January 2019

SIKSIKA BOW RIVER HAZARD STUDY

Hydraulic Model Creation and Calibration

Submitted to:
Alberta Environment and Parks
11th Floor, Oxbridge Place
9820 - 106 Street NW
Edmonton, AB T5K 2J6

REPORT

Report Number: 1783054

Distribution:

Five Copies - Alberta Environment and Parks
One Copy - Golder Associates Ltd.

Golder Associates

Classification: Public

Executive Summary

Golder Associates Ltd. (Golder) was commissioned by Alberta Environment and Parks (AEP) to undertake the Siksika Bow River Hazard Study (the Study) along the Bow River reach (the study reach) from the Highwood River confluence to a location approximately 2 km downstream of Bow City. There are two irrigation diversion canals (i.e. Carseland Diversion of Bow River Irrigation District and Bassano Dam Diversion of Eastern Irrigation District) and no major tributaries along the study reach.

The study is conducted under the provincial Flood Hazard Identification Program (FHIP). The study consists of seven components. This report documents the methodology and results of one of the components (i.e., the hydraulic model creation and calibration component). This component involves description of the flooding history, model setup, model calibration and validation, sensitivity analysis and generation of open water flood frequency profiles. The modelling results are used to support the flood inundation mapping, flood hazard identification, governing design flood hazard mapping and flood risk assessment components.

Historic Floods

Historic flood events of exceptional magnitudes occurred on the Bow River in 1879, 1897, 1902, 1915, 1929, 1932, 1995, 2005 and 2013. The major floods were commonly associated with high rainfall or rain on snow events during the period from May to July. Prior to construction of the Bearspaw Dam in 1953, the Bow River was subject to both open water and ice jam floods on Bow River. Following the flow regulation changes, no large ice jam floods have occurred along the Bow River downstream of Bearspaw Dam. A typical flood event lasted for a duration of three days with a time to peak of one day.

Hydraulic Model Setup

The latest HEC-RAS program (Version 5.0.5, June 2018) was used to develop the one-dimensional (1D) hydraulic model in the study area. The model was set up with one geometry file using the latest river bathymetry survey and LiDAR data collected after the 2013 flood.

Model Calibration and Validation

The HEC-RAS model was calibrated and validated based on the available high flow and rating curve data. River channel Manning's n roughness coefficient is the main model parameter used in calibrating the HEC-RAS model. The calibrated channel Manning's n values for the high flow conditions range from 0.030 to 0.040 along the study reach. These Manning's n values are within the typical range of roughness values for similar rivers (Chow 1959).

For the 2013 flood event, the average difference between the simulated water levels and the High Water Marks (HWMs) surveyed by AEP is -0.08 m, with individual differences ranging from -0.58 to +0.71 m along the study reach.

Model Sensitivity

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 similar influence on the simulated flood levels as variation of the floodplain roughness values.

The 100-year flood levels are estimated, on average, to be within a range of ±0.24 m along the study reach based mainly on the differences in the simulated flood levels for the ±10% changes from the calibrated channel and floodplain Manning's *n* values.

Flood Profiles

After June 2013 flood, additional flood protection berms were constructed in the Siksika Nation area. Recently, a new emergency spillway was constructed at the Bassano Dam. The HEC-RAS production model was set up for the post-berm conditions based on the calibrated model for the pre-berm conditions.

A total of seven flow change locations along the study reach were selected and included in the production model. The flood peak discharges at these locations were estimated based on the results of the hydrology study report (Golder 2017).

The production model was used to simulate the flood profiles of the 2-, 5-, 10-, 20-, 35-, 50-, 75-, 100-, 200-, 350-, 500-, 750- and 1,000-year flood events for the post-berm conditions.

Acknowledgements

Golder Associates Ltd. (Golder) acknowledges the contributions of the following staff of Alberta Environment and Parks (AEP) to the Hydraulic Model Creation and Calibration component of the Siksika Bow River Hazard Study:

- Mr. Kurt Morrison, AEP's project manager for the study, coordinated the participation from AEP, and provided technical advice and review comments on the study report.
- Mr. Peter Onyshko, AEP's technical advisor for the study, provided study technical review and technical guidance.

The contributions of the following staff from Golder to the study are also acknowledged:

- Dr. Hua Zhang, Golder's project manager, was responsible for regular communications with AEP, collecting the data and information, scheduling meetings with AEP, overseeing the HEC-RAS modelling analysis, and reviewing the study report.
- Dr. Dejiang Long, Golder's senior reviewer and director for the project, was responsible for providing senior inputs and review, quality control and assurance for the study, and reviewing the study report.
- Mr. Jie Chen, Golder's hydrodynamic modelling specialist and project engineer for this study. He was responsible for conducting the HEC-RAS modelling analysis, and preparing the study report.
- Dr. Parnian Hosseini, Golder's hydrodynamic modelling support for this study. She was involved in conducting the HEC-RAS modelling analysis.
- Dr. Getu Biftu, Golder's senior hydrologist, was responsible for providing senior inputs and advice on flood hydrology.

Table of Contents

TABLES

FIGURES

APPENDICES

1.0 INTRODUCTION

1.1 Study Components

Golder Associates Ltd. (Golder) was commissioned by Alberta Environment and Parks (AEP) in August 2017 to undertake the Siksika Bow River Hazard Study (the study) along the Bow River reach (the study reach) from Highwood River confluence to a location approximately 2 km downstream of Bow City. The study was conducted under the provincial Flood Hazard Identification Program (FHIP). The study consists of seven components. A stand-alone report was prepared for each of these components.

This report documents the methodology and results of the hydraulic model creation and calibration component. The scope of this component includes description of the flooding history in the study area, hydraulic model setup, hydraulic model calibration and validation, sensitivity analysis, and generation of open water flood frequency profiles. The results of this component are used in the flood inundation mapping, flood hazard identification, governing design flood hazard mapping, and flood risk assessment components.

1.2 Study Goal and Objective

The overall goal of the study is to enhance public safety and support the assessment and identification of flood hazards in the study area. The study results are intended to reduce potential future flood damages and associated disaster assistance costs, to mitigate flood impacts by informing land use planning decisions, and for emergency preparation.

The specific objective of the hydraulic model creation and calibration component was to develop a calibrated HEC-RAS hydraulic model for the study area based on the latest river bathymetry survey and LiDAR data collected after the 2013 flood. The calibrated HEC-RAS model was used to simulate the 2-, 5-, 10-, 20-, 35-, 50-, 75-, 100-, 200-, 350-, 500- , 750- and 1,000-year flood events.

1.3 Study Area

The study area includes the 221 km long reach of the Bow River as shown in Figure 1. There are two irrigation diversion canals (i.e. Carseland Diversion of Bow River Irrigation District [BRID] and Bassano Dam Diversion of Eastern Irrigation District [EID]) and no major tributaries along the study reach. The downstream boundary of the hydraulic model terminates along the Bow River at a distance of 2 km downstream of Bow City.

The study area is situated in the Siksika Nation, the Hamlet of Bow City, and the lands in five municipal districts and counties, including Municipal District of Foothills No. 31, and the Counties of Newell, Rocky View, Vulcan and Wheatland.

1.4 Work Scope

The scope of the hydraulic model creation and calibration component includes the following:

- Documentation of flooding history;
- Summary of available data;
- Documentation of river and valley features;
- Model setup, model calibration and validation;
- Generation of open-water flood frequency profiles; and
- Model sensitivity analysis.

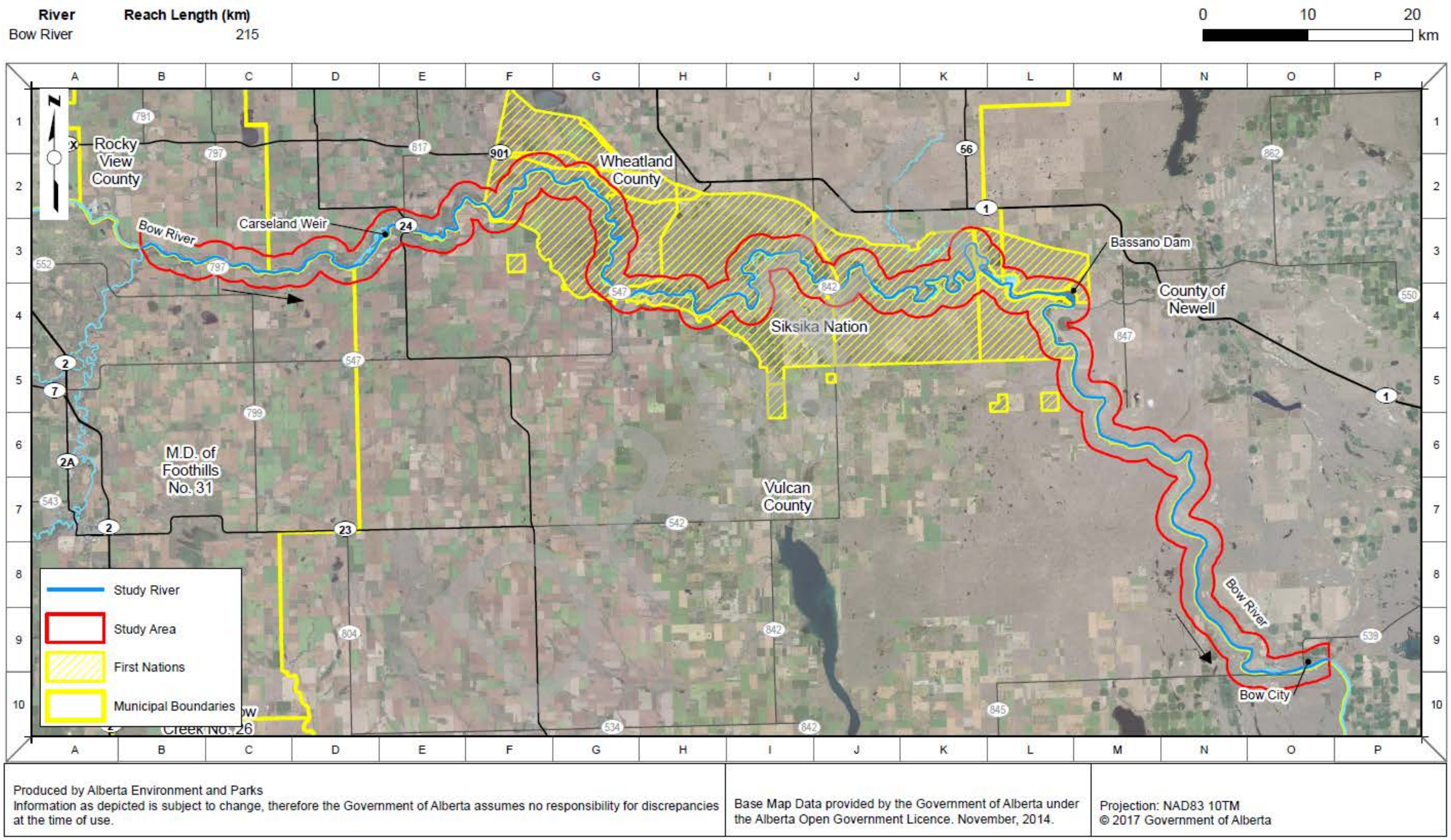


Figure 1: Study Area (Provided by AEP)

2.0 FLOODING HISTORY

2.1 General Information

The flooding history in the study area was reviewed to provide insight into current flood mechanisms and to provide a basis for model setup, calibration and validation. The major sources of information on the flooding history include the data and information collected from AEP, Water Survey of Canada (WSC), Alberta Transportation (AT), Siksika Nation, local residents, local newspapers, and previous study reports.

Major floods along the Bow River in the study area were commonly associated with high rainfall or rain-on-snow events during the period of May to July. A typical flood event on the Bow River lasts for three days with a time to peak of about one day.

2.2 Open Water Floods

2.2.1 Historic and Observed Floods

A summary of the recorded and reported peak instantaneous flows of the major flood events within the study area is provided in Table 1. The water levels and discharges on the Bow River have been recorded at the WSC gauging stations below Carseland Dam since 1910 and below Bassano Dam since 1910.

Note that the name of "WSC Gauging Stations below Carseland Dam" might be misleading because the station is actually located above the dam based on our communications with AEP and email confirmation from Samantha Hussey, Watershed GIS Technologist/Data Control Technologist at the National Hydrological Services, Environment and Climate Change Canada dated October 30, 2018. The reason for the confusion is the station was established in 1956 on the downstream side of the Highway 25 bridge. In 1987 the station was relocated to its current position above the dam to use the weir as an artificial control. The station is still named 'Bow River Below Carseland Dam' because the purpose of this station is to record the quantity of the water below the Bow River Development Main Canal (05BM021). Discharge measurements are still conducted below the dam at highway 25 and the rating curve was developed using those measurements.

The Bow River is subject to frequent flooding. Historic flood events of exceptional magnitude occurred on the Bow River in 1879,1897, 1902, 1915, 1923, 1929, 1932, 1995, 2005 and 2013. There were no large open water floods on the Bow River between 1954 and 1994. There is limited information available regarding historic flooding along the study reach and in the Siksika Nation area.

Table 1: Summary of Recorded Flood Flows

Year		2013	2005	1995	1932	1929	1923
Location	**WSC Station No.**	**Peak Instantaneous Flow (m³/s)**					
Bow River Below Carseland Dam (1)	05BM002	3,300(2)	1,980	1,690	Not Available	Not Available	Not Available
Bow River below Bassano Dam	05BM004	3,380	2,040	1,460	2,310	2,540	2,180

Notes: 1) water level is recorded above the dam. Discharge is measured and reported below the dam.
2) estimated by WSC.

2.2.2 Recent and Recorded Floods

2.2.2.1 Summary

The recent and recorded floods in the study area include the 1995, 2005 and 2013 flood events. The 1995 and 2013 flood events were documented and the high water marks (HWM) data of these floods collected by AEP. The 2013 flood is the largest recorded flood in recent history.

The estimated return periods of the 1995, 2005 and 2013 floods on the Bow River below the Carseland Dam are 20, 35 and 200 years, respectively. The estimated return periods of the 1995, 2005 and 2013 flood on the Bow River below the Bassano Dam are 20, 35 and 100 years, respectively. A comprehensive flood hydrology assessment of the 2013 flood event was provided for the Bow River basin including the Siksika Nation (Golder 2017).

2.2.2.2 June 2013 Flood Event

The Bow River basin experienced severe flooding in late June 2013 following extreme rainfall in the basin, particularly in the upper watershed areas, on June 19, 20 and 21, 2013. Overtopping of Bow River banks and levees resulted in severe flood inundation in the Siksika Nation, and evacuation of many homes and businesses. Some areas of the Siksika Nation were subject to prolonged evacuation as a result of property damage and flood inundation of several neighborhoods.

Flood Impact on the Siksika Nation

The following description of the June 2013 flood event and the flood responses in the Siksika Nation was provided by *CBC News on June 24, 2013* (https://www.cbc.ca/news/canada/hundreds-of-siksika-first-nation-homes-lost-to-flood-1.1398381):

> *Severe flooding has forced around 1,000 Siksika people from their homes on the Alberta reserve, a large portion of which hugs a stretch of the Bow River about 100 kilometres east of Calgary. The disaster has been unfolding there since Friday, when the river poured over its banks and covered some areas with over a metre of floodwater.*
>
> *The four Siksika communities — a popular golf resort on the reserve was also destroyed — hit hardest all sit on low-lying land, nestled beneath foothills. Little Washington residents checking on their homes said there has been some flooding in the past, but it's never been more than a little water in the basement — not even during the major floods of 2005.*

187 homes were affected by June flood on the reserve which need to be replaced or fixed. The Government of Alberta was committing $83 million to rebuild or repair 167 homes and restore damaged infrastructure, a project that could take up to five years to complete according to CBC News dated November 7, 2013.

Photo Source: "Hundreds of Siksika First Nation Homes Lost to Flood" https://www.cbc.ca/news/canada/hundreds-of-siksika-first-nation-homes-lost-to-flood-1.1398381

Flood Damage to the Highway 547 Bridge

According to CBC News dated November 14, 2014 (https://www.cbc.ca/news/canada/calgary/highway-547-bridge-to-siksika-reopens-after-extensive-flood-repairs-1.2835882), the 2013 flood severely damaged Highway 547 bridge over the Bow River and washed out nearby embankment. The following is stated in the report entitled "Bow River Bridge Near Gleichen, AB, After the Flood" (Stantec 2014):

> *The concrete abutment on the north end of the bridge was compromised during the flood in June 2013. The flood washed away approximately 60 m of highway on the bridge's north approach, severing a critical link for the Siksika Nation and surrounding communities and businesses on either side of the river. The closure of the damaged bridge meant people living on the south side of the Siksika First Nation were cut off from the rest of the community.*

Photo Source: http://conf.tac-atc.ca/english/annualconference/tac2014/s-39/mccarron.pdf

Flood Damage to the Carseland Dam Fuse Plug

The design basis memorandum entitled "Carseland Bow River Headworks – Johnson's Island Dyke Fuse Plug Repair" by AMEC in 2015 stated that "*downstream of the mouth of the Highwood River, high discharges and water levels were experienced during the 2013 flood. At Carseland Weir, where the river discharge likely exceeded 3,540 m^3/s (WSC gauge 05BM002 was not operable), a fuse plug in the diversion embankment washed out.*"

AEP kept a record of photographs of the failure of the Emergency Fuse plug at the Carseland Dam during the 2013 flood event on the Bow River. Prior to the June 2013 flood, the fuse plug section was about 175 m in length and its crest was 0.7 m lower than the adjoining main dam crest elevation towards the south. It was built several decades ago and the crest has been used as a roadway.

Mr. David Chalcroft, a senior consultant to AEP, stated the following in his email to Golder September 7, 2015:

> *"During the major Bow River flood on June 21, 2013, the fuse plug was overtopped, but didn't breach, from 11:20 am to 2:38 pm when the first breaching action can be seen in the photos. While the overtopping depth was not noted, it had to be less than 0.7 m since there was no overtopping evident across the adjoining main dam section which has a top elevation 0.7 m higher than the fuse plug crest. The 3 hour period of over-topping before breaching was initiated, is longer than designers would normally want or expect, and may be due to the fact that the fuse plug crest was used as a roadway and was therefore densely compacted. By 3:51 pm, i.e, 1 hour and 15 minutes after first breaching was observed, over 90% of the 175 m long fuse plug had been washed away. The photos appear to show that the "erosion" mechanism was actually erosion of the sand zone underlying the sloping impervious clay zone caused by the turbulence of the water dropping over the edge of the impervious zone at the crest, followed by undercutting of the sand zone, and subsequent dropping down, or "calving off", of sections of the sloping impervious zone, as opposed to "erosion" of the impervious zone material itself. It appears that the approximate vertical drop in water level across the fuse plug was in the 2 m to 3 m range judging by the height of the onlookers and the width of the fuse plug crest."*

Photo Source: *"Carseland Bow River Headworks: Repair of Fuse Plug at Johnson's Island" (AMEC, March 2014)*

Flooding at the Bassano Dam

Bassano Dam was at one of the highest points in the flood of 2013. The Bassano Reservoir reached its maximum water level of 792.0 m at 17:40, June 22, 2013 according to Mr. Ryan Summach of EID. According to a study report prepared by AMEC in 2014:

> "… *Further downstream at the Bassano Dam, the peak discharge is estimated to have reached between 3,900 and 4,200 m^3/s, based on information provided by the Eastern Irrigation District (EID). ESRD commented that when the discharges are high, the river tends to flood the river valley and the station rating curve indicates an unrealistic low discharge value (approximately 3,340 m^3/s) for the measured 2013 peak water level compared to the EID spillway discharge estimates*."

Photo Source: **http://www.vancouversun.com/Bassano+highest+points+flood+2013/9798414/story.html**

Photo Source: https://commons.wikimedia.org/wiki/File:Bassano_Dam_June_23,_2013.jpg

Flood Hydrology Assessment

In July 2015, Golder was retained by AEP to undertake the hydrology study entitled "*Bow, Elbow, Highwood and Sheep River Hydrology Assessment*" for Bow River Basin. The updated flood hydrology information from this hydrology study was used as inputs to several River Hazard Studies conducted under the Provincial Flood Hazard Identification Program, including the Siksika Bow River Hazard Study.

The hydrology study includes use of the June 2013 flood flow data for the Bow River Basin and other river basins along the eastern mountain slopes in southern Alberta, and the preliminary estimates of the annual maximum flows in 2013, 2014 and 2015. Inclusion of the additional flow information, particularly for the large 2013 floods, increases the sample sizes for the flood frequency analyses and reliability of the resulting flood frequency estimates.

Flood Peak Discharges

The June 2013 storm was generally the largest storm observed within Alberta for short duration (6-hour, 12-hour and 24 hour) and for storm coverage areas greater than 2,000 km^2 (Golder 2017). There was residual snow cover in the upper watersheds of the Elbow, Highwood and Sheep Rivers. The peak instantaneous discharges on the Bow River during the June 2013 flood event are provided in Table 2.

Table 2: Peak Instantaneous Discharges of the 2013 Flood Event

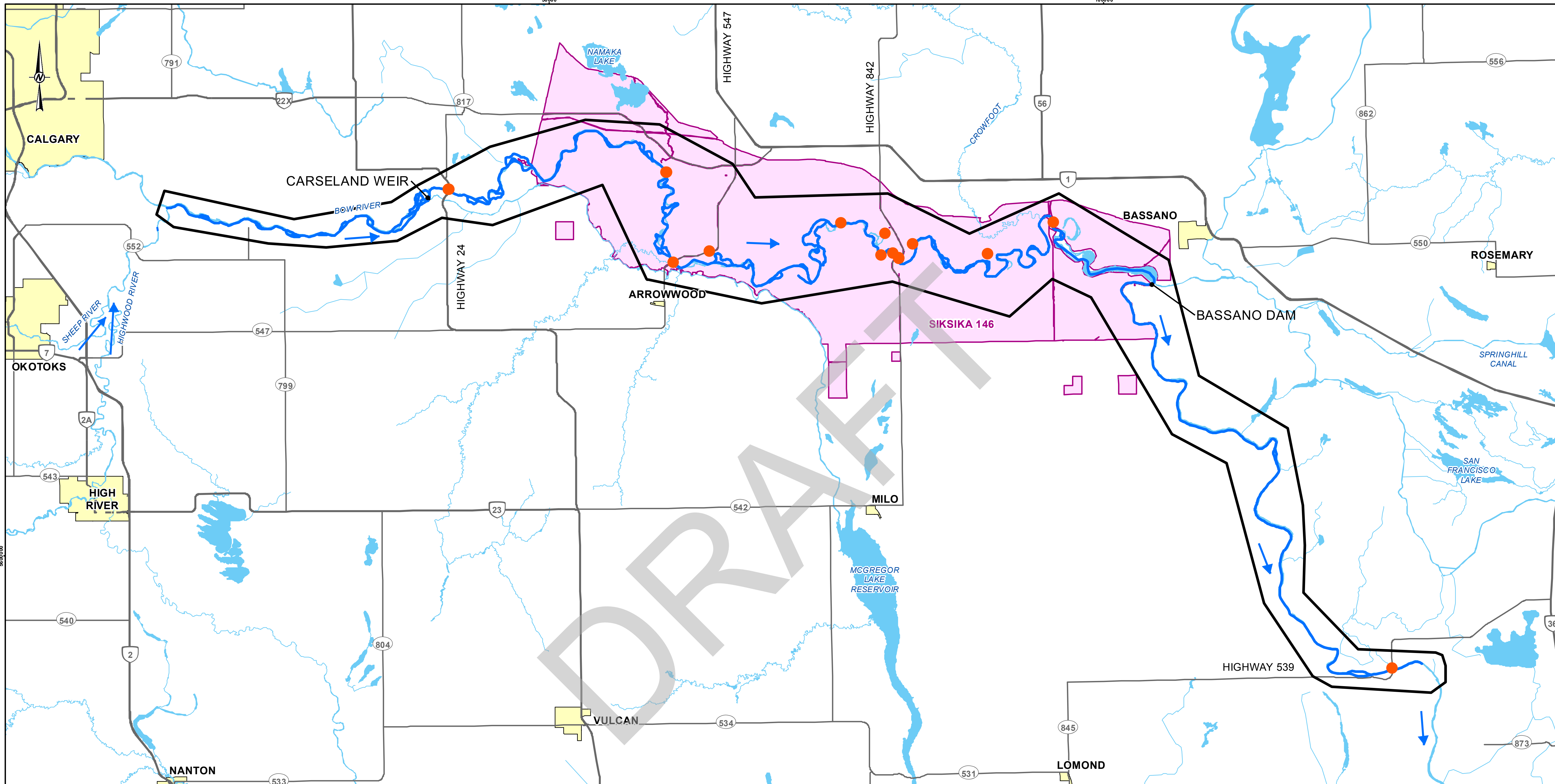
WSC Gauging Station		Peak Instantaneous Discharge (m^3/s)
05BM002	Bow River Below Carseland Dam	3,300[(1)]
05BM004	Bow River Below Bassano Dam	3,380

Notes: (1) estimated by WSC.

High Water Mark Data

AEP conducted a survey of the high water marks (HWMs) along the study reach following the June 2013 flood. The survey was conducted on July 1 and July 26, 2013. The survey extended from Highway 24 bridge crossing to Highway 853 bridge crossing just upstream of the Bow River confluence with the South Saskatchewan River, with the majority of the surveyed HWMs located in the vicinity of the Siksika First Nation, as shown in Figure 2. The survey data points include 34 HWMs and 11 water levels. There are 23 HWMs along the study reach and many of them are relatively close to each other and appear as a single point on Figure 2.

In January 2014, AEP completed the report entitled “High Water Mark Report – Lower Bow River, including Siksika First Nation”. The report presents the HWM survey information including the identification numbers, survey dates, benchmarks, locations (e.g. coordinates and maps), elevations, descriptions, and photographs. The AEP’s report and ArcGIS file of the HWMs are included in Appendix A of this report.



LEGEND

- 2013 HIGH WATER MARK
- FLOW DIRECTION
- PRIMARY HIGHWAY
- SECONDARY HIGHWAY
- WATERCOURSE
- SURVEY REACH
- WATERBODY
- FIRST NATION RESERVE
- POPULATED PLACE
- STUDY AREA

0 15 30

1:350,000 KILOMETRES

REFERENCE(S)

ROADS, RAILWAYS AND POPOPULATED PLACES OBTAINED FROM ALTALIS, © GOVERNMENT OF ALBERTA 2018. ALL RIGHTS RESERVED.
DATUM: NAD 83 CSRS PROJECTION: 3TM 114

CLIENT

ALBERTA ENVIRONMENT AND PARKS

Alberta Government

CONSULTANT

Golder Associates

YYYY-MM-DD	2019-01-07
DESIGNED	PH
PREPARED	PH
REVIEWED	HZ
APPROVED	HZ

PROJECT

SIKSIKA BOW RIVER HAZARD STUDY

TITLE

LOCATIONS OF 2013 SURVEYED HIGH WATER MARKS

PROJECT NO.	CONTROL	REV.	FIGURE
1783054	2000	0	2

2.2.2.3 June 2005 Flood Event

The return period of the 2005 flood on the Bow River is estimated at 35 years at the Carseland Dam and below the Bassano Dam. However, there was little historic flood information regarding the June 2005 flood event documented along the study reach.

Flood Peak Discharges

The reported peak instantaneous discharges during the June 2005 flood event are provided in Table 3.

Table 3: Peak Instantaneous Discharges of the 2005 Flood Event

WSC Gauging Station		Peak Instantaneous Discharge (m^3/s)
05BM002	Bow River Below Carseland Dam	1,980
05BM004	Bow River Below Bassano Dam	2,040

2.2.2.4 June 1995 Flood Event

The return period of the 1995 flood on the Bow River is estimated at 20 years at Carseland Dam and below Bassano Dam.

Flood Peak Discharges

The peak instantaneous discharges reported for the June 1995 flood event are provided in Table 5.

Table 4: Peak Instantaneous Discharges of the 1995 Flood Event

WSC Gauging Station		Peak Instantaneous Discharge (m^3/s)
05BM002	Bow River Below Carseland Dam	1,690
05BM004	Bow River Below Bassano Dam	1,460

High Water Mark Data

AEP surveyed the HWMs along the study reach following the June 1995 flood. The survey was conducted on June 13, 1995. The survey was conducted at Hidden Valley Resort & Golf Course in the Siksika Nation. The survey included three HWMs at three different locations.

The June 1995 HWM survey report presents the HWM survey information including the identification numbers, survey dates, benchmarks, elevations, location descriptions, and photographs. The survey report is included in Appendix A of this report.

2.3 Ice Jam Floods

No major ice-jam floods on the Lower Bow River have been observed or reported. However, there were some local freeze-up and breakup events observed along the study reach. There is no recent report or record of any ice-jam flooding within the study area.

3.0 AVAILABLE DOCUMENTS AND DATA

3.1 Hydrology Summary

The Bow River originates in the Rocky Mountains and traverses the foothills before reaching Calgary on the edge of the Prairies. The stream flows through a mix of Alpine, Subalpine, Boreal Foothill and Aspen Parkland eco-regions. The land use in the river basin ranges from urban Calgary, to agricultural lands in parts of the foothills, and to forest in the remainder of the foothills and in the mountains.

The topography of Bow River basin extends from Rocky Mountains, following by Foothills (Porcupine Hills) to Western Alberta Plains with a ground elevation drop of more than 2,000 m. When the moist-air from the southeast was lifted along the Foothills and Rocky Mountains, a large amount of rainfall would occur in the basin. This could result in extreme flooding when the basin has been previously saturated by snowmelt.

The Bow River is joined by several tributaries, including the Elbow River, Nose Creek, Fish Creek and Pine Creek within Calgary. The Elbow River is the largest tributary to the Bow River within Calgary, and flows into the Glenmore Reservoir before entering the Bow River, just downstream of downtown Calgary. The Highwood River is a major tributary to the Bow River downstream of Calgary.

The two WSC gauging stations within the study area have a gross drainage area of 15,700 km^2 with an effective drainage of 14,700 km^2 below the Carseland Dam and a gross drainage area of 20,300 km^2 with an effective drainage area of 17,800 km^2 below Bassano Dam. There are no major tributaries along the study reach.

Table 5 presents a summary of the flood frequency estimates at key locations within the study area. These estimates are the instantaneous flood peak discharges for the natural/naturalized flow conditions, extracted from the Bow, Elbow, Highwood, and Sheep River Hydrology Assessment Report (Golder 2017).

Table 5: Summary of Flood Frequency Estimates in the Study Area

Location	Instantaneous 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
Bow River below Highwood River Confluence	582	867	1,140	1,500	1,870	2,150	2,530	2,840	3,750	4,690	5,420	6,390	7,180
Bow River below Carseland Dam (05BM002)	604	917	1,210	1,580	1,950	2,230	2,590	2,880	3,730	4,590	5,240	6,080	6,770
Bow River at Highway 547	599	923	1,230	1,620	2,010	2,310	2,690	2,990	3,890	4,790	5,480	6,370	7,090
Bow River at Highway 842	597	925	1,240	1,630	2,030	2,330	2,720	3,030	3,950	4,870	5,560	6,470	7,210
Bow River below Crowfoot Creek	591	932	1,260	1,680	2,100	2,420	2,820	3,150	4,120	5,090	5,820	6,790	7,560
Bow River below Bassano Dam (05BM004)	591	932	1,260	1,680	2,100	2,420	2,830	3,160	4,130	5,100	5,840	6,810	7,580
Bow River at Highway 539	581	913	1,230	1,620	2,010	2,300	2,660	2,950	3,790	4,620	5,240	6,030	6,660

3.2 DTM Data

A detailed description of the Digital Terrain Model (DTM) data is provided in a separate study report entitled "Siksika Bow River Hazard Study – Survey and Base Data Collection Report" (Golder 2018a). The DTM was derived from survey-verified high-accuracy Light Detection and Ranging (LiDAR) remote sensing data set.

3.3 Survey Data

A detailed description of the survey data is provided in a separate study report entitled "Siksika Bow River Hazard Study – Survey and Base Data Collection Report" (Golder 2018a). The survey data was collected using a combination of instruments including Real-Time Kinematic (RTK) GPS, Acoustic Doppler Profiler (ADP), Digital Echo Sounder, and Total Station.

3.4 Existing Hydraulic Model

There is no existing hydraulic model developed for the study area.

3.5 High Water Marks

The HWM reports and data available for this study are listed in Table 6. There are no HWMs for the 2005 flood event.

Table 6: Available High Water Mark Reports and Data

No.	Report Title	Author
1	High Water Mark Report – 1995 Highwater Marks, Southern Alberta June High Water	Alberta Environment and Parks
2	High Water Mark Report – Lower Bow River, including Siksika First Nation, July 1 and 26, 2013	Alberta Environment and Parks

3.6 Gauging Stations

There are two active WSC hydrometric gauging stations located within the study area as listed below and shown in Figure 11:

- 05BM002 – Bow River below Carseland Dam
- 05BM004 – Bow River below Bassano Dam

The rating curves of river stages versus discharges for these two stations (see Figures 8 and 9) were used in the model calibration step of this study.

3.7 Areal Flood Photography

There is no aerial flood photography available to this study.

4.0 RIVER AND VALLEY FEATURES

4.1 General Description

Bow River is a tributary of the South Saskatchewan River in southern Alberta. The river flow originates in the snowpack and glaciers of the Rocky Mountains and traverses through the foothills before reaching the Prairies.

In the study area, the Bow River flows east along a reach of about 155 km through the Siksika Nation to Bassano Dam, then turns southeast and flows along a reach of about 66 km to the downstream study boundary near Bow City. Downstream of the study reach, the Bow River flows southeast toward its confluence with the South Saskatchewan River.

There are man-made structures along the study reach, include highway bridges (see Table 7), weir and flood control structures.

4.2 Channel and Floodplain Characteristics

Channel Characteristics

The Bow River study reach was divided into two sub-reaches (i.e. upper reach and lower reach) as shown in Figure 3. The river channel bed and bank materials consist of gravel, sand, silt and clay.

The upper reach extends from the upstream study boundary to the Bassano Dam. The total length of the upper reach is about 155 km. Within the upper reach, the Bow River has braided and multiple channels in which the secondary channels may convey a significant percentage of flows during large flood events. The upper reach has typical channel bottom width of 80 m, bankfull width of 120 m, and bankfull depth of 4.5 m. The upper reach has an average channel bed slope of 0.10% and sinuosity of 1.1.

The lower reach extends from the Bassano Dam to the downstream study boundary near the Bow City. The total length of the lower reach is about 66 km. This river reach is entrenched within the plains and confined on both sides by valley walls. The river has single channel with convoluted meanders. The lower reach has typical bottom width of 150 m, bankfull width of 170 m, and bankfull depth 5.3 m. The lower reach has an average channel bed slope of 0.06% and sinuosity of 1.0.

Floodplain Characteristics

The floodplains along the upper reach are relatively wide. The floodplain width is typically 500 m (excluding the channel width) within a range of 300 to 1,200 m. The vegetation cover on the floodplains of the upper reach consists mainly of grasses, dense willows and tall trees. Some isolated zones of urban land cover exist near Highway 24.

The lower reach has relatively small floodplains. The floodplain width is typically 170 m within a range of 30 to 700 m. The vegetation cover in the floodplain areas along the lower reach consists mainly of grasses and scattered willows/trees.

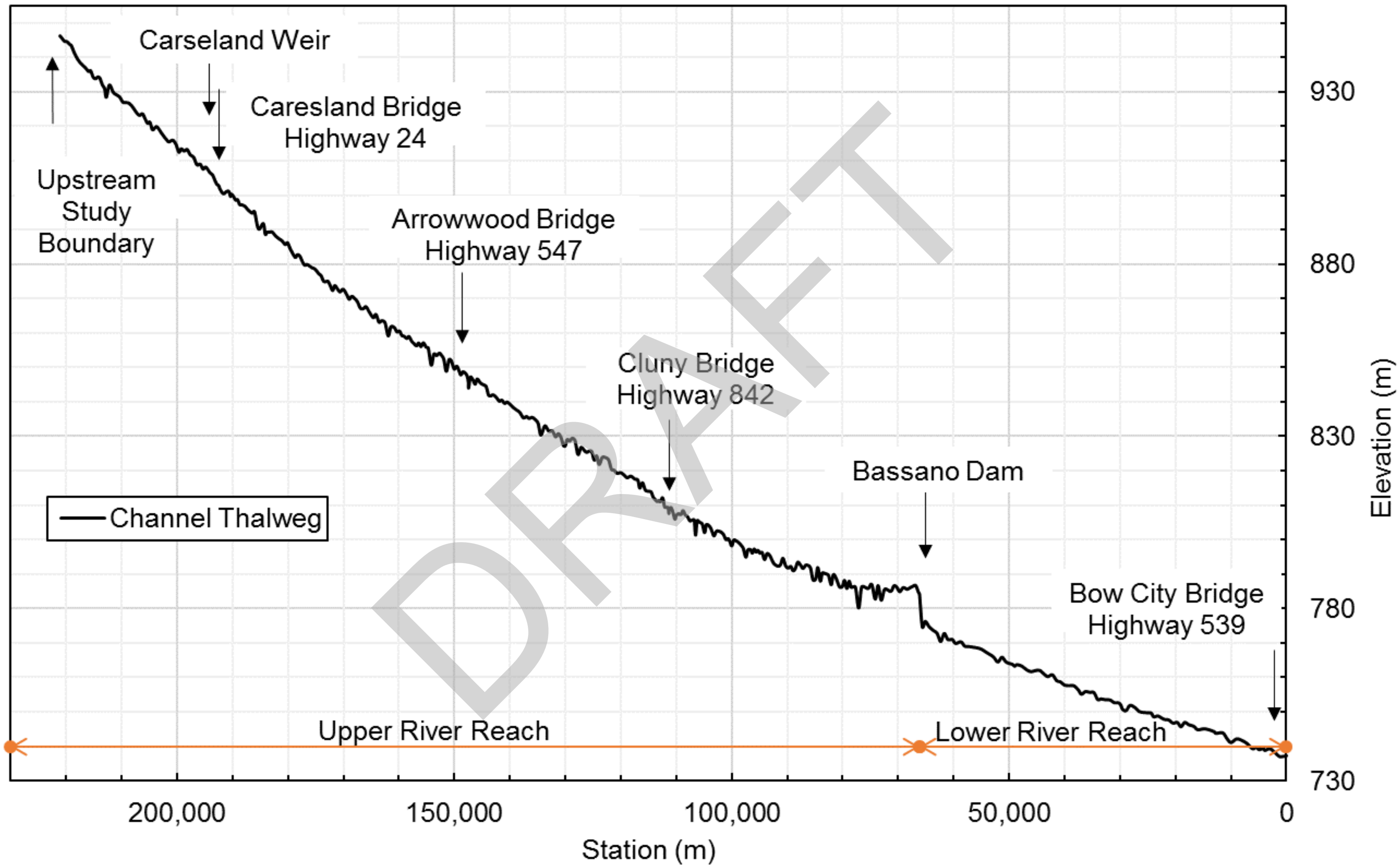


Figure 3: Bow River Sub-Reaches

4.3 Major Tributary

No major tributary enters the Bow River within the study area.

4.4 Bridges, Culverts and Weirs

A detailed description of the bridges, culverts and weirs is provided in the report entitled "Siksika Bow River Hazard Study – Survey and Base Data Collection Report" (Golder 2018a). A summary description of these bridges, culverts and weirs is provided below.

Bridges

There are four bridges along the Lower Bow River study reach as listed in Table 7.

Table 7: List of Bridges within the Lower Bow River Study Reach

No.	Name	Description	Type
1	Highway 24 Bridge	4 km Southeast of Carseland, Alberta	5-Span
2	Highway 547 Bridge	12 km South of Gleichen, Sikaika Nation	4-Span
3	Highway 842 Bridge	7.5 km South of Cluny, Sikaika Nation	5-Span
4	Highway 539 Bridge	Near the Bow City	4-Span

The Highway 842 Bridge was severely damaged during the June 2013 flood, and it was rebuilt in 2014.

Culvert

There is no culvert along the study reach.

Weirs and Dams

There is one weir structure (i.e. Carseland Weir) along the study reach. The Caresland Bow River Headworks includes the Carseland Weir, a sluiceway, canal headgates, and Johnson's Island Fuse Plug Dyke.

The Carseland Weir is located approximately 2.5 km upstream of Highway 24 Bridge. The weir is used to facilitate diversion of river flows into the Caresland Bow River Headworks Canal and measurement of discharges by WSC. The Carseland Dam Fuse Plug is located at the left bank of the Bow River. It was rebuilt in 2014 as the old fuse plug was washed out during the June 2013 flood.

4.5 Flood Control Structure

There is only one flood control structure along the study reach. It is a flood control berm comprised of interlocking concrete blocks, which is located along the right bank of the Bow River adjacent to the Hidden Valley Resort & Golf Course, just upstream of the Highway 842 Bridge near Cluny (see Table 8). The location of this structure is presented in the Survey and Base Data Collection Report (Golder 2018a).

Table 8: Flood Control Structure along the Study Reach

No.	Side of River[(a)]	Length	Name	Description	Type
1	Right	1,540 m (upper berm) 500 m (lower berm)	Concrete Berm	Concrete block structure adjacent to Hidden Valley Resort	Berm

Note: (a) Right and left sides of the river are relative to an observer looking downstream.

5.0 MODEL CONSTRUCTION

5.1 HEC-RAS Program

5.1.1 Program Description

The latest HEC-RAS program (Version 5.0.5, June 2018) was used to develop the one-dimensional (1D) hydraulic models for 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 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.

The HEC-RAS program was designed to perform one-dimensional (1D), two dimensional (2D) or combined 1D and 2D hydraulic calculations for a full network of natural and constructed channels. The program supports steady-state and unsteady-state hydraulic simulation. HEC-RAS can be used to calculate water surface profiles for gradually varied flow. In this study, the program was used for 1D steady-state simulation.

The basic computational procedure for 1D 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, levees and other structures. The program is capable of simulating the water surface profiles associated with subcritical, supercritical and mixed flow regimes. The program can be used for evaluation of floodway encroachments in floodplain management and flood hazard studies. In this study, the program was run in sub-critical flow only as the Froude Number values appear to be less than 1.0 along the study reach.

The main assumptions of 1D steady-state modelling are listed below:

- Flow is steady;
- 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;
- Flow is gradually varied except at hydraulic structures;
- The channel slope is less than 10%; and
- The flow is perpendicular to the cross section alignment.

The HEC-GeoRAS module (Version 10.1) was used to prepare cross section data based on the recent LiDAR and river survey data (Golder 2018a). 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

5.1.2.1 Model Domains

It is generally desirable to use a single geometry file to simulate floods of various return periods. Therefore, the model domain needs to be defined for covering inundation extents of the largest flood event to be simulated. The 1D model domain was defined in consideration of the simulation results of a HEC-RAS 2D model. The HEC-RAS 2D model was set up based on the LiDAR DEM without inclusion of the channel bathymetry to produce conservative water level estimates.

The flood extents of the 1,000-year flood event were estimated using the HEC-RAS 2D modelling results. The 1D model domain was defined to include the flood extents simulated using the 2D model and a buffer zone covering additional areas with elevations of 2 to 3 m higher than the flood levels simulated using the 2D model.

To account for the downstream boundary effects, a short river reach downstream of the study reach was included in the 1D model. The cross sections for this short reach were obtained from the post-June 2013 open-water survey on the Bow, Oldman and South Saskatchewan Rivers prepared for AEP (Golder 2015).

5.1.2.2 Separate Branch

The 1D HEC-RAS model is based on assumed constant water level at each cross section including both main channel and overbank areas. This assumption also applies to any side channels included in each cross section, unless these side channels are explicitly represented with separate branches in the model.

There is no separate branch along the study reach represented in the model.

5.1.2.3 Boundary Conditions

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

- Discharge at the upstream model boundary.
- Normal flow condition (with an estimated energy slope of 0.036%) at the downstream model boundary.

5.2 Geometric Data Base

5.2.1 Cross Section Data

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

- River survey data collected for this study (Golder 2018a); and
- River survey data collected in 2014 and 2015 for other projects (Golder 2015a & 2015b)
- 2017 LiDAR data provided by AEP.

The alignments of the cross sections in the floodplain areas were defined in consideration of the following:

- Simulated water surface isolines generated using the HEC-RAS 2D model;
- Topographic contours;
- Estimated flow directions; and
- Key structures.

It is preferable that cross sections are aligned along the water surface isolines simulated using the HEC-RAS 2D model, so that the water levels along the alignment are approximately the same at each cross section. HEC-GeoRAS was used to define the main channels, overbank flow paths, bank stations, cross section river stations, and the connections between the main and branch channels.

Table 9 provides an overview of the river reaches and the number of cross sections in each reach represented in the model.

Table 9: Cross Sections Used in the Siksika Bow River HEC-RAS Model

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
Lower Bow River	US to Bassano Dam	Upstream Boundary to Bassano Dam	221217	66056	155,161	335
	Bassano Dam to DS	Bassano Dam to Downstream Boundary near Bow City	66056	50	66,006	93
					TOTAL	**428**

The total length of the study reach is 221 km. The study reach is represented by 428 cross sections, with an average spacing of approximate 520 m between adjacent cross sections.

5.2.2 Roughness Coefficients

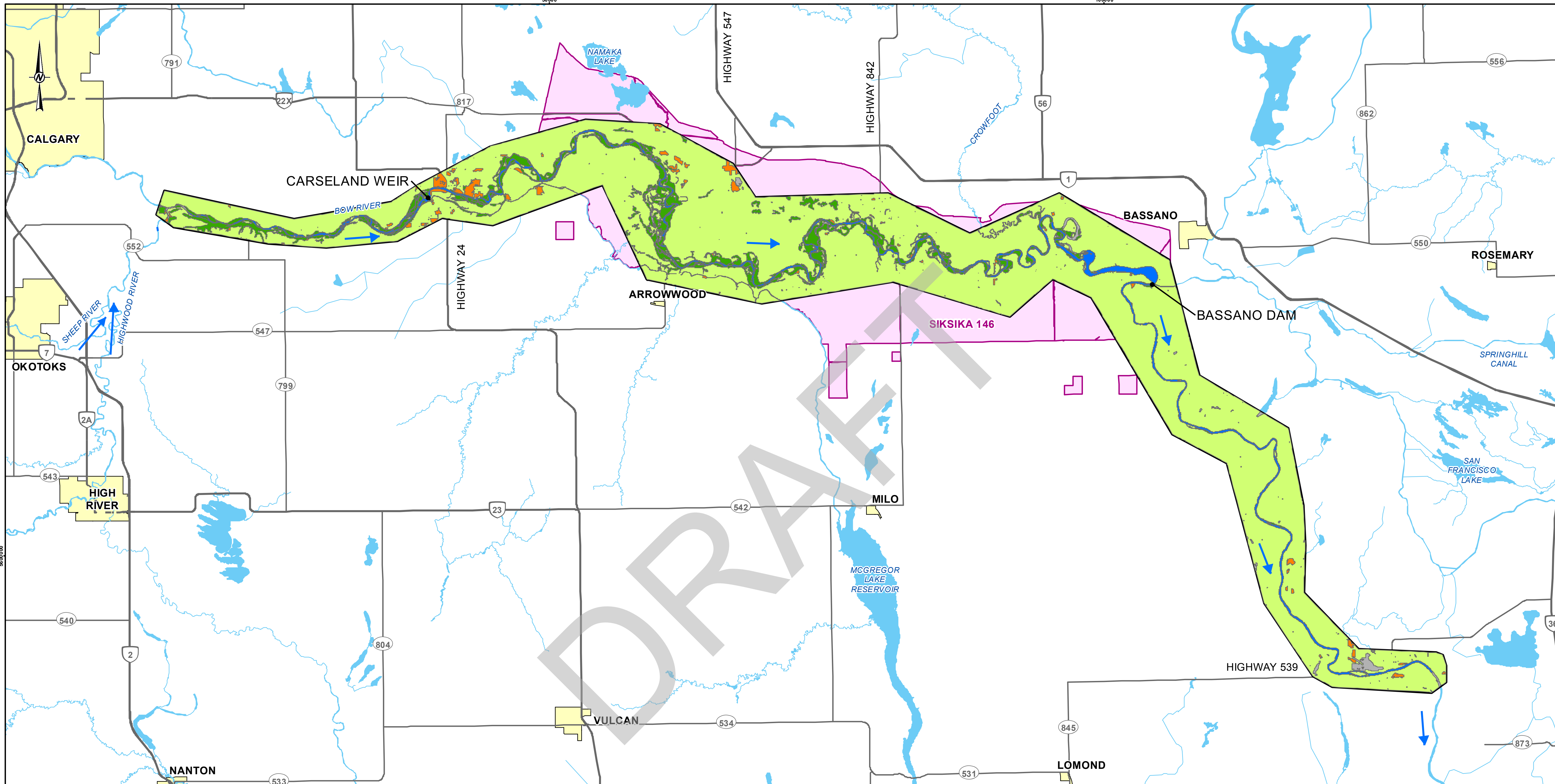
The left and right bank stations defining the main channel were determined using HEC-GeoRAS based on the 2017 LiDAR data, 2016 aerial imagery and survey data. Manning's roughness *n* values were specified using the distributed roughness approach, which allows for multiple, varying roughness values within 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; and
- Land use information from Government of Alberta.

Five roughness classes were used for the model setup. The initial Manning's *n* values assigned to the classes are listed in Table 10. These initial values were selected based on channel bed materials, vegetation types, etc. (Chow 1959; USACE 2016b). These roughness values were modified at some locations during the model calibration process. The roughness values were specified in the cross sections using HEC-GeoRAS. Figure 4 shows the distribution of the roughness classes.

Table 10: Roughness Classes and Initial Manning's n Values

Number	Description	Initial Manning's *n*
1	Rivers-Main Channel	0.030 ~ 0.040
2	Urban Mixture	0.080
3	Ponds	0.038
4	Grassland/Farmland	0.045 ~ 0.070
5	Trees/Bushes	0.080 ~ 0.120



LEGEND

FLOW DIRECTION	POPULATED PLACE
PRIMARY HIGHWAY	STUDY AREA
SECONDARY HIGHWAY	Grassland/Farmland
WATERCOURSE	Ponds
SURVEY REACH	Rivers-Main Channel
WATERBODY	Trees/Bushes
FIRST NATION RESERVE	Urban Mixture

0 15 30

1:350,000 KILOMETRES

REFERENCE(S)

ROADS, RAILWAYS AND POPOPULATED PLACES OBTAINED FROM ALTALIS, © GOVERNMENT OF ALBERTA 2018. ALL RIGHTS RESERVED.
DATUM: NAD 83 CSRS PROJECTION: 3TM 114

CLIENT

ALBERTA ENVIRONMENT AND PARKS

Alberta Government

CONSULTANT

Golder Associates

YYYY-MM-DD	2019-01-07
DESIGNED	PH
PREPARED	PH
REVIEWED	HZ
APPROVED	HZ

PROJECT

SIKSIKA BOW RIVER HAZARD STUDY

TITLE

DISTRIBUTION OF ROUGHNESS CLASSES

PROJECT NO.	CONTROL	REV.	FIGURE
1783054	2000	0	4

5.2.3 Bridges, Culverts, Weirs and Dams

Bridges

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

- River and bridge surveys conducted in 2017 (Golder 2018a); and
- As-built drawings provided by AEP in 2017.

All existing bridges (see Section 4.4) were represented in the HEC-RAS model, including those which may not affect water levels during floods. The bridge deck, pier and abutment information were included in the model. Losses through bridges were calculated in the model using the energy equation (i.e., standard step method). Flows over the bridge and approaching embankment were calculated using the standard weir equation.

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

To properly model overland flows that can bypass bridges on floodplains, the multiple flow analysis was implemented. This allows the HEC-RAS model to calculate distribution of flows that are conveyed through the bridge openings and bypassed around the bridges in the floodplains. The bypassed flow in multiple analysis was modelled as an open channel flow. Not using the multiple flow analysis approach would result in bypassed flows being modelled as flows over a broad-crested weir.

There are large variations of bridge types, abutments, approaches and embankments within the study area. At individual bridge locations, ineffective areas upstream and downstream of the bridges were carefully selected. This included selection of permanent and non-permanent ineffective areas where appropriate.

The initial values of the contraction and expansion coefficients at bridges were selected to be 0.3 and 0.5, respectively. These are typical values listed in the HEC-RAS User Manual. They were modified at some locations during the model calibration process.

Culvert

There is no major culvert in the study area (see Section 4.4). Therefore, there is no culvert represented in the HEC-RAS model.

Weir

The Carseland Weir is an uncontrolled overflow weir. The weir has an invert elevation of 908.7 m, a crest elevation of 913.7 m and a width of 150 m. This weir was modelled using its stage-discharge rating curve (see Figure 5).

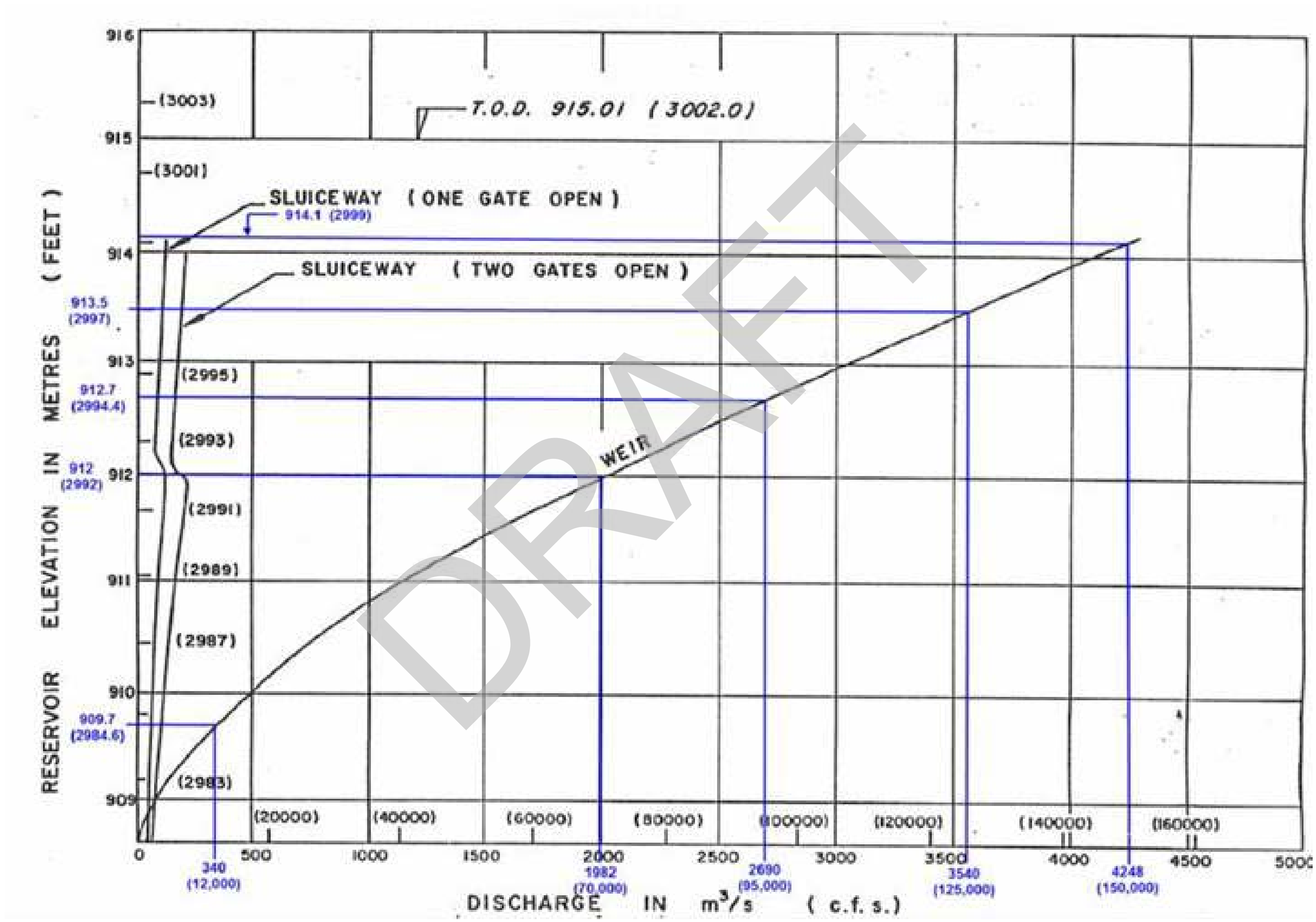


Figure 5: Carseland Weir Stage ~ Discharge Rating Curve (AMEC 2015)

5.2.4 Flood Control Structures

The flood control structures considered in this study were identified in the Survey and Base Data Collection Report (Golder 2018). Only the structures that are regularly maintained by the stakeholders and designed to provide a certain level of protection were included in this study. It does not include private flood protection berms.

The flood control structures are represented in the HEC-RAS model as Levees. The top-of-levee elevations were based on the LiDAR data obtained in 2017 and the surveyed data (Golder 2018a) for model calibration and simulation of flood frequency profiles.

5.3 Model Calibration and Validation

5.3.1 Methodology

The Manning's *n* and contraction/expansion coefficients are the two primary model parameters which values were adjusted if necessary 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 from previous hydraulic modelling studies.

Manning's *n* values may reduce with increased stage. The high flow calibrations were performed to determine appropriate Manning's n values across a wide range of flows. The following scenarios were included in the model calibration and validation:

- High Flow Calibration: Available HWMs and peak flow estimates for the 2013 flood event were used for high flow calibration. The flood event was selected because it is the largest event in recent history and has been well-documented in terms of peak flow estimates and available HWMs.
- Calibration based on Gauging Station Data and Rating Curves: The stage-flow rating curves at the two active WSC gauging stations (i.e. 05BM002 and 05BM004) were used for the model calibration.
- High Flow Validation: Available HWMs and peak flow estimates from the 1995 historic flood event were used for the model validation without changing the calibrated model parameter values.

The model calibration process involved multiple iterations to adjust the model parameter values, conduct simulations, and compare the simulated water levels to the HWMs or the water levels as indicated by the rating curves. The objective of the model calibration was to achieve good matches between the simulated water levels and the HWMs or water levels.

The model validation process involved simulation of the flood conditions not used in the model calibration by maintaining the calibrated model parameter values and comparing the simulated water levels to the surveyed HWMs or recorded water levels. The objective of the model validation was to confirm if the calibrated model can be reliably used to simulate other flood flow conditions. The results of the model validation are discussed in Section 5.3.5.

5.3.2 High Flow Calibration

The HEC-RAS model for the study reach was calibrated based on the 2013 HWMs. The 2013 flood along the study reach has an estimated return periods of 100 to 200 years.

The 2013 HWMs were initially used to adjust the values of the channel Manning's *n,* floodplain Manning's *n* and the bridge contraction/expansion coefficients, where necessary. The model calibration was achieved by adjusting the model parameter values in a way that the simulated water levels were in good match with the HWMs while maintaining parameters within realistic range as described in literatures and from our professional experience.

In simulating the 2013 flood, all bridges in the HEC-RAS model were assumed to remain in place, and no debris accumulation was modelled. This assumption may result in locally underestimated water levels upstream of the bridges, as there were large debris noted at several bridges during the 2013 flood.

Table 11 lists the discharges used for simulating the 2013 floods.

Table 11: 2013 Flood Peak Flow Estimates Used for the Model Calibration

River Reach	Discharge (m^3/s)	Comment
Upstream Boundary to Bassano Dam	3,300(1)	Estimated by WSC
Bassano Dam to Downstream Boundary	3,380(2)	Recorded data by WSC

Notes:
(1) The discharge was the estimated peak flow on the Bow River at Carseland Dam (05BM002) by Water Survey Canada.
(2) The discharge was based on the recorded peak flow on the Bow River at Bassano Dam (05BM004) by Water Survey Canada.

Figure 6 compares the simulated water surface profile to the 2013 flood HWMs along the study reach. The average difference between the simulated water levels and the HWMs is -0.08 m with individual differences ranging from -0.58 m to +0.71 m (see Figure 7).

Table B.1 in Appendix B summarizes the differences between the simulated water levels and the HWMs. Figures B-1 and B-2 in Appendix B compare the simulated water surface profile to the HWMs for the 2013 flood and 1995 flood, respectively. Some of the 2013 flood HWMs were located at large distances away from the river main channel and may not accurately represent the water levels along the river main channel. Therefore, the HWMs along the main channel were considered more reliable in representing the actual water levels on the Bow River.

The calibrated main channel Manning's *n* values for the high flow conditions range from 0.030 to 0.040. They are in the same range as those calibrated for the Bow River channel through Calgary (Golder 2018b). They are within the typical range of roughness values for similar rivers with gravel and cobble bed materials under high flow conditions (Chow 1959).

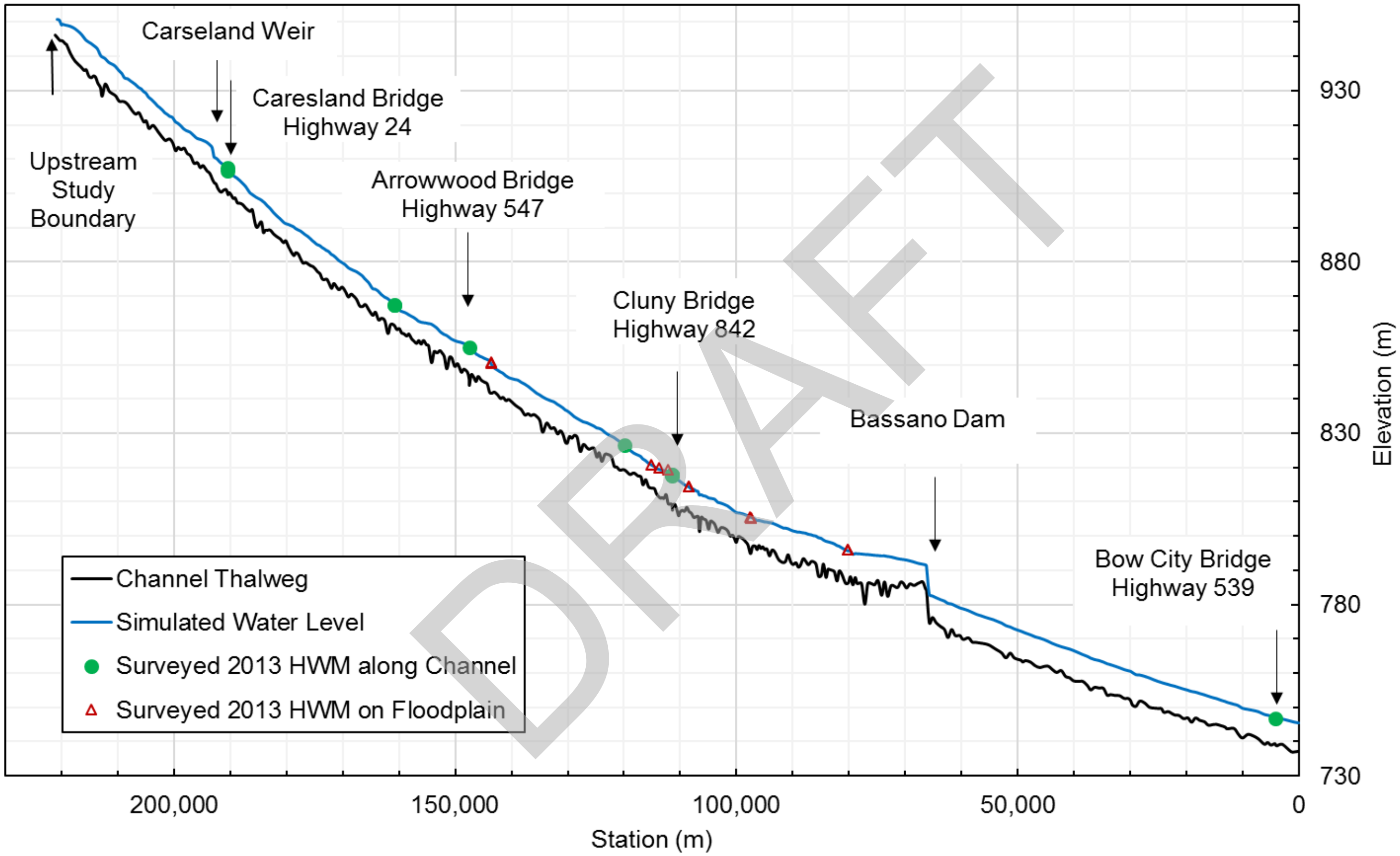


Figure 6: Comparison of Simulated Water Surface Profile and Surveyed HWMs along the Study Reach for the 2013 Flood Event

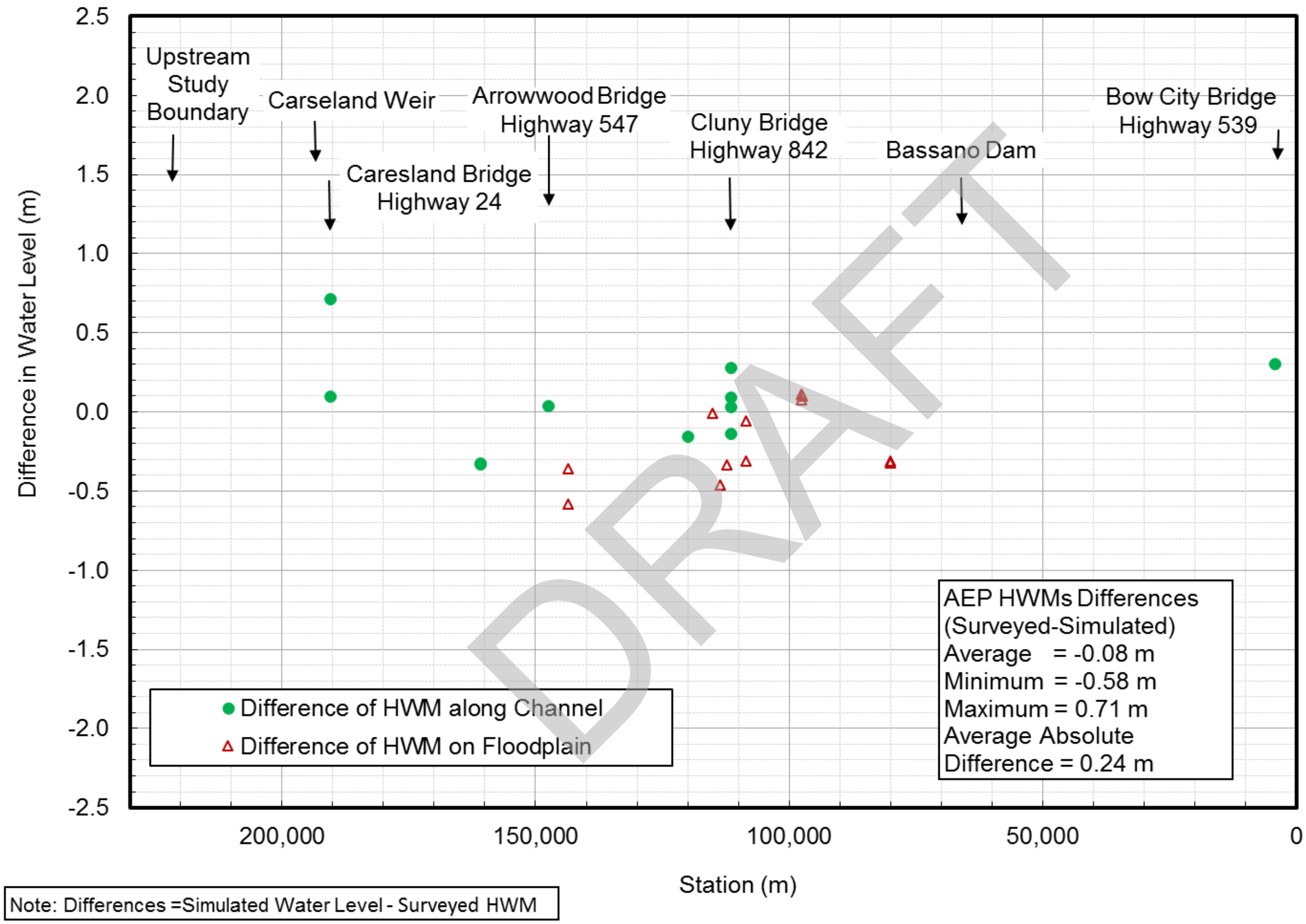


Figure 7: Simulated and Surveyed Water Level Differences along the Study Reach for the 2013 Flood

5.3.3 Stage-Flow Rating Curves

The model calibration was conducted also based on the stage-flow rating curves for the following WSC gauging stations:

- 05BM002 – Bow River below Carseland Dam; and
- 05BM004 – Bow River below Bassano Dam.

The simulated water levels at these two stations were compared to those indicated by the rating curves shown in Figure 8 and Figure 9. The actual measurements used to develop the rating curves by WSC were also plotted in Figures 8 and 9. The results shown in these two figures are summarized below:

- Figure 8 shows that the simulated and measured water levels at WSC Station 05BM002 are comparable. This shows that the calibrated model can be reliably used for simulating flood flows at the gauging station. The calibrated Manning's n value for flood flows is 0.035.
- Figure 9 shows that the simulated and measured water levels at WSC Station 05BM004 are comparable. This figure shows that the calibrated Manning n values are higher for low flows (less than 500 m^3/s) than high flows. It indicates that the calibrated model can be reliably used for simulating flood flows with return periods of 2 years (591 m^3/s) or greater at the gauging station. The calibrated Manning's n for flood flows is 0.030.

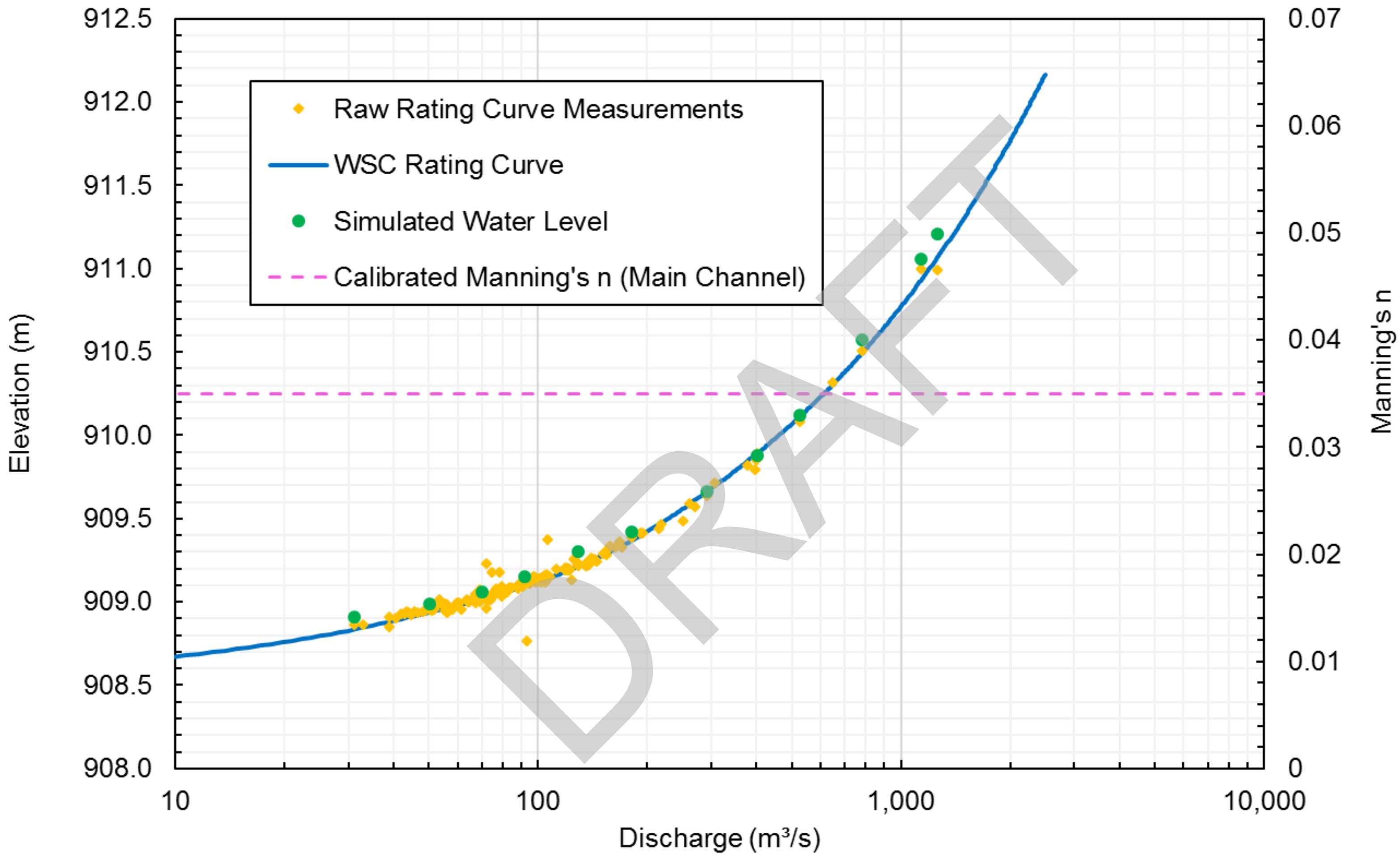


Figure 8: Calibration Results based on the Stage-Flow Rating Curve at WSC Gauging Station 05BM002

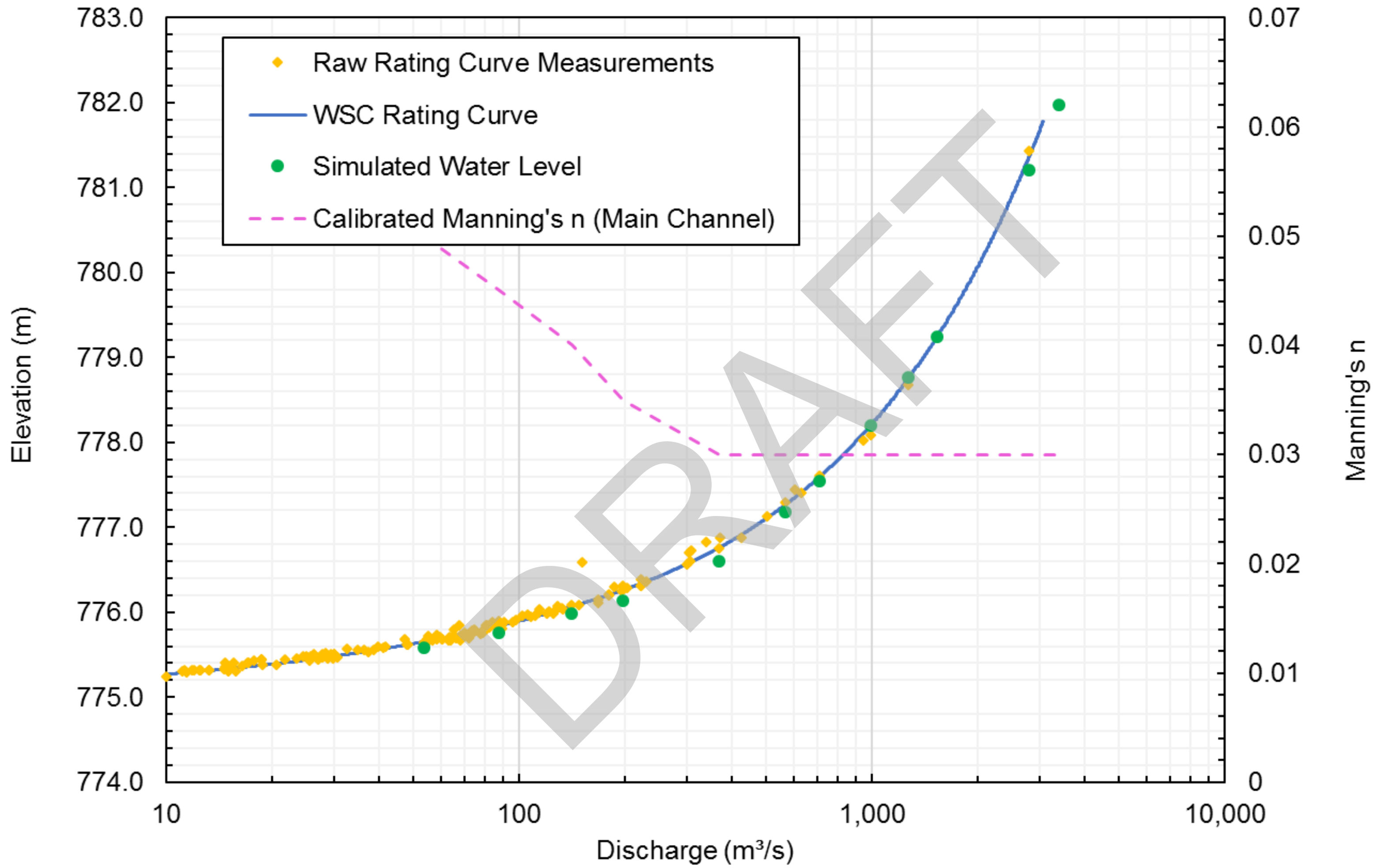


Figure 9: Calibration Results based on the Stage-Flow Rating Curve at the WSC Gauging Station 05BM004

5.3.4 High Flow Validation

The calibrated model was validated based on the information for the 1995 flood event, which has an estimated return period of 20 years. The model was validated based on three available surveyed HWMs at the Hidden Valley Resort & Golf Club in the Siksika Nation. There are no exact coordinates of the surveyed HWM data, and the locations of these HMWs were estimated based on a location sketch provided in the 1995 HWM survey report.

Table 12 lists the discharges used for simulating the flood event along the study reach.

Table 12: Bow River Peak Flow Estimates – 1995 Flood Event

Bow River Reach	Peak Flow (m^3/s)	Comment
Upstream Boundary to Bassano Dam	1,690	Recorded by WSC
Bassano Dam to Downstream Boundary	1,460	Recorded by WSC

The model validation results are presented in Figure B-2 in Appendix B. In general, the simulated water levels are considered reasonable compared to the three surveyed HWMs at the Hidden Valley Resort & Golf Club in consideration of the approximate locations of the HWMs.

The average differences between the simulated water levels and the surveyed HWMs are, on average, 0.23 m, and ranges from -0.95 m to 1.40 m. The validation results show that the calibrated values of Manning's n can be used to simulate the river floods with return periods of 2 to 1,000 years.

5.3.5 Calibration Results

The HEC-RAS model for the study reach was calibrated for high flow conditions. The calibrated model was validated using the 1995 flood HWM data. The model calibration and validation results are summarized as follows:

- The high flow calibration results show that the simulated water levels compare well to the available HWMs. The channel and floodplain Manning's *n* values, as well as contraction and expansion loss coefficients at bridges and other locations, were calibrated based on the 2013 flood HWMs. The calibrated channel and floodplain Manning's *n* values for high flow conditions are within the typical range of roughness values for similar rivers and floodplains (Chow 1959).
- The calibration results based on the stage-flow rating curves for the two WSC gauging stations show that constant Manning's n values for the Bow River main channel can be reliably used for simulating flood flows with return periods of 2 to 1,000 years.
- The validation results show that the simulated water levels generally compare well with the HWMs, although the simulated water levels within the Hidden Valley Resort & Golf Club were slightly higher than the mean value of the three surveyed HWMs. The calibrated model for the study reach is considered validated.

In conclusion, the calibrated HEC-RAS model, set up with one geometry file, can be reliably used in this study for simulating various flood events with return periods ranging from 2 to 1,000 years.

5.4 Model Parameters and Additional Setup Considerations

5.4.1 Manning's Roughness Coefficient

5.4.1.1 Channel Roughness

The calibrated channel roughness values range from 0.030 to 0.040. The longitudinal distribution of the roughness values along the study reach is shown in Figure 10. The approach, model calibration and selection of channel Manning's values are as follows:

- The Manning's n value of 0.030 for the most upstream river reach (i.e. first seven cross sections) was selected to be the same as the calibrated Manning's n value as in the Bow and Elbow Hydraulic Model used for the short river reach below Highwood River confluence.
- A constant Manning's n value of 0.035 was selected between the downstream end of the above short reach and the Carseland Weir based. This selection was mainly based on the model calibration results using the flow rating curve at the WSC Station 05BM002 (Bow River below Carseland Dam), and in consideration of the channel bed materials (consisting of mainly gravels and cobbles) and channel sinuosity.
- The main channel Manning's n values for the Bow River reach between Carseland Weir and Bassano Dam, were selected to be in a range of 0.032 to 0.040, in consideration of the model calibration results, channel bed materials (consisting of mainly gravels and cobbles) and channel sinuosity.
- There is only one HWM available the for the river reach between the Bassano Dam and model downstream boundary. The model for this river reach was calibrated based on one 2013 HWM data surveyed at Highway 539 Bridge and the flow rating curve for the WSC Station 05BM004 (Bow River below Bassano Dam). A constant Manning's n value of 0.030 was selected for this river reach in consideration of model calibration results, channel bed materials, and channel sinuosity.

The selected Manning's n values are in the reasonable range in comparison to typical values (Chow 1959), and are considered representative of the river channel roughness along the study reach.

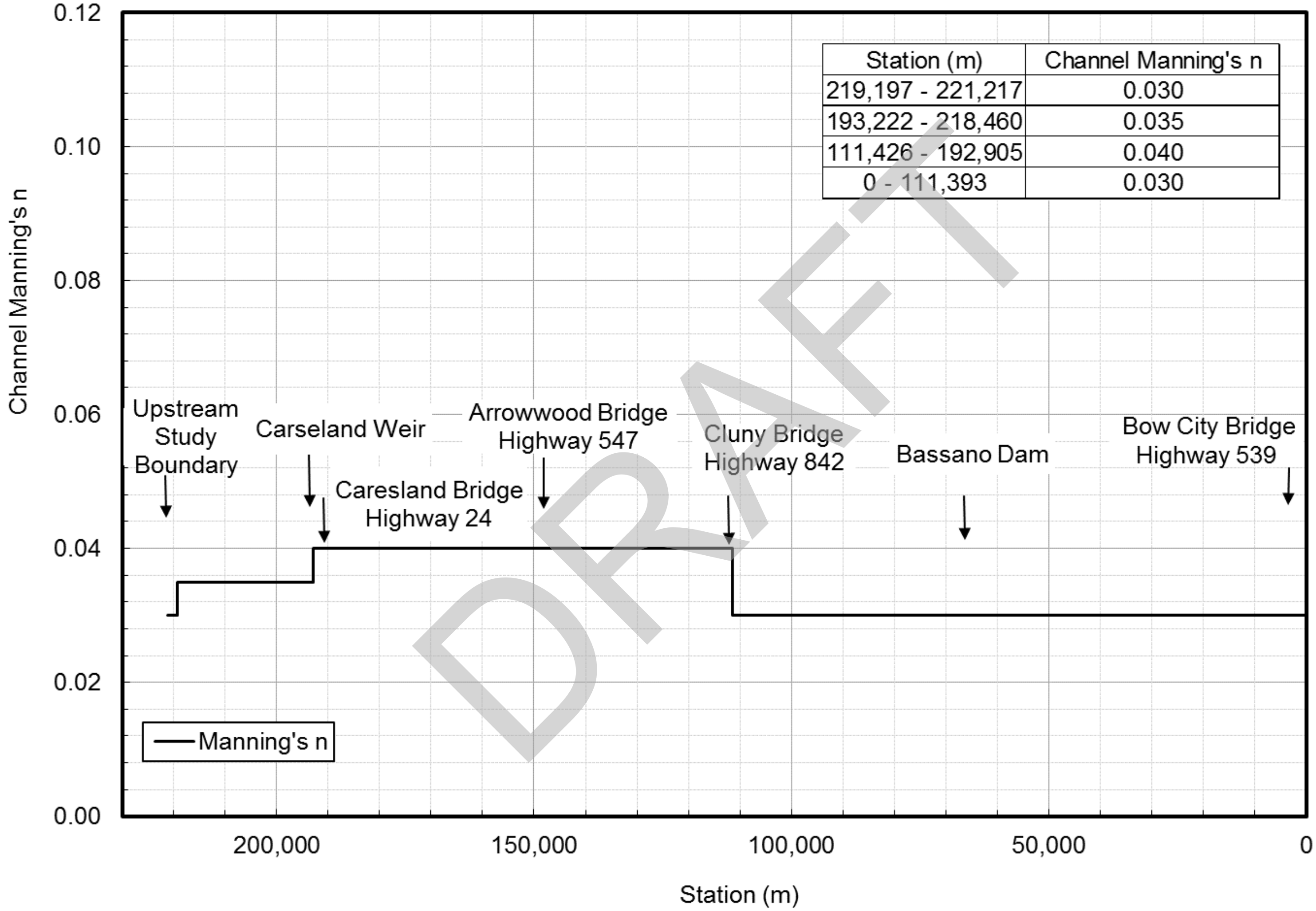


Figure 10: Selected Channel Roughness Values along the Study Reach

5.4.1.2 Overbank Roughness

During the high flow calibration process, the initially-estimated Manning's n values for the overbank areas were adjusted for those areas where the simulated water levels were largely different from the HWMs. Table 13 presents the final Manning's n values based on various land uses on the floodplains.

Table 13: Manning's n Values for Various Land Uses on the Floodplains

Land Use	Initial Manning's n Value	Calibrated Manning's n Value
Urban Mixture	0.080	0.080
Ponds	0.038	0.038
Grassland / Farmland	0.050	0.045 -0.070
Trees / Bushes	0.100	0.080 - 0.140

5.4.2 Expansion and Contraction Coefficients

During the calibration process, some of the values of the contraction/expansion coefficients were adjusted. The calibrated contraction coefficient values range from 0.1 to 0.5, and the calibrated expansion coefficient values from 0.3 to 0.8.

5.4.3 Obstructions and Ineffective Flow Areas

Considerable efforts were spent to identify and define the ineffective flow areas so that one geometry file can be used to simulate various floods with return periods of 2 to 1,000 years. The ineffective flow areas were defined in considerations of local topography, structures, and flow connection between adjacent cross sections.

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

- Topographical low areas such as ponds: permanent ineffective flow areas were specified to block off low-lying areas that do not effectively convey flows.
- Topographical low areas that can be activated: non-permanent ineffective flow areas are specified to block off low-lying areas that can become active after the water level is above a certain elevation.
- Bridge decks and embankments: ineffective flow areas are specified at the cross sections upstream and downstream of the bridges to block off the flow areas if the water level is lower than the top-of-embankment elevation.

5.4.4 Flow Splits, Islands and Diversions

There is no separate branch represented in the model for simulating flow splits between the main and side channels along the study reach.

There is no large island situated along the study reach.

The Carseland Diversion Canal and Bassano Dam Diversion Canal are not represented in the HEC-RAS model. The flow conveyance in these two canals is considered to be relatively small during flood events. Modelling performance of these canals is outside of the study scope.

5.5 Open Water Flood Frequency Profiles

5.5.1 Production Model

Recently, an emergency spillway was constructed on the Bassano Reservoir. The HEC-RAS production model was developed based on the calibrated HEC-RAS model to include the hydraulic effects of this emergency spillway constructed post the 2013 flood event. Spillway details were not coded into the model. The HEC-RAS production model was set up to simulate performance of the dam using all spillways according to the operations rating curve supplied by EID.

In this study, the peak flows used in the HEC-RAS production model were estimated based on the most recent hydrology assessment (Golder 2017). 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 post-berm production model.

5.5.2 Flow Change Locations

A total of seven flow change locations along the study reach were selected and included in the production model. As shown in Figure 11, they include six locations along the upper reach between the Highwood River confluence and Bassano Dam and one location along the lower reach from Bassano Dam to the model downstream boundary.

The flow change locations were selected based on the following considerations:

- The number of flow zones proposed along the study reach matches with the number of assigned flow nodes in the 2017 Hydrology Report in order to make full use of the results from the report (Golder 2017); and
- The flow change locations were selected to be representative for a given distance upstream and downstream from each assigned flow node, in considerations hydraulic factors (e.g., tributary confluence, hydraulic structure, morphological change, etc.).

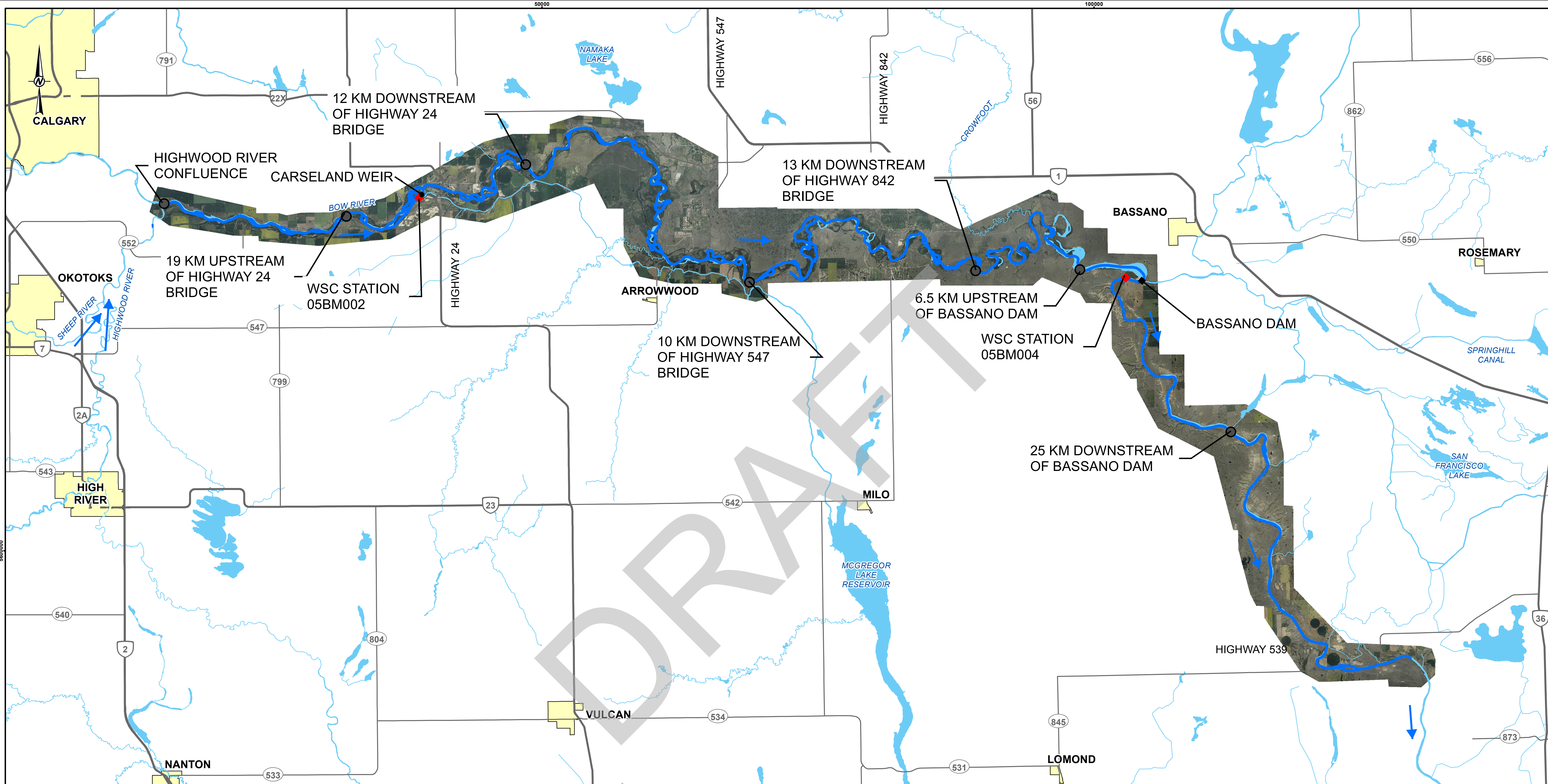
5.5.3 Flood Peak Discharges

The flood peak discharges along the study reach were estimated based on the relationships derived using the flood peak flow estimates in the hydrology study (Golder 2017). The hydrologic study provides the estimates of flood peak flows and drainage areas for the following seven locations:

- Bow River below Highwood River;
- Bow River below Carseland Dam (05BM002);
- Bow River at Highway 547;
- Bow River at Highway 842;
- Bow River below Crowfoot Creek;
- Bow River below Bassano Dam (05BM004); and
- Bow River at Highway 842.

5.5.4 Summary of Flood Peak Flows

The estimates of flood peak flows at all of the flow change locations included in the HEC-RAS production model are summarized in Table 14.



LEGEND

- FLOW DIRECTION
- PRIMARY HIGHWAY
- SECONDARY HIGHWAY
- WATERCOURSE
- SURVEY REACH
- WATERBODY
- POPULATED PLACE
- Flow Change Location
- WSC STATIONS

0 15 30 KILOMETRES
1:350,000

REFERENCE(S)

ROADS, RAILWAYS AND POPOPULATED PLACES OBTAINED FROM ALTALIS, © GOVERNMENT OF ALBERTA 2018. ALL RIGHTS RESERVED.
DATUM: NAD 83 CSRS PROJECTION: 3TM 114

CLIENT
ALBERTA ENVIRONMENT AND PARKS
Alberta Government

CONSULTANT
Golder Associates

YYYY-MM-DD	2019-07-22
DESIGNED	PH
PREPARED	PH
REVIEWED	HZ
APPROVED	HZ

PROJECT
SIKSIKA BOW RIVER HAZARD STUDY

TITLE
FLOW CHANGE LOCATIONS IN THE HEC-RAS PRODUCTION MODEL

PROJECT NO.	CONTROL	REV.	FIGURE
1783054	2000	0	11

Classification: Public

Table 14: Summary of Flood Peak Flows at the Flow Change Locations Included in the HEC-RAS Production Model

Location	HEC-RAS Cross Section	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
Bow River below Highwood River Confluence	221,217	604	917	1,210	1,580	1,950	2,230	2,590	2,880	3,750	4,690	5,420	6,390	7,180
Bow River below Carseland Dam	190,457	604	923	1,230	1,620	2,010	2,310	2,690	2,990	3,890	4,790	5,480	6,370	7,090
Bow River at Highway 547	147,557	599	925	1,240	1,630	2,030	2,330	2,720	3,030	3,950	4,870	5,560	6,470	7,210
Bow River at Highway 842	111,426	597	932	1,260	1,680	2,100	2,420	2,820	3,150	4,120	5,090	5,820	6,790	7,560
Bow River below Crowfoot Creek	81,122	591	932	1,260	1,680	2,100	2,420	2,830	3,160	4,130	5,100	5,840	6,810	7,580
Bow River below Bassano Dam	64,379	591	932	1,260	1,680	2,100	2,420	2,830	3,160	4,130	5,100	5,840	6,810	7,580
Bow River at Highway 539	4,112	581	913	1,230	1,620	2,010	2,300	2,660	2,950	3,790	4,620	5,240	6,030	6,660

5.5.5 Model Boundary Conditions

The boundary conditions of the HEC-RAS production model are listed below:

- Discharges specified at the upstream end of the study reach.
- The specified flood peak flow changes at the six cross sections along the study reach as listed in Table 15.
- Normal flow condition with an energy slope of 0.036% specified at the model downstream boundary.

5.5.6 Open Water Flood Frequency Profiles along the Bow River Study Reach

The simulated open water flood profiles along the study reach are presented in Figures C-1 to C-5 in Appendix C.

The simulated open water flood water levels at individual cross sections are listed in Tables C.1 and C.2 in Appendix C.

5.6 Model Sensitivity

A model sensitivity analysis was conducted to evaluate the effects of changing model roughness values and downstream boundary conditions on simulated water levels. The discharges used for the model sensitivity analysis were the 100-year flood peak flows. The results of the sensitivity analysis were used to quantify the level of uncertainty associated with the simulated flood levels along the study reach.

The analysis of sensitivity to Manning's *n* involves the following three sets of Manning's *n* values for the river channels and floodplains and two set of downstream boundary conditions:

- First set corresponding to ±10% changes of the calibrated channel Manning's *n* values only.
- Second set corresponding to ±10% changes of the calibrated floodplain Manning's *n* values only.
- Third set corresponding to ±10% changes of the calibrated channel and floodplain Manning's *n* values.
- Fourth set corresponding to ±20% changes of the specified energy slope at the downstream boundary.

Figures D-1 to D-4 in Appendix D graphically present the differences between the simulated water levels for the 100-year flood along the study reach. The results of the sensitivity analysis indicate the following:

- The uncertainty in the simulated flood levels, on average, are within a range of ±0.13 (with standard deviation of 0.09 m) along the entire study reach, based on the differences in the simulated flood levels for the ±10% changes to the calibrated channel Manning's *n* values only.
- The uncertainty in the simulated flood levels, on average, are within a range of ±0.12 m (with standard deviation of 0.05 m) along the entire study reach, based on the differences in the simulated flood levels for the ±10% changes to the calibrated floodplain Manning's *n* values only.
- The uncertainty in the simulated flood levels, on average, are within a range of ±0.24 m (with standard deviation of 0.10 m) along the entire study reach, based on the differences in the simulated flood levels for the ±10% changes of the calibrated channel and floodplain Manning's *n* values.
- The ±20% changes of the energy slope at the downstream boundary influence the simulated flood levels in a river reach of approximately 10 km upstream of the boundary.

6.0 CONCLUSIONS

6.1 Model Calibration and Validation

The HEC-RAS model, set up with one geometry file for the Siksika Bow River study reach, was calibrated and validated based on the available high flow and flow 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 channel Manning's n values for the high flow conditions range from 0.030 to 0.040 along the 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 similar influence on the simulated flood levels as variation of the floodplain roughness values.

The 100-year flood levels are estimated, on average, to be within a range of ±0.24 m along the study reach based mainly on the differences in the simulated flood levels for the ±10% changes from the calibrated channel and floodplain Manning's *n* values.

6.3 Flood Profiles

After June 2013 flood, one emergency spillway was constructed at the Bassano Dam. The HEC-RAS production model was set up to simulate performance of the dam using all spillways according to the operations rating curve supplied by EID.

A total of seven flow change locations along the study reach were selected and included in the production model. The flood peak discharges at these locations were estimated based on the results of the hydrology study report (Golder 2017).

The production 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 along the study reach.

Report Signature Page

This report is prepared and reviewed by the undersigned.

GOLDER ASSOCIATES LTD.

APEGA PERMIT TO PRACTICE #05122

Prepared by: Reviewed by:

Original singed by:

Jie Chen, M.Sc., P.Eng.
Water Resources Engineer

Original singed by:

Dejiang Long, Ph.D., P.Eng.
Principal, Senior Water Resources Engineer

Original singed by:

Parnian Hossein, Ph.D., E.I.T
Water Resources Specialist

Original singed by:

Hua Zhang, Ph.D., P.Eng.
Associate, Senior Water Resources Engineer

JC/HZ/DL/js/al/jlb

https://golderassociates.sharepoint.com/sites/17409g/technical work/02_hydraulic modelling/final report_January 2019/final report_siksika bow model creation & calibration_july 24 2019.docx

REFERENCES

Alberta Environment. 1996. High Water Mark Report – 1995 Southern Alberta June High Water. February 1996

Alberta Environment and Sustainable Resource Development. 2014. 2013 High Water Mark Report – Lower Bow River, including Siksika First Nation. January 2014.

AMEC. 2014. Carseland Bow River Headworks: Repair of Fuse Plug at Johnson's Island. CWRA 2014 Conference. March 2014.

AMEC. 2015. Design Basis Memorandum - Carseland Bow River Headworks – Johnson's Island Dyke Fuse Plug Repair. January 2015.

Bassano Dam Diversion of Eastern Irrigation District (EID). 2018. Bassano Dam Emergency Spillway – Future Operating Plan in a Flood. January 2018.

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

Golder. 2015a. Open-Water Survey for the Bow, Oldman and South Saskatchewan Rivers. September 2015.

Golder February 2015b. Phase II - Open-Water Survey for Bow River Reaches: Bathymetry, Sediment and Vegetations. November 2015.

Golder 2017. Bow, Elbow, Highwood and Sheep River Hydrology Assessment. Prepared for Alberta Environment and Parks. February 2017.

Golder 2018a. Siksika Bow River Hazard Study - Survey and Base Data Collection. Prepared for Alberta Environment and Parks. January 2018.

Golder 2018b. Hydraulic Model Creation and Calibration - Bow and Elbow River Hazard Study. Prepared for Alberta Environment and Parks. December 2018.

M.A.N. - GHH Canada Inc. 1986. Bassano Dam Project Drawing List: As Built Drawings – Bassano Dam Structure and Mechanical. September 1986.

MPE Engineering Ltd. And Klohn Crippen Berger. 2017. Bassano Dam Emergency Spillway Structure. June 2017.

P.F.R.A. 1972. Bow River Project – Carseland Dam As Constructed Drawings. January 1972.

Stantec Consulting Ltd. 2014. Bow River Bridge Near Gleichen, AB, After the Flood. September 2014.

USACE (US Army Corps of Engineers). 2016a. HEC-RAS River Analysis System - User's Manual, Version 5.0.

USACE. 2016b. HEC-RAS River Analysis System - Hydraulic Reference Manual, Version 5.0.

APPENDIX A

Digital Deliverables – Historic Flood Data and Information

(TO BE PROVIDED SEPARATELY AS PART OF THE FINAL REPORT)

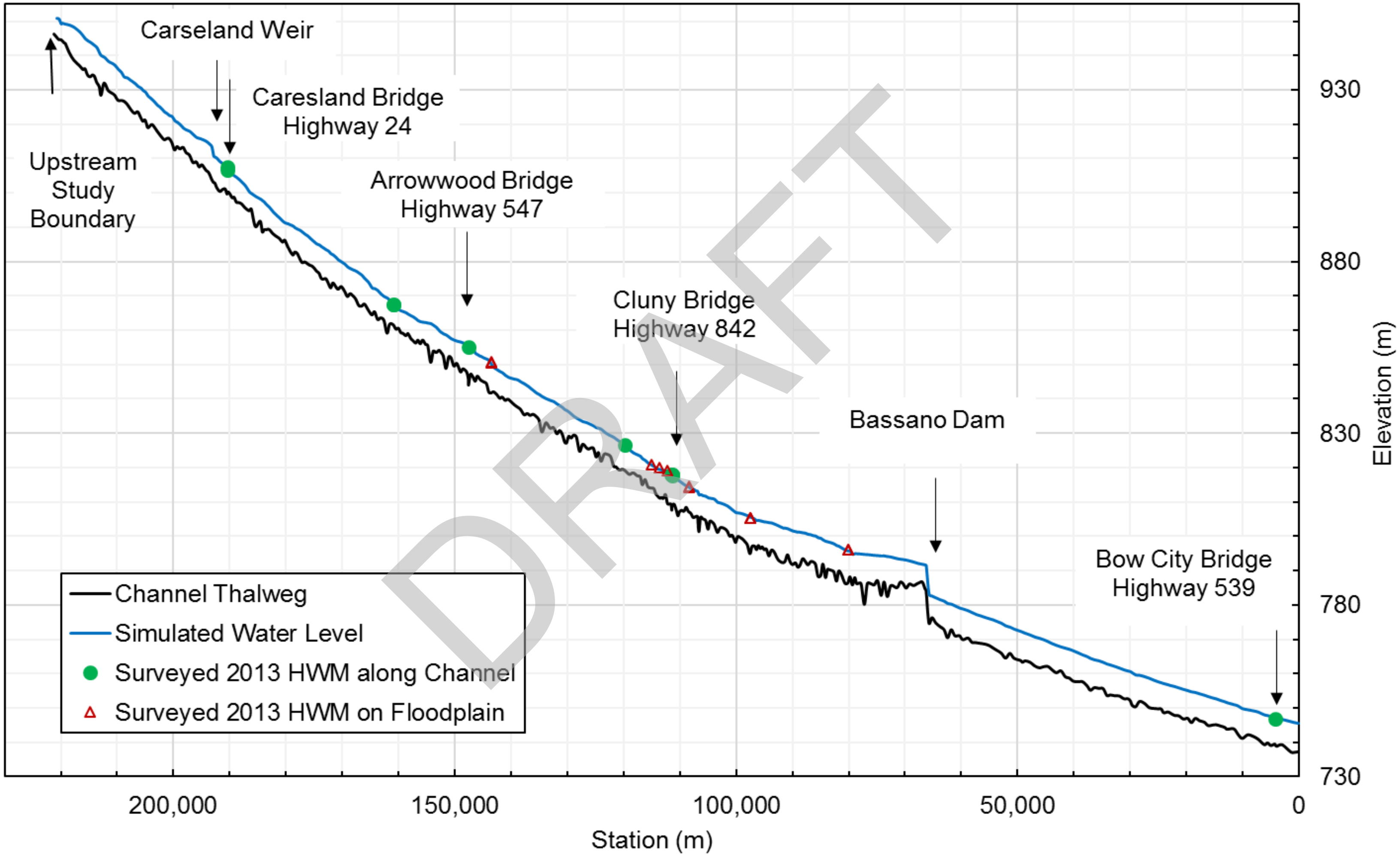
APPENDIX B

Model Calibration and Validation Results

Table B.1: Comparison of Simulated and Surveyed High Water Marks along the Bow River Study Reach for the June 2013 Flood Event

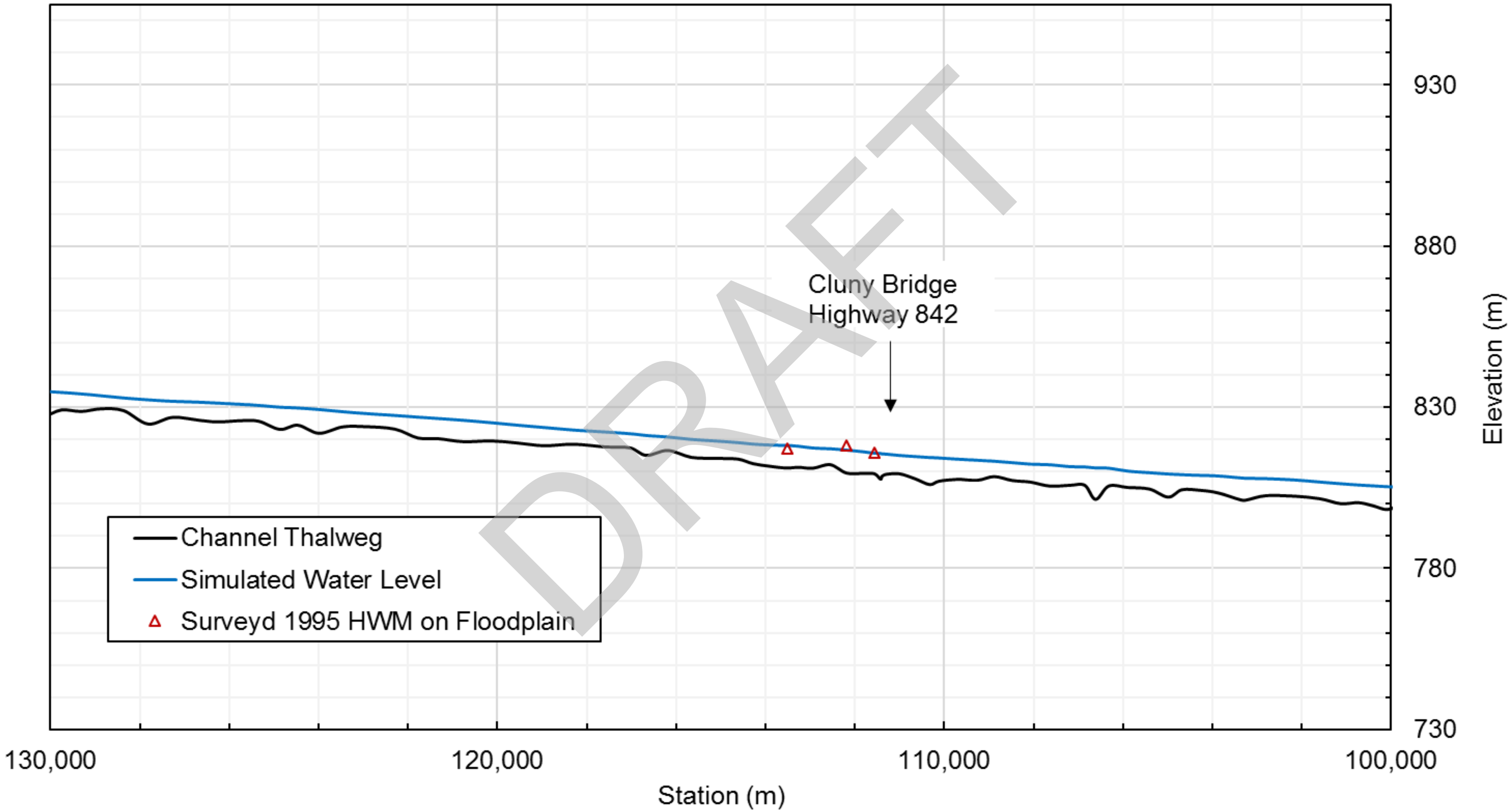
Distance from the Upstream Study Boundary (km)	Interpolated HEC-RAS Station	Surveyed HWM (m)	Simulated Water Level (m)	Difference (Simulated - Surveyed) (m)	Simulated Discharge (m^3/s)	Surveyed Date	Description	Notes
30.79	190432	906.54	907.25	0.71	3300	7/1/2013	Downstream left bank of Highway 24 Bridge	
30.73	190484	907.41	907.51	0.10	3300	7/1/2013	Upstream left bank of Highway 24 Bridge	Fuse Plug elevation
60.36	160856	867.57	867.24	-0.33	3300	7/1/2013	13 km upstream of Highway 547 Bridge	Behind the structure
60.36	160854	867.56	867.24	-0.32	3300	7/1/2013	13 km upstream of Highway 547 Bridge	Behind the structure
73.67	147546	855.14	855.18	0.03	3300	7/26/2013	Downstream right bank of Highway 547 Bridge	The bridge got washed out
77.64	143579	850.68	850.10	-0.58	3300	7/26/2013	4 km dowsntream of Highway 547 Bridge (1 km from the left bank)	
77.64	143579	850.46	850.10	-0.36	3300	7/26/2013	4 km dowsntream of Highway 547 Bridge (1 km from the left bank)	
101.36	119857	826.47	826.31	-0.16	3300	7/26/2013	8 km upstream of Highway 842 Bridge	
106.11	115106	820.72	820.71	-0.01	3300	7/26/2013	4 km upstream of Highway 842 Bridge (1 km from the left bank)	Far from main channel
107.53	113692	819.86	819.40	-0.46	3300	7/26/2013	2.3 km upstream of Highway 842 Bridge	Seems behind the levee
108.96	112256	819.21	818.88	-0.33	3300	7/26/2013	1 km upstream of Highway 842 Bridge	Seems behind the levee
109.80	111414	818.05	817.91	-0.14	3300	7/1/2013	Upstream left bank of Highway 842 Bridge	
109.79	111424	817.99	818.02	0.03	3300	7/1/2013	Upstream left bank of Highway 842 Bridge	
109.75	111466	817.83	818.11	0.28	3300	7/1/2013	100 m upstream of Highway 842 Bridge	
109.83	111391	817.59	817.68	0.09	3300	7/1/2013	Downstream left bank of Highway 842 Bridge	
112.78	108437	814.58	814.27	-0.31	3300	7/26/2013	3 km downstream of Highway 842 Bridge	
112.77	108446	814.34	814.28	-0.05	3300	7/26/2013	12 km downstream of Highway 842 Bridge (500 m from the left bank)	
123.70	97517	805.40	805.48	0.08	3300	7/26/2013	12 km downstream of Highway 842 Bridge (500 m from the left bank)	
123.72	97499	805.36	805.47	0.11	3300	7/26/2013	12 km downstream of Highway 842 Bridge (500 m from the left bank)	
123.75	97466	805.36	805.46	0.10	3300	7/26/2013	12 km downstream of Highway 842 Bridge (500 m from the left bank)	
141.08	80138	795.97	795.65	-0.32	3300	7/26/2013	14 km upstream of Bassano Dam	
141.09	80132	795.96	795.65	-0.31	3300	7/26/2013	14 km upstream of Bassano Dam	
217.12	4102	746.76	747.06	0.30	3380	7/1/2013	Downstream left bank of Highway 539 Bridge	

Figure B-1: Comparison of Simulated Water Surface Profile and Surveyed HWMs along the Bow River Study Reach for the 2013 Flood Event



Classification: Public

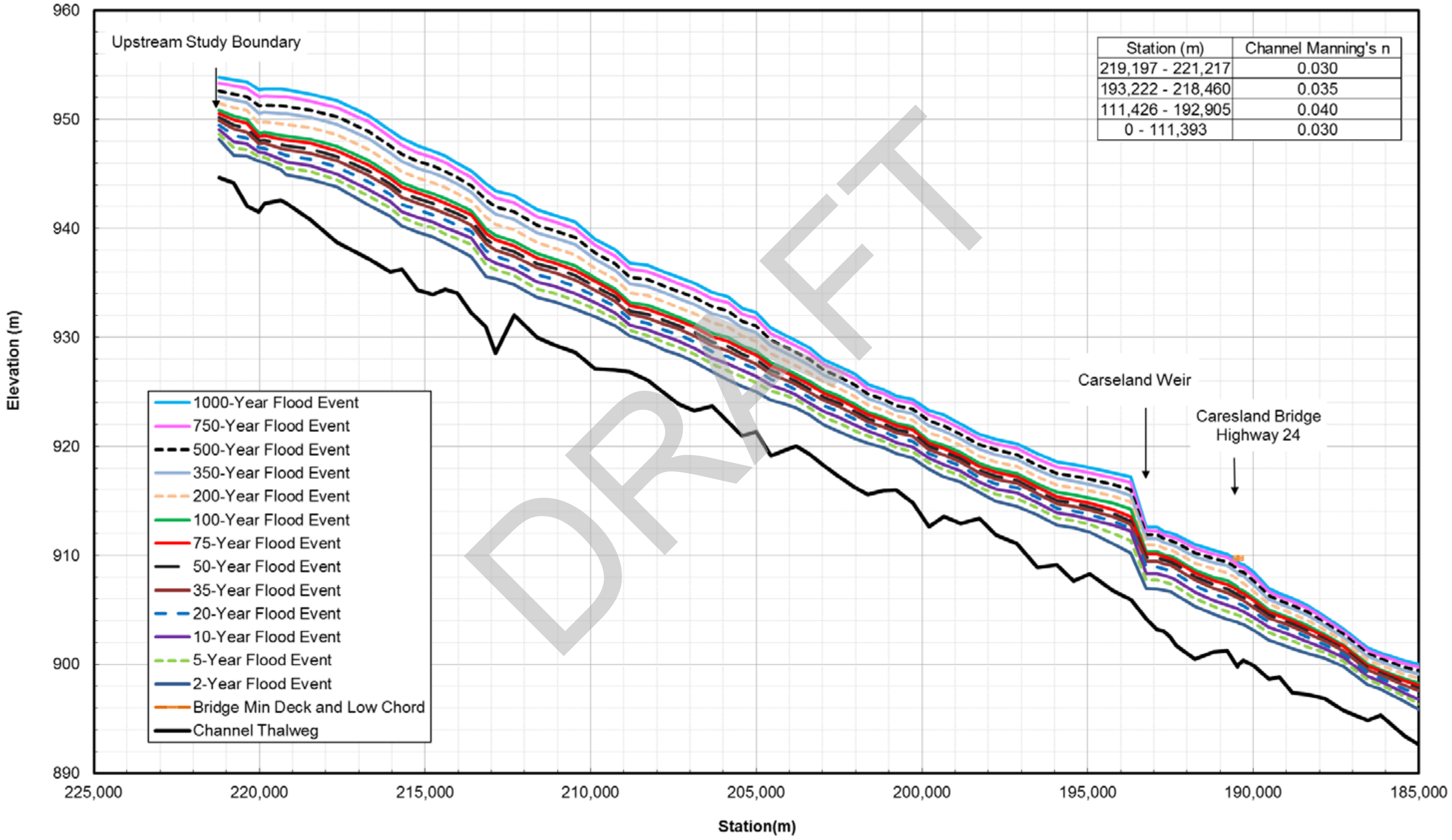
Figure B-2: Comparison of Simulated Water Surface Profile and Surveyed HWMs along the Bow River Study Reach for the 1995 Flood Event



APPENDIX C

Open Water Flood Frequency Profiles

Figure C-1: Simulated Water Surface Profiles along the Bow River Study Reach - Part 1



Station (m)	Channel Manning's n
219,197 - 221,217	0.030
193,222 - 218,460	0.035
111,426 - 192,905	0.040
0 - 111,393	0.030

Figure C-2: Simulated Water Surface Profiles along the Bow River Study Reach - Part 2

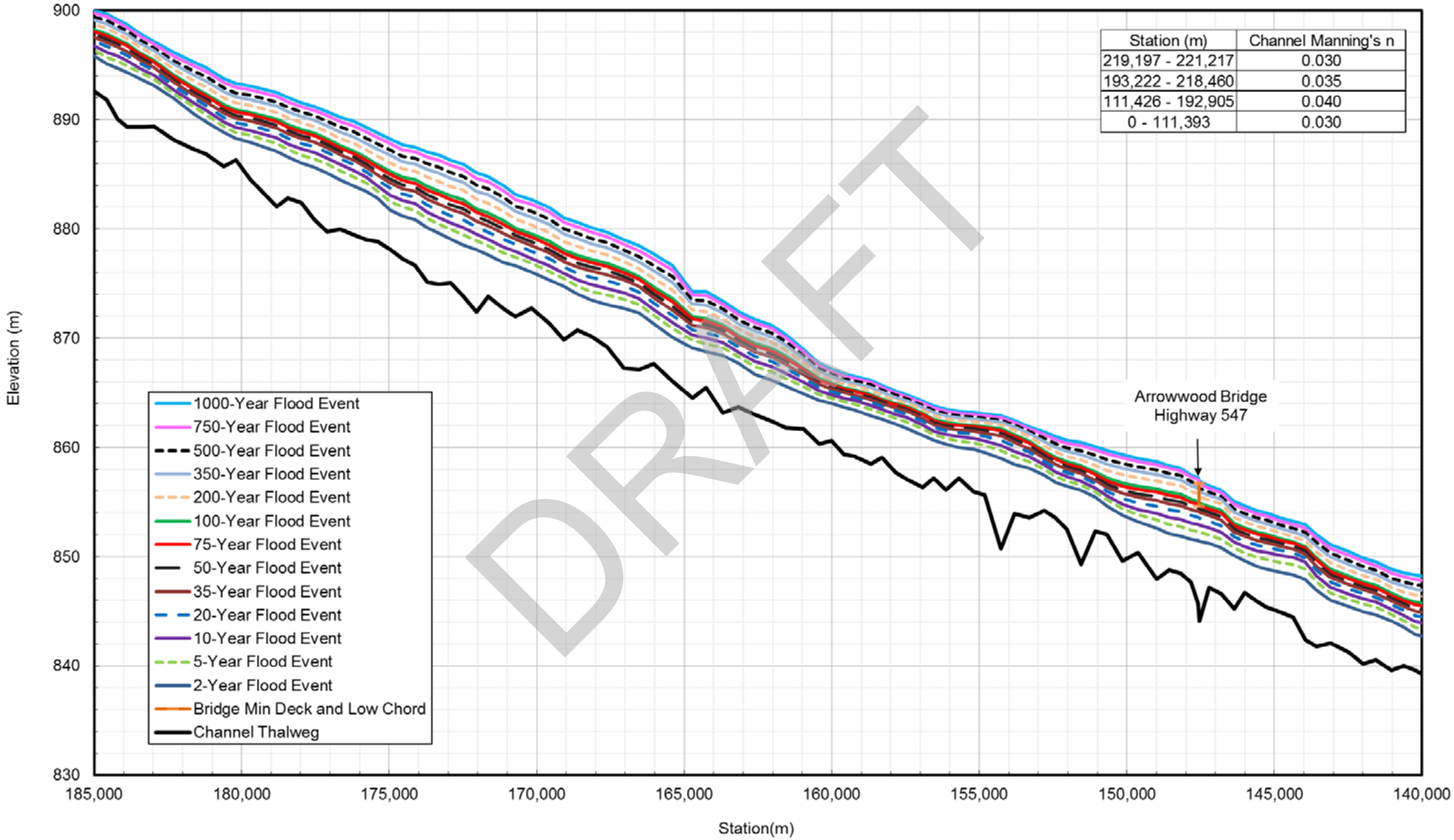


Figure C-3: Simulated Water Surface Profiles along the Bow River Study Reach - Part 3

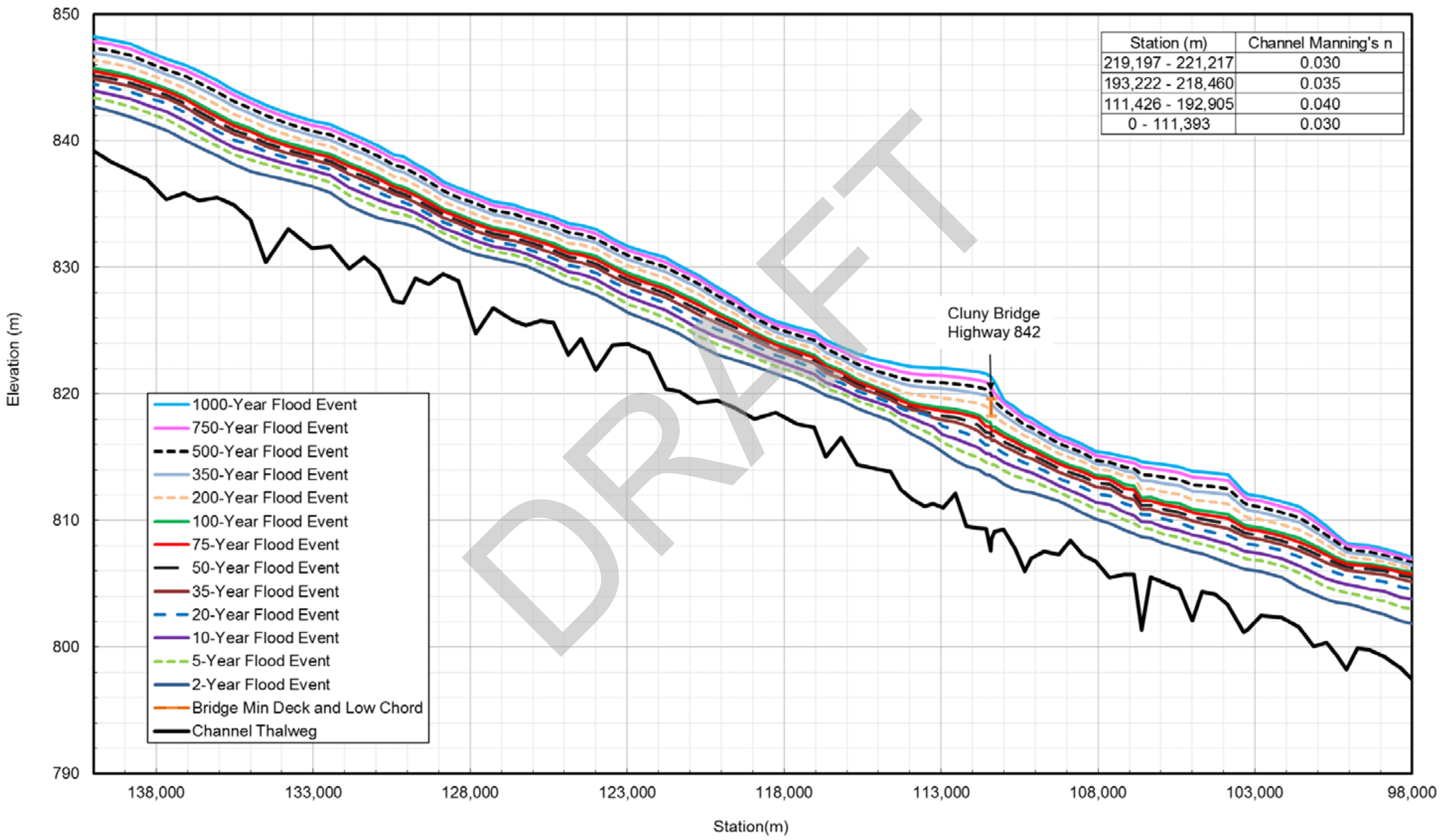
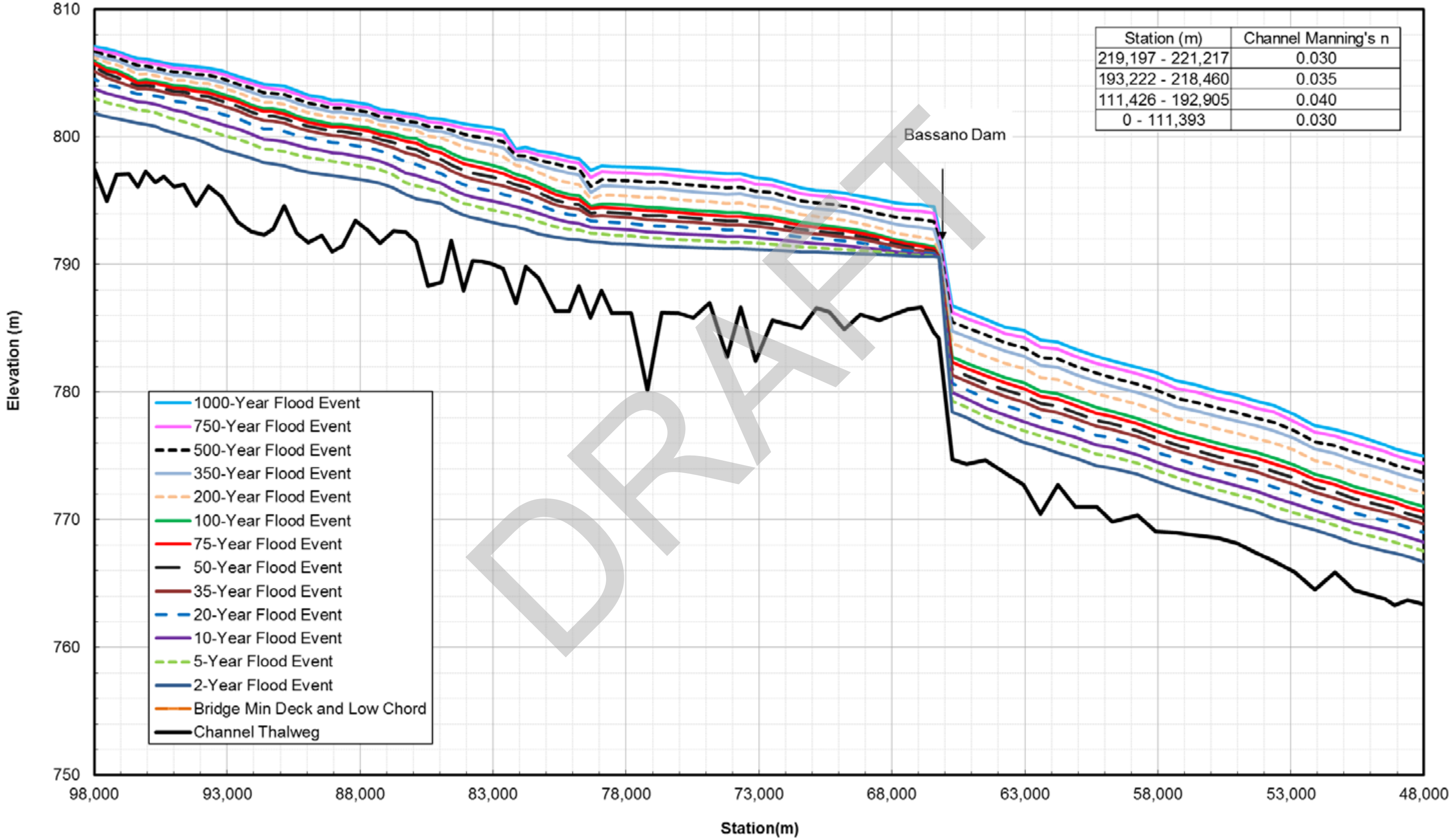
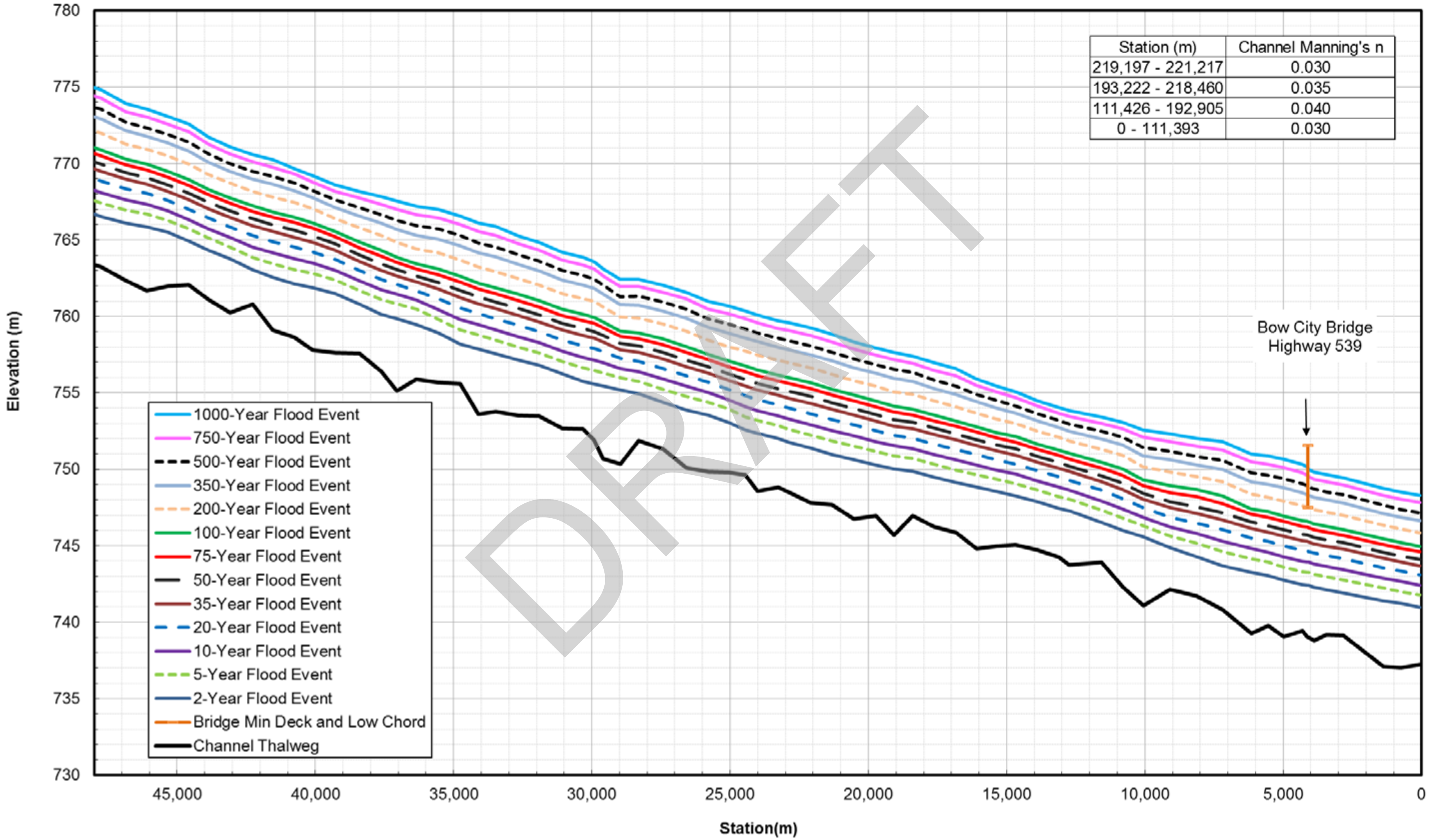


Figure C-4: Simulated Water Surface Profiles along the Bow River Study Reach - Part 4



Station (m)	Channel Manning's n
219,197 - 221,217	0.030
193,222 - 218,460	0.035
111,426 - 192,905	0.040
0 - 111,393	0.030

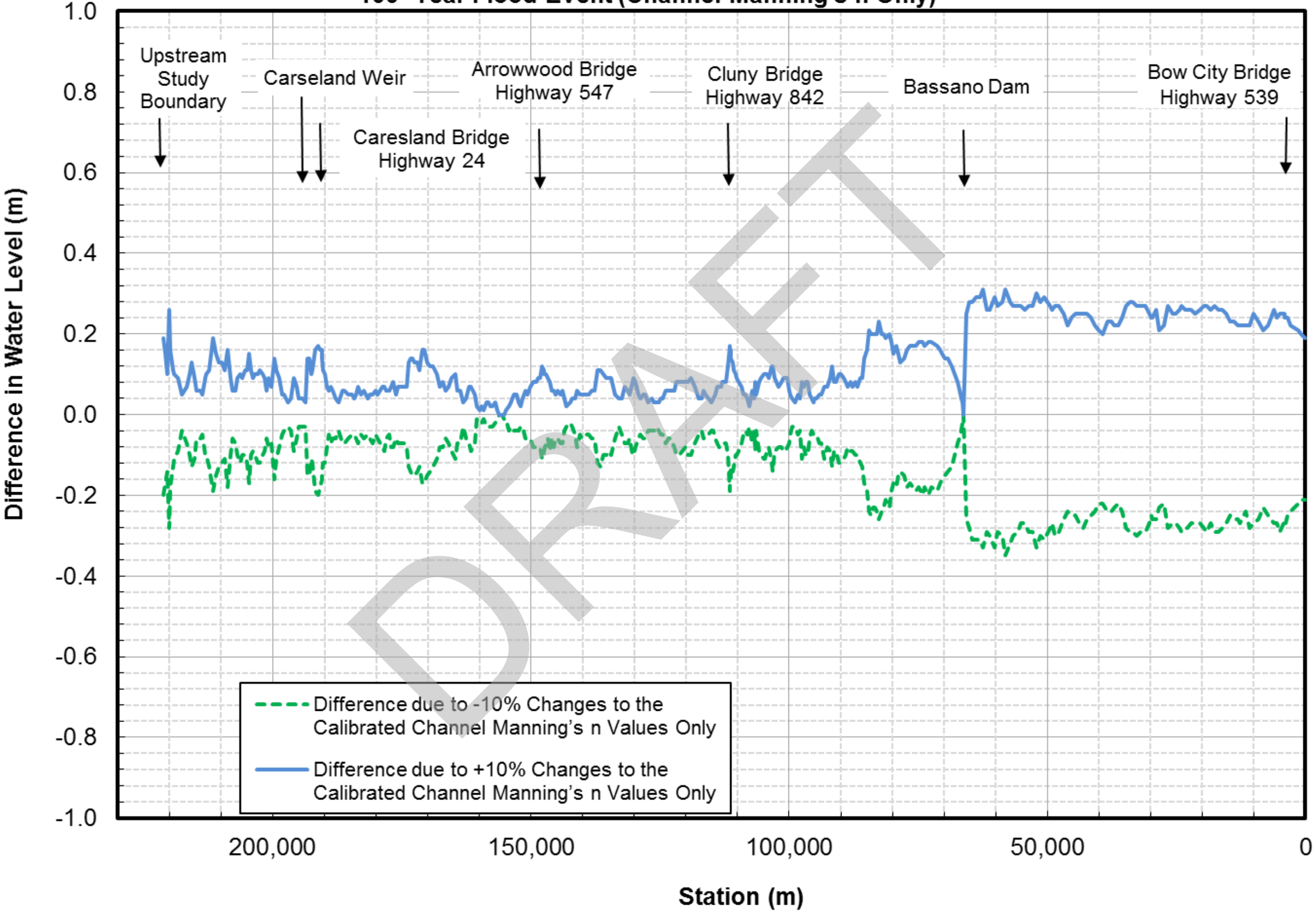
Figure C-5: Simulated Water Surface Profiles along the Bow River Study Reach - Part 5

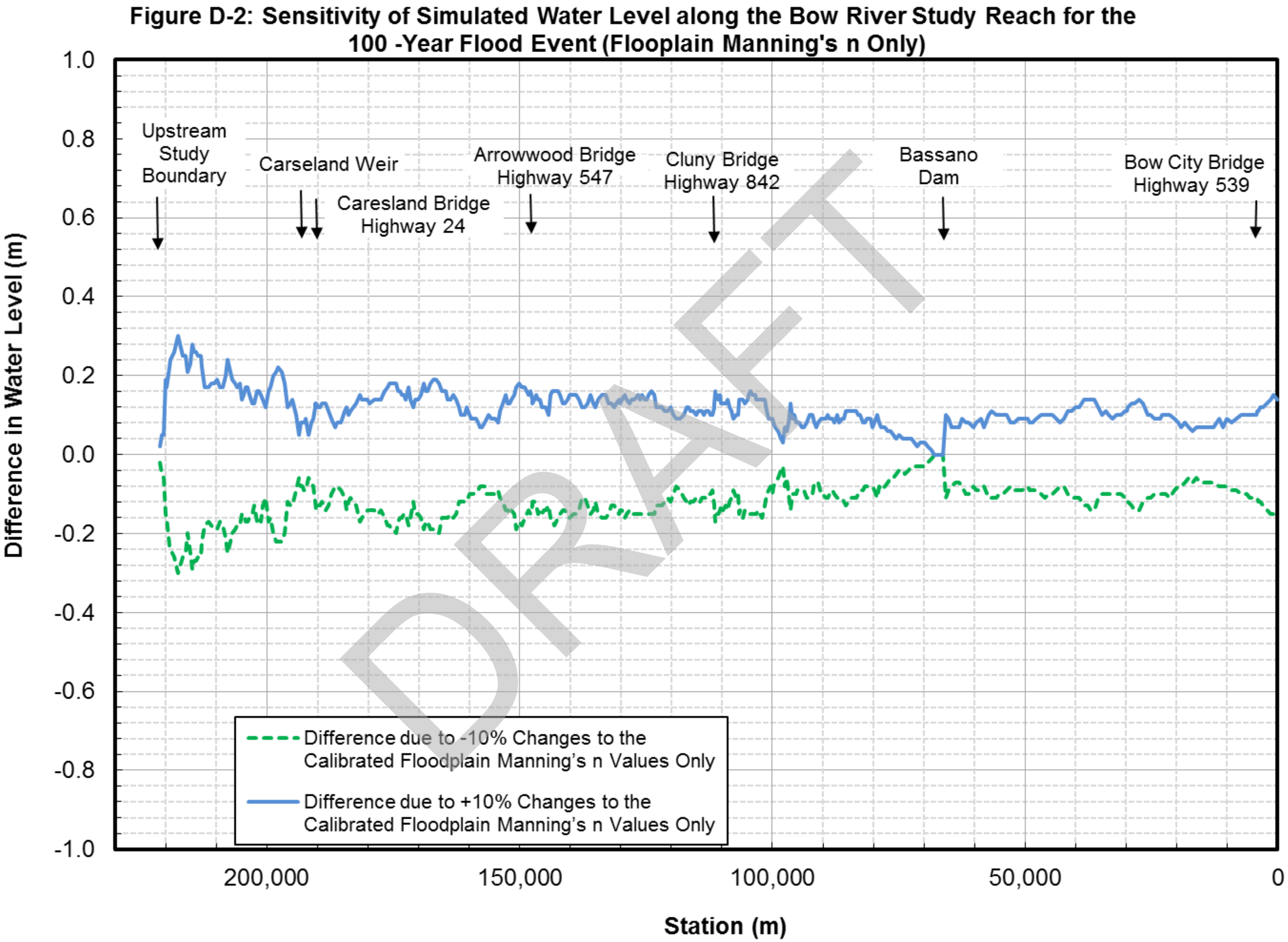


APPENDIX D

Model Sensitivity Analysis Results

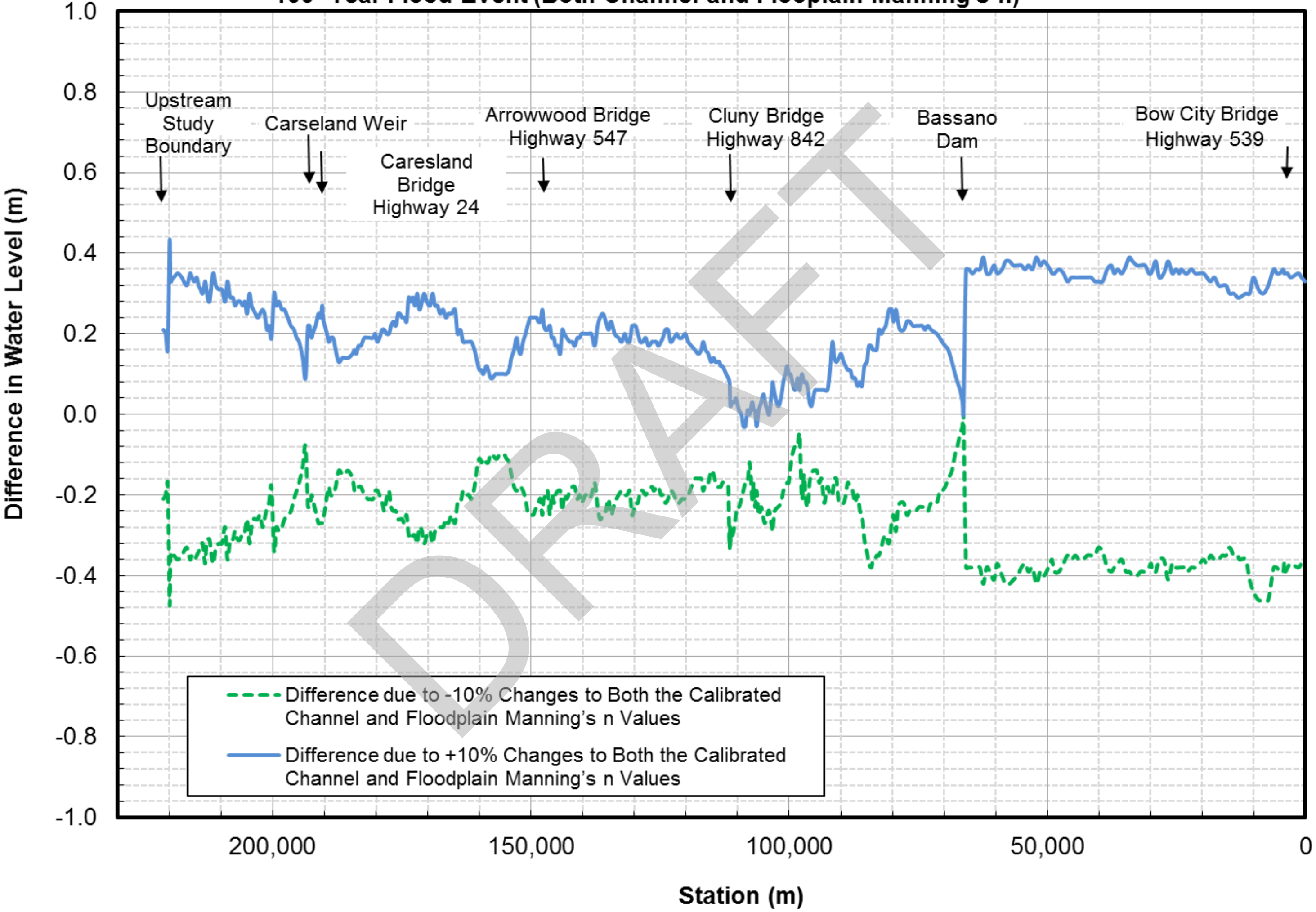
Figure D-1: Sensitivity of Simulated Water Level along the Bow River Study Reach for the 100 -Year Flood Event (Channel Manning's n Only)





Classification: Public

Figure D-3: Sensitivity of Simulated Water Level along the Bow River Study Reach for the 100 -Year Flood Event (Both Channel and Flooplain Manning's n)



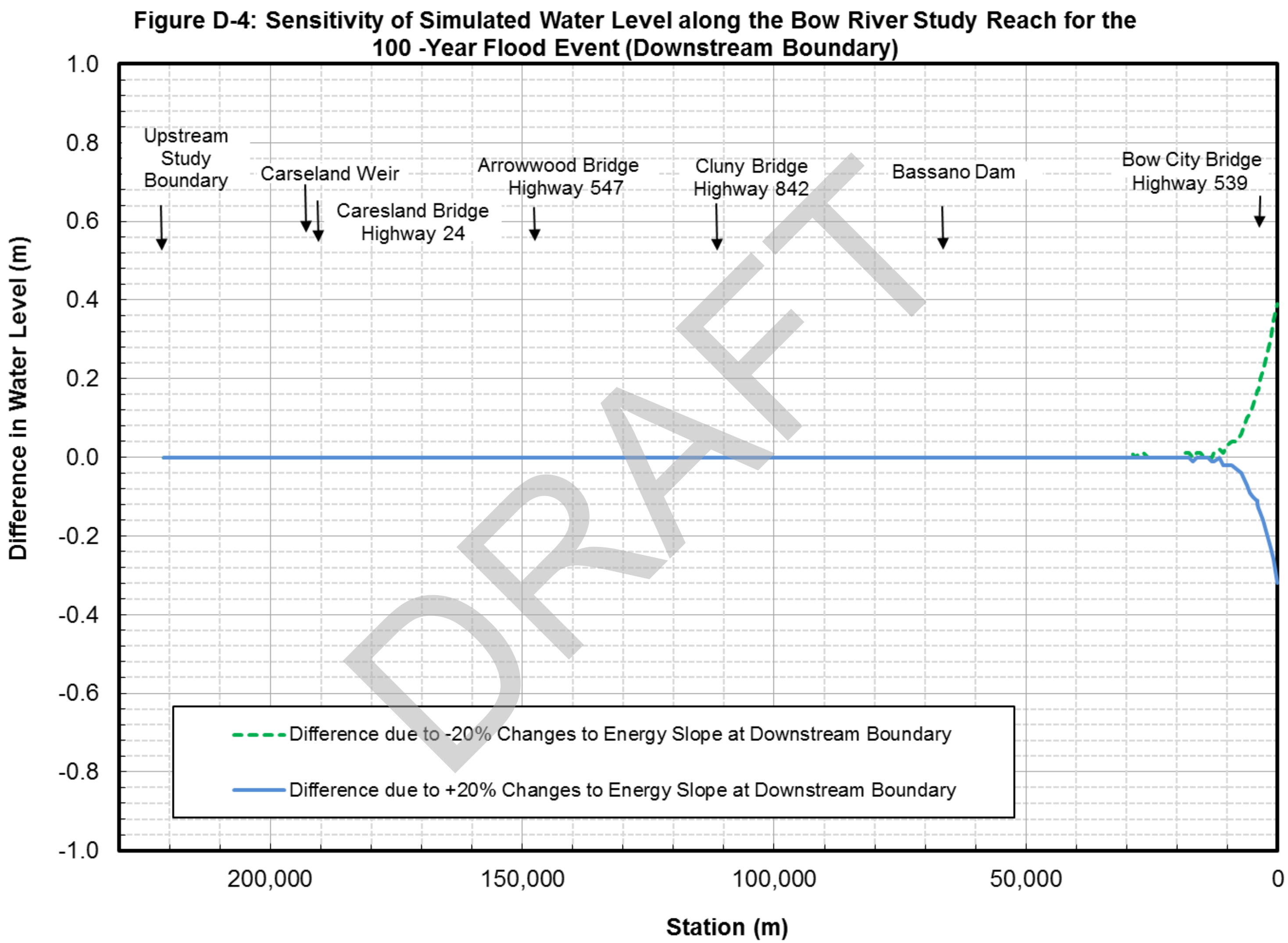


Figure D-4: Sensitivity of Simulated Water Level along the Bow River Study Reach for the 100 -Year Flood Event (Downstream Boundary)
Upstream Study Boundary
Carseland Weir
Caresland Bridge Highway 24
Arrowwood Bridge Highway 547
Cluny Bridge Highway 842
Bassano Dam
Bow City Bridge Highway 539
Difference in Water Level (m)
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
200,000
150,000
100,000
50,000
0
Station (m)
Difference due to -20% Changes to Energy Slope at Downstream Boundary
Difference due to +20% Changes to Energy Slope at Downstream Boundary
DRAFT

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

For more information, visit golder.com

Africa	+ 27 11 254 4800
Asia	+ 86 21 6258 5522
Australasia	+ 61 3 8862 3500
Europe	+ 44 1628 851851
North America	+ 1 800 275 3281
South America	+ 56 2 2616 2000

solutions@golder.com
www.golder.com

Golder Associates Ltd.
102, 2535 - 3rd Avenue S.E.
Calgary, Alberta, T2A 7W5
Canada
T: +1 (403) 299 5600

Golder Associates