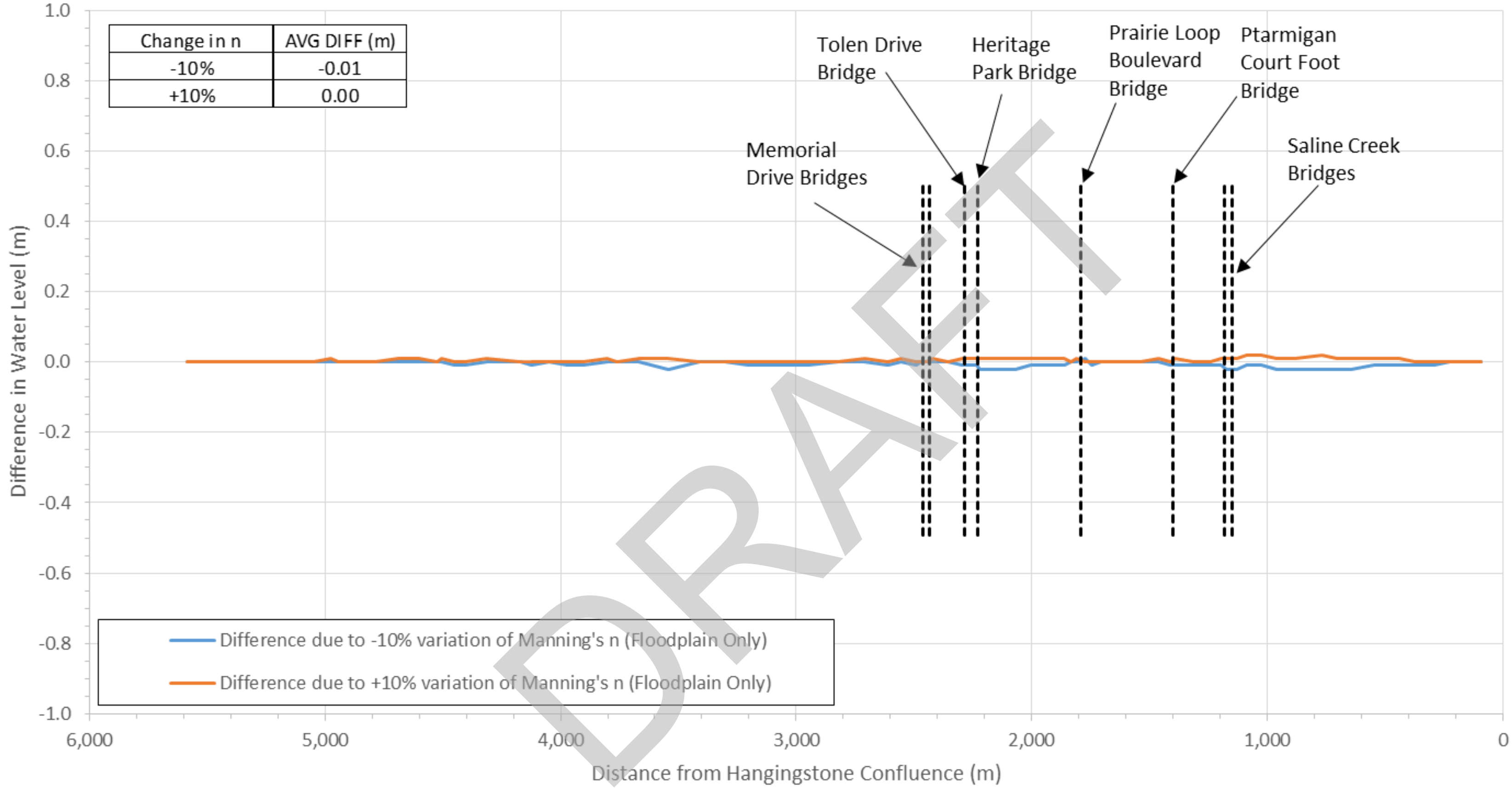


Figure C.7: Channel and Floodplain Roughness Sensitivity Analysis for Hangingstone River

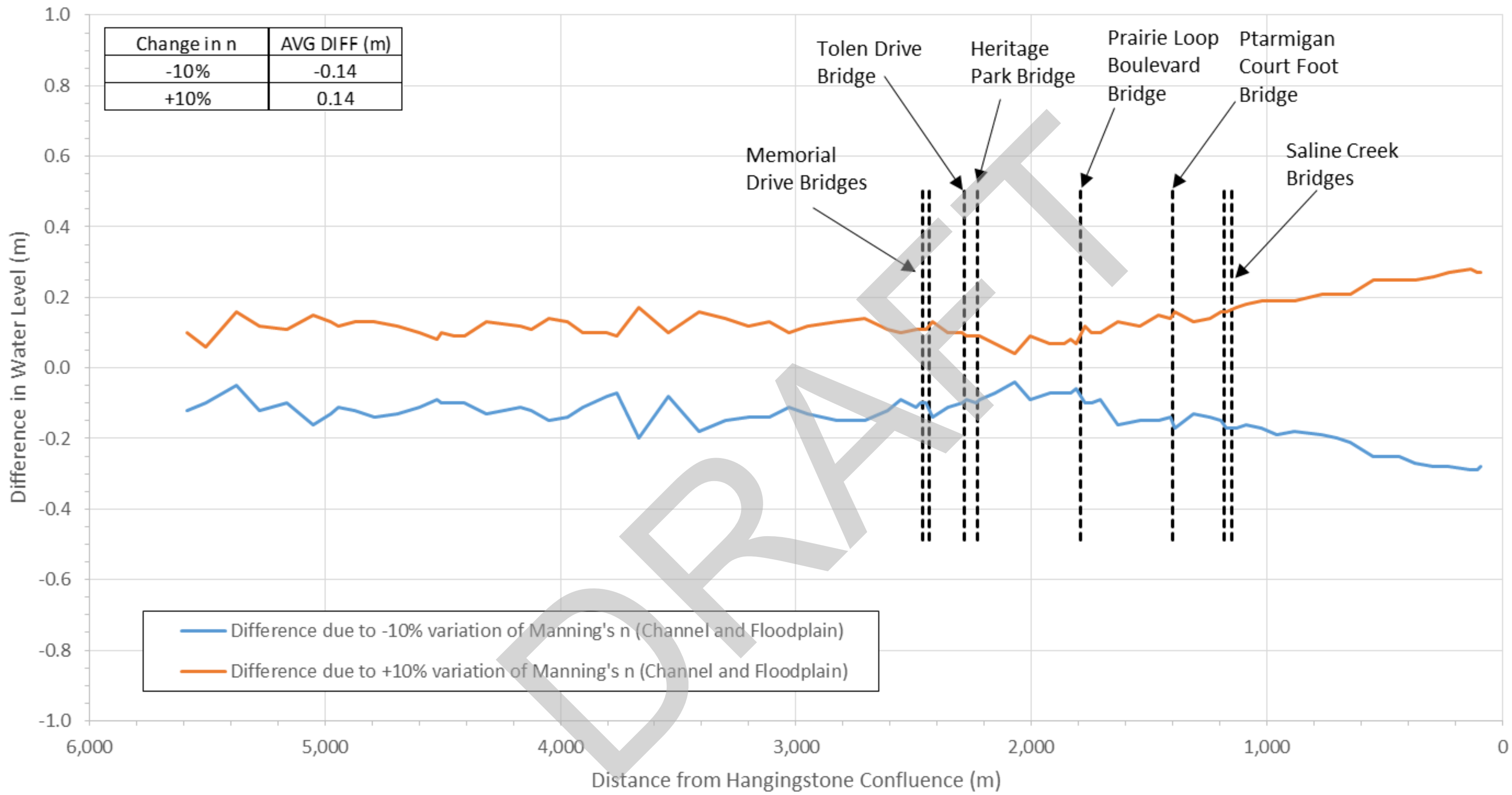


Figure C.8: Downstream Boundary Condition Sensitivity Analysis for Hangingstone River

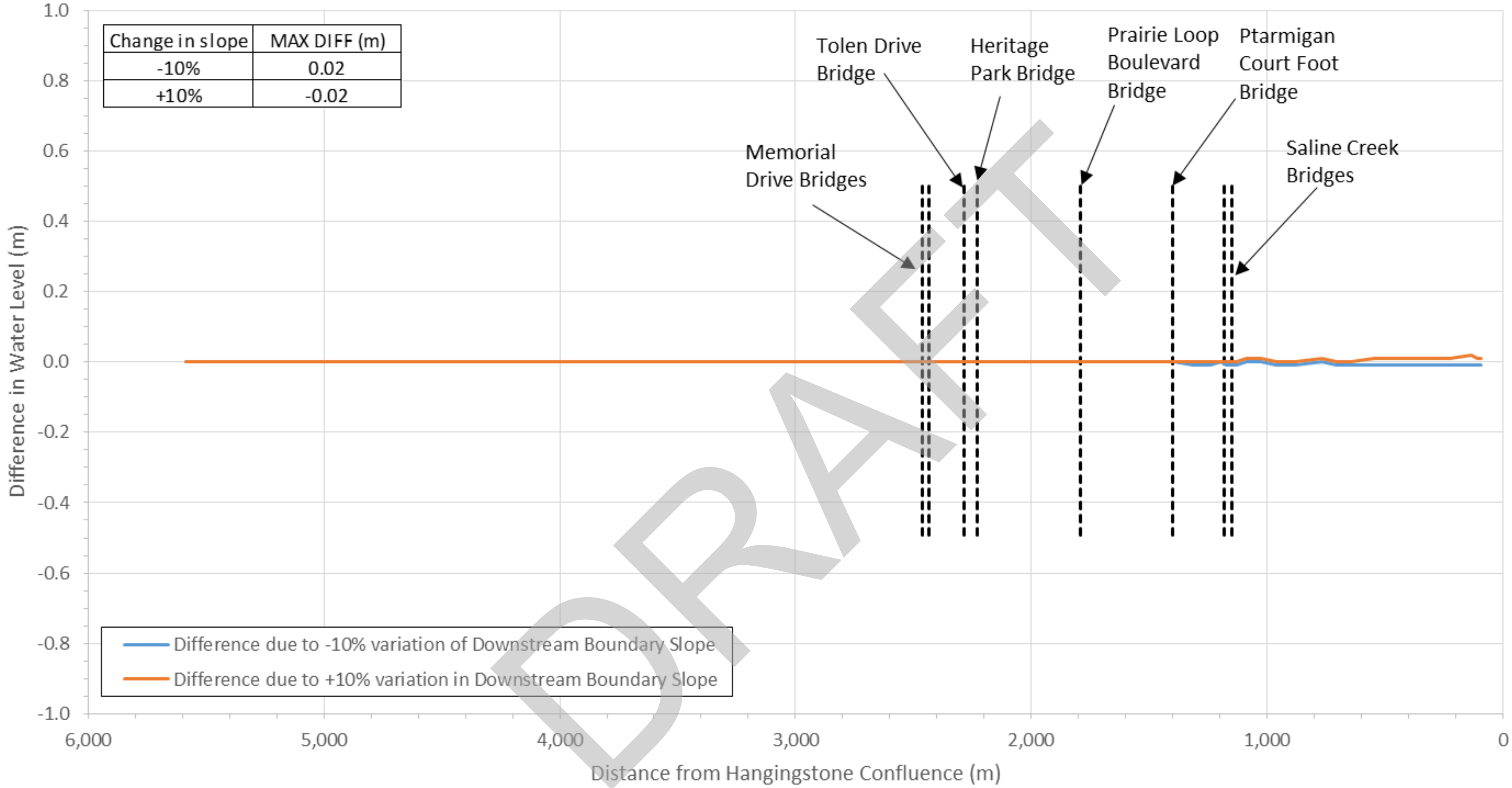


Figure C.9: Channel Roughness Sensitivity Analysis for Clearwater River

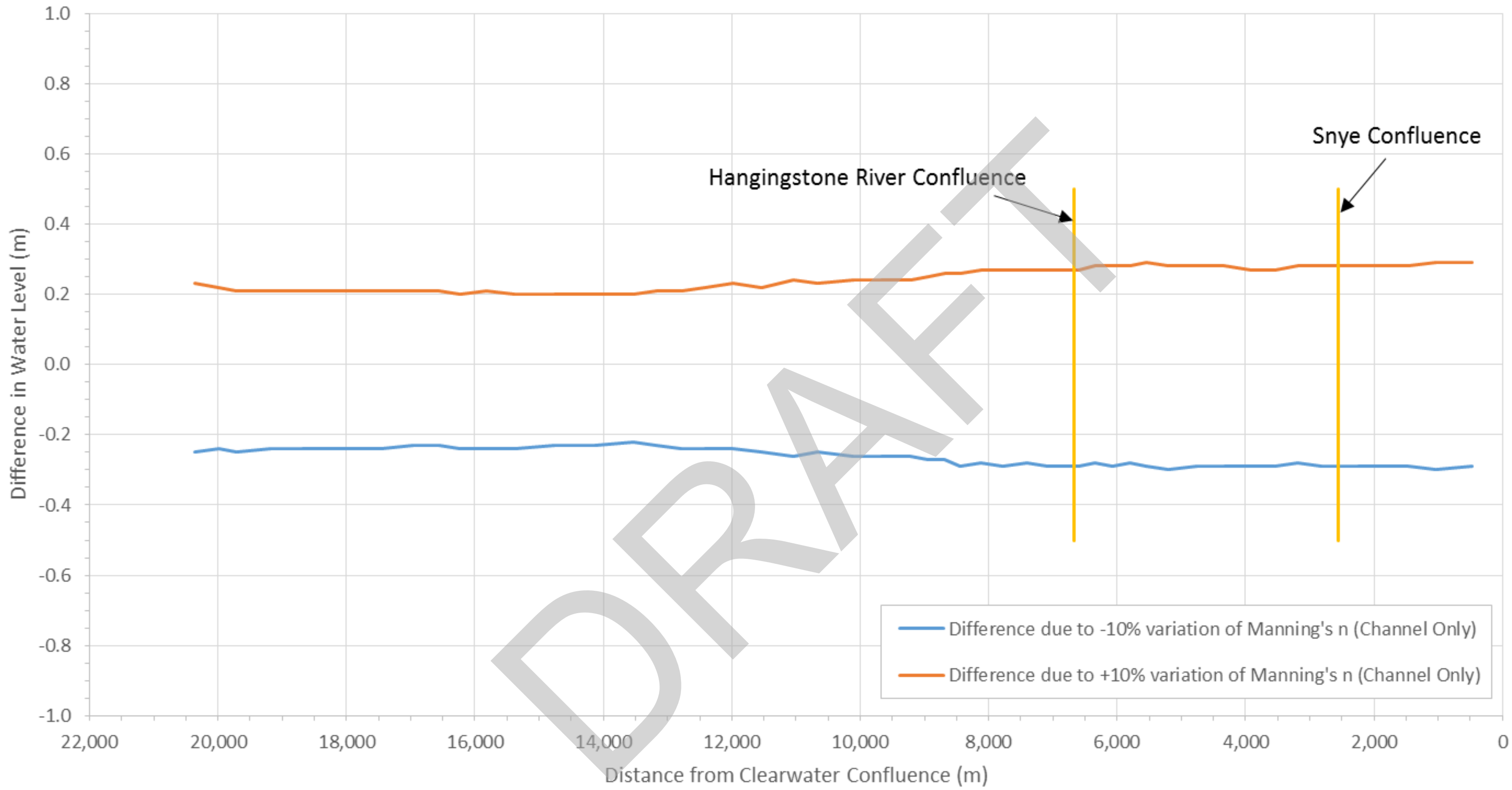


Figure C.10: Floodplain Roughness Sensitivity Analysis for Clearwater River

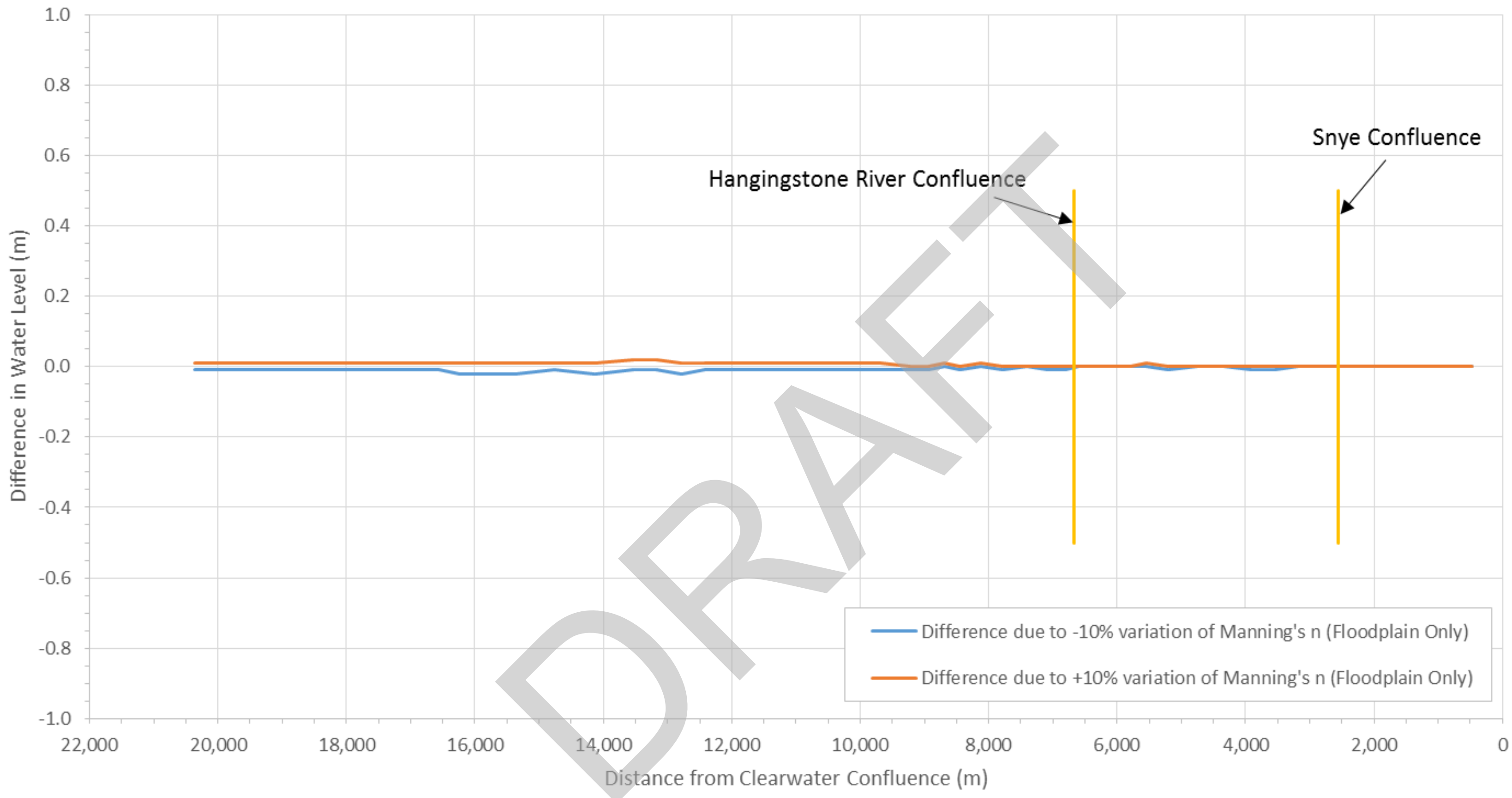


Figure C.11: Channel and Floodplain Roughness Sensitivity Analysis for Clearwater River

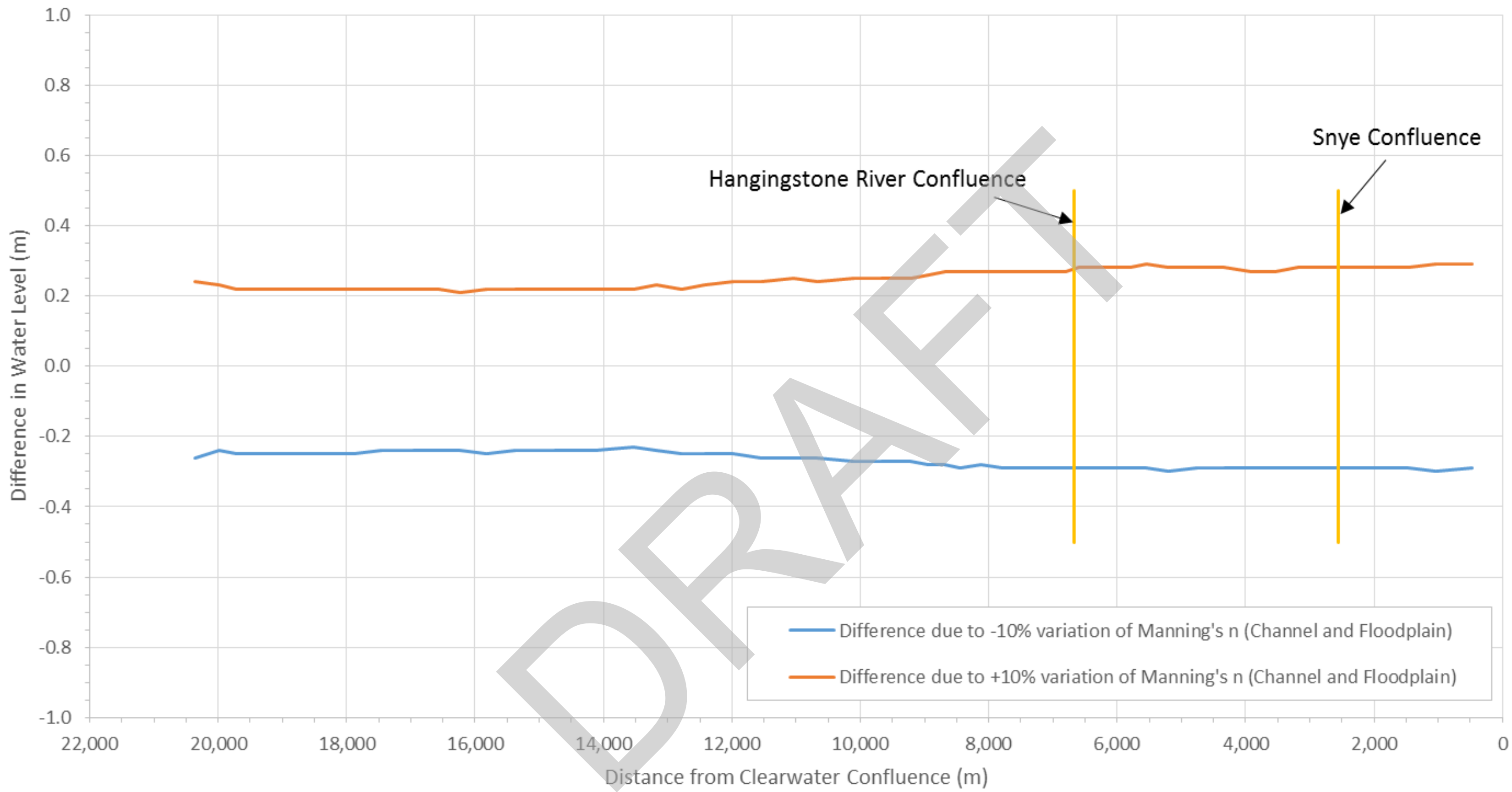


Figure C.12: Downstream Boundary Condition Sensitivity Analysis for Clearwater River

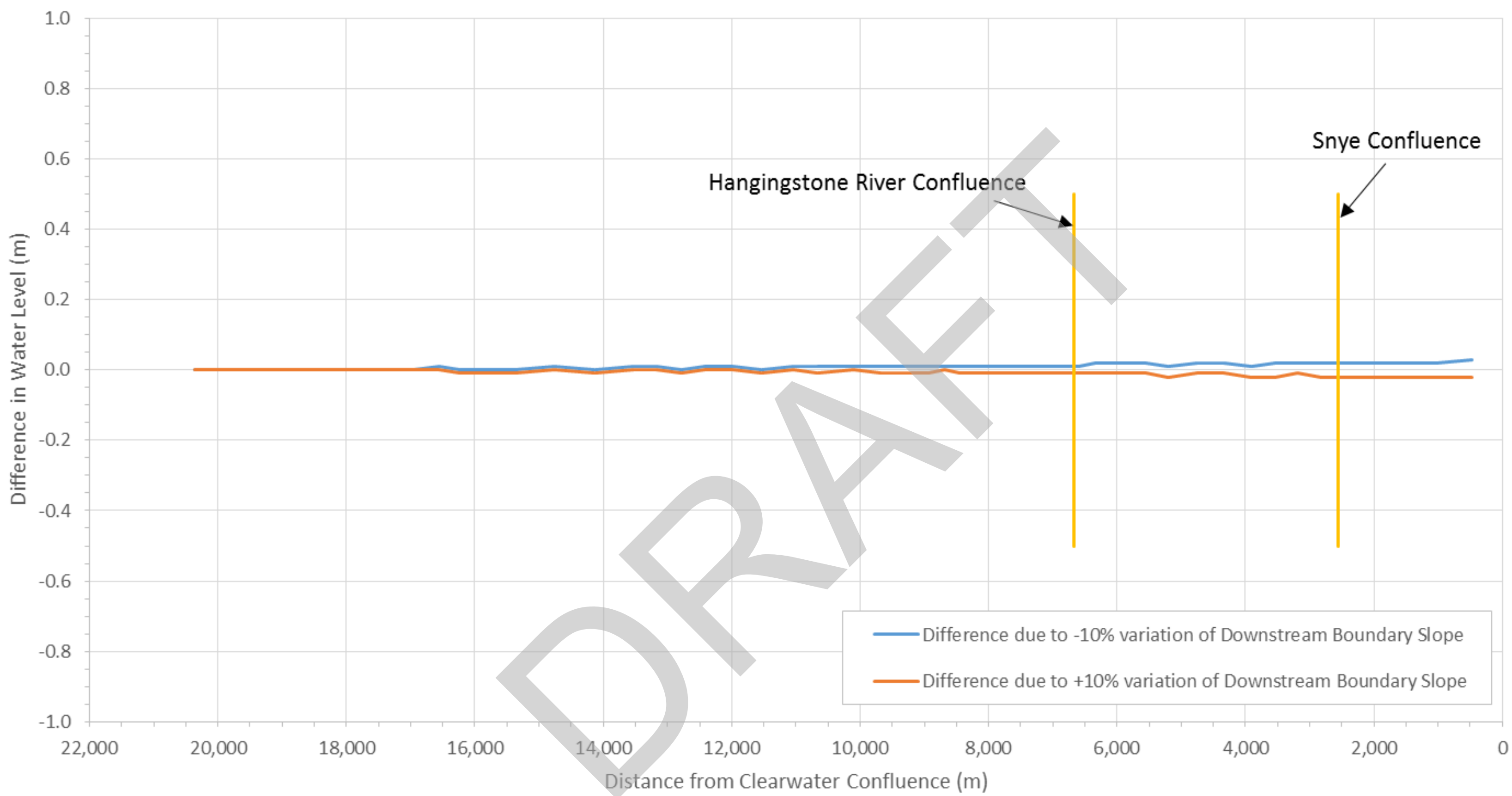


Figure C.13: Channel Roughness Sensitivity Analysis for the Snye

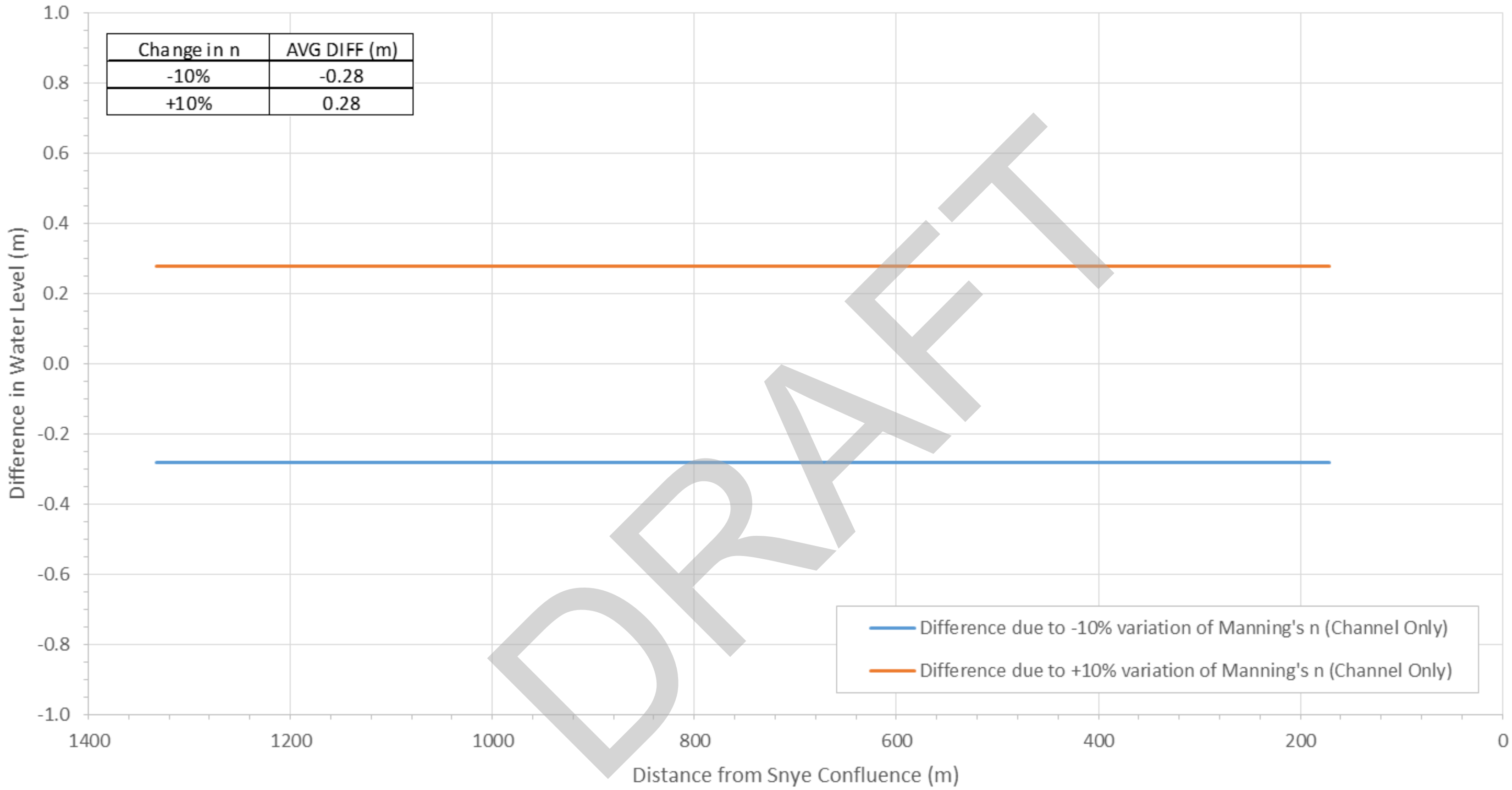


Figure C.14: Floodplain Roughness Sensitivity Analysis for the Snye

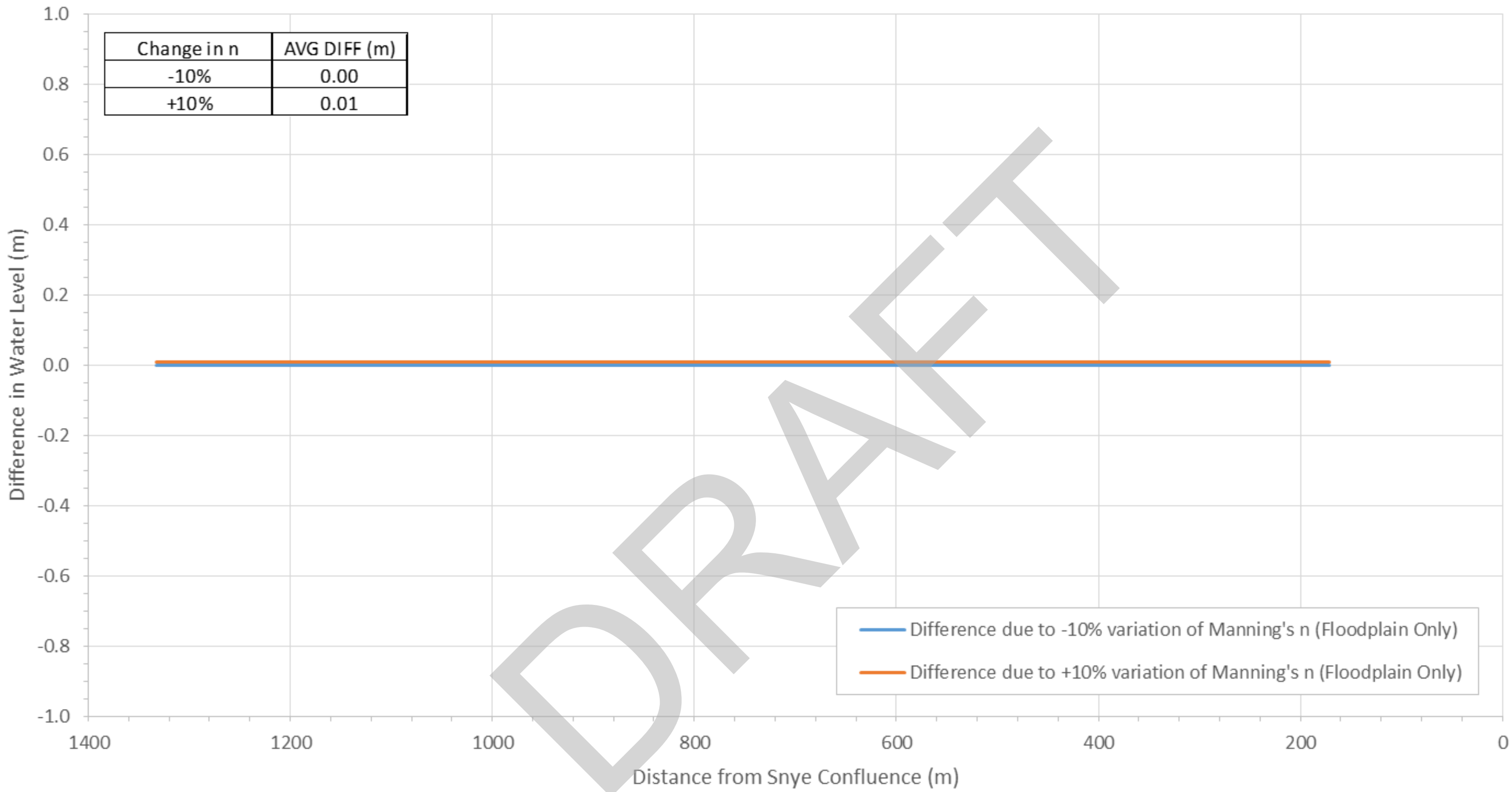


Figure C.15: Channel and Floodplain Roughness Sensitivity Analysis for the Snye

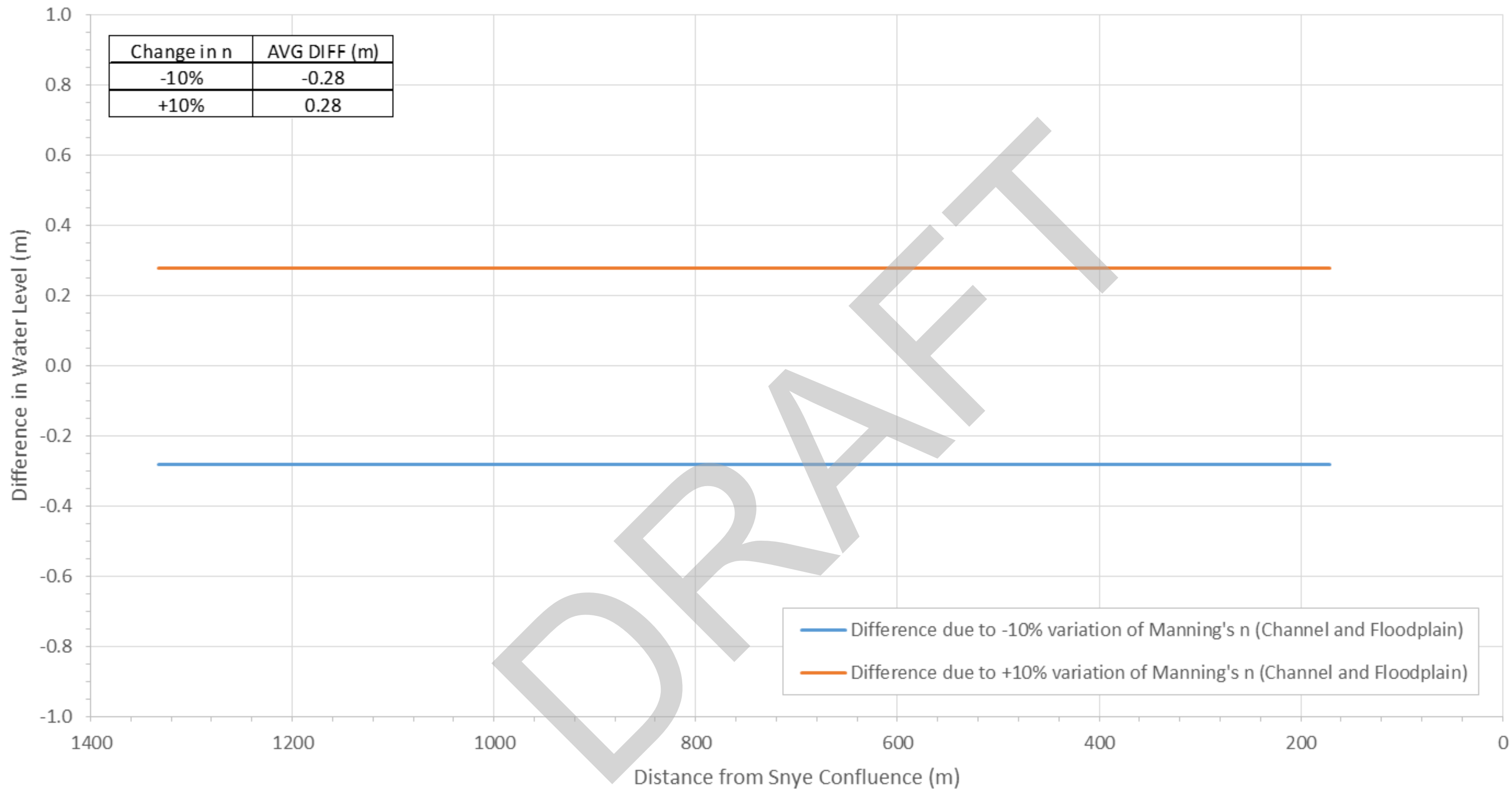
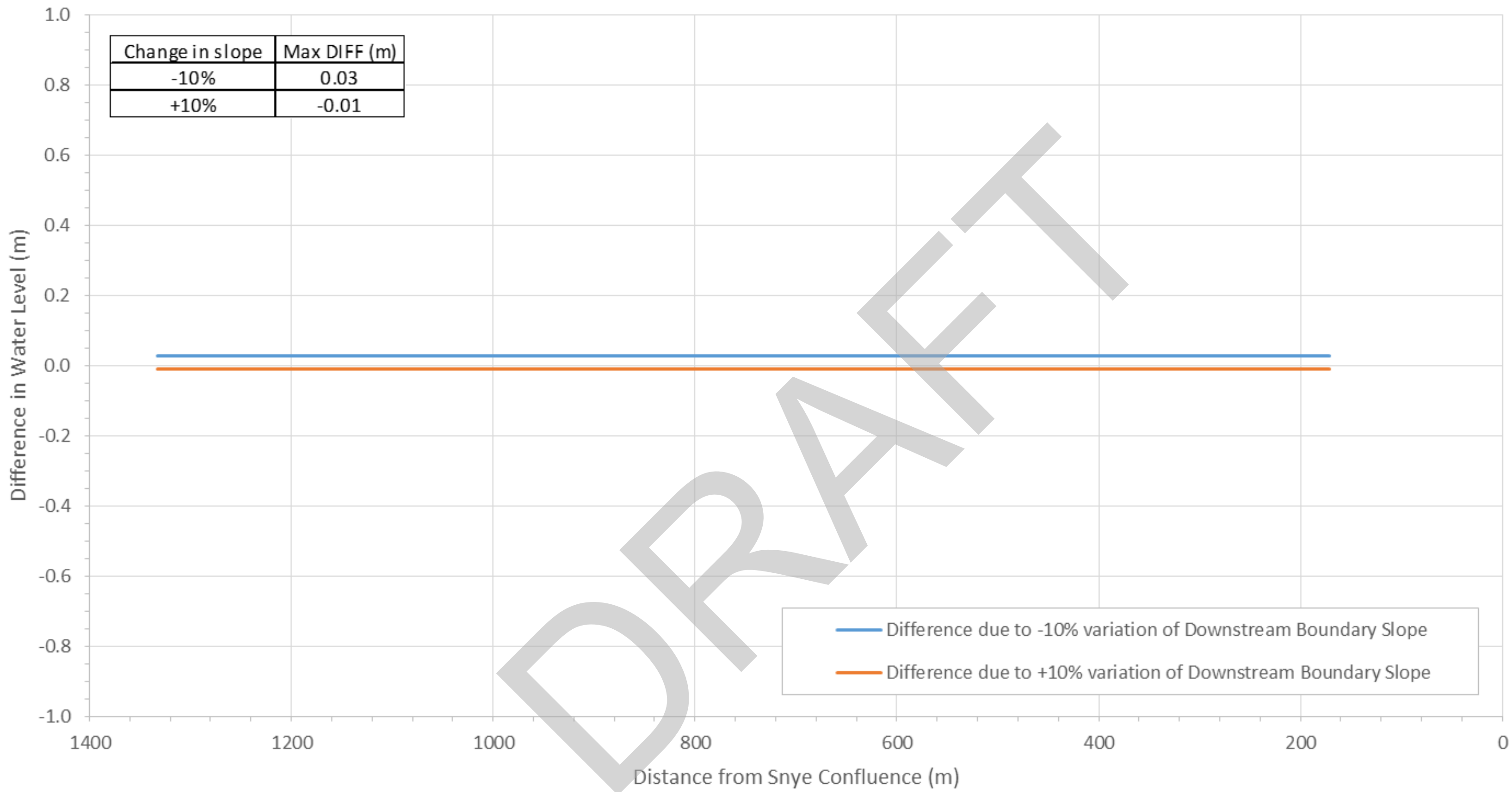


Figure C.16: Downstream Boundary Condition Sensitivity Analysis for the Snye



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