KGS GROUP
CONSULTING ENGINEERS

Newfoundland Labrador

CLIMATE CHANGE FLOOD RISK MAPPING STUDY AND THE DEVELOPMENT OF A FLOOD FORECASTING SERVICE: HAPPY VALLEY – GOOSE BAY AND MUD LAKE
FINAL REPORT

FINAL - REV 2

KGS Group 18-3217-001
July 2020

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in association with
4DM
Providing solutions through mapping technology...

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Water Resources Management Division
Department of Municipal Affairs and Environment
Government of Newfoundland and Labrador
4th Floor, Confederation Building, West Block
PO Box 8700, St. John's, NL
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ATTENTION: Dr. Amir Ali Khan, Ph.D., P.Eng.
Manager – Water Rights, Investigations, and Modelling Section

RE: Climate Change Flood Risk Mapping Study and the Development of a Flood Forecasting Service: Happy Valley – Goose Bay and Mud Lake
Final Report – Rev 2

Dear Mr. Khan:

Please find attached KGS Group's updated Final Report (Rev. 2) main document for the Climate Change Flood Risk Mapping and the development of a Flood Forecasting Service for the Communities of Happy Valley – Goose Bay and Mud Lake. The final report has been updated to address comments provided by WRMD.

Please let me know if you have any questions regarding this final document.

Yours truly,

David S. Brown, P.Eng.
Water Resources Department Head /
Associate Principal

DSB/as
Attachment

Cc: Mohammad Khayer (WRMD)

EXECUTIVE SUMMARY

Kontzamanis Graumann Smith MacMillan (KGS Group) was retained by the Water Resources Management Division (WRMD) of the Province of Newfoundland and Labrador to provide engineering services to complete flood risk and flood hazard mapping for the lower Churchill River, and to develop a flood forecasting service for communities located on the river. The engineering study included the development of detailed hydraulic and hydrologic models to serve as the basis for the flood risk mapping, and the incorporation of those models into a fully automated forecasting service that provides daily forecast flows and water levels at key locations on the Churchill River.

To complete this study, KGS Group led a diverse, highly experienced Project Team, with members from different companies, in the development of the flood risk maps and flood forecasting system. The composition of the Project Team, and the roles of each of our subconsultants included:

- ***KGS Group –*** KGS Group was responsible for the overall management of the project and was responsible all aspects of the study, including mainly, the development of the hydrologic and hydraulic models used for flood risk mapping and flood forecasting system.
- ***Dr. Karl-Erich Lindenschmidt –*** Dr. Lindenschmidt worked closely with KGS Group's in house national recognized ice expert to develop the ice-affected hydraulic model. Dr. Lindenschmidt was also responsible for the state-of-the-art Monte Carlo statistical method used in the ice-affected flood risk mapping and flood forecasting models.
- ***4DM Inc. –*** 4DM were responsible for the development of the software framework (i.e. HydrologiX) that automated the collection and processing of the various sources of data in the model, as well as the development of specialized software to automate the running of the different models in the system to generate flood forecasts for the Churchill River.
- ***N.E. Parrott Surveys Limited –*** N.E. Parrott Surveys were responsible for the completion of the topographic and bathymetric surveys in Happy Valley – Goose Bay

and Mud Lake. N.E. Parrot Surveys is based in Happy Valley – Goose Bay and as such are highly familiar with flooding in the area and provided valuable local knowledge and context to flooding in the area.

- ***Atlis Geomatics –*** Atlis Geomatics are highly experienced LiDAR and aerial imagery surveyors, and were responsible for the collection and processing of the LiDAR and aerial imagery data.
- ***Zuzek Inc. –*** Zuzek Inc. were responsible for providing expert guidance on tidal aspects that would affect water level on Lake Melville and the lower reaches of the Churchill River.

The scope of services for this study was based primarily on the terms of reference defined in the Request for Proposal issued by WRMD. The scope and the general approaches taken by the Project Team to fulfill that scope are summarized below.

- ***Background Information Review*** – A large amount of background information was reviewed relating to flooding on the Churchill River. The data was reviewed for any gaps or errors, and any gaps or errors that were identified were resolved.
- ***Field Program*** – An extensive field survey program was completed to acquire key topographic information within the study area, including the survey of bridge and culvert crossings and calibration points for the LiDAR survey, as well as a detailed bathymetric survey along the Churchill River and Mud Lake channels.
- ***LiDAR and Aerial Photography –*** A LiDAR and aerial imagery capture was completed for Happy Valley – Goose Bay, Mud Lake, and the Churchill River downstream of Muskrat Falls. The collected LiDAR data was used in combination with the bathymetric survey data to develop a detailed bare earth digital elevation model of the study area.
- ***Remote Sensing and Land Use Classification*** – Land use was classified throughout the Churchill River watershed based on available satellite imagery using artificial intelligence.
- ***Hydrologic Investigations and Modelling*** – Hydrologic assessments were completed to estimate the 20 and 100 year AEP flows on the Churchill River. A detailed hydrologic

model was also developed and calibrated to route the 20 and 100 year AEP rainfall events on the Churchill River watershed. Similarly, hydrologic models of Otter Creek, and seven unnamed creeks in Happy Valley – Goose Bay were developed to route the 20 and 100 year AEP rainfall events.

- ***Climate Change and Future Development Assessment*** – Projected impacts due to climate change were assessed for flows on the Churchill River, Otter Creek and the seven unnamed creeks in Happy Valley – Goose Bay, Lake Melville water levels and ice processes on the Churchill River. Anticipated development conditions were also reviewed for Happy Valley – Goose Bay.

- ***Hydraulic Investigations and Modelling*** – Hydraulic models were developed using HEC-RAS and RIVICE to represent open water and ice-affected conditions on the Churchill River from Muskrat Falls to Lake Melville. These models were calibrated to observed water levels on the Churchill River. Hydraulic models were also developed for Otter Creek and seven unnamed creeks in Happy Valley – Goose Bay.

- ***Sensitivity Analyses –*** The sensitivity to changes to key parameters was assessed for the hydrologic and hydraulic models.

- ***Flood Risk Mapping –*** Flood risk and flood hazard maps were developed for Happy Valley – Goose Bay and Mud Lake for the 20 and 100 year open water and ice-affected floods on the Churchill River for both current climate and climate change conditions. The flood risk maps were presented to and reviewed by representatives from Happy Valley – Goose Bay and Mud Lake, and comments provided by the representatives were incorporated into the final version of the maps. Flood risk and flood hazard maps were also developed for Happy Valley – Goose Bay for the 20 and 100 year rainfall events for both current climate and climate change conditions.

- ***Flood Forecasting –*** An automated flood forecasting system was developed for the Churchill River based on the hydrologic and hydraulic models developed for this study. The system automatically acquires key meteorological and hydrometric data and provides year round daily flow and water level forecasts at key locations on the Churchill River.

BACKGROUND INFORMATION REVIEW

An extensive array of background information was acquired, including precipitation and temperature data, historical water level and flow data, and historical flood observations on the Churchill River. This information provided context to the history of flooding on the Churchill River, and was used to assist in the calibration of the hydrologic and hydraulic models. The data was thoroughly reviewed to identify and resolve any errors or gaps in the data. As well, the historic flood event inventory managed by WRMD was reviewed and additional flood events on the Churchill River were added to the inventory.

FIELD PROGRAM

A detailed field program was completed to capture critical topographic and bathymetric data on the Churchill River, Mud Lake channels, Otter Creek, and local creeks north of Happy Valley – Goose Bay, culvert and bridge details, as well as ground elevations throughout the study area to assist with the calibration of the LiDAR survey. Eighty cross sections were surveyed along the Churchill River, with section spacing ranging from 1 km between Muskrat Falls and the Trans Labrador Highway bridge, and 500 m spacing between the Trans Labrador Highway bridge to Lake Melville. Eleven cross sections were surveyed on the Mud Lake channels from Mud Lake to the Churchill River. Detailed surveys were completed for the Trans Labrador Highway bridge and Mud Lake Footbridge, and culvert details were surveyed for 19 crossings in Happy Valley – Goose Bay. Ground elevations were surveyed at 12 locations throughout the study area to assist in the calibration of the LiDAR survey. Ground elevations were also surveyed at 20 locations throughout the study area to confirm the flood extents shown in the flood risk mapping.

LIDAR AND AERIAL PHOTOGRAPHY

LiDAR and aerial imagery were collected throughout the study area. However, due to persistent poor weather conditions such as rain, high winds, or low cloud cover, the LiDAR survey was only partially completed during summer 2018. Poor weather conditions persisted throughout the summer of 2019, which delayed the completion of the LiDAR survey until September 13, 2019. The LiDAR data, in combination with the bathymetric survey data, was used to develop a bare earth digital elevation model of the study area, which was the basis for the flood risk mapping. The aerial imagery was also incorporated into the flood risk mapping.

REMOTE SENSING AND LAND USE CLASSIFICATION

Satellite imagery was collected throughout the Churchill River watershed from the European Space Agency's Sentinel-2 satellite imagery dataset. A variety of corrections were applied to the imagery to account for meteorological differences between the images, which were then combined into a seamless mosaic. Artificial intelligence software was then trained and used to classify the land use of the imagery throughout the watershed. The land use classification was then combined with assumed soil conditions to generate a map throughout the watershed of the U.S. Soil Conservation Service's curve numbers.

HYDROLOGIC INVESTIGATIONS AND MODELLING

Several hydrologic analyses were completed to accurately define the 20 and 100 year AEP flows on the Churchill River. These analyses included a single station frequency analysis of the Water Survey of Canada gauge at Muskrat Falls, a regional flood frequency analysis for all of Labrador, and the development and calibration of a detailed hydrologic model of the Churchill River and its tributaries from Churchill Falls to Lake Melville. Hydrologic models were also developed for Otter Creek and seven unnamed creeks in Happy Valley – Goose Bay. Analyses of precipitation in the Churchill River watershed were completed to update existing intensity-duration-frequency curves representative of the current climate, and to define climate change intensity-duration-frequency curves. These curves were then used to define the 20 and 100 year rainfall events on the Churchill River watershed, which were routed using the calibrated hydrologic model to define the flows on the Churchill River associated with the rainfall events. The routing of the 20 and 100 year rainfall events using the hydrologic model estimated considerably lower flow on the Churchill River at Muskrat Falls than the single station frequency analysis and regional flood frequency analysis methods, which were in good agreement. This is as expected, as the large floods on the Churchill River are spring flood events driven by a combination of snow melt and rain on snow, as opposed to a rain event alone. The 20 and 100 year flows estimated using the single station frequency analysis were adopted for the subsequent hydraulic modelling and flood risk mapping tasks.

CLIMATE CHANGE AND FUTURE DEVELOPMENT CONDITIONS

An assessment was completed to define the anticipated impacts to Churchill River, Otter Creek and the unnamed creek flows, Lake Melville water levels, and ice thicknesses on the Churchill River associated with climate change. Under changing climate conditions, the 20 and 100 year AEP flows on the Churchill River are anticipated to increase by 2% by the end of the 21st century. Similarly, water levels on Lake Melville are projected to increase by 0.70 m due to the anticipated sea level rise. Finally, due to the reduced degree days of freezing, end of winter ice thicknesses on the Churchill River are anticipated to be reduced by a factor of 0.766. These climate change impacts were incorporated into the hydraulic modelling of the climate change 20 and 100 year floods on the Churchill River.

HYDRAULIC INVESTIGATIONS AND MODELLING

Open water and ice-affected models of the Churchill River were developed and calibrated using HEC-RAS and RIVICE. Two separate open water models were developed, each specifically tailored and optimized for the task at hand, specifically one model of the Churchill River for inclusion in the forecasting system, and one model of the Churchill River and Mud Lake channels for flood risk mapping. These models were both calibrated to open water conditions from 2017 and 2018, while the flood risk mapping model was also calibrated to open water conditions in 2019. Both models were found to be well calibrated. The flood forecasting model was subsequently incorporated into the forecasting system, while the flood risk mapping model was used to simulate the 20 and 100 year flood for current climate and climate change conditions. These water levels were then incorporated into the flood risk mapping.

The RIVICE model was developed based on the cross sections included in the forecasting model, albeit with some modifications to meet the software requirements. The model was then calibrated to freezeup jam conditions from 2016, and breakup jam conditions from 2012, as well as the historic 2017 ice jam flood. The model was found to accurately represent the historical jam conditions. Following the model calibration, the RIVICE model was used to complete a suite of over one thousand Monte Carlo simulations. Frequency analyses of the resulting water levels at each cross section were then completed to define the 20 and 100 year ice-affected water levels. These water levels were then incorporated into the flood risk mapping.

Open water models of Otter Creek and the seven unnamed creeks were developed using HEC-RAS. Standard model parameters were adopted for these models, which were used to define water levels and velocities on the creeks associated with the 20 and 100 year rainfall events for both current climate and climate change conditions.

SENSITIVITY ANALYSES

Sensitivity analyses were completed for the hydrologic and hydraulic models to assess the sensitivity of each model to changes to key parameters. For the hydrologic models, these parameters included the roughness included in the routing equations, as well as key groundwater infiltration parameters. The hydrologic models were generally not sensitive to changes to these parameters, with the exception of the models of Otter Creek and the unnamed creeks, which were sensitive to changes to the hydraulic conductivity.

For the open water hydraulic models, the sensitivity analyses considered the Manning's roughness coefficient and inflow to the model (i.e. from Muskrat Falls for the Churchill River, and routed rainfall for the creek models). The Churchill River model was sensitive to changes to both parameters, with changes increasing in the upstream direction, while the creek models were sensitive to changes to flow, but not roughness. For the ice-affected hydraulic model of the Churchill River, the sensitivity analysis considered the Manning's roughness coefficient of the channel bed, the flow from Muskrat Falls, the Lake Melville water level, and key ice parameters (i.e. ice porosity, ice pan thickness, and volume of ice). The model was not sensitive to changes to the ice pan thickness, but was sensitive to the other parameters. The model was most sensitive to the flow on the Churchill River.

FLOOD RISK MAPPING

Flood risk maps were developed for the open water and ice-affected 20 and 100 year floods on the Churchill River for current climate and climate change conditions. The flood risk mapping was defined based on the simulated water levels from the hydraulic models, which were overlaid on top of the bare earth digital elevation model, with the aerial imagery shown as the mapping background. The flood risk maps were carefully reviewed to identify and remove any hydraulically isolated areas. In addition to the flood risk maps, comparison maps showing the differences between the current climate and climate change conditions for each flood were developed to clearly indicate the anticipated changes to the flood risk associated with climate change. Separate maps were also developed showing infrastructure affected by flooding for each condition.

In addition to the flood risk maps, flood hazard maps, which included sets of maps showing the velocity, depth and flood hazard, were developed for the open water and ice-affected 20 and 100 year floods for current climate conditions. Velocity and depth maps were defined based on results from the hydraulic models, while the flood hazard was defined based on the flood hazard matrix provided in the Terms of Reference.

A similar approach was followed to define flood risk maps on Otter Creek and seven unnamed creeks in Happy Valley – Goose Bay for 20 and 100 year rainfall events for both current climate and climate change conditions. Flood hazard maps, which included sets of maps showing velocity, depth, and flood hazard, were also developed for the 20 and 100 year flood events under current climate conditions.

FLOOD FORECASTING

A comprehensive, automated flood forecasting system was developed for the Churchill River system. The forecasting system runs year-round and provides forecast flows and water levels at key locations on the Churchill River, and automatically adjusts the forecast to consider freezeup, stable winter, breakup and open water conditions based on real-time monitoring of ice coverage and water temperature data. The forecasting system automatically retrieves meteorological, hydrometric, and ice thickness and coverage data on a user-defined schedule, stores the data in a database, and preprocesses this data for use in the hydrologic and hydraulic forecasting models. The hydrologic model incorporated into the forecasting system was based on the hydrologic model developed for the flood risk mapping, but optimized to work with available meteorological forecasting data. The open water hydraulic model incorporated into the system was optimized for defining forecast water levels at key locations along the river based on the forecast discharge from Muskrat Falls and Lake Melville water levels. The ice-affected hydraulic model runs a Monte Carlo assessment considering the forecast flow at Muskrat Falls, Lake Melville water level, and ice thickness and cover conditions, and provides a range of forecast water levels representing how favourable conditions are in the ensuing days. The forecast water levels are compared to threshold values stored in the forecasting system, and will trigger an alert to specified contacts if the forecast water levels exceed those threshold values.

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LIST OF ABBREVIATIONS

1D	1-dimensional
ADRS	Automatic Data Retrieval System
AEP	Annual Exceedance Probability
AHCDD	Adjusted and Homogenized Climate Change Data
ASPRS	American Society for Photogrammetry and Remote Sensing
ATLIS	Atlis Geomatics
AWS	Amazon Web Services
CaPA	Canadian Precipitation Analysis
CAP-CP	Common Alert Protocol - Canadian Profile
CDED	Canadian Digital Elevation Data
CDEM	Canadian Digital Elevation Model
CGVD28	Canadian Geodetic Vertical Datum of 1928
CN	Curve Number
CRFFS	Churchill River Flood Forecasting System
CRUD	Create Read Update and Delete
CSRS	Canadian Spatial Reference System
DA	Drainage Area
DDS	Dynamically Dimensioned Search
DEM	Digital Elevation Model
DFO	Department of Fisheries and Oceans
ECCC	Environment and Climate Change Canada
ESA	European Space Agency
GDPA	Global Deterministic Prediction System
GEV	Generalized Extreme Value
GPS	Global Positioning System
HEC-DSS	Hydrologic Engineering Centre’s Data Storage System
HEC-HMS	Hydrologic Engineering Centre's Hydrologic Modelling System
HEC-RAS	Hydrologic Engineering Centre's River Analysis System
IDF	Intensity-Duration-Frequency
IDW	Inverse Distance Weighting
IMU	Inertial Measurement Unit
JSON	JavaScript Object Notation
LAF	Lake Attenuation Factor
LiDAR	Light Detection and Ranging
MNDWI	Modified Normalized Difference Water Index
MTM	Modified Transverse Mercator
NAD83	North American Datum of 1983
NDWI	Normalized Difference Water Index
NEPSL	N.E. Parrott Surveys Limited

LIST OF ABBREVIATIONS (CONT)

NSE	Nash Sutcliffe Efficiency
NST	Newfoundland Standard Time
NVA	Non-vegetated Vertical Accuracy
NVDI	Normalized Difference Vegetation Index
R^2	Regression Correlation Coefficient
RBF	Radial Basis Function
RCP	Representative Concentration Pathway
RDPA	Regional Deterministic Precipitation Analysis
RFFA	Regional Flood Frequency Analysis
RMSE	Root Mean Square Error
ROI	Region of Interest
RTK	Real Time Kinematic
SAM	Sundry Average Method
SBET	Smoothed Best Estimate of Trajectory
SCS	Soils Conservation Service
SEE	Standard Error of the Estimate
SSFA	Single Station Frequency Analysis
SVM	Support Vector Machine
SWE	Snow Water Equivalent
SWIR	Short Wave Infrared
UTC	Coordinated Universal Time
UTM	Universal Transverse Mercator
VVA	Vegetated Vertical Accuracy
WMS	Web Map Services
WRMD	Water Resources Management Division
WSC	Water Survey of Canada

1.0 INTRODUCTION

1.1 BACKGROUND

The communities of Happy Valley – Goose Bay and Mud Lake are located in central Labrador on or adjacent to the Lower Churchill River near Lake Melville. Happy Valley – Goose Bay is the largest community in central Labrador, with over 8,000 residents in the town. Mud Lake is a small community located approximately 10 km east of Happy Valley – Goose Bay with approximately 80 residents. Access to Mud Lake is usually gained via boat or snowmobile, depending on the season. Mud Lake Road is located on the eastern extent of Happy Valley – Goose Bay along the north bank of the Churchill River, and includes approximately 22 domiciles along the road. Due to their proximity to the Lower Churchill River, these communities have experienced some degree of flooding during recent history. However, during the spring of 2017, a sudden and major ice jam flood took place near the outlet of the Lower Churchill River, resulting in extreme water levels on the river and devastating flooding to the communities of Mud Lake and Happy Valley – Goose Bay along Mud Lake Road.

Water levels on the Churchill River during the 2017 flood started to rise on May 11, 2017, with water levels on the river and on Mud Lake sharply rising on May 16, 2017. The water then rapidly rose to levels deemed unsafe on the early hours of May 17, 2017 which triggered an evacuation of Mud Lake. The evacuation had to be performed using helicopters as water levels and ice conditions were not amenable to evacuation by boat. By May 19, 2017 all but one resident and most pets had been transported from Mud Lake to Happy Valley - Goose Bay and remained there for a number of days. In the fall of 2017, some of the residents were still living in Happy Valley - Goose Bay area and unable to move back home. The flooding caused great stress to the residents of both Mud Lake and Happy Valley – Goose Bay and had a devastating effect on the community and surrounding area.

Following the flood event, Dr. Karl-Erich Lindenschmidt, with the assistance of KGS Group, carried out an independent review of flood event of May 2017. This work included a critical review of all aspects that could have contributed to the flooding that occurred in May 2017. As part of that review, KGS Group and Dr. Lindenschmidt reviewed a vast amount of background data and developed a detailed understanding of the history, climate, hydrology, and hydraulic aspects of the Lower Churchill River.

The independent review concluded that parts of Mud Lake are generally prone to flooding, although perhaps not routinely in the recent history, and that the general characteristics of the lower river are such that they are favourable for flooding and ice jamming. Considering this, as well as the level of flow control available on the river at Churchill Falls and the soon to be completed Muskrat Falls, it was recommended that a flood management program be implemented. Any such flood management program should include an ice management and detailed ice monitoring program. The flood management program should also include the definition of an effective communication plan between the Government of Newfoundland and Labrador, Nalcor, and downstream residents and stakeholders, as well as possible warning systems. Such a program would help to minimize the sudden flooding, stressful evacuations, and damages that occurred at Mud Lake in May of 2017.

One of the important steps in this flood management program is being considered as part of this study, and includes the development of flood risk mapping and the development of a comprehensive flood forecasting system. Both of these end products will provide residents in Happy Valley – Goose Bay and Mud Lake with early warnings of potential flood events and will help to reduced damages, stress, and worst case scenario, loss of life.

To complete this study, KGS Group led a diverse, highly experienced Project Team, with members from different companies, in the development of the flood risk maps and flood forecasting system. The composition of the Project Team, and the roles of each of our subconsultants included:

- ***KGS Group –*** KGS Group was responsible for the overall management of the project and was responsible all aspects of the study, including mainly, the development of the hydrologic and hydraulic models used for flood risk mapping and flood forecasting system.
- ***Dr. Karl-Erich Lindenschmidt –*** Dr. Lindenschmidt worked closely with KGS Group's in house national recognized ice expert to develop the ice-affected hydraulic model. Dr.

Lindenschmidt was also responsible for the state of the art Monte Carlo statistical method used in the ice-affected flood risk mapping and flood forecasting models.

- ***4DM Inc. –*** 4DM were responsible for the development of the software framework (i.e. HydrologiX) that automated the collection and processing of the various sources of data in the model, as well as the development of specialized software to automate the running of the different models in the system to generate flood forecasts for the Churchill River.

- ***N.E. Parrott Surveys Limited –*** N.E. Parrott Surveys were responsible for the completion of the topographic and bathymetric surveys in Happy Valley – Goose Bay and Mud Lake. N.E. Parrot Surveys is based in Happy Valley – Goose Bay and as such are highly familiar with flooding in the area and provided valuable local knowledge and context to flooding in the area.

- ***Atlis Geomatics –*** Atlis Geomatics are highly experienced LiDAR and aerial imagery surveyors, and were responsible for the collection and processing of the LiDAR and aerial imagery data.

- ***Zuzek Inc. –*** Zuzek Inc. were responsible for providing expert guidance on tidal aspects that would affect water level on Lake Melville and the lower reaches of the Churchill River.

1.2 STUDY GOALS OBJECTIVES

The primary objectives of this study include the completion of Light Detection and Ranging (LiDAR) and bathymetric surveys, the development, calibration and implementation of hydrologic and open water and ice-affected hydraulic models to be used to define flood risk maps and inundation maps associated with the 1 in 20 and 1 in 100 year Annual Exceedance Probability (AEP) flood events. These models will then serve the basis of an automated flood forecasting system for the communities of Happy Valley – Goose Bay and Mud Lake.

The flood risk maps developed as part of this project enhance WRMD's understand of the potential for flooding in Happy Valley – Goose Bay and Mud Lake for both current climate conditions, as well as those affected by climate change in the future. The flood forecasting tool developed for this project will further enhance WRMD's capacity to proactively monitor, anticipate, manage and respond to future flood events.

1.3 SCOPE OF WORK

The Scope of Work for this study includes:

- Estimation of the water levels and flows for the 1:20 and 1:100 AEP flood associated with current climate and climate change conditions.
- Development of flood risk maps associated with the 1:20 and 1:100 AEP floods.
- Development of maps showing flood plain changes associated with the 1:20 and 1:100 AEP floods for current and climate change conditions.
- Development of flood inundation, flood velocity, and flood hazard maps for the current climate and existing development conditions for the 1:20 and 1:100 AEP floods.
- Development of the linked hydrologic and hydraulic datasets and models used in the development of the flood risk maps.
- Evaluation, development and implementation of a flood forecasting service for the Town of Happy Valley – Goose Bay and the community of Mud Lake using the hydrologic and hydraulic models developed for the flood risk mapping component of this study. The service will factor in all meteorological, hydrologic and hydraulic factors that trigger flooding, and will be integrated with the Government of Newfoundland and Labrador Water Resources Management Department (WRMD) automated data retrieval systems.
- Development of a river ice model as part of the flood forecasting service to model ice generation and breakup from December to June.
- Implementation of the flood forecasting service for WRMD in St. John's, including training for key WRMD personnel.
- Development of a user guide for the flood forecasting service.
- Hydraulic capacity assessments of existing hydraulic structures within the study area for the 1:20 and 1:100 AEP floods for current climate and current development conditions, as well as climate change and current development conditions.

2.0 BACKGROUND INFORMATION REVIEW

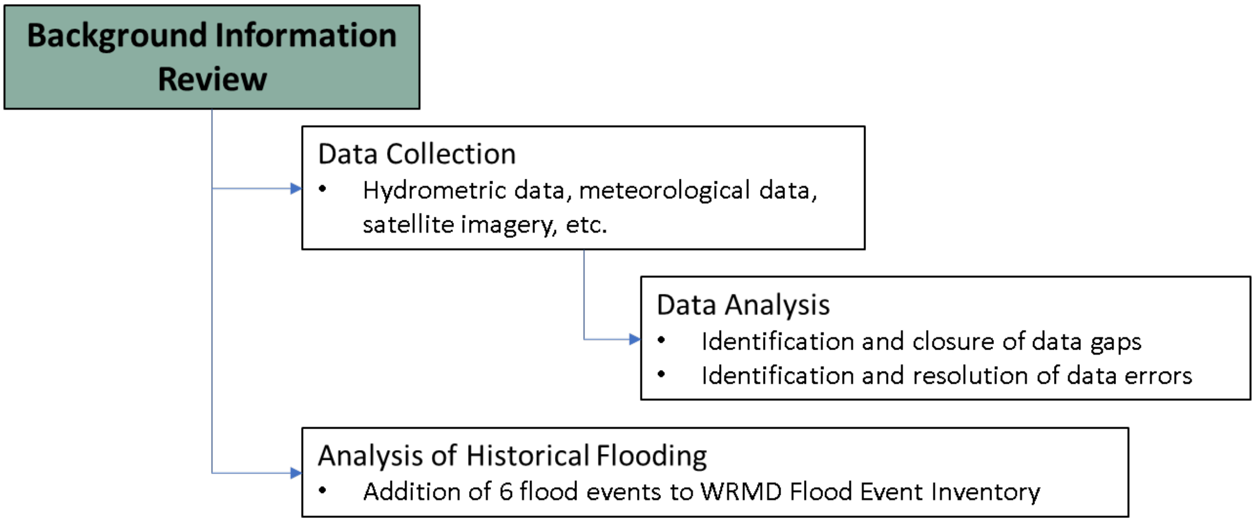
2.1 OVERVIEW

A thorough review of available background information was completed as part of this study to provide the Project Team with key context on the history of flooding along Mud Lake Road in Happy Valley – Goose Bay and Mud Lake, to provide a basis for the various analyses completed for the study, and to assist in the development and calibration of the hydrologic and hydraulic models. The collected background data included aerial imagery and photographs, previously collected survey data, satellite imagery, design drawings, water level and flow data, meteorological data, and a variety of reports related to the Churchill River. This data was collected from a variety of sources, including residents of Happy Valley – Goose Bay and Mud Lake, the Government of Newfoundland and Labrador, Water Survey of Canada (WSC), Nalcor, Environment and Climate Change Canada (ECCC), and Natural Resources Canada.

As part of the background information review, a review of previous flood events on the Churchill River was completed for inclusion in the Government of Newfoundland and Labrador's Flood Event Inventory. The review identified six historical flood events on the Churchill River that were added to the Flood Event Inventory.

The tasks completed as part of the background information review are shown on Figure 1.

FIGURE 1
OVERVIEW OF BACKGROUND INFORMATION REVIEW



2.2 DATA COLLECTION

Over the course of this study, extensive background information was reviewed and assessed that was obtained from WRMD, WSC, Nalcor, ECCC, Natural Resources Canada and local residents. A considerable portion of this background information was previously provided to KGS Group as part of the Independent Review of the 2017 Flood. This information included:

- Aerial and land-based imagery of the May, 2017 flood.
- Various historical photographs from local residents.
- Mud Lake property assessments carried out subsequent to the May 2017 flood.
- HEC-RAS cross sections of the Churchill River.
- LiDAR and topographic data along the Churchill River.
- Muskrat Falls bathymetry.
- Satellite and remote sensing imagery.
- Churchill River Bridge drawings.
- Hydrometric information at Churchill Falls and Muskrat Falls Generating Stations.
- Historical water level and flow data from Water Survey of Canada on the Churchill River and adjoining tributaries.

- Water Survey of Canada rating curve for the Churchill River above Upper Muskrat Falls.
- Snow data within the Churchill River basin.
- Provincial weather station data at 6 locations near Churchill River.
- ECCC climate normals for Happy Valley – Goose Bay, Churchill Falls, Wabush and Schefferville.
- ECCC historical climate data for Happy Valley – Goose Bay, Churchill Falls, Wabush and Schefferville.
- Various reports documenting ice processes on the Churchill River, Ice observation reports.
- Freeze up observations.
- Various reports documenting sedimentation and morphological studies on the Churchill River.

Considerable additional data was retrieved to assist in the development of the hydraulic and hydrologic models, and to further understand the meteorological, hydrologic and hydraulic conditions that lead to flooding on the Lower Churchill River, including:

- Additional streamflow, water level and water temperature data collected by WSC and WRMD.
- Meteorological data collected by ECCC and WRMD.
- Intensity-Duration-Frequency (IDF) curves.
- Records of historical flooding, including from WRMD's updated Flood Events Inventory.
- Hydraulic structures such as culverts and bridges in the study area.
- Hydrometric data from the Churchill Falls Generating Station and Muskrat Falls Spillway.
- Aerial photography and satellite photography.
- Ice coverage and ice thickness measurements.
- Mapping data.
- Land use information.
- Lake and sea levels.
- Stream cross sections.
- Culvert size, invert and obvert elevation, and top of road elevation information from the Town of Happy Valley – Goose Bay

A detailed summary of the background data collected as part of this project is included in Appendix A.

2.3 DATA ANALYSIS

Following the thorough review of the available background data, the Project Team completed an assessment of any potential data gaps, and to identify if any errors were present in the background information. Based on this assessment, the Project Team identified that a key data gap was that several water level gauges on the Churchill River were either in a local datum or in the Canadian Geodetic Vertical Datum of 1928 (CGVD 28) vertical datum, requiring the conversion to the Canadian Geodetic Vertical Datum of 2013 (CGVD 2013) vertical datum.

As part of KGS Group's survey program, the WSC gauge station 03PC001 (i.e. Churchill River at English Point) was surveyed to convert the local datum to CGVD 2013. Furthermore, WRMD converted the assumed datums to CGVD28 for many of their gauges in the study area. This allowed for the calculation of the conversion offset for the assumed datums to first convert the data to CGVD28, and then convert the data to CGVD 2013. Specifically, the relevant stations that WRMD converted to CGVD28 included stations 03OE017 (i.e. Mud Lake at Mud Lake), 03OE019 (i.e. Churchill River below Traverspine River), 03OE016 (i.e. Churchill River at Happy Valley) and 03OE018 (i.e. Churchill River at the end of Mud Lake Road). Furthermore, DFO provided KGS Group with their offset from the chart datum of the Terrington Basin station to CGVD 2013. A geodetic correction was then completed for each gauge station from CGVD28 to CGVD 2013 using the ESRI ArcMap software. The offsets for each gauge, as well as the applicable periods of record, are shown on Table 1.

TABLE 1
CONVERSION OF GAUGE DATUMS TO CGVD2013

Gauge Station Number	Gauge Station Name	Datum	Applicable Date Range	Conversion Factor to CGVD 2013 (m)
03OE018	Churchill River at End of Mud Lake Road	CGVD28	All	-0.014
03PC001	Churchill River at English Point	CGVD 2013	Oct. 2, 2018 to Present	0.000
03PC001	Churchill River at English Point	Assumed Datum	Prior to Oct. 2, 2018	-2.210
03OE017	Mud Lake at Mud Lake	CGVD28	Oct. 24, 2017 to Present	-0.025
03OE017	Mud Lake at Mud Lake	Assumed Datum	Prior to Oct. 24, 2017	-1.763
03OE019	Churchill River below Traverspine River	CGVD28	Aug. 19, 2018 to Present	+0.043
03OE019	Churchill River below Traverspine River	Assumed Datum	Prior to Aug. 19, 2018	-0.296
03OE016	Churchill River at Happy Valley	CGVD28	Oct. 24, 2017 to Present	+0.055
03OE016	Churchill River at Happy Valley	Assumed Datum	Prior to Oct. 24, 2017	-4.603
03OE014	Churchill River 6.15 KMs below Lower Muskrat Falls	CGVD28	All	+0.127
1350	Terrington Basin	Chart Datum	All	-0.581

Over the course of the 2018 – 2019 winter, some gauge malfunctions occurred on the Churchill River. Working closely with WRMD and WSC, any gauge outages were shared between WRMD and KGS Group, and any sudden changes to water levels were identified and assessed to determine if the changes in water levels were due to actual water level changes or due to ice impacting the gauges. The gauge outages and erroneous measurements due to ice impacts are summarized in Table 2.

TABLE 2
GAUGE OUTAGES AND ERRONEOUS MEASUREMENTS

Date	Gauge Station #	Gauge Station Name	Cause of Measurement Error	Correction (m)
April 7, 2019	03OE019	Churchill River below Traverspine River	Transmission Failure	N/A
April 7, 2019	03OE014	Churchill River 6.15 KMs below Lower Muskrat Falls	Transmission Failure	N/A
November 2018	03OE018	Churchill River at the End of Mud Lake Road	Ice Impact	-0.3 m (Approx.)
May 2019	03OE018	Churchill River at the End of Mud Lake Road	Ice Impact	-0.729
March 19, 2019	03PC001	Churchill River at English Point	WSC Adjustment	-0.136
July, 2019	03PC001	Churchill River at English Point	WSC Adjustment	+0.136

2.4 ANALYSIS OF HISTORICAL FLOODING ON THE CHURCHILL RIVER

A thorough review was completed of the available information pertaining to flood events on the Lower Churchill River and compared it to the existing Historical Flood Event Inventory provided by WRMD. The Historical Flood Event Inventory already included two historical flood events on the Churchill River, specifically ice jam floods that occurred on December 4, 2006 and May 17, 2012. Six additional flood events were identified that occurred on the Lower Churchill River, specifically:

- ***May 20 to May 25, 1978*** – Flooding occurred along the banks of the lower Churchill River over several days due to ice buildup and spring runoff. An area of Birch Island Road was submerged under floodwater and washed out, and the Communications Branch of the MOT experienced some flooding inside of the transmitter building and was only accessible via canoe.
- ***May 3, 1983*** – High flood conditions prior to the river ice breakup resulted in the evacuation of four houses in Mud Lake. A Disaster Operations Committee in Happy Valley – Goose Bay closely monitored water levels on the river in case additional evacuations were required from Mud Lake. Large ice jams were also present on the Goose River, requiring extensive blasting operations to prevent damage to the Goose River bridge.
- ***May 18, 1998*** – Ice jamming on the lower Churchill River resulted in basement flooding in several houses in Happy Valley – Goose Bay, as well as in the garage of a local business owner.

- ***April 24, 2000*** – High winds caused ice buildup on the Churchill River at Mud Lake and near the mouth of the river, resulting in flooding of Mud Lake Road. Residents of Mud Lake were also concerned about possible basement flooding. Water levels were reported to have increased by 5 feet. Water levels receded by several inches once the winds had subsided, but were still well above normal water levels for that time.
- ***May 13 to May 22, 2001*** – Flooding in the basement of a Mud Lake resident rose to a depth of 44 inches due to ice jamming on the Churchill River near the mouth of the river. Water levels stayed high until May 22, at which point they began to recede.
- ***May 11 to May 22, 2017*** – Water levels on the Churchill River began to rise on May 11, 2017, and suddenly increased on May 16. Water levels rose further to levels deemed unsafe on the early hours of May 17, resulting in the evacuation of the resident from Mud Lake to Happy Valley – Goose Bay. Extensive flooding was also reported on Mud Lake Road. Significant damage occurred to properties in both areas.

Historical flood events that occurred in Happy Valley – Goose Bay or Mud Lake are summarized in Appendix B. An updated version of the full flood event inventory is included as part of the digital files and data submitted as part of this project.

3.0 FIELD PROGRAM

3.1 OVERVIEW

An extensive field survey program was completed for this project to measure the ground level of key infrastructure throughout the study area, such as bridges and culverts, and to measure the riverbed elevation along several sections of the lower Churchill River. Eighty riverbed sections along the Churchill River were surveyed, with section spacing of 1 km from Muskrat Falls to the Trans Labrador Highway, and 500 m spacing from the Trans Labrador Highway to Lake Melville. As well, 11 sections were surveyed on the Mud Lake channels from Mud Lake to the Churchill River. Detailed surveys of the Trans Labrador Highway Bridge and Mud Lake Footbridge, as well as nineteen culvert crossings within the Town of Happy Valley – Goose Bay, were also completed so that the bridge and culvert crossings could be accurately represented in the hydraulic models.

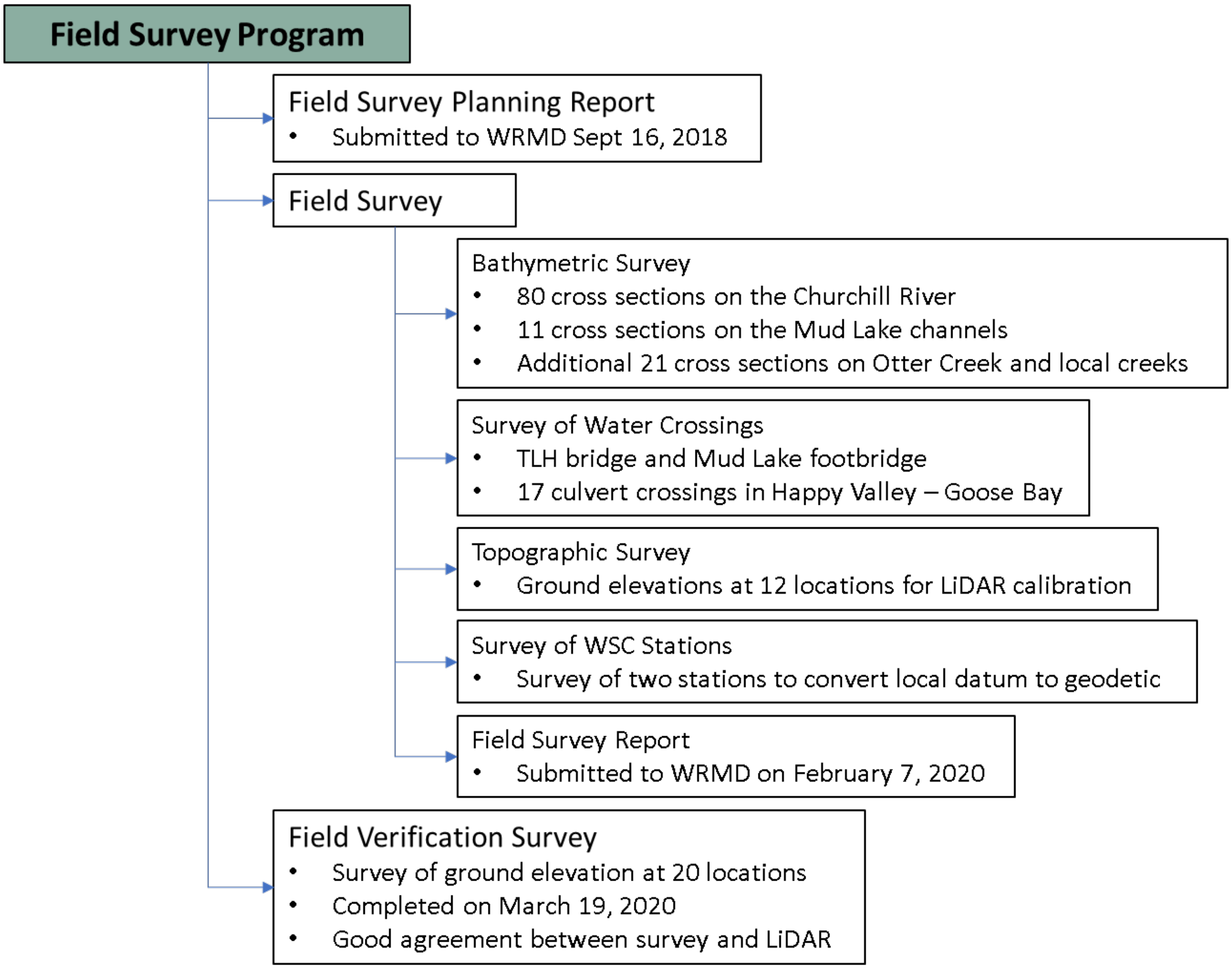
Ground elevations were also surveyed throughout the study area to assist in the calibration of the LiDAR survey, as described in Section 4.0, and to ensure that the LiDAR data accurately represents the ground elevation throughout the study area.

The information gathered from the field survey was used to develop and calibrate the hydraulic models, as described in Section 9.0, which in turn were used in the forecasting system and as the basis for the flood risk mapping products.

A separate verification survey was completed to confirm the LiDAR ground elevations and the flood extents shown on the flood risk mapping. Twenty ground elevations were surveyed in Happy Valley – Goose Bay and Mud Lake, and despite challenging snow conditions, were found to be in good agreement with the LiDAR data and flood extents.

The tasks completed as part of the field survey are shown on Figure 2.

FIGURE 2
OVERVIEW OF FIELD PROGRAM



3.2 FIELD SURVEY

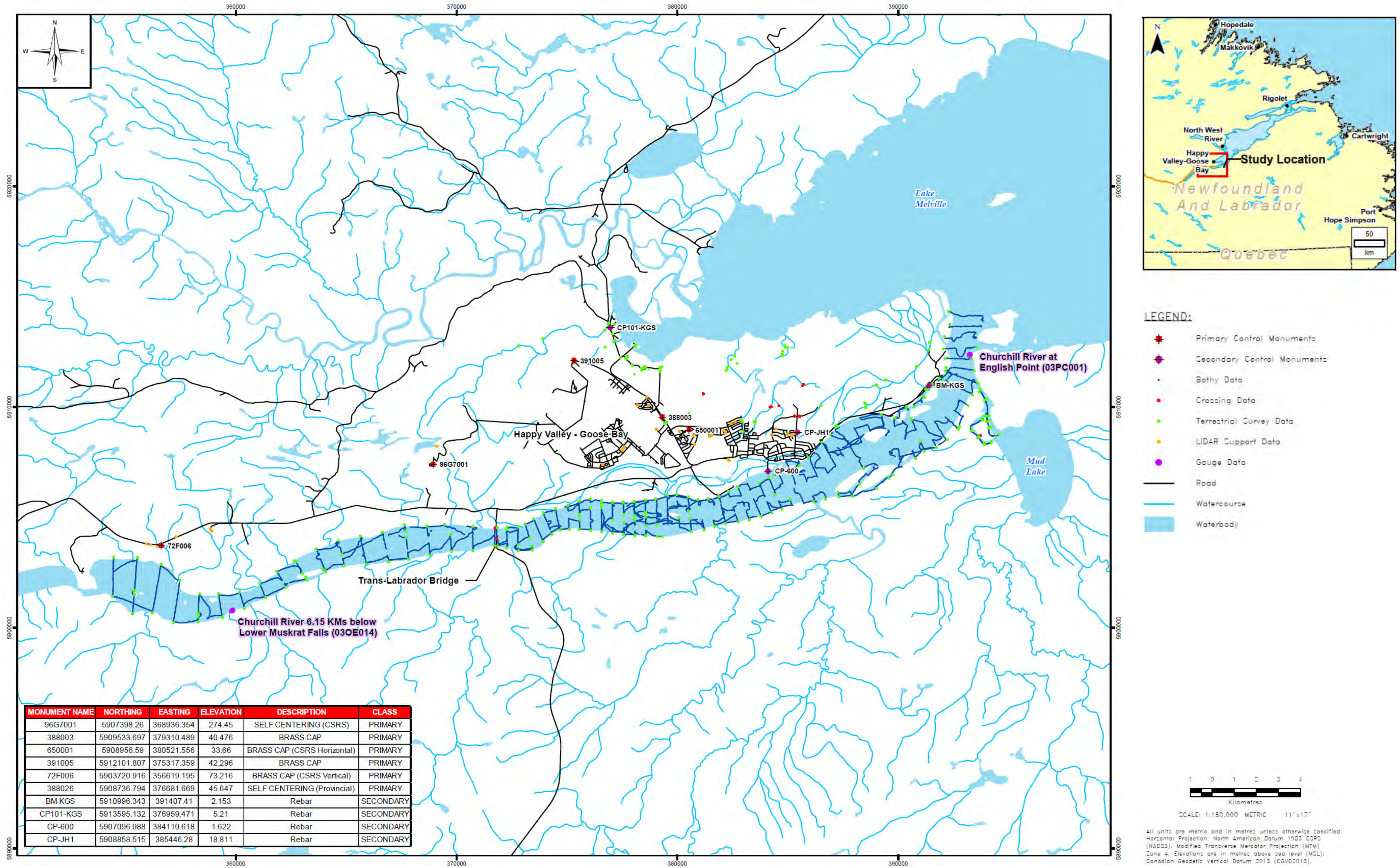
3.2.1 Projections and Survey Control

KGS Group's subconsultant, N.E. Parrott Surveys Limited (NEPSL), captured survey data within the project area over a total of 27 days in August and September 2018. Additional culvert data was also surveyed during May 2020. All survey collection was completed as specified in the RFP and our proposal. All data provided is in NAD83 CSRS (North American Datum of 1983), Modified Transverse Mercator (MTM) Zone 4 projection for horizontal reference for this project, in Atlantic time zone with daylight savings applied. The vertical reference datum for the project is the CGVD2013, GEOID2013 and was used for the determination of all orthometric heights for elevation datum. An overview of all survey data captured is shown in Figure 3.

NEPSL used existing federal monuments from the Canadian Spatial Reference System (CSRS): 72F006, 96G7001 (3D), 650001, as primary control, to support LiDAR capture and ground survey activities. NEPSL confirmed coordinate values by completing a maximum constrained analysis on the primary control on published values. The primary control point values were held as fixed values for the final adjustment on secondary control points established to support survey activities. NEPSL completed multiple static networks creating redundant baselines. The adjustments were run with a 95% confidence value.

A summary of the final control point values is provided in Table 3.

FIGURE 3
OVERVIEW OF SURVEY DATA



MONUMENT NAME	NORTHING	EASTING	ELEVATION	DESCRIPTION	CLASS
96G7001	5907398.26	368936.354	274.45	SELF CENTERING (CSRS)	PRIMARY
388003	5909533.697	379310.489	40.476	BRASS CAP	PRIMARY
650001	5908956.59	380521.556	33.66	BRASS CAP (CSRS Horizontal)	PRIMARY
391005	5912101.807	375317.359	42.296	BRASS CAP	PRIMARY
72F006	5903720.916	356619.195	73.216	BRASS CAP (CSRS Vertical)	PRIMARY
388026	5908736.794	376681.669	45.647	SELF CENTERING (Provincial)	PRIMARY
BM-KGS	5910996.343	391407.41	2.153	Rebar	SECONDARY
CP101-KGS	5913595.132	376959.471	5.21	Rebar	SECONDARY
CP-600	5907096.988	384110.618	1.622	Rebar	SECONDARY
CP-JH1	5908858.515	385446.28	18.811	Rebar	SECONDARY

TABLE 3
FINAL CONTROL POINT VALUES

Control ID	Northing (m)	Easting (m)	Elevation (m)	Description	Type	Order
96G7001	5907398.260	368936.354	274.264	SELF CENTERING	CACS	1st vertical 1st horizontal
72F006	5903720.916	356619.195	73.216	SELF CENTERING	CACS	1st vertical 1st horizontal
650001	5908956.590	380521.556	33.511	SELF CENTERING	CACS	1st vertical 1st horizontal
NEW BM KGS	5910996.343	391407.410	2.007	REBAR	PROJECT	2nd vertical 2nd horizontal
388003	5909533.697	379310.489	40.327	SELF CENTERING	NEPSL	N/A
391005	5912101.807	375317.359	42.147	SELF CENTERING	NEPSL	N/A
CP101-KGS	5913595.132	376959.471	5.061	REBAR	PROJECT	2nd vertical 2nd horizontal
CP-600	5907096.988	384110.618	1.483	REBAR	PROJECT	2nd vertical 2nd horizontal
CP-JH1	5908858.515	385446.280	18.666	REBAR	PROJECT	2nd vertical 2nd horizontal

Projection: Newfoundland-MTM Zone 4, Geoid: cgg2013an83, Confidence level: 95%

3.2.2 Bathymetric Survey

NEPSL captured 80 bathymetric cross sections along the Churchill River over 12 days in August and September 2018. The locations of the bathymetric cross sections (1 km spacing from Muskrat Falls to the Trans Labrador Highway and 0.5 km spacing from the Trans Labrador Highway to the mouth of Churchill River) were uploaded into a Real Time Kinematic (RTK) dual frequency Global Positioning System (GPS) that allowed the survey crew to capture the cross section at the pre-set locations. However, due to the nature of the river, some of the sections had to be adjusted in the field due to obstacles that posed risk hazards such as sand bars and high flow.

At each cross section, a photo was captured at the time of survey and water elevations were taken on both sides of the river, as per the project specifications from the RFP, with Atlantic time zone and day light savings applied. NEPSL took 1 – 2 ground shots within 5m of the edge of water to use to validate LiDAR data. When possible, NEPSL took a last shot at the top of bank. Sandbars were surveyed in a similar fashion. Site photos are included in Appendix D.

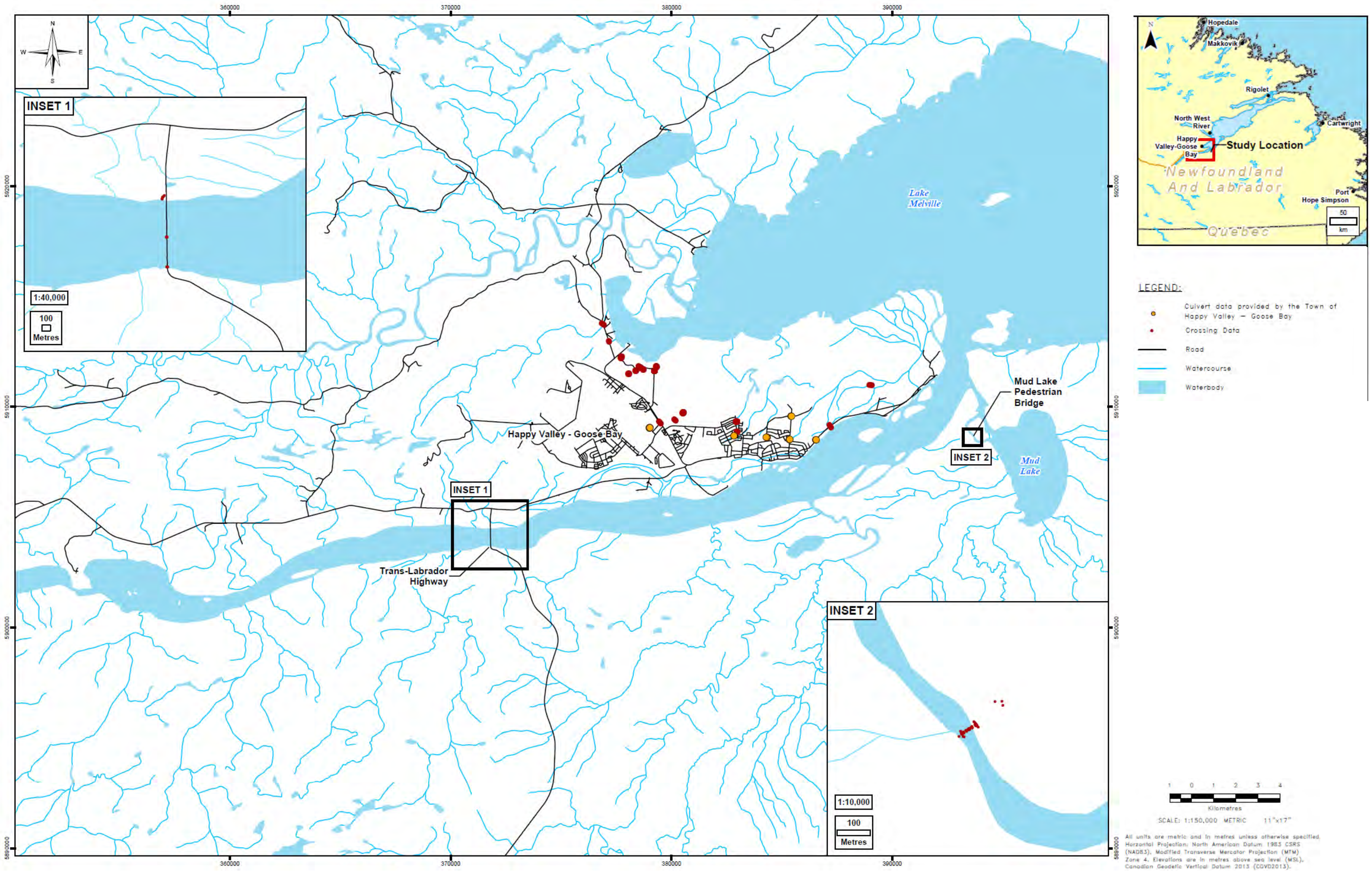
3.2.3 Survey of Water Crossings

NEPSL completed a survey at two bridge crossings, the Trans Labrador Highway Bridge and Mud Lake pedestrian bridge, as shown in Figure 4. The top of road profile was surveyed and extended across the entire width of the flood plain. Field survey information of dimensions and elevations of existing structures were referenced to geodetic datum. Bridge survey details included: span, joints, thickness of the girder, edge of water, and a full cross section both upstream and downstream of the structure.

A total of nineteen culvert crossings were surveyed similar to the bridge crossings. Details surveyed at these crossings included: number of culverts, invert and obvert of both ends of the culverts, type of material, condition, invert of creek both upstream and downstream of structure, edge of water both upstream and downstream of the culverts as well as a full cross sections of the flood plain both upstream and downstream of the culverts. A table summarizing the culvert details is included in Appendix C. Site photos of the culvert crossings, including summaries of the culvert information, are included in Appendix D.

In addition to the culvert crossing surveyed by NEPSL, the Town of Happy Valley – Goose Bay also provided culvert crossing data on the creeks. This information is also shown on Figure 4.

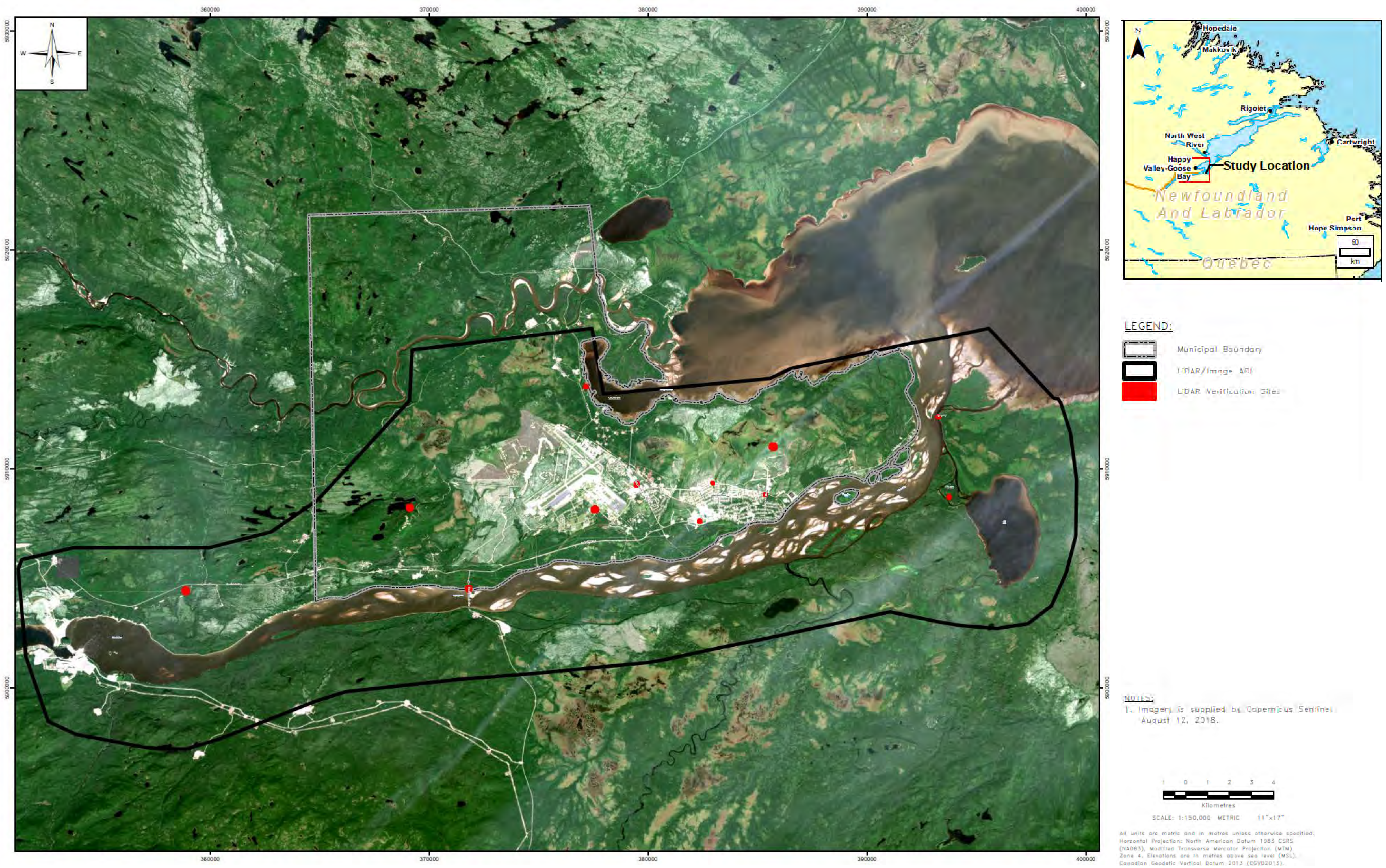
FIGURE 4
OVERVIEW OF SURVEYED CROSSINGS



3.2.4 Topographic Survey

All topographic survey capture was completed using GPS RTK style surveying. Topographic survey data was used for LiDAR validation and quality control. NEPSL completed topographic surveys in twelve designated locations, across the project area, of features such as concrete driveways, existing fence lines, and items that can easily be identified from an air photo, as shown on Figure 5. The points captured of these features was used to calibrate and validate LiDAR data. Site photos are included in Appendix D.

FIGURE 5
LOCATION OF LIDAR CALIBRATION POINTS



3.2.5 Water Survey of Canada Stations

Two main WSC Stations were surveyed on the Churchill River. The western gauge is Churchill River 6.15 kms below Lower Muskrat Falls (i.e. 03OE014). The eastern gauge is Churchill River at English Point (i.e. 03PC001), shown on Figure 6. Photographs were taken at each site and the surveyed information included existing benchmarks, gauge elevations, hut locations, and water level shots. Water level shots were provided with time stamps in Atlantic time zone with daylight savings applied. This data was used to allow for the WSC data recorded in the local datum to be converted to geodetic. Site photos are included in Appendix D.

FIGURE 6
SURVEYED WATER SURVEY OF CANADA GAUGES

3.3 FIELD VERIFICATION

A field verification survey was completed by NEPLS to confirm the LiDAR ground elevation throughout the study area, particularly at buildings that are located near the flood extents identified in the flood risk mapping. The survey was completed on March 19, 2020. The field verification survey was completed in deep snow conditions, and as such there is potential that some survey points may have been measuring the top of hard snow or ice, rather than the actual ground elevation. However, in general, there was good agreement between the surveyed ground elevations and the LiDAR data, with an average error of 0.15 m. However, the majority of the average error is caused by the surveyed ground elevation at three locations, where ice likely affected the ground elevation measurement. Without these locations (i.e. points 108, 110 and 115 in Table 4), the average difference is 0.08 m. The comparison of the surveyed ground elevations and LiDAR elevations is shown on Table 4. The ground elevations that were measured as part of the field verification survey are shown on Figure 7.

TABLE 4
LIDAR FIELD VERIFICATION

Point	Northing (m)	Easting (m)	Survey Elevation (m)	LiDAR Elevation (m)	Difference (m)
101	5908847	393331	2.11	2.10	0.02
102	5908867	393309	1.64	1.67	-0.03
103	5908981	393243	1.98	1.76	0.22
104	5908295	393811	3.21	3.34	-0.13
105	5908274	394065	3.12	3.09	0.03
106	5908250	394056	3.24	3.10	0.15
107	5908294	394060	3.27	3.17	0.10
108	5908429	393886	2.04	1.43	0.60
109	5908464	393810	1.98	1.89	0.09
110	5909453	393745	1.72	1.23	0.48
111	5910889	391209	1.75	1.63	0.12
112	5911457	391978	2.47	2.54	-0.07
113	5911456	392037	2.96	3.02	-0.06
114	5911494	392066	3.12	3.17	-0.05
115	5911774	392165	2.21	1.79	0.42
116	5911669	392118	2.82	2.80	0.03
117	5911618	392094	3.27	3.28	-0.01
118	5907704	385907	3.26	3.30	-0.04
119	5907842	385835	3.37	3.26	0.11
120	5907794	385842	5.17	4.96	0.21

FIGURE 7
FIELD VERIFICATION SURVEY LOCATIONS

4.0 LIDAR AND AERIAL PHOTOGRAPHY

4.1 OVERVIEW

LiDAR and aerial photography surveys were completed as part of this project to measure the ground surface elevation throughout the study area and to provide high resolution imagery for use in the flood risk and flood hazard maps.

LiDAR surveys are completed by flying over a given area and using pulsed lasers to measure the distance between the ground and the aircraft, which provide very accurate measurements of the ground surface elevations. However, clear weather conditions are needed to complete a LiDAR survey, as any rain or low cloud cover can interfere with the laser pulses. Similarly, the aerial photography that is collected during the LiDAR survey can also be affected by rain or low cloud cover. While emerging LiDAR survey technology can use unmanned aerial vehicles (i.e. drones), the use of drones is only suitable for small study areas due to the limited operational range of drones. For larger study areas, such as that included in this study, only larger manned aircraft can be used to complete the LiDAR survey.

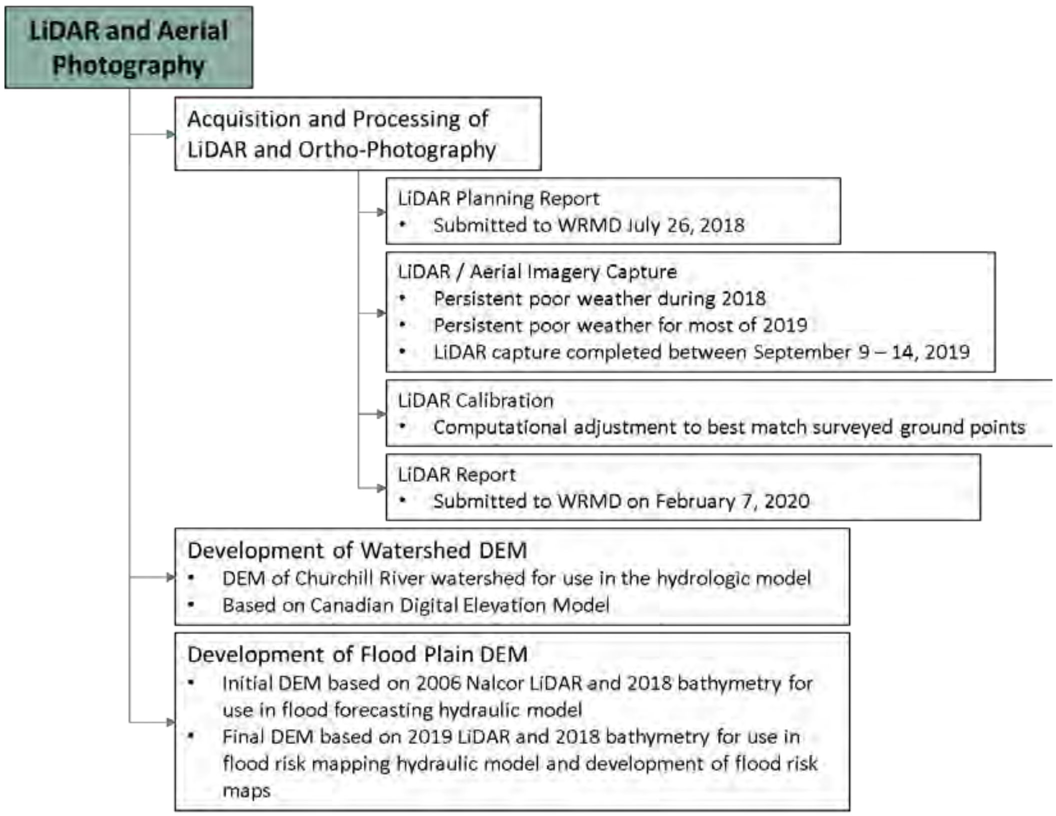
Nearly continuous rain, high winds, or low cloud cover prevented the completion of the LiDAR survey during 2018, with only a third of the study area being surveyed during 2018. The LiDAR survey for this study was required to meet the Federal Airborne LiDAR Data Acquisition Guideline, Version 1.1, 2017, with LiDAR survey specifications defined for the high flood risk category. To satisfy these requirements, optimal weather conditions were required during the capture of the LiDAR survey. The poor weather conditions persisted well into the summer of 2019, resulting in the LiDAR survey being completed between September 11th to September 13th, 2019.

The LiDAR survey information, in combination with below-water survey information, was used to make a ground elevation model of both the above and below-water ground surface. This ground elevation model was then used to define the physical characteristics for the hydraulic models of the Churchill River from Muskrat Falls to Lake Melville, as well as the Mud Lake channels from Mud Lake to the Churchill River. Because of the weather delays that affected the 2018 – 2019 LiDAR survey, and to ensure that the Churchill River Flood Forecasting System (CRFFS) was in place before the spring melt of 2019, an initial ground surface elevation model was created using the LiDAR survey information that was collected in 2006 and the below-water survey information collected in 2018. This ground surface model was used to create the hydraulic model of the Churchill River used in the forecasting system, which was optimized to define water level forecasts at key locations on the Churchill River based on the forecast flows from the hydrologic model.

In addition to the ground elevation model of the Churchill River from Muskrat Falls to Lake Melville, a larger scale ground elevation model was developed for the entirety of the Churchill River basin. This larger scale ground elevation model, which extends from Labrador City to Lake Melville, was built based on lower resolution data developed by Natural Resources Canada. This information was used to represent the physical characteristics for the hydrologic model of the watershed that was used to estimate the flows on the Churchill River based on rainfall, snowmelt, and temperature data.

The tasks completed as part of the LiDAR and aerial imagery capture are shown on Figure 8.

FIGURE 8
OVERVIEW OF LIDAR AND AERIAL IMAGERY CAPTURE



4.2 ACQUISITION AND PROCESSING OF LIDAR AND AERIAL PHOTOGRAPHY

KGS Group retained ATLIS Geomatics (ATLIS) to complete the LiDAR and aerial photography surveys. ATLIS commenced the LiDAR and aerial photography survey of the study area during the summer of 2018, which, as noted above, was originally planned to be completed in the summer of 2018 once the snow cover was fully melted, water levels had receded to normal summer levels on the Churchill River, and prior to the fall. The LiDAR and aerial photography surveys required 3 consecutive days of clear weather to allow for the capture of the data throughout the study area.

ATLIS initially intended to deploy to Happy Valley – Goose Bay on August 9, 2019, but poor forecasted weather conditions prevented ATLIS from deploying until August 22, 2018. While on site, ATLIS was able to complete approximately 30% of the LiDAR and aerial imagery survey on

August 24 and 25, 2018, but were persistently interrupted by poor weather conditions. ATLIS remained on site until August 31, 2019, but opted to depart Happy Valley – Goose Bay due to poor forecast weather conditions for the next few weeks. KGS Group and ATLIS closely monitored the weather forecast at Happy Valley – Goose Bay throughout the remainder of 2018 to identify any potential times with favourable weather conditions for ATLIS to complete the LiDAR and aerial imagery capture. An opportunity arose on October 3 and 4, 2018, but ATLIS' aircraft was grounded due to regulated scheduled maintenance. No other favourable weather periods occurred during 2018 prior to the accumulation of snowfall in the area. As a result of the unfavourable weather conditions, the LiDAR and aerial survey collection was rescheduled to 2019.

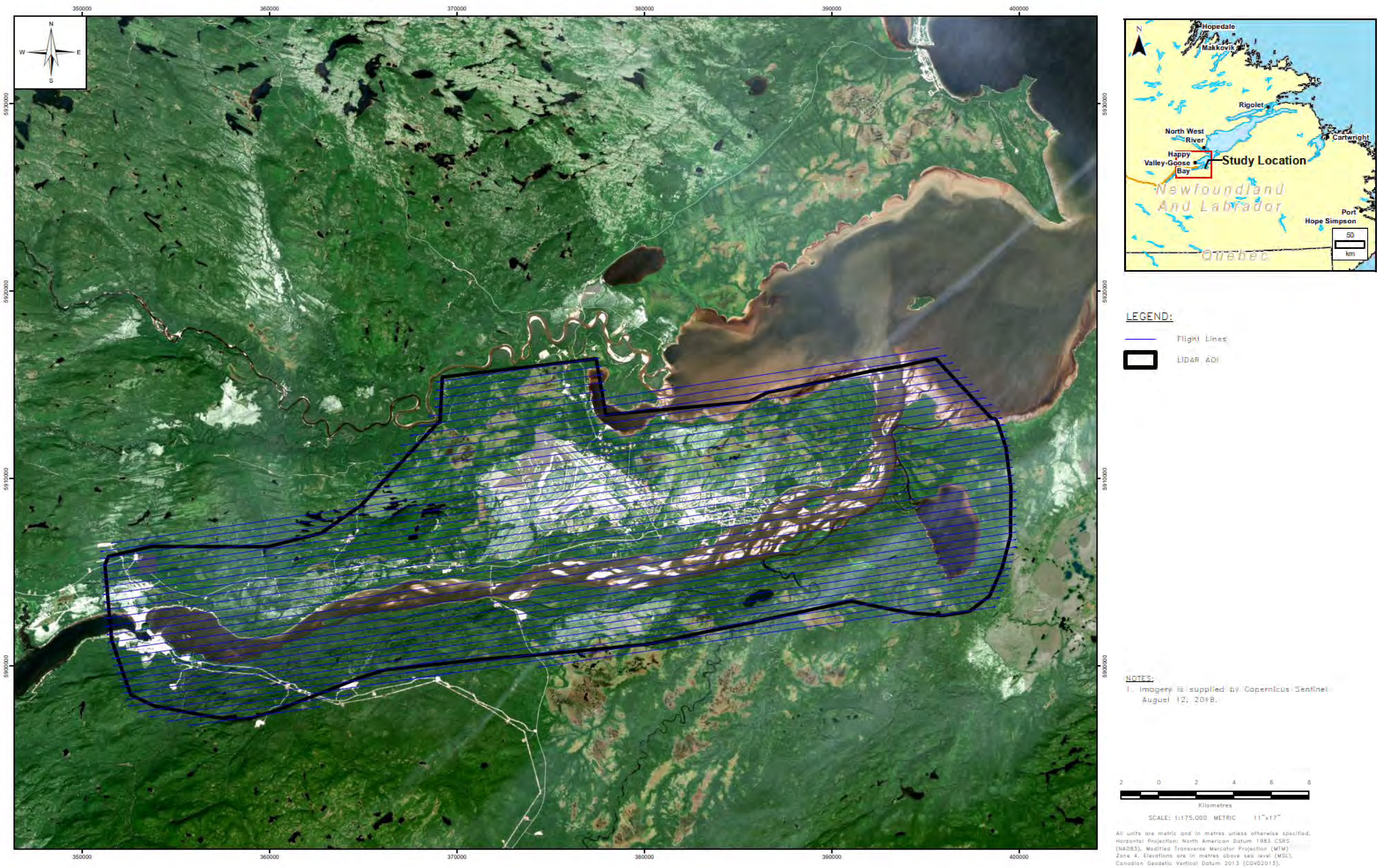
The weather during summer of 2019 presented similarly challenging conditions, with unfavorable weather conditions throughout the summer of 2019. Accordingly, the poor weather conditions resulted in additional delays in the completion of the LiDAR and aerial photography survey. In close cooperation with WRMD, and due to the critical importance of completing the LiDAR and aerial imagery capture, KGS Group and ATLIS decided to station the LiDAR aircraft and crew on standby in Happy Valley – Goose Bay to allow for a successful capture at a moment notice when the weather conditions allowed for. The decision was made based on a review of the hourly weather patterns, which indicated that short windows to capture the data were occasionally available during some days. Only flying for a few hours per day would require the LiDAR to be captured over a longer period of 7 to 8 days. Once the crew was mobilized and situated on the project site, the LiDAR and aerial imagery was successfully captured the week of September 9th to 14th. The weather conditions for the capture were generally favourable, but the occasional presence of low-level clouds slowed the process of the capture.

The flight report documenting the parameters of the LiDAR capture is included in Appendix E. Table 5 outlines the LiDAR acquisition specifications for the capture, which were defined based on the Federal Airborne LiDAR Acquisition Guideline – Version 1.1 (2017). The extent of the LiDAR and aerial imagery survey, as well as the flight lines flow to complete the survey, are shown on Figure 9. ATLIS also collected stereopair imagery using a Leica RCD30 80MP RGBN camera at the same time as the LiDAR point cloud to support hydro break line development over the project area.

TABLE 5
LIDAR ACQUISITION SPECIFICATIONS

LIDAR ACQUISITION SPECIFICATIONS	
Flying Height (metres AGL)	1300 m
Aircraft Ground Speed (knots)	105
Pulse Rate (KHz)	424
Scan Rate (Hz)	53
Full Field of View (degrees)	40
Multi-Pulse	YES
Nominal Swath Width (Metres)	946 m
Swath Overlap (percentage)	30%
Nominal Point Spacing Across Track (Metres)	0.6
Nominal Point Spacing Along Track (Metres)	0.5
Average Pulse Density (points per m²)	8.3
LiDAR Sensor	Leica ALS70

FIGURE 9
LIDAR CAPTURE AREA



Additional quality control reviews were completed on the delivered datasets from ATLIS. A qualitative assessment was completed on the raw point cloud dataset and the DEM to ensure complete project coverage. The raw point cloud was also inspected to check for point densities at 5 different test sites (in both heavily vegetated and non-vegetated areas) and found an average point density of 8 points/m² on all returns.

ATLIS completed a validation of the 140 surveyed ground calibration points against the DEM for non-vegetated areas. A summary of the validation completed by ATLIS is provided in Table 6 and describes the non-vegetated vertical accuracy of the LiDAR data. A detailed table with all the validation completed by ATLIS can be found in the LiDAR Flight Report in Appendix E.

TABLE 6
SUMMARY OF VERTICAL ACCURACY ON HARD SURFACES

SURVEY DATA - DEM VALIDATION (BY ATLIS)	
Average Vertical Error	-0.001 m
Standard Deviation	0.044 m
Minimum Error	-0.012 m
Maximum Error	0.013 m
RMSE	0.044 m
RMSE (95 % Confidence – Hard Surface)	0.086 m
Count	140

KGS Group also completed an analysis of the surveyed ground points. The 222 ground survey points collected across the study area in areas of varying ground conditions (i.e. conditions that could affect the LiDAR returns) were used to complete additional assessments on the DEM. In particular, vegetated areas of various height classes were selected from the ground survey points to confirm the LiDAR representation of the bare earth ground elevation. However, these points were only used to confirm the bare earth elevation, and were not used to verify the vegetation heights as measured by the LiDAR data, as required in the Federal Airborne LiDAR standards. Accordingly, the LiDAR classification completed as part of the post-processing only included ground and water returns only, and did not include the development of a full featured DEM.

A summary of these statistics, including the non-vegetated vertical accuracy (NVA) and vegetated vertical accuracy (VVA) is shown in Table 7.

TABLE 7
LIDAR QUALITY CONTROL ANALYSIS

Site Class	Site Description	Min	Max	Mean	RMSE	NVA RMSE 95%	VVA RMSE 95%	RMSE 95%	NVA Spec (Pass /Fail)
Class 1	Firm Ground	-0.058	-0.015	-0.041	0.012	0.024		0.100 to 0.150	PASS
Class 2	High Grass	-0.564	0.373	-0.177	0.243		0.476	0.300	PASS
Class 3	Brush Land	-0.685	0.317	-0.352	0.259		0.508	0.300	PASS
Class 4	Urban	-0.162	0.036	-0.045	0.050	0.098		0.100 to 0.150	PASS
Class 5	High Vegetation	-0.611	0.218	-0.128	0.294		0.577	0.300	PASS

Horizontal accuracy of LiDAR point data is based on the positional accuracy of the GPS, the height above ground of the craft during the capture and the Inertial Measurement Unit (IMU) calibration. The Root Mean Square Error (RMSE) (95% confidence) for the 2019 LiDAR capture was derived using the American Society for Photogrammetry and Remote Sensing (ASPRS) Positional Accuracy Standards (2014) for the determination of positional accuracy from the known values from the LiDAR capture. This specification is a standard for describing LiDAR accuracy. A calculated value of 20 cm was obtained using adopted standards from the specification.

After the LiDAR survey was completed, ATLIS was responsible for processing the LiDAR data. ATLIS developed a detailed LiDAR workflow methodology that was used in other similar flood mapping projects and was adopted for the Churchill River Flood Risk and Forecasting project. ATLIS also confirmed that the coverage of the project area was complete. The details of the flight data processing and quality control performed in conjunction with the LiDAR flight are described in the LiDAR flight report in Appendix E.

The LiDAR data was processed in a series of steps by ATLIS. The LiDAR data processing included:

- Resolution of the GPS kinematic corrections for aircraft position data using kinematic aircraft GPS and static ground GPS data collected over geodetic controls. (Software: Waypoint Inertial Explorer, Leica Geo Office).
- Development of a smoothed best estimate of trajectory (SBET) file that blends post-processed aircraft position with altitude data. (Software: Waypoint Inertial Explorer).
- Calculation of laser point position by associated SBET information to each laser point return time, with offsets to scan angle and intensity. This process produced the raw laser point cloud data in LAS format (ASPRS v1.4), which contained scan angle, return number, intensity, and x, y, z information for each point. The laser points were collected in Latitude and Longitude for x and y, and GPS Ellipsoid for elevation. During post processing, the MTM CSRS Zone 4 projection was applied to derive the horizontal values, and the CGVD 2013 geoid was applied to derive the orthometric elevation values form the raw telemetry data. (Software: Leica Cloud Pro).
- Importation of the raw laser points into subset bins, filtering for noise, and manual adjustment of the relative accuracy calibration. Any points that would create sinks in the final DEM were removed and classified as noise. Ground points were then classified for individual flight lines to be used for relative accuracy testing and calibration. (Software: TerraScan v19).
- Testing of the relative accuracy using ground classified points per each flight line and completing automated line-to-line calibrations for system altitude parameters (pitch, roll, heading), mirror flex (scale) and GPS/IMU drift. Calibrations were then performed on ground classified points from paired flight lines. (Software: TerraMatch v19, TerraScan v19).
- Assessment of the fundamental vertical accuracy via direct comparisons of ground classified points to ground RTK survey data. (Software: TerraScan v19).

4.3 DEVELOPMENT OF WATERSHED DIGITAL ELEVATION MODEL

A digital elevation model (DEM) of the Churchill River watershed was developed. This DEM was used to assist in the development of the hydrologic model in HEC-HMS to define various model components and parameters, including the definition of sub-basins, sub-basin slopes, and sub-basin lengths.

The DEM was developed based on the Canadian Digital Elevation Model (CDEM). The CDEM was developed by Natural Resources Canada based on the existing Canadian Digital Elevation

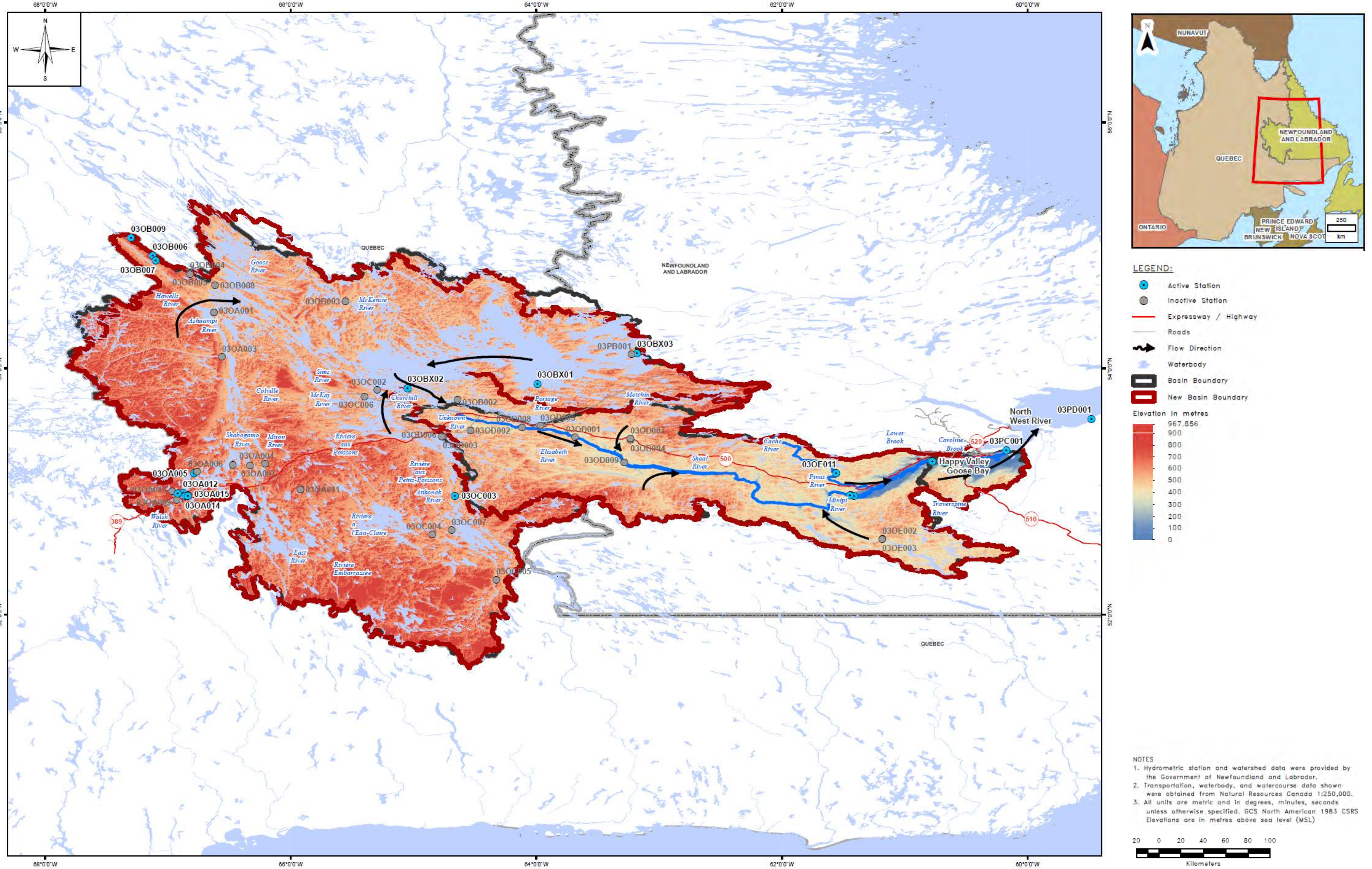
Data (CDED). The CDEM has a longitudinal resolution of approximately 15 m and a latitudinal resolution of approximately 25 m. The CDEM is derived from CDED, which provides elevations at 5 m intervals. Accordingly, elevations in the DEM are interpolated in between the 5 m elevation intervals from the CDED dataset.

Based on the documentation provided by Natural Resources Canada for the CDEM, the expected vertical accuracy of the CDEM within the study ranges from 0 – 10 m. However, given the overall low vertical resolution of the CDEM and high relief within the study area, this represents a relatively small error and is considered to be acceptable.

As an independent check on the watershed delineation that had previously provided by WRMD as part of the review of the 2017 flood on the Churchill River, the Churchill River watershed boundary was delineated using various processing tools included the Arc Hydro extension in ArcGIS ArcMap 10.6. The watershed boundary was then manually inspected to ensure that the basin boundaries were accurately represented. Minor discrepancies were observed between the two delineations, which were likely due to differences between the DEMs used to define the two watersheds, as well as different processes used to delineate the watershed. To ensure consistency with current information at WRMD, KGS Group adopted the watershed delineation provided by WRMD.

The watershed DEM, as well as the watershed delineation adopted by for this study is shown on Figure 10. The DEM is shown in the NAD 1983 CSRS, CGS projection due to the large spatial extent of the watershed, and to avoid any distortion associated with the watershed extending into multiple MTM zones.

FIGURE 10
WATERSHED DEM



4.4 DEVELOPMENT OF FLOOD PLAIN DIGITAL ELEVATION MODEL

At the onset of this study, KGS Group intended to develop a detailed DEM of the Lower Churchill River and surrounding flood plain based on a combination of the bathymetric survey data described in Section 3.2.2 and the LiDAR survey data. This DEM would serve the basis of the open water and ice-affected hydraulic models to be used for the flood risk mapping and flood forecasting products. However, inclement weather prevented the successful completion of the LiDAR survey during 2018, as described in Section 4.2.

To ensure that the flood forecasting system for the Lower Churchill River was in place for the 2019 spring freshet, an initial flood plain DEM was developed based on a combination of the surveyed bathymetry data and LiDAR data that had previously been collected by Nalcor in 2006. The Final flood plain DEM was developed subsequent to the completion of the LiDAR survey. While many features on the Lower Churchill River, including the channel banks and islands, were in good agreement between the two datasets, the positioning of the sandbars on the river had moved considerably over the years between the different LiDAR captures (2006 and 2019) due to ongoing geomorphological processes (i.e. erosion and deposition). Accordingly, some discrepancies were observed between the LiDAR and bathymetric survey datasets in the DEM and resulting cross sections. These discrepancies, which are represented as surface discontinuities in the initial flood plain DEM, were not resolved in the DEM since considerable effort would be required to estimate the movement and topography of the sandbars throughout the study area. Instead, adjustments were made to the cross sections incorporated into the Flood Forecasting model to account for some of the movement of the sandbars. This process was completed as part of the hydraulic model calibration process, described further in Section 9.2.3.

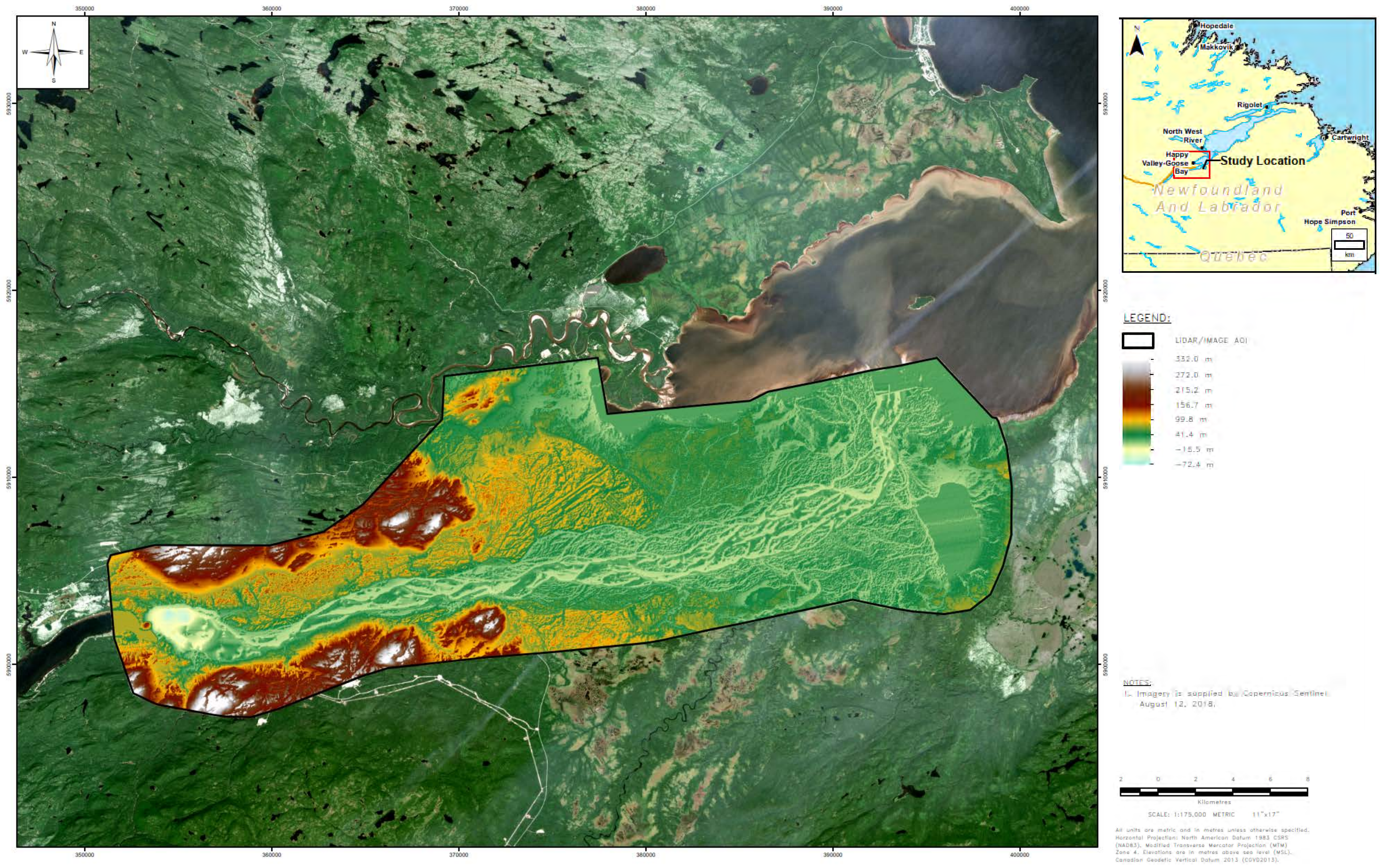
Following the completion of the LiDAR survey, the final DEM of the Churchill River flood plain was developed for inclusion in the Flood Risk Mapping hydraulic model, which consisted of a topographic DEM defined based on the 2019 LiDAR survey, and a bathymetric DEM defined based on the 2018 bathymetric survey data.

To define the LiDAR DEM, the raw point cloud LAS data set was loaded into a LAS dataset in LP360, and statistics for each tile were calculated in order to create derivative products, including a DEM of the LiDAR dataset. Using Modelbuilder in LP360, a process was implemented to iterate through every tile containing data. The tile index extent was buffered, allowing for the DEM to be created past the tile boundary and eliminating any voids between tiles. The model was loaded in LP360 using a ground LAS layer and breaklines, and the data between points was interpolated using a binning approach, where the average elevation of the points was assigned to the final cell elevation. The void fill method used was Natural Neighbour. The DEM was computed directly from the full resolution LAS data, and grid spacing (0.5m) was determined for the final output. The DEM surface was checked for artifacts, gaps, and positional accuracy. Upon completion, the tiles were exported to ASCII files and converted to ESRI float grid format.

The two main components used to define the bathymetric DEM were the bathymetric survey data and 3D breaklines of the shoreline defined based on the LiDAR survey data. ATLIS developed 3D dual breaklines across the entire project area using DATEM software. The breaklines were developed on an image frame-by-frame basis using the aerial imagery collected during the LiDAR survey as the data source. The breaklines were then checked by ATLIS for fit and accuracy against the aerial imagery. The generated breakline coverage was interpolated using the full resolution LAS data to assign the elevation value to the vectors.

Interpolated breaklines were created to help define the bathymetry between the surveyed bathymetric cross sections by using the two datasets along with the aerial imagery collected during the LiDAR survey. The interpolated breaklines were used to match the DEM elevations between the surveyed bathymetric cross sections by interpolating the surveyed cross sections along the alignment of the breaklines. The aerial imagery was used as a check to avoid any obvious barriers such as islands. Surveyed shoreline points from the field survey were disregarded if an island or sandbar was no longer present in the aerial imagery. This process was necessary due to the highly mobile river bottom. Nearshore breaklines were then created to help establish proper slopes along the mainland, islands and sandbars. The shoreline breaklines defined based on the LiDAR data helped seamlessly merge the sonar DEM into the LiDAR DEM to create a bare-earth DEM representative of 2019 conditions. The bare-earth DEM is shown on Figure 11.

FIGURE 11
BARE EARTH DEM



5.0 REMOTE SENSING AND LAND USE CLASSIFICATION

5.1 OVERVIEW

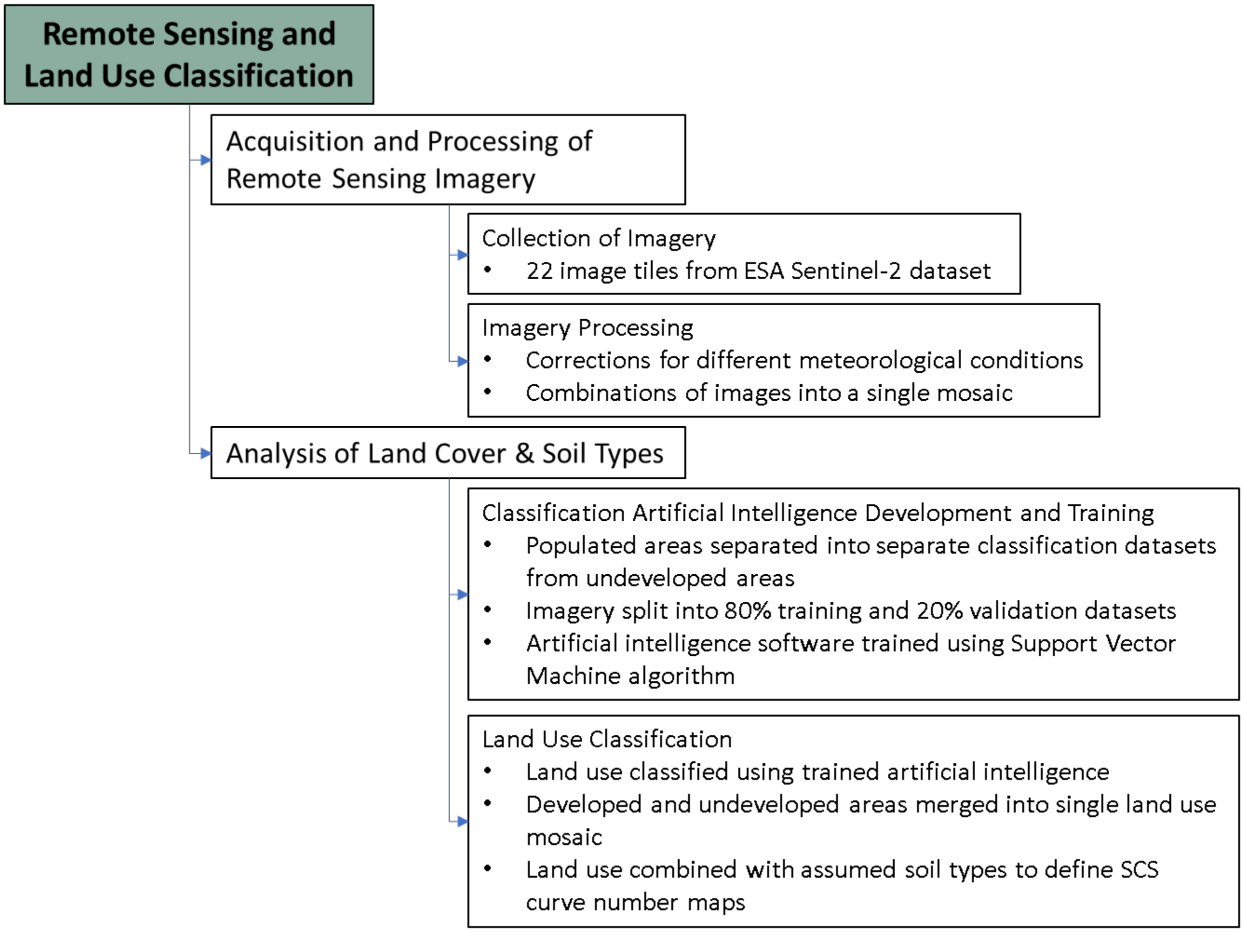
Land use throughout all of the Churchill River basin was classified using high resolution satellite imagery collected by the Sentinel-2 satellites. The Sentinel-2 satellites collect images using different sensors to capture different portions of the light spectrum, and capture high resolution imagery over large swaths of land typically every 5 days. The imagery that was used to classify the land use within the study area was summer imagery (i.e. June to September) from 2016, 2017 and 2018. The imagery dataset was then processed to account for atmospheric variability due to temperature and water vapor.

The land use of the satellite imagery within the study area was classified using artificial intelligence software. The artificial intelligence software was first trained using a set of known land cover areas, and following the successful training of the software, classified all of the land use within the study area.

The final land use classification was used to define a separate map of parameters known as Curve Numbers, which are a representation of how a given land use and soil type will drain water either by groundwater flow or overland flow. This map of curve numbers is used in hydrologic modelling to model how rainfall and snowmelt flow within a river basin. While the map was developed for this study, the hydrologic model ultimately relied on a different representation of groundwater processes and did not use the Curve Number map, as described further in Section 6.0.

The tasks completed as part of the remote sensing and land use classification task are summarized on Figure 12.

FIGURE 12
OVERVIEW OF REMOTE SENSING AND LAND USE CLASSIFICATION TASKS



5.2 LAND USE CLASSIFICATION APPROACH

As part of this project, the Project Team completed updated detailed land cover classification for the Churchill River watershed using the most up to date remote sensing information. The land cover classification used available and current multispectral images acquired by Sentinel-2 optical satellite sensors. Land cover mapping utilized 20 m spatial resolution over the geographic extent of the Churchill River watershed with a 5 km buffer, covering approximately 108,240 km^2. Sentinel-2 (ESA, 2013) is a satellite constellation of a pair of polar-orbiting satellites that were designed to acquire images of the earth surface over large areas ~ 290 km swaths in discrete spectral (color) bands from visible to the Short-Wave Infrared (SWIR) at resolutions from 10m to 60m. Data is typically collected every 5 days over areas of interest assuming no clouds. The intended use of the imagery is for land cover mapping, forestry, agriculture monitoring and natural disaster mapping. In this project imagery from Sentinel-2 optical bands from blue to Near Infrared part of the spectrum at 20m were used for the land cover mapping.

The land cover classification scheme followed the classifications identified by WRMD. However, the classification scheme was altered to eliminate the “Unclassified” class and add a “Mixed Barren” class. All image pixels were assigned a classification. The final land cover classification scheme adopted for the classification is shown in Table 8. The updated land cover classification map can be used by WRMD to monitor long-term changes in land cover and for completing any future flood risk studies in the Churchill River watershed.

TABLE 8
LAND COVER CLASSIFICATION SCHEME

Land Cover	Examples
Forest	Forests
Residential	Small homes and subdivisions
Commercial	Large building and parking lots, schools, shopping malls, industries, plants, etc.
Deforested Areas	Patches of treed and un-treed areas adjacent to forest roads, areas with open green fields in forested zones.
Barren Land	Non-vegetated areas.
Fields/Pastures/Open Space	Agriculture areas, farmer fields, parks, cemeteries, golf courses, etc. within urban area, low lying grass areas near airport, vegetated areas.
Swamps/Wetlands/Waterbodies	Swamps, wetlands, lakes, ponds, and rivers
Mixed Barren	Sparsely vegetated areas.

In addition to the available multispectral Sentinel-2 images, the land cover classification also incorporated information from Google Earth to support training and validation dataset. As some classes (i.e., Commercial, Residential, and Field/Pasture/Open area) exist around the communities of Happy Valley – Goose Bay and Mud Lake, the community and non-community areas were classified separately, and then merged together for the final land cover map.

Some assumptions were required to complete the land cover classification. These assumptions include:

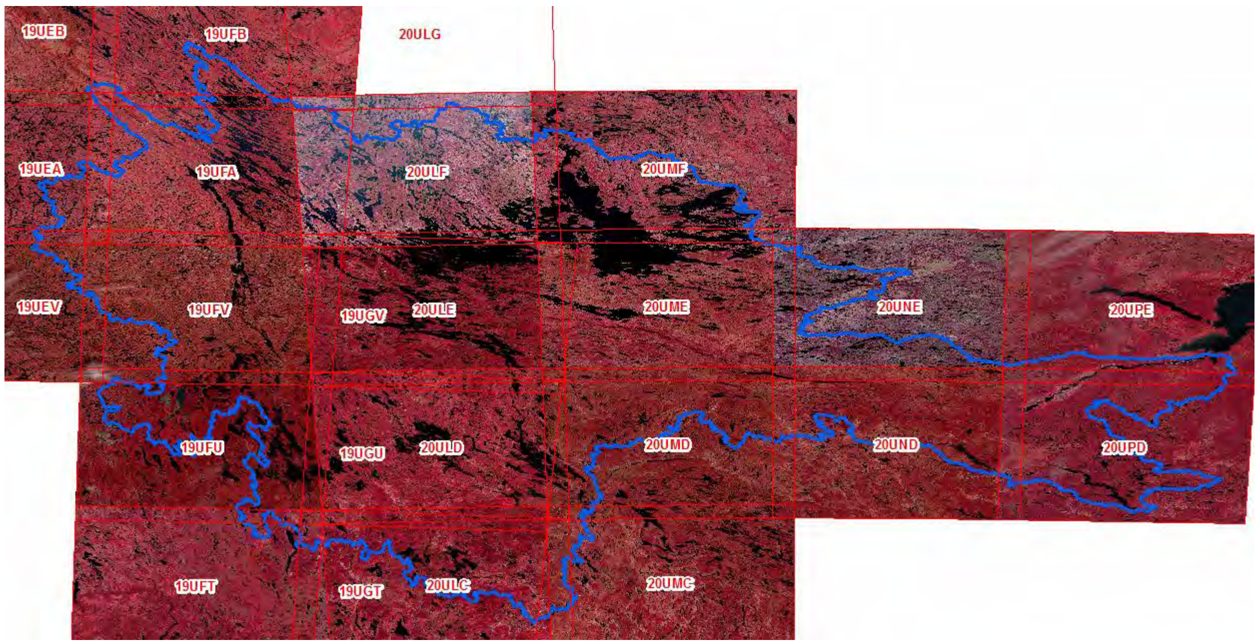
- A minimum mapping unit of approximately 0.5 ha. This approximately represented 12 pixels for land cover classes. At a spatial resolution of 20 m (i.e. 400 m^2), the detection threshold corresponded to an approximate resolution of 50 m. The resulting mapping corresponds to a 1:50,000 scale map.
- Land cover classification was based on available Sentinel-2 imagery, ancillary data, aerial photo interpretation, and input from staff. No ground truthing was completed as part of the development of the land cover classification. Ground truthing is used to verify and associate land cover type to what is seen in the imagery. The data set is used for training the classification process and validating the classified image. Given the remoteness of the areas, it was not feasible to conduct ground truthing. Ancillary data sources were used to develop the training and validation data. This included online imagery from Google maps and Google Earth and communications with the forestry representatives in the watershed area. Training sets were collected as Region of Interest (ROI) points. A check was completed to examine the ROI separability. The results indicated good separability of the selected ROI, indicating the training sets were good examples of the target classes.

5.3 ACQUISITION AND PROCESSING OF REMOTE SENSING IMAGERY

5.3.1 Acquisition of Sentinel-2 Imagery

Sentinel-2 images were downloaded from European Space Agency (ESA) Sci-hub archive for the summer period (i.e., June, July, August, and September) of 2016, 2017, and 2018. Level 1C data was acquired, which had undergone radiometric calibration, geometric correction, and conversion to top of atmosphere reflectance. Reflectance values are normalized for downwelling solar irradiance (i.e. the amount of sunlight). The target coverage was Churchill River watershed with a 5 km buffer. A review of the data archives from Sentinel-2 identified the need for 22 image tiles to provide a comprehensive coverage of the watershed area as shown on Figure 13.

FIGURE 13
SENTINEL-2 IMAGE COVERAGE OF THE CHURCHILL RIVER WATERSHED



The image tiles available for the areas that could be used with the land cover map were located in Universal Transverse Mercator (UTM) 19N and 20N. Ten image tiles were required in UTM zone 19N, and 12 were required in UTM zone 20N. All images were screened with the least cloud coverage over the watershed area, except a small area on a tile near Churchill Falls acquired by the Sentinel-2 satellite on September 2, 2017. The tile was replaced in the analysis with a tile acquired on July 17, 2017 to eliminate the cloud coverage from the classification.

5.3.2 Sentinel-2 Imagery Processing

Once the images were selected, the effects of the temporal difference in atmospheric conditions between the selected images that will be used for the land cover mapping were minimized. Atmospheric constituents such as water vapor and aerosols can influence the downwelling irradiance values through scattering and absorption process. Using radiative transfer models, atmospheric correction was applied to minimize this effect and to normalize the images used in the classification. The atmospheric correction process used the ESA Sen2Cor module to convert from Level 1C to Level 2A at-ground reflectance. Weather conditions for each image tile were checked on the day of image acquisition for ozone, visibility, and altitude data, which was incorporated into the atmospheric correction. The corrected images were resampled in the Sen2Cor module to covert the spectral bands (B2, B3, B4, B5, B6, B7, B8a, B11, and B12) to reflectance and to adjust the spatial resolution from 10 m to 20 m. The process resulted in 9 distinct spectral bands from visible to SWIR for image classification. The wavelength distribution of the spectral bands associated with the Sentinel-2 sensor is shown on Table 9.

TABLE 9
SENTINEL-2 SPECTRAL BANDS AND SPATIAL RESOLUTION

Spectral Band	Center Wavelength (nm)	Band Width (m)	Spatial Resolution (m)
Band 2	490	65	10
Band 3	560	35	10
Band 4	665	30	10
Band 5	75	15	20
Band 6	740	15	20
Band 7	783	20	20
Band 8a	865	20	20
Band 11	1610	90	20
Band 12	2190	180	20

Once the tile images were converted to Level 2A, image registration was reviewed by comparing the image tiles with GIS road network shapefiles to ensure the image tiles were properly aligned. To keep the classification consistent over the 22 image tiles, a seamless mosaic was completed in ENVI 5.3. Specifically, all the image tiles were projected in UTM 20N. In the seamless mosaic, histogram matching was completed over the 22 image tiles with no feathering along the seamless lines. A nearest neighbour interpolation method was implemented for mosaic image resampling to minimize any modification to the spectral values. Next, image stack layers were developed in preparation for the land cover classification. A combination of spectral bands and spectral indices were used to separate land cover features such as forested areas (i.e. coniferous/deciduous), water and paved areas. Specifically, the following spectral indices were applied:

Normalized Difference Vegetation Index (NDVI) – highlight vegetation areas – (b8a – b4) / (b8a + b4).

- Modified Normalized Difference Water Index (MNDWI) – highlight water areas and minimize false classification in urban areas – (b3 – b11) / (b3 + b11).
- Normalized Difference Water Index (NDWI) – highlight water areas and minimize false classification outside urban areas – (b3 – b8a) / (b3 + b8a).

For the mosaic image, NVDI, MNDWI/NDWI were applied. An image stack of 11 layers was then created with the following layers:

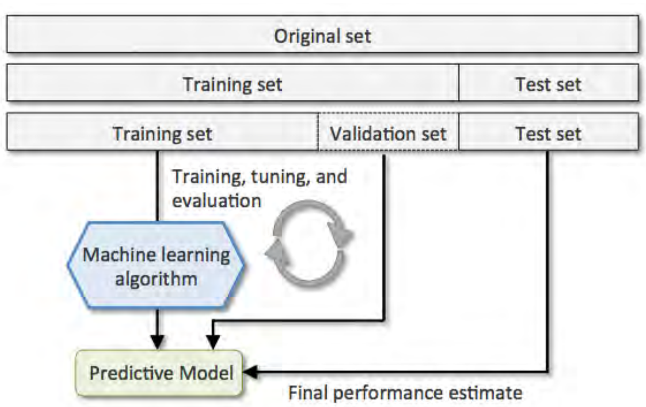
- Spectral bands: B2, B3, B4, B5, B6, B7, B8a, B11, and B12;
- NDVI;
- MNDWI/NDWI.

5.4 LAND USE CLASSIFICATION

The land use classification was completed using a machine learning classification methodology. The process involved collecting training and test data sets to train and evaluate the model performance.

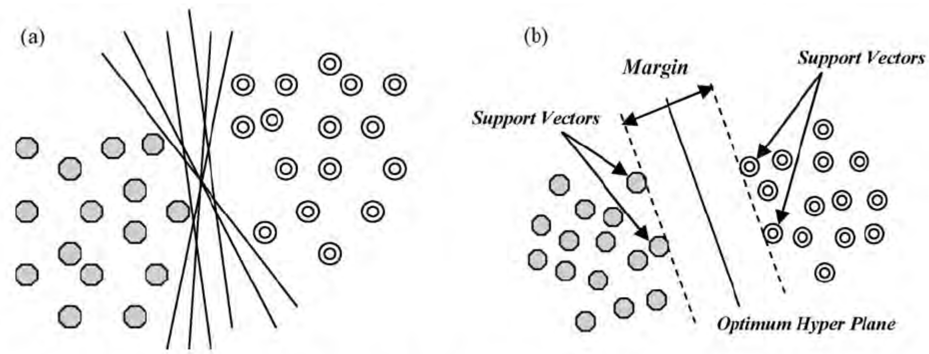
Figure 14 illustrates the high-level process involved in machine learning classification.

FIGURE 14
MACHINE LEARNING CLASSIFICATION



The machine learning algorithm used for the land cover classification was Support Vector Machine (SVM) implemented in ENVI/IDL 5.4 and the scikit-learn Python based machine learning framework. SVM is a supervised learning or heuristic algorithm that performs image classification based on statistical learning theory. The aim of SVM for classification is to determine hyper planes that optimally separate the classes as conceptually illustrated on Figure 15.

FIGURE 15
SUPPORT VECTOR MACHINE HYPER PLANE



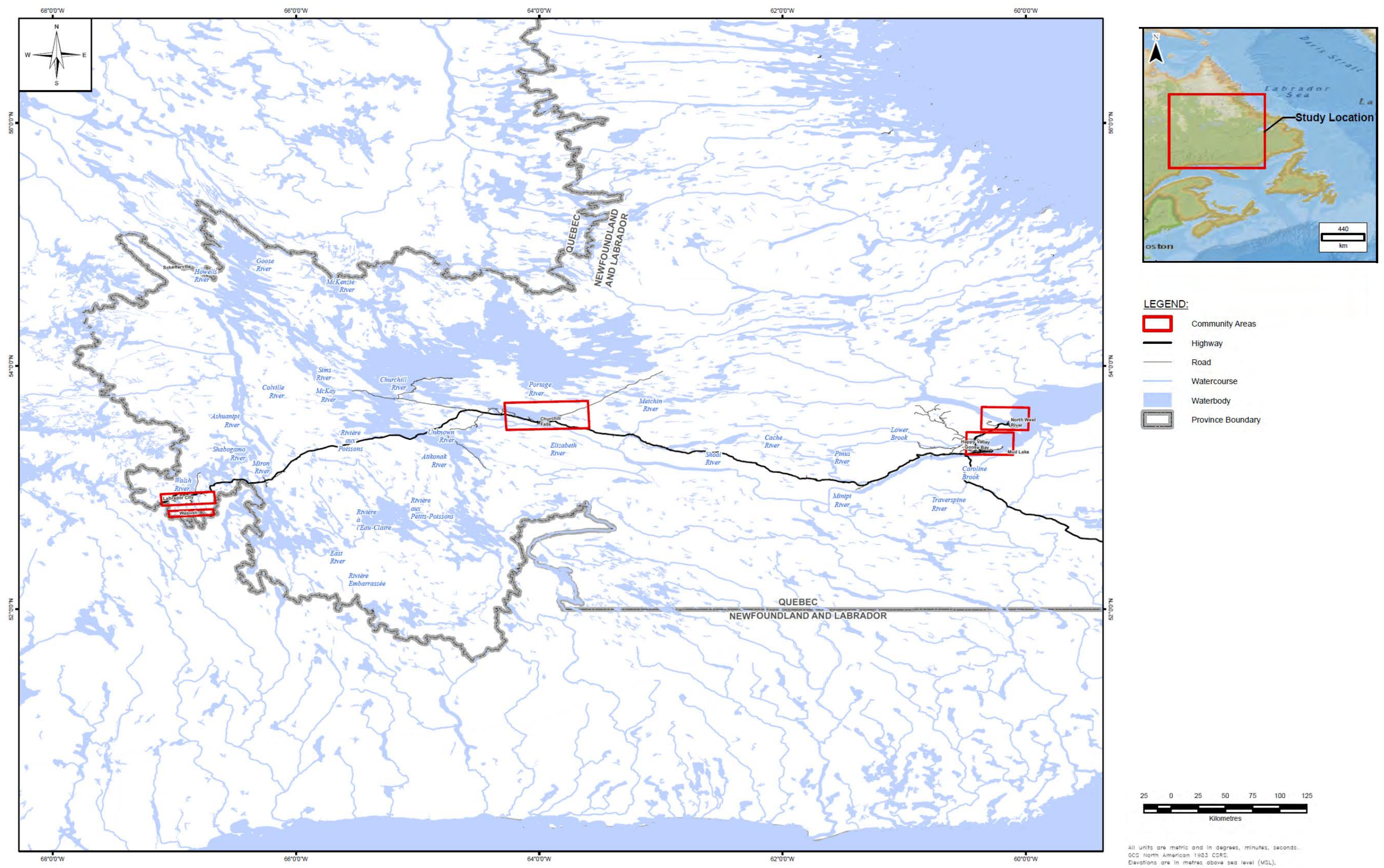
Hyper planes for linearly separable data (a). Optimum hyper plane and support vectors (b).

Source: Noi Thanh and Kappas (2018)

Different kernels are used to reduce the computations in highly dimensional space by using a kernel function to enable the data points to spread in such a way that a linear hyper plane can be fitted. A common kernel function used in remote sensing classification is the Radial Basis Function (RBF) kernel with SVM. In land cover classification studies, according to Knorn et al. (2009) the RBF kernel of the SVM classifier is commonly used and shows a good performance. There are two parameters that need to be set when applying the SVM classifier with RBF kernel: the optimum parameters of cost I or penalty and the kernel width parameter (γ). The C parameter determines the size of misclassification allowed for non-separable training data, which makes the adjustment of the rigidity of training data possible (Exelis Visual Information Solutions, 2013). The kernel width parameter (γ) affects the smoothing of the shape of the class-dividing hyper plane. Larger values of C may lead to an over-fitting model, whereas increasing the γ value will affect the shape of the class-dividing hyper plane, which may affect the classification accuracy results (Huang et al., 2002).

For the classification process, the land cover classes included Forest, Residential, Commercial, Deforested areas, Barren, Mixed barren, Field/Pasture/Open area, and Water/Wetland. As Commercial, Residential, and Field/Pasture/Open area land cover only exists around the community areas, multi-level classification was required for the classification. This was accomplished by defining a small rectangular subset around the community areas for classification that included Commercial, Residential, and Field/Pasture/Open area while excluding these three classes outside of the subset. The community areas are shown in red on Figure 16.

FIGURE 16
COMMUNITY AREAS IN THE CHURCHILL RIVER WATERSHED



The classification included separate analysis areas for Happy Valley – Goose Bay, Churchill Falls, Labrador City and Wabush, which are within the watershed boundary. Other communities in the watershed, as shown by the blue boundary in Figure 16, were not separated out as the amount of buildings and paved areas were relatively small. For the non-community classification, there were four classes: Forest, Barren, Mixed barren, and Water/Wetland. Deforested areas were manually digitized in the post processing of the classification. The Forest class was separated into Coniferous forest and deciduous forest, while the Water/Wetland class was separated into Water, Wetland, and Mixed Water (i.e. water mixed with trees). For the classification of community subsets, six classes were considered in the classification, specifically Forest, Residential, Commercial, Barren, Mixed barren, and Water/Wetland. Field/Pasture/Open areas were manually digitized in the post processing of the classification. Similar to the non-community classification, the Forest class was separated into Coniferous forest and deciduous forest while the Water/Wetland class was separated into Water, Wetland, and Mixed Water. No Mixed Water class existed for Churchill Falls, Labrador City or Wabush.

To keep NDVI and MNDWI/MDWI in consistent DN range with spectral bands, NDVI and MNDWI were linearly stretched between 0 and 10000 for the three community subsets while NDVI and NDWI were linearly stretched between 0 and 7500 for the non-community areas.

To apply SVM classification, a training set of known land cover values was defined. The supervised classification methodology used for the classification requires defining a training and validation data set to set the SVM model condition. The training sets for developing the SVM model were defined based on visual interpretations from Google Earth. Training sets were collected using ENVI software as Region of Interest (ROI) points. A check was completed using ENVI image processing software to examine the ROI separability. The results indicated good separability of the selected ROI, indicating the training sets were good examples of the target classes.

The collected training data was split into training and validation subsets, with the training subset representing 80% of the initial training data, and the validation subset representing 20% of the initial training data. Splitting the 80% of the data into training dataset and 20% of the data into a validation dataset is common practice in the training of artificial intelligence, and is based in part on the Pareto Principle (M. Gen and R. Cheng, 1999). A confusion matrix was defined to calculate the Kappa score, which is a measure of how accurately all of the classes have been classified (i.e. a Kappa score of 1.0 is perfect), to assess the accuracy of the ROI selected for training the classifier. For the non-community areas, the overall accuracy and the Kappa score were 98.8% and 0.959, respectively. For the three community subsets, the overall accuracy and Kappa scores were 95.9% and 0.952 for Happy Valley – Goose Bay, 95.8% and 0.950 for Churchill Falls, and 99.0% and 0.988 for Labrador City & Wabush. Individual class accuracies, including the F-score, which is a statistical representation of how accurately each individual land use class has been classified (i.e. an F-score of 1.0 is perfect) for each classification are shown in Table 10 to Table 13.

TABLE 10
CLASS ACCURACY RESULTS - NON-COMMUNITY AREAS

Class	Producer Accuracy	User Accuracy	F-Score
Coniferous	91.0%	96.9%	0.938
Deciduous	96.5%	99.0%	0.977
Barren	99.5%	99.9%	0.997
Mixed Barren	97.5%	98.8%	0.981
Water	100.0%	99.0%	0.995
Wetland	89.1%	91.0%	0.900
Mixed Water	75.3%	92.9%	0.832

TABLE 11
CLASS ACCURACY RESULTS - HAPPY VALLEY - GOOSE BAY

Class	Producer Accuracy	User Accuracy	F-Score
Residential	89.9%	84.8%	0.873
Commercial	88.8%	93.3%	0.910
Coniferous	99.6%	98.7%	0.991
Deciduous	100.0%	99.5%	0.997
Barren	71.4%	74.5%	0.729
Mixed Barren	99.8%	99.3%	0.996
Water	100.0%	99.9%	1.000
Wetland	99.7%	99.3%	0.995
Mixed Water	95.4%	99.1%	0.972

TABLE 12
CLASS ACCURACY RESULTS - CHURCHILL FALLS

Class	Producer Accuracy	User Accuracy	F-Score
Residential	83.9%	98.1%	0.904
Commercial	94.3%	95.3%	0.948
Coniferous	100.0%	98.6%	0.993
Deciduous	100.0%	97.9%	0.989
Barren	93.3%	80.0%	0.862
Mixed Barren	97.1%	92.6%	0.948
Water	100.0%	100.0%	1.000
Wetland	86.7%	100.0%	0.929

TABLE 13
CLASS ACCURACY RESULTS - LABRADOR CITY & WABUSH

Class	Producer Accuracy	User Accuracy	F-Score
Residential	98.4%	97.6%	0.980
Commercial	96.6%	96.6%	0.966
Coniferous	100.0%	100.0%	1.000
Deciduous	98.5%	98.5%	0.985
Barren	99.0%	99.2%	0.991
Mixed Barren	99.7%	98.8%	0.992
Water	100.0%	100.0%	1.000
Wetland	90.9%	100.0%	0.952

5.5 POST PROCESSING

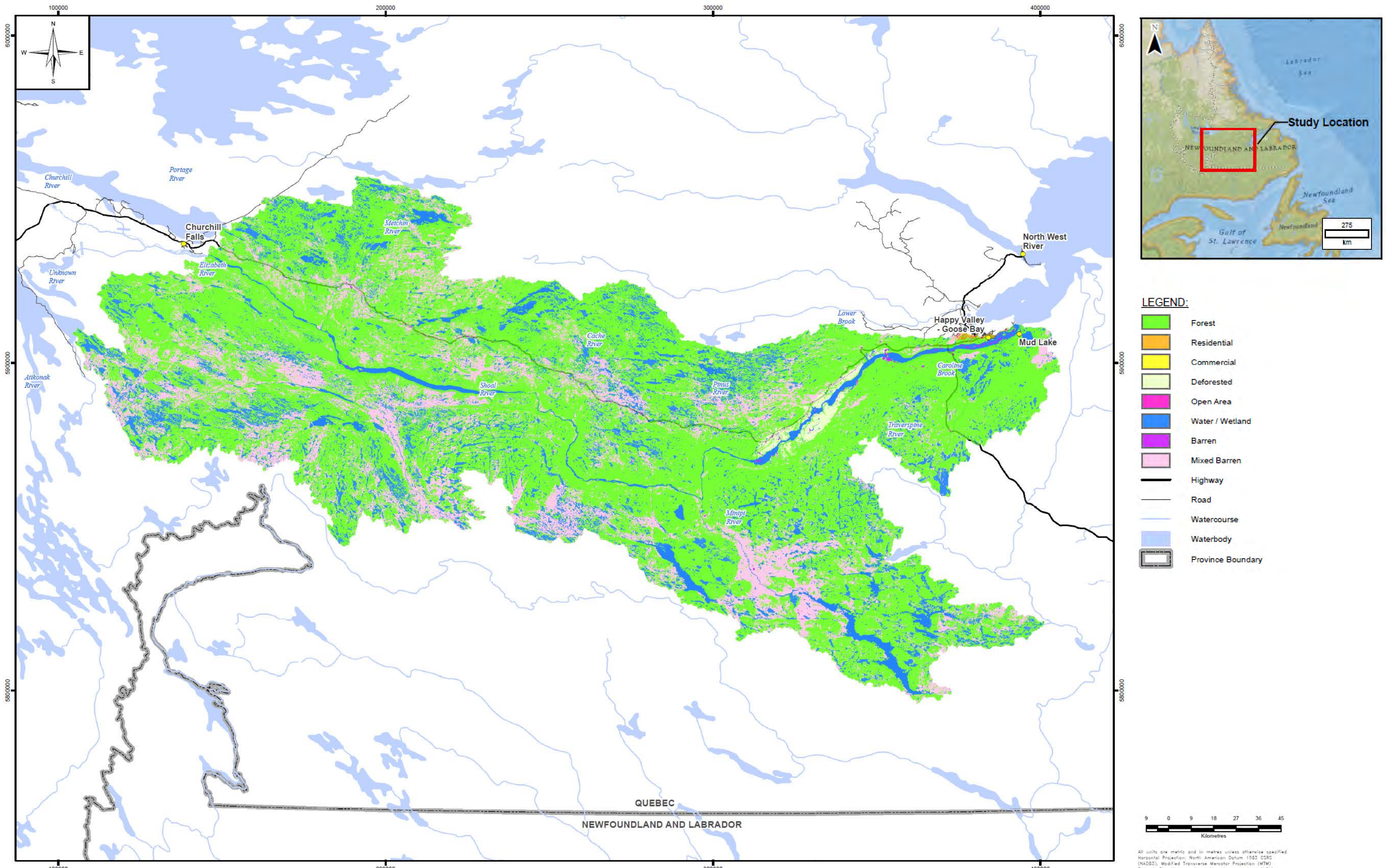
Post classification was completed to finalize the land cover classification, including the merging of land cover classes, filtering, creating a mosaic of the different classifications, manual digitization, and adjustments as required.

Coniferous and Deciduous classes were combined into the Forest class. Water, Wetland, and Mixed water were combined into the Water/Wetland class. The Field/Pasture/Open area was manually digitized in the Happy Valley – Goose Bay subset. The Deforested areas were also manually digitized at Muskrat Falls. Furthermore, the Residential class was manually edited, in particular in the Happy Valley – Goose Bay subset.

A majority filter process was implemented to minimize any isolated classified pixels with the classified image. The size of the filter affected the degree of homogeneity of the surrounding area, and as such a 3x3 filter size was selected for the three community subsets while a 5x5 filter size was selected for the non-community areas. The three community classification maps were merged with the non-community classification map. The merged classification map was then clipped to the Churchill River watershed boundary with a 5 km buffer. A geodetic transformation from WGS84 to NAD83 with the UTM projection was also completed.

The final land cover classification map is shown on Figure 17.

FIGURE 17
LAND COVER CLASSIFICATION MAP



The land coverage areas and percentage of land cover is provided below in Table 14

TABLE 14
CHURCHILL RIVER BASIN LAND COVER TYPE AREAS AND PERCENTAGE

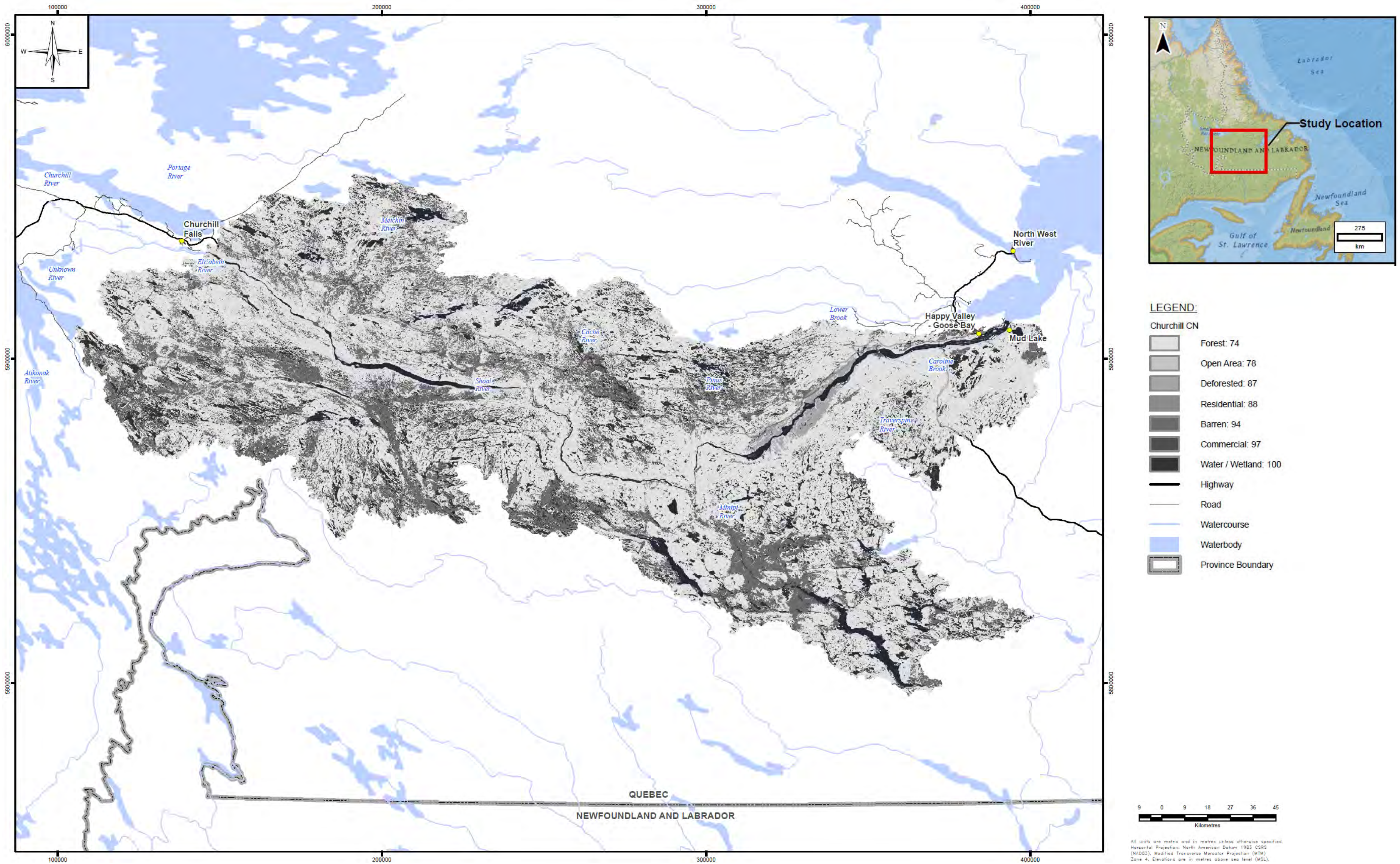
Class Name	Class Value	Pixel Number	Area (km2)	Percentage
Forest	1	140,541,683	56,217	51.94%
Residential	2	80,165	32	0.03%
Commercial	3	16,275	7	0.01%
Deforested	4	34,672	14	0.01%
Open Area	6	7,856	3	0.00%
Water / Wetland	7	70,930,927	28,372	26.21%
Barren	51	416,867	167	0.15%
Mixed Barren	52	58,574,025	23,430	21.65%
Total		**270,602,470**	**108,241**	**100%**

5.6 CURVE NUMBER MAPPING

The land cover classification was used to create a map of the watershed showing the US Soils Conservation Service (SCS) Curve Numbers (CN). CN values are an empirical parameter used in hydrological modeling for determining the amount surface runoff. Curve Numbers require a combination of land cover and soil type data. An investigation was completed to determine the extent of available soils information in the watershed. Soils information within the Churchill River watershed was unavailable, and as specified by WRMD, the soil type in the watershed was assumed as Soil Type B. The Mixed Barren class was added to Barren class and assigned the CN Value of 94.

A raster process was applied to assign the SCS Curve number to the 20m raster. The resulting SCS Curve number map is shown on Figure 18.

FIGURE 18
CN MAP



6.0 HYDROLOGIC INVESTIGATIONS AND MODELLING ON THE CHURCHILL RIVER

6.1 OVERVIEW

Flood flows on the lower Churchill River were estimated using three separate methods, specifically by completing a statistical analysis of recorded flows on the Churchill River, completing a statistical analysis of recorded flows on rivers throughout Labrador, and by developing a computer model of the Churchill River basin to simulate snowmelt and rainfall processes.

The statistical analysis of recorded flows on the Churchill River was based on flows recorded by Water Survey of Canada at Muskrat Falls. The analysis considered recorded flows that were available after the completion of the Churchill Falls Generating Station, and fit a statistical distribution to the yearly maximum flows. This statistical fit was then used to estimate the flow rate for 20 and 100 year floods.

A similar analysis was completed for various rivers throughout Labrador where recorded flows are available. By fitting statistical distributions to the yearly maximum flows for each river, a dataset of 20 and 100 year flood flows were defined for each river. By analyzing the different flow rates relative to the drainage area upstream of each flow recording gauge and the proportion of lake area to the total drainage area for each river, a set of equations was developed to estimate the 20 and 100 year flood flows for any river within Labrador. These equations were in good agreement with the statistical analysis of recorded flows on the Churchill River.

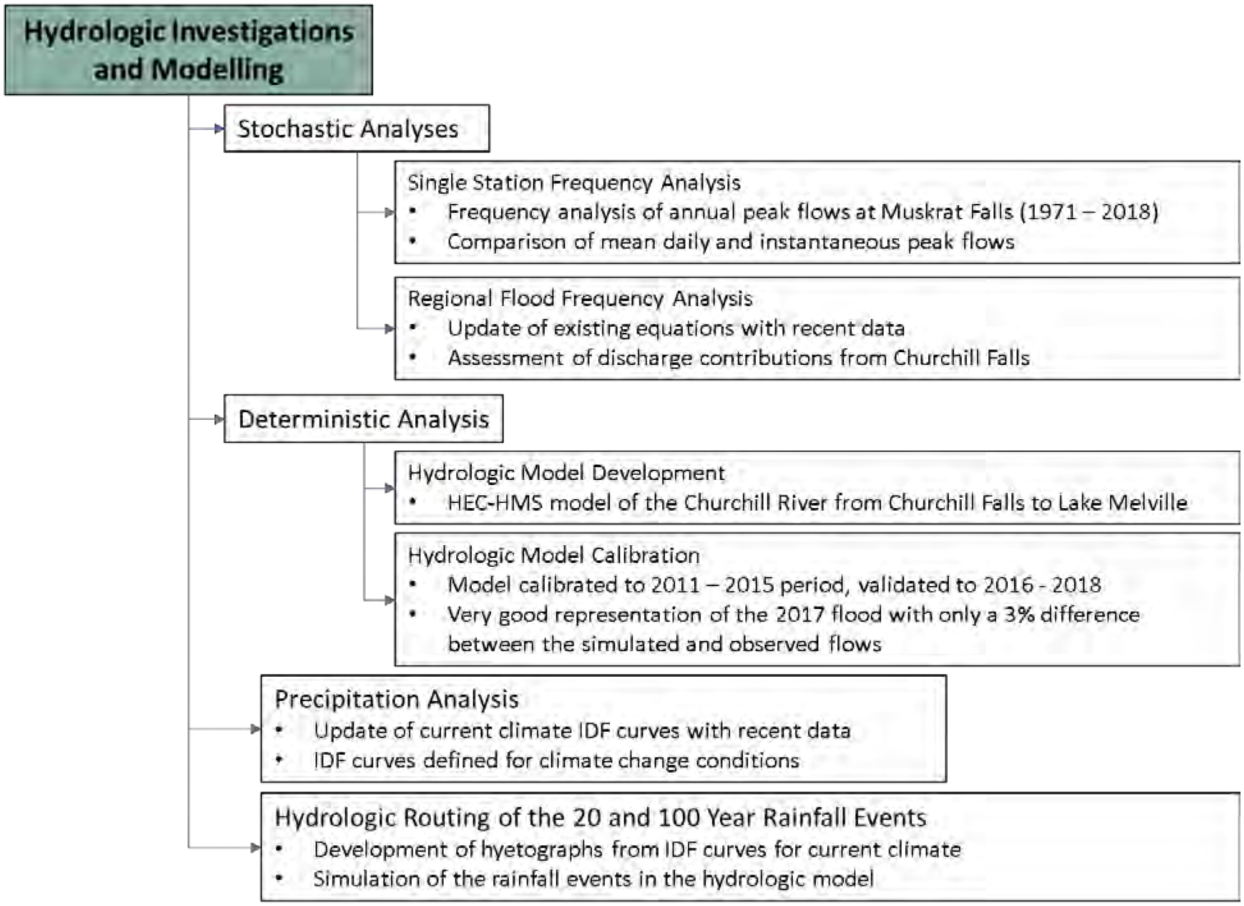
A computer model of the Churchill River (i.e. a hydrological model) was developed to model flows on the Churchill River for a wide variety of meteorological conditions. Hydrological models are used to represent the various meteorological processes that occur within a river's drainage area, including rainfall, the accumulation of snow, snowmelt, and groundwater losses by representing rivers and tributaries, as well as their drainage areas, numerically. For this study the model represented the Churchill River and tributaries between Churchill Falls to Lake Melville, with inflows added into the model representing the outflow from the Churchill Falls

Generating Station. The model was adjusted to represent recorded flows in the Churchill River basin from 2011 to 2018, and was found to accurately represent the historical observed flows, in particular high flows that occurred during the spring of 2017. The model was then used to estimate the flows on the Churchill River for a 20 and 100 year rainfall. Since high flows on the Churchill River are dominated by snowmelt rather than rainfall, the modelled flows were considerably lower than those estimated using statistical analyses.

The hydrologic model was built into the forecasting system to estimate flows on the Churchill River at Muskrat Falls based on available forecast temperature and precipitation data. The model was successfully used during the 2019 spring to predict flows on the Churchill River.

The tasks completed as part of the hydrologic investigations and modelling are shown on Figure 19.

FIGURE 19
OVERVIEW OF HYDROLOGIC INVESTIGATIONS AND MODELLING



6.2 STOCHASTIC ANALYSES

6.2.1 Single Station Frequency Analysis

A single station frequency analysis (SSFA) was carried out for the WSC gauge 03OE001 – Churchill River at Muskrat Falls. As part of the SSFA, it was initially intended to naturalize flows on the Churchill River by back-calculating the historical natural outflow record at Churchill Falls based on stage-storage curves and historical water levels on the Ossokmanuan and Smallwood reservoirs, calculated inflows to Churchill Falls, plant and spillway discharges from Churchill Falls, operating rules for the Churchill Falls Generating Station, and the natural rating curve of Churchill Falls. However, through discussions with Nalcor, it became apparent that insufficient historical information was available to naturalize the historical flows at Churchill Falls. Accordingly, instead a SSFA of historical flows at WSC gauge 03OE001 was completed for the regulated record of the Churchill River (i.e. 1971 – 2018).

As part of the SSFA, a check of the dataset was completed to ensure that the required assumptions to carry out a SSFA were met. Statistical tests in the HYFRAN statistical hydrology software showed that no trends were present in the dataset, and that the dataset was homogenous. However, the dataset did not pass the statistical test for independence, which was found to be due to data from 1971 – 1983, during which time the annual peak flows on the Churchill River at Muskrat Falls exhibited only minor variations. A test of the sensitivity of the AEP flow estimates to including the non-independent years showed that the 20-year and 100-year AEP flow estimates only varied by 3% and 1%, and as such, the AEP flows were not considered to be sensitive to the inclusion of the non-independent data. However, for estimating extreme flood flows, such as the 100-year AEP flood, longer periods of record generally reduce the uncertainty in the flow estimates. Accordingly, the full regulated record from 1971 to 2018 was included in the analysis.

A comparison was completed comparing the instantaneous and mean daily annual peak flows on the Churchill River at Muskrat Falls. WSC has recorded instantaneous annual peak flows from 1954 to 2018, excluding 1968 – 1970, 1979, 1989 and 1990. However, only the data from 1971 to 2018 were considered in the comparison to account for the operations of the Churchill Falls Generating Station. The comparison showed that instantaneous flows were 1% larger than corresponding mean daily flows. Accordingly, the instantaneous flows were used in the SSFA where available, and increased mean daily flows by 1% where instantaneous measurements were not available.

A review of peak flows was carried out to determine if it was appropriate to separate the peak flows into snowmelt and rainfall events. All peak flows occurred during the spring freshet, with the exception of 1996, which occurred in November. The low spring freshet flow during 1996 was due to considerably lower than average snow depth at the end of winter, as well as considerably lower than average flows on the Churchill River prior to the spring freshet. The occurrence of the annual peak flow on November 14, 1996 can likely be attributed to a period of very warm weather across the watershed from November 8 to 11, that considerably melted the snowpack in the watershed. Accordingly, KGS Group did not separate the peak flow dataset for the SSFA.

The SSFA of the annual peak flows of the regulated hydrologic record was completed using the HYFRAN statistical hydrology software. Several probability distributions were fit to the dataset, including:

- Extreme Value distribution;
- Lognormal distribution;
- Three-Parameter Lognormal distribution;
- Log Pearson Type 3 distribution.

In addition to the different distributions, a variety of parameter estimation methods were considered using HYFRAN, including:

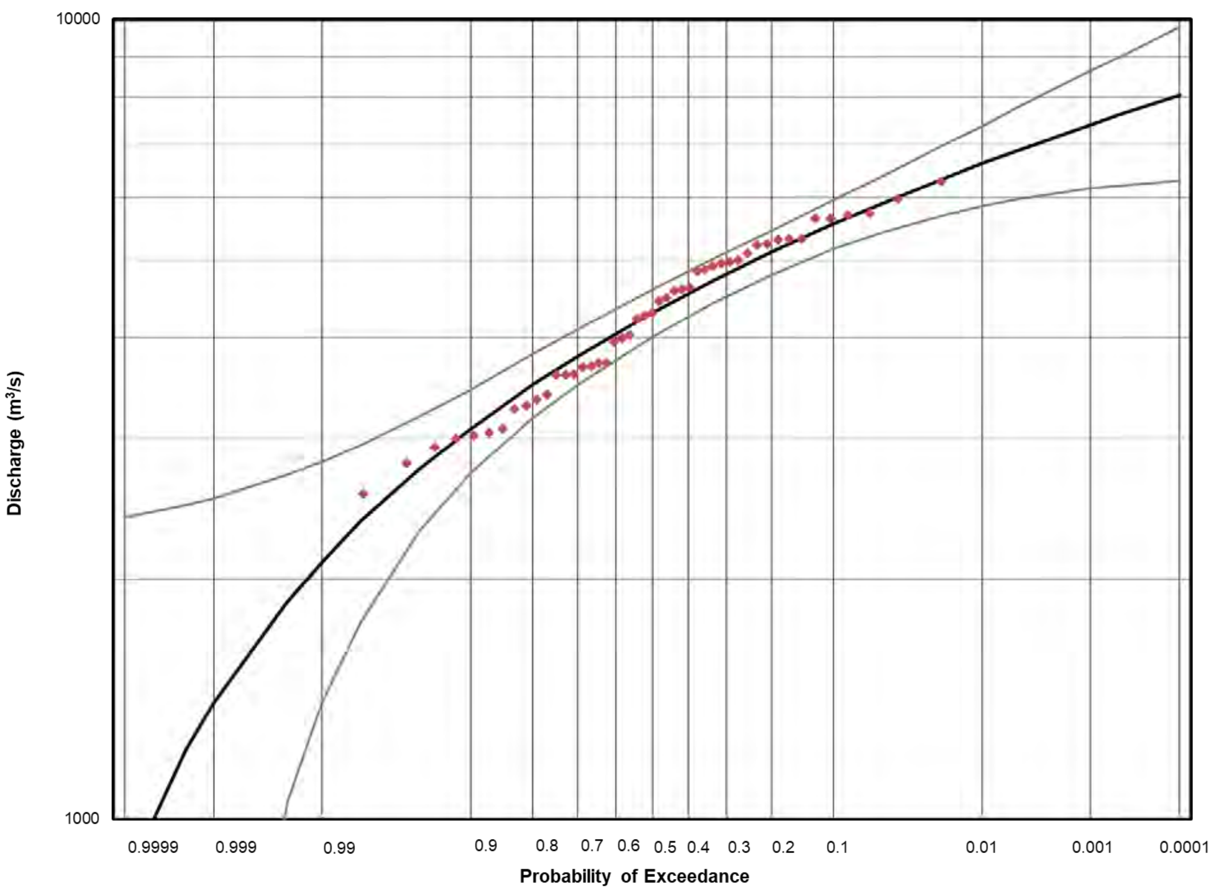
- Method of moments;
- Method of weighted moments;
- Sundry average method;
- U.S. Water Resources Council;
- Maximum Likelihood.

Of the probability distributions fit to the dataset, the 3-Parameter Lognormal distribution was found to be most representative, with the distribution parameters estimated using the method of moments. The appropriateness of the frequency curve was assessed considering the p-value and chi statistic from the Chi-squared test, as well as a visual inspection of the frequency curve. Frequency flows based on this distribution for the Churchill River at Muskrat Falls are summarized in Table 15, and shown on Figure 20.

TABLE 15
FREQUENCY FLOWS

Return Period	Flow (m^3/s)
100	6,610
50	6,330
20	5,920
10	5,560
5	5,130
3	4,720
2	4,300

FIGURE 20
MUSKRAT FALLS FREQUENCY CURVE



As a check, a SSFA was completed for the unregulated flow record on the Churchill River at Muskrat Falls (i.e. from 1954 to 1970). A 3-Parameter Lognormal distribution was fit to the dataset, and the 20-year and 100-year AEP flows were estimated as 6,950 m^3/s and 7,720 m^3/s, representing a difference of approximately 15% from the regulated period. This difference was anticipated due to the storage of peak flows upstream of the Churchill Falls Generating Station. Accordingly, the AEP flows estimated based on the regulated period (i.e. 1971 – 2018) shown in Table 15 were considered reasonable.

6.2.2 Regional Flood Frequency Analysis

The regional flood frequency analysis (RFFA) methodology was reviewed as described in the 2014 report "Regional Flood Frequency Analysis for Newfoundland and Labrador" by AMEC Environment & Infrastructure (AMEC) and 2016 report "Regional Flood Frequency Analysis for Newfoundland and Labrador Using the L-Moments Index-Flood Method" by Y. Lu. The analyses carried out in both reports were reviewed and it was found that the methodologies documented in each study were applicable to this study. However, given the wide application of the methodology used by AMEC in their report, the RFFA described in AMEC's report were updated using more recently available data.

Twelve hydrometric gauging stations in Labrador were assessed to develop the regional flood frequency equations for ungauged locations. The twelve stations included in the RFFA update are summarized in Table 16.

TABLE 16
RFFA STATIONS

Station ID	Gauge Name	Drainage Area (km^2)	Period of Record
02XA003	Little Metchin River above Lac Fourmont	4,540	1978 - 2016
02XA004	River Joir near Provincial Boundary	2,060	1980 - 1996
03NE001	Reid Brook at Outlet of Reid Pond	76	1996 - 2015
03NF001	Ugjoktok River below Harp Lake	7,570	1973 - 2016
03NG001	Kanairiktok River below Snegamook Lake	8,912	1979 - 1995
03OC003	Atikonak River above Panchia Lake	15,776	1973 - 2018
03OD007	East Metchin River	895	1999 - 2013
03OE003	Minipi River below Minipi Lake	2,336	1979 - 2014
03OE010	Big Pond Brook below Big Pond	71	1994 - 2014
03OE011	Pinus River	782	1986 - 2016
03PB002	Naskaupi River below Naskaupi Lake	4,609	1978 - 2012
03QC002	Alexis River near Port Hope Simpson	2,318	1976 - 2016

Prior to carrying out a SSFA for each gauge, statistical tests were completed on the datasets to ensure that they satisfied the required assumptions of independence, a lack of trend, and homogeneity. The results of these tests are summarized in Table 17.

TABLE 17
RFFA DATA TESTS

Station ID	Independence	Trend	Homogeneity
02XA003	Pass (5%)	Pass (5%)	Pass (5%)
02XA004	Pass (5%)	Pass (5%)	Pass (5%)
03NE001	Pass (5%)	Fail	Pass (5%)
03NF001	Pass (5%)	Pass (5%)	Pass (5%)
03NG001	Pass (1%)	Fail	Pass (1%)
03OC003	Pass (5%)	Pass (5%)	Pass (5%)
03OD007	Pass (5%)	Pass (5%)	Pass (5%)
03OE003	Pass (5%)	Pass (5%)	Pass (5%)
03OE010	Pass (5%)	Pass (5%)	Pass (5%)
03OE011	Pass (5%)	Pass (5%)	Pass (5%)
03PB002	Pass (5%)	Pass (5%)	Pass (5%)
03QC002	Pass (5%)	Pass (5%)	Pass (5%)

WSC stations 03NE001 and 03NG001 failed the statistical tests for trend. an additional review of the annual peak flow was completed for these stations and found that the trends in the dataset were due to relatively lower peak flows during the last few years of the hydrologic record for each river. As a check, a comparison of the frequency flows for the two stations for the full record and with the lower flow period removed from the record was completed. The comparison showed that the effect of removing the lower flow period had only a minor effect (i.e. less than 5%) on the calculated frequency flows, and were therefore not considered sensitive to the lower flow period. Accordingly, the full hydrologic record was considered in defining the frequency flows for these gauge stations.

Similar to the analysis carried out as part of the SSFA, the HYFRAN statistical hydrology software was used to fit probability distributions to the peak flow data for each gauge station. A 3-parameter Log-Normal distribution was found to be the most representative distribution overall for the gauge stations, and was as such fit for each gauge station. The estimated frequency flows for each of the gauge stations are summarized in Table 18, and the frequency curves for each gauge station are included in Appendix F.

TABLE 18
SSFA FREQUENCY FLOWS

Station ID	Drainage Area (km^2)	Q2 (m^3/s)	Q5 (m^3/s)	Q10 (m^3/s)	Q20 (m^3/s)	Q50 (m^3/s)	Q100 (m^3/s)
02XA003	4,540	658	801	881	950	1030	1090
02XA004	2,060	334	430	493	552	628	684
03NE001	76	16.6	21.4	24.1	26.4	29.1	31
03NF001	7,570	1110	1410	1580	1730	1910	2040
03NG001	8,912	1160	1490	1670	1820	2010	2130
03OC003	15,776	1170	1370	1480	1580	1690	1770
03OD007	895	183	240	277	313	360	395
03OE003	2,336	233	292	326	357	393	419
03OE010	71	15.1	18.4	20.1	21.5	23.1	24.2
03OE011	782	115	146	164	180	200	214
03PB002	4,609	469	561	614	659	713	750
03QC002	2,318	538	657	772	776	838	880

As part of the RFFA update, the relationship of the frequency flows to the watershed drainage area (DA) was defined by carrying out a single variable linear regression analysis. A multiple linear regression analysis was also completed to define the relationship between frequency flows, watershed drainage area, and lake attenuation factor (LAF), which represents the influences of lakes within a watershed to the watershed runoff response. However, it was found that including LAF in the multiple linear regression analysis resulted in equations with a higher standard error than regression equations developed on drainage area only, and as such were excluded from any further analysis.

To facilitate the regression analyses, a Log_{10} transformation was applied to both sides of the regression equation. As such the statistical parameters of the regressions describe the log-transformed equations.

The resulting updated RFFA equations for the single variable regression analysis, including the Log_{10} transformed regression correlation coefficient (R^2) and standard error of the estimate (SEE) are summarized in Table 19.

TABLE 19
SINGLE VARIABLE RFFA FLOWS

AEP Event (Years)	Formula	R^2	SEE
2	$Q = 0.430 \times DA^{0.837}$	0.971	0.117
5	$Q = 0.562 \times DA^{0.851}$	0.967	0.124
10	$Q = 0.638 \times DA^{0.849}$	0.965	0.128
20	$Q = 0.703 \times DA^{0.847}$	0.963	0.132
50	$Q = 0.782 \times DA^{0.845}$	0.959	0.137
100	$Q = 0.838 \times DA^{0.845}$	0.957	0.141

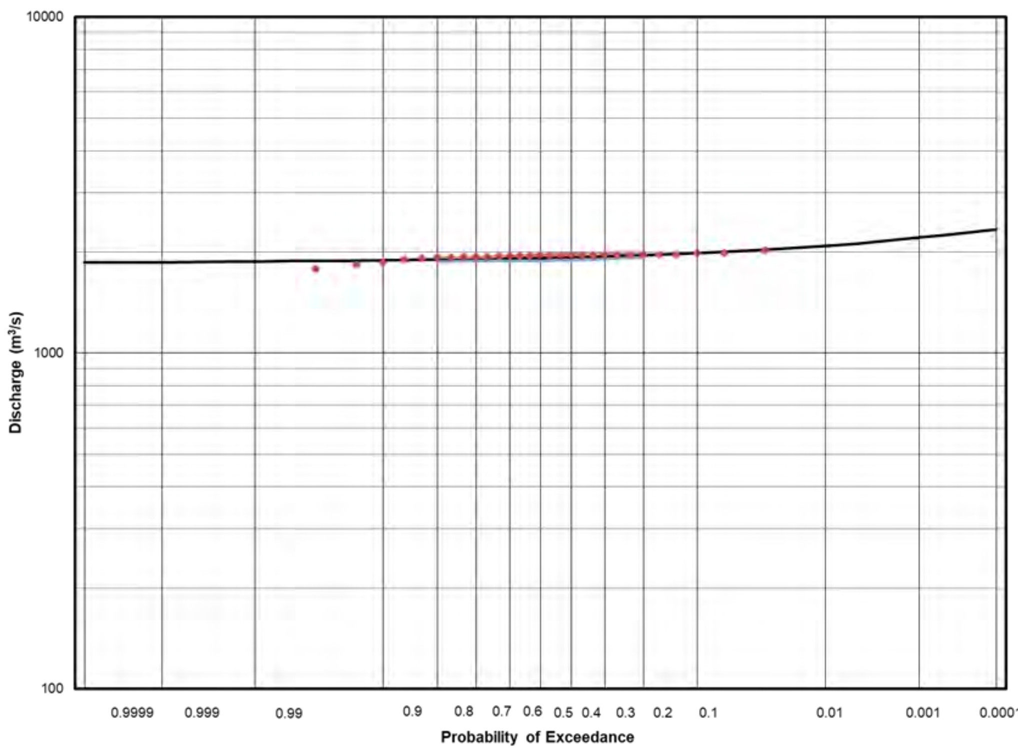
The above RFFA equations were applied to the Lower Churchill River to define the 20-year and 100-year AEP flows at Muskrat Falls. However, due to the effects of regulation associated with Churchill Falls, applying the RFFA equations to the full Churchill River watershed upstream of Muskrat Falls would not be appropriate. As such, the AEP flows at Muskrat Falls were calculated by combining the RFFA AEP flows for the Churchill River watershed between Churchill Falls and Muskrat Falls with AEP discharges from the Churchill Falls Generating Station.

A review of the plant discharges from Churchill Falls Generating Station showed that there was considerable variability in the annual peak discharges from the plant during the initial period of regulation from 1971 to 1981, with annual peak flows ranging from approximately 730 m^3/s to 3,770 m^3/s. This variability can be attributed to the filling of the large Smallwood reservoir, and the development and refinement of the operating rules for the plant. However, subsequent to 1981, the annual peak discharges from the plant were much more consistent, ranging from 1,780 m^3/s to 2,020 m^3/s. Accordingly, the AEP discharges from the Churchill Falls Generating Station were defined by carrying out a SSFA on the historical annual peak discharges from the Churchill Falls Generating Station that only considered the typical operations (i.e. 1982 – 2018) of the plant. The SSFA followed the same methodology outlined in Section 6.2.1, and a 3-Parameter Lognormal distribution was fit to the dataset. The AEP discharges from the Churchill Falls Generating Station are summarized in Table 20, and the frequency curve is shown on Figure 21.

TABLE 20
CHURCHILL FALLS GENERATING STATION AEP FLOWS

Return Period	Flow (m^3/s)
100	2,090
50	2,060
20	2,020
10	2,000
5	1,970
3	1,950
2	1,930

FIGURE 21
CHURCHILL FALLS FREQUENCY CURVE



The 20-year and 100-year AEP flows on the Churchill River at Muskrat Falls were calculated using the updated RFFA equations and the AEP discharges from Churchill Falls Generating Station as 5,456 m^3/s and 6,104 m^3/s, with 3,436 m^3/s and 4,014 m^3/s representing the local contribution from Churchill Falls to Muskrat Falls, and 2,020 m^3/s and 2,090 m^3/s representing the contribution from the Churchill Falls Generating Station. These flows closely match to the corresponding 20-year and 100-year AEP flow estimates defined by the SSFA method described in Section 6.2.1 of 5,920 m^3/s and 6,610 m^3/s.

The flow estimates defined by the SSFA method were considered more representative than those defined by the RFFA method since the SSFA was completed based on a continuous historical flow record immediately upstream of the area of interest. Furthermore, fewer assumptions were included in the SSFA than the RFFA, including the assumed flow contributions from the Churchill Falls Generating Station. Accordingly, the AEP flow estimates defined by the SSFA method were adopted for the subsequent analyses for this study, as described further in Section 6.6.

6.3 DETERMINISTIC ANALYSIS

6.3.1 Hydrologic Model Development

A hydrologic model was developed for the Churchill River from Churchill Falls to Lake Melville using the Hydrologic Engineering Centre's Hydrologic Modelling System (HEC-HMS) (U.S. Army Corps of Engineers, 2018). The Geospatial Hydrologic Modelling (HEC-GeoHMS) extension was not used to develop the HEC-HMS model since the extension was not available for Esri ArcMap 10.6 at the time of the model development.. HEC-HMS is a hydrologic model typically used for modelling rainfall and runoff using a variety of hydrologic methods, including surface storage and interception, infiltration, transform of excess precipitation, baseflow, routing, short and long radiation, evapotranspiration, and snowmelt.

While the initial intent for this study was to develop a hydrologic model of the full Churchill River watershed, modelling outflows from the Churchill Falls Generating Station was found to be not feasible, as operations of the station are driven by consumer demand rather than any set operating rules, and as such cannot be reliably predicted for a given set of hydrologic conditions.

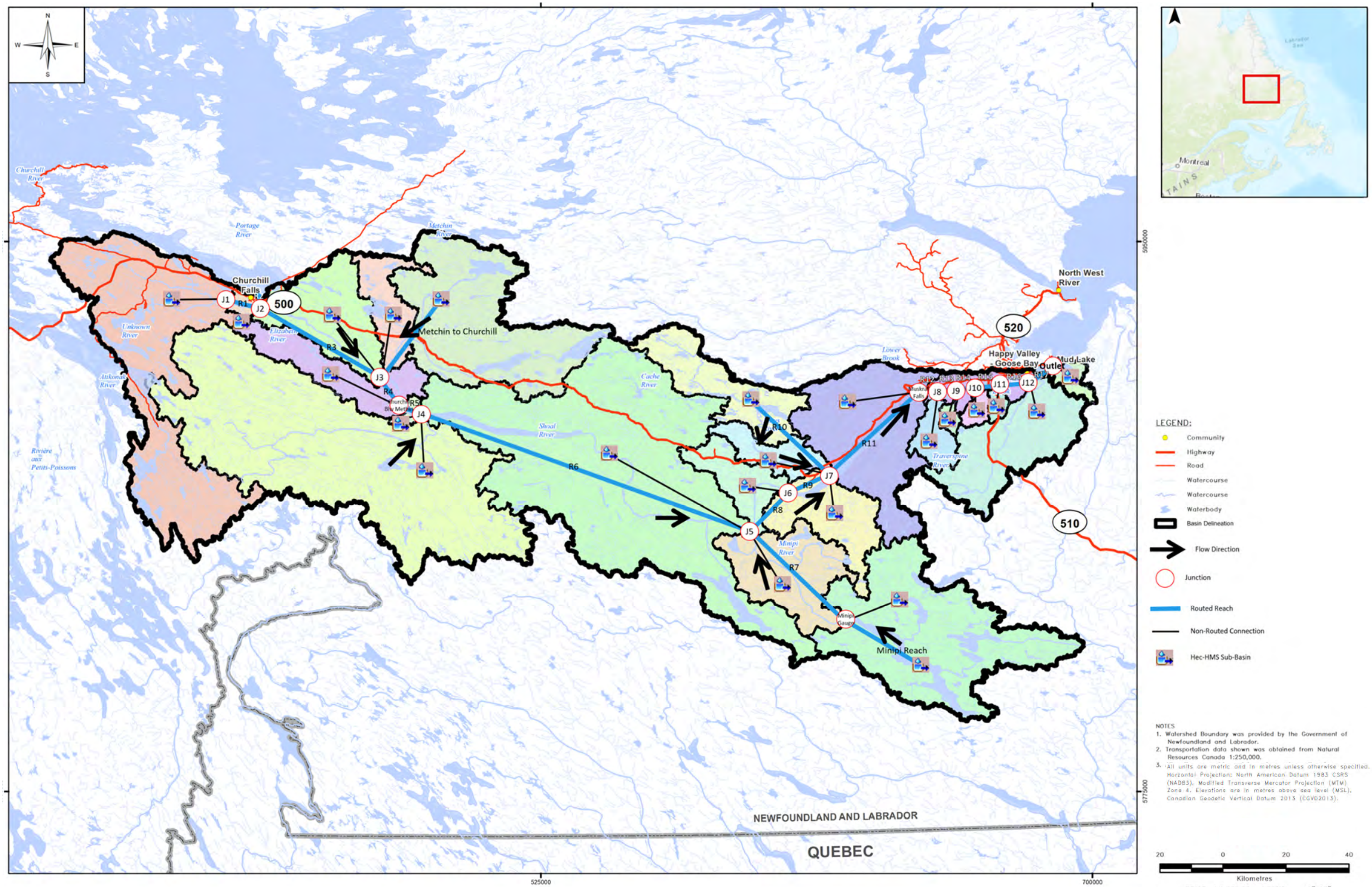
The HEC-HMS model was set up as a sub basin model. Sub-basins within the model were defined based on the watershed DEM, described in Section 4.3, using a combination of the Esri

ArcGIS and Green Kenue software packages. A total of 23 basins were delineated in the Lower Churchill River including four unregulated, gauged basins:

1. The Churchill River above Churchill Falls Tailrace (i.e. WSC Station 03OD008);
2. East Metchin River (i.e. WSC Station 03OD007);
3. Minipi River (i.e. WSC Station 03OE003);
4. The Pinus River (i.e. WSC Station 03OE011).

Additional sub-basins were defined for points of hydrologic interest, such as the area upstream of the WSC gauge on the Churchill River below Metchin (i.e. WSC Station 03OD009), as well as for the Fig River basin. Other delineated sub-basins included the ungauged downstream sections of each gauged river, the area upstream of the WSC gauge on the Churchill River at Muskrat Falls (i.e. WSC Station 03OE001), and major tributaries between Muskrat Falls and English Point. The delineated sub-basins, as well as the HEC-HMS representation of the Churchill River basin are shown on Figure 22.

FIGURE 22
CHURCHILL RIVER SUB-BASINS AND MODEL REPRESENTATION



Following the sub-basin delineation, terrain pre-processing was completed to fill surface depressions within the watershed DEM, define flow direction within the model using the '8-point method', and the generation of the stream network within the model. Physical characteristics of the watershed such as stream characteristics, curve numbers, and basin lag times were estimated from the watershed DEM and land cover classification maps described in Section 5.0. Other model parameters were estimated to define the initial parameterization of the HEC-HMS model, and were subsequently adjusted during the model calibration and validation process.

Various physical processes were included in the HEC-HMS model using standard hydrologic methods included in the modelling software. These processes, as well as the hydrologic method incorporated into the model to describe them, are summarized in Table 21.

TABLE 21
PHYSICAL PROCESSES REPRESENTED IN THE HEC-HMS MODEL

Physical Process	Modelling Method
Canopy Interception	Simple Canopy
Surface Depression Storage	Simple Surface
Infiltration	Green & Ampt
Transform	Clark Unit Hydrograph
Baseflow	Recession
Routing	Muskingum-Cunge
Snow Melt	Temperature Index
Evapotranspiration	Average Monthly

The above physical processes are represented in HEC-HMS via a multitude of model parameters. Some of these parameters are based on physical parameters (e.g. hydraulic conductivity), although many are numerical abstractions that cannot be physically estimated. Accordingly, while the documentation for HEC-HMS does provide suggestions for some parameters, generally the documentation only provides recommended upper bounds on the parameters during the model calibration optimization. These parameters are described in Table 22, as well as the minimum, maximum and recommended values for each parameter, where available.

TABLE 22
HEC-HMS MODEL PARAMETERS

Process	Parameter	Unit	Description	Minimum Value	Maximum Value	Recommended or Default Value
Sub-basin	Basin Area	km2	Sub-basin area	N/A	N/A	N/A
Canopy	Initial Storage	%	Percent of canopy storage that is full at simulation start	0	100	N/A
Canopy	Max Storage	mm	Maximum canopy storage prior to rain fall through	0	N/A	N/A
Canopy	Crop Coefficient	unitless	Ratio applied to potential evapotranspiration	0	1	N/A
Surface	Initial Storage	%	Percent of surface storage that is full at simulation start	0	100	N/A
Surface	Max Storage	mm	Maximum surface storage prior to runoff	0	N/A	N/A
Loss	Initial Content	unitless	Initial saturation of the soil at simulation start	0	1	N/A
Loss	Saturated Content	unitless	Maximum water holding capacity (i.e. porosity)	0	1	N/A
Loss	Suction	mm	Wetting front suction	0	1000	10.6 - 71.4
Loss	Conductivity	mm/hr	Soil hydraulic conductivity	0	250	0.06 - 21.00
Loss	Impervious	%	Percentage of the subbasin that is impervious	0	1	N/A
Transform	Time of Concentration	hr	Maximum travel time in a subbasin	0.1	500	N/A
Transform	Storage Coefficient	hr	Coefficient to represent storage effects	0	150	N/A
Baseflow	Initial Discharge	m3/s	Initial discharge at the start of the simulation	0	100000	N/A
Baseflow	Recession Constant	unitless	Rate at which baseflow recedes between storm events per day	0.000011	N/A	0.3 - 0.95
Baseflow	Flow	m3/s	Minimum baseflow	0	N/A	N/A
Routing	Length	m	Channel length	N/A	N/A	N/A
Routing	Slope	m/m	Channel slope	N/A	N/A	N/A
Routing	Manning's n	unitless	Channel roughness	0	1	N/A
Routing	Bottom Width	m	Channel bottom width	N/A	N/A	N/A
Routing	Side Slope	unitless	Channel side slope (ratio of X Horizontal to 1 Vertical)	N/A	N/A	N/A
Temperature Index	PX Temperature	C	Threshold for precipitation to fall as rain or snow	N/A	1	N/A
Temperature Index	Base Temperature	C	Used in combination with air temperature and meltrate to calculate snowmelt	N/A	N/A	N/A
Temperature Index	Wet Meltrate	mm / C Day	Multiplies the difference between air and base temperature to define snowmelt	N/A	N/A	0
Temperature Index	Rain Rate Limit	mm/day	Value to discriminate between wet and dry melt	N/A	N/A	0
Temperature Index	ATI Meltrate Coefficient	unitless	Coefficient to update the meltrate index per timestep	N/A	N/A	0.98
Temperature Index	Cold Limit	mm/day	Threshold for rapid snowpack temperature changes due to high precipitation	N/A	N/A	0
Temperature Index	ATI Coldrate Coefficient	unitless	Coefficient to update the cold content index per timestep	N/A	N/A	0.5
Temperature Index	Water Capacity	%	Amount of melted water that must accumulate in the snowpack prior to infiltration or runoff	N/A	N/A	3 - 5%
Temperature Index	Groundmelt	mm/day	Snowmelt due to partially or unfrozen ground	N/A	N/A	N/A
MeltRates	Table	mm / C Day	User-defined meltrate as a function of antecedent temperature index	N/A	N/A	1 - 4 mm/C day
ColdRates	Table	mm / C Day	User-defined coldrate as a function of antecedent temperature index	N/A	N/A	1.22 - 1.32 mm / C day

Initial parameters for many of the physical processes included in the HEC-HMS model were based on recommended values, where available, and were subsequently adjusted as part of the model calibration process. These physical processes included the canopy interception, surface depression storage, infiltration, transform, baseflow and snowmelt. Parameters for the routing and evapotranspiration processes were estimated based on available topographic and hydrometric data.

The slope, flow length, and channel width parameters for the Muskingum-Cunge routing method were estimated from the DEM. The Churchill River channel shape was approximated as trapezoidal and Manning's n values were considered as calibration parameters.

Average monthly evapotranspiration applies a constant magnitude of evapotranspiration to a basin within each month. Monthly evapotranspiration rates were estimated by subtracting the total rainfall that occurred during that month from the total precipitation that fell during that month. The total precipitation was estimated using the available rainfall data, and the runoff was estimated using observed flow records at gauged locations. Groundwater was assumed to not make a significant contribution to observed flow records.

Initially, infiltration in the HEC-HMS model was modelled using the SCS Curve Number method, but this method was found to poorly represent the soil conditions in the study area and resulted in unrealistic model parameters for several physical processes to compensate for the poor performance of the SCS Curve Number method. Instead, the Green & Ampt method was adopted to represent infiltration processes, which led to a considerable improvement in the HEC-HMS model performance and realistic calibrated model parameters for the various physical processes included in the model. The Green & Ampt method infiltrates precipitation based on a simplified version of the actual soil moisture profile, as defined in Mein and Larson (1973):

$$f(t) = K_s + K_S \frac{|\Psi_f|(\theta_s - \theta_i)}{F} \qquad \text{(Eq. 1)}$$

Where f(t) represents the infiltration rate, K_s is the hydraulic conductivity, Ψ_f is the depth of the soil wetting front, θ is the moisture content for the initial (i) and saturated (s) states, and F is the cumulative infiltrated water.

Initial infiltration parameters, including the hydraulic conductivity, depth of the soil wetting front, and initial and saturated moisture contents were estimated based on standard values, and were adjusted as part of the calibration process.

As previously noted, the HEC-HMS model was set up as a sub basin model. Sub basin models require meteorological inputs from point locations, which are used to drive runoff responses. Precipitation time series were defined by spatially averaging precipitation data from the Canadian Precipitation Analysis (CaPA) product within grid points defined for each sub basin.

CaPA data is a combination interpolation and reanalysis product which incorporates a large number of data sources, including ground-based climate station data, radar, satellite and others to estimate precipitation occurrence, magnitude, and spatial positioning over Canada as a 10 km gridded product. CaPA data is used as an alternative to spatially interpolating ground-based climate station data from nearby climate stations. Data sparsity and paucity in the Lower Churchill River watershed would introduce considerable uncertainty into any interpolation method. Furthermore, Environment Canada gauge data suffers from well documented systematic biases including wind driven undercatch (most significant in determining solid precipitation quantity), wetting loss, evaporation, and trace precipitation loss. Environment Canada offers an alternative data product with adjustments for the systematic biases present in the ECCC data product in the form of the Adjusted and Homogenized Climate Change Data (AHCCD). AHCCD does not address the sparsity and paucity issues and does not have sufficient temporal extent to be a relevant alternative. The CaPA data was expected to offer notable improvements over other currently available products, but is still a source of considerable uncertainty for the HEC-HMS model. Some of the uncertainty associated with the CaPA data can be reduced when large spatial averages are considered, and therefore, ten spatially averaged daily precipitation time series were created, with smaller sub basins being grouped with larger ones.

CaPA data only includes precipitation data, and therefore an alternative data source was required to define temperature inputs into the model. Temperatures were generated based on an inverse distance weighting (IDW) interpolation of ECCC ground based climate station data. Temperatures vary less spatially than precipitation, and as such using a station interpolated product is more acceptable than for precipitation. The interpolation was completed to generate temperature inputs for the locations as the precipitation input data. Temperature data is used by the temperature index snow melt model of HEC-HMS to determine if precipitation occurred in solid or liquid form and for determining spring melt rates.

Flows on the Churchill River are subject to significant regulation from the Churchill Falls Generating Station. Historical discharges from Churchill Falls were incorporated into the HEC-HMS model as an inflow source.

6.3.2 Hydrologic Model Calibration and Validation

The HEC-HMS model was calibrated to the 2011-2015 period and validated to the 2016-2018 period. While the simulation of 2010 was included in the model, the simulation of that year was used to define the initial soil moisture conditions in the model domain, since the model starts from a uniformly dry state. The choice to build the model as a continuous model rather than an event model was made to improve the quality of the forecasting product. However, an additional benefit of a continuous calibration is an expected improvement in the estimation of 1:20 and 1:100 year responses. Automatic calibration was completed using a Dynamically Dimensioned Search (DDS) algorithm with over 50,000 total optimization runs to achieve an acceptable representation of the observed historical conditions. The automated calibration process was supervised to ensure that the calibrated parameters defined by the optimization algorithm were within standard accepted ranges. A comparison of the observed and simulated flows at Muskrat Falls is shown on Figure 23, and is also shown schematically on Figure 24.

FIGURE 23
COMPARISON OF OBSERVED AND SIMULATED MUSKRAT FALLS FLOWS

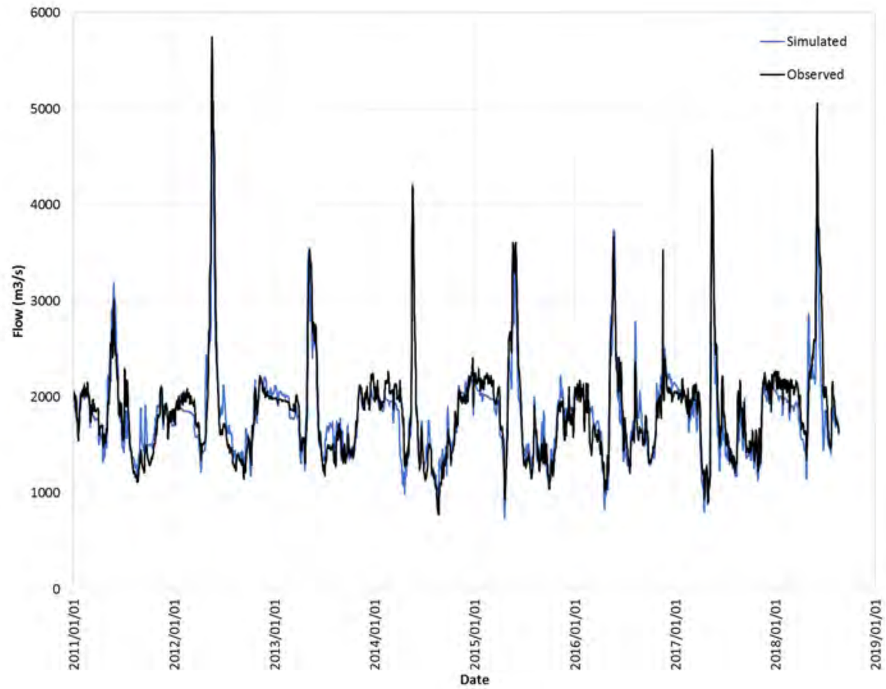
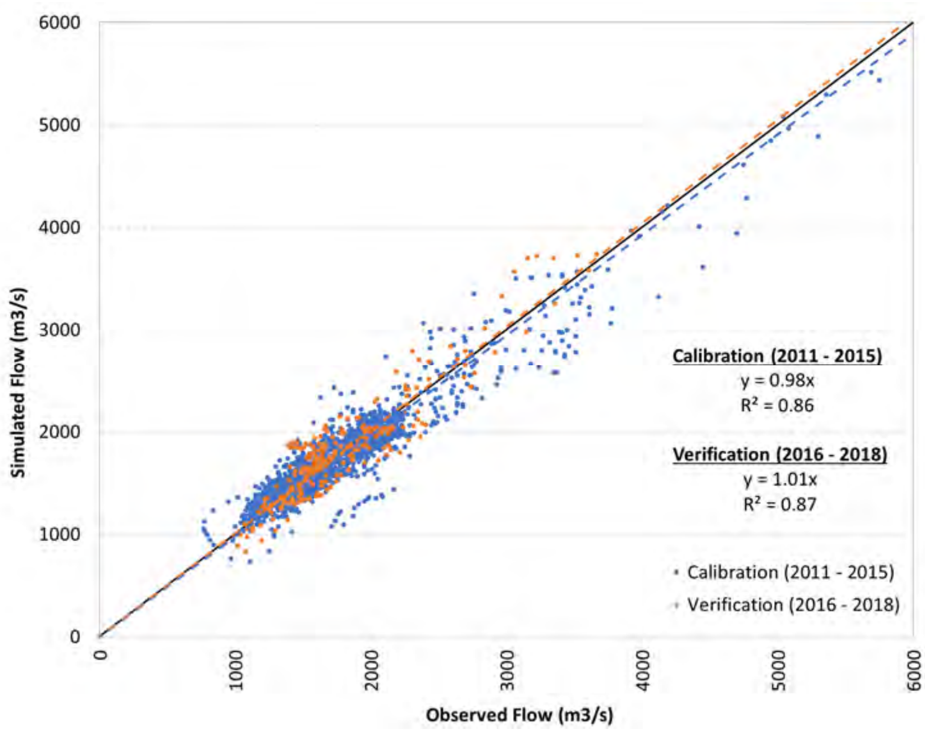


FIGURE 24
HYDROLOGIC MODEL PERFORMANCE



The final calibration was able to accurately represent the complex physical processes occurring in the Lower Churchill River watershed. The model performance shown on Figure 24 shows an R^2 value of 0.86 for the calibration period and an R^2 value of 0.87 for the validation period, and a slope of nearly 1 for both calibration and validation, which suggested the model has no bias towards under - or over-estimating rainfall-runoff responses over the simulated 2011-2018 period. Typically, annual peak flows occur in spring, with only the 2018 snow melt peak occurring later on June 3rd. Over the 8 year simulation period, the average difference between the simulated and observed peak flow was 0.19% with an average difference in peak timing of 0.5 days.

Calibrated parameters were generally within or close to suggested parameter ranges for the selected methods. Infiltration parameters were estimated through calibration as soil information was limited. Calibrated times of concentration were similar to those estimated from the DEM and land class maps, and the storage time was calibrated over a larger range to account for small lakes in each sub basin since no information on the lakes was available.

Overall, the calibration Nash Sutcliffe Efficiency (NSE) score at the Muskrat Falls location was 0.88 and the validation NSE was 0.81 NSE, both are within the literature suggested range of 0.7-0.9 suggesting the model was high performing.

A schematic representation of the HEC-HMS model, including key parameters for the various physical processes, is included in Appendix G.

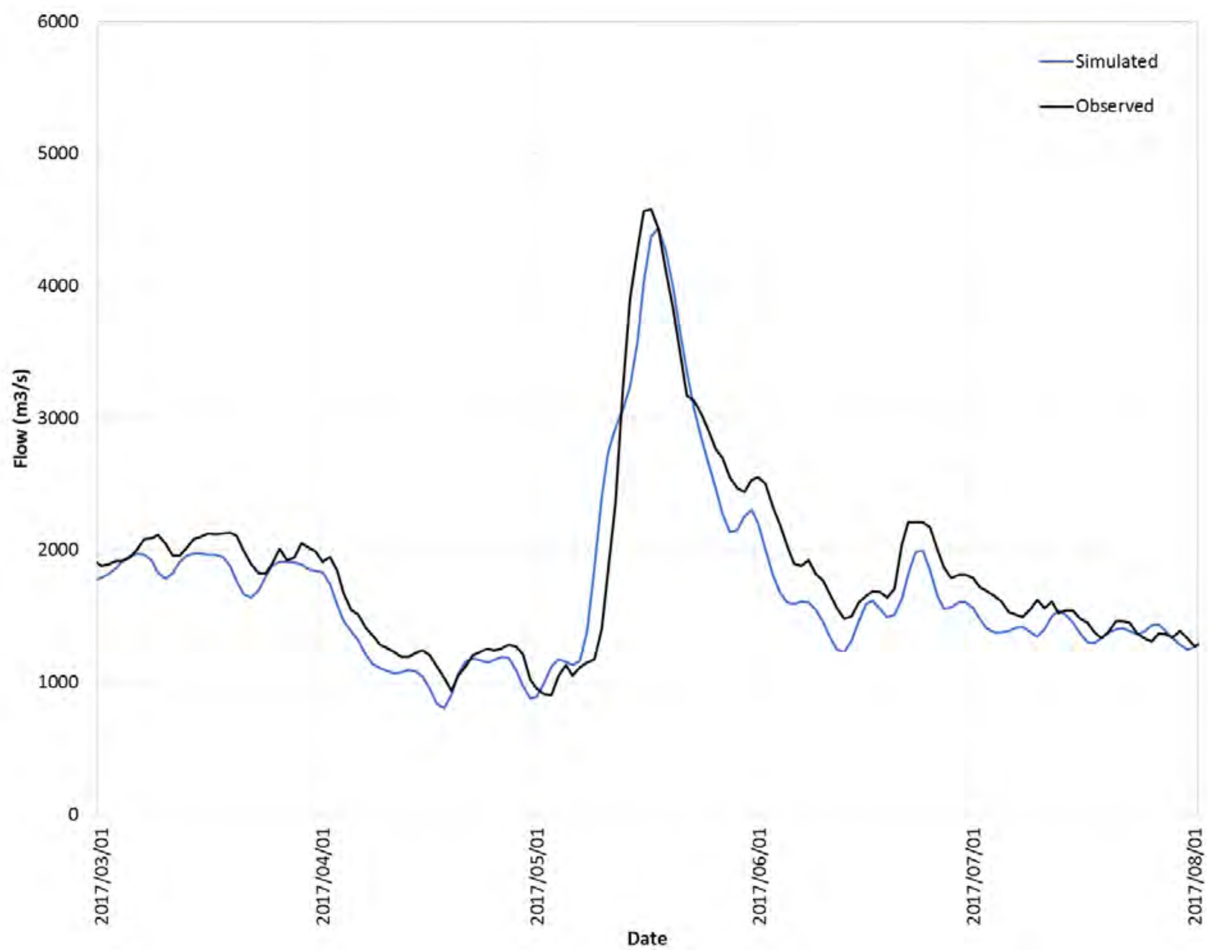
6.3.3 Simulation of The 2017 Flood

The spring 2017 flood was included in the model validation, and given the severity of the flood, the results of the model simulation of that flood were reviewed with a higher degree of scrutiny. In general, the HEC-HMS model was found to accurately represent the 2017 spring flood event. The model representation of the Churchill River flows leading up to, during, and subsequent to the flood were in very good agreement with flows recorded by WSC at Muskrat Falls. The model very accurately represented the shape of the hydrograph (i.e. increases or decreases in flows), and also very accurately represented the timing of any flow changes, typically within 1 to 2 days. As well, and more crucially, the model accurately represented the peak recorded flow on the

Churchill River, with a difference between the simulated and observed peak flow of only 3%. This value is considered to be very accurate for a hydrologic model and is well within the accuracy of flow measurements, which is typically between 5% and 10%. As well, the simulated timing of the peak flow occurred within 1 day of the recorded peak flow, which is considered to be highly accurate.

A comparison of the simulated and observed flows at Muskrat Falls for the 2017 spring flood is shown on Figure 25.

FIGURE 25
MODEL REPRESENTATION OF THE SPRING 2017 FLOOD



In addition to the model representation of flows recorded by WSC on the Churchill River at English Point, the model was also found to be in good agreement with the observed hydrologic and meteorological conditions that preceded the spring 2017 flood documented in KGS Group's report "*Independent Review of the May 17th, 2017 Churchill River Flood Event*" (KGS Group, 2017). In particular:

- The model showed an average or below-average snow water equivalent (SWE) throughout the model domain. This is in good agreement with the snow depth measurements reviewed in the 2017 report.
- The simulated flows on the Churchill River were higher than normal during the 2016 freeze up and 2016 – 2017 winter, and lower than normal during the 2017 early spring.
- The simulated SWE melted far faster during spring 2017 than for other years included in the simulation. This again is in good agreement with the abrupt snowmelt documented in the 2017 report.

Given the accurate model depiction of the hydrograph shape, timing, and peak flow, as well as the good agreement between the model and the key meteorological and hydrologic conditions documented in the 2017 report, the model was found to accurately depict the spring 2017 flood on the Churchill River.

6.4 Precipitation Analysis

6.4.1 Existing Conditions IDF Curves

An update was completed for several IDF curves for inclusion in the hydrologic model to define flow rates on the Churchill River and small creeks within the study area for the 20 and 100-year return period rainfall events. At the onset of this study, it was envisioned that the full Churchill River watershed would be included in the HEC-HMS model, and as such the IDF curves for four representative climate stations within or near the Churchill River watershed were updated, including:

- Churchill Falls A (ECCC Station 8501132);
- Goose A (ECCC Station 8501900);
- Wabush Lake A (ECCC Station 8504175);
- Schefferville A (ECCC Station 7117825).

However, as previously described in Section 6.3.1, it was not feasible to include the area upstream of Churchill Falls in the hydrologic model, and as such the updated IDF curves for Wabush Lake A and Schefferville were not considered in the subsequent hydrologic routing of the 20 and 100-year rainfall events.

Precipitation records were reviewed for each of the four ECCC stations. The status of each station, as well as the data available for each station are summarized in Table 23.

TABLE 23
IDF PRECIPITATION STATIONS

Station	Status	Period of Record	
		All Durations	6 hr, 12 hr, 24 hr Durations
Churchill Falls A	Active	1961 – 2013	
Goose A	Inactive	1969 – 1992	1994 – 2013
Wabush Lake A	Inactive	1974 – 2002	2003 – 2012
Schefferville A	Inactive	1965 - 1992	

The annual maximum precipitation values for the 5 minute, 10 minute, 15 minute, 30 minute, 1 hour, 2 hour, 6 hour, 12 hour and 24 hour periods for each station are included in Appendix H.

Frequency curves were computed for the observed peak precipitation for durations of 5, 10, 15, 30 minutes, and for 1, 2, 6, 12 and 24 hours. The frequency curves were computed using the HYFRAN software program and were fitted using the Gumbel distribution with the method of moments. This method follows procedures documented in the 2015 update Report on the IDF curves for the Province of Newfoundland and Labrador by Conestoga-Rovers and Associates.

The updated IDF curves for Goose Bay, Churchill Falls, Wabush A and Schefferville A are shown on Figure 26 to Figure 29, and are included in a tabular format in Appendix I.

FIGURE 26
GOOSE BAY UPDATED IDF CURVE

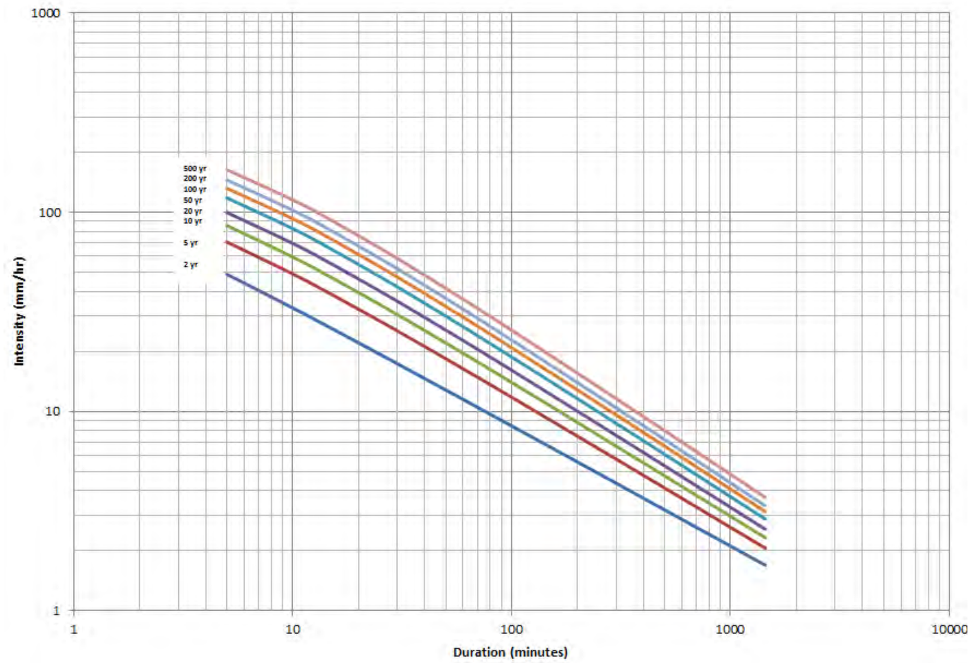


FIGURE 27
WABUSH A UPDATED IDF CURVE

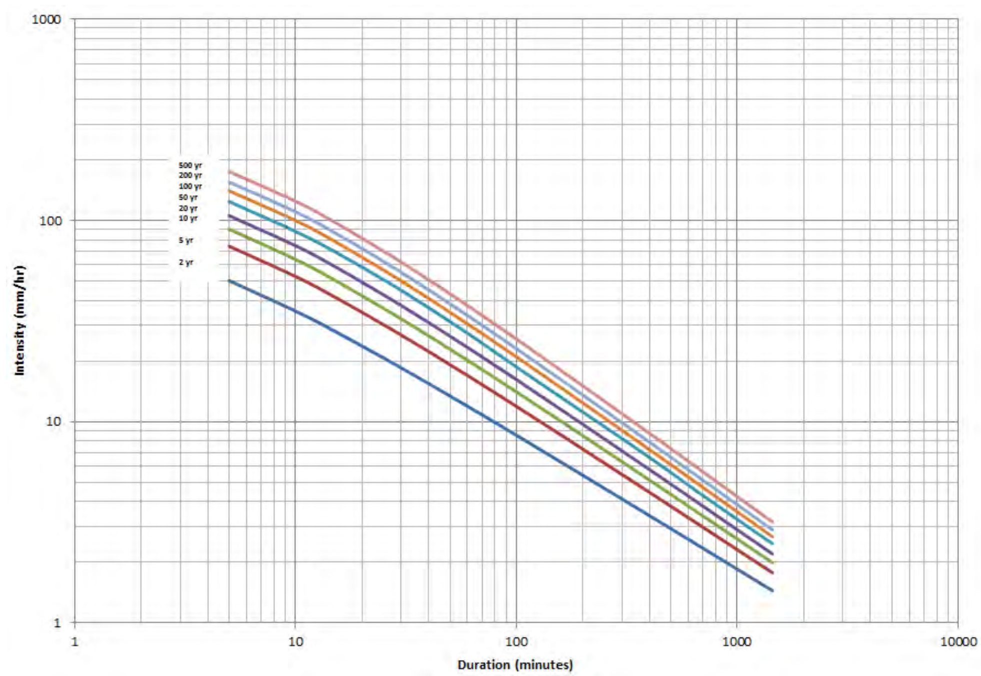


FIGURE 28
CHURCHILL FALLS A UPDATED IDF CURVE

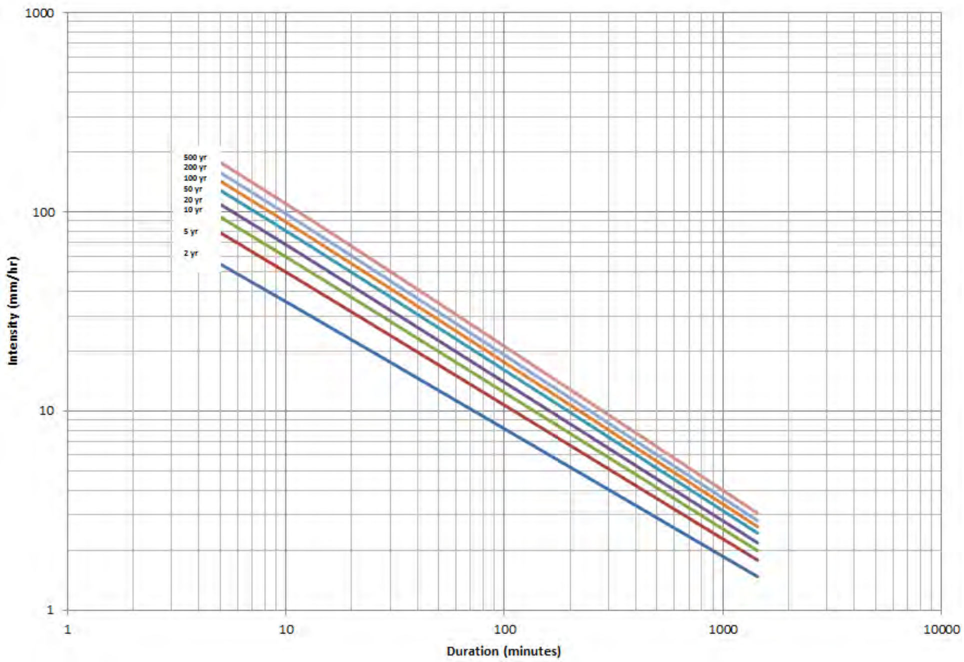
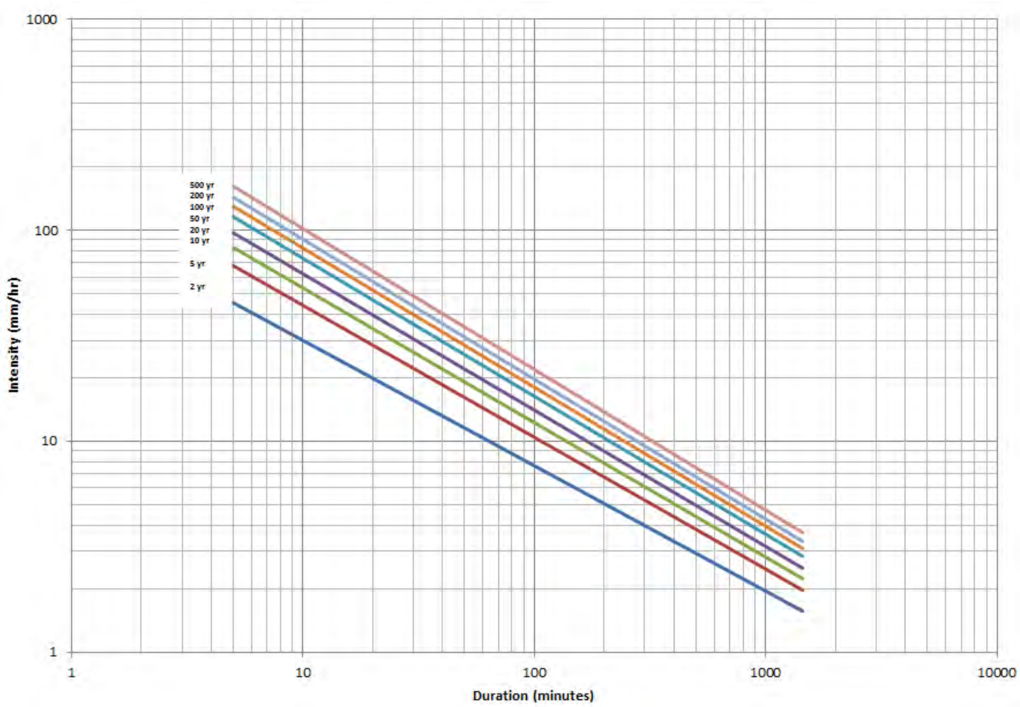


FIGURE 29
SCHEFFERVILLE A UPDATED IDF CURVE



6.4.2 Climate Change IDF Curves

Future climate change due to increase carbon dioxide emissions is expected to increase global temperatures and result in increased precipitation. For this study, the Representation Concentration Pathway 8.5 or RCP 8.5 scenario was adopted to assess the impacts associated with climate change. This RCP provides a future concentration scenario that would lead to the most severe climate change impact compared to the other RCP's. Based on this scenario, a set of climate change IDF curves were developed based on the 2018 Update Report of the Projected Impacts of Climate Change for the Province of Newfoundland and Labrador.

Anticipated median precipitation depths for RCP 8.5 were estimated for the 5, 10, 15, 30 minutes, and for 1, 2, 6, 12 and 24 hour durations as part of the 2018 Update Report. The corresponding rainfall intensity for each duration was calculated and then an IDF curve was fit to each return rainfall event. This step was completed to ensure that each of the curves were smooth and followed a similar trend. The climate change IDF curves for Goose Bay, Churchill Falls, Wabush A and Schefferville A are shown on Figure 30 to Figure 33, and are included in a tabular format in Appendix J.

FIGURE 30
GOOSE BAY A CLIMATE CHANGE IDF CURVE

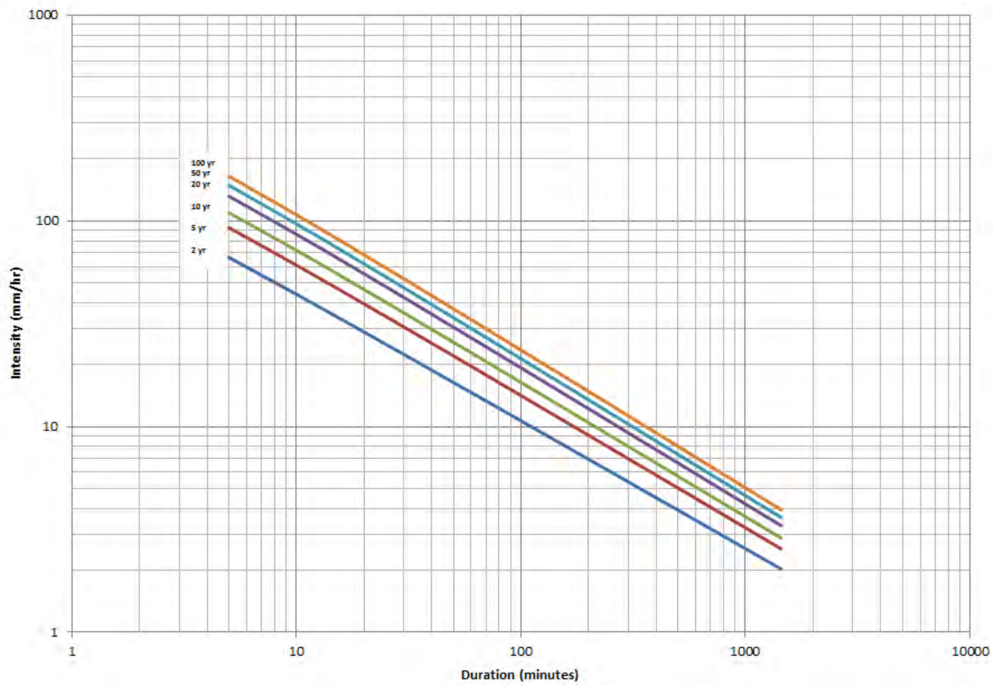


FIGURE 31
CHURCHILL FALLS A CLIMATE CHANGE IDF CURVE

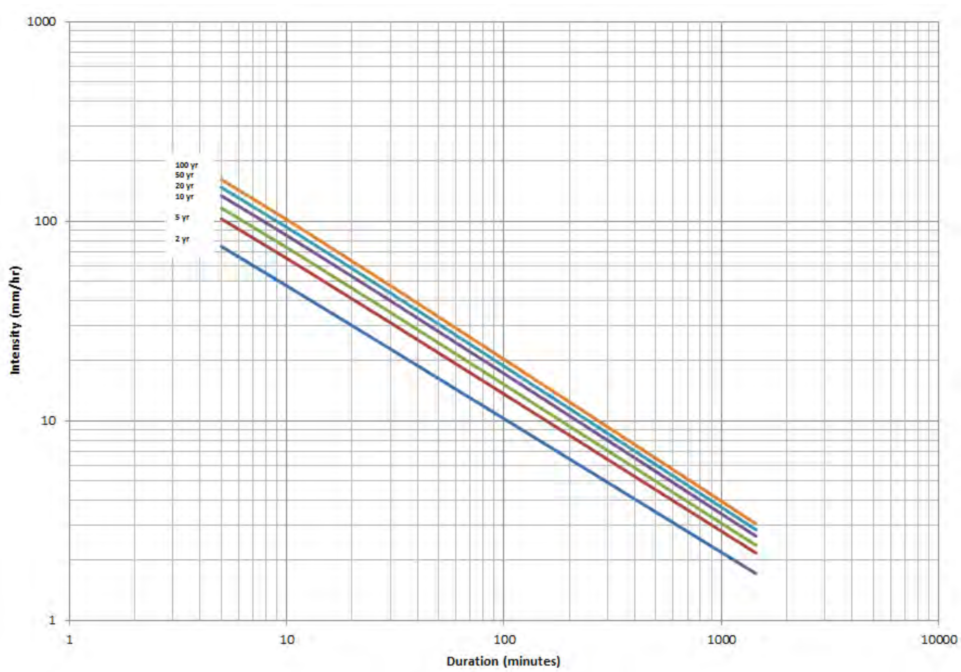


FIGURE 32
WABUSH LAKE A CLIMATE CHANGE IDF CURVE

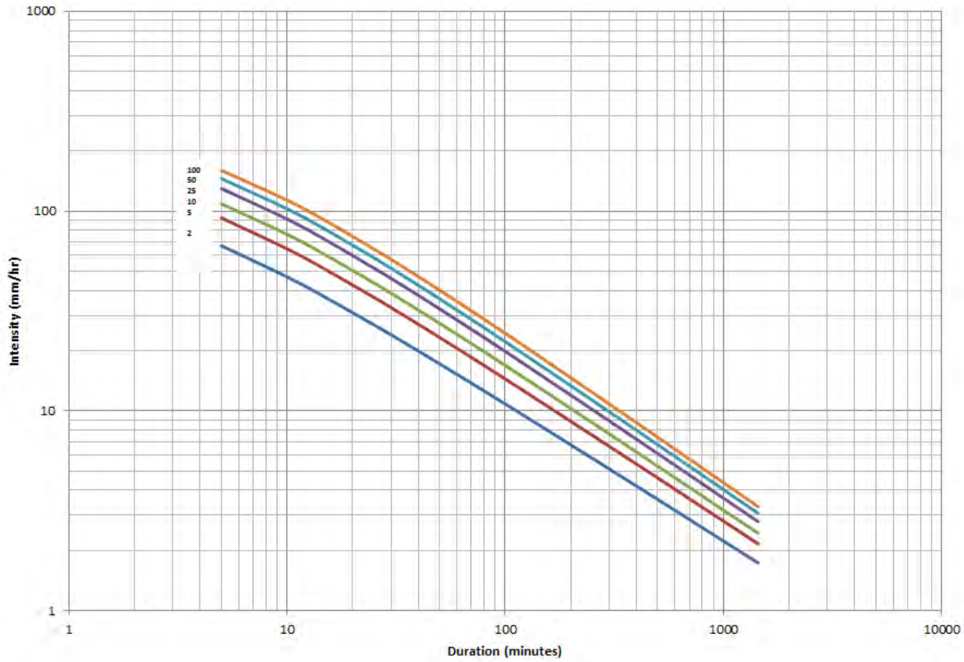
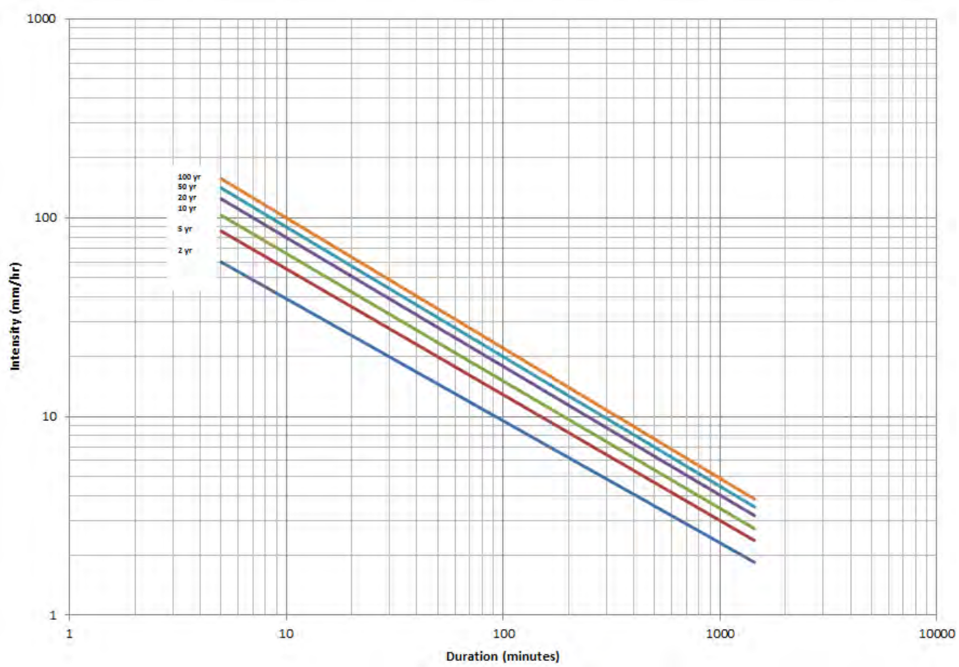


FIGURE 33
SCHEFFERVILLE A CLIMATE CHANGE IDF CURVE



6.5 HYDROLOGIC ROUTING OF THE 1:20 AND 1:100 AEP RAINFALL EVENTS

Based on the precipitation analysis described in Section 6.4, synthetic hyetographs were developed representing the 20 and 100-year design storms at the Goose A and Churchill Falls A stations. The synthetic hyetographs were defined using the alternating block method, which considers accumulated precipitation from various durations of the same return period storm to define the rainfall for any given point of the storm, with the highest intensity occurring at the mid-point of the storm. Storm durations of 1, 2, 6, 12 and 24 hours were used for the alternating block method. The design hyetographs for Goose A and Churchill Falls A are shown on Figure 34 and Figure 35.

FIGURE 34
GOOSE A RAINFALL HYETOGRAPHS

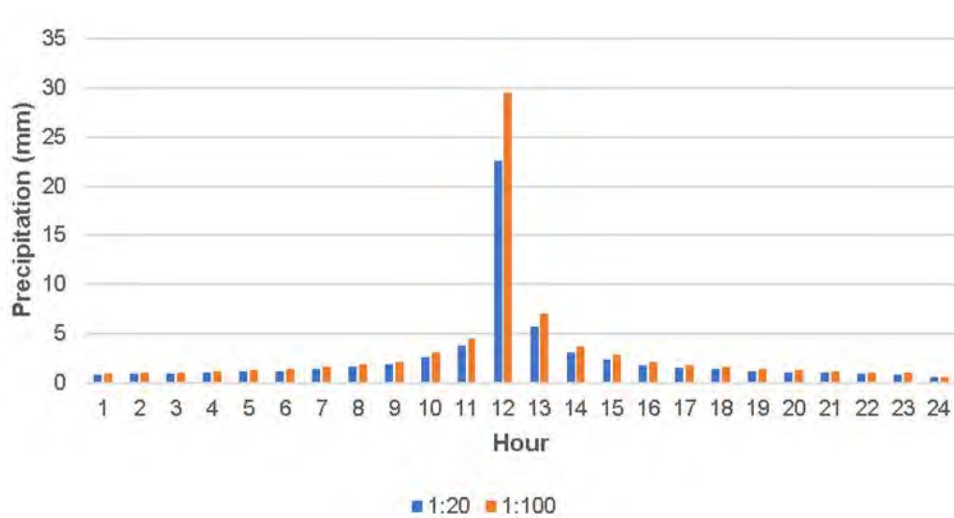
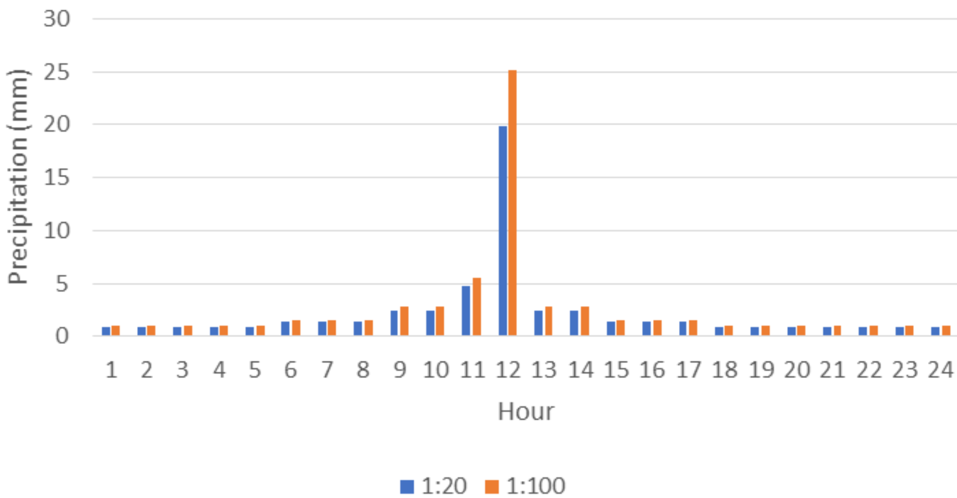
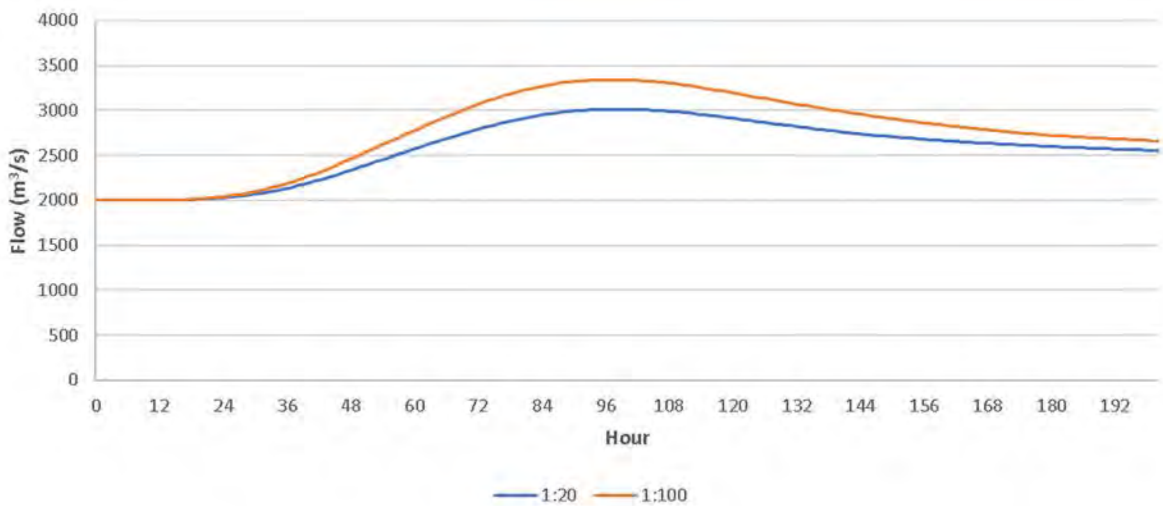


FIGURE 35
CHURCHILL FALLS A RAINFALL HYETOGRAPHS



The 20 and 100-year rainfall events were incorporated into the HEC-HMS model using an inverse distance-weighted interpolation scheme to define the rainfall for each sub-basin in the model. Accordingly, it was assumed that the 20 and 100-year rainfall events would occur concurrently in each of the sub-basins with a continuous inflow from the Churchill Falls Generating Station of 2,000 m^3/s, which approximately corresponds to the 20 and 100-year discharges from the station. Furthermore, evapotranspiration was assumed to be negligible for the 20 and 100-year rainfall events. Initial moisture conditions in the sub-basins were defined based on the typical summer wet soil moisture conditions from the model calibration. The resulting hydrographs at Muskrat Falls corresponding to the 20 and 100-year rainfall events are shown on Figure 36.

FIGURE 36
ROUTED 20 AND 100-YEAR RAINFALL EVENTS AT MUSKRAT FALLS



The routed 20 and 100-year rainfall events resulted in peak discharges of 3,015 m^3/s and 3,340 m^3/s at Muskrat Falls, which approximately correspond to a 2-year flow on the Churchill River. The Churchill River flows associated with the 20 and 100-year rainfall events were anticipated to be relatively minor compared to typical spring freshet flows, given that high flows on the Churchill River are strongly associated with snow melt rather than rainfall.

6.6 ADOPTED 20 AND 100-YEAR FLOWS

A comparison of the estimated 20 and 100-year flows on the Churchill River based on the SSFA, RFFA and deterministic analysis shows that the hydrological routing of the 20 and 100-year rainfall events considerably underestimates the 20 and 100-year flows on the river. The underestimation of the deterministic analysis is due to snow melt being the primary driver of high flows on the lower Churchill River, rather than rainfall. Accordingly, the 20 and 100-year flows estimated by the deterministic analysis were considered to be not representative of a true 20 and 100-year flow on the Churchill River, and were not considered for inclusion in the subsequent hydraulic modelling and flood risk mapping.

While the RFFA and SSFA resulted in similar estimates of the 20 and 100-year flows, the flow estimates based on the SSFA were considered more representative than those estimated based on the RFFA given that the SSFA was completed based on a continuous historical flow record immediately upstream of the area of interest. As well, the SSFA included fewer assumptions than the RFFA, including the assumed flow contributions from the Churchill Falls Generating Station. While regulation of the Churchill Falls Generating Station could not be corrected for in the SSFA, it is anticipated that the Churchill Falls Generating Station will continue to operate for the foreseeable future following the same operational procedures, and as such the estimated frequency flows should be applicable for as long as the station is in operation. Lastly, the frequency flows defined based on the SSFA were higher, and thus more conservative than those defined based on the RFFA. Accordingly, the 20 and 100-year flows based on the SSFA were adopted for inclusion in the hydraulic modelling and flood risk mapping, as shown in Table 24.

TABLE 24
ADOPTED 20 AND 100-YEAR FLOWS

Return Period	Flow at Muskrat Falls (m^3/s)
100-Year	6,610
20-Year	5,920

7.0 HYDROLOGIC MODELLING OF THE OTTER CREEK AND LOCAL CREEKS

7.1 OVERVIEW

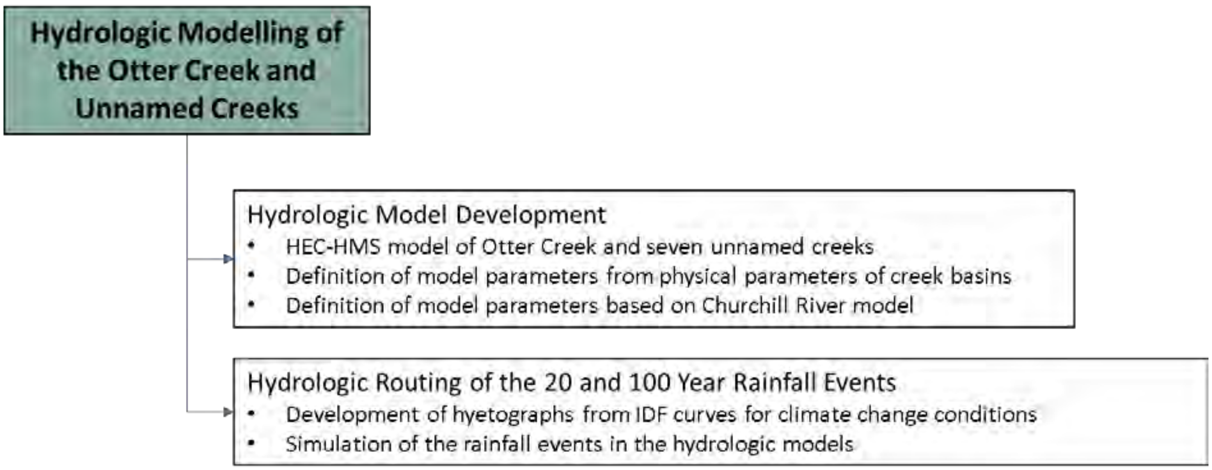
Hydrological models were developed of Otter Creek and seven unnamed creeks in Happy Valley – Goose Bay to convert the 1:20 and 1:100 AEP rainfall events into flows on those creeks for both current climate and climate change conditions. The model representations of the creeks and their drainage area were developed using the LiDAR data that was collected as part of this project.

Since recorded flows are not available on these creeks, some of the model parameters were set based on the physical characteristics of each creek, while other parameters were set to match those from the calibrated Churchill River model, where recorded flow information was available to better define the parameters.

Once the models were developed, they were used to define the flow on each of the creeks by simulating the 1:20 and 1:100 year AEP rainfall events in Happy Valley – Goose Bay for both current climate and climate change conditions. The flows resulting from these simulations were used in hydraulic models to define water levels on the creeks, which were then used to develop flood risk maps on the creeks.

The tasks completed as part of the hydrologic modelling of Otter Creek and the seven unnamed creeks is shown on Figure 37.

FIGURE 37
OVERVIEW OF THE HYDROLOGIC MODELLING OF OTTER CREEK AND UNNAMED CREEKS



7.2 HYDROLOGIC MODEL DEVELOPMENT

The RFFA method used to define the flood flows on the Churchill River is not appropriate to define the flood flows on Otter Creek and the seven unnamed creeks due to the considerably smaller drainage area associated with each creek than the range of drainage areas included in the RFFA assessment. Similarly, there are no nearby appropriate gauged rivers with comparably small drainage areas to consider using as an index station for a SSFA. Rather, flows on Otter Creek and the seven unnamed creeks were defined using HEC-HMS models of each creek, and simulating the 1:20 and 1:100 year AEP rainfall events in Happy Valley – Goose Bay.

Similar to the hydrologic model developed for the Churchill River, the hydrologic models of Otter Creek and the seven unnamed creeks were developed using HEC-HMS and the HEC-GeoHMS extension. The HEC-HMS models was set up as sub basin models. Sub-basins within the model were defined based on the LiDAR data collected as part of this study. The sub-basins were initially defined using Esri ArcGIS and were adjusted as required to account for the local ditches and culverts located within the basins. The number of sub-basins included in each hydrologic model is summarized in Table 25, and the basins and sub-basins of each model are shown on Figure 38 and Figure 39.

TABLE 25
SUB-BASINS INCLUDED IN HYDROLOGIC MODELS

Creek	Number of Sub-Basins
Otter Creek	5
Local Creek 1	1
Local Creek 2	1
Local Creek 3	3
Local Creek 4	3
Local Creek 5	3
Local Creek 6	8
Local Creek 7	3

FIGURE 38
OTTER CREEK AND LOCAL CREEKS 1 TO 3

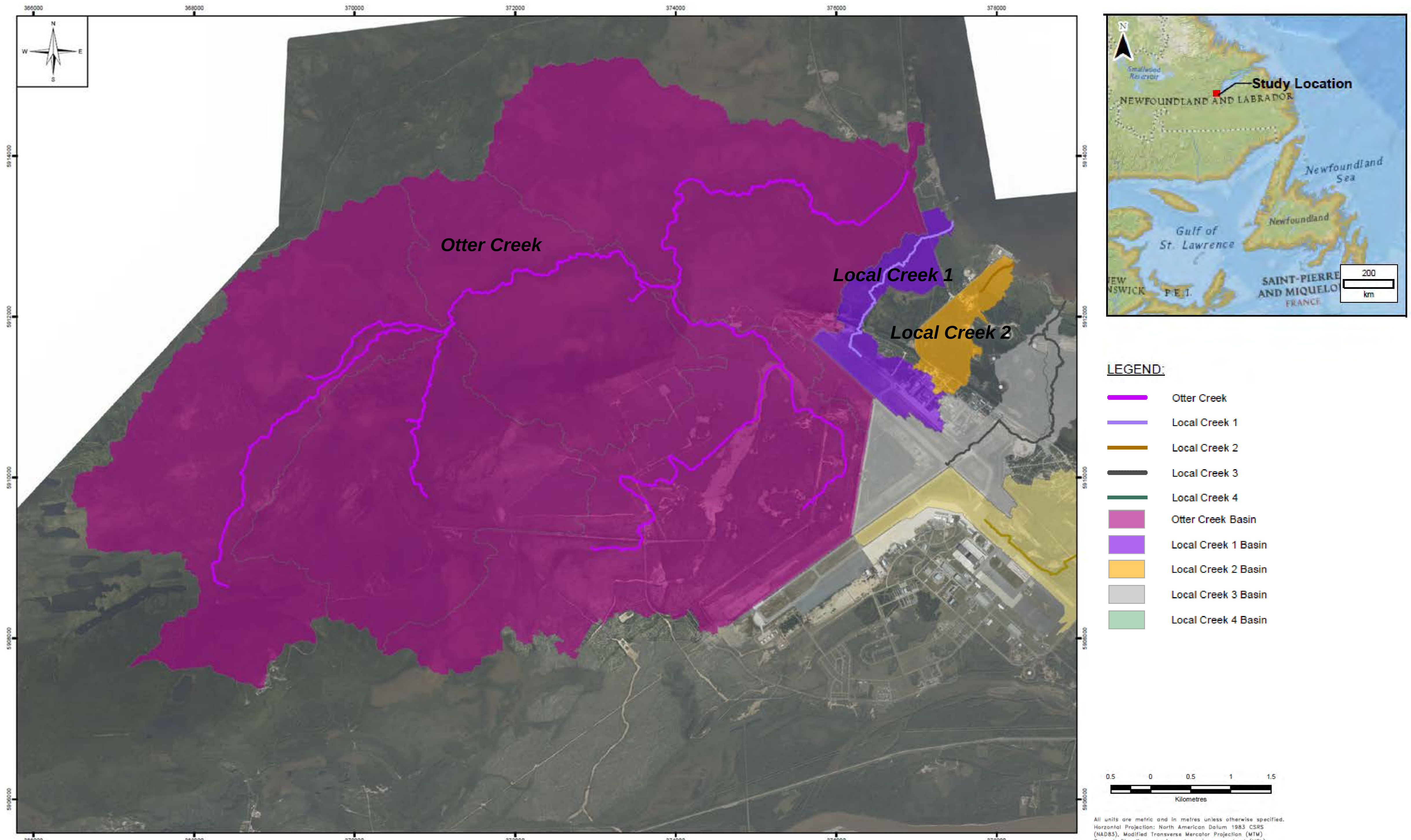
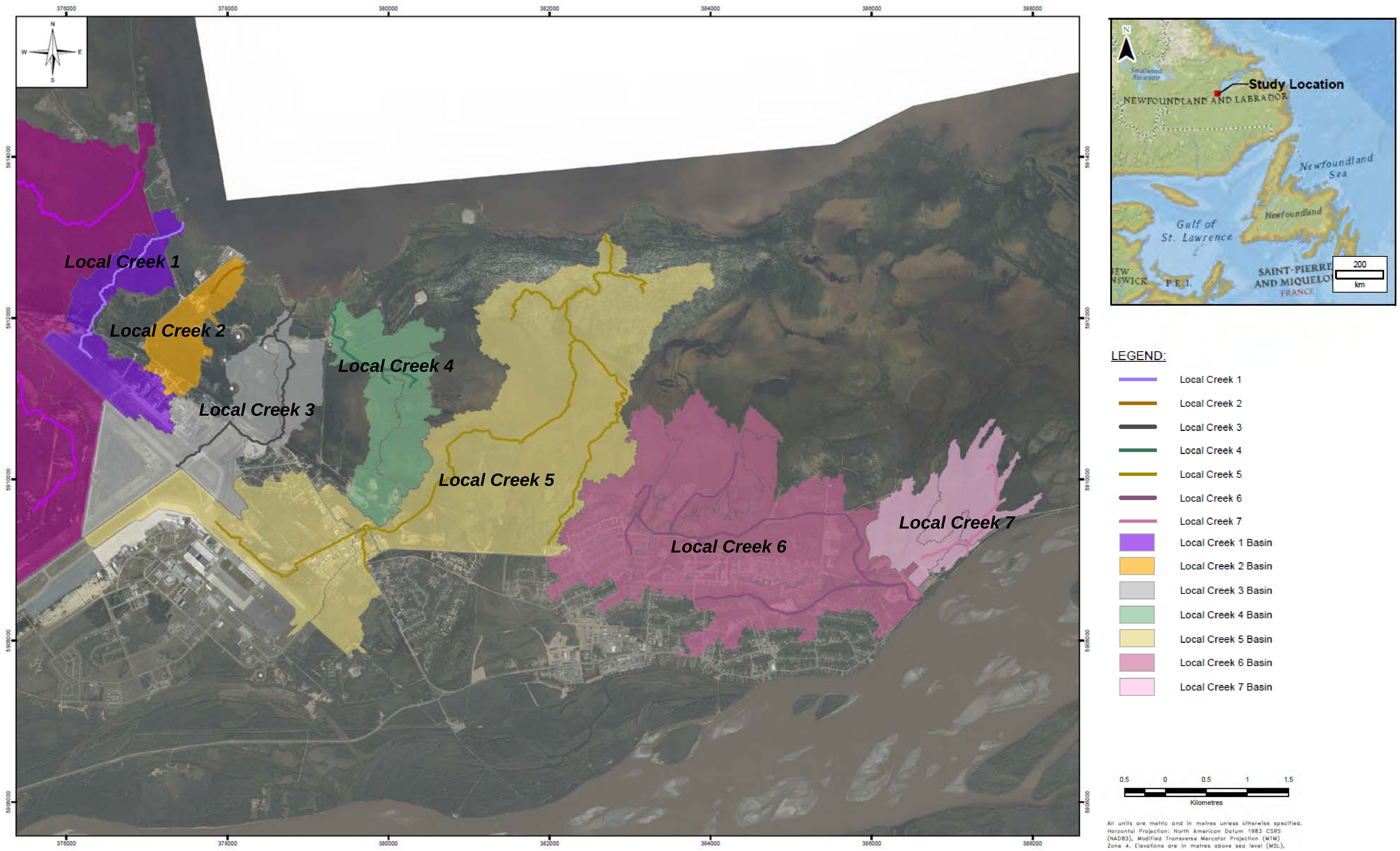


FIGURE 39
LOCAL CREEKS 4 TO 7



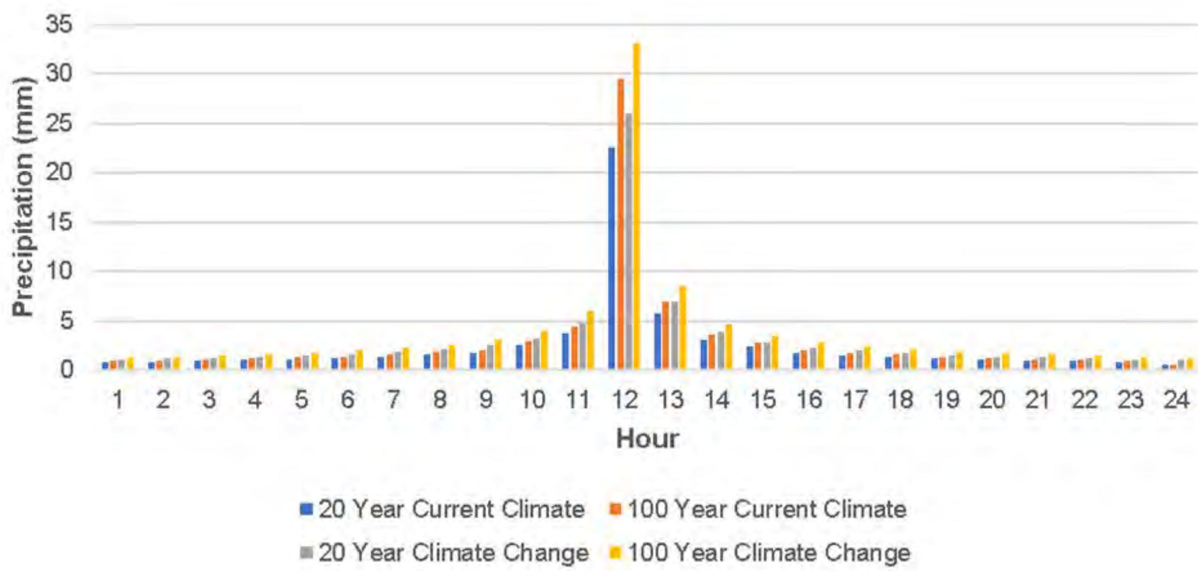
Following the sub-basin delineation, terrain pre-processing was completed to fill surface depressions within the watershed DEM, define flow directions within the model to generate the stream networks within the models. Physical characteristics of the watershed such as stream characteristics, basin slopes, and basin lag times were estimated from the watershed DEM. Other model parameters were defined based on the Churchill River model, since recorded flows were not available to calibrate the parameters.

The Otter Creek and unnamed creek HEC-HMS models used the same modelling methods as the Churchill River model to represent the various physical processes, which were previously summarized in Table 21. As previously noted, these physical processes are represented in HEC-HMS via a multitude of model parameters, which typically would be initially estimated and then adjusted as part of the model calibration process. However, since recorded flows are not available on these creeks, some of the model parameters were defined based on the physical characteristics of the creeks in the LiDAR data, while others were estimated from the Churchill River model.

7.3 HYDROLOGIC ROUTING OF THE 20 AND 100 YEAR AEP RAINFALL EVENTS IN HAPPY VALLEY – GOOSE BAY

Given the close proximity of each of the creek basins to Happy Valley – Goose Bay, precipitation and temperature data from the Goose A ECCC station (i.e. ECCC Station 8501900) were directly incorporated into the hydrologic models. Similar to the Churchill River model, historical air temperature and precipitation data were used to define a typical summer condition as a starting point for the 20 and 100 year AEP rainfall simulations. The AEP rainfall simulations incorporated the synthetic hyetographs for the Goose A ECCC station previously described in Section 6.4 to represent the current climate rainfall in the model, and synthetic hyetographs for climate change conditions were defined following the same methodology (i.e. the alternating block method). The current climate and climate change condition hyetographs for the Goose A ECCC station are shown on Figure 40.

FIGURE 40
CURRENT CLIMATE AND CLIMATE CHANGE HYETOGRAPHS AT GOOSE A



The resulting peak flows at the outlet of each creek are summarized in Table 26. These flows, as well as those at the outlets of the sub-basins included in the models, were incorporated into the hydraulic modelling described in 10.0.

TABLE 26
CREEK OUTFLOWS

Creek	Peak Flow at Outlet (m^3/s)			
	Current Climate		Climate Change	
	1:20 Year AEP	1:100 Year AEP	1:20 Year AEP	1:100 Year AEP
Otter Creek	16.8	34.1	25.6	43.8
Local Creek 1	1.2	2.5	1.9	3.2
Local Creek 2	0.7	1.7	1.2	2.1
Local Creek 3	2.2	5.0	3.7	6.5
Local Creek 4	0.6	1.3	2.3	3.6
Local Creek 5	4.0	8.8	6.5	11.4
Local Creek 6	4.7	10.3	7.5	13.4
Local Creek 7	1.6	3.4	2.5	4.4

8.0 CLIMATE CHANGE AND FUTURE DEVELOPMENT ASSESSMENT

8.1 OVERVIEW

To account for the projected impacts associated with climate change, a review and assessment was completed of the projected impacts to temperature, precipitation, and the potential for ice growth, and how these impacts could affect flooding on the Churchill River and Mud Lake channels.

The anticipated impacts to flows on the Churchill River due to climate change was assessed considering the anticipated changes to the snowpack caused by the projected rising temperature and precipitation. The assessment compared the current and climate change snowpack using current climate and climate change temperature and precipitation data at Churchill Falls and Happy Valley – Goose Bay, which were considered to be representative of the Churchill River basin. The current climate and climate change data was accessed from the Climate Atlas of Canada. While there is similar climate data in the Government of Newfoundland and Labrador's report *"Projected Impacts of Climate Change for the Province of Newfoundland & Labrador: 2018 Update"* (J. Finnis, 2018), the climate information is only provided on a seasonal, rather than monthly, basis. Monthly data was not available when requested from WRMD. As such for a more complete assessment, the Climate Atlas of Canada data was adopted. The assessment showed a small increase in flows on the Churchill River due to the projected climate change impacts.

As an independent check, the anticipated impacts to flows on the Churchill River were also assessed using the hydrologic model, as well as the projected changes to precipitation and temperature due to climate change at the end of the century documented in the Finnis report (J. Finnis, 2018). Precipitation and temperature data representing the current climate were simulated in the hydrologic model. Then using the exact same model, the anticipated end of century climate change temperatures and precipitation were simulated. Statistical relationships were fit to the annual peak flows for the current climate and climate change simulation results to define the changes for the 20 and 100-year flood flows. The changes were in very good agreement with the snowpack assessment. The changes in modelled flows at Muskrat Falls were then applied to the flows used in the hydraulic model for the flood risk mapping, described later in Section 9.2.6.

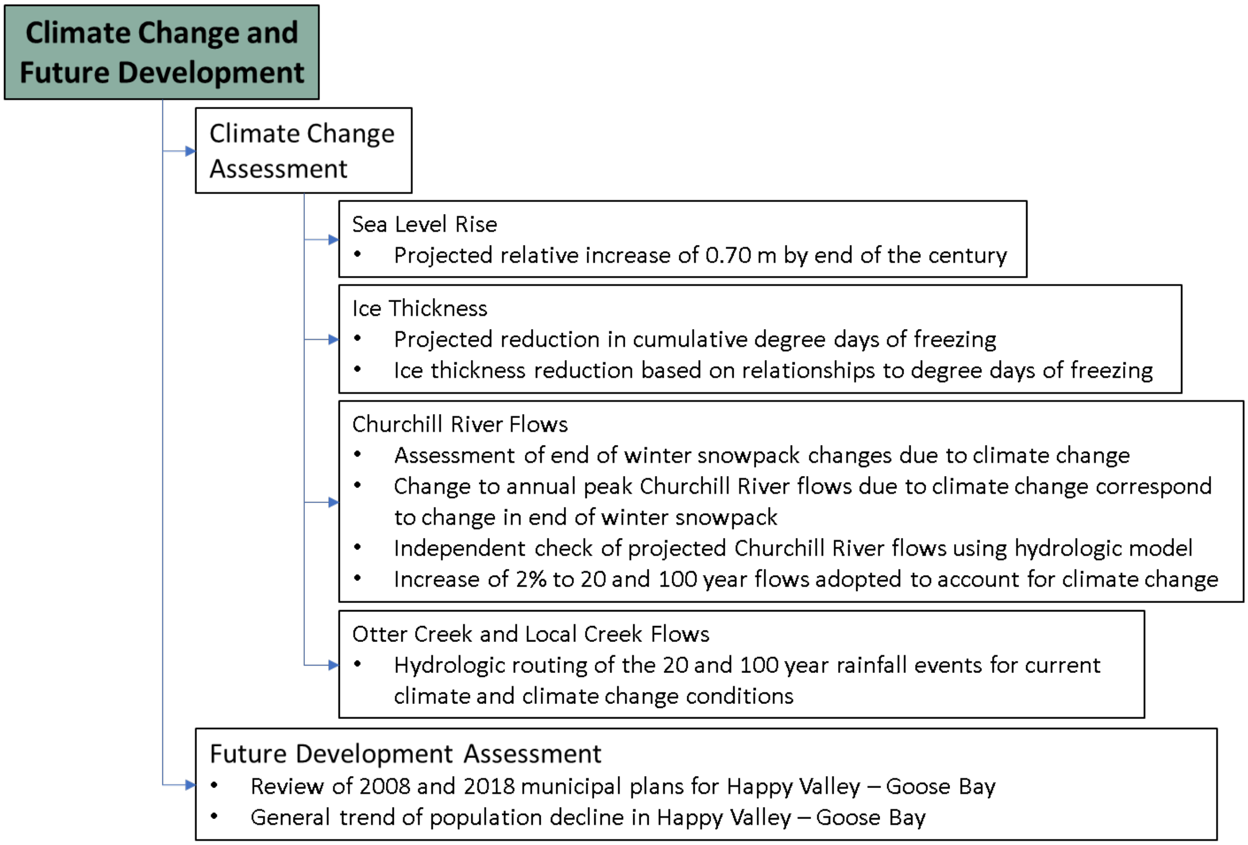
Flows on the Otter Creek and local creeks in Happy Valley – Goose Bay were estimated by simulating the 20 and 100 year rainfall events using the hydrologic model. To assess the potential impacts associated with climate change, the climate change 20 and 100 year rainfall events were simulated using the same hydrologic model. The resulting flows on Otter Creek and the local creeks were then incorporated into the hydraulic models of those creeks.

Another key aspect in the river modelling that is anticipated to change due to climate change are the water levels on Lake Melville. This change was accounted for based on the expected sea level rise relative to ground elevation documented in the report "*Past and Future Sea-Level Change in Newfoundland and Labrador: Guidelines for Policy and Planning*" by M. Batterson and D. Liverman (2010). In short, it is anticipated that the Lake Melville water level will rise by 0.70 m by the end of the century.

Ice processes, including ice jamming, are expected to be affected by climate change due to the projected rising temperatures. This was accounted for in the ice-affected hydraulic model by adjusting the ice thickness in the model based on the projected change to the sum of the daily average temperature of cold days (i.e. degree days of cooling), which is used as a basis for calculating ice growth over the winter season. As well, due to the reduction in ice thickness, the ice volume available to form a jam was also reduced, since the volume of ice is equal to the ice coverage multiplied by the ice thickness.

The tasks completed as part of the climate change assessment are summarized on Figure 41.

FIGURE 41
OVERVIEW OF CLIMATE CHANGE AND FUTURE DEVELOPMENT ASSESSMENT



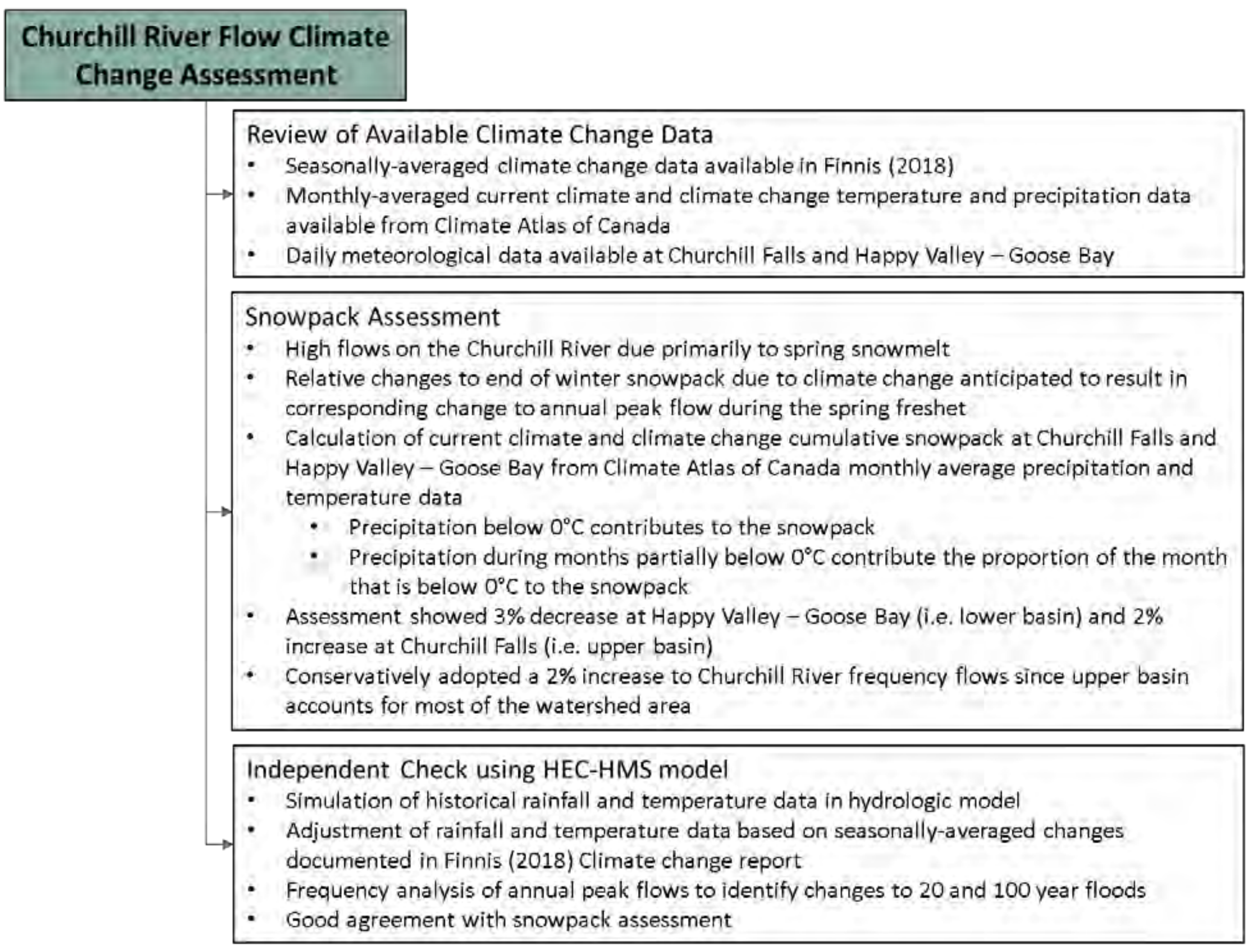
8.2 CLIMATE CHANGE ASSESSMENT

An assessment was completed of the potential impacts to the hydrology and ice processes on the Churchill River so that these potential impacts could be considered in the flood risk maps. The model parameters that were adjusted to account for impacts associated with climate change are described in the following sections.

8.2.1 Churchill River Flows

While the terms of reference indicated that the 20 and 100 year hyetographs for the current and future climate change conditions should be simulated in the hydrologic model, it was found that this approach considerably underestimated the 20 and 100 year flows on the Churchill River. This was anticipated since flooding on the Churchill River is overwhelmingly dominated by snowmelt driven flooding. Rather, flows on the Churchill River were defined based on a frequency analysis of historical observed flows at Muskrat Falls, and as such, a different approach was required to account for the impacts of climate change on these flows. To assess the anticipated impacts, KGS Group assumed that any change to the snowpack within the Churchill River basin would result in a proportional change to the spring freshet flow. As an independent check, historical and climate change temperature and rainfall data were modeled using the hydrologic model. The process for assessing the climate change impacts to the Churchill River flows is shown on Figure 42.

FIGURE 42
CHURCHILL RIVER FLOW CLIMATE CHANGE ASSESSMENT



As part of the assessment, the projected impacts documented in the Finnis (2018) report were reviewed. In that report, a variety of climate indices are compared from the 20th century climate, which was defined as 1968 to 2000, to the projected climate change indices for the 2041 to 2070 and 2071 to 2100 timeframes. The projected data is reported as seasonally-averaged values, (i.e. one mean temperature is provided for December, January and February for both the 20th century climate and future climate conditions). However, to assess the precipitation that contributes to snowpack, monthly average temperature and precipitation are required since during the spring and fall some precipitation falls as either snow or rainfall, depending on the temperature. Instead, the assessment considered average monthly temperature and precipitation data available data from the Climate Atlas of Canada (2019), and considered the impacts projected to the 2051 to 2080 timeframe under the representative concentration pathway (RCP) 8.5, which corresponds to a scenario in which greenhouse gases continue to increase at current rates through to the end of the century.

A comparison of the mean monthly temperatures for the current climate (i.e. 1976 to 2005) and climate change (i.e. 2051 to 2080) conditions at Happy Valley – Goose Bay and Churchill Falls showed that mean monthly temperatures will increase from 3°C to 7°C throughout the year, considerably shortening the amount of time that precipitation will actively accumulate into the snow pack (i.e. precipitation when temperature is less than 0°C). Mean monthly precipitation for the current climate and climate change conditions at Happy Valley – Goose Bay and Churchill Falls were also compared, and showed that mean monthly precipitation will increase by 2% to 26% annually, with the largest increases occurring in November to March. The mean monthly temperatures for both climate conditions for Happy Valley – Goose Bay and Churchill Falls are shown on Figure 43 and Figure 44. Any precipitation that occurs when temperatures are below 0°C, as shown in red on the figures, will to contribute to the snowpack. The mean monthly precipitation for both climate conditions for Happy Valley – Goose Bay and Churchill Falls are shown on Figure 45 and Figure 46.

FIGURE 43
MEAN MONTHLY TEMPERATURE AT HAPPY VALLEY - GOOSE BAY

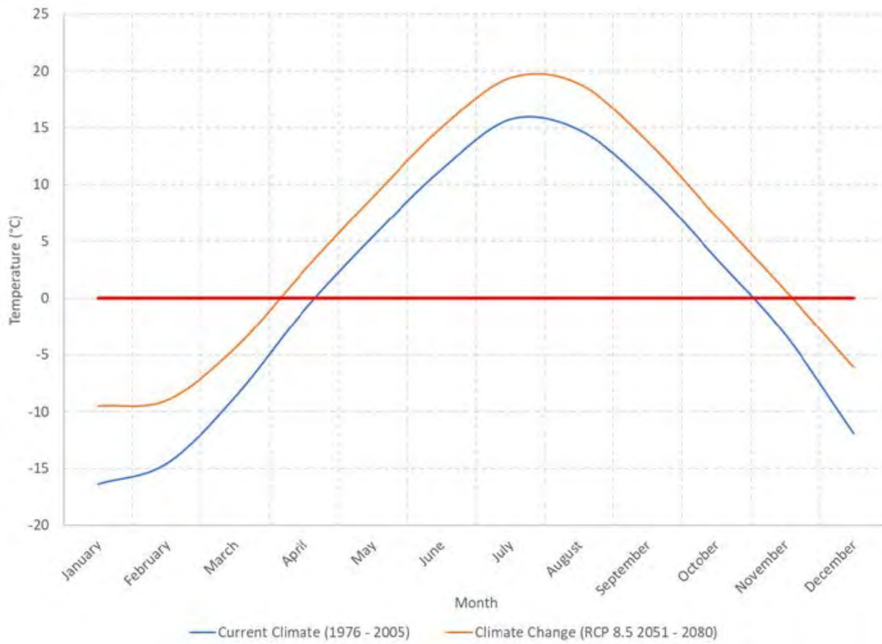


FIGURE 44
MEAN MONTHLY TEMPERATURE AT CHURCHILL FALLS

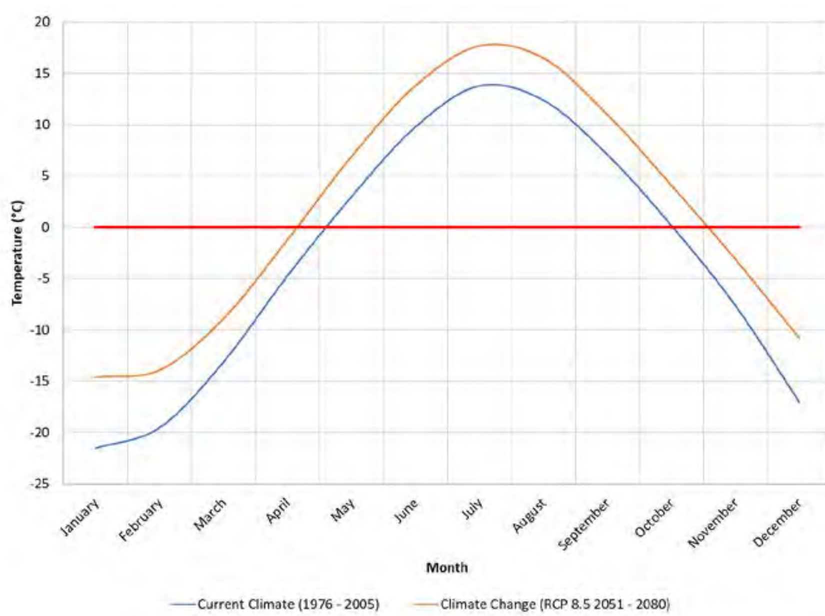


FIGURE 45
MEAN MONTHLY PRECIPITATION AT HAPPY VALLEY - GOOSE BAY

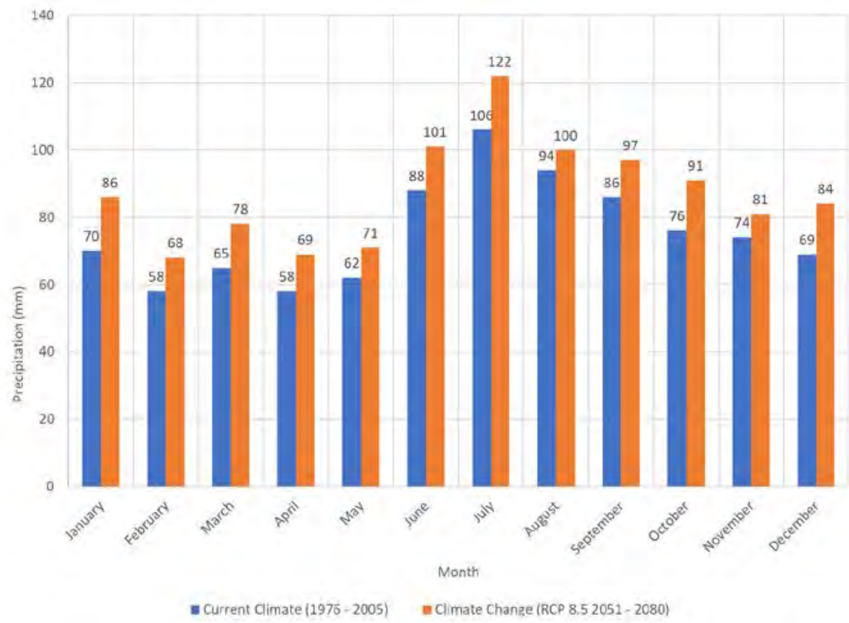
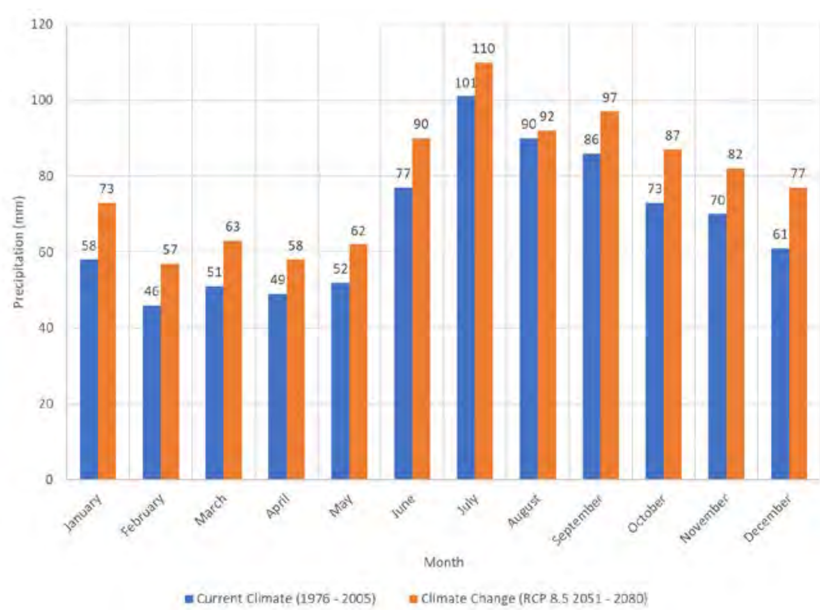


FIGURE 46
MEAN MONTHLY PRECIPITATION AT CHURCHILL FALLS



The comparison of temperature and precipitation for current climate and climate change conditions indicate that while there will be more precipitation falling during the winter months, the length of the winter period to accumulate that precipitation as snowpack will be considerably shortened due to rising temperatures. To estimate the impact of this change, the total annual amount of precipitation that would contribute to the snowpack was calculated by assuming that any snow that falls below 0°C contributes to the snowpack. For months that would only partially contribute to the snowpack (i.e. months that cross the 0°C threshold), the precipitation that was assumed to contribute to the snowpack was taken as the product of the total precipitation for that month and the proportion of the month that was below 0°C. The total calculated precipitation assumed to contribute to the snowpack for the current climate and climate change conditions is shown on Table 27.

TABLE 27
WINTER SNOWPACK ACCUMULATION

Climate Condition	Happy Valley - Goose Bay (mm)	Churchill Falls (mm)
Current Climate	375	377
Climate Change	364	386
Change (%)	-3%	+2%

The accumulated snowpack is projected to change by between -3% and 2% by the 2050 to 2080 timeframe due to the projected impacts from climate change. This range is in good agreement with the projected trends in the maximum snow water equivalent documented in the report “Canada’s Changing Climate Report 2019” by Environment and Climate Change Canada (2019). The report showed that the maximum snow water equivalent for the 2020 to 2050 timeframe over the Churchill River basin was projected to change from -2.5% to 2.5% per decade.

As an independent check on the anticipated impacts to flows on the Churchill River due to climate change, the HEC-HMS model, as described in Section 6.3, was used to simulate the flows on the Churchill River for current climate and climate change conditions. These simulations considered available temperature and precipitation data, as well as temperature and precipitation data that was adjusted to consider climate change.

As previously noted, the climate data included in the Finnis (2018) report was provided as seasonally averaged values, and could not be directly incorporated into the HEC-HMS model.

Rather, historical climate data, specifically mean daily temperature and precipitation for Churchill Falls (i.e. a combination of ECCC Stations 8501132, 850A131 and 8501130) and Happy Valley – Goose Bay (i.e. ECCC Station 8501900) were used as the basis of the current climate data, and were then adjusted as described in the following paragraphs to represent climate change conditions. While the historical climate data is generally available from the 1968 to 2000 timeframe, considerable temperature and precipitation data is missing from the ECCC stations at Churchill Falls from 1993 to 2000. Accordingly, the 1968 to 1993 timeframe was used to define the 20th century climate.

Climate change datasets for temperature and precipitation were defined by adjusting each parameter by the amount or ratio of change documented for the 2071 to 2100 timeframe in the Finnis (2018) report. Specifically, temperature data was adjusted on a seasonal basis at each station by the temperature changes documented in the report. To define the climate change precipitation, ratios of the projected precipitation to the 20th century climate precipitation documented in the Finnis (2018) report were defined for each season and station in the Churchill River watershed. To minimize the impacts of the geographic variability in the projected precipitation data, an average of the ratios at Happy Valley – Goose Bay, Churchill Falls, Schefferville, and Wabush Lake was defined for each season. The average ratios were then multiplied by the historical daily precipitation records at Churchill Falls and Happy Valley – Goose Bay on a seasonal basis to define the climate change precipitation record.

Temperature and precipitation for both the current climate and climate change conditions were incorporated into the HEC-HMS model using the same distance weighted method that was used for the temperature data in the initial model calibration. Flow discharges from the Churchill Falls Generating Station, which are available from 1972 to present, were not adjusted to account for any changes to climate change due to the very high complexity of the reservoir management at the generating station. Since Churchill Falls discharge data was only available subsequent to 1972, and since considerable climate data was missing from 1993 to 2000 at Churchill Falls, the simulations only considered the 1972 to 1993 period, with 1972 serving as a spin-up year.

The precipitation data used for the climate change assessment (i.e. distance weighted ECCC precipitation data) was different than that used in the initial HEC-HMS model development and calibration (i.e. CaPA data), and as such the HEC-HMS model used for the climate change assessment was optimized for the ECCC climate data. The optimization process adjusted the model parameters based on minimizing the peak-weighted RMSE between the simulated and historical flows at Muskrat Falls. The optimized model was generally found to accurately represent the historical observed flows at Muskrat Falls, with an NSE score of 0.76. While this NSE score is somewhat lower than the initial model calibration, the inverse-distance weighting of the two ECCC stations provides a more rudimentary estimate of precipitation throughout the model domain and does not account for local weather phenomena that were not measured by the two stations that would generally be captured in the CaPA data. Nonetheless, the model was considered to be well calibrated for the purpose of assessing the relative differences to flows on the Churchill River due to climate change.

Following the successful optimization of the climate change HEC-HMS model, the climate change precipitation and temperature data were simulated in the model. The simulated flows at Muskrat Falls varied considerably due to the projected impacts of climate change. These changes ranged from a decrease in flow of -44% to an increase in flow of 47%, depending on the year. The average change to the annual peak flow was a decrease of 8%. However, rather than rely on the average change, which may be affected by more frequent and lower flow floods, a frequency analysis of the simulated Muskrat Falls flows was completed to identify the impacts to extreme floods for the current climate and climate change flows. A Log-Pearson Type III – Sundry Average Method (SAM) curve was found to be the best fit for the current climate and climate change annual peak flows. The 20 and 100-year AEP flows for both conditions, as well as the AEP flows defined by the SSFA, are shown in Table 28.

TABLE 28
CLIMATE CHANGE FREQUENCY FLOWS

AEP Event	SSFA (m3/s)	Current Climate HEC-HMS (m3/s)	Climate Change HEC-HMS (m3/s)
20 Year	5,920	5,988	5,943
100 Year	6,610	6,591	6,799

The frequency flows based on the HEC-HMS simulation of the 20th century climate is in very good agreement with the SSFA frequency flows, indicating that the HEC-HMS model is accurately representing the frequency flows at Muskrat Falls on the Churchill River. The projected impacts to the Churchill River flows at Muskrat Falls due to climate change lower the 20 year AEP flow by 1%, and increase the 100 year AEP flow by 3%. These changes are in very good agreement with the anticipated impacts to Churchill River flows defined by the snowpack assessment.

Based on the above assessments, an increase of 2% was incorporated into the 20 and 100 year flows on the Churchill River for the open water hydraulic modelling. For the ice-affected modelling, the flows included in the frequency curve used to define inflows on the Churchill River as part of the Monte Carlo framework were increased by 2%.

8.2.2 Otter Creek and Local Creek Flows

As described in Section 7.3, flows on Otter Creek and the seven unnamed creeks in Happy Valley – Goose Bay were defined by simulating the climate change 20 and 100 year AEP rainfall events in the hydrologic models for those creeks.

8.2.3 Sea Level Rise

Sea level rise was accounted for in the climate change modelling based on the anticipated impacts reported in the Batterson and Liverman's report (2010). In that report, the sea level is projected to rise by 0.79 m by the year 2099. However, Labrador is also undergoing vertical uplift due to crustal rebound following the last glacial period. Accordingly, the relative sea level increase is projected to be approximately 0.70 m by the year 2099. While this timeframe is slightly beyond the 2051 to 2080 timeframe considered in assessing the impacts from climate change to flows and ice thickness on the Churchill River, it was conservatively adopted as a representative adjustment to account for climate change in the flood risk modelling.

In the open water hydraulic modelling for the climate change scenarios (described in Section 9.2.6), the Lake Melville water levels were increased by 0.70 m to account for sea level rise.

In the ice-affected hydraulic modelling for the climate change scenarios (described in Section 9.3.4), the statistical distribution representing the tidal range on Lake Melville was increased by 0.70 m.

8.2.4 Ice Thickness

Information on the projected changes to the degree days of cooling are not presently available in the Government of Newfoundland and Labrador's report "*Projected Impacts of Climate Change for the Province of Newfoundland & Labrador: 2018 Update"* (J. Finnis, 2018). Accordingly, the impacts associated with climate change to ice thickness on the Churchill River were assessed using data available from the Climate Atlas of Canada. In particular, the assessment considered the cumulative degree days of freezing for current climate and climate change conditions at Happy Valley – Goose Bay for the 2051 to 2080 timeframe under the RCP 8.5 scenario. The cumulative degree days of freezing were only considered at Happy Valley – Goose Bay since only ice downstream of Muskrat Falls will be available to form a jam following the completion of the Muskrat Falls Generating Station project.

The cumulative degree days of freezing is projected to decrease from 2,052°C - day to 1,204°C - day by the 2051 to 2080 timeframe. Since ice growth is a function of the square root of the cumulative degree days of freezing, the anticipated reduction in ice thickness is defined by the ratio of the square roots of the climate change cumulative degree days of freezing and current climate degree days of freezing. Accordingly, all ice thickness ranges included in the Monte Carlo simulations that are part of the ice-affected hydraulic modelling for the climate change scenarios (described in Section 9.3.4), (i.e. ice pan thickness, ice front thickness, intact downstream ice cover thickness) were reduced by a factor of 0.766. Since the volume of ice available to form a jam is similarly dependent on the ice thickness, the maximum volume of ice used to define the GEV range was similarly reduced by a factor of 0.766.

8.3 FUTURE DEVELOPMENT CONDITIONS

A review was completed of the 2008 and 2018 municipal plans for the Town of Happy Valley – Goose Bay to assess any trends in population changes and to identify any potential impacts to flows on the lower Churchill River. The municipal plans showed that the population of the Town of Happy Valley – Goose Bay has generally been declining by -0.3% to -7.9% since 1996, although has recently begun to rebound (i.e. +7.4%) as of 2016. However, the recent population rebound is likely associated with the ongoing construction of the Muskrat Falls Generating Station, and may not be representative of an overall trend. Furthermore, the 2018 municipal plan indicates that housing construction has slowed considerably since the 2009 to 2013 boom in housing construction associated with the construction of the Muskrat Falls Generating Station, and that while additional housing would be required to meet the projected population needs in 2021, there would be a surplus of housing from 2026 to 2036. Accordingly, while there may be additional construction activities in the Town of Happy Valley – Goose Bay that could impact the overall land use, this impact is anticipated to be small. Furthermore, considering that flows on the Churchill River are dominated by snowmelt and rainfall throughout the very large, undeveloped basin, any changes to land use in the Town of Happy Valley – Goose Bay or Mud Lake are anticipated to have a negligible impact on flood flows on the Churchill River.

9.0 HYDRAULIC INVESTIGATIONS AND MODELLING OF THE CHURCHILL RIVER

9.1 OVERVIEW

Using the information from the ground elevation models, described in Section 4.4, KGS Group and our subconsultant Dr. Karl-Erich Lindenschmidt developed hydraulic models of the Churchill River and Mud Lake channels that were used to convert flows at Muskrat Falls into water levels along the river. Three separate models were developed:

- ***Flood Forecasting Open Water Model*** – A model of open water conditions on the Churchill River from Muskrat Falls to Lake Melville. This model was based on the ground elevation model built with the 2006 LiDAR data to ensure that the model would be incorporated into the forecasting system prior to the 2019 freshet. The 2006 LiDAR data was used to develop the model because the 2019 LiDAR was not unavailable at the time of the model development. The model was developed and optimized for inclusion in the flood forecasting system, and carefully calibrated to optimize the forecasting accuracy based on the forecast Churchill River flows and Lake Melville water levels.

- ***Flood Risk Mapping Open Water Model*** – A model of open water conditions on the Churchill River from Muskrat Falls to Lake Melville. This model also included the Mud Lake channels from Mud Lake to the Churchill River. It was based on the ground elevation model built with the 2019 LiDAR survey data. This model was developed to include the Mud Lake channels in addition to the Churchill River, and was optimized to work with the estimated 20 and 100 year flows on the Churchill River. It was also used to define the water levels included in the flood risk and flood hazard maps for open water conditions.

- ***River Ice Model*** – A model of ice-affected conditions on the Churchill River only from Muskrat Falls to lake Melville. This model was created prior to the completion of the LiDAR survey so that it could be included in the Flood Forecasting System prior to the 2019 spring melt. This model was also used to define the water levels included in the flood risk and flood hazard maps for ice-affected conditions. However, since the ice-affected model did not include the flood plain area, rather only the bathymetric representation of the main channel surveyed in 2018, it did not require updating with the 2019 LiDAR.

The different open water hydraulic models were set up so that each model could be optimized for the specific task at hand, specifically to optimize the forecasting model to work best within the framework of the Flood Forecasting System, described further in Section 14.3.4, and to have a separate model optimized to accurately characterize the hydraulic conditions on the

Churchill River and Mud Lake for the 20 and 100 year floods. In particular, the forecasting model was optimized to forecast water levels on the Churchill River using the forecast discharge at Muskrat Falls, and was found to accurately represent water levels in Mud Lake based on a representative location on the Churchill River. For the flood risk mapping model, it was critical to represent the Mud Lake channels in the hydraulic model so that inundation and flood risk information could be provided within the community of Mud Lake.

The open water models of the Churchill River used flows from Muskrat Falls and water levels on Lake Melville to calculate the water level at several points along the Churchill River. The models were calibrated so that modelled historical flow and water levels on the Churchill River matched recorded water levels and flows for different timeframes, each representing a different flow condition on the river. The modelled timeframes included the summer of 2017, the fall of 2017, and the summer of 2018, which was identified by local residents in Happy Valley – Goose Bay and Mud Lake as a flood that occurred during open water conditions. Since the flood risk mapping model was created after the completion of the LiDAR Survey in September 2019, an additional timeframe was modelled to further check that the model was accurate, specifically the open water flows in spring and early summer of 2019. Both models were found to accurately represent recorded water levels on the Churchill River, and the flood risk mapping model was found to also accurately represent the recorded water levels in the community of Mud Lake.

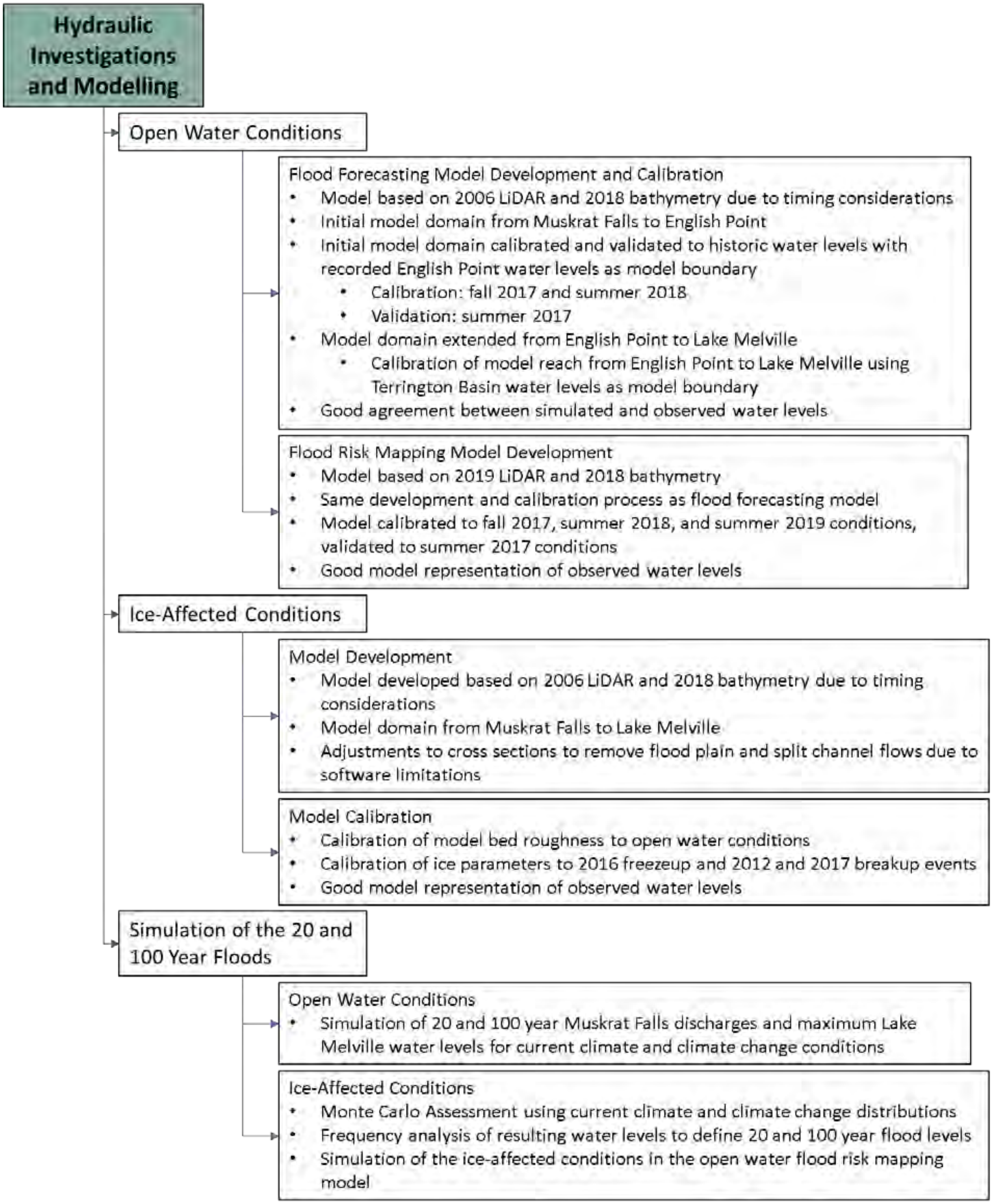
Once the forecasting model was found to accurately match the recorded water levels and flows, it was added to the Churchill River Flood Forecasting System, as described in Section 13.0. Similarly, once the flood risk mapping model was found to accurately match the historical water levels on the Churchill River and Mud Lake channels, it was used to model the 20 and 100 year floods for the current climate and climate change conditions. The water levels from the models were then combined with the ground elevation model to develop the flood risk and flood hazard maps for open water conditions, as described further in Section 12.0.

Similar to the open water models, the ice-affected model of the Churchill River used flows from Muskrat Falls and water levels on Lake Melville to calculate water levels along the Churchill River. However, information about ice on the river was also included in the model to represent freeze-up and ice jam processes on the river. The ice information was estimated using available satellite information and ice depth measurements, and from similar studies on comparable rivers to the Churchill River. The ice-affected model of the Churchill River was carefully adjusted so that the model accurately represented historical water levels during three flood conditions, specifically the freeze-up ice jam that occurred during the fall of 2016, the breakup ice jam that occurred during the spring of 2012, and the major ice jam that occurred during the spring of 2017. The model was found to accurately represent these historical floods.

Following the model adjustment, the ice-affected model was used to model the 20 and 100 year ice jam floods on the Churchill River for both the current climate and future climate change conditions. The water levels from the models were then combined with the ground elevation model to develop the flood risk and flood hazard maps for ice-affected flood conditions, as described further in Section 12.0. The ice-affected model was also added to the Churchill River Flood Forecasting System, as described in Section 13.0, and uses forecast flows and water levels, as well as measured ice information, to estimate ice-affected water levels on the Churchill River from the onset of the fall freeze-up to the end of the spring breakup period.

The tasks completed as part of the hydraulic investigations and modelling are summarized on Figure 47.

FIGURE 47
OVERVIEW OF HYDRAULIC INVESTIGATIONS AND MODELLING



9.2 OPEN WATER CONDITIONS

9.2.1 Overview of Open Water Hydraulic Models

As previously noted, two open water hydraulic models were developed for the Lower Churchill River, specifically:

- ***Flood Forecasting Model –*** This model extended from Muskrat Falls into Lake Melville and used forecast tidal levels on Lake Melville at Terrington Basin as the downstream boundary. This model was optimized to provide accurate water level forecasts based on the forecast flows from the hydrologic model, and was developed based on the 2018 bathymetric survey data collected by KGS Group and the 2006 Nalcor LiDAR data since the 2019 LiDAR data was not available at the time of the model development. This model was incorporated into the flood forecasting system prior to the 2019 freshet.
- ***Flood Risk Mapping Model –*** This model extended from Muskrat Falls to Lake Melville, and also included the Mud Lake channels from Mud Lake to the confluence with the Churchill River. The model used forecast tidal levels on Lake Melville at Terrington Basin as the downstream boundary condition. This model was developed based on the topographic survey and 2019 LiDAR capture completed for this study, and was optimized for the flood risk mapping component of this study.

The detailed 1-dimensional (1D) hydraulic models of the Lower Churchill River from Muskrat Falls to Lake Melville were developed using the USACE Hydraulic Engineering Center's River Analysis System (HEC-RAS) (U.S. Army Corps of Engineers, 2016) software version 4.1. The ArcGIS HEC-GeoRAS extension was not used since the extension was not available for Esri ArcMap version 10.6 at the time of the model development. HEC-RAS is a 1D river analysis software capable of completing steady and unsteady state hydraulic modelling by applying an iterative solution procedure (i.e. standard step method) to energy equations for steady state conditions and an implicit finite difference scheme to the continuity and momentum equations for unsteady state conditions. HEC-RAS has frequently and successfully been applied to flood risk mapping studies, and was identified as the preferred modelling software by WRMD in the Terms of Reference for this study.

The development and calibration of these two open water models are summarized in the following sections of this report.

9.2.2 Flood Forecasting Model Development

As previously noted in Section 9.2.1, the Flood Forecasting Model was developed based on the surveyed bathymetry data collected by KGS Group and the 2006 Nalcor LiDAR data, and was incorporated into the flood forecasting system prior to the 2019 spring freshet. The Flood Forecasting Model was developed and calibrated in two steps.

- ***Step 1*** – First, cross sections were incorporated into the model from Muskrat Falls to English Point so that the model could be calibrated using historical recorded water levels at the WSC Gauge at English Point (i.e. WSC gauge 03PC001) as the downstream model boundary.
- ***Step 2 –*** Following the successful completion of the model calibration upstream of English Point, additional cross sections were incorporated into the model to extend the model domain to Lake Melville so that the forecast tidal water levels on Lake Melville at Terrington Basin (i.e. DFO station 1350) could be used as the downstream boundary condition in the model. The additional reach length incorporated into the model was then calibrated to reproduce the observed water levels at English Point as best as possible.

The two-step process used to develop and calibrate the Flood Forecasting model was necessary to minimize the potential impacts to model accuracy from the rudimentary approach used to define forecast water levels at the DFO station at Terrington Basin. In short, DFO defines the predicted tidal levels on Lake Melville on an annual basis, and does not account for any local weather phenomenon or inflows into the Lake, including wind setup, storm surges, or any increases in levels to the lake due to high inflows, and only consider the tidal influence on the lake level. As such, the forecast water levels at the Terrington Basin station are not perfectly representative of the observed conditions on Lake Melville near the confluence with the Churchill River, since the lake level at the mouth of the Churchill River can be affected by processes beyond only tidal influences. Accordingly, calibrating the model by first using the recorded water levels at English Point as the model boundary ensured that physical processes not considered in the model (i.e. wind setup, storm surges) did not affect the calibration, since they were already taken into account in the recorded water levels at English Point.

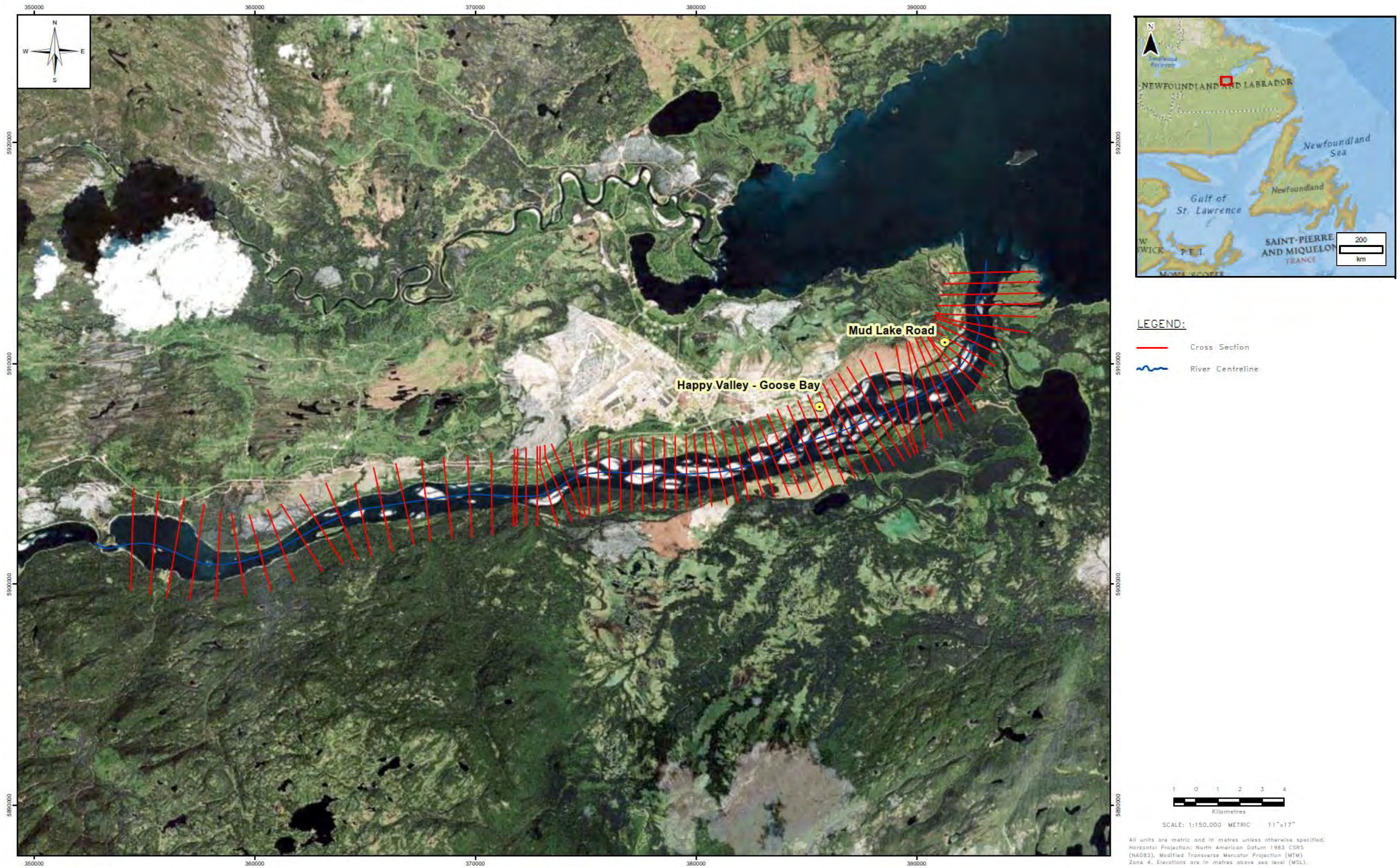
Cross Sections

As previously described in Section 3.2, an extensive bathymetric survey was completed on the Lower Churchill River that included the survey of 80 cross sections on the river. Cross sections were surveyed every 1 km between Muskrat Falls and the Trans Labrador Highway, and every 500 m between the Trans Labrador Highway and Lake Melville. These cross sections were combined with the 2006 LiDAR data provided by Nalcor, with the bathymetry defined by the bathymetric survey data and the topography defined by the LiDAR data.

As previously noted in Section 4.4, the portion of the cross sections representing the sand bars were carefully adjusted to account for the movement of the various sandbars that would have taken place between the 2006 LiDAR survey and the bathymetric survey completed for this project. The required adjustment for each cross section was estimated based on available aerial imagery and the typical height of the sandbars apparent in the LiDAR data. Furthermore, while there is considerable uncertainty in the cross-section adjustments, the uncertainty was accounted for by adjusting the Manning's roughness coefficients as part of the model calibration process.

In total, 72 cross sections were incorporated into the HEC-RAS model of the Lower Churchill River, representing approximately 43 km of the river, as shown on Figure 48. Plots of each cross section included in the model are included in Appendix K.

FIGURE 48
CHURCHILL RIVER CROSS SECTIONS INCLUDED IN THE FLOOD FORECASTING MODEL



Boundary Conditions

The Flood Forecasting model included an inflow boundary at the upstream end of the model representing inflows into the model domain from Muskrat Falls. Due to the implementation of the model into the forecasting system, local inflows from the tributaries in the model were not included. However, these inflows are generally minor and do not largely influence the hydraulic conditions on the lower Churchill River.

For the initial model (i.e. first step model upstream of English Point), the downstream boundary condition was defined as the recorded water levels at the WSC gauge at English Point (i.e. 03PC001). For the extended model (i.e. second step model that was extended to Lake Melville), the downstream boundary condition was defined as the water levels forecast by DFO at Terrington Basin (i.e. Station 1350).

Structures

Only one structure was included in the HEC-RAS model of the Churchill River, specifically the Trans Labrador Highway Bridge. The bridge was incorporated into the HEC-RAS model based on both survey data collected as part of the field program and design drawings of the bridge provided by WRMD.

Manning's Roughness Coefficient

Manning's roughness coefficients were estimated for the hydraulic model based on the calibration of the model to observed water levels and flows. Due to the presence of several islands and sandbars within the lower Churchill River, horizontally varied Manning's roughness coefficients were required to represent the varied roughness across each cross section, specifically channel around the various sandbars, and for parts of the cross section representing islands and sandbars. Roughness coefficients for channels ranged from 0.020 to 0.0285, while the roughness coefficients for sandbars and islands were set to 0.035. Roughness coefficients for the flood plain were set to 0.055. The assumed roughness values fit well within the standard values, and as such were considered acceptable. The roughness coefficients for the cross sections are shown graphically with each cross section in Appendix K.

Contraction and Expansion Coefficients

Expansion and contraction coefficients in HEC-RAS are used to represent energy losses between cross sections due to changes in the cross-section geometries. As described in the documentation for HEC-RAS, the contraction and expansion coefficients for natural channels with gradual transitions are typically on the order of 0.1 and 0.3, and 0.3 and 0.5 at typical bridge sections. However, due to the highly braided nature of the Lower Churchill River, as well as the potential losses associated with flow over the sand bars during flood conditions, the contraction and expansion coefficients were increased to 0.3 and 0.5 for all of the cross sections.

9.2.3 Calibration and Validation of the Flood Forecasting Model

Following the development of the Flood Forecasting open water hydraulic model, the model was calibrated and validated using available recorded flows and water levels on the Churchill River. Subsequent to the 2017 flood, WRMD considerably expanded the hydrometric monitoring network on the river, and as such more consideration was given to the newly available water level and flow data that was available subsequent to the 2017 flood. Given the high quality of the data (i.e. continuous hourly water levels at several locations), and highly dynamic conditions on the river due to operations of the Muskrat Falls spillway and tidal effects on Lake Melville, the model was calibrated and validated to three unsteady state continuous periods. As well, the unsteady state calibration allowed for the model to be calibrated over a much wider range of conditions than a series of steady state simulations, and was therefore considered the best approach to model calibration.

Three periods were considered as part of the model calibration and validation, each representing a high flow, moderate flow, and low flow condition on the river. These periods included:

- ***Summer 2018 (i.e. June 1 to July 31, 2018)*** – This period was identified as a high open water condition during a meeting with the Local River Watch Committee. During that meeting, local residents in Happy Valley – Goose Bay and Mud Lake indicated that high water levels and flows occurred during the spring 2018 freshet, and that those high-water levels took place during open water conditions. Accordingly, the open water portion of the 2018 spring freshet provided an ideal combination of a wide range of flows on the water levels on the Lower Churchill River and an improved network of available recorded hydrometric data on the river. Flows on the Churchill River during the open water portion of the freshet and subsequent return to typical conditions ranged from 1,400 m^3/s to 5,100 m^3/s.

- ***Fall 2017 (i.e. October 15 to November 15, 2017)*** – This period represented low flows and water levels on the Lower Churchill River prior to the onset of ice formation. Flows on the river ranged from 1,000 m^3/s to 1,850 m^3/s.
- ***Summer 2017 (i.e. June 15 to September 15, 2017)*** – This period represents low to moderate flow conditions on the Lower Churchill River subsequent to the 2017 spring freshet. Flows on the river ranged from 1,200 m^3/s to 2,200 m^3/s.

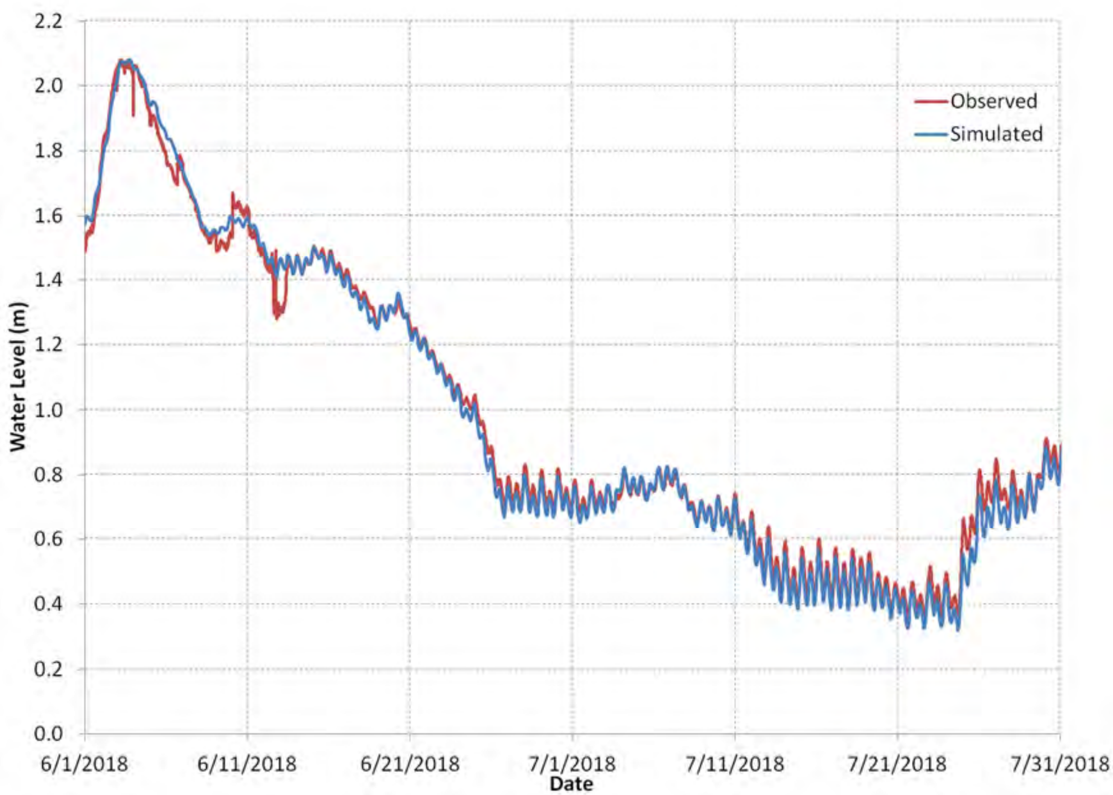
As previously noted, the Flood Forecasting model was developed and calibrated in a two-step process, with the model first being defined from Muskrat Falls to English Point so that the recorded historical water levels could be used as the downstream boundary condition for the model. The upstream boundary condition was defined based on the calculated discharges from the Muskrat Falls spillway provided by Nalcor.

The Flood Forecasting model was calibrated to the Summer 2018 and Fall 2017 periods, and validated to the Summer 2017 period. The data used for the model calibration and validation was recorded real time hourly data, and was not subjected to any quality control. Accordingly, there are potential errors in the recorded data. The overall performance of the initial model calibration for each period is described, below.

Summer 2018

Observed water levels for the Summer 2018 calibration period included hourly water levels recorded by WRMD at Happy Valley – Goose Bay and by WSC at gauge station 03OE014 (i.e. Churchill River 6.15 kms Below Lower Muskrat Falls). The HEC-RAS model accurately depicted the recorded flows at Happy Valley – Goose Bay, as shown on Figure 49, with a RMSE of 0.03 m. A maximum difference between the simulated and observed water levels of 0.17 m occurred on June 12, but it appears that this discrepancy can be attributed to an error with the recorded data, since the recorded water levels suddenly drop and rebound over a short period.

FIGURE 49
COMPARISON OF SUMMER 2018 OBSERVED AND SIMULATED WATER LEVELS AT HAPPY VALLEY – GOOSE BAY (FLOOD FORECASTING MODEL)



The model also accurately represented the recorded water levels downstream from Muskrat Falls, with an overall RMSE of 0.07 m and a maximum discrepancy of 0.17 m between the observed and simulated water levels, as shown on Figure 50. However, similar to the recorded water levels at Happy Valley – Goose Bay, the recorded water levels show a sudden rise in water levels on July 1 and sudden drop in water levels on July 7 and 8. Accordingly, the maximum discrepancy can likely be attributed to an error in the recorded data.

FIGURE 50
COMPARISON OF SUMMER 2018 OBSERVED AND SIMULATED WATER LEVELS 6.15 KMS BELOW LOWER MUSKRAT FALLS (FLOOD FORECASTING MODEL)

Fall 2017

The model was also calibrated to recorded water levels on the Lower Churchill River collected at WRMD's Happy Valley – Goose Bay gauge and WSC's gauge station 03OE014. The model accurately represented the recorded water levels at Happy Valley – Goose Bay and below Muskrat Falls, with an RMSE of 0.04 m and 0.08 m, as shown on Figure 51 and Figure 52.

FIGURE 51
COMPARISON OF FALL 2017 OBSERVED AND SIMULATED WATER LEVELS AT HAPPY VALLEY – GOOSE BAY (FLOOD FORECASTING MODEL)

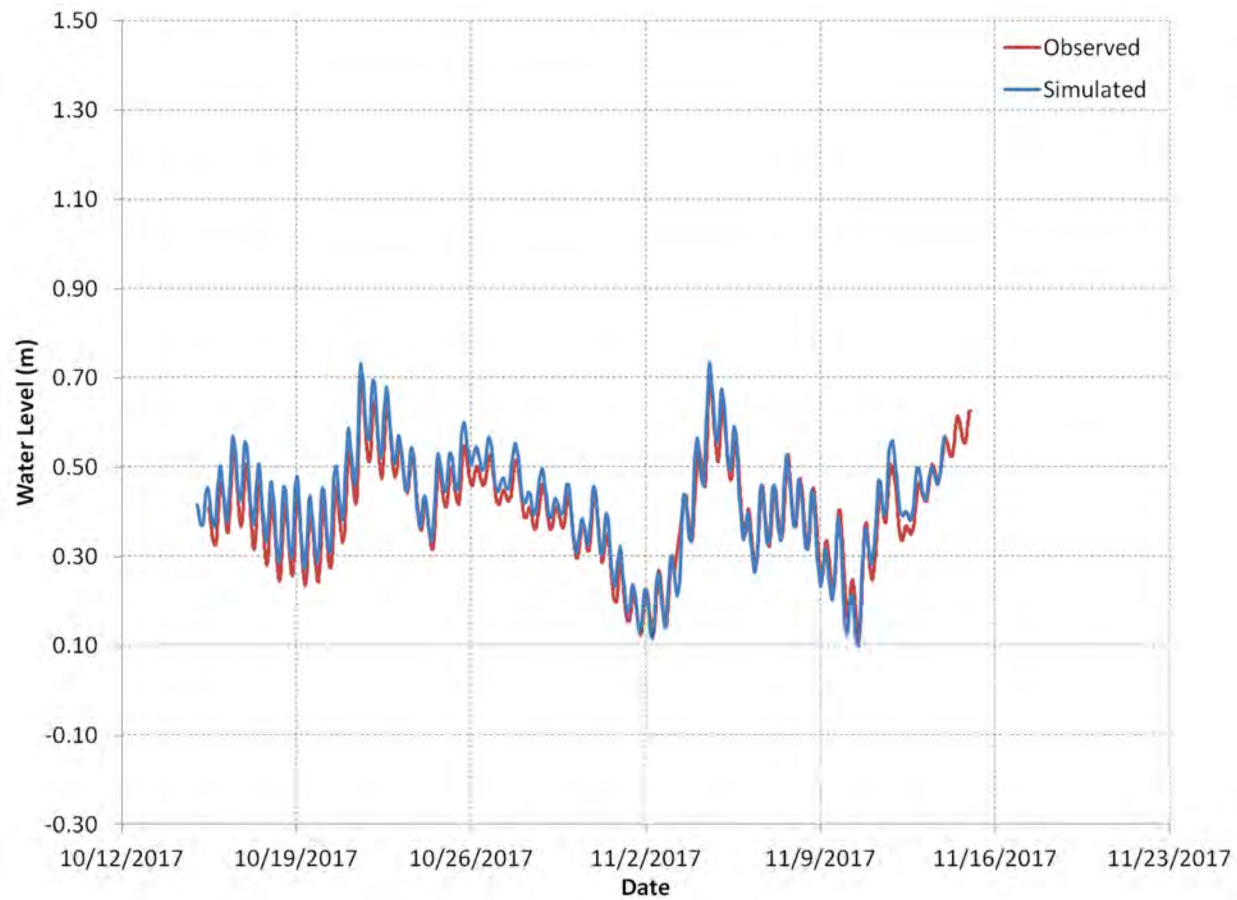
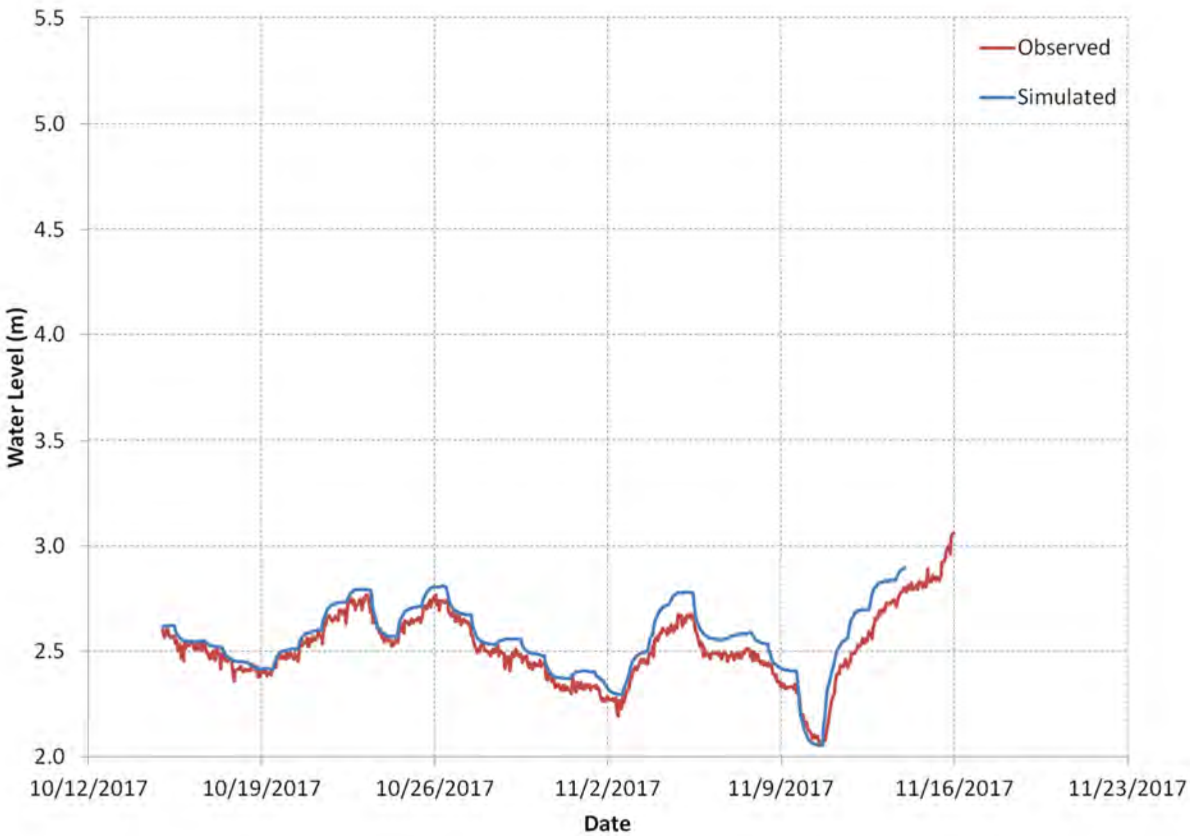


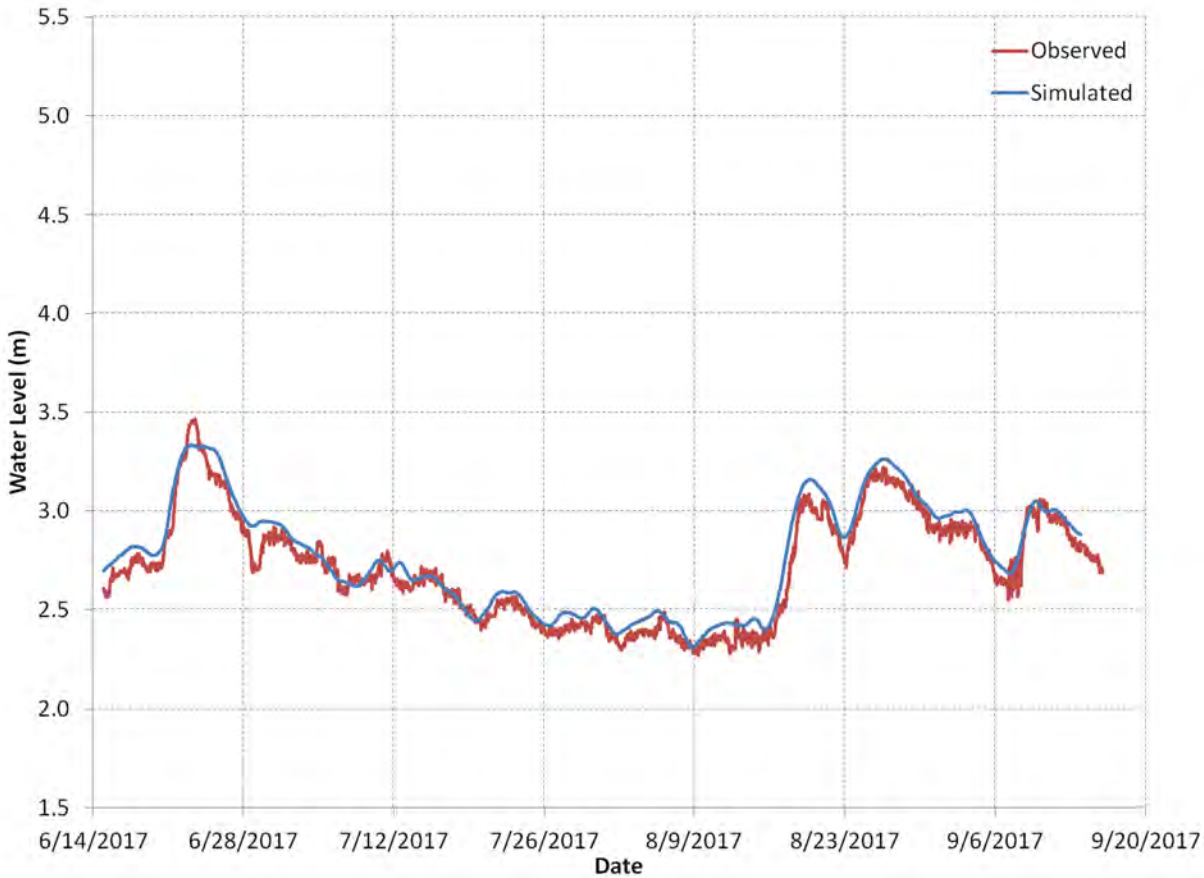
FIGURE 52
COMPARISON OF FALL 2017 OBSERVED AND SIMULATED WATER LEVELS 6.15 KMS BELOW LOWER MUSKRAT FALLS (FLOOD FORECASTING MODEL)



Summer 2017

The model was validated to recorded hourly water levels at the WSC gauge station 03OE014. Hourly data at the WRMD station at Happy Valley – Goose Bay was unavailable, since the gauge was installed during fall 2017. The model accurately represented the hourly water levels, with an RMSE of 0.07 m. Two considerable differences between the observed and simulated water levels occurred on June 23 and June 29, with the recorded water levels suddenly fluctuating by approximately 0.15 m. Given that that the fluctuations were short lived, KGS Group anticipates that the fluctuations were measurement error at the gauge either due to local flow effects or an instrumentation malfunction. A comparison of the simulated and recorded water levels is shown on Figure 53.

FIGURE 53
COMPARISON OF SUMMER 2017 OBSERVED AND SIMULATED WATER LEVELS 6.15 KMS BELOW LOWER MUSKRAT FALLS (FLOOD FORECASTING MODEL)



Calibration of the Extended Model from English Point to Lake Melville

As previously noted, the Flood Forecasting Model was extended to include the river reach from English Point to Lake Melville such that the model could incorporate and utilize forecast tidal predictions provided by DFO for Terrington Basin (i.e. DFO Station 1350). No adjustments were made to the model upstream of English Point, since that portion of the model was considered to be well calibrated.

The reach length incorporated into the Forecasting Model was calibrated to the recorded water levels at English Point for the same three events (i.e. Summer 2018, Fall 2017, Summer 2017) using the DFO tidal prediction data as the downstream boundary condition. A comparison of the recorded and simulated water levels at English Point for the Spring 2018, Fall 2017, and Summer 2017 periods are shown on Figure 54 to Figure 56. A comparison of the calibration accuracy for the initial and extended Flood Forecasting models is shown in Table 29.

FIGURE 54
COMPARISON OF SPRING 2018 OBSERVED AND SIMULATED WATER LEVELS AT ENGLISH POINT (FLOOD FORECASTING MODEL)

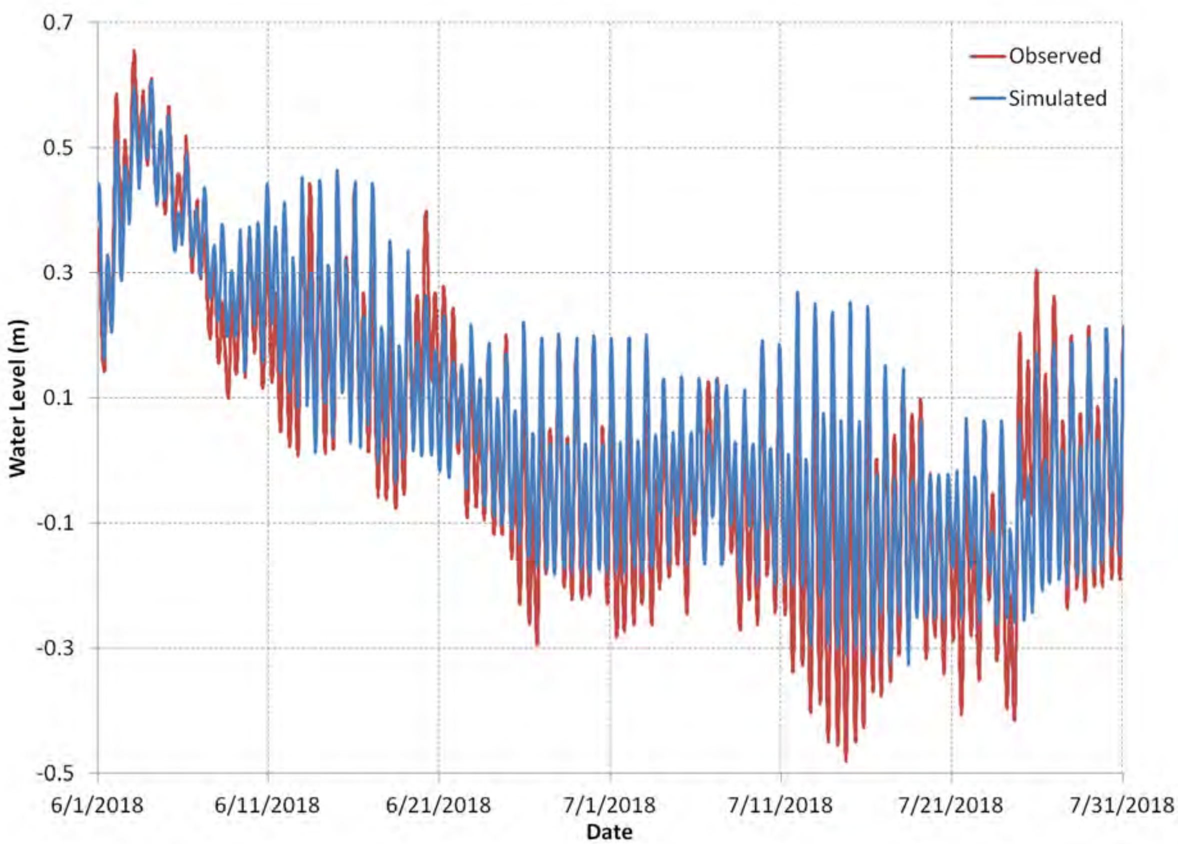


FIGURE 55
COMPARISON OF FALL 2017 OBSERVED AND SIMULATED WATER LEVELS AT ENGLISH POINT (FLOOD FORECASTING MODEL)

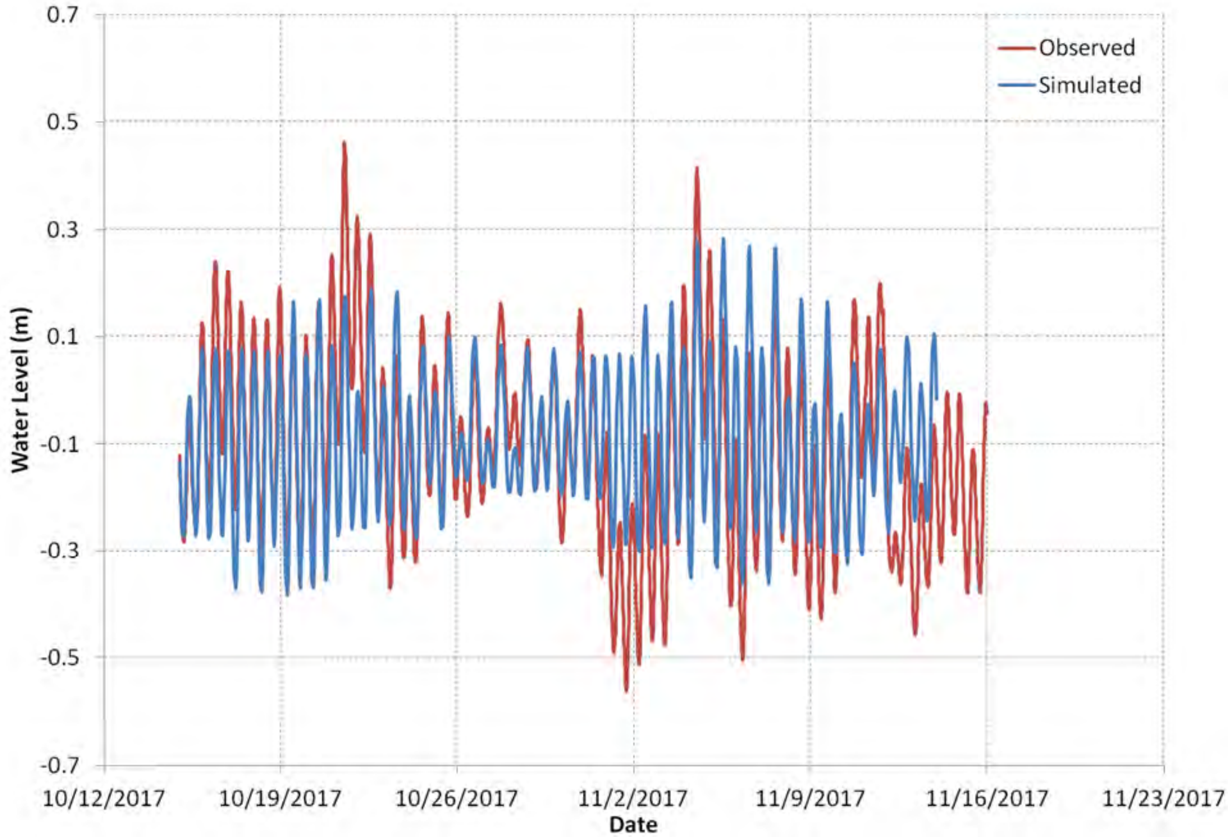


FIGURE 56

COMPARISON OF SUMMER 2017 OBSERVED AND SIMULATED WATER LEVELS AT ENGLISH POINT (FLOOD FORECASTING MODEL)

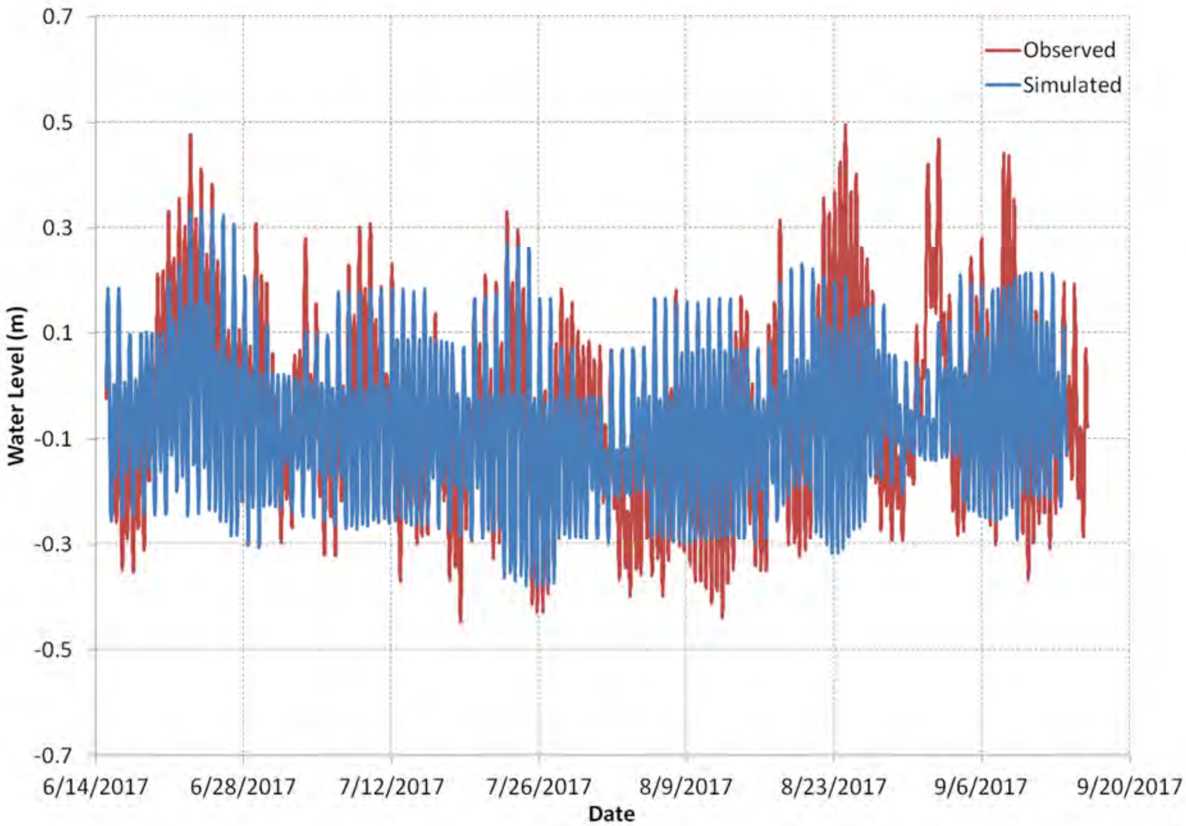


TABLE 29

COMPARISON OF THE INITIAL AND EXTENDED FLOOD FORECASTING MODEL RMSE

Location	Initial Model RMSE (m)			Extended Model RMSE (m)		
	Spring 2018	Fall 2017	Summer 2017	Spring 2018	Fall 2017	Summer 2017
English Point	- - -	- - -	- - -	0.08	0.13	0.11
Happy Valley – Goose Bay	0.04	0.04	- - -	0.04	0.06	- - -
Below Muskrat Falls	0.08	0.08	0.07	0.08	0.08	0.07

While the implementation of the DFO tidal prediction data on Lake Melville as the downstream model boundary condition does not result in a perfect representation of observed water levels at English Point, the model does generally represent the anticipated range in water levels well. Furthermore, the use of the tidal boundary condition largely does not affect the model calibration farther upstream on the Churchill River, as shown by the very similar RMSE values at Happy Valley – Goose Bay and below Muskrat Falls. The Forecasting Model was therefore considered to be well calibrated.

Due to the geomorphology of the sandbars in the lower Churchill River, the calibration of the forecasting model should be monitored on an ongoing basis to identify if the ongoing geomorphology is affecting the model calibration. This monitoring should coincide with WRMD's ongoing monitoring of the sandbar movement on the Churchill River, and should any sudden changes be noted in the sandbar monitoring, or any considerable differences arise between the observed and simulated water levels, model recalibration would be required to account for the geomorphological changes in the river, including adjustment to the model cross sections or changes to the roughness parameters.

9.2.4 Flood Risk Mapping Model Development

As previously noted in Section 9.2.1, the Flood Risk Mapping model was developed based on the surveyed bathymetry data and 2019 LiDAR data collected by KGS Group. Similar to the Flood Forecasting Model, the Flood Risk Mapping model was developed and calibrated in two steps to minimize the potential impacts to model accuracy from using the Terrington Basin water levels as the downstream boundary in the model.

The Flood Risk Mapping model was very similar to the Flood Forecasting model on the Churchill River since the bathymetry for both models was defined based on the survey data collected as part of this project, although fewer discrepancies related to the movement of the sandbars on the river were present due to the relatively short time between the bathymetric survey and LiDAR capture. However, some interpretation and adjustment were required to adjust the cross sections at locations where the riverbed was below water but too shallow to traverse by boat.

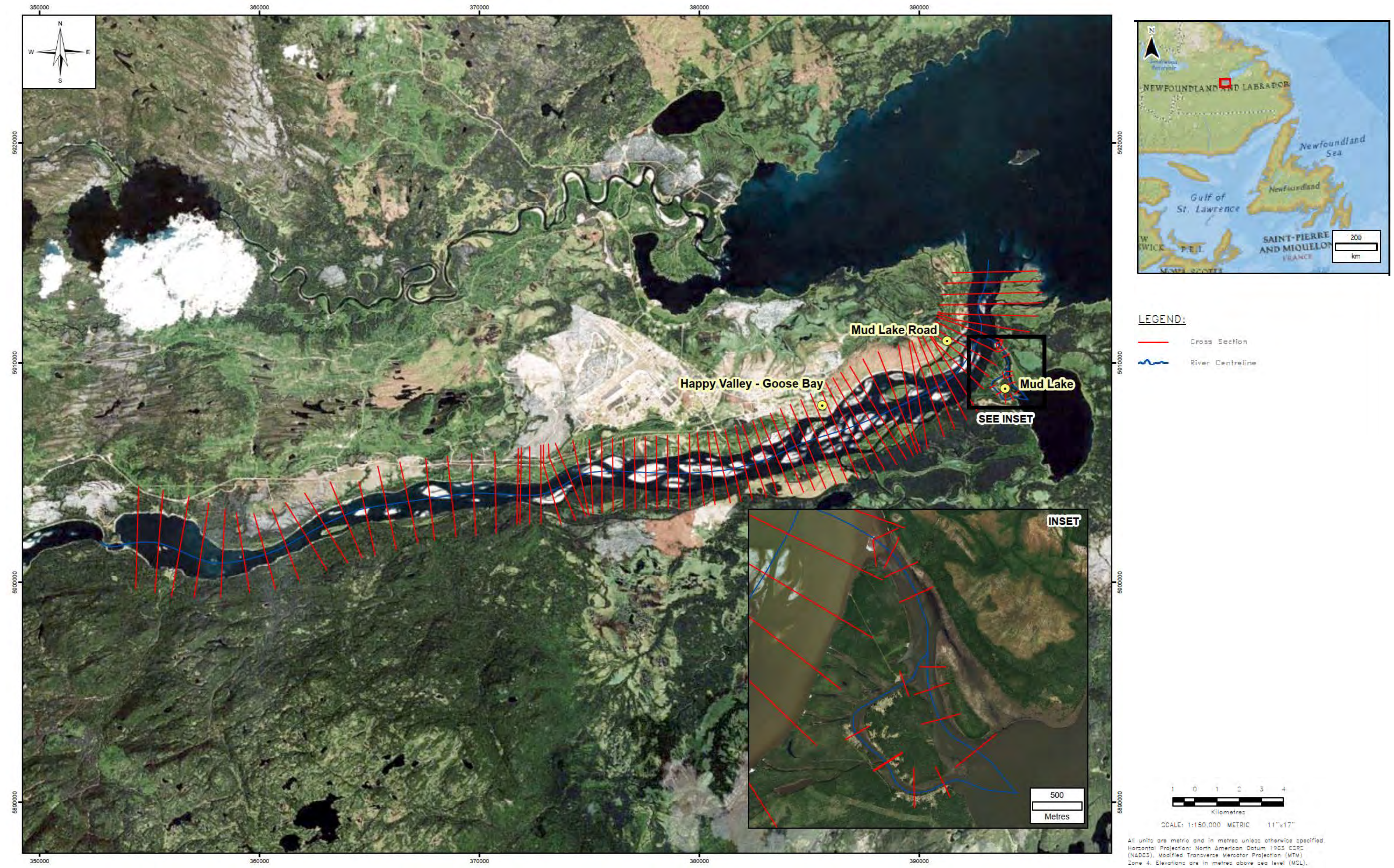
In addition to the Churchill River, the Flood Risk Mapping model also included the Mud Lake channels from the confluence with the Churchill River to Mud Lake. The Mud Lake channels were represented in the model based on the surveyed cross sections collected and 2019 LiDAR data collected by KGS Group.

Cross Sections

As previously described in Section 9.2.2, the HEC-RAS model of the Churchill River consisted of 72 cross sections on the Churchill River spaced at every 1 km between Muskrat Falls and the Trans Labrador Highway, and every 500 m between the Trans Labrador Highway and Lake Melville. The Mud Lake Channels in the model consisted of 14 cross sections, 12 of which were based on the bathymetric survey data, and 2 that were estimated based on nearby cross sections and the 2019 LiDAR data. The locations of the cross sections included in the model are shown on Figure 57. Plots of each cross section included in the model are included in Appendix L.

FIGURE 57

CROSS SECTIONS INCLUDED IN THE FLOOD RISK MAPPING MODEL



Boundary Conditions

The Flood Risk Mapping model included an inflow boundary at the upstream end of the model representing inflows into the model domain from Muskrat Falls. Point source inflows were defined in the model to represent contributions from the small tributaries to the lower Churchill River in the model, including the Traverspine River and inflows into Mud Lake. In total, six tributary inflows were included in the model.

For the initial Flood Risk Mapping model (i.e. first step model upstream of English Point), the downstream boundary condition was defined as the recorded water levels at the WSC gauge at English Point (i.e. 03PC001). For the extended model (i.e. second step model that was extended to Lake Melville), the downstream boundary condition was defined as the water levels forecast by DFO at Terrington Basin (i.e. Station 1350).

Bridge Structures

The Trans Labrador Highway Bridge was included in the HEC-RAS model of the Churchill River, and was defined based on both survey data collected as part of the field program and design drawings of the bridge provided by WRMD. The footbridge over the Mud Lake Channel was also incorporated into the model based on the survey data collected as part of the project.

Based on the results of the hydraulic modelling, the Trans Labrador Highway Bridge and Mud Lake Channel Bridge can safely convey the 20 and 100 year flows for both the current climate and climate change conditions. The hydraulic conditions at the bridges associated with the 20 and 100 year flows are shown in Table 30.

TABLE 30
HYDRAULIC CONDITIONS AT THE TRANS LABRADOR BRIDGE AND THE MUD LAKE CHANNEL BRIDGE

Location	Climate Condition	AEP Flood	Flow (m^3/s)	Upstream Water Level (m)	Downstream Water Level (m)	Head Loss (m)	Bridge Clearance (m)	Velocity (m/s)
Trans Labrador Bridge	Current Climate	20-Year	6,033	4.25	4.21	0.04	5.31	1.2
		100-Year	6,744	4.51	4.46	0.05	5.05	1.3
	Climate Change	20-Year	6,154	4.32	4.27	0.05	5.24	1.2
		100-Year	6,878	4.57	4.53	0.04	4.99	1.3
Mud Lake Channel Bridge	Current Climate	20-Year	25	1.33	1.33	0	1.08	0.3
		100-Year	31	1.51	1.51	0	0.9	0.3
	Climate Change	20-Year	31	1.67	1.67	0	0.74	0.3
		100-Year	37	1.82	1.82	0	0.59	0.3

Lateral Structures

To account for any overflow from the Churchill River to the Mud Lake Channel and Mud Lake, a lateral weir structure was incorporated into the HEC-RAS model to convey flow from the east bank of the Churchill River into the Mud Lake Channel. The crest of the weir was defined based on a LiDAR profile along the riverbank.

Storage Areas

A storage area was defined in the model to represent Mud Lake. The storage of Mud Lake was found to dampen the tidal effects in the community of Mud Lake. The storage curve for the lake was defined using the product of the lake area and lake depth. The lake area was initially estimated based on satellite imagery and adjusted as part of the model calibration, and the lake depth was assumed based on nearby surveyed cross sections.

Manning's Roughness Coefficient

Manning's roughness coefficients were estimated for the hydraulic model based on the calibration of the model to observed water levels and flows. Unlike the Flood Forecasting model, an aggregate roughness coefficient was applied to the channel and sandbar for each cross section, with roughness coefficients ranging from 0.023 to 0.025 on the Churchill River from Muskrat Falls to the confluence with the Mud Lake Channel and 0.045 downstream of the Mud Lake Channel. Initially, separate roughness coefficients were assigned to the sandbars and channel sections, however, over the course of the model calibration it was found that an aggregate roughness coefficient resulted in a better model calibration. The roughness coefficients on the Mud Lake Channels were set to 0.041. Overbank roughness coefficients on both Churchill River and the Mud Lake Channels were set to 0.055. The roughness coefficients fit within the standard values, and as such were considered acceptable. The roughness coefficients for the cross sections are shown graphically with each cross section in Appendix L.

Contraction and Expansion Coefficients

The expansion and contraction coefficients on the Churchill River were set to 0.3 and 0.5 on the Churchill River to account for the additional losses associated with the sandbars on the river. The expansion and contraction coefficients on the Mud Lake Channels were set to 0.1 and 0.3 due to the gentle transitions on the channels.

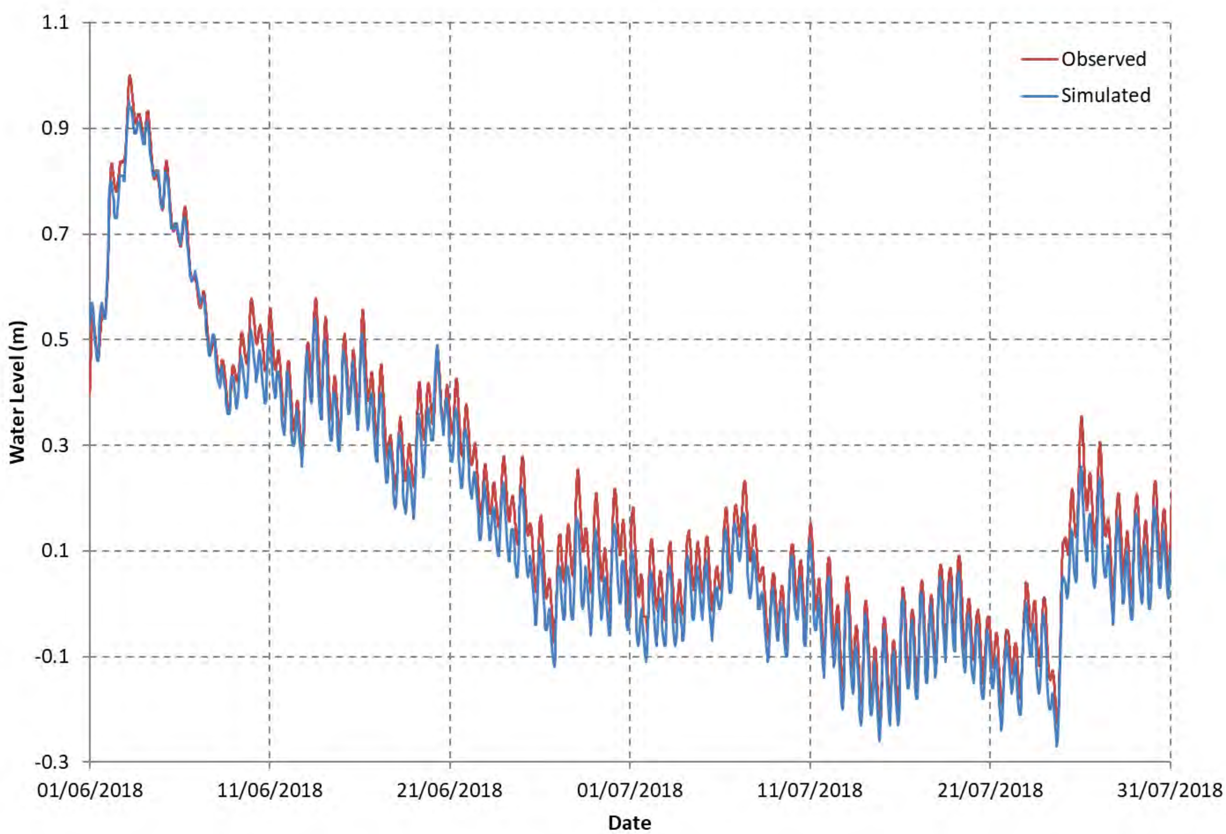
9.2.5 Calibration and Validation of The Flood Risk Mapping Model

The calibration of the Flood Risk Mapping model followed the same process as the Flood Risk Mapping model and considered the same flood events (i.e. Summer 2018, Fall 2017 and Summer 2017). However, due to the addition of the Mud Lake Channels into the model, and the additional hydrometric data that was available following the completion of the model, the model was further validated to the ice-free portion of the Spring 2019 freshet (i.e. May 20, 2019 – July 19, 2019). Flow conditions ranged from approximately 4,700 m^3/s to 1,500 m^3/s. Inflows to the tributaries included in the model were defined based on the simulated outflow from the HEC-HMS model for each of the HEC-RAS calibration timeframes.

Summer 2018

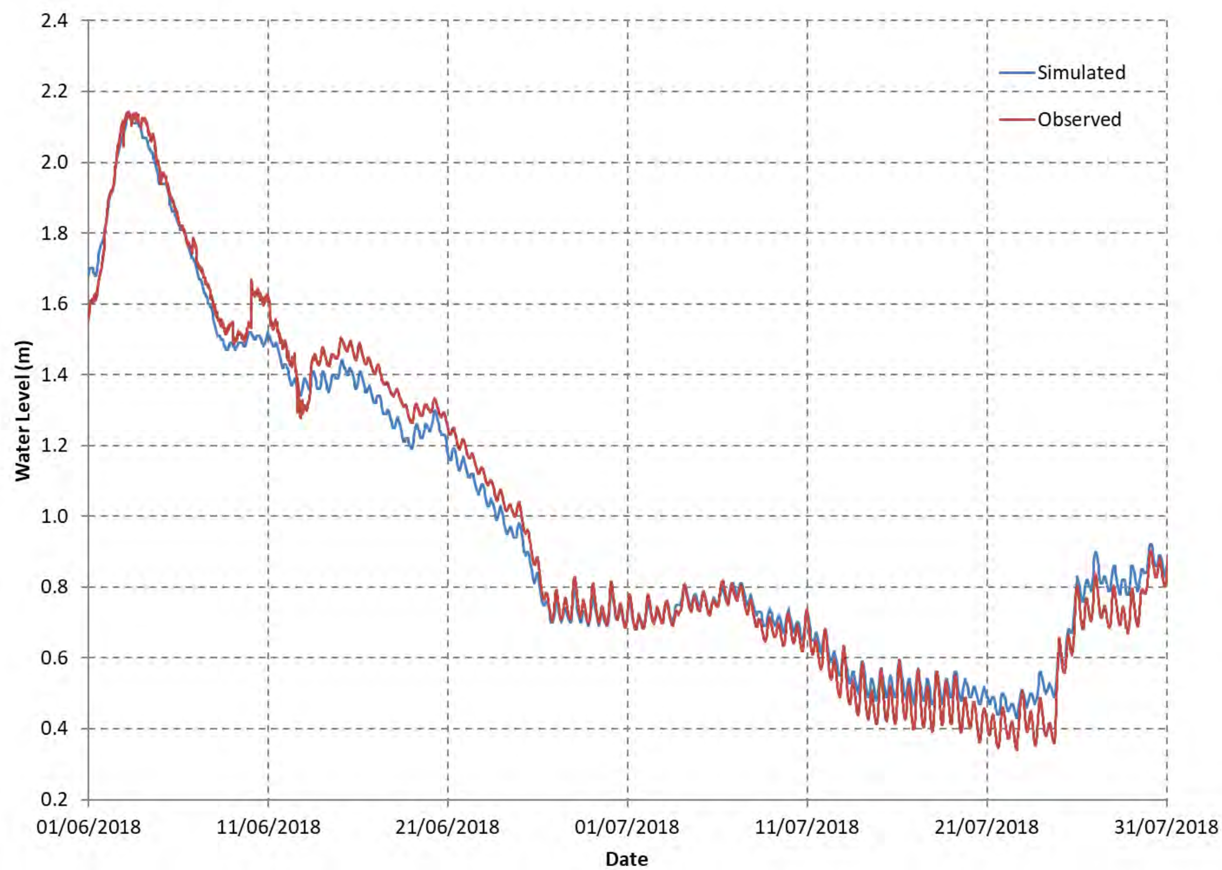
The HEC-RAS model accurately depicted the recorded flows at Mud Lake, as shown on Figure 58, with an RMSE of 0.05 m. The maximum difference between the simulated and observed water levels of 0.12 m occurred on June 28. This discrepancy is due to the model slightly underestimating the tidal range during low flow conditions.

FIGURE 58
COMPARISON OF SUMMER 2018 OBSERVED AND SIMULATED WATER LEVELS AT MUD LAKE (FLOOD RISK MAPPING MODEL)



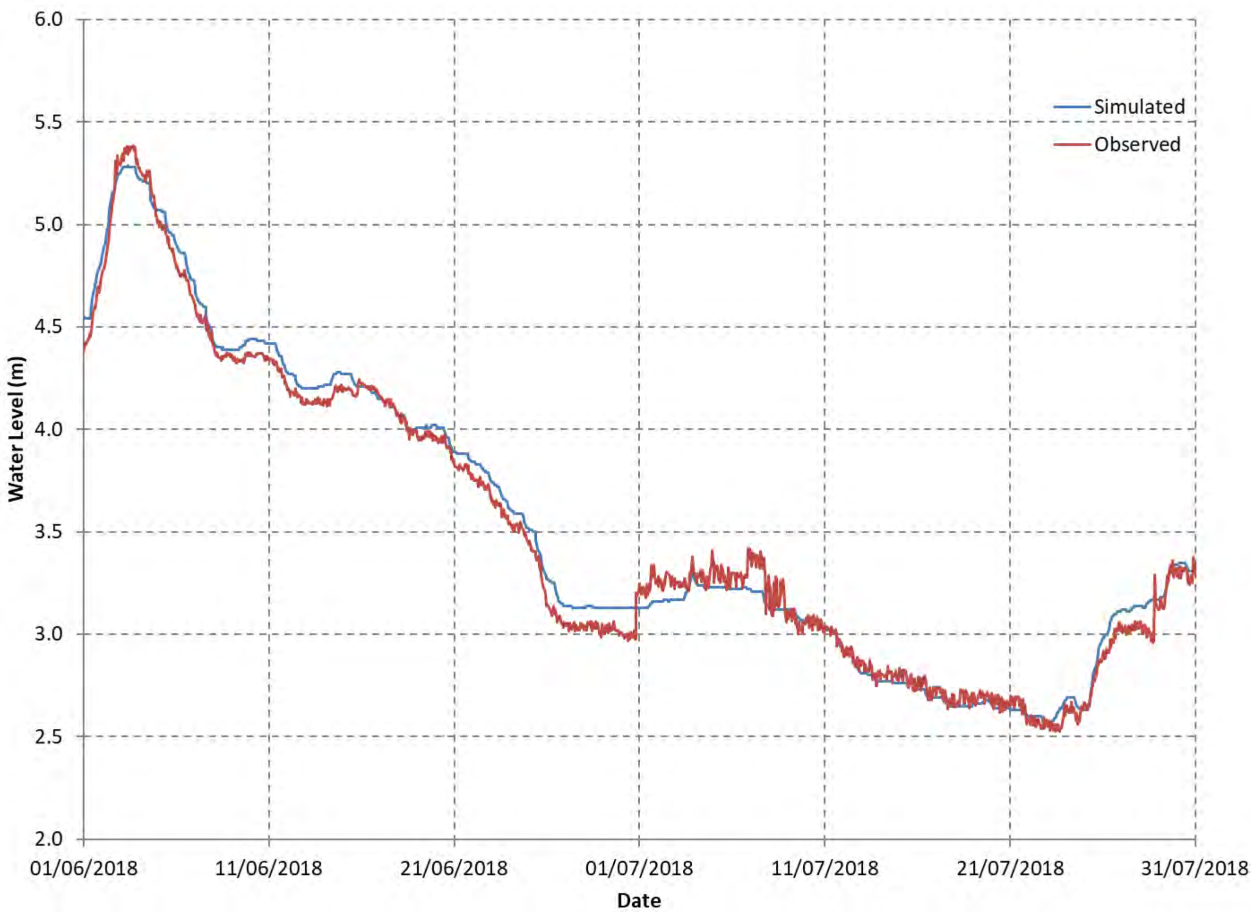
The model accurately represented water levels at Happy Valley – Goose Bay, as shown on Figure 59, with a RMSE of 0.05 m. A maximum difference between the simulated and observed water levels of 0.17 m occurred on June 10, but it appears that this discrepancy can be attributed to an error with the recorded data, since the recorded water levels suddenly increases and drops over a short period.

FIGURE 59
COMPARISON OF SUMMER 2018 OBSERVED AND SIMULATED WATER LEVELS AT HAPPY VALLEY – GOOSE BAY (FLOOD RISK MAPPING MODEL)



The model also accurately represented the recorded water levels downstream from Muskrat Falls, with an overall RMSE of 0.07 m and a maximum discrepancy of 0.21 m between the observed and simulated water levels, as shown on Figure 60. However, similar to the recorded water levels at Happy Valley – Goose Bay, the recorded water levels show a sudden rise in water levels on July 1 and sudden drop in water levels on July 7 and 8, as well as a sudden change in water levels on July 28. Accordingly, the maximum discrepancy can likely be attributed to an error in the recorded data.

FIGURE 60
COMPARISON OF SUMMER 2018 OBSERVED AND SIMULATED WATER LEVELS 6.15 KMS BELOW LOWER MUSKRAT FALLS (FLOOD RISK MAPPING MODEL)

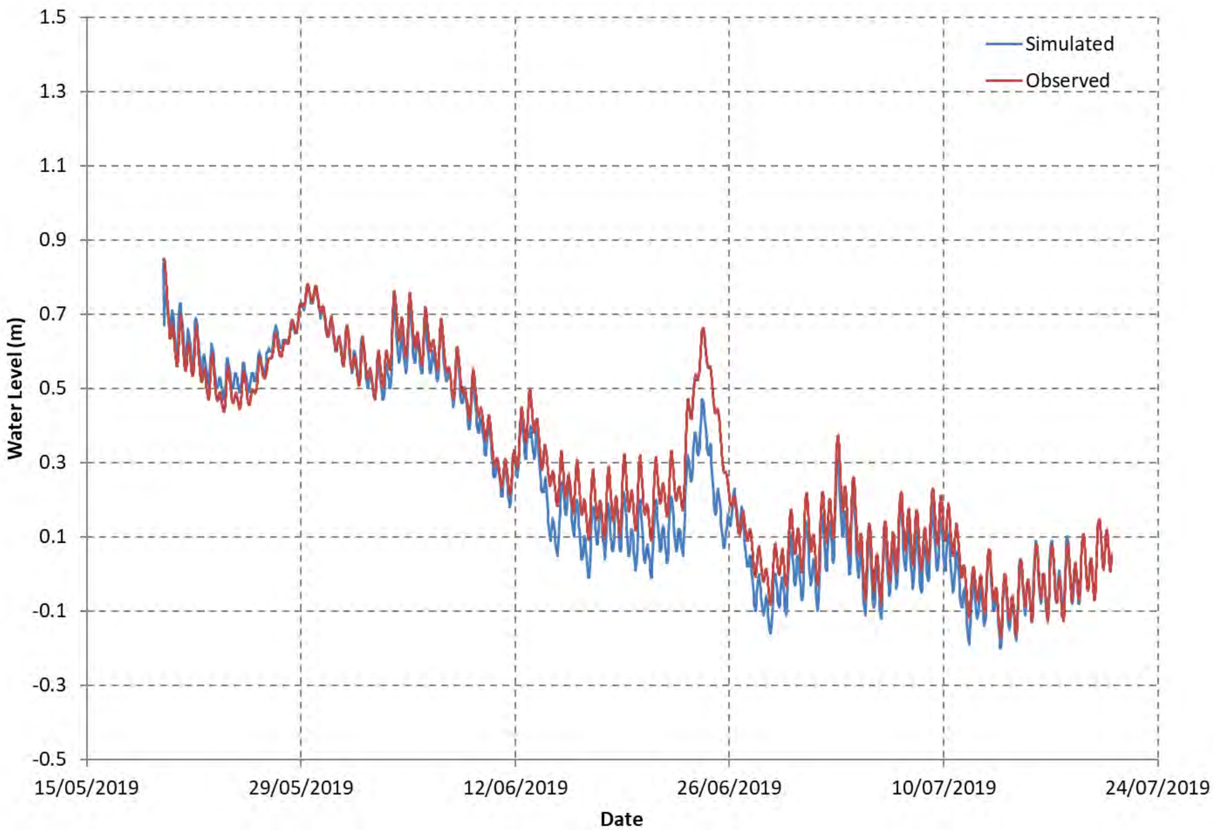


Spring 2019

The HEC-RAS model accurately depicted the recorded flows at Mud Lake, as shown on Figure 61, with an RMSE of 0.07 m. The maximum difference between the simulated and observed water levels of 0.18 m occurred on June 24. This discrepancy appears to be due to wind setup on Lake Melville due to Hurricane Dorian.

FIGURE 61

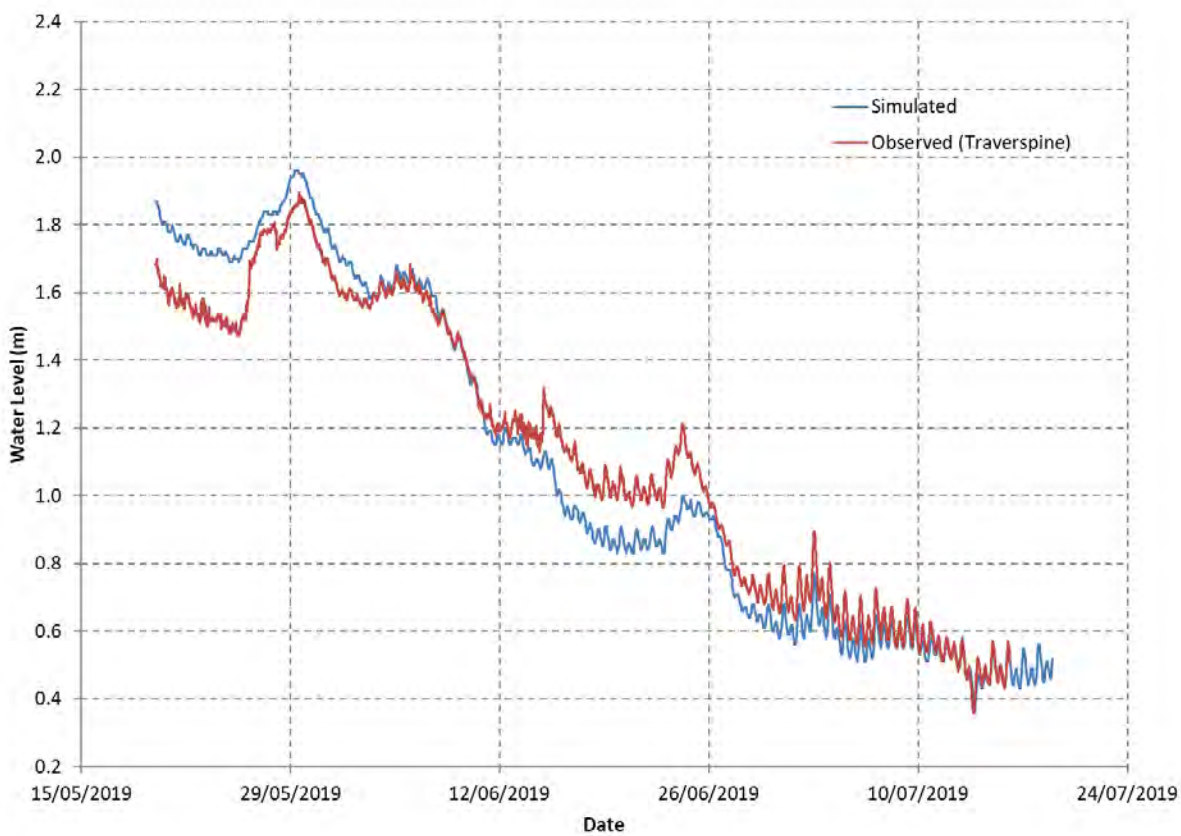
COMPARISON OF SUMMER 2019 OBSERVED AND SIMULATED WATER LEVELS AT MUD LAKE (FLOOD RISK MAPPING MODEL)



The model accurately represented water levels at Happy Valley – Goose Bay, as shown on Figure 62, with a RMSE of 0.10 m. However, the WSC gauge at Happy Valley – Goose Bay had malfunctioned, and instead the gauge across the Churchill River (i.e. Churchill River Below Traverspine River) was used as the calibration gauge. A difference between the simulated and observed water levels of 0.20 m occurred on between May 20 and May 26, but it appears that this discrepancy can be attributed to an error with the recorded data, since the recorded water levels suddenly increases on May 26. A similar error is present on June 15. Accordingly, some of the errors and the higher RMSE are likely attributable to errors in the gauge measurements.

FIGURE 62

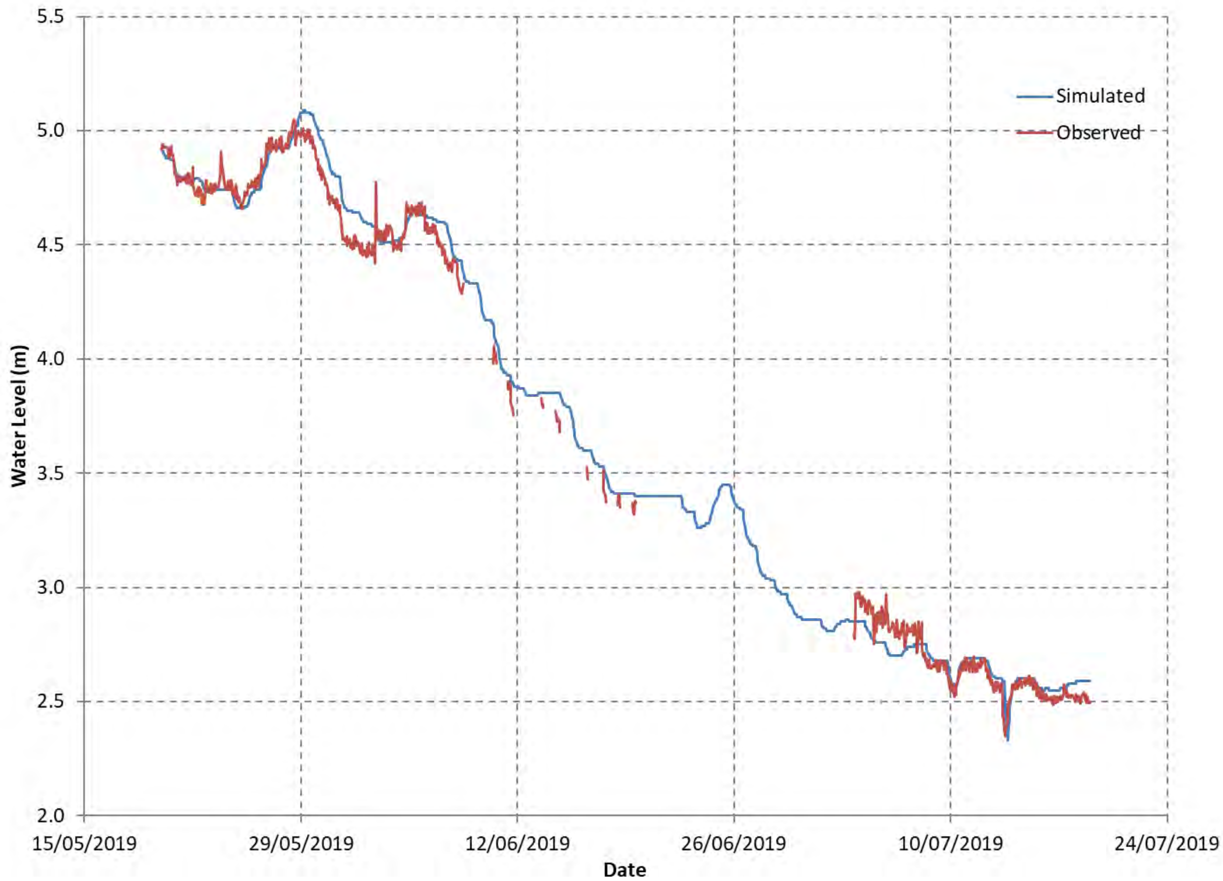
COMPARISON OF SUMMER 2019 OBSERVED AND SIMULATED WATER LEVELS AT HAPPY VALLEY – GOOSE BAY (FLOOD RISK MAPPING MODEL)



The model also accurately represented the recorded water levels downstream from Muskrat Falls, with an overall RMSE of 0.08 m and a maximum discrepancy of 0.3 m between the observed and simulated water levels, as shown on Figure 63. However, there are many missing records and discontinuities in the recorded water levels, and the recorded water levels show a sudden spike on June 2. The maximum discrepancy can likely be attributed to an error in the recorded data.

FIGURE 63

COMPARISON OF SUMMER 2019 OBSERVED AND SIMULATED WATER LEVELS 6.15 KMS BELOW LOWER MUSKRAT FALLS (FLOOD RISK MAPPING MODEL)



Fall 2017

The model was also calibrated to recorded water levels on the Lower Churchill River collected at WRMD's Happy Valley – Goose Bay gauge and WSC's gauge station 03OE014. The model accurately represented the recorded water levels at Happy Valley – Goose Bay and below Muskrat Falls, with an RMSE of 0.09 m and 0.09 m, as shown on Figure 64 and Figure 65.

FIGURE 64

COMPARISON OF FALL 2017 OBSERVED AND SIMULATED WATER LEVELS AT HAPPY VALLEY – GOOSE BAY (FLOOD RISK MAPPING MODEL)

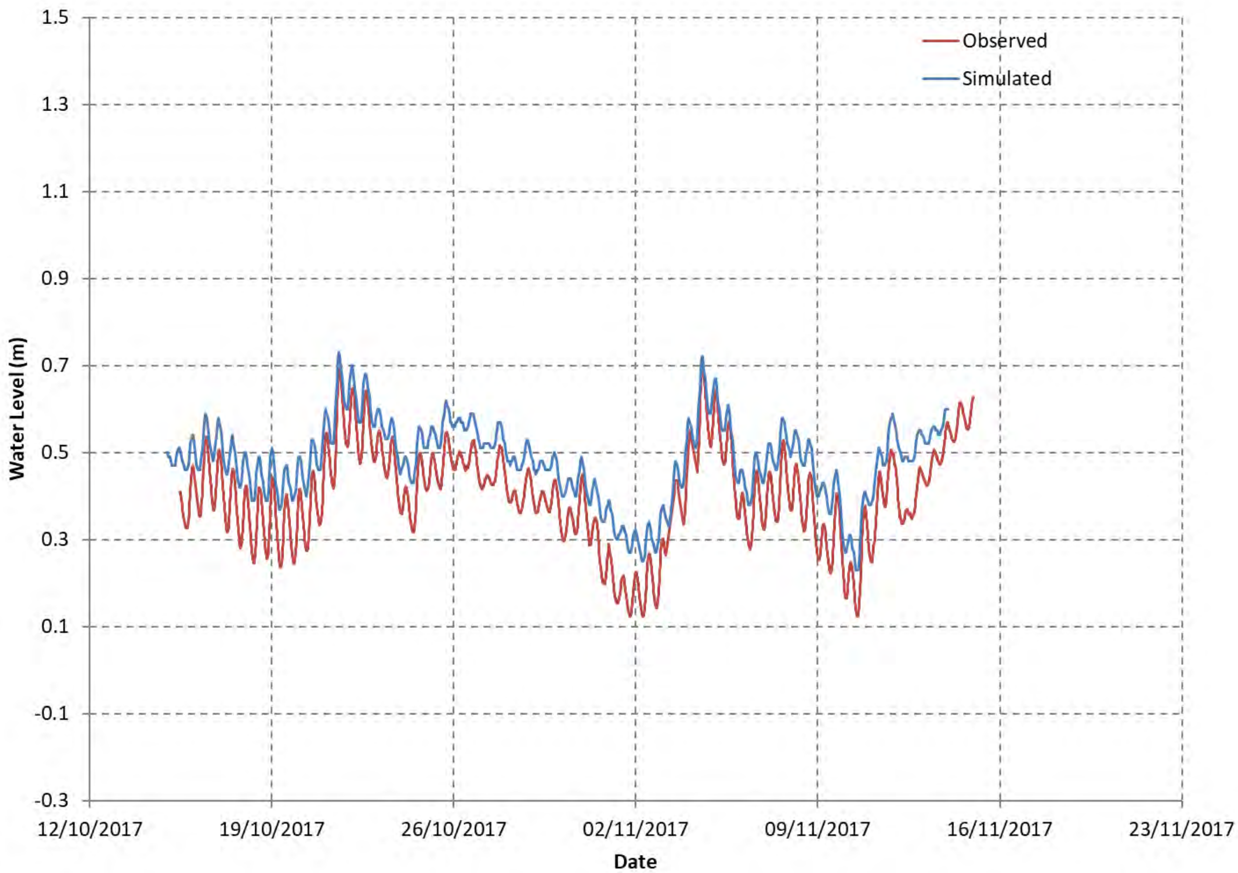


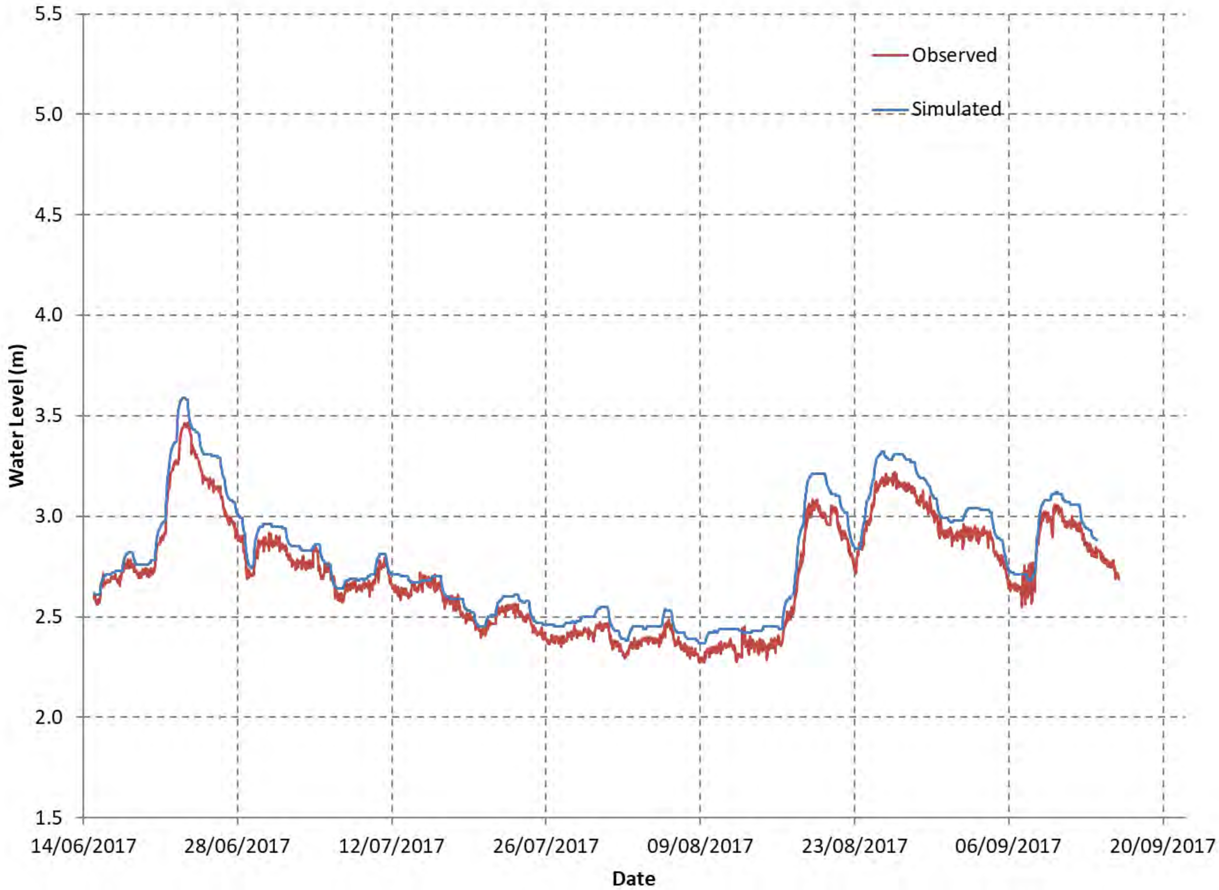
FIGURE 65

COMPARISON OF FALL 2017 OBSERVED AND SIMULATED WATER LEVELS 6.15 KMS BELOW LOWER MUSKRAT FALLS (FLOOD RISK MAPPING MODEL)

Summer 2017

The model was validated to recorded hourly water levels at the WSC gauge station below Muskrat Falls (i.e. 03OE014). Hourly data at the WRMD station at Happy Valley – Goose Bay was unavailable, since the gauge was installed during fall 2017. The model accurately represented the hourly water levels, with an RMSE of 0.09 m. A comparison of the simulated and recorded water levels is shown on Figure 66.

FIGURE 66
COMPARISON OF SUMMER 2017 OBSERVED AND SIMULATED WATER LEVELS 6.15 KMS BELOW LOWER MUSKRAT FALLS (FLOOD RISK MAPPING MODEL)



Calibration of the Extended Model from English Point to Lake Melville

Similar to the Flood Forecasting Model, the Flood Risk Mapping model was extended to include the river reach from English Point to Lake Melville. The additional reach length incorporated into the Flood Risk Mapping Model was calibrated to the recorded water levels at English Point for the same four events (i.e. Summer 2018, Spring 2019, Fall 2017, Summer 2017) using the historical DFO tidal prediction data as the downstream boundary condition.

A comparison of the recorded and simulated water levels at English Point for the Spring 2018, Spring 2019, Fall 2017, and Summer 2017 periods are shown on Figure 67 to Figure 70. In general, the model represented the range of water levels at English Point with a reasonable degree of accuracy. However, similar to the flood forecasting model, the water levels on Lake Melville only consider tidal influences and do not account for any meteorological or hydraulic processes on the lake, such as wind setup. Accordingly, while the model represents the tidal range well, as well as the change in water levels associated with high flows on the Churchill River, the model does not account accurately represent wind setup events, such as the setup that occurred on June 24, 2019 due to Hurricane Dorian. A comparison of the calibration accuracy for the initial and extended Flood Risk Mapping models is shown in Table 31.

FIGURE 67
COMPARISON OF SUMMER 2018 OBSERVED AND SIMULATED WATER LEVELS AT ENGLISH POINT (FLOOD RISK MAPPING MODEL)

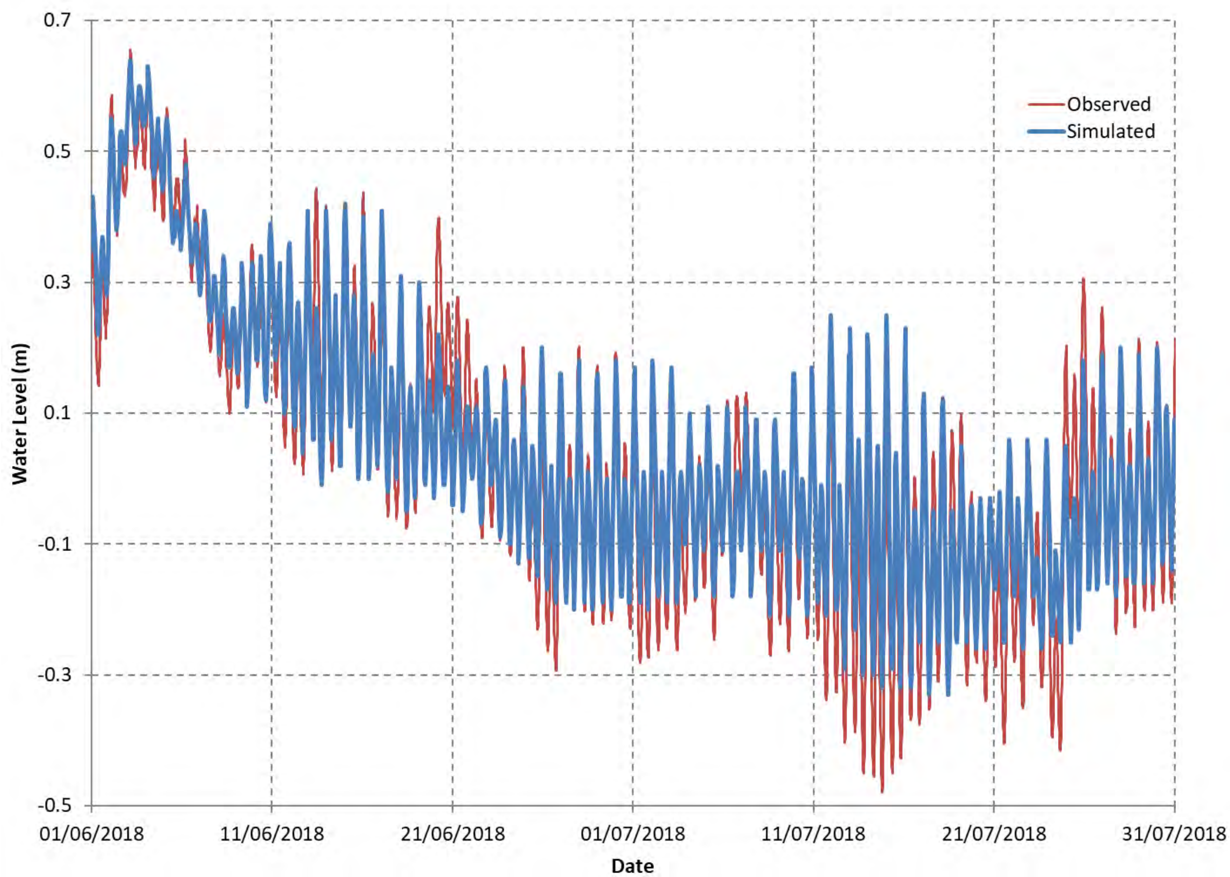


FIGURE 68

COMPARISON OF SPRING 2019 OBSERVED AND SIMULATED WATER LEVELS AT ENGLISH POINT (FLOOD RISK MAPPING MODEL)

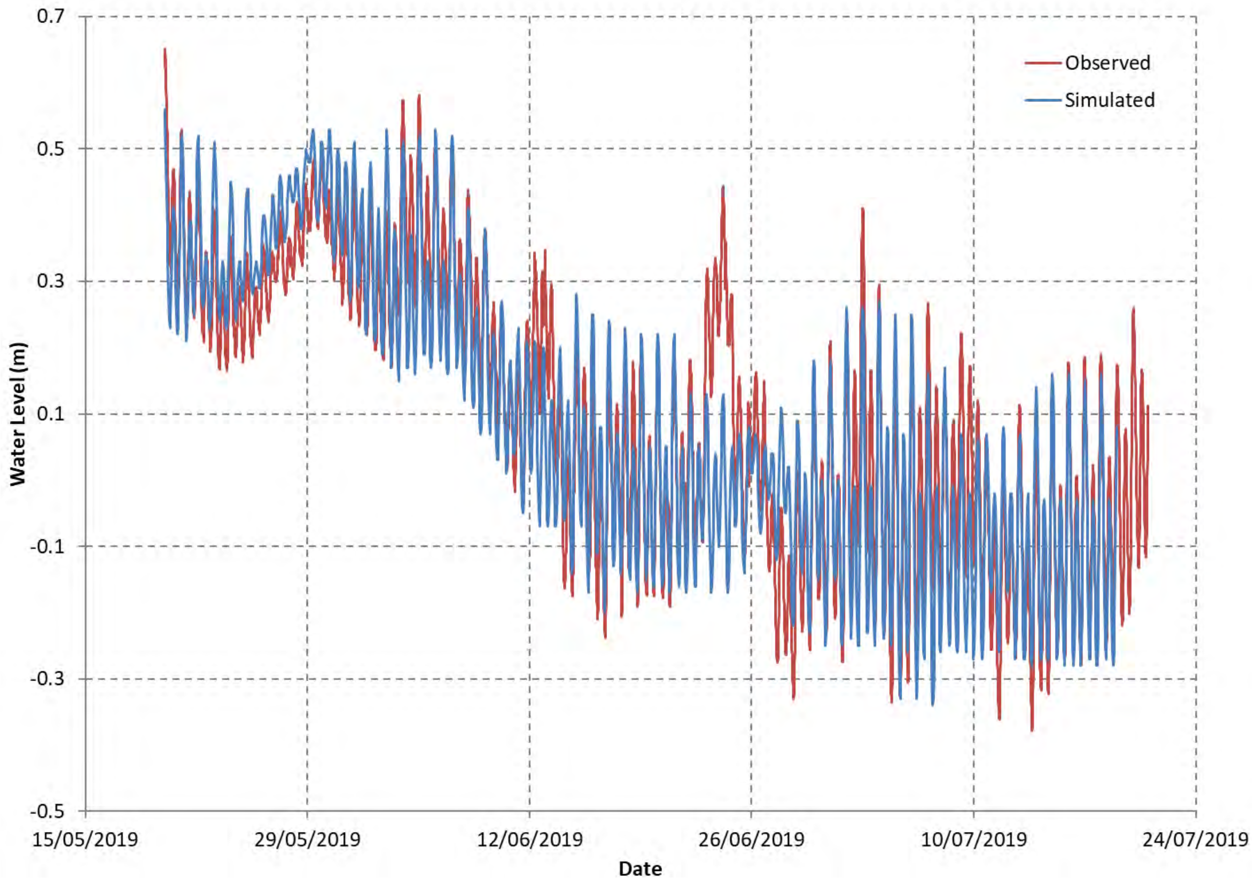


FIGURE 69

COMPARISON OF FALL 2017 OBSERVED AND SIMULATED WATER LEVELS AT ENGLISH POINT (FLOOD RISK MAPPING MODEL)

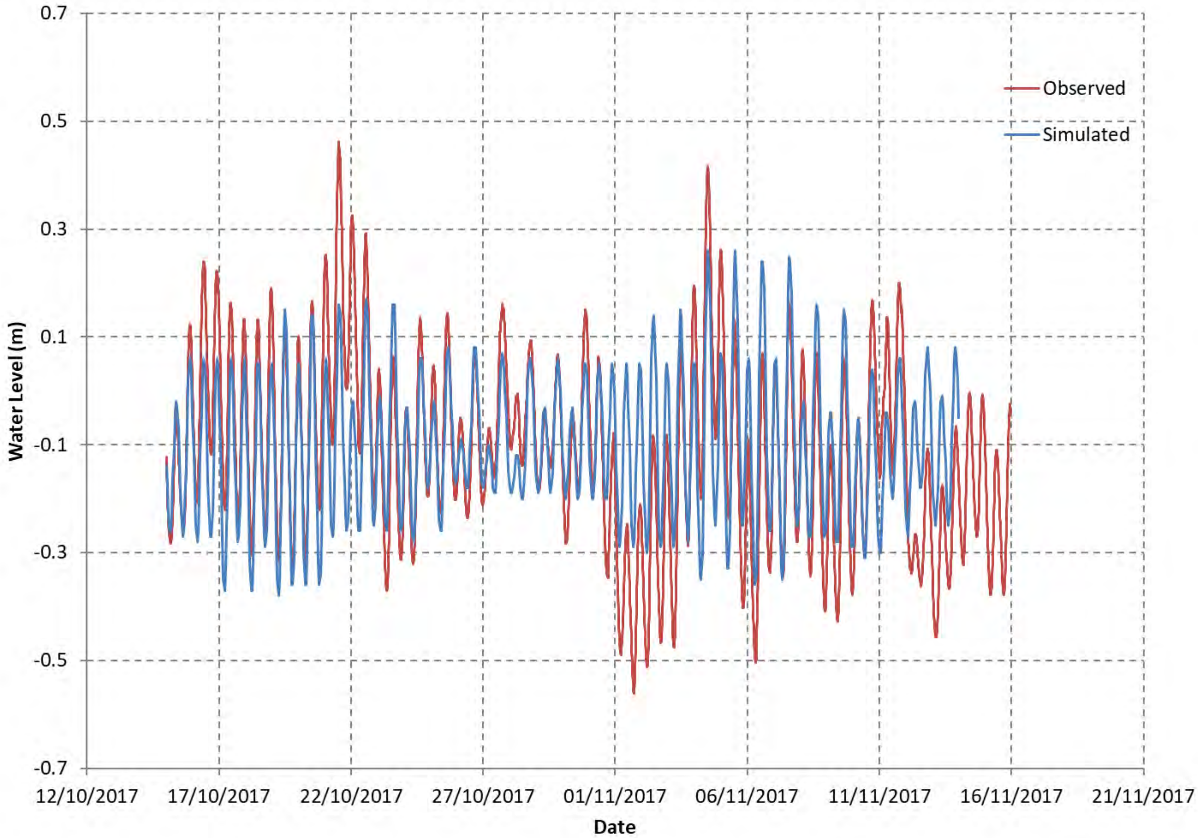


FIGURE 70
COMPARISON OF SUMMER 2017 OBSERVED AND SIMULATED WATER LEVELS AT ENGLISH POINT (FLOOD RISK MAPPING MODEL)

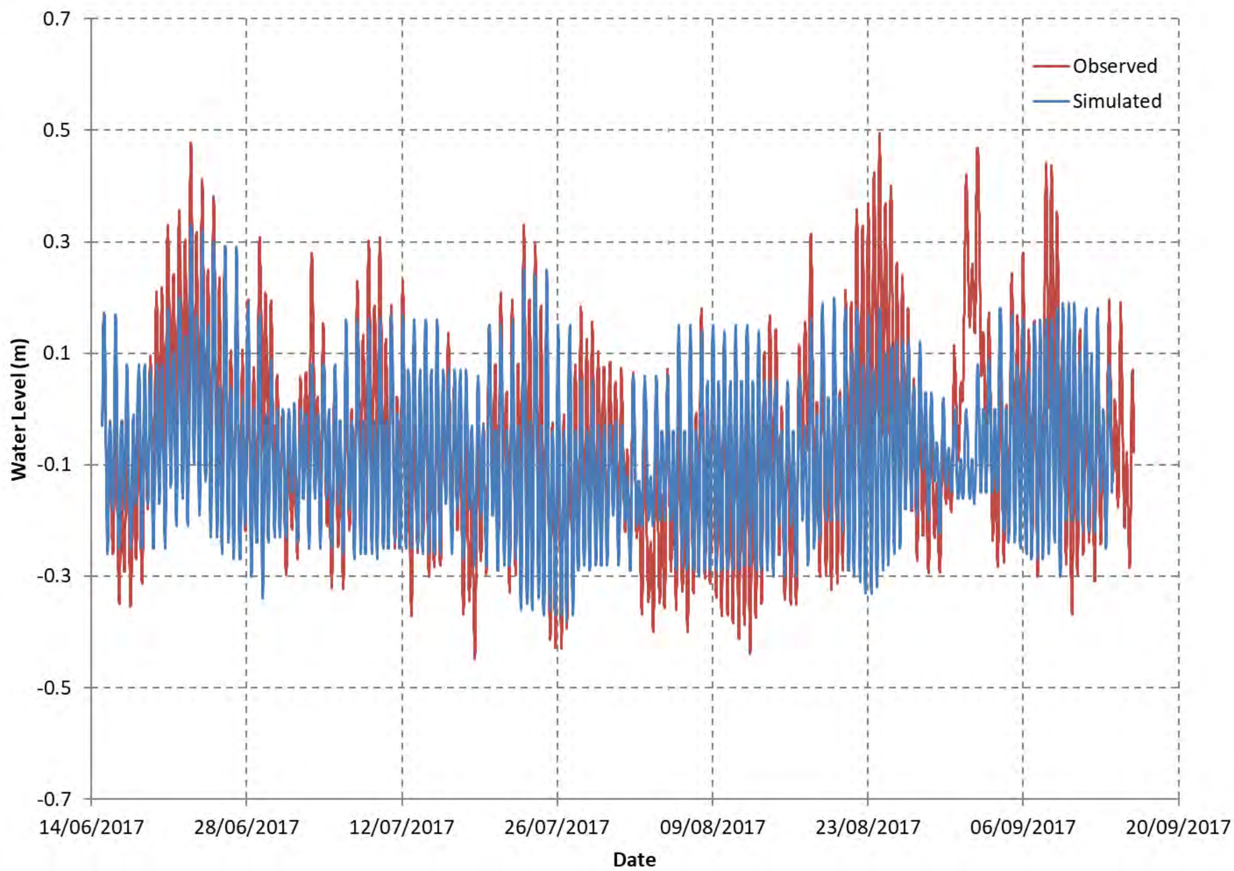


TABLE 31
COMPARISON OF THE INITIAL AND EXTENDED FLOOD RISK MAPPING MODEL RMSE

Location	Initial Model RMSE (m)				Extended Model RMSE (m)			
	Spring 2018	Fall 2017	Summer 2017	Spring 2019	Spring 2018	Fall 2017	Summer 2017	Spring 2019
English Point	- - -	- - -	- - -	- - -	0.07	0.13	0.12	0.09
Happy Valley – Goose Bay	0.05	0.09	- - -	0.07	0.06	0.10	- - -	0.11
Below Muskrat Falls	0.07	0.09	0.09	0.08	0.07	0.09	0.09	0.08
Mud Lake	0.05	- - -	- - -	0.07	0.07	- - -	- - -	0.12

The Flood Risk Mapping model calibration was comparably accurate to the Flood Forecasting model calibration. Since the model was developed and optimized to also consider the Mud Lake channels, the model is able to accurately represent the hydraulic characteristics (i.e. water levels, velocities, etc.) along those channels, which is a critical requirement for this flood risk mapping assessment.

Similar to the Flood Forecasting model, the Flood Risk Mapping model is representative of present-day conditions, and as such the geomorphology of the Churchill River may result in different conditions on the river than those included in the development and calibration of the model. Accordingly, the model calibration should be reviewed on an ongoing basis (i.e. at least every 5 years or after every major flood event) in conjunction with WRMD's ongoing monitoring of the sandbar morphology on the Churchill River, and any considerable changes identified in the sandbar monitoring or deviations in the model calibration may warrant the collection and incorporation of new cross sections into the model, recalibration to future conditions, and re-assessment of the 20 and 100-year floods.

9.2.6 Open Water Hydraulic Modelling of The 20 and 100 Year Floods

Following the successful calibration of the open water Flood Risk Mapping model, the 20 and 100 year floods were simulated for both the current climate and climate change conditions. Future development conditions were not anticipated to affect the flood flows on the Churchill River, as noted in Section 8.3, and as such were not included in the hydraulic modelling. The definition of the boundary conditions for the climate change conditions are described in detail in Section 8.2. Inflows on the tributaries were defined using the RFFA equations, while inflows at Muskrat Falls were defined by the SSFA flows. The water level on Lake Melville was defined as the maximum tidal level from the forecast Terrington Basin water levels for the current climate conditions, which corresponded to 0.22 m. For climate change conditions, the Terrington Basin water levels were increased by the anticipated sea level rise (i.e. an increase of 0.70 m) described in Batterson and Liverman's report (2010), with a corresponding Lake Melville level of 0.92 m. The inflow boundary conditions included in the simulations of the 20 and 100 year floods are summarized in Table 32.

TABLE 32
INFLOWS FOR THE 20 AND 100-YEAR FLOOD SIMULATIONS

Location	River	Cross Section	Current Climate		Climate Change	
			20-Year Flow (m3/s)	100-Year Flow (m3/s)	20-Year Flow (m3/s)	100-Year Flow (m3/s)
Muskrat Falls	Churchill River	41243.4	5,920	6,610	6,038	6,742
Tributary	Churchill River	40242.1	66	77	67	79
Tributary	Churchill River	36181.3	19	23	20	23
Tributary	Churchill River	25199.9	28	33	29	34
Tributary	Churchill River	13613.6	22	26	22	26
Traverspine River	Churchill River	9566.4	247	291	252	297
Mud Lake Inflow	Mud Lake Inlet	100.0	40	47	40	48

Water levels at a number of key locations along the lower Churchill River and Mud Lake Channels resulting from the hydraulic modelling of the 20 and 100 year floods for both the current climate and climate change conditions are summarized in Table 33. The bank levels at each of the key locations is also shown in Table 33 for perspective on flood depths.

TABLE 33
20 AND 100 YEAR FLOOD LEVELS AT KEY LOCATIONS

Location	River	Cross Section	Left Bank Elevation (m)	Right Bank Elevation (m)	Current Climate		Climate Change	
					20 Year Flood Level (m)	100 Year Flood Level (m)	20 Year Flood Level (m)	100 Year Flood Level (m)
Mud Lake near T. Edmunde Residence	Mud Lake Channel	3555	1.4	1.4	1.3	1.5	1.6	1.8
Mud Lake near D. Campbell Residence	Mud Lake Channel	4357	1.5	3.1	1.3	1.5	1.7	1.8
Mud Lake near United Church	Mud Lake Channel	4777	2.6	2.8	1.3	1.5	1.7	1.8
Mud Lake near Hydro Generator	Mud Lake Channel	5223	3.1	2.2	1.4	1.5	1.7	1.8
Mud Lake near C. Best Non-Permanent Residence	Mud Lake Channel	5538	2.2	1.4	1.4	1.5	1.7	1.8
End of Mud Lake Road / English Point	Churchill River	32	2.2	4.4	0.9	1.0	1.3	1.4
Mud Lake Road	Churchill River	482	1.7	5.5	1.0	1.2	1.4	1.6
Mud Lake Road	Churchill River	874	3.1	3.1	1.2	1.4	1.6	1.7
Mud Lake Road	Churchill River	1135	2.4	2.0	1.2	1.4	1.6	1.7
Mud Lake Road	Churchill River	1799	2.5	3.3	1.3	1.4	1.6	1.8
Mud Lake Road	Churchill River	2246	1.9	2.0	1.4	1.5	1.7	1.8
Mud Lake Road	Churchill River	2704	1.5	1.9	1.4	1.6	1.8	1.9
Below Traverspine River	Churchill River	9049	4.6	3.0	2.3	2.5	2.4	2.6
Happy Valley - Goose Bay	Churchill River	9566	5.8	3.0	2.4	2.6	2.5	2.7
Happy Valley - Goose Bay	Churchill River	10078	5.5	3.3	2.4	2.6	2.6	2.8
Happy Valley - Goose Bay	Churchill River	10602	5.6	2.5	2.5	2.7	2.7	2.8
Below Trans Labrador Highway	Churchill River	24064	9.4	20.9	4.2	4.5	4.3	4.6
Above Trans Labrador Highway	Churchill River	24201	11.2	15.6	4.2	4.5	4.3	4.6
6.15 km Below Muskrat Falls	Churchill River	36181	6.5	7.1	5.7	6.0	5.7	6.0

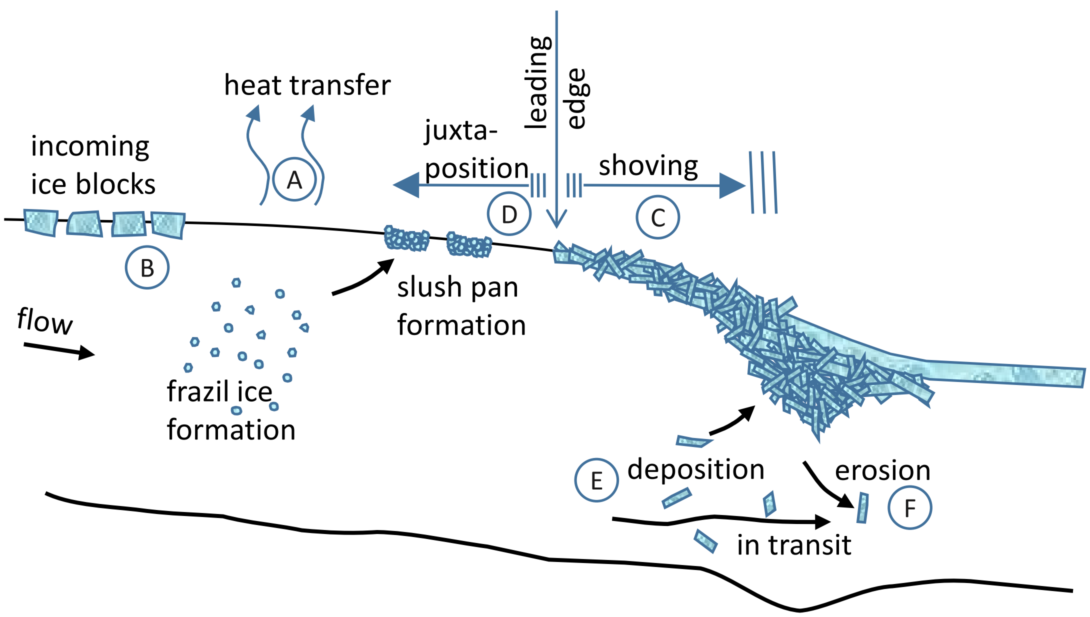
The resulting 20 and 100 year flood levels for both the current climate and climate change conditions were used to develop the Flood Risk and Flood Hazard maps as described in Section 12.0.

9.3 ICE-AFFECTED CONDITIONS

9.3.1 Overview of Ice Processes

The river ice model RIVICE was used to simulate freeze-up, mid-winter and breakup/jamming conditions along the lower Churchill River. The key river ice processes simulated in RIVICE that are relevant to this study are shown on Figure 71 and described below.

FIGURE 71
RIVICE PROCESSES SIMULATED IN THE RIVICE MODEL



Source: Sheikholeslami et al. (2017)

There are two sources of ice for the establishment of an ice cover and/or ice jam. The first source is frazil ice, represented as ‘A’ on Figure 71, that is generated in the river during autumn freeze-up when the overlying air temperature is freezing, inducing a transfer of heat from the river water to the atmosphere, and the river water temperature drops to a fraction below 0 °C (i.e. super cooling). The frazil crystals conglomerate into flocs and further into slush pans that float to the top and flow along the water surface to the leading edge of the downstream ice cover. The second source is the volume of inflowing ice per time step, represented as 'B' in Figure 71, representing ice blocks broken apart from upstream ice sheets during spring ice-cover breakup. This ice floats along the water surface at the mean flow velocity of the river until it reaches the downstream ice cover's leading edge.

Once the ice reaches the leading edge, two processes are at hand for the progression of the ice cover. The first process is the shoving of the ice cover, represented as 'C' in Figure 71 in the downstream direction through "telescoping" of the ice, which thickens the existing ice cover further downstream. Shoving occurs when the summation of external forces on the cover, specifically the thrust of the flowing water against the leading edge (i.e. F_T), the weight of the ice cover in the sloping direction (i.e. F_W) and the drag force on the ice cover's underside by the flowing water (i.e. F_D) exceed the ice cover's internal resistance (i.e. F_I) plus the frictional force of the ice cover along the river banks (i.e. F_F), given by the equation:

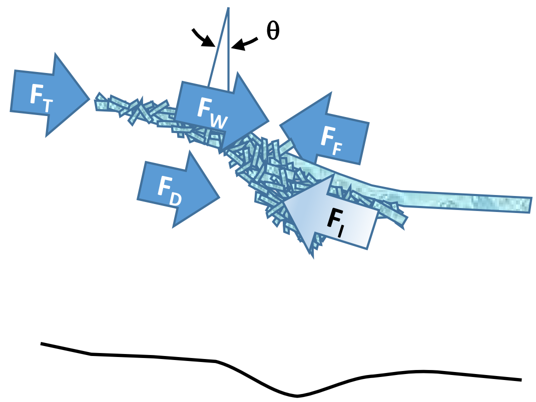
$$F_T + F_W + F_D > F_I + F_F \qquad \text{(Eq. 2)}$$

The second process is the progression of the ice cover upstream through juxtapositioning of the ice cover, represented as 'D' in Figure 71, when the internal resistance within the cover (i.e. F_I) plus the frictional force (i.e. F_F) remain larger than the summation of the external forces (i.e. F_T, F_W and F_D), given by the equation:

$$F_T + F_W + F_D < F_I + F_F \qquad \text{(Eq. 3)}$$

If the internal resistance forces exceed the summation of the external forces and the ice blocks and/or slush pans accumulate at the leading edge, the ice pans stack up against each other to extend the ice cover upstream. As more and more ice accumulates, external forcing anywhere along the juxtapositioned ice cover may be large enough to collapse and shove the ice-cover in the downstream direction. The forces acting on the juxtapositioning ice are shown on Figure 72 and summarized in Table 34.

FIGURE 72
FORCES APPLIED TO AN ICE-JAM COVER



Source: Sheikholeslami et al. (2017)

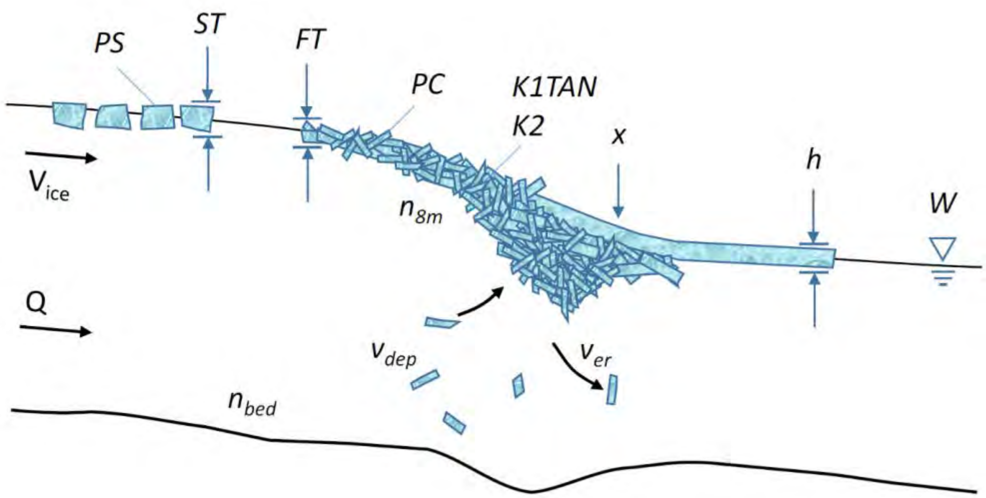
TABLE 34
FORCES APPLIED TO AN ICE-JAM COVER

Force	Description
F_T	Thrust force of the ice
F_D	Drag force from water flowing under the ice
F_W	Weight of the ice cover in the sloping direction
F_F	Frictional force of the ice on the river banks
F_I	Internal resistance of the ice

Ice under the cover may be eroded and transported downstream as ice in-transit. Should the mean flow velocity drop to below a velocity threshold value (i.e. v_d), the ice will deposit on the ice cover underside, as represented as ‘E’ on Figure 71. If the mean flow velocities underneath the ice cover increase and exceed a threshold value (i.e. v_e) the ice will erode from the underside, as represented as ‘F’ in Figure 71.

These processes are represented using parameters specific to the processes in RIVICE, as shown on Figure 73 and summarized in Table 35.

FIGURE 73
PARAMETERS USED TO DESCRIBE THE ICE PROCESSES IN RIVICE



Source: Sheikholeslami et al. (2017)

TABLE 35
PARAMETERS USED TO DESCRIBE THE ICE PROCESSES IN RIVICE

Variable	Description
PS	Porosity of Incoming Ice Pans
ST	Thickness of Incoming Ice Pans
Vice	Volume of Incoming Ice
PC	Ice Cover Front Porosity
FT	Ice Cover Front Thickness
H	Average Ice Cover Thickness
Vdep	Maximum Velocity for Ice Deposition
Ver	Minimum Velocity for Ice Erosion
n8m	Ice Cover Underside Roughness Coefficient
nbed	River Bed Roughness Coefficient
K1TAN	Ice Strength Parameter
K2	Ice Strength Parameter
Q	Churchill River Flow
W	Lake Melville Water Level
x	Ice Jam Toe Cross Section Number

The initial ice cover inserted in RIVICE has an average ice thickness (i.e. *h*). Two processes are available to add ice to the ice cover front that can potentially lead to an ice jam. The first process is the flow of incoming ice for each time step (i.e. V_{ice}) at the upstream boundary. This ice can represent both rubble ice or slush ice pans that are generated upstream of the modelling domain. The thickness and porosity of the ice are represented by the parameters *ST* and *PS*, respectively for both ice types. The second process for ice input to the ice cover front is the generation of slush ice pans through the aggregation of ice crystals (i.e. frazil ice) that form in the open water stretch upstream of the ice cover front. This occurs when the air temperature is cold enough to supercool the water (i.e. water temperature < 0°C). The heat transferred from the water into the atmosphere (i.e. *q*) is calculated using:

$$q = H(T_W - T_A) \quad \text{(Eq. 4)}$$

Where *H* is the heat transfer coefficient which typically lies in the range 15 – 25 W/m^2/°C, T_A is the below-freezing air temperature (°C) and T_W is the temperature of the water (°C). Many factors can affect the water-to-air transfer of heat, including wind speed, the degree of sheltering of the river from the wind (e.g. high sloping banks with trees provide more sheltering) and the amount of longwave radiation (e.g. cloudy conditions), which is an important heat source that can slow down the production of frazil ice. Only the open-water areas contribute to the heat loss, since heat loss through moving ice is considered negligible.

The ice cover front has a thickness of *FT* and a porosity of *PC*. The width of the river at the front is know from the cross-sectional input data, allowing the length of ice extending upstream from the front to be calculated from the inflowing volume of ice:

$$length = \frac{V_{ice}}{width \times ice\ thickness \times ice\ porosity} \quad \text{(Eq. 5)}$$

Coefficients for the roughness of the river bed (i.e. n_{bed}) and the ice-cover's underside (i.e. n_{8m}) are important parameters controlling the hydraulic and ice regimes. Bed roughness is a constant value represented by Manning's coefficient, while ice cover roughness is a function of ice cover thickness. The ice jam's internal strength is described by two ice strength parameters, *K1TAN* and *K2*. *K1TAN* relates the transfer of the ice stresses to the river bank, while *K2* represents the internal resistance of the ice, and is similar to passive conditions in soil mechanics. Important boundary conditions are the upstream discharge of the water (i.e. *Q*) entering the modelled river reach and the downstream water level elevation (i.e. *W*) where the water exits the reach. The location of the toe of the ice jam is represented by the variable *x*. The flow velocity thresholds for ice deposition and erosion are represented by v_{dep} and v_{er}.

The RIVICE model parameters, as well as the acceptable range of values adopted for the Churchill River RIVICE model, are summarized in Table 36. Note that for different rivers, the acceptable range of parameters would be different.

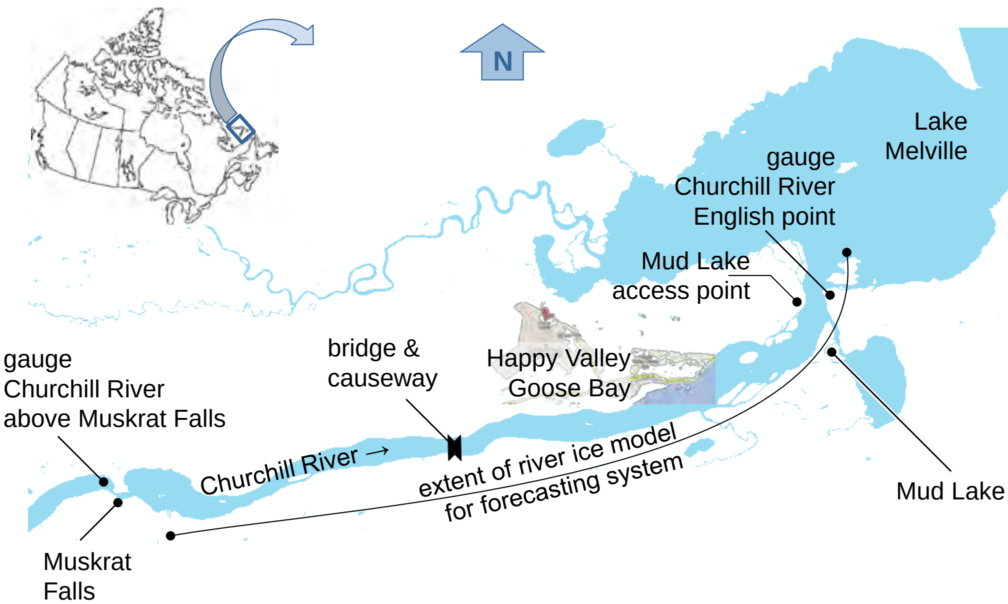
TABLE 36
RIVICE MODEL PARAMETERS AND RANGES

RIPARVAR Parameter	Parameter Description	Minimum	Maximum	Unit
PS	Porosity of Incoming Ice Pans	0.4	0.6	Unitless
ST	Thickness of Incoming Ice Pans	Function of Ice Thickness	Function of Ice Thickness	m
V_{ice}	Volume of Incoming Ice	0.0	Function of Ice Thickness and Ice Cover Extent	m^3/s
PC	Ice Cover Front Porosity	0.4	0.6	Unitless
FT	Ice Cover Front Thickness	Function of Ice Thickness	Function of Ice Thickness	m
h	Average Ice Cover Thickness	0.0	Function of Ice Thickness	m
V_{dep}	Maximum Velocity for Ice Deposition	1.1	1.3	m/s
V_{er}	Minimum Velocity for Ice Erosion	1.7	1.9	m/s
n_{8m}	Ice Cover Underside Roughness Coefficient	0.11	0.12	Unitless
n_{bed}	River Bed Roughness Coefficient	0.025	0.030	Unitless
K1TAN	Ice Strength Parameter	0.14	0.24	Unitless
K2	Ice Strength Parameter	7.3	7.4	Unitless
Q	Churchill River Flow	Function of River Flows	Function of River Flows	m^3/s
W	Lake Melville Water Level	Function of Tidal Levels	Function of Tidal Levels	m
x	Ice Jam Toe Cross Section Number	At River Outlet	5 km U/S of River Outlet	Unitless
T_A	Air Temperature	Function of Air Temperature	Function of Air Temperature	°C
H	Heat Transfer Coefficient	15	25	$W/m^2/°C$

9.3.2 Development of Ice-Affected Hydraulic Model

The river ice modelling aspect of this project focused on the downstream reach of the lower Churchill River from Muskrat Falls to Lake Melville, and corresponded with the same model domain as the open water model, as shown on Figure 74.

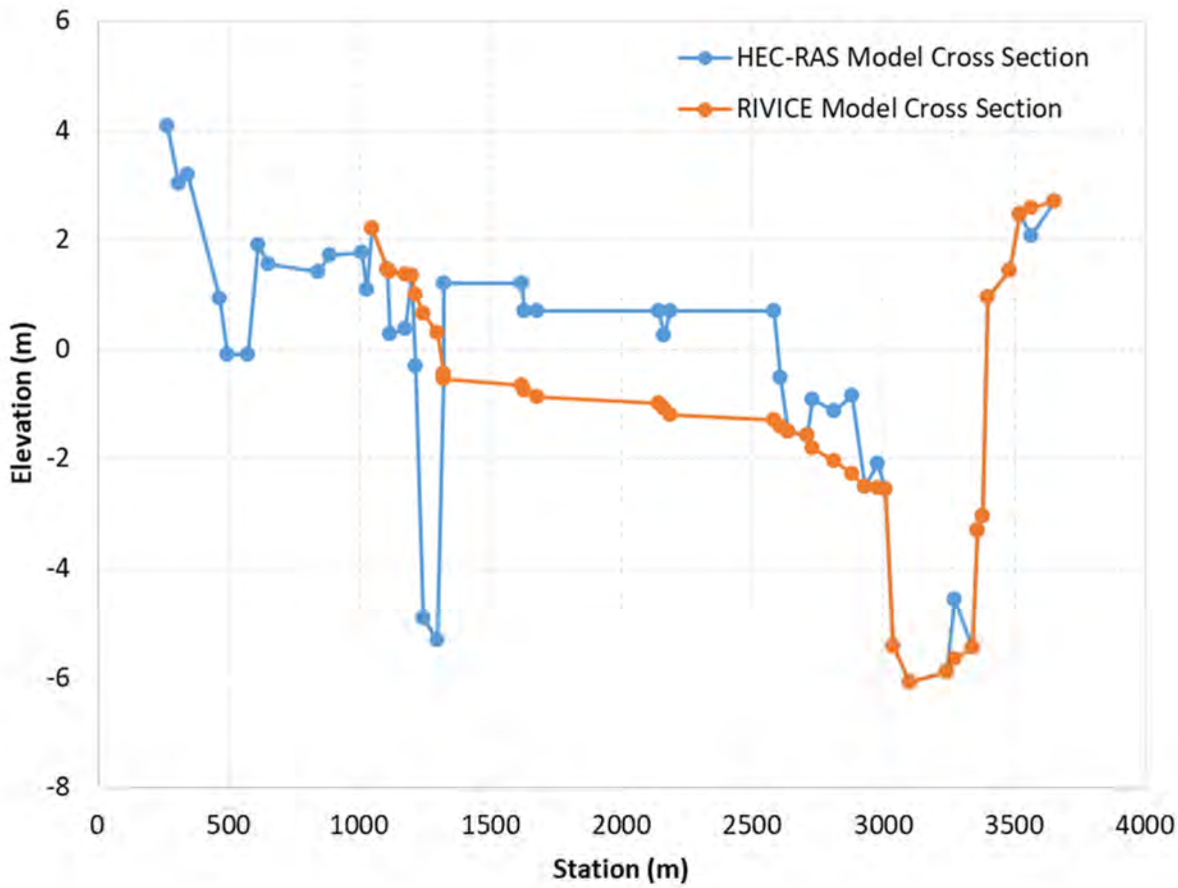
FIGURE 74
RIVICE MODEL DOMAIN



The cross sections incorporated into the RIVICE model were defined based on those included in the flood forecasting HEC-RAS model, and included the same number of surveyed cross sections with matching channel lengths between cross sections. Due to the computational requirements for RIVICE, the number of topographic and bathymetric points that define the HEC-RAS cross sections were reduced to 50 points. As well, due to the limitations of RIVICE, the areas outside of the main channel (i.e. overbank areas) were removed from the cross sections.

RIVICE is presently unable to model braided channels, and as such any cross sections that included more than one channel opening due to the presence of sand bars were manually altered to remove the sand bar. These alterations were completed with great care such that the cross-sectional area of the cross sections were not affected. An example of the cross-section alterations is shown on Figure 75.

FIGURE 75
CROSS SECTION ALTERATION



Following the successful cross section alterations, the cross sections were linearly interpolated in RIVICE at 100 m spacing to improve the spatial resolution of the model.

Considering that the RIVICE model did not include any overbank areas (i.e. only based on the bathymetric survey data), and that the cross sections were altered to remove the sandbars from each cross section, the RIVICE model did not require updating with the cross sections from the Flood Risk Mapping HEC-RAS model that were defined based on the 2019 LiDAR data.

9.3.3 Calibration and Validation of Ice-Affected Hydraulic Model

The RIVICE model was calibrated to three different conditions, specifically:

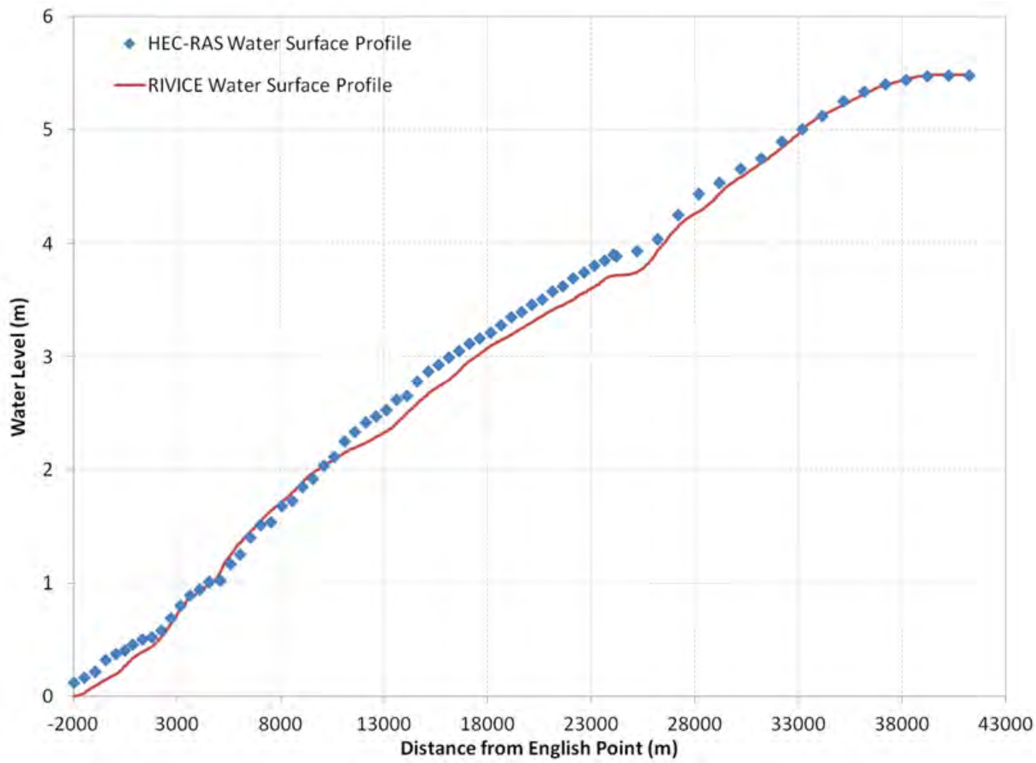
- Open water conditions defined by the HEC-RAS model;
- Freeze-up jamming conditions;
- Breakup ice jamming conditions.

The calibration of the RIVICE model to these three conditions was necessary to ensure that the model was accurately representing the ice-free hydraulics on the river, as well as the freeze-up and breakup ice processes. The calibration of the model to the three conditions is further described below.

Open Water Conditions

The RIVICE model was calibrated to open water conditions on the Lower Churchill River by adjusting the channel bed roughness coefficient to match water surface profiles defined by the flood forecasting HEC-RAS model for a variety of flow conditions. Specifically, the RIVICE model was calibrated to low flow (i.e. 2,000 m^3/s), moderate flow (i.e. 4,000 m^3s) and high flow (i.e. 5,080 m^3/s) conditions. The calibrated channel bed roughness coefficient was defined as 0.03, and a comparison of the calibrated RIVICE model to the HEC-RAS model water surface profile is shown for high flow conditions on Figure 76.

FIGURE 76
RIVICE OPEN WATER CALIBRATION



The calibrated RIVICE model was generally able to represent the open water surface profiles. However, due to the simplifications to the cross sections that were necessary to incorporate the cross sections into RIVICE, the model was unable to perfectly reproduce the HEC-RAS water surface profiles. Nonetheless, the RIVICE model open water calibration was considered to be acceptable.

Freeze-up Jamming Conditions

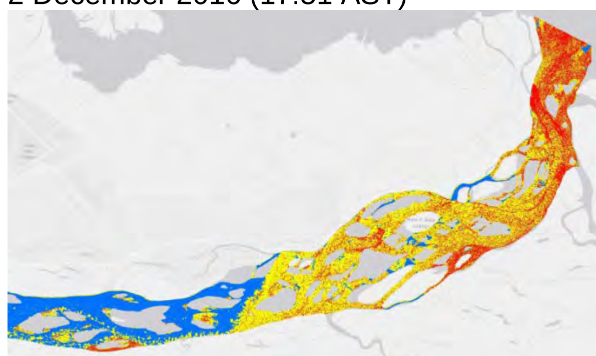
Freeze-up jam floods have historically occurred at the community of Mud Lake and its access point along Mud Lake Road, including for example in the autumn seasons of 2006 and 2007. However, water level records on the Churchill River at English Point are not available prior to 2010, and therefore gauging data is not available to model these events. However, freeze-up backwater levels were relatively extreme during the fall of 2016, and this event was therefore used to calibrate the freeze-up modelling component of the RIVICE model of the Churchill River.

Space-borne radar imagery of the Churchill River was used to determine the rate of juxtapositioning of the ice cover front during initial freeze-up from Lake Melville upstream along the river. The images, as shown on Figure 77, are snapshots of the ice cover during the first three days of the freeze-up event, which began on November 30, 2016.

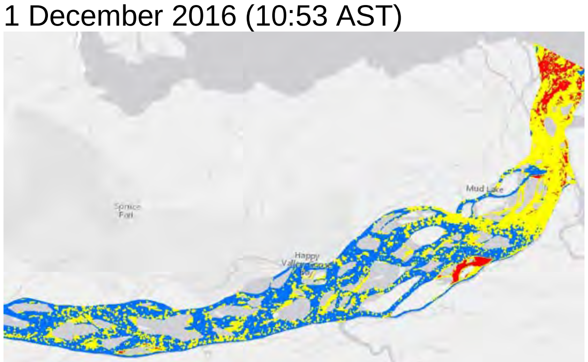
FIGURE 77
ICE CLASSIFICATION EXTRACTED FROM SPACE-BORNE RADAR IMAGES

30 November 2016 (6:12 AST)

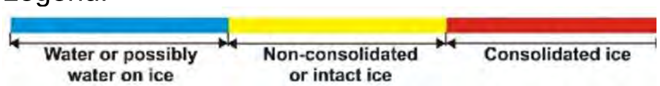
2 December 2016 (17:51 AST)



1 December 2016 (10:53 AST)



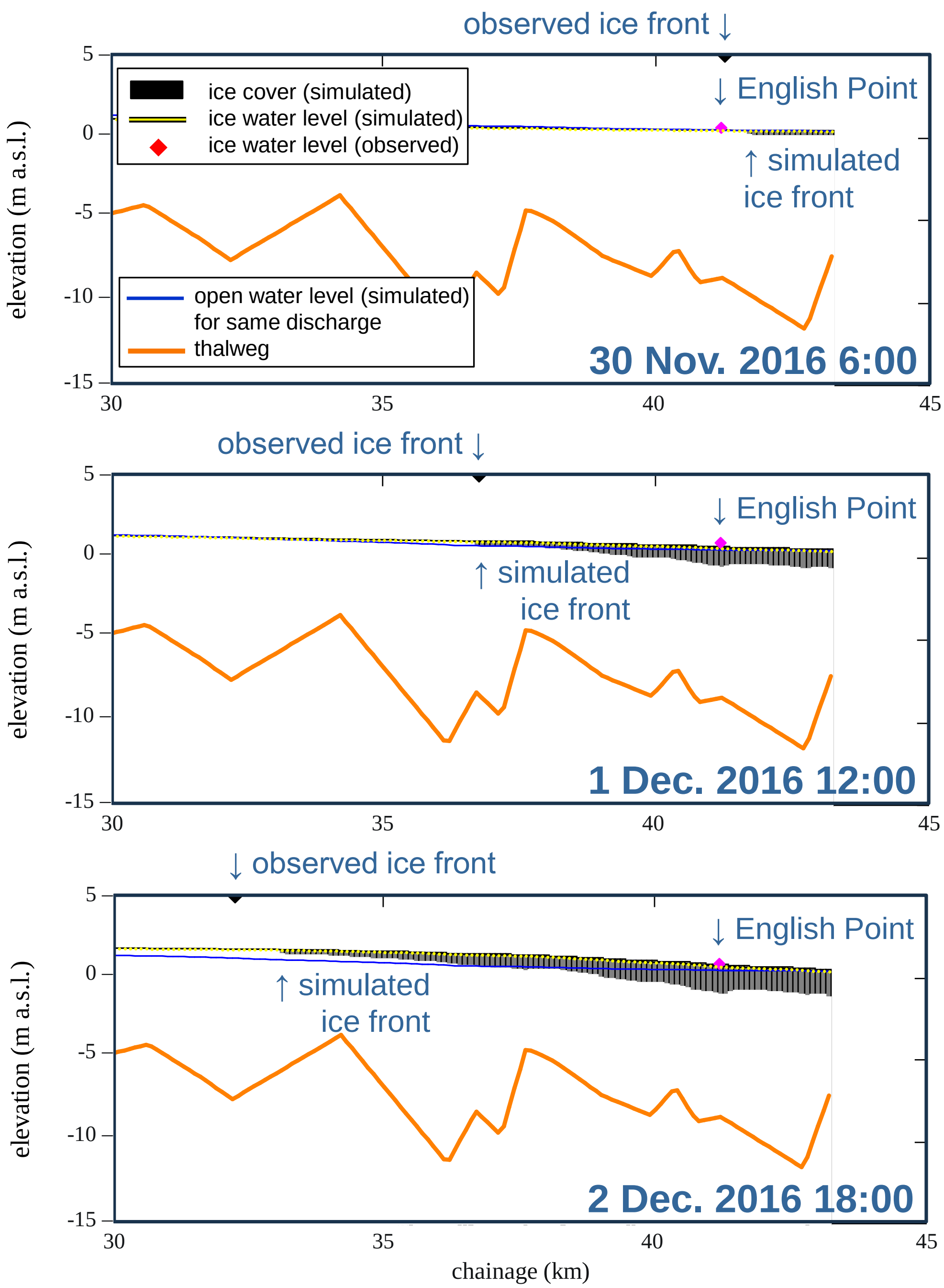
Legend:



Simulations of the ice cover and the backwater staging during the 2016 freeze-up event are provided in Figure 78. Two sources of data were available for the calibration: (1) the peak water level at English Point and (2) the location of the ice-cover front based on the satellite imagery. The heat transfer coefficient (i.e. *H*) was calibrated to be 30 W/m^2/°C, a particularly high value. The high rate of heat transfer is necessary to compensate for the exclusion of islands and sandbars in the model. A higher ice generation rate was required to fill in the volume that would otherwise be taken up by the islands and sandbars in the model domain. A comparison of the calibrated freeze-up ice jam conditions to the observed conditions is also shown on Figure 78.

FIGURE 78

BACKWATER LEVELS AND ICE COVER PROGRESSION FOR THE 2016 FREEZE-UP



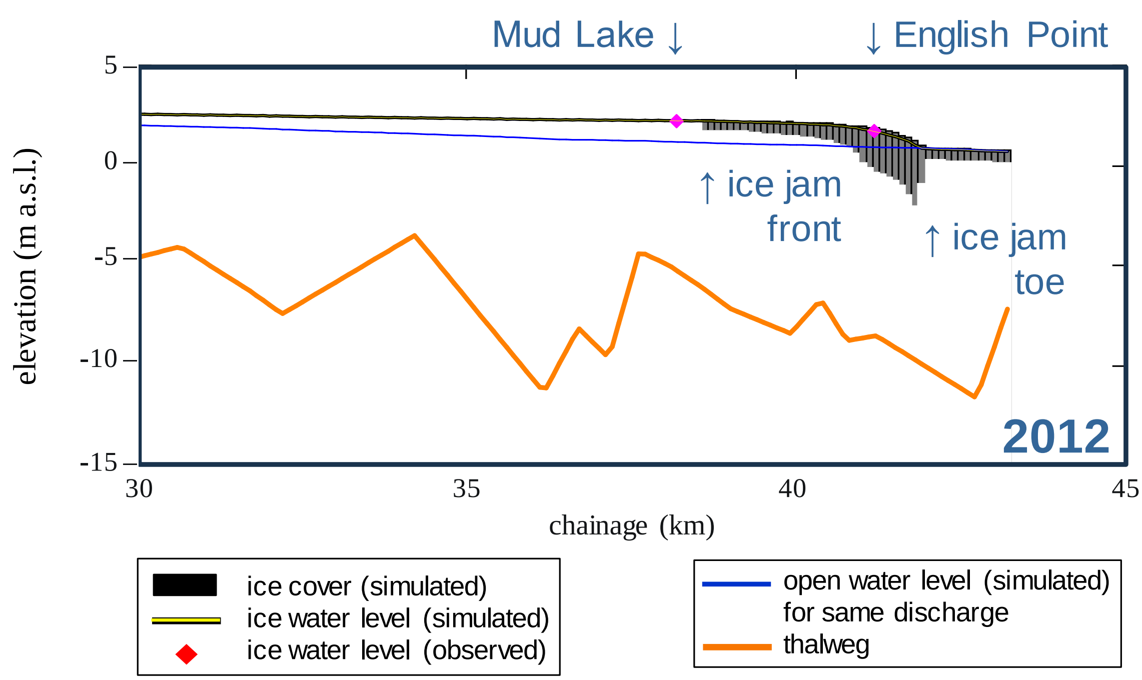
The simulated water levels of 0.19 m, 0.68 and 1.12 m were generally representative of the range of observed water levels at English Point on November 30, December 1 and December 2 of 0.40 m, 0.76 m, and 0.60 m, respectively. While the model representations of the water levels on each day are not perfect, considerable uncertainty is present in both the recorded water levels due to the dynamic nature of the ice jam event and daily averaging of the recorded water levels, as well as in the key ice parameters included in the RIVICE model. However, considering that the model generally represented the range of water levels over the freezeup ice jam, the model was considered to be well calibrated for ice jam events.

Breakup Jamming Conditions

The three largest ice-jam events on record, for which enough data was available to carry out calibration, occurred on May 16, 2012, and May 17 and 18, 2017. The last two jams occurred on two consecutive days and are often viewed as one event. However, the boundary conditions for these two jams are distinct enough to warrant two separate simulations. The breakup ice jamming aspect of the RIVICE model was therefore calibrated to these three jam events. The RIVICE model was calibrated to recorded water levels on the WSC gauge at English Point, as well as approximate anecdotal water level information provided by the residents of Mud Lake for the 2012 and 2017 floods. Various parameters were adjusted as part of the breakup jamming calibration, including the ice strength and roughness parameters. Figure 79 shows the water levels recorded by the English Point gauge during the May 2012 ice jam event. Shoving of the ice to form the ice jam began May 15, 2012, with the peak water level of 1.7 m from the jamming occurring on May 16, 2012. By the end of that day, the jam had released. As well, a high-water mark in Mud Lake was estimated by comparing the flood extent identified by a Mud Lake resident with LiDAR elevations in Mud Lake. The Churchill River flow during the ice jam was 3,780 m^3/s based on recorded flows at Muskrat Falls. There simulated water levels of 1.6 m at English Point and 2.2 m in Mud Lake were in good agreement with the observed water level elevations of 1.7 m and 2.2 m. The RIVICE representation of the ice-jam event is shown on Figure 80.

FIGURE 79
RECORDED WATER LEVELS AT ENGLISH POINT DURING MAY 2012

FIGURE 80
PROFILE OF ICE JAM SIMULATION FOR THE MAY 16, 2012 FLOOD

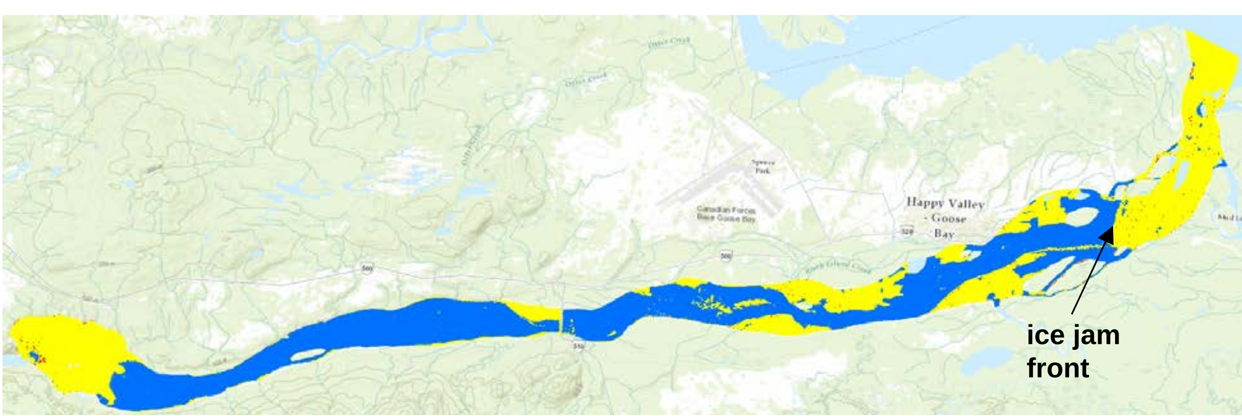


As previously noted, the ice jam that occurred on the Churchill River during May 2017 consisted of two separate ice jam events that took place within a short period of time. The peak water level for the first ice jam reached a level of 2.02 m at English Point occurred on May 17, 2017 with a corresponding flow of 4,300 m^3/s. The peak water level for the second ice jam reached a level of 2.60 m, with a corresponding flow of 4,600 m^3/s. Similar to the 2012 flood, high water marks of 3.2 m and 3.3 m in Mud Lake were estimated by comparing the high water marks identified by a local resident for each jam event with the LiDAR ground elevations in the community. The recorded water levels at English Point are shown on Figure 81.

FIGURE 81
WATER LEVELS RECORDED AT ENGLISH POINT DURING MID-MAY 2017

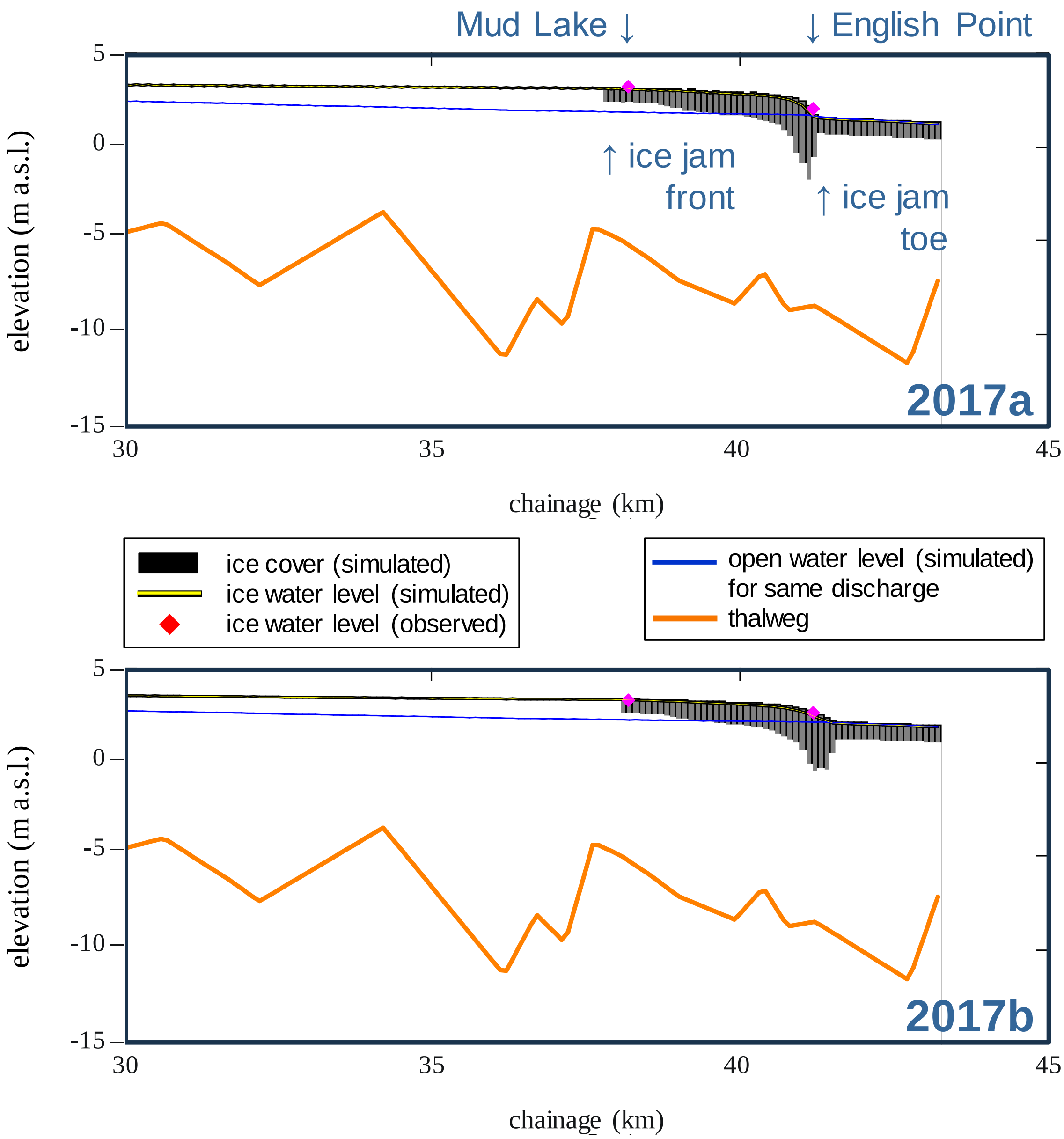
For the May 17 ice jam event, the extent of the ice jam's cover was provided by the satellite ice classification image, shown on Figure 82, was used as an additional objective function.

FIGURE 82
C-CORE ICE COVER CLASSIFICATION ON MAY 17, 2017



The calibrated RIVICE model was found to reasonably represent the first ice jam event during 2017, with simulated peak water levels of 3.1 m in Mud Lake and 1.6 m at English Point being in good agreement with the observed water levels of 3.2 m and 2.0 m. The model representation of the second ice jam was comparably accurate, with the simulated peak water levels of 2.4 m at English Point and 3.3 m in Mud Lake being in good agreement with the observed water levels of 2.6 m and 3.3 m. The RIVICE representations of the ice jams are shown on Figure 83, with 2017a representing the May 17, 2017 ice jam and 2017b representing the May 18, 2017 ice jam. The RIVICE model breakup jam conditions calibration was therefore considered acceptable.

FIGURE 83
WATER LEVELS AND ICE COVERS FOR THE MAY 2017 ICE JAM FLOOD EVENTS



9.3.4 Ice-Affected Hydraulic Modelling of the 20 and 100-Year Floods

Following the successful calibration of the RIVICE model, a suite of over one thousand Monte Carlo simulations was completed to define the 20 and 100 year ice-affected water surface profiles. A large number of simulations is required to ensure that the full range of anticipated conditions is included in the Monte Carlo simulations. The Monte Carlo framework is described in detail in Section 14.3.4, but in short, a series of simulations that incorporate randomly sampled variables from representative statistical distributions are completed to represent the range of possible ice-affected conditions that could occur on the Churchill River. Frequency analyses of the various simulated water levels are then completed at each cross section to define the AEP water levels, such as the 20 and 100 year floods, as well as profiles associated with the 20 and 100 year ice-affected floods.

Inflows to the model for the current climate were randomly sampled from a frequency curve that was defined based on a frequency analysis of the last recorded ice-affected flows at the WSC gauge at Muskrat Falls (i.e. WSC gauge 03OE001). For climate change conditions, the frequency curve was adjusted to account for climate change, as described in Section 8.2.

Water levels at English Point were randomly sampled from a bi-modal distribution based on the forecast water levels at Terrington Basin for the current climate conditions. Similar to the open water conditions, the bi-modal distribution representing the Terrington Basin was raised for the climate conditions to account for the anticipated increase in sea level associated with climate change.

The maximum volume of ice included in the Monte Carlo simulations were sampled from a GEV distribution that is scaled from a maximum ice accumulation rate, as described further in Section 14.3.4. For the current climate conditions, the maximum ice accumulation rate was estimated as 4,000 m^3/s. Due to the reduced cumulative degree-days of freezing for climate change conditions, the maximum ice accumulation incorporated in the climate change simulations was 3,065 m^3/s. This reduction, as described in Section 8.2.4, is based on the Stefan equation, which relates the calculated ice thickness to the square root of the cumulative degree days of freezing, and the projected reduction in cumulative degree days of freezing from 2,052 °C-day to 1,204 °C-day by the 2051 to 2080 timeframe. Ice thicknesses were defined based on a uniform distribution ranging from 0.27 m to 1.0 m for current climate conditions, and 0.20 m to 0.76 m for climate change conditions. These ranges were defined by Dr. Lindenschmidt based on his expert experience, and were reduced to account for climate change conditions due to the reduced degree days of freezing.

Since the RIVICE model only considers hydraulic conditions on the main channel of the Churchill River (i.e. no overbank flow or hydraulic conditions at Mud Lake), overbank velocities on the Churchill River, as well as water levels and velocities on the Mud Lake channels and overbank areas were not defined by the RIVICE model. To define the Churchill River overbank velocities and water levels and velocities on the Mud Lake channels and overbank areas, the 20 and 100 year AEP ice-affected water surface profiles defined using the RIVICE model were reproduced in the HEC-RAS model of the Churchill River and Mud Lake Channels. This was accomplished by defining an ice cover in the HEC-RAS model to match the RIVICE water surface profile for the 20 and 100 year ice-affected floods.

The RIVICE water levels and depths were used to define water levels on the Churchill River and the adjacent overbank areas for the flood risk maps. However, water levels and depths on the Mud Lake channels were defined by the HEC-RAS representation of the 20 and 100 year ice-affected floods. As well, channel and flood plain velocities on both the Churchill River and Mud Lake channels were defined by the HEC-RAS representation of the 20 and 100 year ice-affected floods.

Water levels at a number of key locations along the lower Churchill River and Mud Lake Channels resulting from the hydraulic modelling of the ice-affected 20 and 100 year floods for both the current climate and climate change conditions are summarized in Table 37. The bank levels at each of the key locations is also shown in Table 37 for perspective on flood depths.

TABLE 37
20 AND 100 YEAR ICE-AFFECTED FLOOD LEVELS AT KEY LOCATIONS

Location	River	Cross Section	Left Bank Elevation (m)	Right Bank Elevation (m)	Current Climate		Climate Change	
					20 Year Flood Level (m)	100 Year Flood Level (m)	20 Year Flood Level (m)	100 Year Flood Level (m)
Mud Lake near T. Edmunde Residence	Mud Lake Channel	3555	1.4	1.4	2.2	2.9	2.0	3.2
Mud Lake near D. Campbell Residence	Mud Lake Channel	4357	1.5	3.1	2.2	3.0	2.0	3.3
Mud Lake near United Church	Mud Lake Channel	4777	2.6	2.8	2.3	3.0	2.0	3.4
Mud Lake near Hydro Generator	Mud Lake Channel	5223	3.1	2.2	2.4	3.1	2.1	3.4
Mud Lake near C. Best Non-Permanent Residence	Mud Lake Channel	5538	2.2	1.4	2.4	3.1	2.2	3.5
End of Mud Lake Road / English Point	Churchill River	32	2.2	4.4	1.0	1.9	1.1	1.8
Mud Lake Road	Churchill River	482	1.7	5.5	1.4	2.3	1.4	2.4
Mud Lake Road	Churchill River	874	3.1	3.1	1.6	2.5	1.6	2.7
Mud Lake Road	Churchill River	1135	2.4	2.0	1.9	2.6	1.8	3.0
Mud Lake Road	Churchill River	1799	2.5	3.3	2.1	2.8	2.0	3.1
Mud Lake Road	Churchill River	2246	1.9	2.0	2.3	3.0	2.3	3.3
Mud Lake Road	Churchill River	2704	1.5	1.9	2.5	3.2	2.5	3.4
Below Traverspine River	Churchill River	9049	4.6	3.0	3.0	3.5	3.1	3.9
Happy Valley - Goose Bay	Churchill River	9566	5.8	3.0	3.0	3.5	3.1	3.9
Happy Valley - Goose Bay	Churchill River	10078	5.5	3.3	3.0	3.5	3.1	3.9
Happy Valley - Goose Bay	Churchill River	10602	5.6	2.5	3.0	3.5	3.1	3.9
Below Trans Labrador Highway	Churchill River	24064	9.4	20.9	3.6	4.0	3.7	4.3
Above Trans Labrador Highway	Churchill River	24201	11.2	15.6	3.6	4.0	3.7	4.3
6.15 km Below Muskrat Falls	Churchill River	36181	6.5	7.1	4.8	5.1	4.9	5.2

The resulting 20 and 100 year ice-affected flood levels for both the current climate and climate change conditions were used to develop the Flood Risk and Flood Hazard maps as described in Section 12.0.

10.0 HYDRAULIC MODELLING OF OTTER CREEK AND LOCAL CREEKS

10.1 OVERVIEW

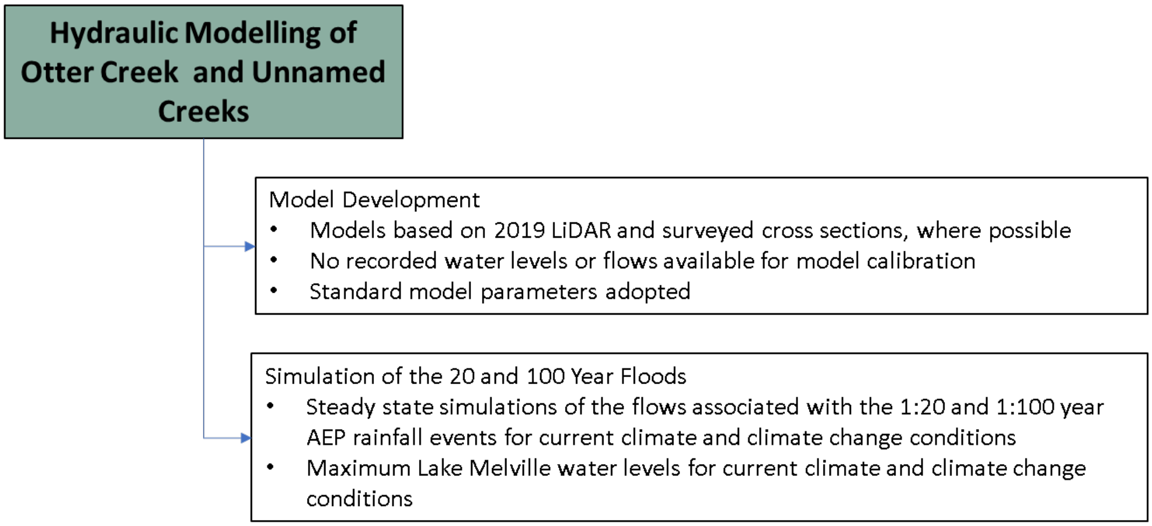
Hydraulic models were developed for Otter Creek and seven unnamed creeks in Happy Valley – Goose Bay that were used to convert the flows defined using the hydrologic models into water levels along the creeks. These models were developed based on a combination of the LiDAR data and survey data collected as part of this project.

Recorded water levels and flows were not available to adjust or calibrate the various parameters in the model. Typically, standard industry accepted model parameter values, such as channel roughness, are used as a starting point in the model and are adjusted, as required, so that the modelled water levels match measured water levels for a given flow condition. However, since no measured flows or water levels are available on the creeks, the standard industry values were adopted for the models. These values are generally representative of the real world conditions that were included in the model.

The hydraulic models used the maximum flow rates from the hydrologic model simulations of the 1:20 and 1:100 AEP rainfall events for current climate and climate change conditions in combination with water levels on Lake Melville and the Churchill River to calculate water levels along each creek. These water levels were then combined with the ground elevation model to develop the flood risk and flood hazard maps on the creeks, as described further in 13.0.

The tasks completed as part of the Otter Creek and unnamed creek hydraulic modelling are summarized in Figure 84.

FIGURE 84
OVERVIEW OF THE HYDRAULIC MODELLING OF OTTER CREEK AND UNNAMED CREEKS



10.2 HYDRAULIC MODEL DEVELOPMENT

10.2.1 Modelling Approach

Similar to the open water Churchill River hydraulic model described in Section 9.2, hydraulic models of Otter Creek and seven unnamed creeks (i.e. local creeks) were developed using HEC-RAS. In general, the hydraulic models were developed following a similar approach. However, for Local Creeks 5 and 6, the upper reaches of the creeks are not natural and are considered to be part of the municipal drainage system for the Town of Happy Valley – Goose Bay. The municipal drainage system includes networks of ditches, culverts, and catch basins to accommodate rainfall and snowmelt within the Town of Happy Valley – Goose Bay. The hydraulic modelling and flood risk mapping of the municipal drainage system was not a part of the scope for this study, and as such was not completed as part of this project. Rather, only the natural part of the creeks were included in the hydraulic modelling and flood risk mapping. Hydraulic modelling and flood risk mapping of the municipal drainage systems in Happy Valley – Goose Bay should be completed as part of a municipal mapping study by the Town of Happy Valley – Goose Bay.

The hydraulic models of the creeks were defined as 1D models, with branches and flow splits defined in each model as required. The models were simulated under steady state conditions, with the exception of Local Creek 7, which due to the highly braided nature of the creek, was simulated under unsteady state conditions with constant inflows to facilitate the calculation of the flow in each reach in the model.

The development of these models is summarized in the following subsections.

10.2.2 Creeks Draining into Lake Melville

The hydraulic models for Otter Creek and Local Creeks 1 to 5 shared many similarities and were generally configured following a consistent approach. The characteristics of these models are summarized below.

Cross Sections

The creeks represented in the hydraulic models of Otter Creek and Local Creeks 1 to 5 were defined largely based on the available LiDAR data. On Otter Creek and Local Creeks 1 and 2, the creek bathymetry was defined by interpolating the channel bed between surveyed cross sections. On the other creeks, there was insufficient data to adequately define the channel bathymetry beyond the LiDAR data, and as such the cross sections were defined based on the LiDAR data. The modelled river length and the number of cross sections included in the models for each creek are summarized in Table 38. The layout of the modelled creeks and cross sections are shown on Figure 85 to Figure 90. Plots of the cross sections are included in Appendix L.

TABLE 38
CREEK LENGTH AND CROSS SECTIONS

Creek	Modelled River Length (km)	Number of Cross Sections
Otter Creek	17.6	53
Local Creek 1	1.8	23
Local Creek 2	2.4	39
Local Creek 3	2.5	49
Local Creek 4	1.5	16
Local Creek 5	7.0	55

FIGURE 85
OTTER CREEK HYDRAULIC MODEL

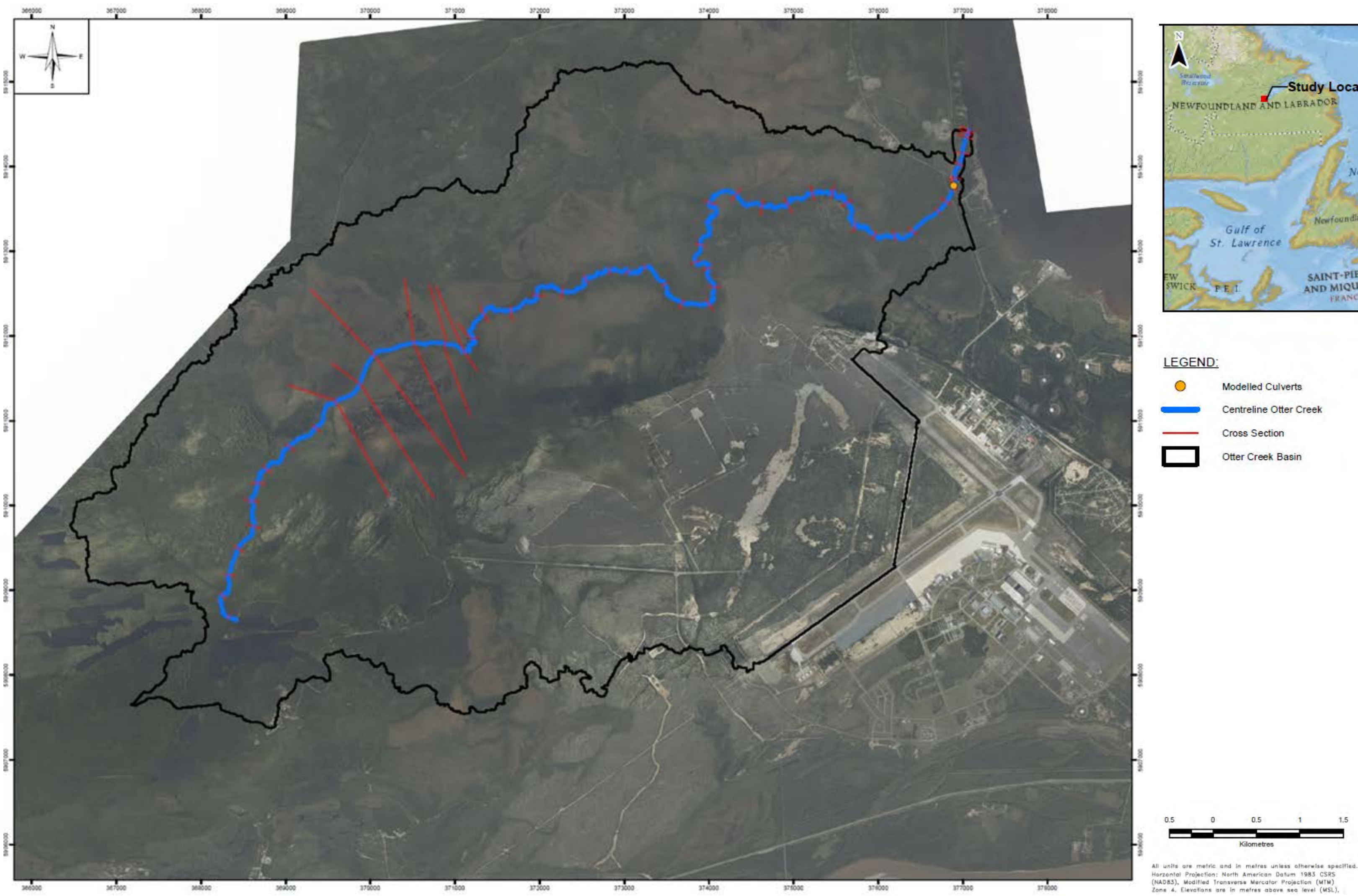


FIGURE 86
LOCAL CREEK 1 HYDRAULIC MODEL

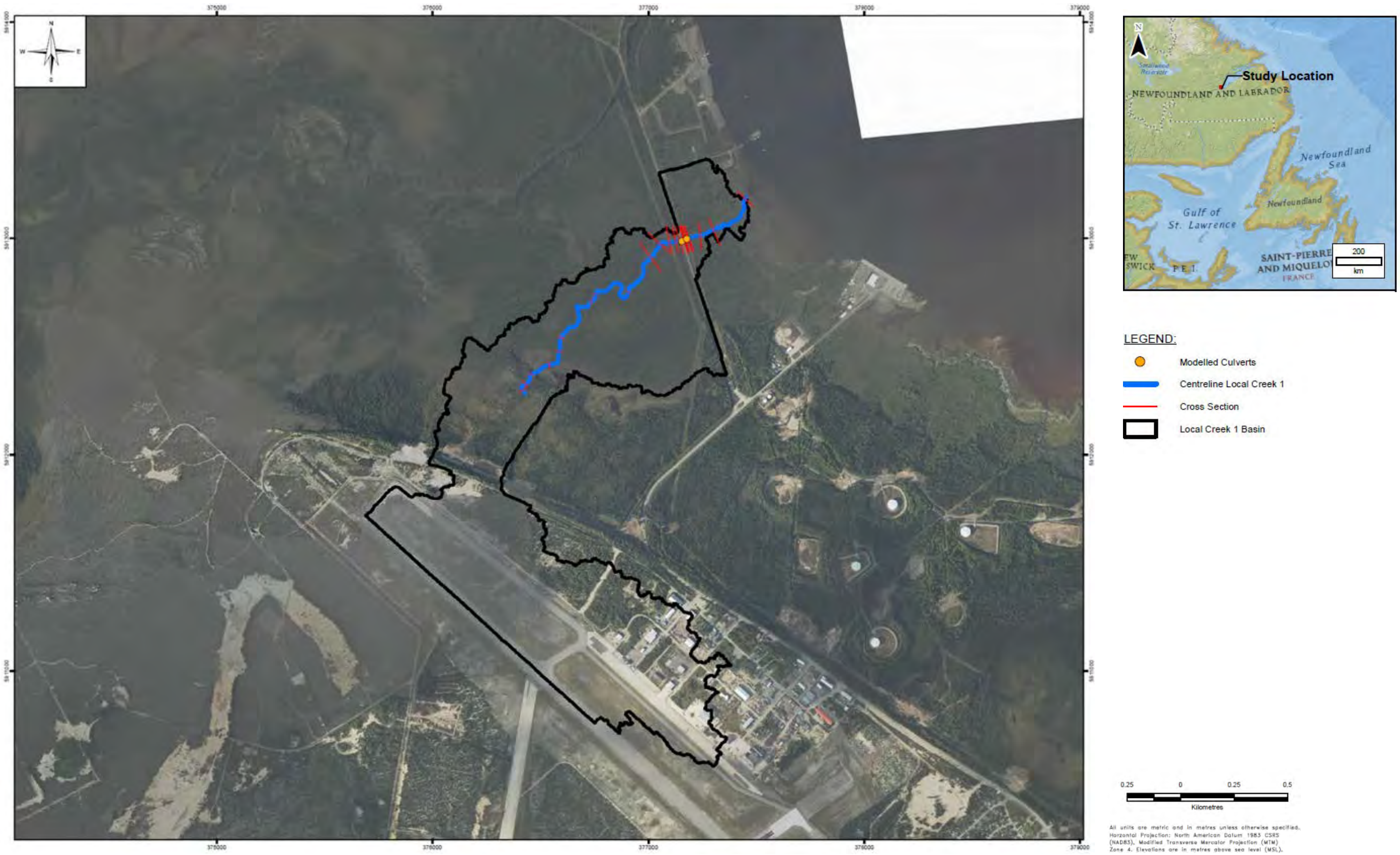


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FIGURE 87
LOCAL CREEK 2 HYDRAULIC MODEL

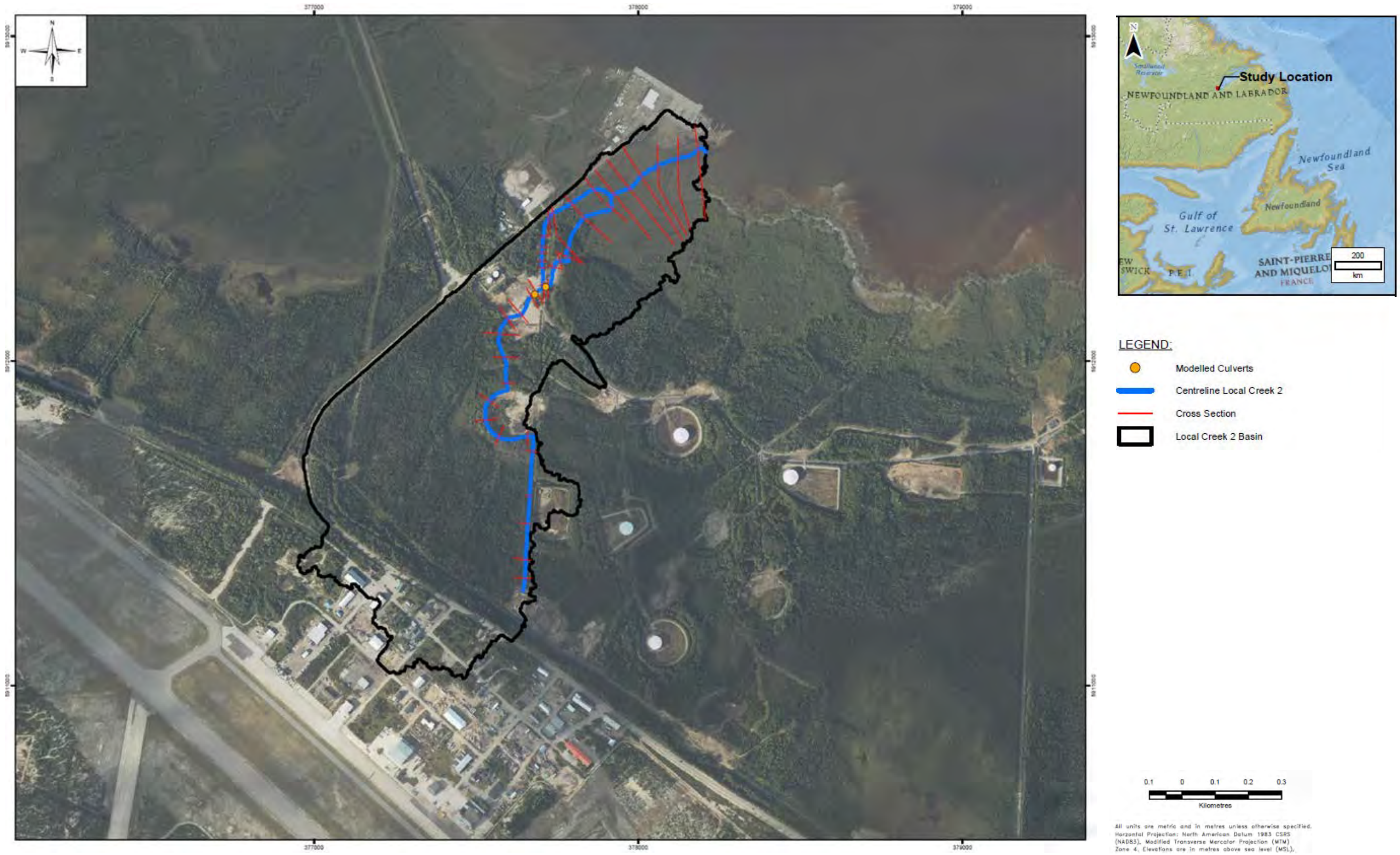


FIGURE 88
LOCAL CREEK 3 HYDRAULIC MODEL

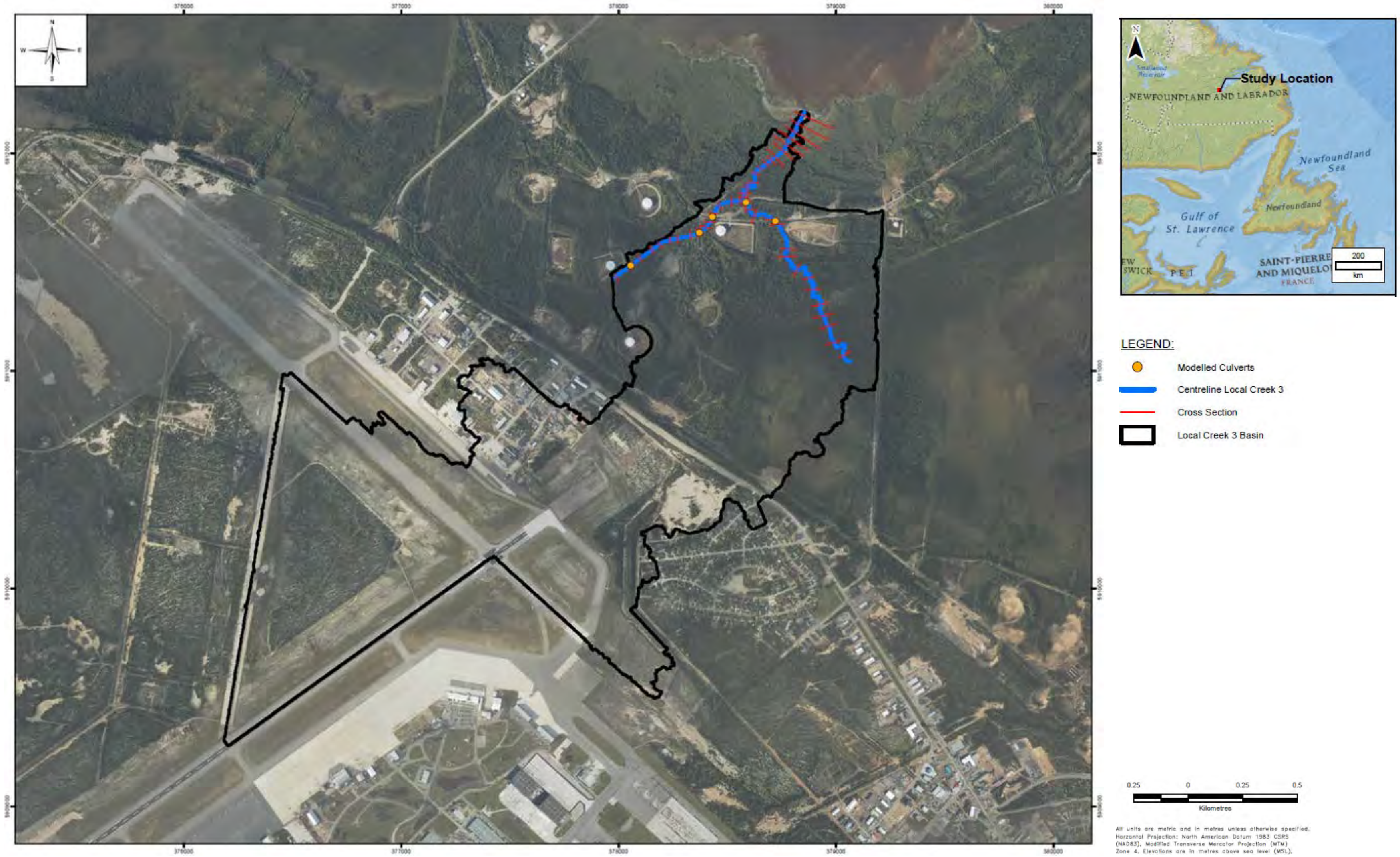


FIGURE 89
LOCAL CREEK 4 HYDRAULIC MODEL

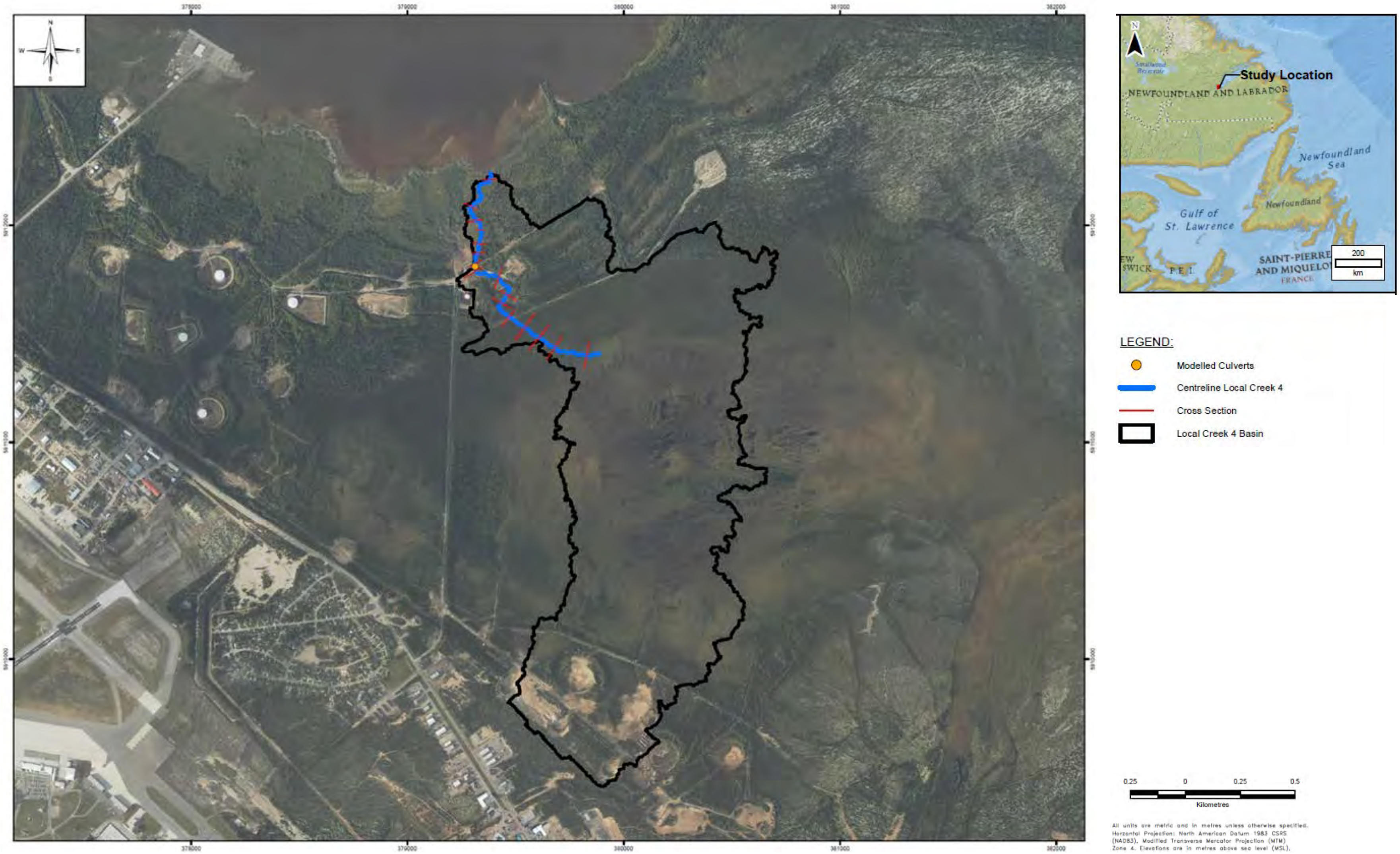
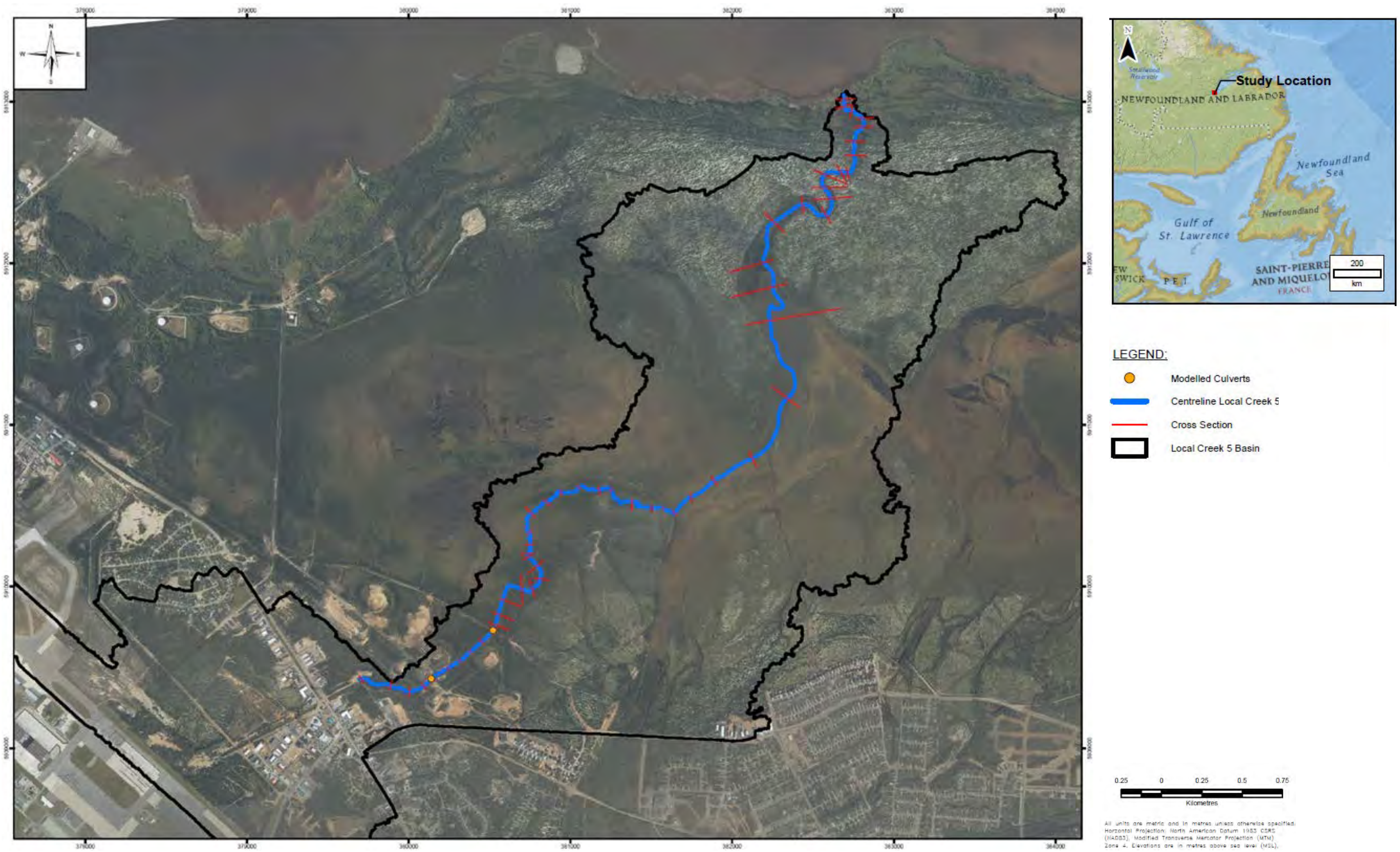


FIGURE 90
LOCAL CREEK 5 HYDRAULIC MODEL



Boundary Conditions

Inflows to the creek models were defined as steady state inflows as follows:

- ***Local Creeks 1, 2, and 4*** – The inflows at the upstream end of the hydraulic models were defined as the peak flow at the downstream end of the hydrologic model. There is considerable drainage area for Local Creeks 1 and 4 upstream of the extents of the hydraulic models, and as such this approach to the integration of the design flows into the hydraulic model is a reasonable, if conservative, approach to representing inflows in the hydraulic models. For Local Creek 2, flows in the upstream portion of the model are well channelized, and as such changing the distribution of the flow would not have any implications to the extents of flooding shown in the model.
- ***Local Creek 2*** – There is a secondary channel that conveys flow during high flow conditions. Flows on this channel were initially set to 0 m^3/s, and were resolved in the HEC-RAS model.
- ***Otter Creek, Local Creek 3, and Local Creek 5*** – The peak inflow from each sub-basin was added to flow on the main stem at the appropriate river station. Furthermore, for Otter Creek, flows in the upstream-most basin were split so that the full basin flow wasn't contributing at the very upstream end of the model.

The creek flows defined in the hydraulic models are summarized in Table 39.

TABLE 39
OTTER CREEK AND LOCAL CREEK INFLOW

Creek	Reach	Station	Current Climate		Climate Change	
			20 Year (m^3/s)	100 Year (m^3/s)	20 Year (m^3/s)	100 Year (m^3/s)
Otter Creek	Otter Creek	17556	0.9	1.8	1.4	2.4
Otter Creek	Otter Creek	12237	4.4	9.2	6.9	11.9
Otter Creek	Otter Creek	11625	8.3	17.3	12.9	22.3
Otter Creek	Otter Creek	8937	10.8	22.2	16.7	28.6
Otter Creek	Otter Creek	7195	13.5	27.4	20.6	35.3
Otter Creek	Otter Creek	2096	16.8	34.1	25.6	43.8
Local Creek 1	Local Creek 1	1816	1.2	2.5	1.9	3.2
Local Creek 2	Upstream Reach	1908	0.7	1.7	1.2	2.1
Local Creek 2	Reach 1	799	0.0	0.0	0.0	0.0
Local Creek 2	Reach 2	769	0.7	1.7	1.2	2.1
Local Creek 2	Downstream Reach	351	0.7	1.7	1.2	2.1
Local Creek 3	Reach 1	1363	0.5	1.0	0.8	1.3
Local Creek 3	Reach 2	1724	1.7	3.9	2.9	5.1
Local Creek 3	Downstream Reach	555	2.2	5.0	3.7	6.5
Local Creek 4	Local Creek 4	1419	0.6	1.3	1.0	1.7
Local Creek 5	Local Creek 5	6960	2.3	4.9	3.7	6.6
Local Creek 5	Local Creek 5	1896	4.0	8.8	6.5	11.4

The downstream boundary conditions for the hydraulic models were set the maximum tidal level on Lake Melville of 0.22 m for current climate conditions, and 0.92 m for climate change conditions.

Structures

Various culvert crossings were included in the hydraulic models. These culverts were defined in the models based on survey data collected as part of this project, and based on culvert information provided by the Town of Happy Valley – Goose Bay. The number of culverts included in the hydraulic models is summarized in Table 40. The locations of the culverts modelled are also shown on Figure 85 to Figure 90.

TABLE 40
OTTER CREEK AND LOCAL CREEK CULVERT CROSSINGS

Creek	Number of Culvert Crossings
Otter Creek	1
Local Creek 1	2
Local Creek 2	2
Local Creek 3	5
Local Creek 4	1
Local Creek 5	2

In addition to the culvert crossings included in the models, a lateral structure was included in the Otter Creek model immediately upstream of Lake Melville to convey flow overland to the east into the lake during flood conditions. The crest of the lateral structure was defined from the LiDAR data along the high ground between the creek and Lake Melville.

Manning's Roughness Coefficient

Manning's roughness coefficients were set in the hydraulic models to uniform values of 0.03. Flow and water level information was not available to calibrate the roughness coefficients.

Contraction and Expansion Coefficients

The contraction and expansion coefficients included in the models were set to 0.1 and 0.3, which are standard values for natural channels with gradual transitions.

10.2.3 Creeks Draining into the Churchill River

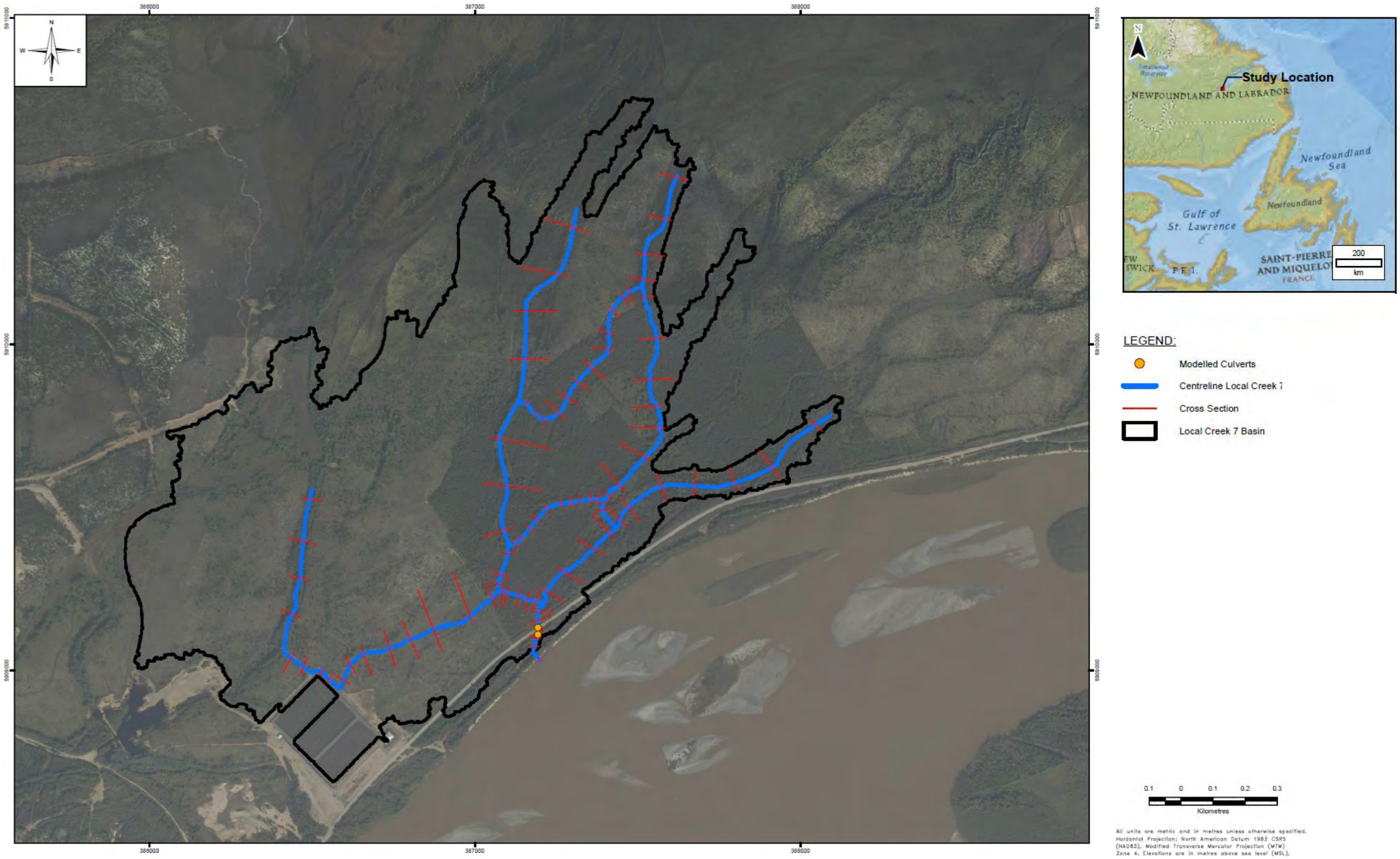
Local Creeks 6 and 7 were simulated in 1D using HEC-RAS, with the channel bathymetry defined based on the LiDAR data. The characteristics of the models are summarized below.

Cross Sections

Cross sections in the hydraulic models for Local Creeks 6 and 7 were defined based on the LiDAR data. The hydraulic model for Local Creek 6 included 3.1 km of river reach split up over four reaches, while Local Creek 7 included 6.4 km of river reach split up over thirteen reaches. The models for Local Creeks 6 and 7 included 37 and 86 cross sections that were cut from the LiDAR data, as shown on Figure 91 and Figure 92.

FIGURE 91
LOCAL CREEK 6 HYDRAULIC MODEL

FIGURE 92
LOCAL CREEK 7 HYDRAULIC MODEL



Boundary Conditions

Inflows into the models were defined at the upstream end of the main branches included in the hydraulic models. The inflows were defined based on the flows from the hydrologic model, although some adjustments were made to account for the different timing of the peak flows and to ensure that the flow at the model outlet matched the hydrologic model. The inflows included in each model are summarized in Table 41.

TABLE 41
OTTER CREEK AND LOCAL CREEK 7 INFLOW

Creek	Reach	Station	Current Climate		Climate Change	
			20 Year (m^3/s)	100 Year (m^3/s)	20 Year (m^3/s)	100 Year (m^3/s)
Local Creek 6	Reach 1	1588	3.5	7.7	5.6	10
Local Creek 6	Reach 2	1865	1.2	2.6	1.9	3.4
Local Creek 6	DS Reach 4	808	4.7	10.3	7.5	13.4
Local Creek 6	DS Reach 3	451	0.01	0.01	0.01	0.01
Local Creek 6	DS Reach 2	465	0.01	10.3	7.5	13.4
Local Creek 6	DS Reach 1	101	4.7	10.3	7.5	13.4
Local Creek 7	US Reach 1D	1541	0.4	0.9	0.65	1.15
Local Creek 7	US Reach 3B	1774	0.4	0.9	0.65	1.15
Local Creek 7	US Reach 2A	2406	0.1	0.2	0.1	0.2
Local Creek 7	US Reach 1A	1660	0.7	1.5	1.1	1.9

The downstream boundary conditions for the 20 and 100 year floods on Local Creek 6 and 7 models were conservatively defined as the water levels on the Churchill River associated with the 20 and 100 year floods under climate change conditions. However, due to the very steep slope of the creeks as they approach the Churchill River, the Churchill River water levels do not cause any backwater flooding into the creeks. The boundary condition water levels are summarized in Table 42.

TABLE 42
LOCAL CREEK 6 AND 7 DOWNSTREAM BOUNDARY CONDITIONS

Creek	Current Climate Boundary Condition Water Level (m)		Climate Change Boundary Condition Water Level (m)	
	20 Year Flood	100 Year Flood	20 Year Flood	100 Year Flood
Local Creek 6	2.4	2.5	2.4	2.5
Local Creek 7	2.2	2.4	2.2	2.4

Structures

Two culvert crossings were included in the Local Creek 6 model, one that conveys flow through Mud Lake Road, and one that conveys flow through Corte Real Road. Similarly, the Local Creek 7 model included two culvert crossings, one that conveys flow through Mud Lake Road, and one that conveys flow through a trail immediately south of Mud Lake Road. The geometry of the culvert crossings was defined based on survey data collected as part of this project.

Manning's Roughness Coefficients

Similar to the other creek models, a uniform Manning's roughness coefficient of 0.03 was adopted for the models.

Contraction and Expansion Coefficients

The contraction and expansion coefficients included in the models were set to 0.1 and 0.3, which are standard values for natural channels with gradual transitions.

10.3 SIMULATION OF THE 20 AND 100 YEAR FLOODS

Following the development of the hydraulic models, the flows associated with the 1:20 and 1:100 year AEP rainfall events were simulated in each model. The flow and water level at each cross section included in each flood condition (i.e. 20 and 100 year floods for current climate and climate change conditions) are summarized in Appendix M.

10.4 CULVERT CAPACITY ASSESSMENT

The capability of the culvert crossings included in the Otter Creek and unnamed creek hydraulic models were assessed for each of the flood events. Based on similar assessments completed for WRMD, for this assessment it was assumed that the maximum allowable headwater level would correspond to the limit at which the surface of the road on top of the culvert would be overtopped.

The water levels for the 20 and 100 year flood events for current climate and climate change conditions, as well as the road crest elevation for each culvert crossing are summarized in Table 43. Water levels that exceed the road crest elevation are shown in red.

TABLE 43
HYDRAULIC CAPACITY ASSESSMENT

Creek	Reach	Station	Road Crest Elevation (m)	Culvert Size	Current Climate		Climate Change	
					20 Year Water Level (m)	100 Year Water Level (m)	20 Year Water Level (m)	100 Year Water Level (m)
Otter Creek	Otter Creek	700	4.71	2 x 1.6 m dia.	4.70	**4.80**	**4.77**	**4.84**
Local Creek 1	Local Creek 1	419	6.96	1 x 1.0 m dia.	4.84	5.89	5.22	6.66
Local Creek 1	Local Creek 1	395	4.72	1 x 0.8 m dia.	3.23	**4.80**	4.26	**4.88**
Local Creek 2	Upstream Reach	805	8.65	1 x 0.8 m dia.	7.61	**8.69**	8.07	**8.72**
Local Creek 2	Reach 2	763	6.97	1 x 0.6 m dia.	**7.03**	**7.14**	**7.09**	**7.18**
Local Creek 3	Reach 1	1274	16.71	1 x 0.9 m dia.	15.59	15.96	15.83	16.15
Local Creek 3	Reach 1	916	12.35	1 x 0.9 m dia.	11.49	11.84	11.71	12.02
Local Creek 3	Reach 1	820	9.85	3 x 0.5 m dia.	9.10	9.30	9.18	9.57
Local Creek 3	Reach 2	770	9.74	1 x 0.8 m dia.	9.09	**9.83**	**9.79**	**9.86**
Local Creek 3	Reach 2	580	7.36	1 x 1.2 m dia.	5.21	6.19	5.62	7.07
Local Creek 4	Local Creek 4	590	8.20	1 x 1.2 m dia.	7.13	7.50	7.36	7.68
Local Creek 5	Local Creek 5	6475	26.06	2 x 1.1 m dia.	25.61	**26.14**	25.96	**26.25**
Local Creek 5	Local Creek 5	5975	23.59	2 x 1.2 m dia.	22.93	23.58	23.34	**23.70**
Local Creek 6	Reach 2	1475	10.14	1 x 0.7 m dia.	**10.31**	**10.41**	**10.37**	**10.44**
Local Creek 6	DS Reach 1	60	9.71	1 x 1.0 m dia.	**9.73**	**9.80**	**9.77**	**9.82**
Local Creek 7	Downstream Reach	120	9.02	1 x 1.3 m dia.	8.03	8.71	8.38	**9.05**
Local Creek 7	Downstream Reach	90	7.30	1 x 0.8 m dia.	**7.44**	**7.62**	**7.54**	**7.69**

11.0 SENSITIVITY ANALYSES OF THE HYDROLOGIC AND HYDRAULIC MODEL INPUTS

11.1 OVERVIEW

As an independent check of the relative accuracy and calibration of the models used for this study, a number of tests on the models was completed to test the model sensitivity to changes to key model parameters. Sensitivity tests are completed by running the same information, such as precipitation or river flows, through a model, and adjusting an individual model parameter for each simulation to see how the change affects the model results.

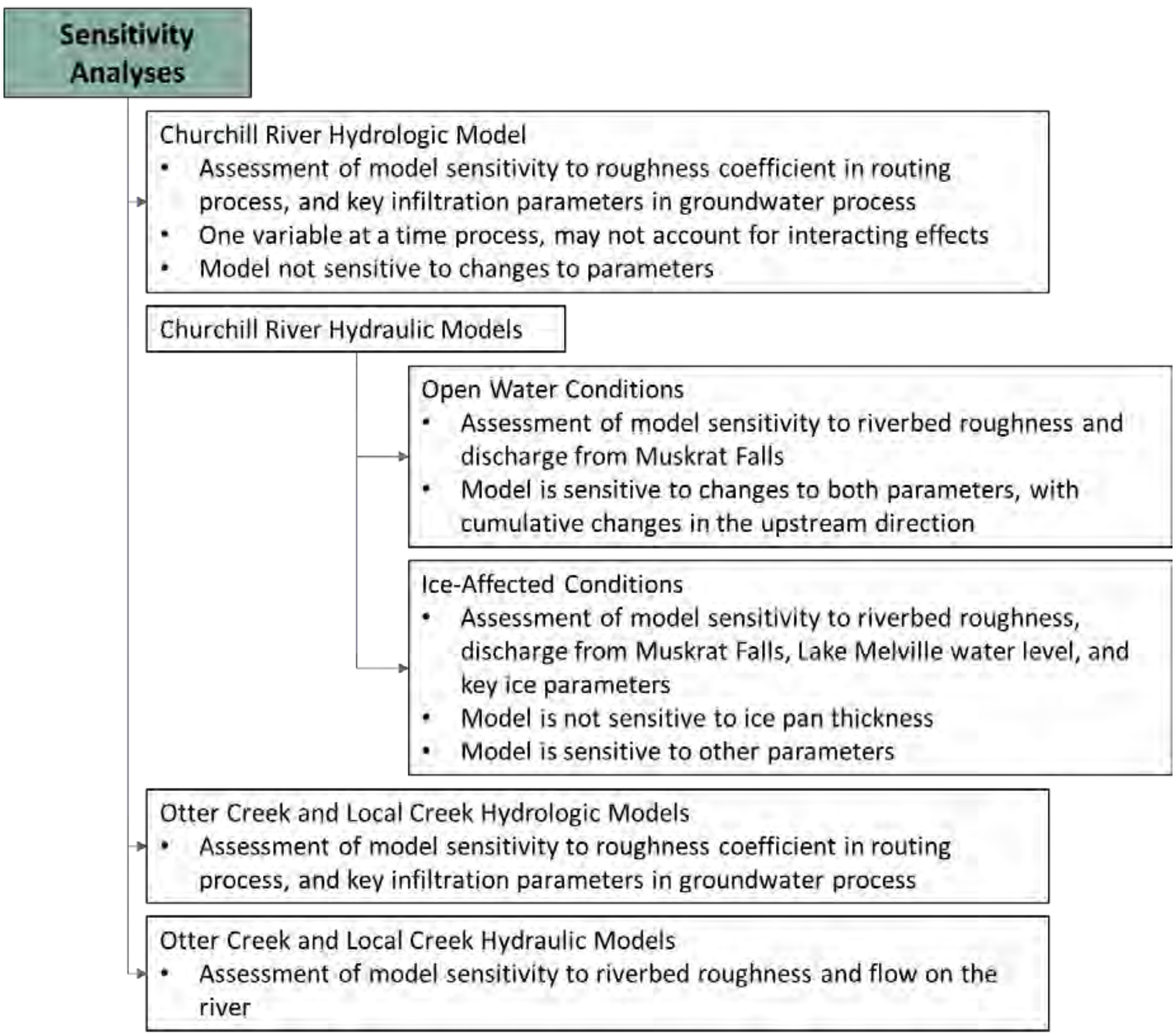
For the hydrological model, the sensitivity test checked how sensitive the model was to the parameters that represents channel roughness included in the hydrologic routing function of the model, as well as the parameters that represent how much rainfall gets absorbed by the ground during rain and melt events. The parameters were increased and decreased by 10%, 20% and 30%. The tests considered the model sensitivity to these changes by comparing the modelled flows at Muskrat Falls. The tests showed that the model was most sensitive to the ground absorption model parameters, although the model was not considered to be very sensitive.

Similar tests were completed for the open water and ice-affected hydraulic models. For the open water model, the tests considered the model sensitivity to changes to the inflow at Muskrat Falls, and to the parameter that represents the riverbed roughness. The sensitivity was checked by comparing the modelled water levels at key locations along the Churchill River. The sensitivity tests showed that the model is sensitive to changes to either parameter. However, given the model sensitivity and the thorough model calibration process, the parameters built in to the model are considered to be representative.

For the ice-affected model, several model parameters were adjusted to test the model sensitivity. These parameters included the ice pan porosity, ice pan thickness, volume of ice, riverbed roughness, discharge from Muskrat Falls, and Lake Melville water levels. The model was most sensitive to the ice porosity and Muskrat Falls discharge parameters, moderately sensitive to the volume of ice, riverbed roughness, and Lake Melville water levels, and not sensitive to the ice thickness parameter. However, many of the model parameters are either estimated from available forecast information (i.e. Muskrat Falls discharge and Lake Melville water levels), based on observations (i.e. ice thickness and volume of ice), or are based on expert knowledge (i.e. channel bed roughness and ice porosity). Similar to the open water model, given the model sensitivity and the thorough model calibration process, the parameters built in to the model are considered to be representative.

An overview of the sensitivity analysis tasks is shown on Figure 93.

FIGURE 93
OVERVIEW OF SENSITIVITY ANALYSIS TASKS



11.2 CHURCHILL RIVER HEC-HMS MODEL

A sensitivity analysis was completed for the HEC-HMS model to assess the model sensitivity to changes to key model parameters, specifically the SCS Curve Number and the Manning's coefficient included in the routing function. While the terms of reference for this study indicate that the sensitivity analysis should consider the SCS Curve Number, the SCS Curve Number method was not used in the HEC-HMS model, and instead the Green & Ampt method was used. Accordingly, the sensitivity analysis instead considered changes to the hydraulic conductivity and suction parameters in the Green & Ampt loss method. These parameters, as well as the Manning's roughness coefficient, were adjusted from -30% to +30% in the HEC-HMS model, which was then used to simulate the 100-year rainfall event.

The sensitivity analysis was completed by altering one parameter at a time, which may not account for interacting effects associated with the different physical processes included in the model. Accordingly, this analysis assumed that any interacting effects between the model parameters are minimal, and that the model input parameters are largely independent.

The model sensitivity was assessed at Muskrat Falls. The change in simulated flow at Muskrat Falls relative to the changes to the model parameters are summarized in Table 44.

TABLE 44
HEC-HMS MODEL SENSITIVITY

Parameter	Change to Parameter					
	-30%	-20%	-10%	+10%	+20%	+30%
Hydraulic Conductivity	8%	6%	3%	-1%	-3%	-5%
Suction	4%	2%	1%	-1%	-2%	-3%
Manning's Roughness	1%	1%	0%	0%	-1%	-1%

The sensitivity analysis showed that the model is only slightly sensitive to changes to the hydraulic conductivity, and even less sensitive for the other parameters considered in the assessment. A large change to the hydraulic conductivity (i.e. +30% or -30%) results in a considerably smaller change to the maximum flow at Muskrat Falls (i.e. less than 10%), and as such the model is not considered to be sensitive to changes to the hydraulic conductivity parameter. Similarly, the model is not considered to be sensitive the changes to the suction or Manning's roughness coefficient parameters.

11.3 CHURCHILL RIVER HYDRAULIC MODELS

11.3.1 HEC-RAS Model

A sensitivity analysis was completed to assess the HEC-RAS model (i.e. open water model) sensitivity to changes to the Manning's roughness coefficients of the main channels, as well as to the peak discharge at Muskrat Falls. For the sensitivity analysis of the model to changes to the Manning's roughness coefficients, the roughness coefficients of the main channels of the Churchill River and Mud Lake channels were adjusted by -30% to +30%, and the model was then used to simulate the 100-year open water flood conditions (i.e. a Muskrat Falls discharge of 6,610 m^3/s). For the sensitivity analysis of the model to changes in peak discharges from Muskrat Falls, the 100-year flood discharge was adjusted by -30% to +30% and simulated in the final calibrated model. The results of these simulations were then compared to the simulated 100-year flood conditions using the calibrated model.

The model sensitivity to changes to the Manning's roughness coefficients and to the peak discharge from Muskrat Falls at key locations throughout the study area are summarized in Table 45 and Table 46. Rather than showing the water level changes as a relative percentage, in which the actual elevation change is based on the cross section location (i.e. for the 100 year flood, a 10% change at English Point would correspond to approximately 0.10 m, while a 10% change at 6.15 km Below Muskrat Falls would correspond to approximately 0.60. m), the water level changes shown in Table 45 and Table 46 are reported as the actual elevation difference. The simulated water levels at each of the cross sections for the sensitivity analysis simulations are included in Appendix N.

TABLE 45
HEC-RAS MODEL SENSITIVITY TO MANNING'S ROUGHNESS COEFFICIENT

Location	Change in Water Level (m)					
	-30%	-20%	-10%	+10%	+20%	+30%
English Point	-0.35	-0.24	-0.12	0.12	0.24	0.35
Mud Lake	-0.53	-0.34	-0.16	0.17	0.33	0.48
Happy Valley - Goose Bay	-0.56	-0.36	-0.17	0.17	0.32	0.47
6.15 km Below Muskrat Falls	-0.85	-0.55	-0.27	0.25	0.50	0.73

TABLE 46
HEC-RAS MODEL SENSITIVITY TO MUSKRAT FALLS DISCHARGE

Location	Change in Water Level (m)					
	-30%	-20%	-10%	+10%	+20%	+30%
English Point	-0.32	-0.22	-0.11	0.11	0.22	0.33
Mud Lake	-0.47	-0.3	-0.14	0.16	0.31	0.46
Happy Valley - Goose Bay	-0.55	-0.35	-0.17	0.16	0.32	0.46
6.15 km Below Muskrat Falls	-0.88	-0.57	-0.28	0.26	0.51	0.75

The sensitivity analysis showed that the HEC-RAS model is sensitive to changes to both the Manning's roughness coefficients and discharge from the Churchill River, with the model sensitivity increasing cumulatively towards Muskrat Falls. Changes to either the Manning's roughness coefficients or the Muskrat Falls discharge impact the calculated head loss between each cross section, and the change to the headlosses are compounded from the downstream end of the model at Lake Melville to the upstream end of the model at Muskrat Falls.

11.3.2 RIVICE Model

A sensitivity analysis was completed to assess the RIVICE model sensitivity to changes to the key hydraulic and ice processes. The sensitivity analysis was completed by changing the key parameters in the model by -30% to +30%, with the exception of the Lake Melville water level, which was adjusted by -0.75 m to 0.75 m. The range considered in the sensitivity analysis of the Lake Melville water level was approximately twice as large as the tidal range at the gauge, resulting in both higher and lower water levels than were considered as part of the model calibration. A simulation was completed for each changed condition in the RIVICE model, and compared to a baseline simulation where no parameters were adjusted. The parameters that were considered in the sensitivity analysis included:

- Ice porosity,
- Ice pan thickness,
- Volume of ice,
- Channel roughness,
- Discharge from Muskrat Falls, and
- Lake Melville water level.

The results of these simulations were then compared to the base simulations with no adjustments to the above key parameters. The model sensitivity at key locations associated with changes to the ice parameters and discharge from Muskrat Falls are shown on Table 47, while the model sensitivity to changes to Lake Melville water levels are shown on Table 48.

The simulated water levels for each sensitivity analysis simulation at each cross-section location is included in Appendix O.

TABLE 47
RIVICE MODEL SENSITIVITY TO ICE PARAMETERS AND MUSKRAT FALLS DISCHARGE

Parameter	Location	Change in Water Level (m)					
		-30%	-20%	-10%	+10%	+20%	+30%
Ice Porosity	English Point	0.41	0.16	0.08	-0.04	-0.10	-0.18
	Happy Valley - Goose Bay	0.34	0.17	0.07	-0.05	-0.11	-0.17
	6.15 km Below Muskrat Falls	0.00	-0.01	0.00	0.00	0.03	0.04
Ice Pan Thickness	English Point	-0.03	-0.01	0.00	0.00	0.00	0.03
	Happy Valley - Goose Bay	-0.04	-0.02	-0.01	0.00	0.00	0.03
	6.15 km Below Muskrat Falls	-0.02	-0.01	0.00	0.00	0.01	0.01
Volume of Ice	English Point	-0.24	-0.14	-0.04	0.06	0.14	0.20
	Happy Valley - Goose Bay	-0.22	-0.14	-0.06	0.06	0.13	0.20
	6.15 km Below Muskrat Falls	0.05	0.04	0.01	0.00	-0.01	-0.01
Bed Roughness	English Point	-0.13	-0.11	-0.12	0.02	0.04	0.08
	Happy Valley - Goose Bay	-0.31	-0.26	-0.18	0.05	0.12	0.20
	6.15 km Below Muskrat Falls	-0.75	-0.52	-0.30	0.21	0.40	0.59
Muskrat Falls Discharge	English Point	-0.77	-0.48	-0.22	0.21	0.40	0.73
	Happy Valley - Goose Bay	-0.68	-0.43	-0.20	0.21	0.42	0.65
	6.15 km Below Muskrat Falls	-0.53	-0.34	-0.18	0.22	0.45	0.63

TABLE 48
RIVICE MODEL SENSITIVITY TO LAKE MELVILLE WATER LEVELS

Location	Change in Water Level (m)					
	-0.75 m	-0.50 m	-0.25 m	+0.25 m	+0.50 m	+0.75 m
English Point	-0.26	-0.19	-0.06	0.03	0.09	0.12
Happy Valley - Goose Bay	-0.33	-0.27	-0.17	0.06	0.13	0.19
6.15 km Below Muskrat Falls	-0.32	-0.29	-0.28	0.10	0.17	0.24

The sensitivity analysis showed that the RIVICE model is sensitive to changes to the ice porosity parameter, with the highest model sensitivity at the downstream end of the model. The RIVICE model is not sensitive to the ice pan thickness parameter, with very small changes to the simulated water level for relatively large changes to the ice pan thickness parameter. The RIVICE model was moderately sensitive to changes to the volume of ice, with the model sensitivity decreasing farther upstream (i.e. away from the location of the ice jam).

The backwater levels were sensitive to changes to the Manning's roughness coefficient, although less sensitive than the HEC-RAS model due the generally lower flows simulated in the model. Similar to the HEC-RAS model, the model sensitivity increases towards Muskrat Falls in the RIVICE model due to the cumulative effects of the increased roughness.

The RIVICE model was most sensitive to changes to the simulated discharge from Muskrat Falls. However, unlike the HEC-RAS model, the RIVICE model is most sensitive to changes to the Muskrat Falls discharge at the downstream end of the model (i.e. near the ice jam), and slightly less sensitive near Muskrat Falls. The RIVICE model was also moderately sensitive to changes to the Lake Melville water level, with changes to the Lake Melville backwater level affecting water levels throughout the model domain.

11.4 OTTER CREEK AND LOCAL CREEK HYDROLOGIC MODELS

Similar to the hydrologic model for the Churchill River, a sensitivity analysis was completed for the HEC-HMS model to assess the model sensitivity to changes to key model parameters. However, rather than completing a sensitivity analysis for every creek model, which would have been redundant considering the similarity between the models, a sensitivity analysis was completed on Local Creek 5, which was representative of the conditions in the various basins. The sensitivity analysis considered changes to the hydraulic conductivity and suction parameters in the Green & Ampt loss method, as well as the Manning's roughness coefficient, which were adjusted from -30% to +30% in the HEC-HMS model, which was then used to simulate the 100-year rainfall event for climate change conditions.

Similar to the Churchill River model, the sensitivity analysis was completed by altering one parameter at a time, which may not account for interacting effects associated with the different physical processes included in the model. Accordingly, this analysis assumed that any interacting effects between the model parameters are minimal, and that the model input parameters are largely independent.

The model sensitivity was assessed at the outlet of the creek into Lake Melville. The changes to the flow into Lake Melville associated with the changes to the model parameters are summarized in Table 49.

TABLE 49
LOCAL CREEK 5 HEC-HMS SENSITIVITY ANALYSIS

Parameter	Change to Parameter					
	-30%	-20%	-10%	10%	20%	30%
Hydraulic Conductivity	23%	15%	8%	-7%	-15%	-23%
Suction	0%	0%	0%	0%	0%	0%
Manning's Roughness	-1%	2%	2%	-2%	-2%	-4%

The sensitivity showed that the model was sensitive to changes to the hydraulic conductivity, but was not sensitive to changes to the suction or roughness parameters. However, the hydraulic conductivity values adopted for the hydrologic models were defined considering the Natural Resources Conservation Service soil type B, which have moderate rates of water transmission, as defined the terms of reference. In reality, based on available surficial mapping, the soil in the study area likely consists of sandier soil and as such would have higher hydraulic conductivity values than were adopted for the hydrologic models. Accordingly, the hydraulic conductivity parameters adopted for the hydrologic models is a conservative representation of the soil conditions in the study area.

11.5 OTTER CREEK AND LOCAL CREEK HYDRAULIC MODELS

A sensitivity analysis was completed for the creeks in Happy Valley – Goose Bay to assess the model sensitivity to changes to the Manning's roughness coefficients and the peak flows on the creeks. Similar to the sensitivity analysis completed for the creek models, the sensitivity analysis was completed for the Local Creek 5 model, which was generally considered to be representative of the hydraulic conditions on the creeks.

The sensitivity analysis was completed considering the 100-year flood for climate change conditions. Similar to the assessment completed for the Churchill River, the water levels resulting from the sensitivity analysis simulations were compared to those with no adjustments made to the model parameters. These changes are summarized at the upstream and downstream ends of the culvert crossings included in the model in Table 50 and Table 51.

TABLE 50
CREEK MODEL SENSITIVITY TO CHANGES TO MANNING'S ROUGHNESS COEFFICIENT

Station	Water Level Change (m)					
	-30%	-20%	-10%	10%	20%	30%
6484	0.00	0.00	0.00	0.00	0.00	0.00
6451	-0.11	-0.07	-0.03	0.05	0.08	0.11
5597	0.00	0.00	0.00	0.00	0.00	0.00
5965	0.00	0.00	0.00	0.00	0.00	0.00

TABLE 51
CREEK MODEL SENSITIVITY TO CHANGES TO FLOW

Station	Water Level Change (m)					
	-30%	-20%	-10%	10%	20%	30%
6484	-0.14	-0.09	-0.04	0.03	0.07	0.10
6451	-0.09	-0.06	-0.03	0.04	0.07	0.10
5597	-0.18	-0.08	-0.04	0.03	0.06	0.09
5965	-0.07	-0.04	-0.02	0.02	0.04	0.06

The sensitivity analysis showed that the hydraulic models are generally not sensitive to changes to the roughness coefficients included in the model, and that the water levels in the model are generally governed by limited culvert capacities and steep topography. However, the hydraulic models are sensitive to flow changes upstream of the culvert crossings, where the limited culvert capacity causes considerable changes to the water levels.

12.0 CHURCHILL RIVER FLOOD RISK MAPPING

12.1 OVERVIEW

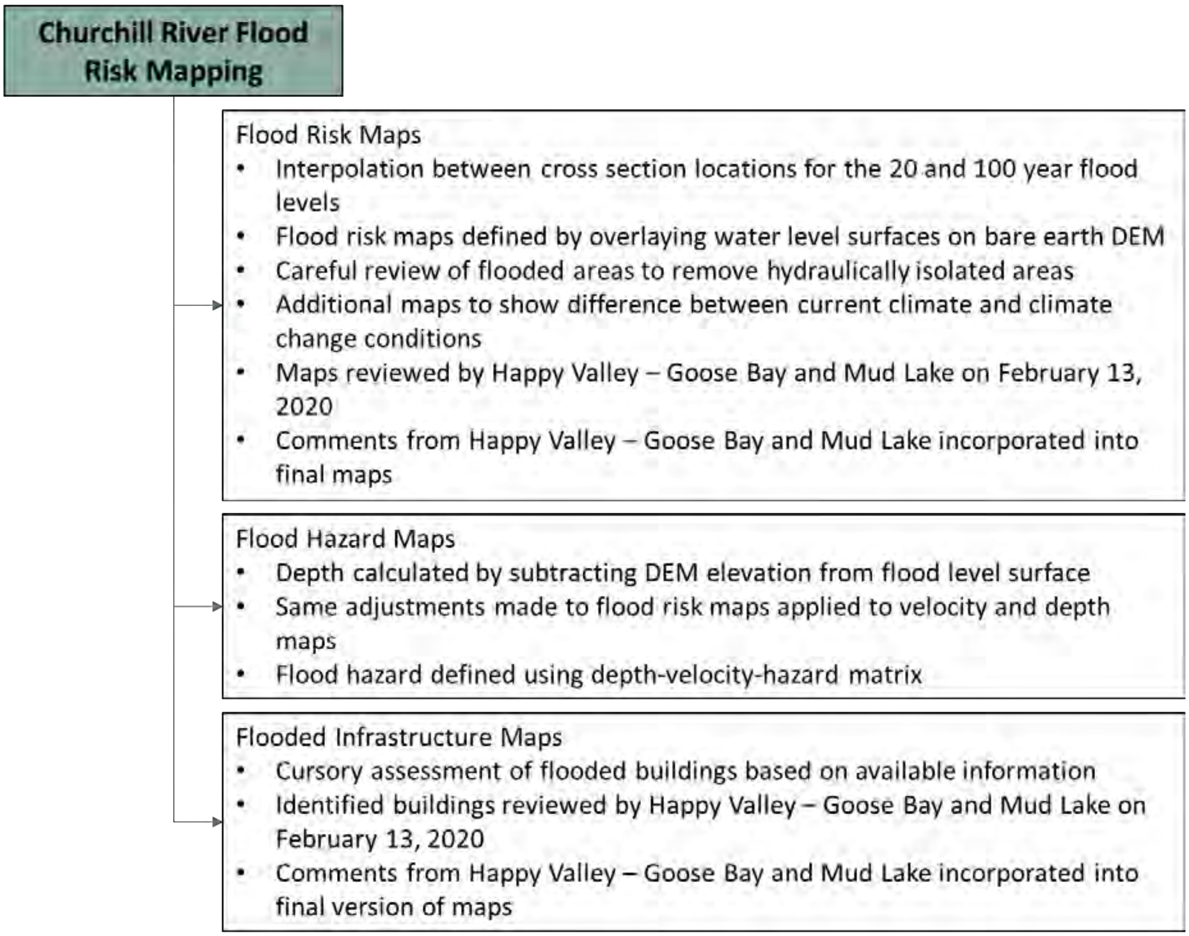
Once water levels on the Churchill River and Mud Lake channels were estimated for the 20 and 100-year floods under the current climate and climate change conditions, the modelled water levels, flooding depths and flow velocities were used in combination with the ground elevation model to develop the flood risk and flood hazard maps.

The flood risk maps, which show the flood extent for each condition, were developed by overlaying the modelled water levels on top of the ground elevation model. Areas where the modelled water level was higher than the ground elevation were shown as flooded, while areas where the ground elevation was higher than the modelled water level were shown as dry. The flooded areas were carefully reviewed to identify any disconnected areas. Since the flooded areas need to be connected for the flooding to actually occur, any disconnected areas were removed from the maps.

In addition to the flood risk maps, separate map sets were developed showing the modelled depth of flooding and flow velocities for each flood condition. The depth of flooding maps were developed by subtracting the ground elevation from the modelled water levels for each condition for any areas that were shown as wet in the flood risk maps. The flow velocity maps were defined based on the modelled river and flood plain velocities from the hydraulic models. Finally, flood hazard maps were defined that consider both the depth of flooding and flow velocities to define different levels of flood hazard, ranging from a low risk, where caution should be exercised, to a high risk, which poses a caution for all, including emergency services.

An overview of the flood risk mapping tasks is shown on Figure 94.

FIGURE 94
OVERVIEW OF CHURCHILL RIVER FLOOD RISK MAPPING TASKS



12.2 FLOOD RISK MAPS

The calibrated hydraulic models described in Section 9.0 were used to simulate the 20 and 100-year floods for the current climate and climate change conditions under both open water and ice-affected conditions. Typically, flood risk mapping projects completed for WRMD have followed the *Map to Map* framework, which provides conventions for the development of the HEC-HMS and HEC-RAS models so that the models can be seamlessly integrated in the definition of the flood risk maps. However, since the HEC-HMS model was not used to define the inflows to the HEC-RAS model, and since additional modelling was completed using the

RIVICE model for ice-affected conditions, the *Map to Map* framework was not implemented for the preparation of the flood risk and flood hazard maps.

The water levels from the hydraulic models were linearly interpolated between each cross section in the model to define a smooth, continuous surface. As previously noted in Section 9.3.4, the ice-affected water levels on the Churchill River were defined based on the results from the RIVICE model, while the ice-affected water levels on the Mud Lake channels were defined by reproducing the RIVICE water levels in the HEC-RAS model. The Mud Lake channels were not incorporated into the RIVICE model due to limitations of the software. The simulated water levels were then overlain on top of the bare earth DEM, as described in Section 4.4, to define the flooded areas within the study area.

The initial flooded areas were carefully reviewed to identify any areas that are shown as flooded but hydraulically disconnected from the flooded area on the Churchill River or Mud Lake channels. Any hydraulically isolated areas were removed from the mapping, with the exception of flooded areas that were separated by a roadway. In these areas, it was assumed that culverts through the road would connect the two flooded areas. The flood zones for each condition were then overlain on top of the detailed aerial photography completed at the same time as the LiDAR survey. Each set of flood risk maps showed both the 20-year and 100-year flood zones, and consisted of 19 map sheets showing the flood zones in developed areas.

In total, 76 flood risk maps were developed to show the flood zones associated with open water and ice-affected conditions for both the current climate and climate change conditions. The flood risk maps for open water and ice-affected conditions under the current climate conditions are included in Appendix P. The flood risk maps for open water and ice-affected conditions under climate change conditions are included in Appendix Q.

In addition to the flood risk maps, a separate series of maps were developed to show the difference between the current climate and climate change conditions for each flood condition (i.e. open water and ice-affected) and flood event. In general, the comparison maps show that additional areas will be flooded due to climate change. However, some areas near Mud Lake and Mud Lake Road will experience somewhat less flooding under ice conditions for the 20 year flood due to the reduced volume of ice available to jam. Similarly, some areas downstream of

Mud Lake Road will experience a slight reduction in flooding due to the reduced volume of ice available to jam. The comparison maps are included in Appendix R.

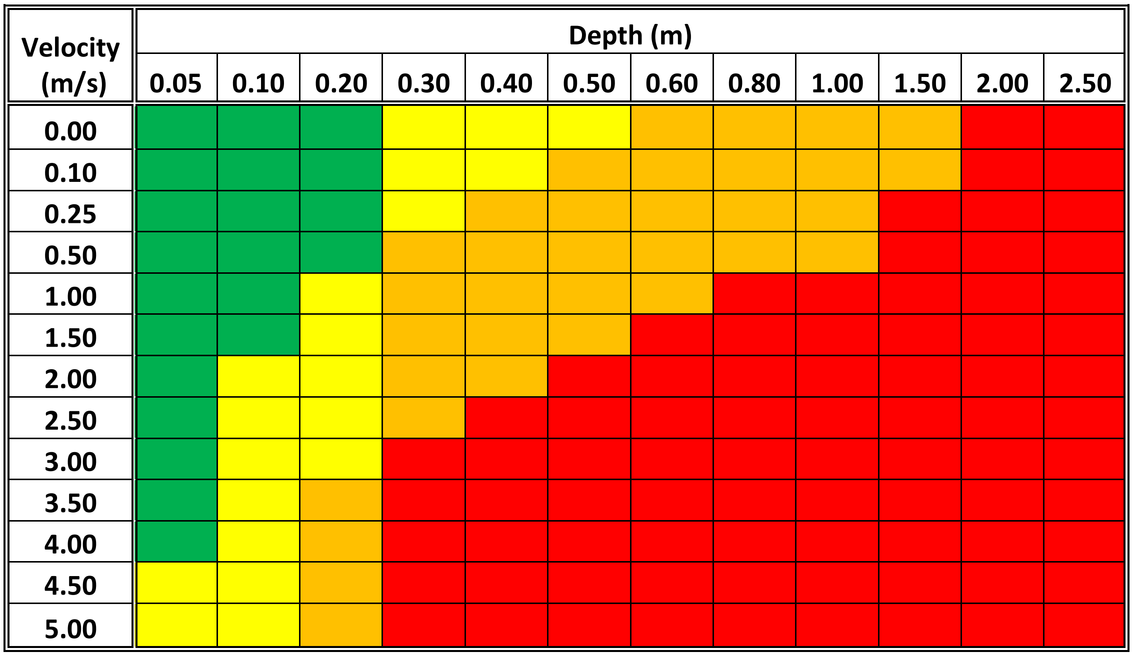
12.3 FLOOD HAZARD MAPS

In addition to the flood risk maps showing the total inundated area, maps were developed showing the depth of flooding, velocity, and flood hazard for the 20 and 100 year floods under open water and ice-affected conditions under both current climate and climate change conditions. Any adjustments made to the flooding extents shown on the flood risk maps, as described in Section 12.2, were similarly incorporated into the depth of flooding, velocity, and flood hazard maps.

The depth of flooding maps were developed by subtracting the elevation information contained in the bare earth DEM, as described in Section 4.4, from the modelled water levels for the 20 and 100-year floods under open water and ice-affected conditions. The velocity maps were developed based on the simulated velocity information from the HEC-RAS model. Similar to the flood risk maps, ice-affected velocities were defined by reproducing the RIVICE water levels in the HEC-RAS model. In addition to providing information on the Mud Lake channels, which were not included in the RIVICE model due to limitations of the software, the HEC-RAS model was also used to define the average velocity in both the main channel of the Churchill River and Mud Lake channels, as well as the flood plain areas adjacent to the main channels.

The flood hazard maps were developed based on the classification scheme defined in the presentation "*Application of Remote Sensing (Digital Terrain Models) in Flood Risk Assessments"* by M. Uden and H. Hall (2007). The classification scheme considers the hazard associated with both velocity an depth of flooding, with green representing a low hazard where caution should be exercised, yellow representing a moderate hazard that may be dangerous for some (i.e. children, the elderly and the infirm), orange represents a significant hazard that is a danger for most, including the general public, and red represents an extreme hazard that is considered to be a danger for all, including emergency services. The classification scheme is shown on Figure 95.

FIGURE 95
FLOOD HAZARD CLASSIFICATION



Source: M. Uden and H. Hall (2007)

The depth of flooding, velocity, and flood hazard maps for the open water and ice-affected 20 and 100 year floods for current climate and climate changed conditions are included in Appendix S.

12.4 FLOODED INFRASTRUCTURE

At the request of WRMD, KGS Group completed a cursory assessment of buildings affected by the 20 and 100 year floods on the Churchill River. An initial assessment was completed by visually inspecting the flood risk maps and identifying any residences affected by the open water and ice-affected 20 and 100 year floods for the current climate and climate change conditions. Residences impacted by flooding were then identified on a separate set of flood risk maps, which were presented by WRMD and KGS Group to the Town of Happy Valley – Goose Bay the Local River Watch Committee for review at a meeting held on February 13, 2020.

Both at the meeting, and subsequent to the meeting members of the Local River Watch Committee and the Town of Happy Valley – Goose Bay provided additional valuable information and insight on the flooded buildings and infrastructure in Happy Valley – Goose Bay and Mud Lake, including:

- The identification of additional non-permanent residences in Mud Lake,
- Identification and correction of main buildings and out-buildings (sheds, boathouses, etc.),
- GIS Shapefiles of roads and buildings in Happy Valley – Goose Bay,
- Additional infrastructure impacted by flooding in Happy Valley – Goose Bay.

Based on KGS Group's assessment and the information provided by the Town of Happy Valley – Goose Bay and the Local River Watch Committee, the total number of flooded buildings that could be flooded for the 20 and 100 year open water floods for current climate and climate change conditions are summarized in Table 52. The total number of possible flooded buildings for the 20 and 100 year ice-affected floods for current climate and climate change conditions are summarized in Table 53.

TABLE 52
NUMBER OF BUILDINGS AFFECTED BY OPEN WATER FLOODING

Location	20 Year Flood (Current Climate)	100 Year Flood (Current Climate)	20 Year Flood (Climate Change)	100 Year Flood (Climate Change)
Mud Lake	2	4	10	14
Mud Lake Road	0	0	3	4
Happy Valley – Goose Bay	0	0	0	0

TABLE 53
NUMBER OF BUILDINGS AFFECTED BY ICE-AFFECTED FLOODING

Location	20 Year Flood (Current Climate)	100 Year Flood (Current Climate)	20 Year Flood (Climate Change)	100 Year Flood (Climate Change)
Mud Lake	16	39	16	48
Mud Lake Road	7	14	6	16
Happy Valley – Goose Bay	0	1	0	2

Maps showing flooded buildings for the open water and ice-affected floods for the current climate and climate change conditions are included in Appendix T.

In addition to the buildings impacted by flooding, the Town of Happy Valley – Goose Bay and the Local River Watch Committee identified additional infrastructure that could be impacted by flooding. These include:

- The Hydro Sub Station located on the Birch Island backroad, which serves as the backup generating station for Happy Valley – Goose Bay,
- The lift station and emergency outflow on Birch Island Road,
- Laydown areas at 5 and 7 Commercial Road,
- Some buildings on Jim Purdy's farm on Mud Lake Road,
- The Hydro Generator on the south side of the Mud Lake community.

It is important to note, the listing of possible flooded buildings described above and in Appendix T, has been based on a high-level assessment. A detailed assessment of the number and type of buildings, whether they are inhabited has not been completed. It is possible that there are additional buildings / structures that are within the flooded area that have not been identified in this report. It is important that the Town of Happy Valley – Goose Bay as well as the Local River Watch Committee review the maps in detail to identify those buildings and critical infrastructure that would be in the flood zone to help them develop their emergency response and mitigation plans.

Given the number of buildings impacted by flooding on the Churchill River, it is recommended that flood mitigation measures be investigated and implemented to better protect the affected buildings from flooding on the river. Flood mitigation measures will help to reduce flood damages and improve the safety and well being of the residents. These measures, which could include the construction of community ring dikes or the raising of buildings above flood levels, should be studied and designed under a future study entitled "Assessment of Flood Protection Measures".

13.0 OTTER CREEK AND LOCAL CREEK FLOOD RISK MAPPING

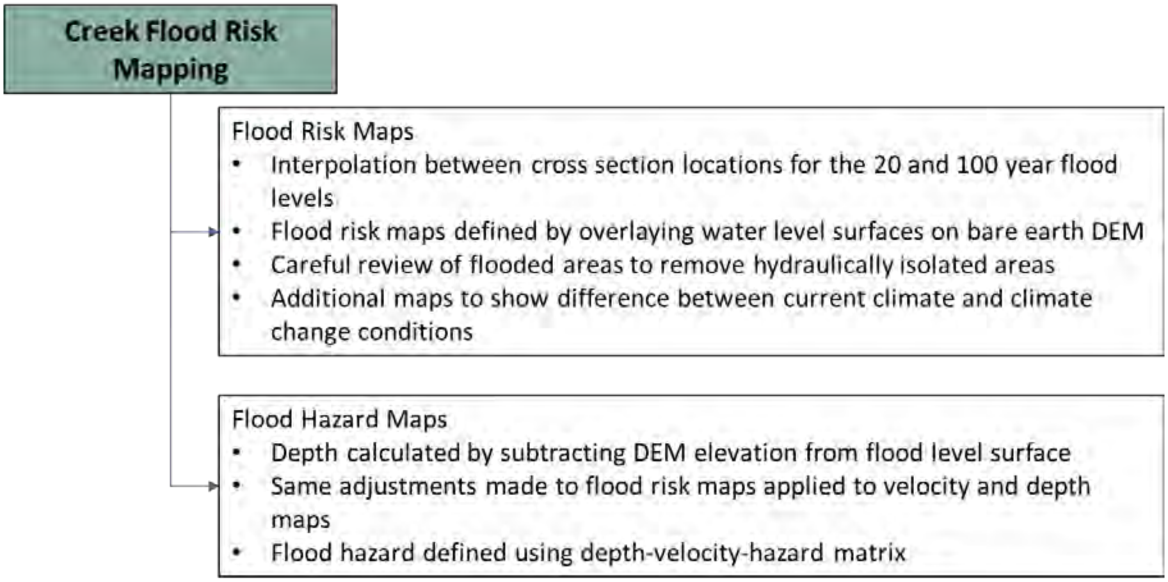
13.1 OVERVIEW

The development of the flood risk maps for Otter Creek and seven unnamed creeks in Happy Valley – Goose Bay generally followed the same process that was completed for the Churchill River. The water levels, water depths and flow velocities defined by the hydraulic models on the creeks for the 20 and 100 year floods for current climate and climate change conditions were used in combination with the ground elevation model to develop the flood risk and flood hazard maps.

The flood risk maps, which show the extent of flooding for the different flood scenarios, were carefully reviewed to identify and remove any disconnected flooded areas, since the flooded areas would need to be connected for flooding to actually occur. A separate set of maps showing the modelled water depth, flow velocities, and flood hazard were also defined for each flood condition for any areas that showed flooding in the flood risk maps.

An overview of the tasks completed as part of the flood risk mapping on Otter Creek and the unnamed creeks is shown on Figure 96.

FIGURE 96
OVERVIEW OF CREEK FLOOD RISK MAPPING



13.2 CREEK FLOOD RISK AND FLOOD HAZARD MAPS

The flood risk and flood hazard maps for the Otter Creek and unnamed creeks were defined following the same approach as the Churchill River. Specifically, the surfaces of the water levels and velocities on these creeks were interpolated between the cross sections included in each model to define smooth, continuous surfaces, which were then overlain on top of the ground surface defined in the DEM to define the flood extents. The flood extents were carefully reviewed for each flood condition to identify and remove any hydraulically isolated areas that are shown as flooded. The flooded areas were then overlain on top of the detailed aerial imagery. Sets of flood risk maps were developed for the current climate and climate change conditions that showed both the 20-year and 100-year flood zones. Each set of maps of included 6 map sheets showing the flood zones in developed areas. The flood risk maps are included in Appendix U.

Maps were also developed showing the depth of flooding, flow velocity and flood hazard for the 20 and 100 year floods under current climate and climate change conditions. The development of these maps followed the same approach that was implemented for the Churchill River flood hazard maps. These flood hazard maps are included in Appendix V.

In addition to the flood risk maps, a separate series of maps were developed to show the difference between the current climate and climate change conditions for each flood event. In general, the comparison maps show that additional areas will be flooded due to climate change. The maps showing the comparison of the current climate and climate change flood risk are included in Appendix W.

13.3 FLOODED INFRASTRUCTURE

Similar to the assessment completed for the Churchill River, KGS Group completed a cursory assessment of buildings affected by the 20 and 100 year floods on Otter Creek and the seven unnamed creeks. The assessment was completed by visually inspecting the flood risk maps and identifying any residences affected by the 20 and 100 year floods for the current climate and climate change conditions. Residences impacted by flooding were only identified on Otter Creek and Local Creek 6. The number of flooded residences are summarized in Table 54, and are shown on maps in Appendix T.

TABLE 54
NUMBER OF BUILDINGS AFFECTED BY CREEK FLOODING

Location	20 Year Flood (Current Climate)	100 Year Flood (Current Climate)	20 Year Flood (Climate Change)	100 Year Flood (Climate Change)
Otter Creek	0	1	2	19
Local Creek 6	3	3	3	3

14.0 FLOOD FORECASTING

14.1 OVERVIEW

The Churchill River Flood Forecasting System was developed for the lower Churchill River downstream of Muskrat Falls that predicts flows on the River using the hydrological model described in Section 6.0, and predicts water levels using the hydraulic models described in Section 9.0. The forecasting system was developed using 4DM's HydrologiX software as the backbone for the system, which gathers a wide variety of near real-time or forecast information from several different sources to generate a forecast on the river. The near real-time and forecast information includes forecast temperature and precipitation data from Environment Canada, near real-time water level, water temperature, and flow data on the Churchill River and tributaries from both Water Survey of Canada and the Water Resources Management Division of the Government of Newfoundland and Labrador, ice thickness and ice coverage information from C-Core, near real-time generating station outflows from Nalcor, and forecast tidal levels on Lake Melville from the Department of Fisheries and Oceans Canada. All of the data is stored in a database in the system for future reference. Some of the data is used as inputs to the forecasting system, while other data is used to check the quality of the forecast on an ongoing basis.

The forecasting system feeds the forecast temperature and precipitation data, as well as the Churchill Falls Generating Station outflows, into the hydrological model of the Churchill River basin to establish a flow forecast on the Churchill River at Muskrat Falls. Depending on the season, the flow forecast is converted to water levels at several locations on the Churchill River using either the open water forecasting model, described in Section 9.2.2, or the ice-affected forecasting model, as described in Section 9.3.2. The forecast water levels at key locations are then automatically compared by the forecasting system against ground levels at those key locations at which flooding is anticipated to start. If the forecast water levels are higher than the ground levels, the system automatically sends warnings to the Government of Newfoundland and Labrador.

The forecasting system runs every day and provides a different type of forecast depending on the seasonal condition of the river, specifically open water conditions, freezeup conditions, mid-winter conditions, and breakup conditions. The system automatically changes between each different seasonal condition based on data that is automatically collected by the system.

The Churchill River Flood Forecasting System was deployed in April, 2019 and successfully forecast high water levels on the lower Churchill River.

An overview of the flood forecasting tasks is shown on Figure 97.

FIGURE 97
OVERVIEW OF FLOOD FORECASTING TASKS

Flood Forecasting Service

- System Definition
  - Conceptual development of the forecasting system
  - Identification of tasks requiring automation
  - Identification of software development work
- System Development
  - CRFFS Database
    - Development of repository of key information required and used by the system
    - Development of automated data feeds to retrieve key forecasting data
  - Integration of Forecasting Models
    - Optimization of hydrologic model to work with forecasting precipitation and temperature data
    - Development of open water flow and water levels tables for each cross section
    - Optimization of the number of Monte Carlo runs to include in the ice-affected forecasting
    - Development of model adapters for the hydrologic and ice-affected hydraulic models, as well as pre- and post-processing tools
    - Development of a forecast cycle to automatically change the forecasting model based on real time monitoring data
  - System Scheduling
    - Automation of processes based on user-defined scheduling
  - Threshold Model and Alert Generator
    - Development of automated system alerts based on user-defined threshold water levels
  - System Frontend
    - Development of user-facing component that provides users with key system information, including forecasts, notifications, and diagnostics
- Model Testing, Deployment and Training
  - Near continuous testing during winter 2018 to summer 2019
  - System deployed to WRMD on April 30, 2019
  - Training session provided for key WRMD staff on April 30 and May 1, 2019
  - System User Manual provided to WRMD on January 31, 2020

14.2 DEFINITION OF THE FLOOD FORECASTING SERVICE

At the onset of the project, the project team brainstormed several potential solutions to developing a flood forecasting system for the Lower Churchill River. However, it quickly became apparent that the requirements for the system would require capabilities to interface between real and near-real time data, and the HEC-HMS, HEC-RAS and RIVICE models. Furthermore, system functionality was required to define what constituted a flood risk, and to convey the flood risk to key users. Accordingly, the Project Team selected 4DM's HydrologiX software, as a large portion of the critical functionality was already incorporated into the software. However, many unique elements required development for the CRFFS to meet the goals of the project.

14.3 DEVELOPMENT OF THE FLOOD FORECASTING SERVICE

14.3.1 Development Environment

Development and testing of CRFFS was completed on a dedicated Windows 2008 R2 64-bit Server running in the VMWare virtual environment. Following completion of the system testing, the server was used for operational running of CRFFS during the 2019 spring freshet prior to its deployment on the Government of Newfoundland and Labrador computer environment. CRFFS implementation utilized the Subversion version control software to enable concurrent and collaborative development activities.

14.3.2 CRFFS Database

The development of CRFFS required the acquisition and processing of a significant amount of data. Input datasets for CRFFS were either produced by the Project Team as part of this project or acquired from the external sources, which included:

- WRMD;
- ECCC;
- WSC;
- DFO;
- C-Core;
- Nalcor Energy.

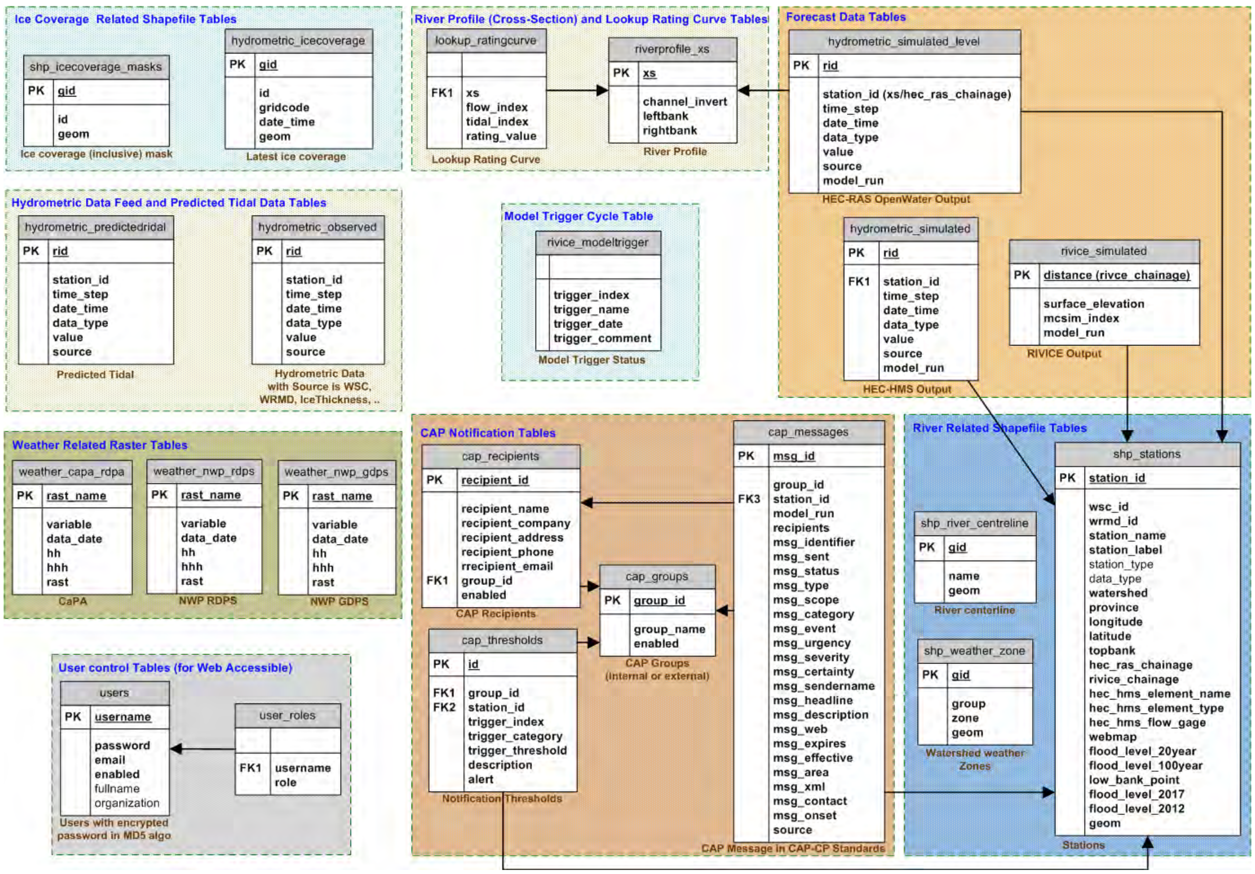
Input datasets were incorporated into CRFFS using two different methods:

- Data Feed – automatic data collection via the CRFFS near real-time data acquisition processors (i.e. 'data feeds'). Data feeds are responsible for the bulk of the data required for CRFFS.
- Data Load – one-time operator driven (i.e. manual) data loading, primarily used for reference or historical data.

A summary of the datasets that were assembled as part of the development and operation of CRFFS are included in Appendix X, and includes a description of the data, the data source, the primary use of the data, whether the data was collected for input to CRFFS or generated by CRFFS as an output, and how the data was incorporated into CRFFS. Key output datasets produced by the system are denoted with "CRFFS" in the *Data Source* column.

CRFFS database uses the PostgreSQL database server with the PostGIS extension for handling spatial data. A data model was created to enable storage and efficient processing of all of the spatial and temporal data necessary for supporting operational flood forecasting in the Churchill River basin. A conceptual overview of the data model is shown on Figure 98.

FIGURE 98
CRFFS DATABASE DATA MODEL



Most of the data necessary for CRFFS to work is obtained automatically via near real-time data acquisition processes. However, for some key components, automated data acquisition processes were unavailable, and as such data was loaded via a one-time manual import of data into the CRFFS database. Data loading was used primarily for static reference or historical data, and required development of custom data loading scripts.

Automated data feeds into CRFFS were developed for a variety of key information in the system. An overview of each data feed incorporated into CRFFS is provided below.

CaPA Data Feed

The CaPA data from ECCC provides objective estimates of precipitation amounts anywhere in Canada. The dataset is compiled from multiple sources and is available at 6-hour temporal and 10 km spatial resolution. CaPA data has been produced as part of ECCC's Regional Deterministic Precipitation Analysis (RDPA) on an on-going near real-time basis since 2011. Data files from the previous 30 days are freely available online from ECCC.

The existing CaPA data acquisition processor available in the HydrologiX system has been reused and enhanced to:

- Streamline and accelerate processing of CaPA GRIB2 data files, including data downloading, reprojection and loading into database.
- Include robust error checking, handling, reporting and logging.
- Better isolate processing of CaPA data from other data feeds, enabling, for example, concurrent processing of CaPA and Numerical Weather Prediction (NWP) datasets.

The CaPA data feed implemented in CRFFS has the following characteristics:

- Data source: Environment Canada Datamart (https://dd.weather.gc.ca/analysis/precip/rdpa/grib2/polar_stereographic/06).
- Variable: cumulative precipitation at surface level (APCP-006-0700cutoff_SFC_0).
- Data time step: 6 hours.
- Data release frequency: every 6 hours (i.e. 4 times per day).
- Data release time: 00:00, 06:00, 12:00 and 18:00 Universal Coordinated Time (UTC).
- Time of data processing in CRFFS: 04:30, 10:30, 16:30 and 22:30 Newfoundland Standard Time (NST), respectively (i.e. 8 hours after the data time to allow sufficient delay for the data to become available).
- Data coverage period: past 30 days.
- File format: GRIB2.
- Estimate of data volume (i.e. GRIB2 files): 2.0 MB/day.

NWP Data Feed

The NWP data feed is used for obtaining and processing the 10-day forecasted precipitation and temperature data that are required as inputs for the hydrological forecasting. The NWP data is provided by ECCC's GEM Regional Deterministic Prediction System (RDPS) for forecast days 1-2 (i.e. hours 0-48), and Global Deterministic Prediction System (GDPS) for forecast days 3-10 (i.e. hours 48-240). The resolution of the RDPS data is 10 km, while the resolution is 16.7 km.

For CRFFS, the NWP data feed available in the HydrologiX system has been redesigned and enhanced along the same lines as the CaPA data feed, resulting in faster, more efficient and robust processing.

Characteristics of the NWP data feed include:

- Data source: Environment Canada Datamart:
  - RDPS: https://dd.weather.gc.ca/model_gem_regional/10km/grib2
  - GDPS: https://dd.weather.gc.ca/model_gem_global/25km/grib2/lat_lon
- Variables:
  - Total precipitation at surface level (APCP_SFC_0)
  - Air temperature at 2m above ground (TMP_TGL_2)
- Data time step: 3 hours.
- Data release frequency: every 12 hours (i.e. 2 times per day).
- Data release time: 00:00 and 12:00 UTC (i.e. 21:30 and 9:30 NST).
- Time of data processing in CRFFS: 04:30 and 16:30 NST, respectively (i.e. 8 hours after the data time to allow sufficient delay for the data to become available).
- Data coverage period: past 24 hours (i.e. datasets with older release times are not available from the Datamart).
- File format: GRIB2.
- Estimate of data volume (i.e. GRIB2 files).
- Temperature: 75 MB/day.
- Precipitation: 140 MB/day.

WRMD Hydrometric Data Feed

The WRMD hydrometric data feed is designed for acquisition and processing of hydrometric data maintained by WRMD. The objective of the WRMD data feed is to obtain observed near real-time flow, water level and water temperature data from the hydrometric gauges available on the Churchill River in WRMD's Automatic Data Retrieval System (ADRS).

The WRMD acquisition processor is a new data feed developed for CRFFS. Development of the WRMD data feed leveraged existing hydrometric data acquisition facilities in the HydrologiX system, which were modified in several ways:

- Allow dynamic data layout (i.e. variable number of columns).
- Extract flow, level and water temperature variables.
- Perform time zone conversion from NST to UTC (i.e. assumes WRMD data is provided in the NST time).
- Resample time series to an hourly time step (i.e. mean hourly values).

Characteristics of the WRMD hydrometric data feed are as follows:

- Data source: Water Resources Management Division (https://www.mae.gov.nl.ca/wrmd/ADRS/v6/Data/)
- Variables:
  - o Flow (FLOW);
  - o Level (STAGE);
  - o Water temperature (WATER_TEMP);
- Data time step: 1 hour.
- Data release frequency: not applicable (updated on a continuous basis).
- Data release time: not applicable.
- Time of data processing in CRFFS: 05:20 NST.
- Data coverage period: past 7 days.
- File format: CSV.
- Estimate of data volume (i.e. GRIB2 files): 0.5 MB/day.

WSC Hydrometric Data Feed

The objective of the WSC hydrometric data feed is to acquire and process near real-time hydrometric data maintained by WSC. Near real-time WSC data available for the lower Churchill River is limited to water levels only, and currently provides data for the same gauges that are available via the WRMD data feed. At present, WSC near real-time water level data (and therefore, WSC data in general) is not used by CRFFS. The purpose of the WSC data feed in CRFFS is to enable future system enhancements by developing contingency (backup) scenarios in case the WRMD data feed is out of service, or has partial data (e.g. some gauges not available or have gaps longer than 7 days).

Implementation of the WSC hydrometric data feed started from a version available in the HydrologiX system, which was limited to processing flow data only. The feed was improved to incorporate processing of water level data.

Characteristics of the WSC hydrometric data feed include:

- Data source: Water Survey of Canada (https://dd.meteo.gc.ca/hydrometric/csv/).
- Variable: water level.
- Data time step: 1 hour.
- Data release frequency: not applicable (i.e. updated on a continuous basis).
- Data release time: not applicable.
- Time of data processing in CRFFS: 05:30 NST.
- Data coverage period: past 30 days.
- File format: CSV.
- Estimate of data volume (i.e. GRIB2 files): 0.2 MB/day.

Ice Thickness Data Feed

The ice thickness data feed acquires ice core sample thickness measurements on the lower Churchill River completed by C-Core on behalf of WRMD. Data is provided on an as-available basis during the ice coverage season, and is used for the ice-affected hydraulic modelling with the RIVICE model during ice formation, winter ice, and break-up periods.

The ice thickness acquisition processor is a new data feed developed in CRFFS that leveraged the WSC hydrometric data acquisition capabilities of the HydrologiX system. Initial implementation of the ice thickness data feed used C-Core's secure FTP site as the data retrieval channel. Subsequently, implementation was shifted to the Amazon Web Services (AWS) cloud computing platform.

Characteristics of the ice thickness data feed are as follows:

- Data source: C-Core (https://s3.ca-central-1.amazonaws.com/river-ice/churchill).
- Variable: ice thickness (i.e. two types: FT and h).
- Data time step: not applicable (i.e. single observation).
- Data release frequency: irregular (i.e. updated on as-available basis). The data feed retrieves the latest available ice thickness data file according to date embedded in the file name. If ice thickness data for this date is already present in the CRFFS database, it is replaced with the newly acquired data.
- Data release time: not applicable (i.e. date only, no time).
- Time of data processing in CRFFS: 05:35 NST.
- Data coverage period: not applicable.
- File format: CSV.
- Estimate of data volume (i.e. GRIB2 files): 0.001 MB/day on days when data is available.

Ice Coverage Data Feed

The ice coverage data feed acquires spatial data on the location and extent of ice coverage on the lower Churchill River. The ice coverage data is derived from satellite observations and is provided by C-Core on behalf of WRMD. Similar to the ice thickness observations, the ice coverage data is provided on an as-available basis during ice coverage season. The primary use of this dataset is for the ice-affected hydraulic modelling in RIVICE during ice formation and break-up periods on the Churchill River. Ice coverage is provided as spatial dataset in the ESRI Shapefile format, containing areas covered by ice and water within the lower Churchill River basin.

The ice coverage acquisition processor is a new data feed developed in CRFFS. Initial implementation of this data acquisition processor used C-Core's secure FTP site as the data retrieval channel, and was subsequently adjusted to use the AWS cloud computing platform instead.

Characteristics of the Ice Coverage data feed are as follows:

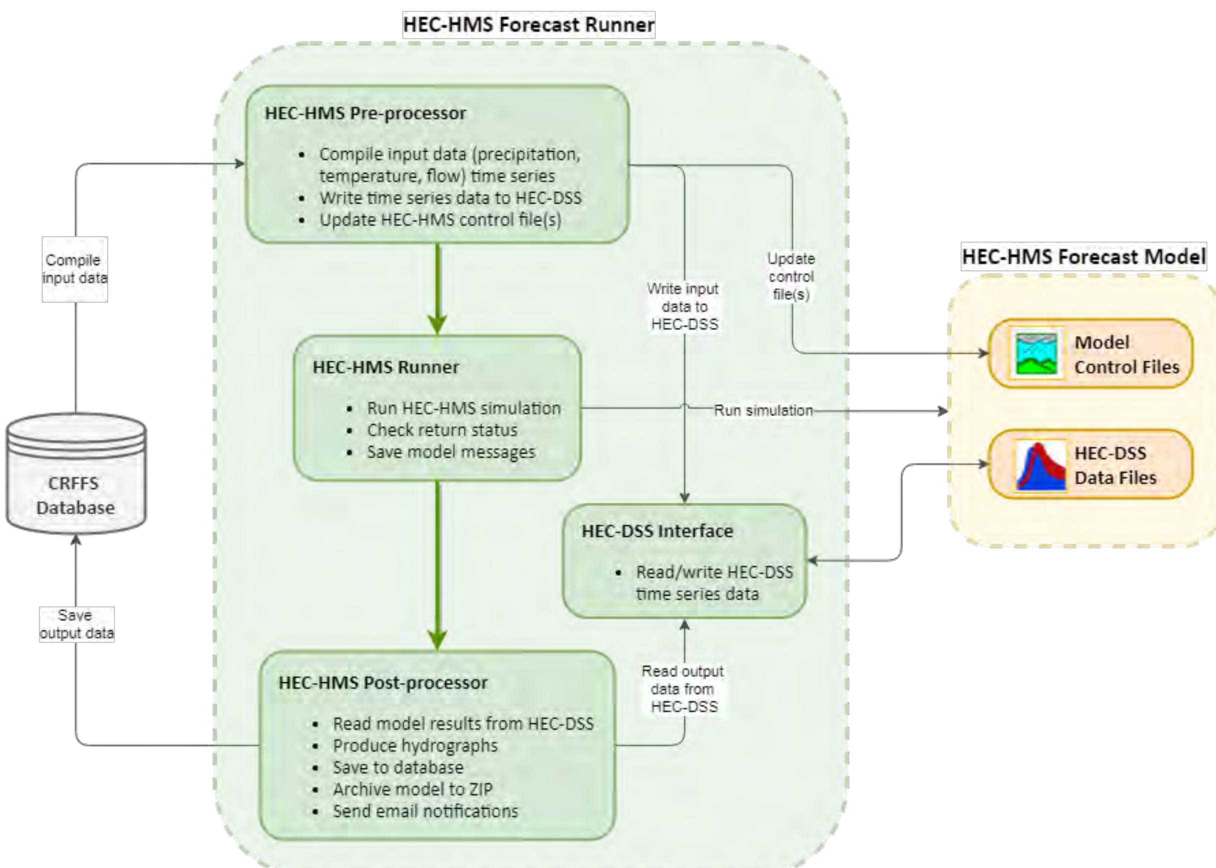
- Data source: C-Core (https://s3.ca-central-1.amazonaws.com/river-ice/churchill).
- Variable: areas (i.e. polygons) within the lower Churchill River basin that are covered by several types of ice (i.e. water on ice, non-consolidated ice or smooth ice, and consolidated ice or rough ice) or open water.
- Data time step: not applicable (i.e. single observation).
- Data release frequency: irregular (i.e. updated on as-available basis). The data feed retrieves the latest available ice coverage shapefile according to date embedded in the file name. If ice coverage data for this date is already present in the CRFFS database, it is replaced with the newly acquired data.
- Data release time: not applicable (i.e. date only, no time).
- Time of data processing in CRFFS: 05:40 NST.
- Data coverage period: not applicable.
- File format: Shapefile.
- Estimate of data volume (i.e. GRIB2 files): 2.5 MB/day on days when data is available.

14.3.3 Hydrologic Forecasting

14.3.3.1 Adjustments to the HEC-HMS Model

Hydrological forecasting was accomplished in CRFFS by incorporating the HEC-HMS model of the Churchill River basin downstream of Churchill Falls into the system using a bespoke software adapter and model runner. The forecast flow hydrographs defined by the HEC-HMS model are used as inputs to the hydraulic models of the Lower Churchill River to define water level forecasts at key locations on the river. An overview of the HEC-HMS Forecast Runner developed and incorporated into CRFFS is shown on Figure 99.

FIGURE 99
OVERVIEW OF THE HYDROLOGICAL FORECASTING IMPLEMENTATION IN CRFFS



The HEC-HMS model that is used in CRFFS for operational near real-time flow forecasting is based on the HEC-HMS model developed for the Churchill River flood plain mapping, as described in Section 6.3. However, some modifications were required to successfully implement the model in a forecasting capacity. These modifications included:

- Additional calibration to fine-tune the model to the adjusted meteorological data and to improve model fit with respect to fall and spring flow.
- Adjustments to meteorological forcing data (i.e. precipitation and temperature) and model time step.
- Design and implementation of forecast strategy.
- Model clean-up, including the removal of model elements that are not related to forecasting. This included design storms, simulations, data files and results related to flood plain mapping.

These modifications are further described in the following subsections.

Additional Model Calibration

The forecasting model was subject to several rounds of additional calibration aimed at improving model performance, including:

- Calibration necessitated by adjustments in meteorological forcing data.
- Calibration for spring freshet peaks (i.e. 2017-2019), in particular the 2019 peak.
- Adjustments in the channel routing time step method to troubleshoot an artifact in modelled flows (i.e. sharp drop at the end of forecast simulation run).

Adjustments to the Meteorological Data and Model Timestep

Similar to the HEC-HMS model used for the flood risk mapping component of this study, the forecasting model uses the CaPA dataset to define precipitation inputs for the hindcast portion of the simulation. To improve the temporal resolution of the precipitation data, the forecasting model uses 6-hourly precipitation totals rather than daily totals. Precipitation for the forecasting portion of the simulation is defined by RDPS and GDPS NWP data from ECCC. The differences between the flood risk mapping and forecasting models are summarized in Table 55.

TABLE 55
DIFFERENCES IN THE METEOROLOGICAL DATA IN CRFFS

	HEC-HMS Flood Plain Mapping Model	HEC-HMS Forecasting Model	
		Hindcast Period	Forecast Period
Modelling Period	2011 – August 2018	May 1 2016 – Present	Present – 3 days into future
Simulation Time Step	Daily	Hourly	Hourly
Precipitation Data	CaPA (daily)	CaPA (6-hourly)	RDPS (days 1-2) and GDPS (day 3) NWP data (6-hourly)
Temperature Data	Churchill Falls A (8501131) and Goose A (8501900) ECCC climate stations, interpolated using inverse distance weighting (daily)	RDPS NWP data, forecast hour 0, i.e. initial conditions (12-hourly)	RDPS (days 1-2) and GDPS (day 3) NWP data (12-hourly)

The forecasting model uses the 'initial conditions' (i.e. forecast hour 0) gridded temperature available in the RDPS data for the hindcast period. In numerical weather modelling, initial atmospheric conditions have significant impact on the quality of forecast, and therefore need to be established with maximum possible accuracy. This is achieved via a process known as data assimilation, which aims to integrate theoretical (simulated by weather models) and observed (ground-based, atmospheric, ocean surface, etc.) state of atmosphere in optimal ways. Therefore, despite technically being part of the weather prediction data, NWP temperature data for forecast hour 0 essentially represents the best estimate of air temperature at the start of forecast, and therefore is treated as the 'observed' temperature data in CRFFS. Using the NWP 'initial conditions' data allows the CRFFS forecasting model to attain better spatial (i.e. 10-km gridded data) and temporal (i.e. 12-hourly) resolution with respect to air temperature compared to ground station data. For the forecasting period, the forecasting model uses the predicted air temperature from the RDPS and GDPS data.

The forecasting model time step was also adjusted to an hourly time step to correspond to the improved temporal resolution of the precipitation and temperature input data and to allow for sub-daily flow forecasting.

Development of the Forecasting Strategy

Conceptually, operational forecasting runs consist of the hindcast and forecast periods. The purpose of the hindcast period is to improve the accuracy of initial conditions at the start of the forecast period, therefore improving the accuracy of the forecast, and to assess and quantify the model performance by comparing simulated and observed flows. The hindcast period can improve the accuracy of the forecast by counteracting the effects of uncertainty in initial conditions (e.g. soil moisture or snowpack) by simulating a sufficiently long period. In practical terms this usually means that hindcast should span several years, which allows the model to pass through several hydrological cycles, thus greatly reducing dependency on initial conditions. As well, the hindcast can allow for the assimilation of observed flows during the hindcast into the model, which can compensate for some model errors. In HEC-HMS, this assimilation is called flow blending and is performed by replacing simulated with observed flows at all locations where the observed flow data is available.

In CRFFS, the hindcast period covers the time interval from a static start date (i.e. May 1 2016) to the forecast start time (i.e. 00:00 UTC today), and the forecast period currently extends 72 hours (i.e. 3 days) from the forecast start time. The May 1, 2016 hindcast start point was defined by the availability of the NWP air temperature data. NWP datasets prior to that time were not available to the Project Team. At present, the hindcast period covers more than 3 years, which is considered sufficient to allow the model to properly develop initial conditions such as soil moisture. The forecast length was set to 3 days as specified by the WRMD team to minimize uncertainty inherent in longer meteorological forecast.

The hindcast start and the forecast period length in CRFFS are fully configurable, subject to availability of data. The hindcast start point can be shifted to a later date as the hindcast grows longer, thus helping to reduce simulation runtime. It is recommended to keep the hindcast period at least 3 years long to eliminate any sensitivity to (uncertain) initial conditions at the start of the hindcast. The forecast period can be extended to a maximum of 10 days (i.e. 240 hours) as allowed by the NWP data used in the CRFFS (i.e. RDPS and GDPS).

The Project Team evaluated the benefits and requirements of using the regular HEC-HMS *simulation runs* or the *forecast alternative* simulations to performing forecasting in HEC-HMS.

The capabilities offered by these two simulation types in HEC-HMS are generally similar, though the *forecast alternative simulation* includes a flow blending feature that was of particular interest for operational forecasting, since it allows correcting model errors when observed flow data is available. Therefore, initial implementation focused on the using a forecast alternative simulation for running forecasts. However, during the testing of CRFFS during the 2018-2019 winter, flow blending was found to adversely affect the CRFFS flow forecasts due to the poor quality of observed flow data, which is significantly affected by ice conditions. Consequently, the *regular simulation run* option was added to the Churchill River HEC-HMS forecasting model, and is presently the default option enabled in CRFFS. CRFFS supports both approaches (simulation runs and forecast alternatives), although the simulation run approach has received more thorough testing compared to the forecast alternative option. Switching between the two options is performed by editing the CRFFS configuration file as described in Section 2.2.4.1 (i.e. Hydrological Forecasting: HEC-HMS Model) of the CRFFS User Manual Section.

The Project Team also considered implementing linked mode runs, which would simulate the hindcast and the forecast periods separately using a saved model state to communicate initial conditions at the start of the forecast period. Using linked model runs may be beneficial, since it allows using separate time steps, for example a finer time step of 3 hours for the forecast period to make better use of NWP data. In the future, this setup would allow for completing multiple forecasts starting from the same initial conditions – a feature that would be useful, for example, for forecasting with ensemble NWP data. However, there are also disadvantages in using linked model runs, specifically that the model setup is considerably more complicated, requiring twice the number of certain model elements (e.g. gauges and meteorological model), and the forecast alternative feature in HEC-HMS version 4.2.1 does not support saved model states, and is essentially limited to one continuous model run. Using saved states with forecast alternatives appears to be supported in HEC-HMS version 4.3, but preliminary testing indicated that it was unstable. Based on the above considerations, the approach implemented in CRFFS was based on a single continuous model run spanning the hindcast and forecast periods. As a consequence, it requires using a uniform 6-hour time step.

14.3.3.2 HEC-HMS Forecast Runner

The HEC-HMS forecasting model was incorporated into CRFFS by developing a unique HEC-HMS forecast runner in CRFFS. The HEC-HMS forecast runner developed in this project is essentially a HEC-HMS model adaptor for the HydrologiX system which enables automated hydrological forecasting using the HEC-HMS forecast model prepared for the lower Churchill River basin. Development of the HEC-HMS forecast runner required the design and implementation of the following key components:

- *HEC-DSS Interface* – for read/write access to the Hydrologic Engineering Centre's Data Storage System (HEC-DSS) file format used by HEC-HMS;
- *HEC-HMS Pre-processor* – for preparation of input data required for running a HEC-HMS forecast simulation;
- *HEC-HMS Runner* – for running the HEC-HMS forecast simulation run; and
- *HEC-HMS Post-processor* – for extraction and saving of relevant model results.

The development of each key component of the HEC-HMS forecast runner are provided below.

HEC-DSS Interface

The HEC family of software, including HEC-HMS, utilizes the proprietary HEC-DSS file format for storing most model input and output data. At present, there is no official or well accepted interface to HEC-DSS data format available for Python. However, there are some alternatives, which include:

- Tools available from USACE HEC:
  - HEC-DSSVue application with Jython scripting;
  - HEC-DSS Utility command line tool.
- Third party tools:
  - pydsstools Python library;
  - vtools Python library;
  - Potential solution using Py4j Python library.

The following criteria were used to select among the alternatives:

- Solution must work in Python 3, preferably 64-bit.
- Solution must be capable of reading and writing HEC-DSS records of type TimeSeriesContainer.
- Solution must be sufficiently documented, robust, preferably supported by USACE HEC.

As a result, solution based on the HEC-DSSVue application in combination with custom Jython scripting was selected since it appears to be the best possible alternative:

- Works with the latest 64-bit Python distribution.
- Can read and write HEC-DSS time series data.
- Jython scripting is documented in the HEC-DSSVue manual.

Implementation of the HEC-DSS Interface component based on the above solution required development of a custom data interchange format for exporting and importing HEC-DSS time series datasets, and Python and Jython modules for reading and writing the custom data interchange format.

HEC-HMS Pre-processor

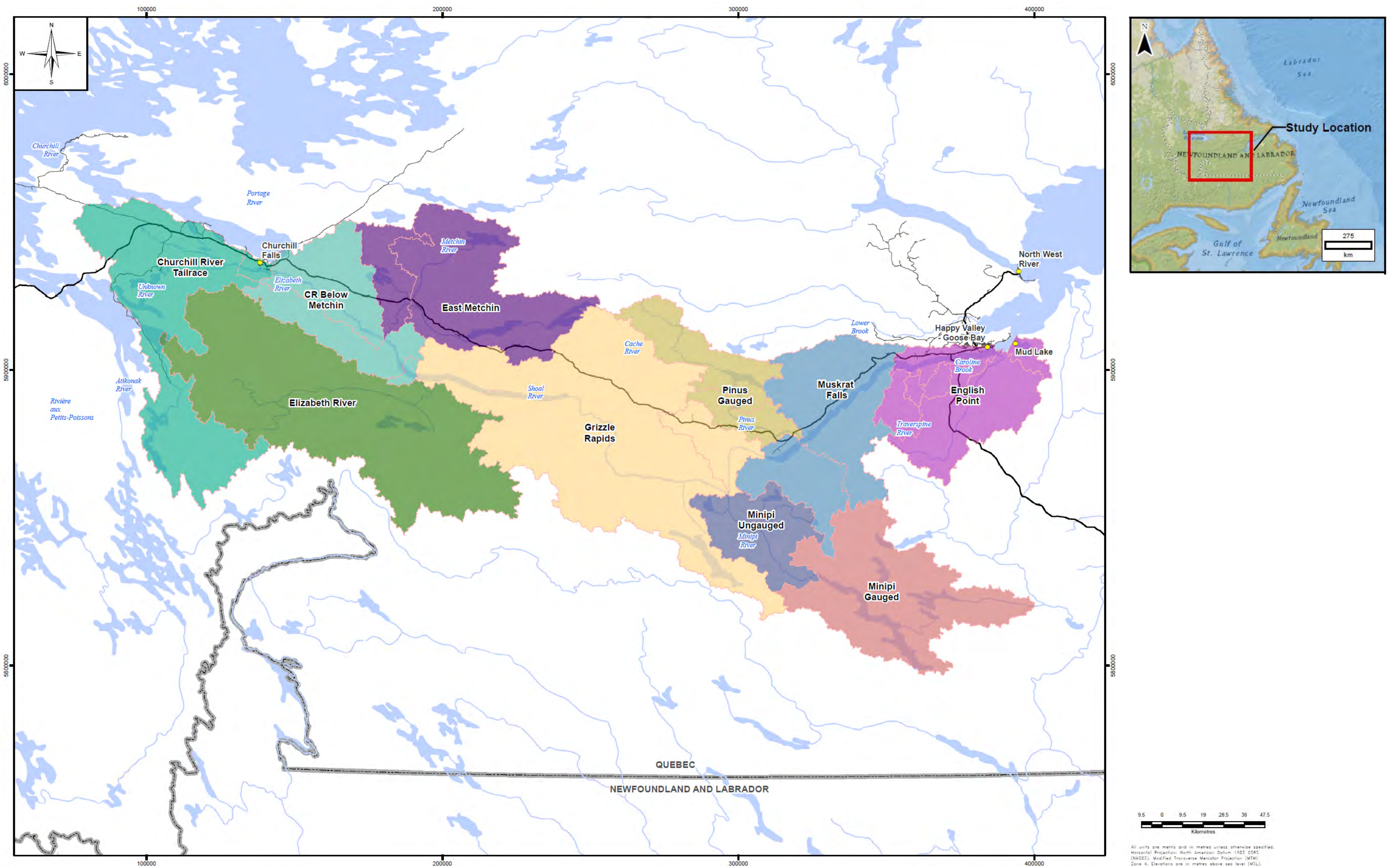
The HEC-HMS pre-processor was developed to prepare all input files necessary to run the HEC-HMS forecast model. Implementation of the pre-processor required design and development of automated functionality, including:

- Compilation of meteorological input time series (i.e. precipitation, temperature), including:
  - Compilation of average values for each meteorological zone for each of the time steps using spatial aggregation. The meteorological zones are shown on Figure 100. The meteorological zones are used for precipitation and temperature, and are equivalent to virtual weather gauges.
  - Data conversion from cumulative to incremental values for precipitation.
  - Reconciling data between the hindcast and the forecast data sources (e.g. CaPA and NWP for precipitation data).

  - Resampling to a uniform 6-hourly time step.
  - Checking for missing data and filling the missing values via linear interpolation.
- Compilation of observed flow data and resampling to a uniform hourly time step.
- Writing the compiled time series to HEC-DSS data files.
- Updating HEC-HMS control file(s) for the simulation run or the forecast alternative.

FIGURE 100

METEOROLOGICAL ZONES USED IN THE HEC-HMS FORECAST MODEL



HEC-HMS Runner

The HEC-HMS Runner is responsible for running a simulation available within a HEC-HMS model instance, verifying successful completion of the simulation run, and collecting model messages generated during the simulation. Implementation of the HEC-HMS Runner component began with a review of available alternatives for programmatically running a HEC-HMS simulation which satisfy the following criteria:

- Must work with HEC-HMS version 4.2.1 used by the HEC-HMS Forecast Model.
- Can be reliably integrated into a Python environment.

The only viable approach was to use the HEC-HMS batch interface in combination with Jython scripting. Implementation of the component was complicated by the finding that the HEC-HMS software (i.e. version 4.2.1) uses a considerably different version of the Jython interpreter (i.e. Jython version 2.5.2) compared to Jython embedded in the HEC-DSSVue software (i.e. Jython version 2.1) used in the HEC-DSS Interface component. Key differences include requirements for naming of scripts, passing arguments to scripts and program exit status codes. The HEC-HMS Runner supports functionality for the *regular simulation* run and a *forecast alternative* run.

HEC-HMS Post-processor

The HEC-HMS Post-processor reads and analyzes the results of the forecast run, stores them in the CRFFS database, and packages model for dissemination. Post-processing a forecast run involves:

- Reading the model output HEC-DSS files and extracting simulated and observed hydrographs for key locations specified in the system database.
- Converting locations IDs from model element names to unified CRFFS location IDs. The CRFFS location IDs typically correspond to WSC and WRMD hydrometric gauge station IDs.
- Producing hydrographs for visual presentation of flow forecast and for evaluation of the model goodness-of-fit, including:
    - Forecast hydrographs showing the tail end of the hindcast period and forecast period, and identifying the date/time the forecast was issued for. The length of hindcast shown is configurable. Forecast hydrographs are primarily useful for

visualizing forecasted flows, and are included in the email notification issued by the HEC-HMS Forecast Runner.

- o Diagnostic hydrographs showing a longer tail portion of the hindcast period, the length of which is configurable. These hydrographs are intended for assessment of the model's performance prior to beginning of the forecast period, and are presented in the CRFFS Frontend.

- Saving results for the extracted locations to the CRFFS database. At present, CRFFS stores only one set of results for a given forecast start date/time. Rerunning the forecast for the same date and time removes the previous results for this date and time from the database and replaces them with the newly generated results. This is sufficient for the current approach of generating a forecast once per day. However, in the future the approach could be extended to handle multiple runs and keep the results for each run.
- Generating and storing an archive (i.e. *.zip) file of the current model snapshot, complete with all input and output data for the current forecast run. The file is made available for downloading via the CRFFS Frontend, and may be used to run additional forecasting simulations outside of CRFFS on a user workstation.
- Send email notifications providing a summary of the forecasting run.

14.3.4 Hydraulic Forecasting

Water levels were forecast at key locations on the lower Churchill River on a continuous year-round basis for both open water and ice-affected conditions. Due to the considerable differences in the hydraulics associated with the open water and ice-affected conditions, two different modeling approaches were implemented to successfully model each condition. The two modeling approaches are described in detail, below.

Open Water Conditions Forecasting

Forecast water levels for open water conditions are determined in CRFFS using a family of stage-discharge tables (i.e. rating curves). Rating curve tables are defined within CRFFS for each cross section in the HEC-RAS model, and consider a wide range of forecast water levels on Lake Melville (i.e. -1.0 m to 1.0 m A.S.L) and forecast flows at Muskrat Falls (i.e. 400 m^3/s to 7,200 m^3s/). The water level range included in the rating curve tables is considerably greater than the actual tidal variation on Lake Melville, which only ranges from approximately -0.5 m to 0.2 m A.S.L., based on the available forecast water levels from DFO. Similarly, the range of flows included in the rating curves is considerably greater than the historical observed flows.

Due to the operation of Churchill Falls, flows on the Churchill River are rarely below 1,000 m^3/s. The upper flow range of 7,200 m^3/s corresponds to an approximately 1 in 600 year flood on the Churchill River.

The incorporation of the open water rating curve tables required implementation of the following key functionality in CRFFS:

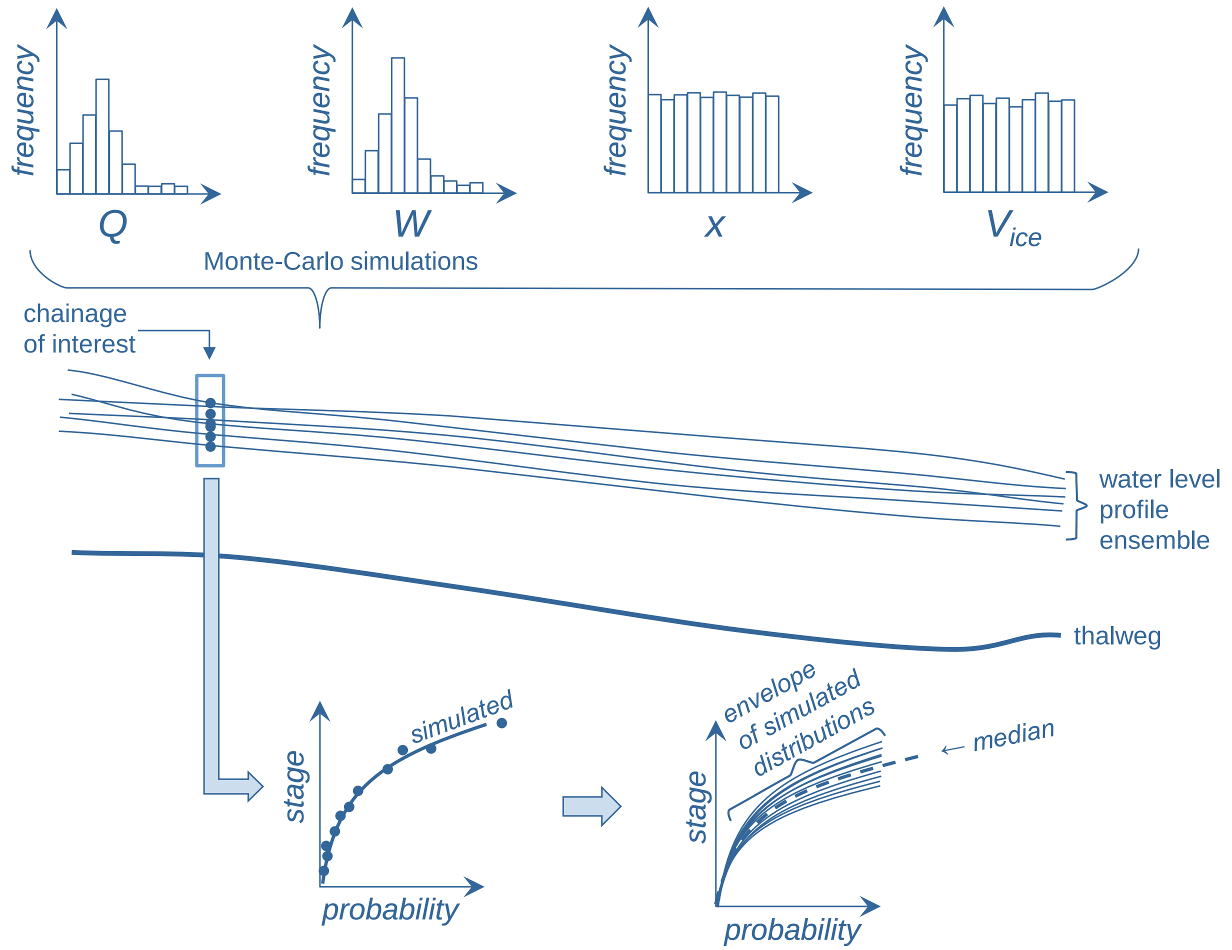
- Capability to load the rating tables from Excel spreadsheets into the CRFFS database and transform the tables into a normalized form optimized for database query.
- Capability to query the database to retrieve the forecasted flow and tidal forecast time series for a given forecast model run (i.e. date/time). This included mapping from the hydrological forecast locations to cross sections. At present, all cross sections use hydrographs from a single forecast location, Churchill River above Upper Muskrat Falls, since incremental differences in flow downstream of this location are considered negligible.
- Functionality to perform conversion of forecasted flow and tidal level time series to forecasted channel level time series (i.e. water level hydrographs) at each cross section. This conversion was performed by applying the following logic to each time step in the hourly forecasted time series:
    - Extract forecasted flow and tidal elevation values.
    - Locate the lower and upper reference values for flow and tidal elevation in the cross-section's rating table, and the corresponding reference values for channel water level at the cross section.
    - Perform bilinear interpolation to convert reference values to forecasted channel water level value.
- Save forecasted level hydrographs for cross sections in the CRFFS database.

Ice-Affected Conditions

CRFFS uses the RIVICE model described in Section 9.3 for performing hydraulic forecasting under ice-affected conditions, in particular during the river freeze-up and ice break-up conditions. To mitigate the high degree of uncertainty in many of the ice modelling parameters, a Monte Carlo framework is implemented using the RIVICE model.

In the Monte Carlo framework, the RIVICE model runs several simulations, with each simulation having the model parameters and boundary conditions randomly selected from appropriate frequency distributions for each parameter and boundary. This approach yields backwater staging at each cross section, which can then be combined to define the probability of the water levels at each cross section. A graphical representation of the Monte Carlo framework is shown in Figure 101.

FIGURE 101
CONCEPTUALIZATION OF THE MONTE CARLO MODELLING APPROACH



As shown in Figure 101, histograms are incorporated into the Monte Carlo framework representing the probability frequency distributions of the boundary conditions, including the upstream inflow Q, downstream water level elevation W, location of the ice cover front x, the inflowing volume of rubble ice accumulating at the ice cover front V_{ice}, and the Lake Melville water level accounting for tidal conditions.

Many of the key RIVICE parameters are defined in the Monte Carlo framework from uniform distributions, with the minimum and maximum values of the uniform distributions defined based on the anticipated ranges in these values on the Lower Churchill River. These parameters include:

- Ice cover and pan porosities.
- Ice pan thicknesses.
- Ice strength coefficients.
- Ice transport coefficients for deposition and erosion of ice.
- Ice roughness.

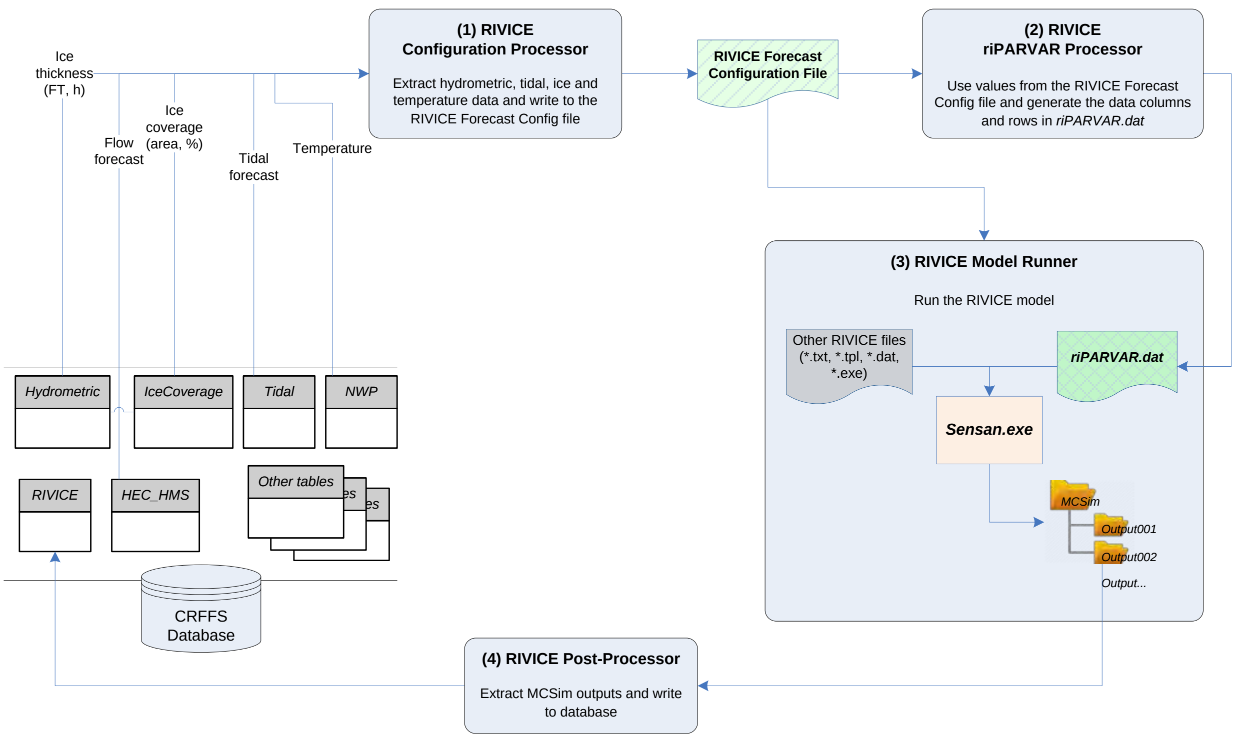
Other key parameters were defined based on measured or forecast ranges. These parameters, and a brief description of the distributions, include:

- ***Inflow*** – The inflow to the model is defined by a uniform distribution between the minimum and maximum flows in the 3-day forecast
- ***Ice Cover Thickness*** – The ice cover thickness is defined by a uniform distribution in between the minimum and maximum measured ice thicknesses collected by C-Core. Early in the winter, prior to the ice thickness being measured, the ice thickness is assumed to be the final measured ice thickness from the previous season.
- ***Volume of Ice*** – The volume of incoming ice into the model domain is defined by a GEV distribution that is scaled from the calculated volume of ice (i.e. the product of the ice thickness and ice coverage). The GEV distribution is scaled by the calculated volume of available ice to form a jam so that the model does not consider higher volumes of ice that are not available. The location, scale, and shape factors of the GEV distribution are similarly scaled from the calculated volume of ice by scaling factors of 0.05, 0.60, and 0.45. These parameters were estimated considering historical ice jam floods on the Churchill River and the approximate available volume of ice to form the jams.
- ***Downstream Boundary Condition Water Level*** – The downstream boundary condition water level was initially defined in the model by a uniform distribution between the minimum and maximum forecast water levels on the Lake Melville. However, during the active monitoring that took place during the 2019 spring freshet, the boundary was found to underestimate water levels within the model, and the boundary condition was changed a uniform distribution between the minimum and maximum water levels at the English Point gauge within the previous 24 hours.
- ***Ice Jam Toe Location*** – The ice jam toe location was defined by a uniform distribution between the downstream end of the model and Happy Valley – Goose Bay.

Several model runs are executed with parameter and boundary condition values extracted randomly from the frequency distributions. The simulations produce an ensemble of backwater level profiles, as shown in the middle of Figure 101. The water level elevations at a given station are then extracted from each profile to form a cumulative frequency distribution of the stages, as shown at the bottom left of Figure 101. Forecast water levels are reported in CRFFS for the 10th percentile, median, and 90th percentiles.

The incorporation of the ice-affected forecasting required the development of a bespoke RIVICE Model Adaptor, which automates preparation of input data necessary for RIVICE, running the RIVICE model, and post-processing the model outputs to extract relevant results. A schematic overview of the RIVICE model adapter is shown on Figure 102.

FIGURE 102
SCHEMATIC OVERVIEW OF THE RIVICE MODEL ADAPTER



The structure of the RIVICE adaptor allows running the RIVICE hydraulic forecast in two alternative modes, specifically:

1. Starting from the *RIVICE Configuration Processor*. As described below, the *RIVICE Configuration Processor* updates the *RIVICE Forecast Configuration File*, which is then used to generate the *riPARVAR.dat* input file for RIVICE. This is the default mode used by CRFFS for operational forecasting;

2. Starting from the *RIVICE riPARVAR Processor*. This bypasses the *RIVICE Configuration Processor*; therefore, the *RIVICE Forecast Configuration File* does not get updated. This mode is suitable for advanced RIVICE modelling which allows the user to edit the *RIVICE Forecast Configuration File* manually before running RIVICE. The advanced mode is not used by CRFFS by default, and is only available through the system's backend for interactive use.

The *RIVICE Model Adaptor* consists of four main components, which are described in detail below.

RIVICE Configuration Processor

The *RIVICE Configuration Processor* is responsible for preparation of the *RIVICE Forecast Configuration* file. The *RIVICE Forecast Configuration* file contains settings necessary for subsequent generation of the main RIVICE input file, *riPARVAR.dat*, by the *RIVICE riPARVAR Processor*. The settings comprise several main categories of information including:

- General settings such as the length and time step of model hindcast (i.e. spinup) and forecast, or the number of RIVICE simulations to run.
- Statistical parameters required for generation of model parameter value distributions for the *riPARVAR.dat* model input file. Most model parameters require just the minimum and maximum bounds, while others may require additional settings, such as the parameters for the generalized extreme value (GEV) distribution used for quantifying volume of ice.
- Time series data, such as air temperature.

Some settings in the *RIVICE Forecast Configuration* file are static, defined during setup and calibration of the RIVICE model. Other settings in the file are dynamic and are updated based on the ice, river flow and weather conditions at the time of forecast. The *RIVICE Configuration Processor* starts with an existing *RIVICE Forecast Configuration* file and updates the dynamic settings using information extracted from the CRFFS database. Various data is used for updating the dynamic configuration settings, specifically:

- Ice thickness and ice coverage area data are used for the estimation of the ice thickness and the volume of ice parameters in RIVICE. The volume of ice parameter is estimated using the average ice thickness and the percent of river channel area covered by ice.

- Forecasted minimum and maximum flows on the Churchill River during the forecast period.
- Forecasted minimum and maximum tidal levels during the forecast period.
- Recent observed and forecasted air temperature spanning the RIVICE spin up and forecast.

RIVICE riPARVAR Processor

The *RIVICE riPARVAR Processor* uses the configuration settings contained in the *RIVICE Forecast Configuration* file to generate the *riPARVAR.dat* data file, which is the main input file for the RIVICE model. In the stochastic (i.e. Monte Carlo) framework utilized by the RIVICE model, each line in the *riPARVAR.dat* input data file corresponds to one RIVICE simulation and provides all input data, besides static data and parameters supplied in other RIVICE files necessary to run the simulation. Particular values for each parameter are created using appropriate random number generators, using a uniform distribution for most parameters, and some specialized statistical distributions for certain parameters, such as the GEV distribution for the volume of ice parameter. A description of the RIVICE parameters, the corresponding riPARVAR variables, the range type, and the data source for each variable are summarized in Table 56.

TABLE 56
RELATIONSHIP BETWEEN RIPARVAR AND RIVICE VARIABLES

RIVICE Variable	RiPARVAR Variable	Parameter Description	Range Type	Data Source
PS	PSMIN, PSMAX	Porosity of Incoming Ice Pans	Fixed	K. Lindenschmidt
ST	STMIN, STMAX	Thickness of Incoming Ice Pans	Dynamic	C-Core Ice Thickness
V_{ice}	VICEMIN, VICEMAX	Volume of Incoming Ice	Dynamic	C-Core Ice Thickness / Coverage
PC	PCMIN, PCMAX	Ice Cover Front Porosity	Fixed	K. Lindenschmidt
FT	FTMIN, FTMAX	Ice Cover Front Thickness	Dynamic	C-Core Ice Thickness
h	HMIN, HMAX	Average Ice Cover Thickness	Dynamic	C-Core Ice Thickness
V_{dep}	VDMIN, VDMAX	Maximum Velocity for Ice Deposition	Fixed	K. Lindenschmidt
V_{er}	VEMIN, VEMAX	Minimum Velocity for Ice Erosion	Fixed	K. Lindenschmidt
n_{8m}	n8MIN, n8MAX	Ice Cover Underside Roughness Coefficient	Fixed	K. Lindenschmidt
n_{bed}	nbMIN, nbMAX	River Bed Roughness Coefficient	Fixed	K. Lindenschmidt
K1TAN	K1MIN, K2MAX	Ice Strength Parameter	Fixed	K. Lindenschmidt
K2	K2MIN, K2MAX	Ice Strength Parameter	Fixed	K. Lindenschmidt
Q	QMIN, QMAX	Churchill River Flow	Dynamic	HEC-HMS Forecast
W	TWLMIN, TWLMAX	Lake Melville Water Level	Dynamic	DFO Predicted Tidal Levels
x	XUPPER, XLOWER	Ice Jam Toe Cross Section Number	Fixed	K. Lindenschmidt
T0 – T10	temp_air	Air Temperature every 12 hours	Dynamic	NWP Data

RIVICE Model Runner

The *RIVICE Model Runner* was developed to run the RIVICE model by executing the model's main program (i.e. *Sensan.exe*) and checking the program's return status to verify that the program completed successfully.

RIVICE Model Post-Processor

The RIVICE Model Post-Processor extracts forecasted water levels from RIVICE stochastic simulation results and saves them into the CRFFS database. RIVICE output files are located in subdirectories in the RIVICE model directory corresponding to the number of model runs performed in the RIVICE simulation.

14.3.5 Threshold Model and Alert Generator

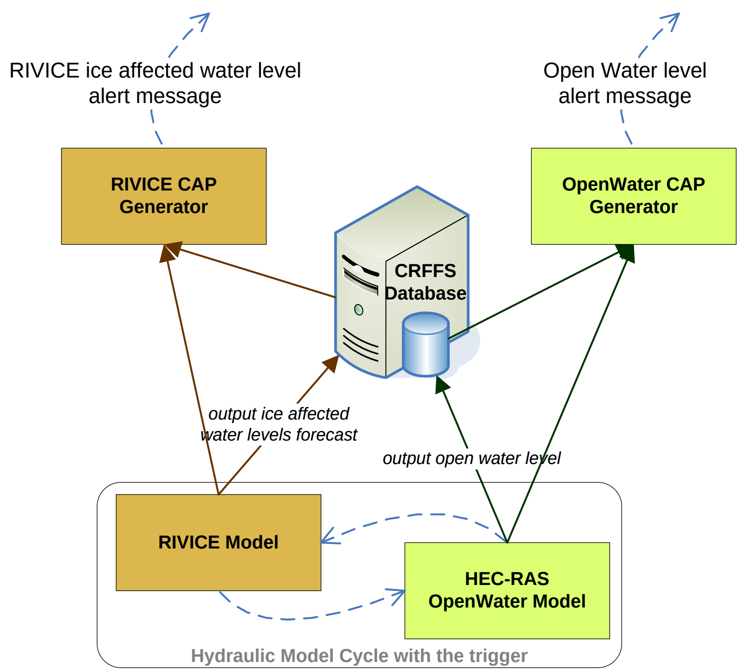
The Threshold Model and Alert Generator component in CRFFS allows automated generation and dissemination of alert messages when forecasted water levels exceed user-defined threshold values. Conceptually, the component is made up of three parts, specifically a threshold model, a trigger model, and a message generator. The threshold model defines water levels of interest at hydraulic forecast locations in the lower Churchill River. The threshold model lists water levels of practical interest or importance at each forecast location. The number of thresholds, their values (i.e. water levels), names and interpretation are user-defined and are managed via the CRFFS frontend, described in Section 14.3.7. The trigger model determines if a threshold level has been exceeded at a particular forecast location. The message generator creates an alert message and disseminates the message to key personnel. Messages are created using the Common Alert Protocol – Canadian Profile (CAP-CP) standard and are sent automatically via email to notification recipients.

Implementation of the Threshold Model and Alert Generator component in CRFFS leveraged existing functionality in HydrologiX, extending it in several ways:

- The threshold model was extended to allow water level thresholds, as opposed to flow thresholds already developed in HydrologiX.
- Implementing new trigger models for the open-water and ice-affected (i.e. RIVICE) hydraulic forecasting scenarios: the *Open-water CAP Generator*, and the *RIVICE CAP Generator*. Both trigger models work by comparing the forecasted level time series (i.e. level hydrograph) with the threshold model; if any of the threshold levels are exceeded during the forecast, the message generator prepares a message summarizing the locations, water levels and durations where and when levels are exceeded. Unlike the *Open-water CAP Generator* which uses simple deterministic forecasted level hydrograph, the *RIVICE CAP Generator* uses the 90^{th} percentile of forecasted water levels at each time step (i.e. essentially a stochastic level hydrograph) as the trigger.

The operation of the Threshold Model and Alert Generator is summarized in Figure 103. The particular trigger model that is activated, either for open-water or ice-affected conditions, depends on the active phase of the hydraulic forecast cycle.

FIGURE 103
OVERVIEW OF THE CRFFS THRESHOLD AND ALERT GENERATOR



14.3.6 CRFFS Web Services

CRFFS is a web-based application and relies on Web Services to move information from the backend of the system to the web pages. Spatial and non-spatial web services were enabled in the system.

14.3.7 CRFFS Frontend

The CRFFS frontend is the user-facing component of the forecasting system used to disseminate key information included in the system to users. The CRFFS frontend includes several key components:

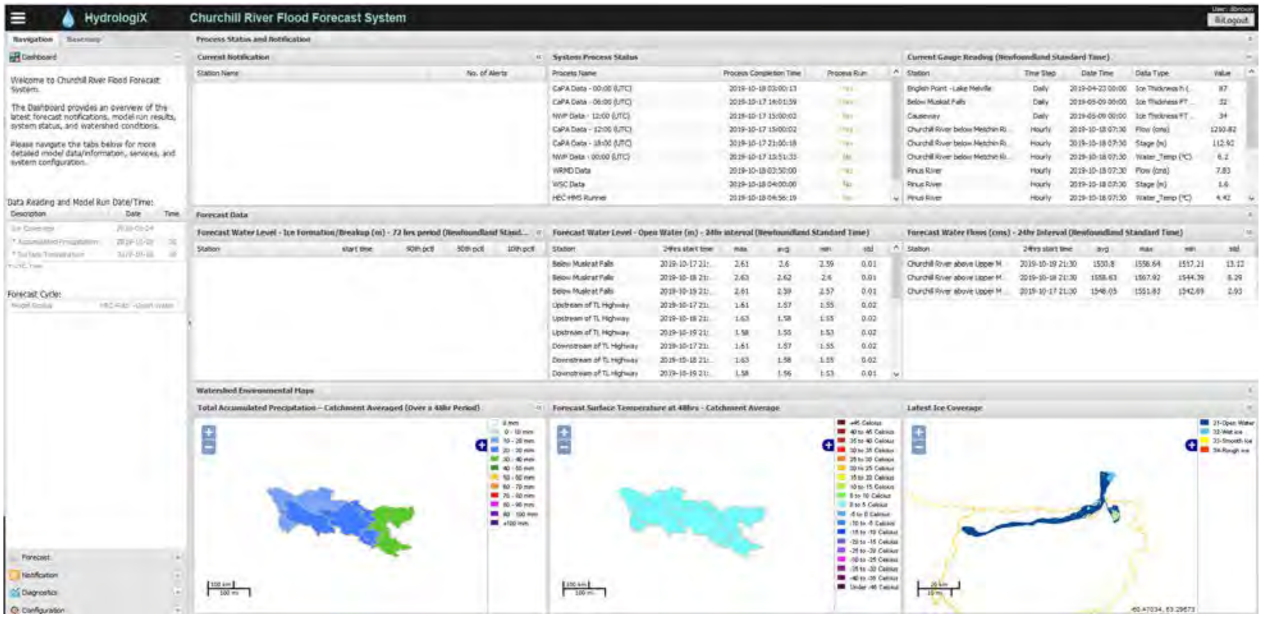
- ***Dashboard –*** The dashboard portlet is the main landing page for CRFFS of the CRFFS frontend that summarizes the status of several features of the CRFFS and allows for users to identify any critical information at a glance.
- ***Forecast*** – This portlet provides the forecast flows at Muskrat Falls, as well as the forecast water levels at the various key locations included in the system and along the river profile.
- ***Notification –*** This portlet lists out any notifications generated by CRFFS.
- ***Diagnostics –*** This portlet provides diagnostic hydrographs that compare simulated and observed flows, where available, to allow users to monitor the performance of the hydrological model.
- ***Configuration –*** This portlet allows users to configure recipients for notifications generated by CRFFS, as well as the configuration of forecast water levels for each forecasting station to generate notifications.

Many of the above sections of CRFFS were previously incorporated into HydrologiX, but considerable development and modification was required to depict both new sources of information, as well as the various new outputs built into the system for CRFFS. These sections are described further in the following subsections.

Dashboard Portlet

The Dashboard tool provides an overview of the latest forecast notifications, model run results, system status, and watershed conditions. The information is split into ten windows, each containing unique information relevant to CRFFS. An overview of the dashboard section is shown on Figure 104.

FIGURE 104
OVERVIEW OF THE DASHBOARD PORTLET



The dashboard portlet provides both spatial and non-spatial data, split into ten windows. Non-spatial data is retrieved using web services in JavaScript Object Notation (JSON) format from the CRFFS backend to the Dashboard web portlet, and includes:

- A description of the acquisition date for the ice coverage, precipitation and temperature data, as well as indication of the current model forecast cycle status.
- Statistic count number of alert messages.
- A listing of the system processes, their status, and the completion date of each process.
- Latest gauged data, including the gauge data reading, data type, and the date that the data was acquired.
- Forecast 90th percentile, 50th percentile and 10th percentile ice-affected water levels from the RIVICE Monte Carlo simulations
- Forecast daily average water levels from the open water forecast.
- Daily average flow from the HEC-HMS forecast.

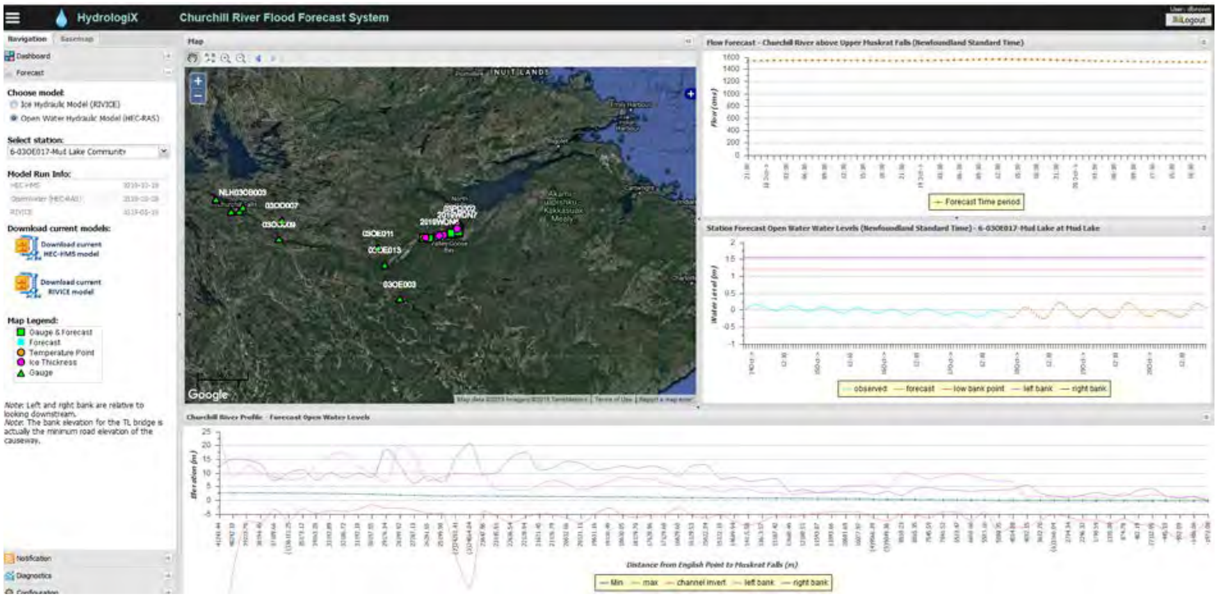
Spatial data is enabled using Spatial Web Map Services (WMS). The spatial data in the CRFFS dashboard portlet includes:

- A map of catchment-based averaged forecast precipitation over 48hrs.
- A map of catchment-based forecast temperature at ground level 48hrs from the forecast start time.
- A map of the latest ice coverage data, and a map of the hydrometric gauges and forecast gauges. These services are in OGC standards (i.e. WMS, WFS).

Forecast Portlet

The forecast portlet provides users with forecast flows from Muskrat Falls, recent real-time and forecast water levels on the Churchill River at each forecast station, and a forecast water surface profile along the Churchill River. The forecast portlet also allows users to download the daily updated HEC-HMS and RIVICE models. However, the RIVICE models are not updated during the open water period. An overview of the forecast portlet is shown on Figure 105.

FIGURE 105
OVERVIEW OF THE FORECAST PORTLET



Similar to the dashboard portlet, the forecast portlet includes both spatial and non-spatial data, split into five windows. The spatial data consists of a map showing the location of the hydrometric stations, forecast locations, temperature stations and ice thickness measurement locations.

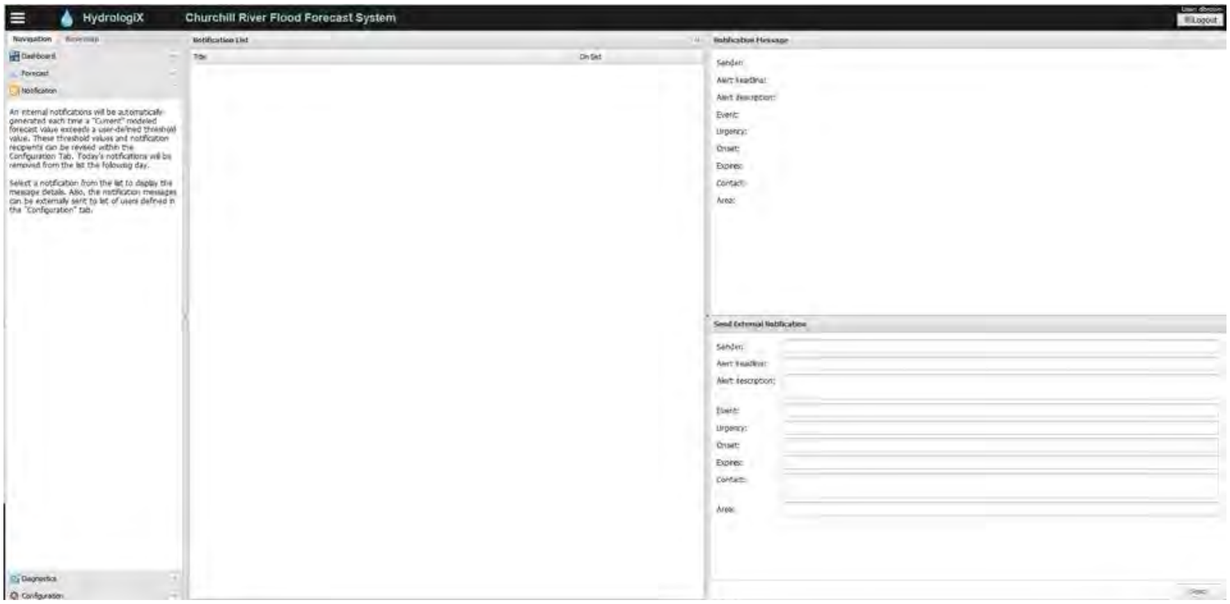
Non-spatial data shown in the forecast portlet includes:

- A summary of the model information, including links to download the current runs of the HEC-HMS and RIVICE models, as well as the date showing when each model was most recently run. This section also allows users to switch between ice-affected and open water forecasts, and to select the forecast station for display in the portlet.
- Time series of forecast flows at Muskrat Falls from the HEC-HMS model.
- Water level forecasts, which includes the low bank elevation (i.e. the point at which overland flooding in the vicinity of the forecast location can occur), left and right bank (i.e. main channel banks), time series of near real time observed data and forecast water levels, depending on the forecast model cycle status.
    - Forecast 90th percentile, 50th percentile and 10th percentile water levels from the RIVICE Monte Carlo simulations for ice-affected conditions, or
    - Forecast hourly water levels for open water conditions.
- A water level profile along the Churchill River that includes the channel invert, the left and right banks of the main channel, and forecast water levels depending on model forecast cycle status.
    - Forecast 90th, 50th and 10th percentile water levels from the RIVICE Monte Carlo simulations for ice-affected conditions, or
    - Forecast minimum and maximum water levels for open water conditions.

Notification Portlet

The notification portlet lists the alerts generated by CRFFS. The notification portlet also allows users to view the alert messages, and to forward the alerts to external recipients. An overview of the notification portlet is shown on Figure 106.

FIGURE 106
OVERVIEW OF THE NOTIFICATION PORTLET



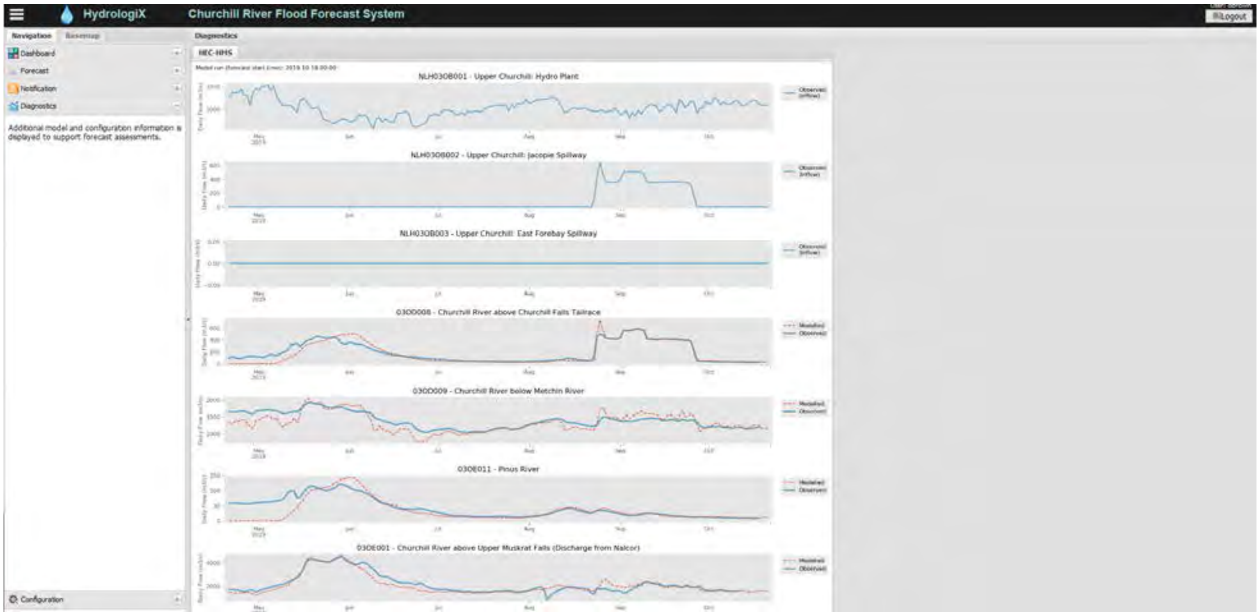
A web service was also implemented for sending email notifications using the Common Alert Protocol CAP as email messages services, which included:

- Serve RSS/Feed for listing the header of alert message from current hydraulic model.
- Serve selected alert message content. The message can be select from RSS/Feed list above.
- Create CRUD (i.e. Create Read Update and Delete) process for modifying selected alert message and send to external receivers.

Diagnostics Portlet

The diagnostics portlet provides simulated and observed hydrographs from the HEC-HMS model for key locations within the model domain, as well as inflow hydrographs for the Churchill Falls Generating Station, Jacopie Spillway, and East Forebay Spillway. These hydrographs can be reviewed by system users to ensure that the HEC-HMS model is accurately representing observed flows and to identify if additional model recalibration is required. An overview of the diagnostics portlet is shown on Figure 107.

FIGURE 107
OVERVIEW OF THE DIAGNOSTIC PORTLET



Configuration Portlet

The configuration portlet is used in CRFFS to set water level thresholds to trigger system alerts, as well as to specify the recipients of those alerts. The recipients and thresholds are configured in separate windows of the configuration portlet, as shown on Figure 108 and Figure 109.

FIGURE 108
OVERVIEW OF THE CONFIGURATION PORTLET – RECIPIENTS MANAGEMENT

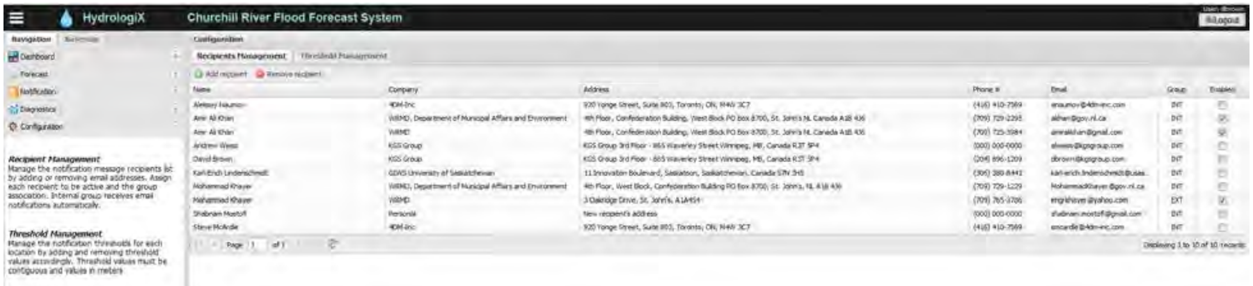
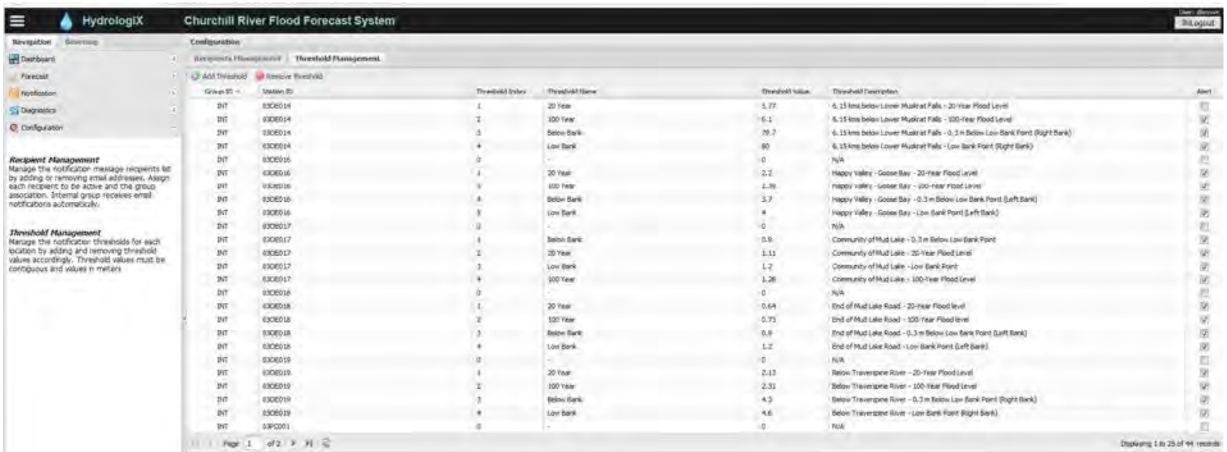


FIGURE 109
OVERVIEW OF THE CONFIGURATION PORTLET – THRESHOLD MANAGEMENT



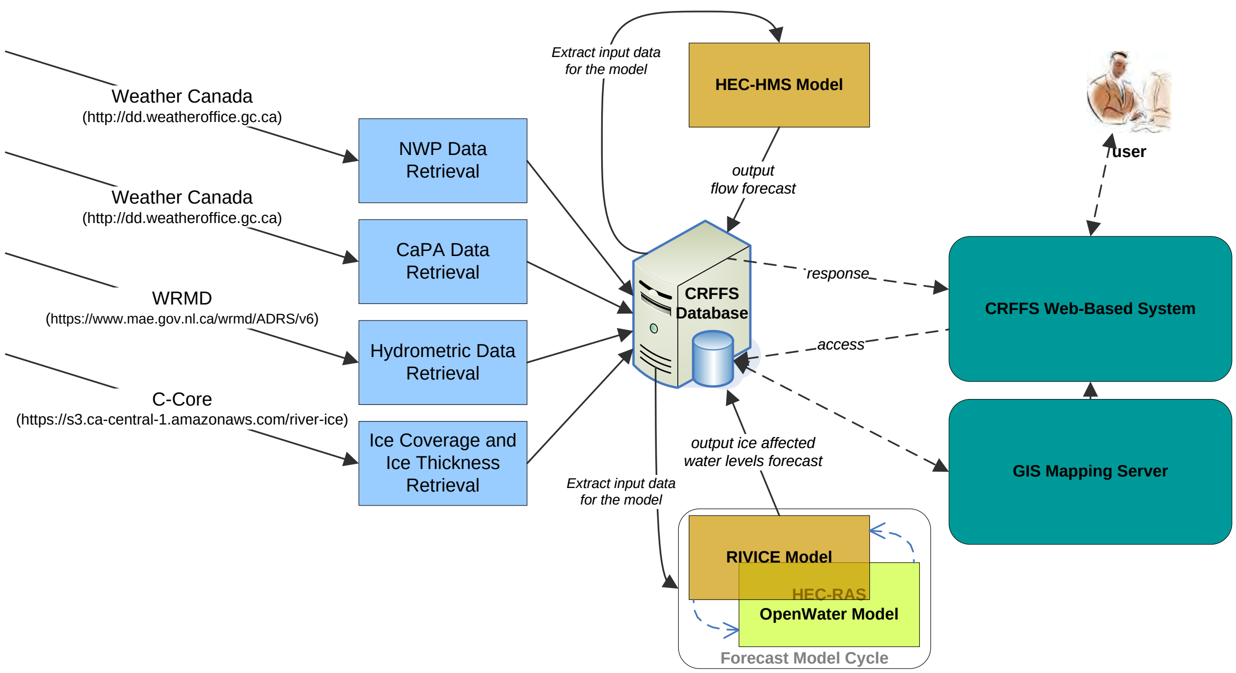
The recipient's management tab of the configuration portlet allows for the management of the notification message recipients list by adding, removing or modifying recipient information. This also allows for the assignment of each recipient as active/inactive and the appropriate group association.

The Threshold management tool allows for the management of the threshold level values for each of the forecast stations. The notification thresholds for each location can be changed by adding and removing threshold values accordingly. Threshold values must be contiguous (i.e. like a river flood gauge marker). For each station, the threshold values must increase according to the increment of the threshold indices for that station.

14.4 INTEGRATION OF THE HYDROLOGIC AND HYDRAULIC MODELS

The hydrologic and hydraulic models were integrated together in CRFFS using the HydrologiX framework. As previously noted, extensive modifications and development was completed to HydrologiX to enable the various data feeds, pre- and post-processors, the integration of the HEC-HMS and RIVICE models, as well as the open water forecasts, threshold model, alert generator, and web services. The overall integration of the various components is shown conceptually on Figure 110.

FIGURE 110
CONCEPTUAL INTEGRATION OF CRFFS COMPONENTS



Once all of the various components were integrated into CRFFS, a flood forecasting model cycle was integrated into the system to account for the dynamic environmental conditions on the Churchill River. The model cycle is an automated process that assesses the water temperature gauges from Rabbit Island and Happy Valley Goose Bay, satellite derived ice coverage extracted from SAR and optical satellite imagery, hydrological forecast flows and calendar dates as trigger points to define the current environmental condition in CRFFS and the corresponding modelling approach to define the forecast water levels. The forecast model cycle has 5 conditions that are enabled in the system, specifically:

- Open Water;
- Ice Formation (i.e. Freeze Up);
- Winter (i.e. Stable Ice);
- Break Up – Ice Jam (i.e. Condition A);
- Break Up – Thermal Decay (i.e. Condition B).

The Forecast Model Cycle in CRFFS uses Windows Task Scheduler to trigger some software processes. Other processes are triggered by parameters assessed by the model cycle. The forecast model cycle starts with the open water condition, and converts the forecast flows from the HEC-HMS model to water levels using the rating curve tables defined using the HEC-RAS model. As previously noted, forecasted water levels are based on the stage-discharge tables defined for each cross section in the calibrated Flood Forecasting HEC-RAS model, the forecast flows at Muskrat Falls from the HEC-HMS model, and the predicted tidal levels on Lake Melville at Terrington Basin.

Prior to the model cycle moving forward to the ice formation condition, the system begins retrieving and checking the water temperature data on an hourly basis from WRMD against threshold values that trigger the ice formation modelling in RIVICE. Currently, the start date for retrieving the water temperature data is set for November 1st, but can be adjusted in the CRFFS configuration file. The temperature threshold for the Rabbit Island and Happy Valley – Goose Bay gauges were set to 0.05 °C and 0.15 °C based on a review of available water temperature and freeze-up information. Both temperature thresholds must be met to trigger the freeze up modelling in RIVICE. Once the freezeup condition is met, CRFFS continues to operate under the freezeup condition regardless of if the temperature condition changes.

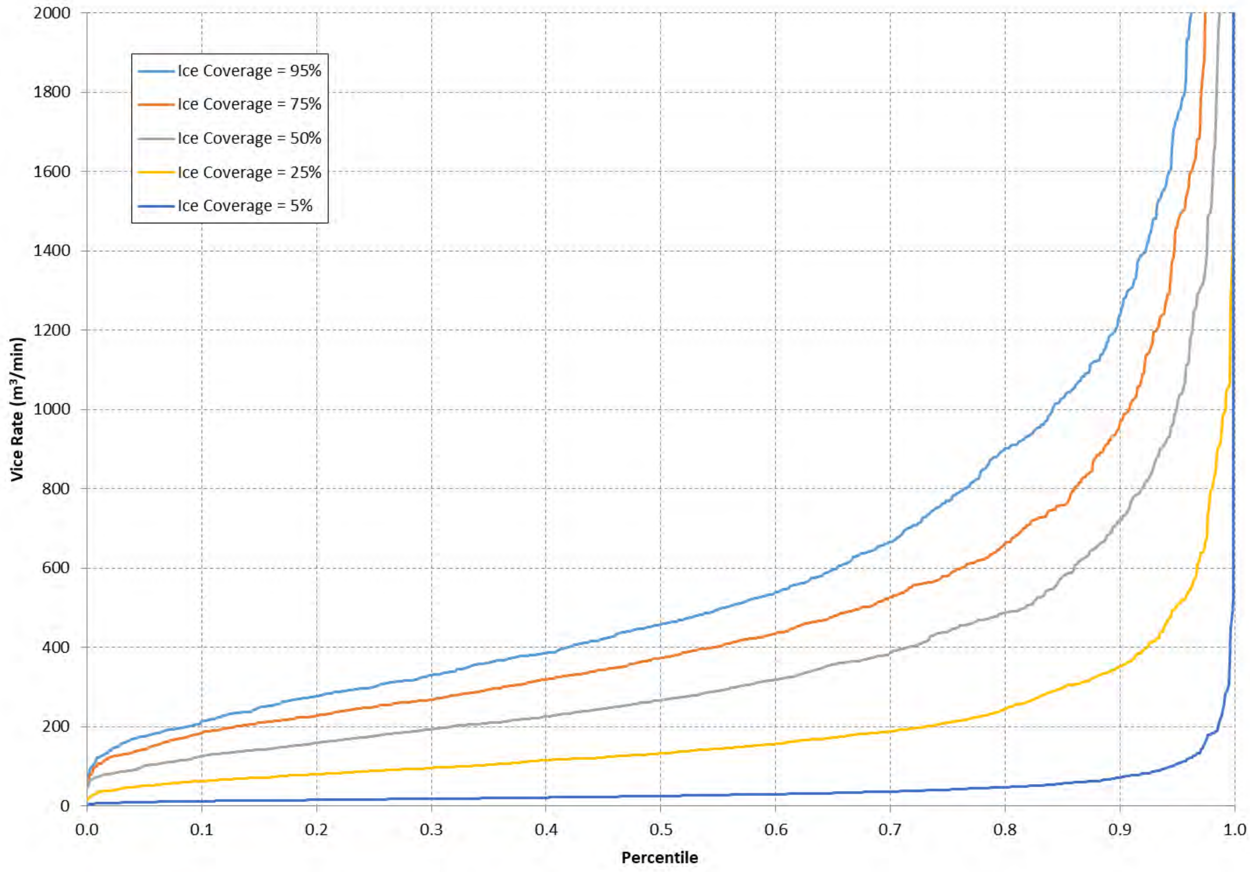
Freezeup conditions are simulated in the RIVICE model by eliminating any incoming volumes of ice into the model (i.e. V_{ice}). Rather, ice is only generated in the model based on frazil ice generation defined by the forecast air and water temperatures. As well, the possible ice jam toe location is limited to between Happy Valley – Goose Bay and English Point, since any jams outside of this area will not affect any of the communities on the Churchill River.

Once CRFFS is forecasting in the freeze up condition, the system retrieves the ice coverage data and checks the coverage against a threshold condition of 50%. Once the threshold is exceeded, the forecast model cycle proceeds into a stable ice condition where RIVICE is used to simulate a stable ice cover. The stable ice coverage is simulated in RIVICE by eliminating any incoming ice into the model domain, and setting the jam toe location to the upstream extent of the model at Muskrat Falls. That is, there is a uniform ice coverage that extends from Lake Melville to Muskrat Falls. The ice thickness is defined based on the measured ice thicknesses provided by WRMD. Ice coverage and flows are monitored by the model cycle, and once ice coverage drops below 90%, the cycle moves into the ice breakup condition.

The forecast model cycle has two ice breakup conditions that may occur depending on the ice coverage and forecast flows. CRFFS considers both thermal and ice-jamming breakup. An assessment of historical breakup events showed that ice jams do not occur for flows less than 2,000 m^3/s, since for the ice to break up, it will need to exceed the freeze-up water levels. Therefore, for the thermal breakup condition, the ice cover is treated as a stable ice cover, and is modelled in an identical manner. For the ice jam condition, RIVICE dynamically models the development of potential ice jams using the Monte Carlo framework.

Breakup ice jams are simulated in RIVICE by simulating an incoming volume of ice pans on the Churchill River based on an estimated volume of ice available on the Churchill River for jamming. The total volume of ice is estimated based on the product of the areal extent of the latest available C-Core ice coverage imagery and the latest ice thickness measurement. The volume of ice in the RIVICE model is defined based on a GEV distribution that is defined by key parameters scaled by the total volume of ice. Accordingly, as the ice cover breaks up and is conveyed downstream, the calculated total volume of ice is reduced, resulting in a lower chance of a high V_{ice} rate in the Monte Carlo RIVICE simulations and a corresponding large ice jam flood. The relationship between the ice coverage and the GEV distribution for the V_{ice} rate is shown on Figure 111.

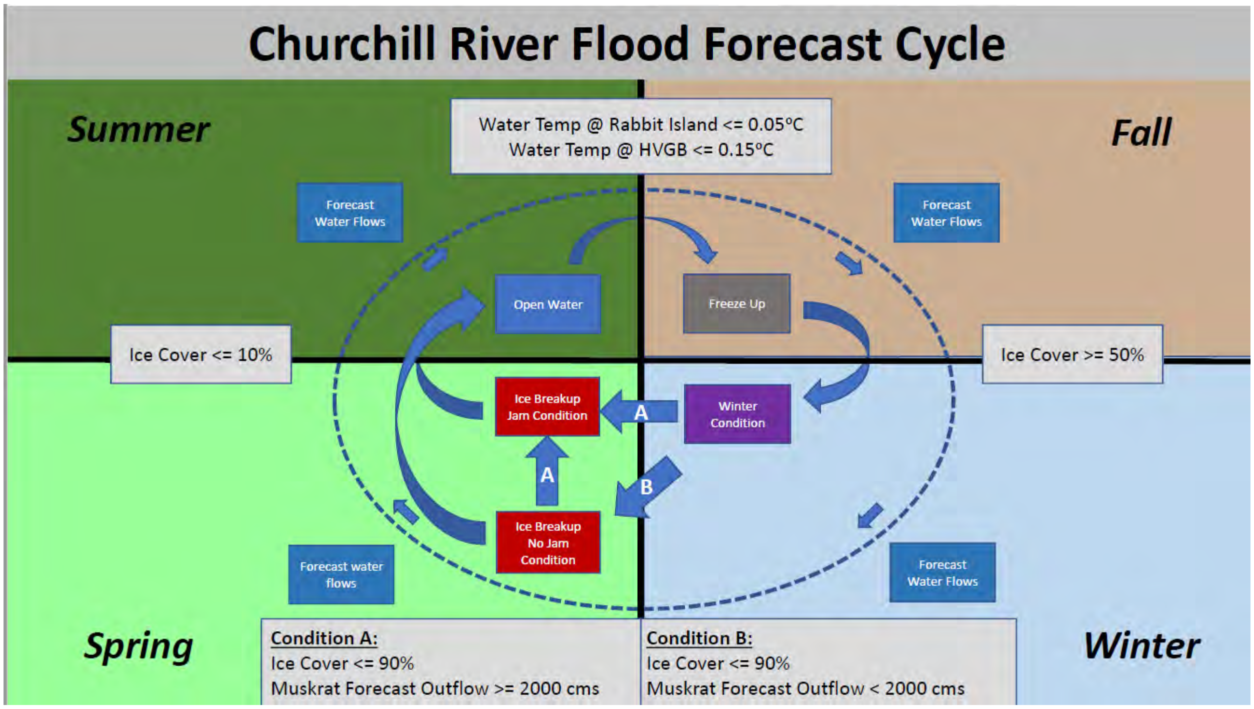
FIGURE 111
RELATIONSHIP BETWEEN ICE COVERAGE AND V_{ICE} RATE



Frazil ice generation is not included in the breakup modelling, since the ice cover on the river will inhibit any frazil generation. The ice jam toe location is considered in the Monte Carlo RIVICE simulations between Lake Melville and upstream of Mud Lake Road. The range of possible ice jam locations was based on an assessment of the river characteristics. However, the location of ice jams on the Lower Churchill River should be carefully monitored, and should any jams occur outside the range included in the Monte Carlo simulations, the range should be adjusted.

Once ice coverage drops to less than 10% then forecast model switch back open water forecast and the model cycle starts over. The forecast cycle is illustrated below in Figure 112

FIGURE 112
CRFFS FORECAST CYCLE



14.5 MODEL TESTING, DEPLOYMENT AND TRAINING

14.5.1 Model Testing

During the development of the flood forecasting system, CRFFS was deployed on a dedicated Windows server running on the VMWare virtual environment hosted by 4DM. The deployment of the system allowed for the Project Team to confirm the functionality of the various system components, and to evaluate and adjust the performance of the various forecasting components prior to the deployment of the system.

The model testing phase allowed for the Project Team to make key adjustments to the forecasting system that greatly improved the accuracy of the forecasts. In particular, adjustments were made to the statistical distribution used to define V_{ice} and certain aspects of the forecasting cycle to ensure a smooth transition within the cycle.

The adjustment of the V_{ice} statistical distribution was necessary to realistically depict the movement of ice on the Churchill River. Initially, the V_{ice} distribution was set to a uniform distribution between zero and the calculated ice coverage. However, the uniform distribution was found to produce V_{ice} values considerably larger than was calibrated for the 2017 flood, resulting in higher forecast water levels in Mud Lake and Happy Valley – Goose Bay for lower flow conditions. As such, the Project Team considered different distributions to define the range of V_{ice} in the Monte Carlo simulations, and found that using the GEV distribution resulted in both the scaling of the V_{ice} distribution as the ice receded and a reasonable range of anticipated ice jam conditions.

As part of the model testing phase, the Project team also tested CRFFS for the ice-affected portions of the forecasting cycle. In particular, this yielded key insights into how different components within the model can contribute to flooding on the Churchill River, thus allowing the Project Team to configure each portion of the forecasting cycle to accurately depict the ice processes. In particular, testing revealed that it was necessary to eliminate the potential for frazil ice generation during the break-up jam simulations, otherwise the RIVICE model could potentially generate frazil ice that would not form in the real world due to the ice cover of the river.

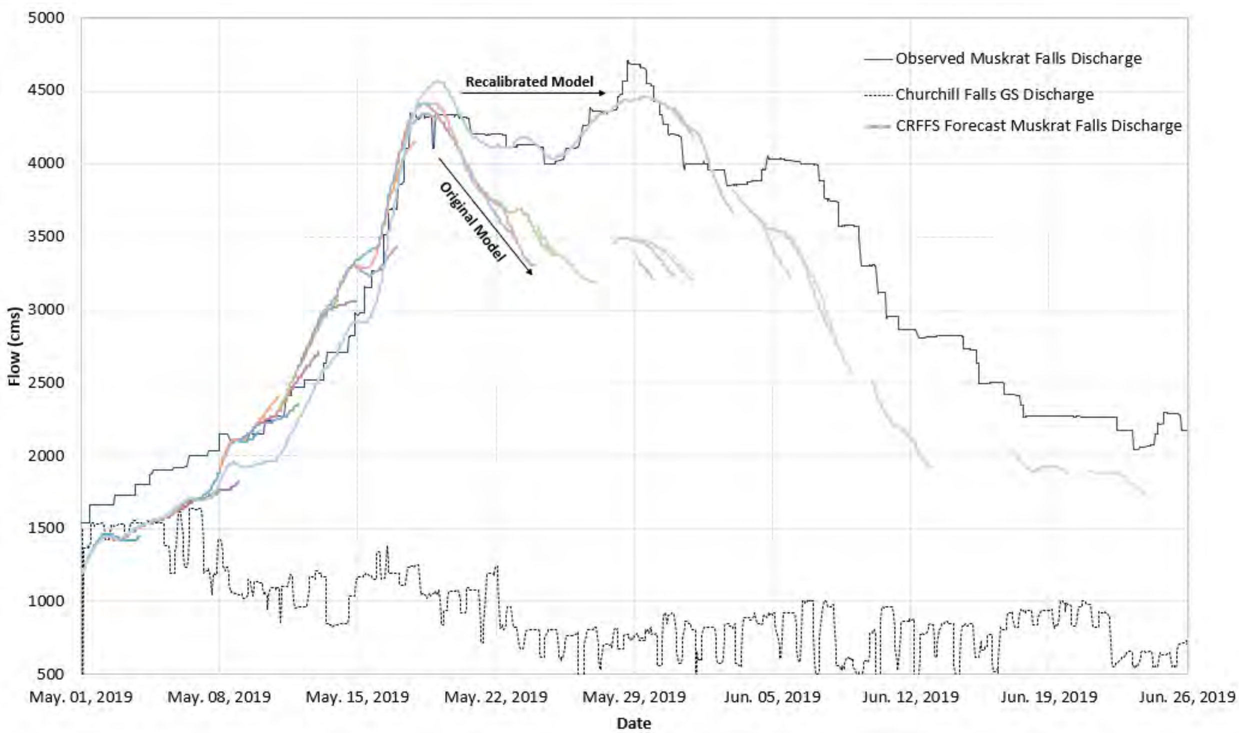
The Project Team and WRMD actively monitored the performance of the forecasting system during the 2019 freshet to ensure the model was accurately forecasting water levels on the Churchill River. On May 11, 2019, during the break-up of ice on the Churchill River, the system showed that the forecast 90th percentile water levels would exceed the river banks at Mud Lake. This allowed for the Government of Newfoundland and Labrador to issue an ice jam advisory for the Churchill River. On May 17, 2019, further ice accumulation on the Lower Churchill River resulted in flooding along portions of Mud Lake Road, although CRFFS did not issue any warnings. Following a review of the available information, the Project Team determined that while the forecast 90th percentile water levels generated by CRFFS did show some flooding along Mud Lake Road, the flooding occurred in between locations that the system actively monitors to send notifications. Accordingly, additional monitoring locations should be incorporated into CRFFS as part of the ongoing maintenance of the system to ensure that potential flood issues are identified.

The forecasting system was able to accurately simulate the peak flows and the timing of the peak. However, following the peak flow, CRFFS forecast lower flows than were observed at Muskrat Falls. The Project Team completed an assessment of the potential cause for the discrepancy in forecast flows, and identified the snow melt process in the HEC-HMS model as the cause. Accordingly, the project team completed a recalibration of the snow melt parameters based on the ongoing spring freshet. The calibration objective was to represent the ongoing freshet while minimizing any impacts to the model calibration and validation. The parameters were adjusted as part of the calibration, including a description of the parameter and how they were adjusted, include:

- **Px Temperature**: This value is the air temperature limit that differentiates whether precipitation falls as rain or as snow. This value was slightly lowered as part of the optimization so that more precipitation falls as rainfall.
- **Base Temperature**: The difference between the base temperature and air temperature is a main driver in calculating snowmelt. It was lowered slightly as part of the optimization so that the snowpack doesn't melt quite as quickly due to air temperature.
- **Wet Melt Rate**: This value represents the melt rate of the snow pack when rain is falling on the snow pack at a rate greater than a defined limit. This value was raised so that rainfall melts the snow pack quicker.
- **Rain Rate Limit**: This value is the minimum required rainfall rate for the model to apply the Wet Melt Rate. This value was lowered so that less intense rainfall events will trigger the wet melting rate.
- **Melt Rate Coefficient**: This value is used in the calculation of the melt rate when the rainfall is less than the Rain Rate Limit. It was lowered slightly to slow the melt due to air temperature.
- **Cold Limit**: This parameter accounts for changes in the snowpack temperature due to precipitation. It was lowered slightly so that precipitation has a bit more of an effect on the temperature of the snowpack.
- **Cold Rate Coefficient**: This value is used in the calculation of the temperature of the snowpack. It was slightly lowered so that the snowpack temperature fluctuates a little less.
- **Water Capacity**: This parameter represents the amount of water that must accumulate in the snowpack before water is available for runoff or infiltration. This value was raised so that the snowpack can hold a bit more water prior to runoff.

Following the recalibration of the HEC-HMS model, the updated HEC-HMS model was uploaded to CRFFS to replace the existing model. The updated model represented the flood freshet with an acceptable level of accuracy, as shown on Figure 113.

FIGURE 113
CRFFS REPRESENTATION OF THE 2019 FRESHET



14.5.2 System Deployment

The Project Team deployed CRFFS on two laptops provided by WRMD for the project. The deployed system was provided to WRMD on April 30, 2019. Following the successful deployment of CRFFS on the laptops, the Project Team successfully deployed CRFFS on a server environment hosted by the Government of Newfoundland and Labrador.

14.5.3 Training Session

The Project Team provided a 2-day training session between April 30 and May 1, 2019 for key staff from WRMD to familiarize them with CRFFS and its key components. The training session included detailed explanation on the RIVICE and Monte Carlo framework, operational training on the backend of the CRFFS system, as well as several hands-on exercises covering the various front-end components of the CRFFS system, including on the use of tools to extract and analyze the system forecasts.

15.0 LIST OF ASSUMPTIONS

Several simplifying assumptions were made over the course of this study. These assumptions were made based on sound scientific principles, and in some instances were made to account for limited or unavailable information. These assumptions included:

Assumptions in Hydrologic Modelling

- A minimum mapping unit of 0.5 ha was adopted for the land use classification.
- Soil types in the Churchill River were assumed as Soil Type B to develop the SCS Curve Number map.
- Groundwater was assumed to not make a significant flow contribution to recorded flows on the Churchill River.
- The 20 and 100 year rainfall events at Churchill Falls and Happy Valley – Goose Bay were assumed to fall concurrently.
- The rainfall for the 20 and 100 year rainfall events between Churchill Falls and Happy Valley – Goose Bay were defined by assuming an inverse distance weighting scheme between the two towns.
- Discharge from Churchill Falls during the 20 and 100 year rainfall events was assumed to correspond to 20 and 100 year discharges from the generating station.
- Evapotranspiration was assumed to be negligible during the 20 and 100 year rainfall events.
- The watershed conditions prior to the 20 and 100 year rainfall events were assumed to be consistent with typical summer wet soil conditions, and were defined based on the model calibration.
- The 20 and 100 year flows defined by the RFFA would include corresponding 20 and 100 year discharges from the Churchill Falls generating station.

Assumptions in Climate Change and Future Development Assessment:

- Future climate conditions will match those defined by the RCP 8.5 climate change scenario.
- Relative changes to end of winter snowpack depth were assumed to directly relate to relative changes to the annual peak flows during the spring freshet.
- Any snow that fell when temperatures were below 0 °C were assumed to contribute to the snowpack.

- During months that would only partially contribute to the snowpack (i.e. months that cross the 0°C threshold), the precipitation was assumed to contribute to the snowpack based on the product of the total precipitation for that month and the proportion of the month that was below 0°C.
- Seasonally-averaged impacts due to climate change were assumed to uniformly affect the monthly-averaged temperature and precipitation data.
- Any changes to the land use in Happy Valley – Goose Bay were assumed to have a negligible impact on flows on the Churchill River

Assumptions in Hydraulic Modelling

- The bathymetry of the lower Churchill River remained static for the period of record for which the models were calibrated and validated to.
- The depth of Lake Melville was assumed based on nearby surveyed cross sections.
- Storm surge or wind setup on Lake Melville was not accounted for in the modelling.
- Inflows between Muskrat Falls and Lake Melville were considered insignificant for the Flood Forecasting Model.
- Volume of inflowing ice to the lower Churchill River is limited to the reach of Muskrat Falls to Lake Melville. The presence of the Muskrat Falls G.S. will, when fully operational, restrict ice from upstream of the G.S. as the ice in the head pond will melt in place.
- A GEV distribution was assumed to represent the volume of inflowing ice on the Lower Churchill River in the Monte Carlo assessments.

Assumptions in Sensitivity Analyses

- Model input parameters in the sensitivity analyses were assumed to be independent, and that any interacting effects between the parameters in the sensitivity analyses would be negligible.

Assumptions in Flood Risk Mapping

- Hydraulically isolated areas in the flood risk maps divided by roadways were assumed to be connected by culvert crossings.

Assumptions in Forecasting System

- Forecasting beyond a three-day outlook will provide limited additional benefit.
- The initial ice thickness in the freezeup mode of CRFFS is defined based on the last ice thickness measurement from the preceding season.

16.0 CONCLUSIONS

The following conclusions can be made from the flood risk mapping and flood forecasting project for Happy Valley – Goose Bay and Mud Lake:

- Flows on the Churchill River representing the 20 and 100 year floods were estimated using SSFA and RFFA methodologies. Both approaches provided estimates of the 20 and 100 year flows on the river that were in good agreement.
- A detailed hydrologic model of the Churchill River watershed between Churchill Falls and Lake Melville was developed and calibrated observed flows in the watershed between 2011 and 2015, and validated to observed flows between 2016 and 2018. The model provides a very good representation of historical observed flows throughout the Churchill River watershed. The model also represented the May 2017 flood event very well.
- Hydrologic routing of the 20 and 100 year rainfall events using the hydrologic model resulted in considerably lower discharges on the Churchill River than the estimates of the 20 and 100 year flood flows based on SSFA and RFFA methodologies. This was due to high flows on the Churchill River being primarily driven by snowmelt and rain on snow as opposed to rainfall only. Accordingly, the 20 and 100 year flood flows estimated using the SSFA methodology were adopted for subsequent analyses.
- Hydrologic models were developed for the Otter Creek and seven unnamed creeks in Happy Valley – Goose Bay, and were used for routing of the 20 and 100 year rainfall events to define flows on those creeks.
- Impacts to flows, water levels, and ice thicknesses on the Churchill River were estimated for the end of the century based on climate change studies. The 20 and 100 year flood flows on the Churchill River are anticipated to increase by 2%, water levels on Lake Melville are anticipated to rise by 0.70 m, and ice thicknesses are anticipated to be reduced by a factor of 0.766.
- Impacts to flows on Otter Creek and seven unnamed creeks in Happy Valley – Goose Bay were assessed by simulating climate change rainfall events using the hydrologic models.
- Open water hydraulic models were developed for inclusion in the flood forecasting system and to complete the flood risk mapping. Each model was specifically tailored and optimized for each task. Both models were calibrated to observed water levels from fall 2017 and summer 2018, and validated to observed water levels from summer 2017. The flood risk mapping model was also calibrated to observed water levels from summer 2019. Both models were found to accurately represent hydraulic conditions on the Churchill River.
- An ice-affected hydraulic model of the Churchill River was developed and calibrated to freezeup and ice jam flood events, specifically the 2016 freezeup jam, the 2012 breakup

jam, and the historic 2017 breakup jam. The model was found to accurately represent the ice-affected conditions on the Churchill River.

- A Monte Carlo framework was implemented with the ice-affected hydraulic model was implemented to estimate the 20 and 100 ice-affected year flood levels on the Churchill River.
- Hydraulic models were developed for Otter Creek and seven unnamed creeks in Happy Valley – Goose Bay to defined water levels on those creeks associated with the 20 and 100 year rainfall events.
- Open water and ice-affected flood risk and flood hazard maps were developed for current climate and climate change conditions on the Churchill River. The mapping deliverables included 80 flood risk maps, 80 maps showing the comparison of flood risk for current climate and climate change conditions, 80 flood depth maps, 80 velocity maps, and 80 flood hazard maps.
- Flood risk and flood hazard maps were developed for both current climate and climate change conditions on Otter Creek and seven unnamed creeks in Happy Valley – Goose Bay, including 14 flood risk maps, 14 maps showing the comparison of the current climate and climate change flood risk maps, 14 flood depth maps, 14 flood velocity maps, and 14 flood hazard maps.
- Several buildings are impacted by flooding on the Churchill River for both open water and ice-affected floods under current climate conditions. More buildings are impacted by flooding under climate change conditions. Under open water conditions, approximately 2 and 4 buildings are flooded by the 20 and 100 year floods for current climate conditions, while approximately 13 and 18 buildings are impacted by the 20 and 100 year open water floods under climate change conditions. Similarly, approximately 23 and 54 buildings are impacted by the 20 and 100 year ice-affected floods for current climate conditions, while approximately 22 and 66 buildings are impacted by the 20 and 100-year ice-affected floods under climate change conditions.
- Buildings in Happy Valley – Gosee Bay are also impacted by flooding on Otter Creek and Local Creek 6. Approximately 3 and 4 buildings are flooded by the 20 and 100 year floods for current climate conditions, while approximately 5 and 22 buildings are impacted by the 20 and 100 year floods under climate change conditions.
- A fully automated forecasting system was developed for Happy Valley – Goose Bay and Mud Lake. The system runs continuously throughout the year and automatically adjusts the forecasts to represent freezeup, stable winter, breakup, and open water conditions. The system automatically retrieves input data and generates flow and water level forecasts at key locations on the Churchill River. Forecast information is displayed through a web interface.
- The forecasting system was successfully implemented prior to the 2019 spring freshet. The system successfully forecast high water on the Churchill River, and enabled the Government of Newfoundland and Labrador to issue an ice jam advisory for the Churchill River.

17.0 RECOMMENDATIONS

Over the course of this project, several recommendations were identified relating to the flood risk mapping and flood forecasting aspects of this study. These recommendations include:

- Presently there is a mix of vertical datums adopted for the hydrometric gauges on the Churchill River. The hydrometric gauges operated on the Churchill River should be updated to report the data in the CGVD 2013 vertical datum.
- The Water Survey of Canada hydrometric station at Muskrat Falls was taken out of service prior to the operation of the Muskrat Falls spillway. Currently, discharges at Muskrat Falls are estimated by Nalcor based on flow equations for the spillway structure. However, the ongoing commissioning of generating units at the station may affect the accuracy of these estimates. Accordingly, a rating curve should be developed at WSC station 03OE014 (i.e. Churchill River 6.15 kms Below Lower Muskrat Falls) to supplement and confirm the flow estimates provided by Nalcor. However, the flows estimated by the rating curve may not be accurate during winter conditions due to ice effects, or tidal effects, but nonetheless can act as a useful supplement and redundancy to the discharges estimated by Nalcor. As an alternate, a site located upstream of the extents of the Muskrat Falls head pond could be used as a suitable flow metering station.
- The network of hydrometric stations operated by WRMD on the Lower Churchill River are required by the forecasting system, and as such must continue to be operated. Furthermore, having a hydrometric station on either side of the river provides valuable data redundancy along the river, and has proven to be valuable in identifying any errors in the hydrometric data.
- WRMD should continue to monitor snow water equivalent information throughout the Churchill River watershed. This information can be highly valuable in identifying any calibration optimizations in the hydrologic model of the Churchill River included in the forecasting system.
- Mapping of the subsurface geology throughout Labrador should be completed to supplement the surficial geology information that is available. This information can be used to refine the SCS Curve Number map and to improve the model representation of soil infiltration characteristics in the HEC-HMS model.
- WRMD should continue to monitor the geomorphology on the Churchill River. This monitoring should occur concurrently with regular reviews of the Churchill River hydraulic model calibrations to ensure that those models are accurately representing the hydraulic conditions on the river. Should the geomorphological monitoring identify any large changes to the river, or the hydraulic models are found to poorly represent the hydraulic conditions on the river, the hydraulic models may require recalibration.

- Given the ongoing geomorphology and WRMD's monitoring program, the flood forecasting and flood risk mapping hydraulic models, as well as the flood risk maps, should be reviewed at a minimum of every 5 years or after each significant flood event to ensure that the models and maps are representative of the hydraulic conditions on the Churchill River. As necessary, the models and maps should be updated with more recent data.
- Given the number of buildings impacted by flooding on the Churchill River, it is recommended that flood mitigation measures be investigated and implemented to better protect the affected buildings from flooding on the river. Flood mitigation measures will help to reduce flood damages and improve the safety and well being of the residents. These measures, which could include the construction of community ring dikes or the raising of buildings above flood levels, should be studied and designed under a future study entitled "Assessment of Flood Protection Measures".
- The temporal resolution of the current climate and climate change data included in the Finnis (2018) report should be improved from seasonally-averaged values to monthly-averaged values.
- The Town of Happy Valley – Goose Bay should complete flood risk mapping of the municipal drainage system in the Town.
- The performance of the hydrologic model included in CRFFS should be monitored on an ongoing basis, and should be recalibrated as required. It would be recommended to review the model calibration at a minimum of every 5 years.
- The threshold values included in the CRFFS forecast cycle should be monitored on an ongoing basis, and adjustments to those values should be made as additional data becomes available.
- The number of Monte Carlo runs included in CRFFS was initially based on the necessary model run time on 4DM's internal server. Since additional computational capacity is likely available on the production server for the system, the computation time to complete the Monte Carlo simulations should be reviewed. If possible, the number of Monte Carlo simulations should be increased to provide as many simulations as possible while still delivering the forecast results in a reasonable timeframe. This should be reviewed each time the OCIO hardware for the server is improved to make sure to optimize the computations on any new faster hardware.
- CRFFS should be improved to provide automated reports summarizing the daily forecasts.
- Additional forecasting locations could be incorporated into CRFFS to account for the potential for localized flooding due to ice jams.
- It is critical to ensure an ongoing annual maintenance and system support program for the CRFFS. This program would ensure that the CRFFS continues to function as designed and intended, continues to function as software changes occur, and allow for system improvements to be implemented once they have been identified.

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