GOVERNMENT OF NEWFOUNDLAND AND LABRADOR

# Climate Change Flood Risk Mapping Study for Placentia, Carbonear, Victoria and Salmon Cove

Revision:
Final Rev 0

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September 30, 2022

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Attention: Dr. Richard Harvey, Ph.D., P.Eng.
Manager – Water Rights, Investigations, and Modelling Section

**Re: Climate Change Flood Risk Mapping Study for Placentia, Carbonear, Victoria and Salmon Cove Final Report Rev. 0**

Dear Dr. Harvey:

KGS Group is pleased to submit our Final Report for Climate Change Flood Risk Mapping Study for Placentia, Carbonear, Victoria and Salmon Cove. This report has been updated to address comments provided by WRMD for the Rev. B version of the report.

Should you have any questions regarding the report or would like to discuss any aspects of the report further, please do not hesitate to contact the undersigned or Mr. Andrew Weiss.

Yours truly,

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

ALW/ go
Attached

# 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 communities of Placentia, Carbonear, Victoria and Salmon Cove. The engineering study included the development of detailed hydraulic and hydrologic models to serve as the basis for the flood risk mapping.

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

- ***KGS Group*** was responsible for the overall management of the project and was responsible for all aspects of the study, including mainly the development of the hydrologic and hydraulic models used for flood risk mapping, and the development of the flood risk maps.
- ***Dr. Karl-Erich Lindenschmidt*** worked closely with KGS Group's in-house nationally recognized ice expert to assess the impacts of ice jamming within the communities.
- ***DHI Water & Environment Inc.*** were responsible for the development, calibration and implementation of the coastal hydraulic models in Placentia Bay and Conception Bay, which included assessments of storm surge, wind setup, and wave runup in the coastal areas of the communities considered in this study.
- ***N.E. Parrott Surveys Limited*** were responsible for the completion of the topographic and bathymetric surveys in Placentia, Carbonear, Victoria and Salmon Cove. N.E. Parrot Surveys is based in Happy Valley – Goose Bay, with satellite offices on the Island of Newfoundland, and as such are highly familiar with flooding in the area and provided valuable local knowledge and context to the study.
- ***Zuzek Inc.*** were responsible for providing expert guidance on tidal aspects that would affect coastal water levels in Conception Bay, Placentia Bay, and Northeast Arm, Southeast Arm and Swan Arm in Placentia.

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 acquired and reviewed relating to flooding in Placentia, Carbonear, Salmon Cove and Victoria. 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 and bathymetric information within the study area, including the survey of bridge and culvert crossings, as well as validation data for the existing topographic data used for the study.
- ***Remote Sensing and Land Use Classification*** – Land use was classified throughout the study areas based on available satellite imagery and soils information.

- ***Hydrologic Investigations and Modelling*** – Hydrologic analyses were completed to estimate the 20 and 100-year annual exceedance probability (AEP) flows in Placentia, Carbonear, Salmon Cove and Victoria. Detailed hydrologic models were also 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 various rivers and creeks in the study area and sea levels along the coastal areas. Anticipated development conditions were also reviewed for Placentia, Carbonear, Salmon Cove and Victoria.
- ***Hydraulic Investigations and Modelling*** – Coastal and riverine hydraulic models were developed and calibrated to define flood levels associated with the 20 and 100-year AEP storm surge and river flows.
- ***Sensitivity Analyses*** – The sensitivity to changes to key parameters was assessed for the hydrologic and hydraulic models.
- ***Flood Risk Mapping*** – Flood risk maps were developed for Placentia, Carbonear, Salmon Cove and Victoria for the 20 and 100-year AEP floods under current climate and climate change conditions. The flood risk maps were reviewed by WRMD and the communities, and any comments provided by WRMD and the communities were integrated into the finalized maps. Flood hazard data, including depth of flooding, flow velocities, and flood hazard associated with the 20 and 100-year AEP floods under current climate and climate change conditions were provided to WRMD in digital format.
- ***Flood Forecasting Strategy*** – Three high-level conceptual flood forecasting strategies were developed. The conceptual strategies were then evaluated qualitatively based on a number of important factors.

**Background Information Review**

An extensive array of background information was acquired, including precipitation data, historical water level and flow data, and historical flood observations in Placentia, Carbonear, Salmon Cove and Victoria. This information provided context to the history of flooding in the communities, 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 in Placentia, Carbonear, Salmon Cove and Victoria were added to the inventory.

**Field Program**

A detailed field program was completed to capture critical topographic and bathymetric data in Placentia, Carbonear, Salmon Cove and Victoria, culvert and bridge details, as well as ground elevations throughout the study area to assist with the validation of the detailed topographic digital elevation model developed by the Federal Government. Five hundred and twenty river cross sections were surveyed in the study area, with an additional 78 bathymetric cross sections surveyed on Northeast Arm, Southeast Arm and Swan Arm. Culvert and bridge details were surveyed for 100 crossings throughout the study area. Water level monitoring equipment was deployed at two locations on the Salmon Cove River, one location on Powells Brook, one location on Island Pond Brook, and one location on the Southeast River. As well, flow measurements were collected on several rivers and creeks on two occasions as part of the study.

**Remote Sensing and Land Use Classification**

Satellite imagery was acquired throughout the watersheds draining into Placentia, Carbonear, Salmon Cove and Victoria study areas from the European Space Agency's SPOT-6 satellite imagery dataset. The land use of the satellite imagery was classified within the study area using a supervised, automated process in GIS software. Soil classification data was acquired from the National Soils Database developed by the Government of Canada. The land use classification was then combined with the soil data to generate a map throughout the study areas 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 rivers and creeks considered in this study. These analyses included a single station frequency analysis of the nearby Water Survey of Canada gauge stations, a regional flood frequency analysis for the southeast and southwest regions of Newfoundland, and the development and calibration of detailed hydrologic models of the Placentia and Carbonear, Salmon Cove and Victoria areas. Analyses of precipitation in the study area 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 AEP rainfall events in the study area, which were routed using the calibrated hydrologic models to define river flows associated with the rainfall events. The routing of the 20 and 100-year AEP rainfall events using the hydrologic models were found to provide the most appropriate flows, and as such were adopted for inclusion in subsequent hydraulic modelling.

**Climate Change and Future Development Assessment**

An assessment was completed to define the anticipated impacts to river and creek flows due to climate change effects on precipitation, as well as impacts to coastal sea levels due to sea level rise. Under changing climate conditions, the 20 and 100-year AEP flows are anticipated to increase by between 21% to 50% in Salmon Cove, Victoria and Carbonear, and by between 14% to 18% in Placentia by the end of the 21st century. Similarly, coastal water levels are projected to increase by 0.62 m to 0.63 m due to the anticipated sea level rise.

**Hydraulic Investigations and Modelling**

Coastal and riverine hydraulic models were developed in Placentia, Carbonear, Salmon Cove and Victoria using MIKE 21 and HEC-RAS. The coastal models, which were developed to simulate storm surge conditions, consisted of a large, north Atlantic region model, as well as two high resolution models of Placentia Bay and Conception Bay. The coastal models were calibrated and validated to available historical tide data. The calibrated model was used to hindcast tidal and storm surge conditions between 1980 and 2020. Model results were extracted at key locations for statistical analyses to define the 20 and 100-year AEP storm surge levels throughout the study areas.

Riverine hydraulic models were developed for the various rivers and creeks assessed as part of this study, and consisted of 1D models, coupled 1D/2D models, and fully 2D models. The hydraulic models were calibrated to available recorded water levels, and were found to accurately represent those recorded water levels. The calibrated models were then used to simulate the 20 and 100-year AEP flood flows to define the flood levels, velocities, and depths that were integrated into the flood risk maps.

River ice jam models were developed for Salmon Cove River, Island Pond Brook and Powells Brook using RIVICE. The models were calibrated to open water conditions, but unrealistically high channel bed roughness coefficients were required to maintain numerical stability in Powells Brook and Island Pond Brook. The RIVICE models were used to simulate ice jamming throughout the river reaches while conveying the 100-year AEP ice affected flow to define the upper limit of ice jam flooding on each reach. Ice jam levels were generally comparable to the 100-year AEP open water levels under 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 not sensitive to changes to the roughness in the routing equations, but were sensitive to changes to the groundwater infiltration parameters.

For riverine hydraulic models, the sensitivity analyses considered the Manning's roughness coefficient and inflow to the model. The models were generally not sensitive to changes to both parameters. The sensitivity of the hydrologic models was thus mitigated by the relative insensitivity of the hydraulic models. This was further mitigated by the steep river valleys, which reduce the impact on flooded area associated with changes in water levels.

**Flood Risk Mapping**

Flood risk maps were developed for the 20 and 100-year AEP floods in Placentia, Carbonear, Salmon Cove and Victoria for current climate and climate change conditions. The flood risk maps were 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, digital flood hazard data, which included the velocity, depth and flood hazard, were developed for the 20 and 100-year AEP floods for current climate and climate change conditions. Velocity and depth data 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.

**Flood Forecasting Strategy**

Three high-level conceptual flood forecasting strategies were developed for the communities of Placentia, Carbonear, Salmon Cove and Victoria. These options ranged from leveraging and monitoring existing meteorological forecasting tools, storm surge prediction tools, and the Government of Newfoundland and Labrador's Hurricane Early Warning System, to a fully integrated and automated forecasting system that would generate hydrologic, hydraulic, and storm surge forecasts based on existing meteorological forecasts.

Following the development of the conceptual options, each option was evaluated based on a set of considerations that would be required to implement each system, such as costs and the effort to maintain and operate each system. The forecasting strategy that leverages the Government of Newfoundland and Labrador's existing monitoring process with additional forecasting tools was found to be the optimal solution.

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## List of Abbreviations

| | |
|---|---|
| 1D | 1-dimensional |
| 2D | 2-dimensional |
| 3PLN | Three-Parameter Lognormal Distribution |
| ADCP | Acoustic Doppler Current Profiler |
| ADV | Acoustic Doppler Velocimeter |
| AEP | Annual Exceedance Probability |
| AHCDD | Adjusted and Homogenized Climate Change Data |
| BIO | Bedford Institute of Oceanography |

| | |
|---|---|
| BODC | British Oceanographic Data Centre |
| CaPA | Canadian Precipitation Analysis |
| CD | Chart Datum |
| CDED | Canadian Digital Elevation Data |
| CDEM | Canadian Digital Elevation Model |
| CFSR | Climate Forecast System Reanalysis |
| CGVD2013 | Canadian Geodetic Vertical Datum of 2013 |
| CGVD28 | Canadian Geodetic Vertical Datum of 1928 |
| CHS | Canadian Hydrographic Service |
| CN | Curve Number |
| CRUD | Create Read Update and Delete |
| CSRS | Canadian Spatial Reference System |
| DA | Drainage Area |
| DEM | Digital Elevation Model |
| DSM | Digital Surface Models |
| DTM | Digital Terrain Models |
| ECCC | Environment and Climate Change Canada |
| ESA | European Space Agency |
| EV-1 | Extreme Value Distribution |
| EVA | Extreme Value Analysis |
| FDRP | Federal Damage Reduction Program |
| FM | Flexible Mesh |
| GEBCO | Global General Bathymetric Chart of the Oceans |
| GEV | Generalized Extreme Value |
| GPS | Global Positioning System |
| HD | Hydrodynamic |
| HEC-GeoHMS | Hydrologic Engineering Centre's Geospatial Hydrologic Modelling System |
| HEC-HMS | Hydrologic Engineering Centre's Hydrologic Modelling System |
| HEC-RAS | Hydrologic Engineering Centre's River Analysis System |
| HHWLT | Higher High Water Large Tide |
| HHWMT | Higher High Water Mean Tide |
| HRDEM | High Resolution Digital Elevation Model |
| IDF | Intensity-Duration-Frequency |
| IPCC | International Panel on Climate Change |
| LAF | Lake Attenuation Factor |
| LiDAR | Light Detection and Ranging |
| LLWLT | Lower Low Water Large Tide |
| LLWMT | Lower Low Water Mean Tide |
| LN | Lognormal Distribution |
| LP3 | Log Pearson Type 3 Distribution |
| LSF | Lakes and Swamp Factor |
| MEDS | Marine Environment Data Section |

| | |
|---|---|
| MOM | Method of Moments |
| MSL | Mean Sea Level |
| MTM | Modified Transverse Mercator |
| MWL | Mean Water Level |
| NAD83 | North American Datum of 1983 |
| NCAR | National Centre for Atmospheric Research |
| NDMP | National Disaster Mitigation Program |
| NEPSL | N.E. Parrott Surveys Limited |
| NOAA | National Oceanic and Atmospheric Administration |
| NONNA | Non-navigational |
| NRCan | Natural Resource Canada |
| NRCS | Natural Resources Conservation Service |
| NSDB | National Soils Database |
| POT | Peak-over-threshold |
| RCP | Representative Concentration Pathway |
| RFFA | Regional Flood Frequency Analysis |
| RTK | Real Time Kinematic |
| SCS | Soils Conservation Service |
| SE | Southeast |
| SEE | Standard Error of the Estimate |
| SMR | Regression Correlation Coefficient |
| SSFA | Single Station Frequency Analysis |
| SW | Spectral Wave |
| USDA | United States Department of Agriculture |
| UTM | Universal Transverse Mercator |
| WRMD | Water Resources Management Division |
| WSC | Water Survey of Canada |

# STATEMENT OF LIMITATIONS AND CONDITIONS

## Limitations

This report has been prepared for the Government of Newfoundland and Labrador in accordance with the agreement between KGS Group and the Government of Newfoundland and Labrador (the "Agreement"). This report represents KGS Group's professional judgment and exercising due care consistent with the preparation of similar reports. The information, data, recommendations and conclusions in this report are subject to the constraints and limitations in the Agreement and the qualifications in this report. This report must be read as a whole, and sections or parts should not be read out of context.

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# 1.0 INTRODUCTION

## 1.1 Background

As part of the Federal Damage Reduction Program (FDRP), the Government of Newfoundland and Labrador completed flood risk mapping projects for a number of communities where flooding had historically occurred. These flood risk mapping projects were completed between 1981, when the Government of Newfoundland and Labrador joined the FDRP, and 1996, including the completion of flood risk mapping studies for Placentia in 1985, and for the communities of Carbonear, Victoria, Salmon Cove, Whitbourne, Heart's Delight, Winterton and Hant's Harbour in 1996. Subsequent to the completion of the FDRP, the Government of Newfoundland and Labrador announced a new Climate Change Adaptation initiative to update existing flood risk mapping studies and complete new flood risk mapping studies with specific considerations for the anticipated impacts of climate change. Additionally, the Government of Canada introduced the National Disaster Mitigation Program (NDMP), which committed ongoing funding to reduce the impacts of natural disasters, including via the completion of flood risk mapping studies.

In light of their ongoing efforts to update existing flood risk maps and develop new flood risk maps for at-risk communities, the Government of Newfoundland and Labrador retained KGS Group to develop updated flood risk maps for the communities of Victoria, Salmon Cove and Carbonear, as well as the communities located within the municipal boundary of Placentia (i.e. Placentia, Jerseyside, Freshwater, Ferndale, Dunville, and Southeast Placentia). The updated flood risk maps were developed considering both the current climate and climate change-affected conditions, as well as both current and anticipated future levels of development within the communities.

The communities considered for this project are located near Conception Bay (i.e. Carbonear, Salmon Cove and Victoria) and Placentia Bay (i.e. Placentia). At both locations, the flood risks are anticipated to be due to a combination of coastal flooding processes, such as tides, storm surge and wave runup, and riverine flooding associated with either high rainfall events, localized ice jamming, or a combination of both.

In Placentia, flooding has historically been caused by abnormally high tides, heavy seas, high winds, wave runup, storm surge, and large rainfall events. The community of Placentia is located on low-lying land adjacent to Placentia Bay, and as such is most exposed to coastal processes that could result in flooding. Other communities within the municipal boundary of Placentia are located farther inland or on higher ground, and therefore are at a reduced risk of flooding due to coastal processes. However, given the complex hydraulics between Placentia Bay, Northeast Arm, Swan Arm and Southeast Arm during larger scale coastal flooding events, such as storm surge, wind setup, and wave runup, potential for flooding within these communities cannot be disregarded. Furthermore, potential for riverine flooding caused by heavy rainfall exists within many of these communities along Mill Brook, Northeast River, Rattling Brook, Smelt Brook, Baldwins Brook, Southeast River, and the various lesser creeks flowing throughout the communities. Flooding due to coastal processes is anticipated to worsen under climate change-affected conditions due to the combination of sea level rise and crustal subsidence in Newfoundland. Riverine flooding is also anticipated to worsen due to the anticipated increase in precipitation events associated with climate change.

Similarly, flooding in Carbonear and Salmon Cove can be caused by a combination of coastal and riverine processes, while flooding in Victoria is driven by riverine processes due to the inland location of the community. The majority of the communities of Carbonear and Salmon Cove are located inland, mitigating the risks associated with coastal flooding, but there are some developments adjacent to Carbonear Bay and Salmon Cove that are likely at risk due to coastal flooding processes. Furthermore, high water levels along the coast will have some impact on riverine flooding in the lower reaches of Salmon Cove River, Island Pond Brook, and Powells Brook. In addition to flooding caused by large rainfall events, there have been incidents of ice jam flooding in Carbonear and Victoria, often caused by large rainfall events occurring during the winter months causing the dislodgement of the ice cover. Similar to Placentia, flood conditions are anticipated to worsen in Carbonear, Victoria and Salmon Cove due to the impacts that climate change will have on the relative sea level and precipitation.

Given the broad range of environmental factors that can contribute to flooding in Placentia, Victoria, Salmon Cove and Carbonear, a clear understanding of each mechanism and how to best incorporate considerations for each in the resulting flood risk mapping is a critical component of this project. To respond to the highly complex and important nature of this project, KGS Group assembled a uniquely qualified and strong team of highly regarded and experienced engineers from within KGS Group as well as from other highly regarded engineering and survey companies with expertise in the water resources industry. The composition of the Project Team, and the roles of each of our subconsultants included:

- ***KGS Group*** was responsible for the overall management of the project and was responsible for all aspects of the study, including the development of the hydrologic and hydraulic models used for flood risk mapping and the development of the flood risk maps.
- ***Dr***. ***Karl-Erich Lindenschmidt*** worked closely with KGS Group's in house national recognized ice expert to assess likelihood of ice jamming and the potential impacts of ice jamming on flood levels in the study areas.
- ***DHI Water & Environment Inc.*** were responsible for the development, calibration and implementation of the coastal hydraulic models in Placentia Bay and Conception Bay, which included assessments of storm surge, wind setup, and wave runup in the coastal areas of the communities considered in this study.
- ***N.E. Parrott Surveys Limited*** were responsible for the completion of the topographic and bathymetric surveys in Placentia, Carbonear, Victoria and Salmon Cove. N.E. Parrot Surveys is based in Happy Valley – Goose Bay, with satellite offices on the Island of Newfoundland, and as such are highly familiar with flooding in the area and provided valuable local knowledge and context to the study.
- ***Zuzek Inc.*** were responsible for providing expert guidance on tidal aspects that would affect coastal water levels in Conception Bay, Placentia Bay, and Northeast Arm, Southeast Arm and Swan Arm in Placentia.

## 1.2 Study Goals and Objectives

The primary objectives of this study include the completion of bathymetric and topographic surveys, and the development, calibration and implementation of hydrologic and hydraulic models to be used to define flood risk maps and inundation maps associated with the 20 and 100-year Annual Exceedance Probability (AEP) flood events. The rivers and creeks considered in the study are shown on Figure 1 and Figure 2.

The flood risk maps developed as part of this project enhance WRMD's understanding of the potential for flooding in Placentia, Carbonear, Victoria and Salmon Cove for both current climate conditions, as well as those affected by climate change in the future. The flood forecasting strategy developed for this project will define potential alternatives to enhance WRMD's capacity to 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 under current climate and climate change conditions, including the river centre lines and hydrometric stations.
- Development of maps showing flood plain changes associated with the 1:20 and 1:100 AEP floods for current climate and climate change conditions.
- Development of maps showing flood plain changes associated with the historical and the new current climate and current development conditions for the 1:20 and 1:100 AEP floods.
- Development of flood inundation, flood velocity, and flood hazard maps for the current climate and climate change conditions with 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.
- Development and evaluation of a conceptual flood forecasting strategy for the communities of Placentia, Carbonear, Salmon Cove and Victoria.
- Completion of a review of the anticipated performance of the flood control structures in the study area relative to the 1:20 and 1:100 AEP floods. Specifically, this review considered the flood wall in Placentia.
- 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.

FIGURE 1: RIVERS AND CREEKS CONSIDERED IN CARBONEAR, SALMON COVE AND VICTORIA

# FIGURE 2: RIVERS AND CREEKS CONSIDERED IN PLACENTIA

# 2.0 BACKGROUND INFORMATION REVIEW

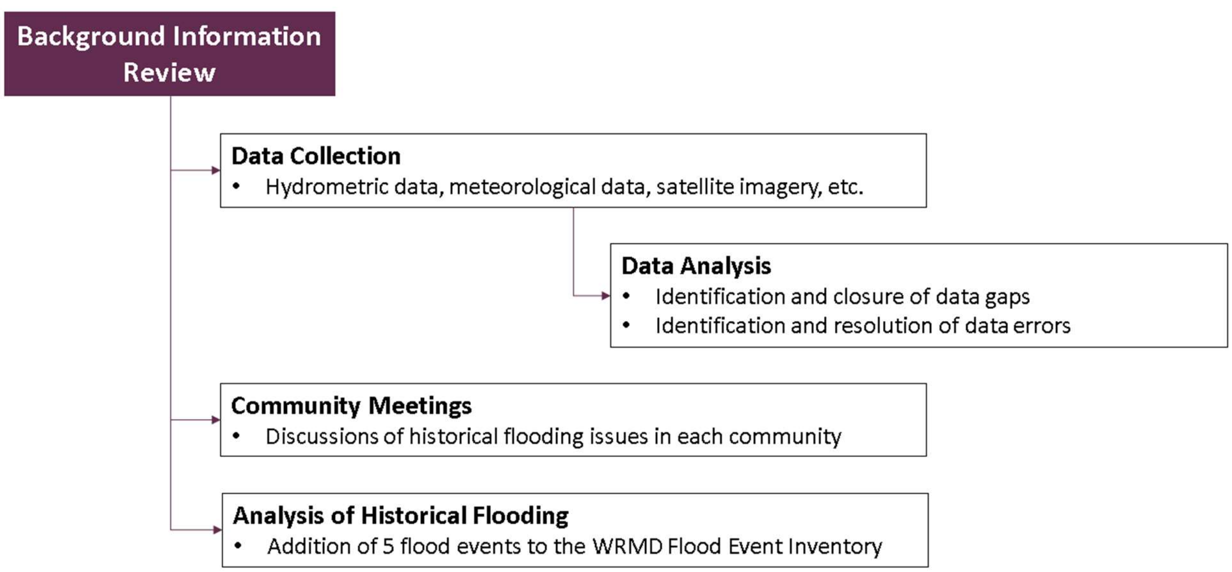
## 2.1 Overview

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 in Placentia, Carbonear, Victoria, and Salmon Cove. This provides a basis for the various analyses completed for the study, and assists in the development and calibration of the hydrologic and hydraulic models. The collected background data included aerial imagery, previously collected survey data, satellite imagery, design drawings, water level and flow data, meteorological data, and reports documenting the previously completed flood risk mapping studies for the communities. This data was collected from a variety of sources, including representatives from the Towns of Placentia, Carbonear, Victoria and Salmon Cove, the Government of Newfoundland and Labrador, Water Survey of Canada (WSC), Environment and Climate Change Canada (ECCC), and Natural Resources Canada.

As part of the background information review, a review of previous flood events in Placentia, Salmon Cove, Victoria and Carbonear was completed for inclusion in the Government of Newfoundland and Labrador's Flood Event Inventory. The review identified five historical flood events in the communities that were added to the Flood Event Inventory.

The tasks completed as part of the background information review are shown on Figure 3.

FIGURE 3: 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, ECCC, Natural Resources Canada and representatives from the Towns of

Carbonear, Salmon Cove, Victoria and Placentia. This information was used to assist in the development and calibration of the hydraulic and hydrologic models, and to further understand the meteorological, hydrologic and hydraulic conditions that lead to flooding. This information included:

- High Resolution Digital Elevation Model (HRDEM) data throughout Carbonear, Placentia, Victoria and Salmon Cove,
- Satellite and remote sensing imagery,
- Construction drawings for the Sound Brook crossing on Highway 102,
- Streamflow and water level data collected by WSC,
- 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,
- Orthoimagery,
- Land use information,
- Soils information,
- Sea levels,
- Stream cross sections,
- Bridge and culvert crossing information,
- Culvert sizes and locations from the towns to supplement our field survey data,

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 the water level gauge on the Northeast River was in a local datum, thus 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 02ZK001 (i.e. Northeast River near Placentia) was surveyed to convert the local datum to CGVD 2013. This allowed for the calculation of the conversion offset for the assumed datum to convert the data to CGVD 2013. To convert the local datum to CGVD 2013, it was necessary to increase the recorded water levels by 4.6 m.

Another gap that was identified in the data was recent precipitation data within the study areas. In general, available recorded precipitation was located far from the study areas (i.e. Carbonear, Salmon Cove and Victoria), or stations were nearby but inactive (i.e. Placentia). To close this data gap, precipitation values defined by the Canadian Precipitation Analysis (CaPA) product were used for the calibration of the hydrologic model. 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 on the Avalon Peninsula would introduce considerable uncertainty into any interpolation method. Furthermore, Environment and Climate Change Canada (ECCC) gauge data suffers from well documented systematic biases including wind driven undercatch, which is most significant in determining solid precipitation quantity, wetting loss, evaporation, and trace precipitation loss.

## 2.4 Community Meetings

KGS Group held a number of meetings with representatives from Placentia, Carbonear, Victoria and Salmon Cove to provide context for the flood risk mapping study and to describe the scope of work that was involved in the study. The meetings provided an opportunity to discuss recent flood events that had occurred in towns and glean key insights from the town representatives to characterize historical flood issues. Furthermore, the meetings allowed for KGS Group to review the proposed locations to be considered in the flood risk mapping to ensure that the main potential sources of flooding were considered as part of the study. Key points of discussions with each of the towns, as well as the date that the meetings occurred, include:

- ***Town of Placentia (November 3, 2021)*** – Representatives from the town concurred with the proposed rivers and creeks being considered in the study, and noted that a small network of ponds near Argentia were not required to be mapped. The town also noted an additional drain that experienced flooding, but since flow on that drain is conveyed into a storm sewer system, it was outside the scope for this project. Representatives from the town noted that the most recent flooding issues were associated with Hurricane Larry, with waves and wave runup unlike anything seen before in Dunville. The town noted that the waves and runup resulted in damage to retaining walls throughout town.
- ***Town of Salmon Cove (November 3, 2021)*** – After reviewing the proposed rivers and creeks to be included in the study, the Town of Salmon Cove concurred with the proposed creeks. The Town identified an additional creek running through Birchcliff Dr. that was of concern and should be included in the study. Representatives from the town also noted that flooding due to storm surge was becoming more prevalent.
- ***Town of Victoria (December 15, 2021)*** – Representatives from the town agreed with the proposed creeks to be included in the flood risk mapping study. High flows were also noted to have occurred through town during Hurricane Larry in September 2021.
- ***Town of Carbonear (November 16, 2021)*** – The proposed rivers and creeks to be included in the study were reviewed with representatives of the Town of Carbonear, who agreed that the proposed rivers and creeks were appropriate. The town did note an additional creek and adjacent flood prone land that should be considered in the study, with the creek flowing under the College of the North Atlantic. The Town also noted that Hurricane Chantal caused considerable flood damage throughout town, but subsequent improvements to the drainage infrastructure reduced flood damages during subsequent hurricanes.

KGS Group held follow-up meetings with the Towns of Placentia, Carbonear, Salmon Cove and Victoria following the completion of the draft flood risk maps. The draft maps were provided to the communities in advance of the meeting to allow for the review of the maps by representatives of the communities and to enable thoughtful discussion during the follow-up meetings. The key points of discussion from those meetings, as well as when they took place, include:

- ***Town of Placentia (April 12, 2022)*** – Representatives from the Town of Placentia noted that the flood risk maps were in good agreement with historical flooding in the area. As well, good agreement was noted between the simulated storm surge heights and observed storm surges during recent large storms. It was noted during the meeting that the town was in the process of evaluating the floodwall in Placentia, and appreciated that they could see how climate change is anticipated to affect the level of protection associated with the floodwall. The town did indicate that flooding on one creek was more extensive than they had previously seen (i.e. Local Creek 2). Based on this input, KGS Group reviewed the hydrologic model and found that the drainage basin defined in the model for the creek was draining too large of a drainage area, and that a portion of the drainage basin is drained by ditching separate from the creek. The hydrologic model was adjusted to represent the smaller drainage basin associated with the creek, which in turn reduced flows on the creek and the extent of the flooding. Representatives from the Town noted concern about the potential policy implications of the flood risk mapping and how that could affect development in Placentia. A meeting should be held between the Government of Newfoundland and Labrador and the Town of Placentia to review and discuss potential policy implications associated with the updated flood maps.
- ***Town of Salmon Cove (April 14, 2022)*** – Representatives from the Town of Salmon Cove found the maps to be in excellent agreement with their historical flood experience, noting several areas where flooding had occurred very similarly to the flooding shown in the flood maps. As part of the meeting, one area near the church was further reviewed with the representatives from the town to ensure that it was accurately represented. The Town representatives agreed that the mapping accurately represented flooding in the area.
- ***Town of Victoria (April 25, 2022)*** – Several flooded areas in the flood maps were noted to be in very good agreement with historical flooding in Victoria by representatives from the Town, including near Beaver Pond, the culvert crossing downstream of Job's Pond, and the culvert crossing near Ash's Lane. Representatives from the Town noted that during high rainfall, there can be direct runoff down the hillsides near Church Road and Ash's Lane. However, it was understood that this was beyond the scope of the study, as the scope of the study only considered flooding from rivers and along the coast and not municipal drains. It was noted that it would be beneficial for there to be a survey completed of the wastewater lagoon dam to ensure adequate freeboard between the flood levels and the dam crest.
- **Town of Carbonear (April 29, 2022)** – Representatives from the Town of Carbonear noted that the flood extents shown in the draft flood risk maps were generally in good agreement with their historical flood experiences and expectations. The town noted that there was more flooding than anticipated on Island Pond Brook near Beach Road, and provided KGS Group with construction drawings of the bridges to confirm that the bridges were accurately represented in the model. The model representation of the bridges was found to be in good agreement with the construction drawings provided by the Town. As well, representatives from the town noted that the flooding near the College of the North Atlantic was more extensive than they had previously seen, but provided contact information for maintenance personnel at the college. The maintenance contact at the College of the North Atlantic recalled an incident approximately 20 years ago where a culvert near Cross Road had collapsed, causing floodwater to flow through the college that required sandbagging in the college hallways. The flood conditions observed by the maintenance personnel are in good agreement with the flooding defined as part of this

study, although the cause of the flooding is due to the culvert capacity being exceeded, rather than the collapse of the culvert.

## 2.5 Analysis of Historical Flooding

A thorough review was completed of the available information pertaining to flood events in Placentia, Carbonear, Victoria and Salmon Cove, which was added to the existing Historical Flood Event Inventory provided by WRMD. The Historical Flood Event Inventory already included a number of historical flood events in those communities, which were generally found to be attributed to hurricanes and post-tropical depressions that brought heavy rainfall to the communities. However, five additional flood events were identified and included in the Historical Flood Event Inventory, specifically:

- ***December 4, 2013*** – A large storm surge and high waves in Placentia caused considerable damage to the boardwalk in Placentia along Veterans Way (formerly Beach Road). The mayor noted that sections of the boardwalk were completely destroyed, while others were lifted up or damaged.
- ***December 15, 2016*** – Storm surges and high waves in Placentia caused infrastructure damage to Veterans Way (formerly Beach Road), resulting in closure of the road. Orcan Drive was also closed due to damage from the storm surge.
- ***November 18, 2020*** – Approximately 200 mm of rain fell in Placentia over two days, resulting in several road washouts. Areas of the community experienced significant damage, including complete closures of certain roads, such as Route 100.
- ***September 10, 2021*** – Previously unseen storm surge and wave runup in Dunville associated with Hurricane Larry resulted in considerable damage to retaining walls throughout the area.
- ***September 10, 2021*** – Very high river flows were noted in the Town of Victoria during Hurricane Larry, resulting in minor flooding in town.

Historical flood events that occurred in Placentia, Carbonear, Salmon Cove or Victoria 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 rivers and creeks considered as part of the study. Five hundred and twenty river cross sections were surveyed. Surveys of one hundred culvert and bridge crossings were completed on the rivers and creeks considered in the study area so that the bridge and culvert crossings could be accurately represented in the hydraulic models. Seventy-eight cross sections were also surveyed on the Northeast Arm, Swan Arm, and Southeast Arm in Placentia in support of the hydraulic modelling.

Ground elevations were surveyed throughout the study area to confirm the accuracy of the HRDEM data, and to ensure that the HRDEM data accurately represents the ground elevation throughout the study area.

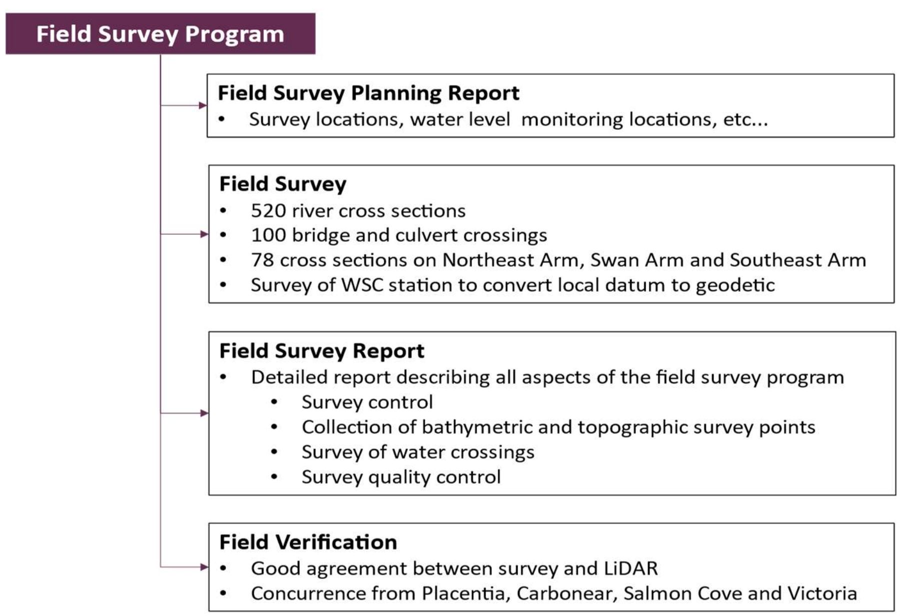
Benchmarks for a WSC station located on the Northeast River near Placentia were surveyed to allow for the conversion of water levels measured in a local datum to a geodetic datum. This conversion allowed for the water levels to be used in the calibration of the hydraulic models.

Flow measurements were completed at select locations in the study area to confirm hydrologic assumptions that were necessary to complete the study. Similarly, automated water level monitoring equipment were deployed at five locations throughout the study area to assist in the calibration of the hydraulic models.

The information gathered from the field survey was used to develop and calibrate the hydraulic models, as described in Section 8.0, which in turn were used as the basis for the flood risk mapping products.

The tasks completed as part of the field survey are shown on Figure 4.

FIGURE 4: OVERVIEW OF FIELD SURVEY PROGRAM



## 3.2 Field Survey

### 3.2.1 PROJECTIONS AND SURVEY CONTROL

The survey control used for this project consisted of provincial monuments and local benchmarks installed by NEPSL. The control established was used to support the bathymetric and topographic survey activities. NEPSL used L1/L2 dual constellation (GPS/ GLONASS) GPS receivers that were setup on the points and logged static data simultaneously. A total of four static occupations were completed. The static data was post processed in the office and referenced to existing 3D monuments in the area. All survey information was processed in 3-degree Modified Transverse Mercator (MTM) Zone 1, North American Datum 1983 (NAD83) Canadian Spatial Reference System (CSRS) projection system and Canadian Geodetic Vertical Datum 2013 (CGVD2013). The published vertical values of the monuments used were listed with the vertical datum CGVD28. Therefore, to coincide with the project requirements, the vertical datum for the points was processed to vertical datum CGVD2013. The absolute confidence levels for the data were 3mm horizontally and 2mm vertically.

Secondary control points included other provincial monuments that were not occupied for static logs. They were established and used as base reference points and helped reduce baseline distances between base and rover receivers.

Tertiary control points consisted of temporary installations of 12” spikes or 20” rebar. These were used when there were no permanent monuments near a given survey area. A total of eight tertiary points were installed for this project. Check shots were completed daily to ensure that both base and rover setups were correct and that the base was broadcasting the correct values.

A list of control points used to complete the topographic and bathymetric surveys are summarized in Table 1 and Table 2, while the locations of the Provincial control points used for this study are shown on Figure 5 and Figure 6.

TABLE 1: PROVINCIAL CONTROL POINTS

| MONUMENT NAME | NORTHING (m) | EASTING (m) | ELEVATION (m) | DESCRIPTION | CLASS | SITE |
|---|---|---|---|---|---|---|
| **82G2363** | 5236764.378 | 234792.206 | 3.522 | C. CYLINDER | PRIMARY | PLACENTIA |
| **82G2378** | 5234806.239 | 232039.480 | 0.932 | C. CYLINDER | SECONDARY | PLACENTIA |
| **81G2770** | 5290817.511 | 287967.858 | 122.549 | BRASS PLUG | PRIMARY | CARBONEAR |
| **82G2351** | 5237142.425 | 238449.552 | 14.953 | C. CYLINDER | SECONDARY | PLACENTIA |
| **82G2384** | 5232619.939 | 231481.820 | 20.948 | BRASS PLUG | SECONDARY | PLACENTIA |
| **82G2388** | 5231258.444 | 235724.923 | 6.370 | C. CYLINDER | SECONDARY | PLACENTIA |
| **81G2028** | 5287617.873 | 287175.486 | 21.652 | BRASS PLUG | PRIMARY | CARBONEAR |
| **81G2293** | 5293816.230 | 292052.119 | 27.880 | BRASS PLUG | PRIMARY | CARBONEAR |

## TABLE 2: ADDITIONAL CONTROL POINTS

| MONUMENT NAME | NORTHING (m) | EASTING (m) | ELEVATION (m) | DESCRIPTION | CLASS | SITE |
|---|---|---|---|---|---|---|
| **NE ARM 1** | 5237386.605 | 241276.915 | 6.322 | VARIES* | TERTIARY | PLACENTIA |
| **SE ARM 1** | 5231764.900 | 233847.276 | 7.988 | VARIES* | TERTIARY | PLACENTIA |
| **SE ARM 2** | 5231554.232 | 236883.629 | 31.710 | VARIES* | TERTIARY | PLACENTIA |
| **FERRY 1** | 5238563.288 | 229579.801 | 12.960 | VARIES* | TERTIARY | PLACENTIA |
| **FERRY 2** | 5238760.045 | 230331.985 | 6.988 | VARIES* | TERTIARY | PLACENTIA |
| **PLACENTIA 1** | 5239609.578 | 239296.462 | 85.862 | VARIES* | TERTIARY | PLACENTIA |
| **PLACENTIA 2** | 5241242.624 | 240316.208 | 45.925 | VARIES* | TERTIARY | PLACENTIA |
| **CARBONEAR** | 5289638.370 | 289125.207 | 83.713 | VARIES* | TERTIARY | CARBONEAR |
| **SALMON COVE** | 5293060.174 | 290352.314 | 23.410 | VARIES* | TERTIARY | CARBONEAR |
| **VICTORIA** | 5292145.024 | 286375.161 | 64.355 | VARIES* | TERTIARY | CARBONEAR |

FIGURE 5: CARBONEAR, SALMON COVE AND VICTORIA CONTROL POINTS

## FIGURE 6: PLACENTIA CONTROL POINTS

### 3.2.2 TOPOGRAPHIC AND BATHYMETRIC SURVEY

All topographic surveying was completed using Global Positioning System (GPS) Real Time Kinematics (RTK) style surveying. Stop and go kinematic occupations of three or more epochs was used for the topographic survey. Positions were collected by using real time correction with UHF radio links that communicate between the rover and the base. Daily check shots were completed on known control points at the beginning and end of each setup to ensure accuracy and reproducibility of survey data and again at the end of the day. Survey data was uploaded daily, reviewed for quality purposes, and used to determine whether there were any areas that required infill. The accuracy of all topographic points was within +/- 1.0 cm horizontal and +/- 2.0 cm vertically.

Cross sections were surveyed in compliance with the specifications documented in the RFP, specifically:

- Surveys at all locations where there can be expected changes in discharge, slope, shape, or roughness. The cross-sections included the below water portion of the channel.
- Sufficient surveyed sections obtained to adequately define representative river geometry and the interval between them should be such that the assumption of uniform flow within a section should be reasonable.
- All cross sections were photographed. Water levels and time of measurement were also recorded for each cross section.
- Sufficient points along each cross section were obtained to accurately define the geometry of the cross section.
- Surveying the river cross section extending to the full extent of the flooding of the main channel and any tributaries that are likely to experience backwater effects.
- Adequate overlap with HRDEM data, surveyed sections extended to a minimum of five meters from the river's edge on either side of the riverbank.

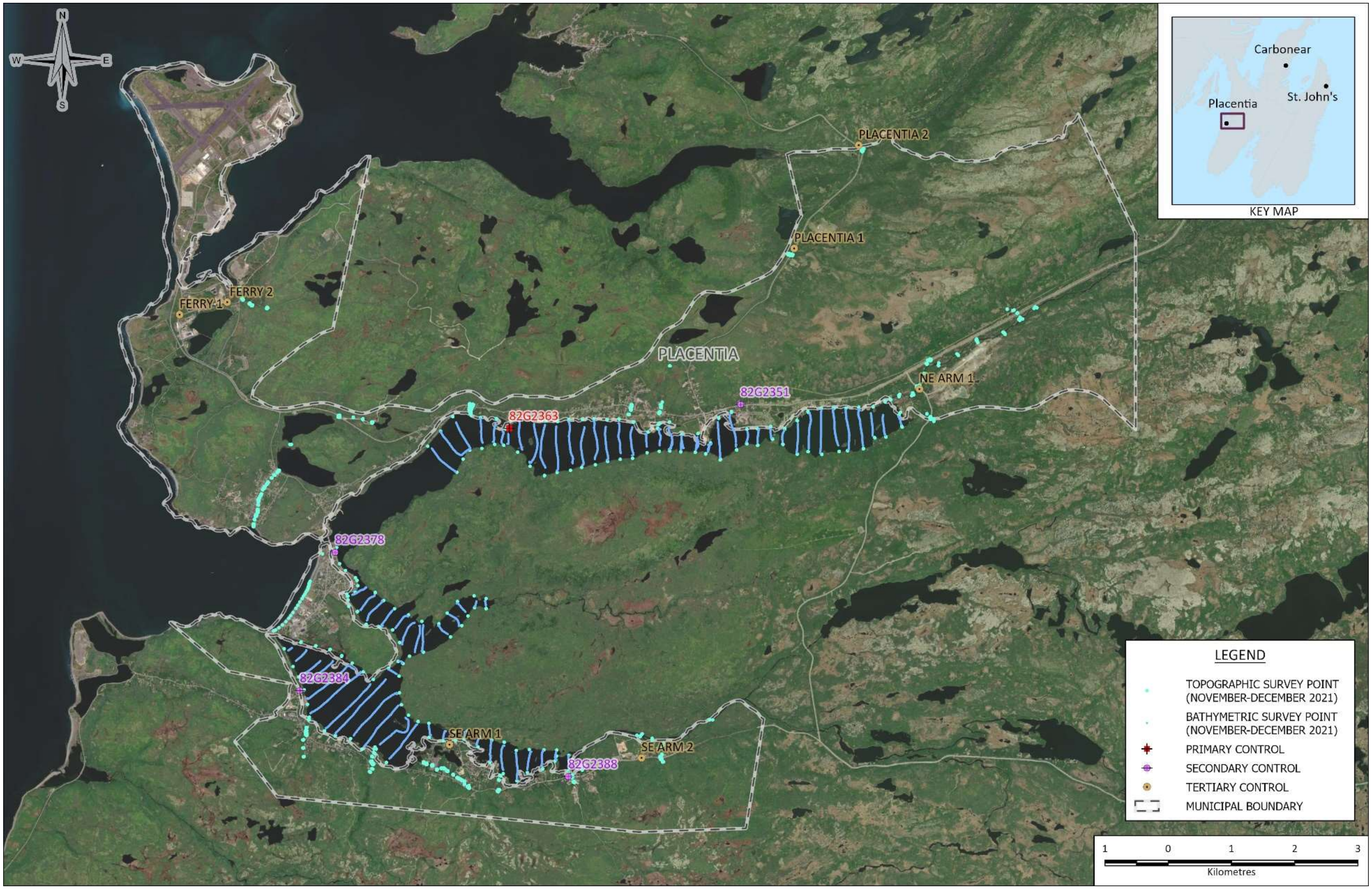
In total, 520 river cross sections were surveyed throughout Carbonear, Placentia, Salmon Cove and Victoria.

To supplement existing coastal bathymetric data, bathymetric cross sections were collected in Placentia. A total of 78 bathymetric transects were completed in Placentia along the Northeast Arm, Swan Arm, and Southeast Arm. The proposed transect locations were selected based on criteria documented in the RFP, as well as considerations for the storm surge modelling. Bathymetric data was not acquired along the western portion of Northeast Arm or into Placentia Bay, as existing bathymetric data was available from the Canadian Hydrographic Service (CHS). The bathymetric survey data points were collected at a range of every 1 m to 10 m along each transect lines using a single beam dual frequency Seafloor Hydrolite – TM Echosounder. This device can collect water depths from 0.5 m to 200 m. The sonar unit was mounted to a boat and coupled to a survey grade GPS receiver. All sonar readings were collected in a continuous manner with accurate RTK positions. When possible and safe to do so, additional RTK/GPS shots were captured along the shoreline and up the banks on both sides of the arms. These shots were completed to extend bathymetric transects into the existing HRDEM coverage and to provide more detail of existing bank geometry. Spot checks were also completed along the breakwater and sea wall in Placentia.

Manual depth checks were completed to validate the echosounder readings each day to ensure that the sonar unit was functioning correctly. As well, cross validation transect lines were collected to confirm that there was no instrument drift by collecting bathymetry sections perpendicular to the lines collected earlier in the day to validate those results were consistent.

The topographic and bathymetric survey data collected in Placentia, Carbonear, Salmon Cove, and Victoria are shown on Figure 7 and Figure 8.

## FIGURE 7: PLACENTIA BATHYMETRIC SURVEY



# FIGURE 8: CARBONEAR, SALMON COVE AND VICTORIA SURVEY

### 3.2.3 WATER SURVEY OF CANADA STATION

Surveying was completed at the Water Survey of Canada (WSC) gauge (02ZK002) to convert the local datum used by WSC to CGVD2013. Tying in the water gauge was a vital component of the flood study as the data from that gauge was used to calibrate one of the hydraulic models. The survey crew surveyed two benchmarks (NL12-010 & NL89-089) and water levels on their visits to site. The WSC gauge is located on the Northeast River (WSC 02ZK002) near Placentia, approximately 3.5km northeast of Dunville off HWY 100. The first site visit was on December 12, 2021. The crew was only able to survey one of the two benchmarks (NL12-010) as the other one was under water and could not be located due to significant precipitation. The second site visit was on December 18, 2021, once the water had receded, and crews were able to locate and tie in the second benchmark even though it was still submerged. The benchmark shots were NL89-089 (6.628m) and NL12-010 (6.117m).

### 3.2.4 SURVEY OF WATER CROSSINGS

A combined total of 100 bridge and culvert crossing sites were surveyed throughout the study area. Locations of hydraulic structures such as culverts and crossings were pre-determined from a desktop review. Based on discussions with representatives from the communities, additional culvert and bridge crossings were identified for survey as they impact the conveyance of flood flows.

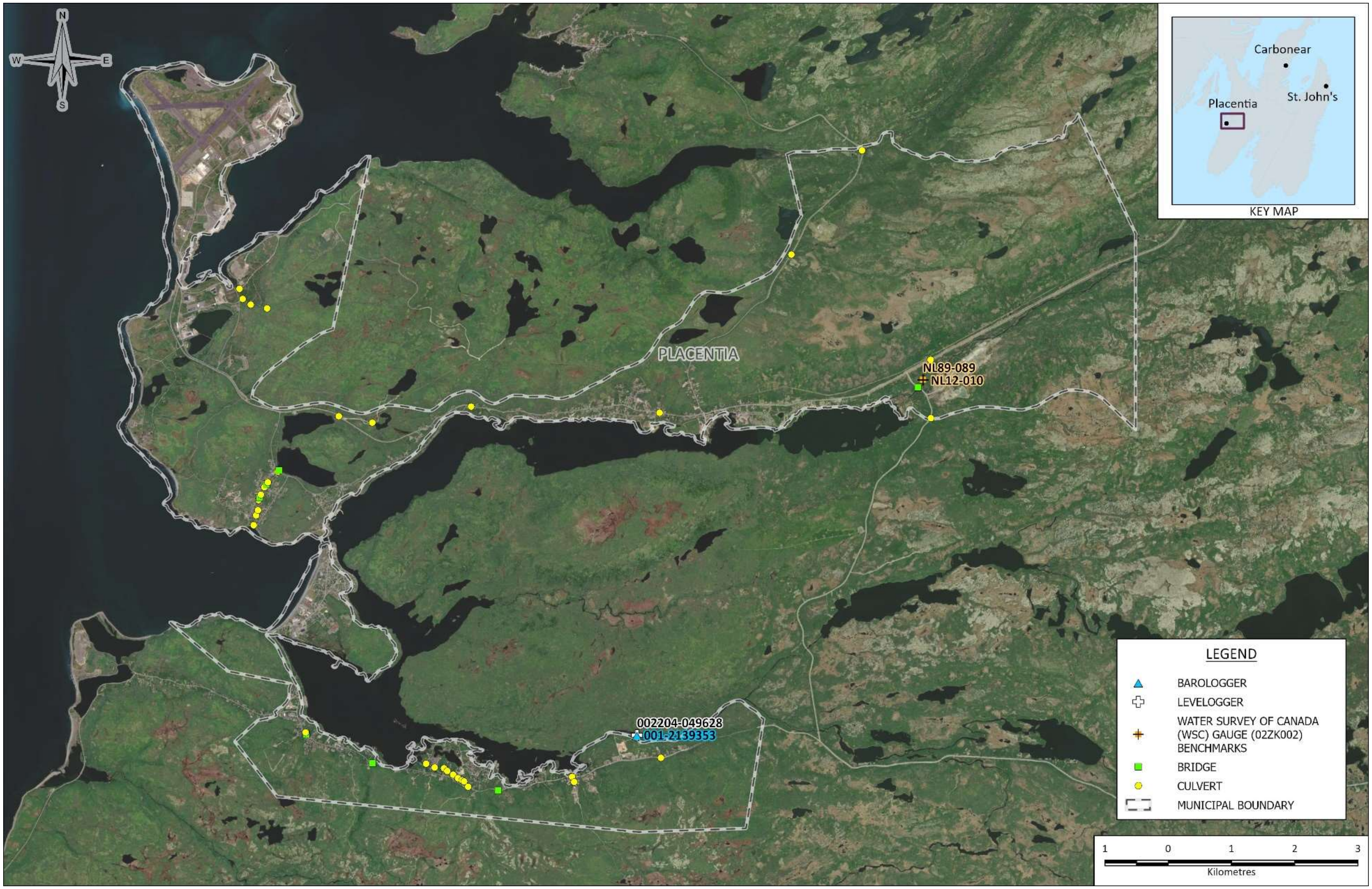
Survey of the culvert and bridge crossings included the following information:

- Location coordinates,
- Size of the structure,
- Upstream and downstream invert elevations,
- Road top elevation over the structure,
- Structure condition,
- Water level during the survey, and
- Upstream and downstream photos.

Two surveyed cross sections upstream and two downstream were obtained at all hydraulic structures. Some culvert inverts were omitted during the survey capture due to highwater and/or safety concerns by the field crews. Details of the bridge and culvert crossings collected as part of the field survey program are included in Appendix C.

The locations of the bridge and culvert crossings that were surveyed, as well as the WSC benchmarks for station 02ZK002, are shown on Figure 9 and Figure 10.

# FIGURE 9: PLACENTIA STRUCTURE SURVEY



## FIGURE 10: CARBONEAR, VICTORIA AND SALMON COVE STRUCTURE SURVEY

## 3.3 Flow and Water Level Monitoring Program

As part of the study, Solinst Levelogger 5-LT M5 water level loggers and Solinst Barologgers (i.e. atmospheric pressure) were deployed to monitor water levels at five specific locations to assist in the hydraulic model calibration. The Leveloggers and Barologger were deployed and started data collection on November 22, 2021, with the last one being deployed on November 27, 2021. The loggers were removed on December 12, 2021, and December 19, 2021. The loggers were setup to collect readings every 15 minutes during the 4-week installation period. Geodetic water elevations were surveyed at the time of installation and retrieval at each location of the water level loggers.

The Leveloggers were deployed at the following locations:

- Southeast River near Placentia
- Powells Brook near Highway 70 in Carbonear
- Island Pond Brook near Highway 70 in Carbonear
- Salmon Cove River near Highway 70 in Salmon Cove
- Salmon Cove River near Highway 70 in Victoria

As part of the water level monitoring, two barometric loggers (i.e. Barologgers) were installed to compensate for atmospheric pressure fluctuations. The Barologgers were installed at:

- Southeast River near Placentia
- Powells Brook near Highway 70 in Carbonear

The precise locations where the leveloggers and barloggers were deployed are shown on Figure 9 and Figure 10, for reference.

Once the data was retrieved from the loggers, KGS Group reviewed the data to verify the data and identify any anomalies in the data set. Geodetic water elevations were used to update the logger data to compensate for actual real-time geodetic elevations that occurred during the collection of the water level data. Once the data was compensated for real-time elevations, the recorded atmospheric pressure data was used to compensate the Levelogger data to account for atmospheric fluctuations. The resulting compensated water levels were subsequently used for calibration of the hydraulic models, and are shown on Figure 11 to Figure 15. It should be noted that an anomaly was observed in the recorded atmospheric pressure data in Carbonear, Salmon Cove and Victoria on December 10, 2021, resulting in an erroneous spike in water levels in the compensated water level data. As such, the water levels on December 10, 2021 were not used in the model calibration.

**FIGURE 11: SOUTHEAST RIVER NEAR PLACENTIA RECORDED WATER LEVELS**

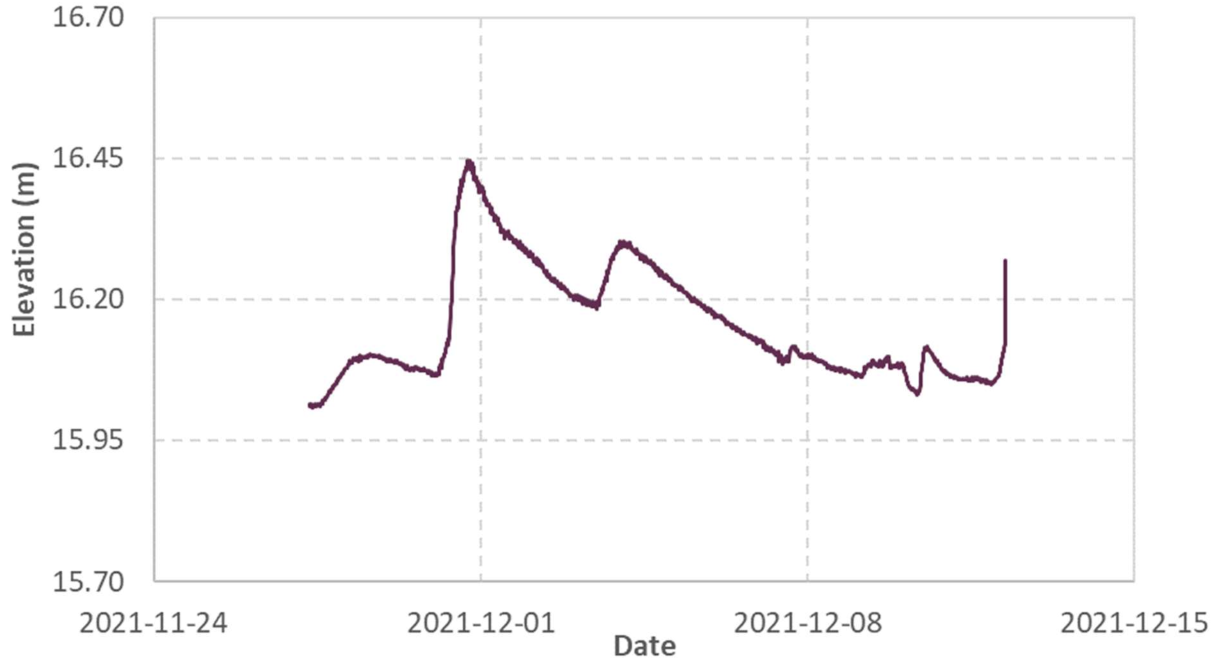
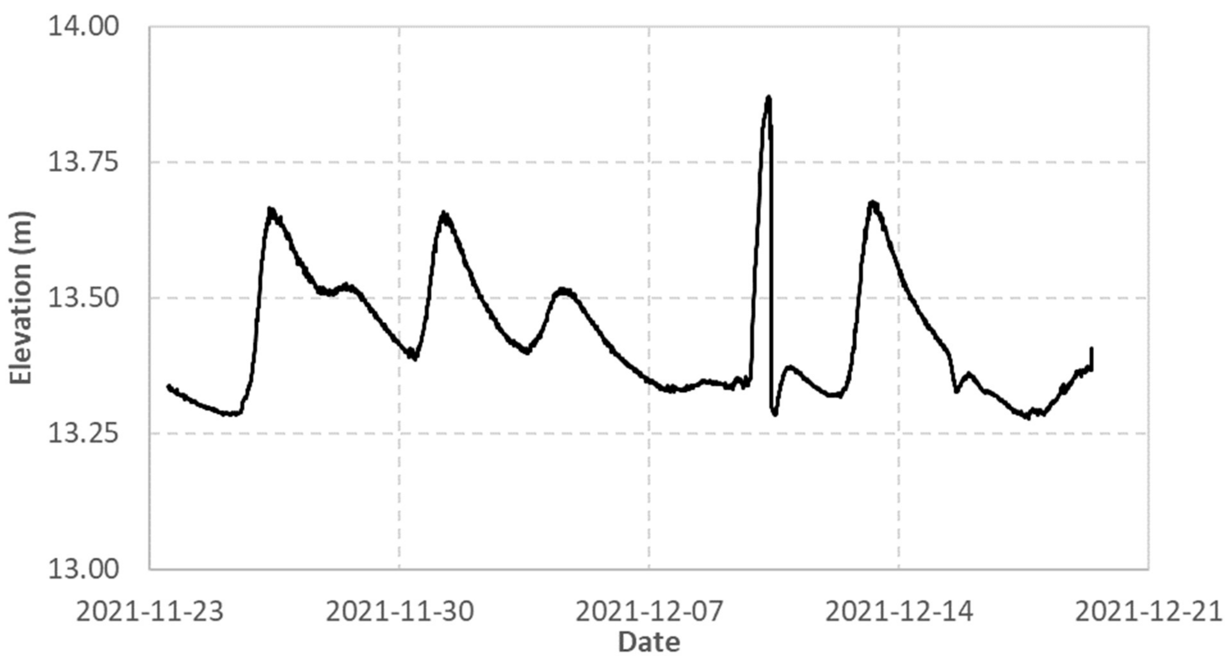
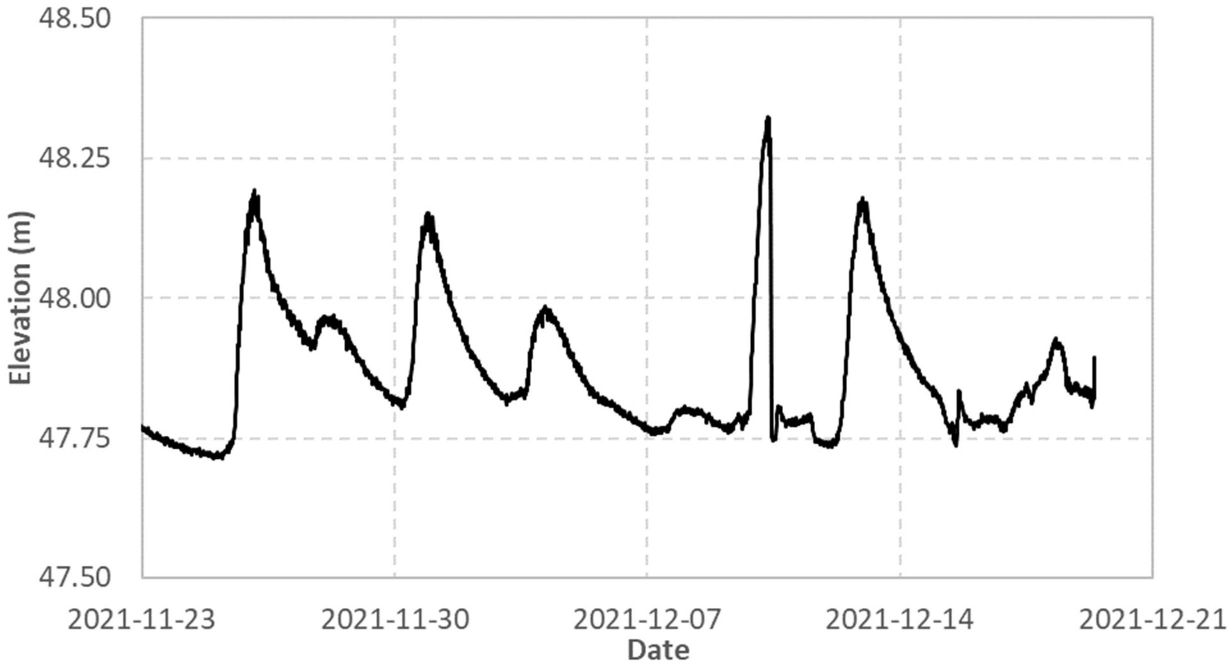



**FIGURE 12: SALMON COVE RIVER AT HIGHWAY 70 (SALMON COVE) RECORDED WATER LEVELS**



### FIGURE 13: SALMON COVE RIVER AT HIGHWAY 70 (VICTORIA) RECORDED WATER LEVELS




### FIGURE 14: ISLAND POND BROOK AT HIGHWAY 70 RECORDED WATER LEVELS

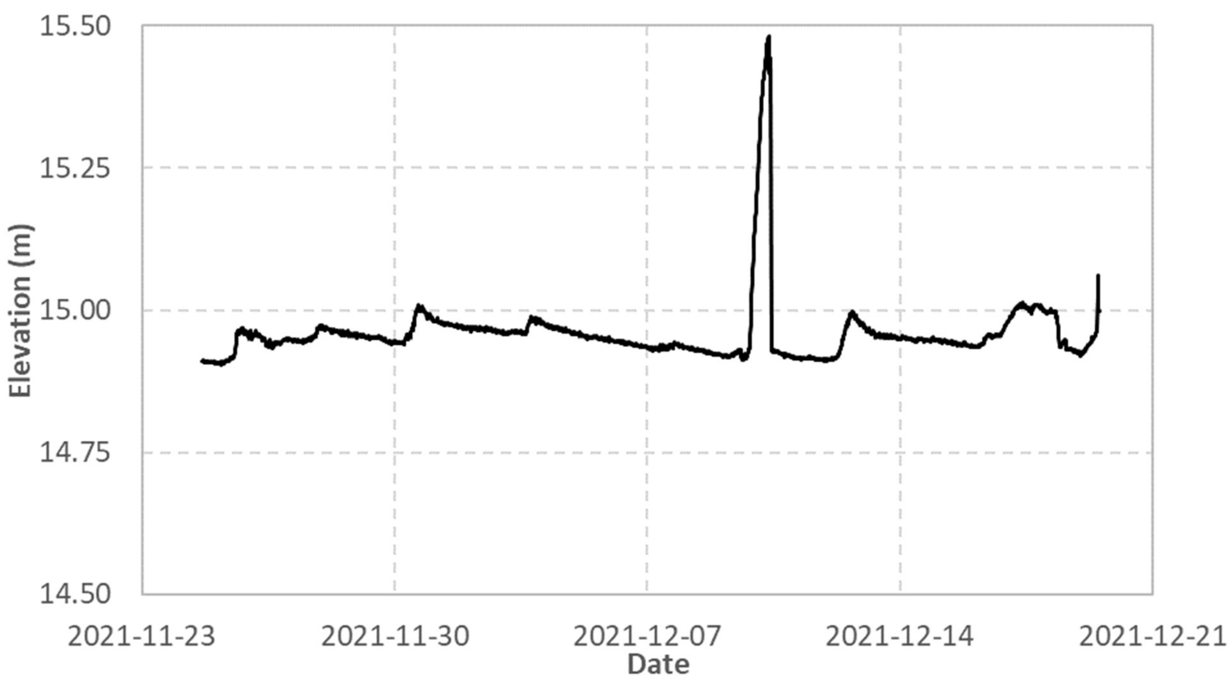
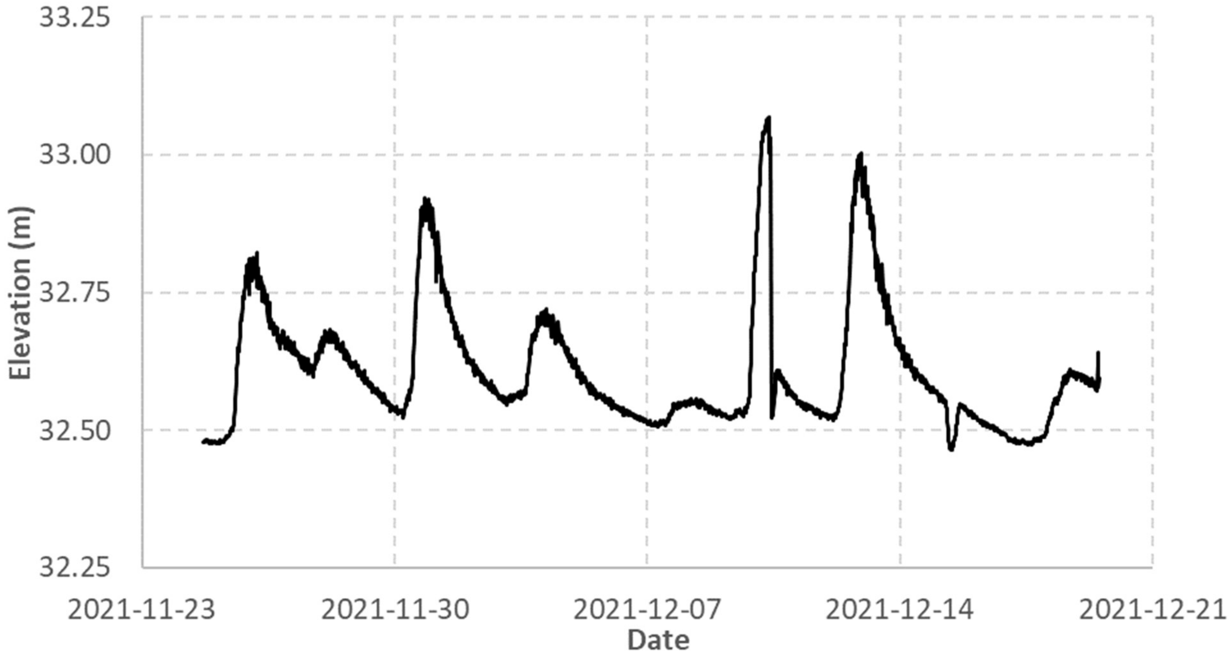


**FIGURE 15: POWELLS BROOK AT HIGHWAY 70 RECORDED WATER LEVELS**




Flow monitoring was completed on select rivers and creeks over the course of two site visits by KGS Group personnel. Specifically, flow measurements were taken on:

- Salmon Cove River at Highway 70 in Salmon Cove,
- Salmon Cove River at Highway 70 in Victoria,
- Powells Brook at Highway 70 in Carbonear,
- Island Pond Brook at Highway 70 in Carbonear,
- Southeast River at Long Hill Road in Placentia,
- The creek flowing through Freshwater at Kelly's Lane in Placentia, and
- Smelt Brook at Highway 91 in Placentia.

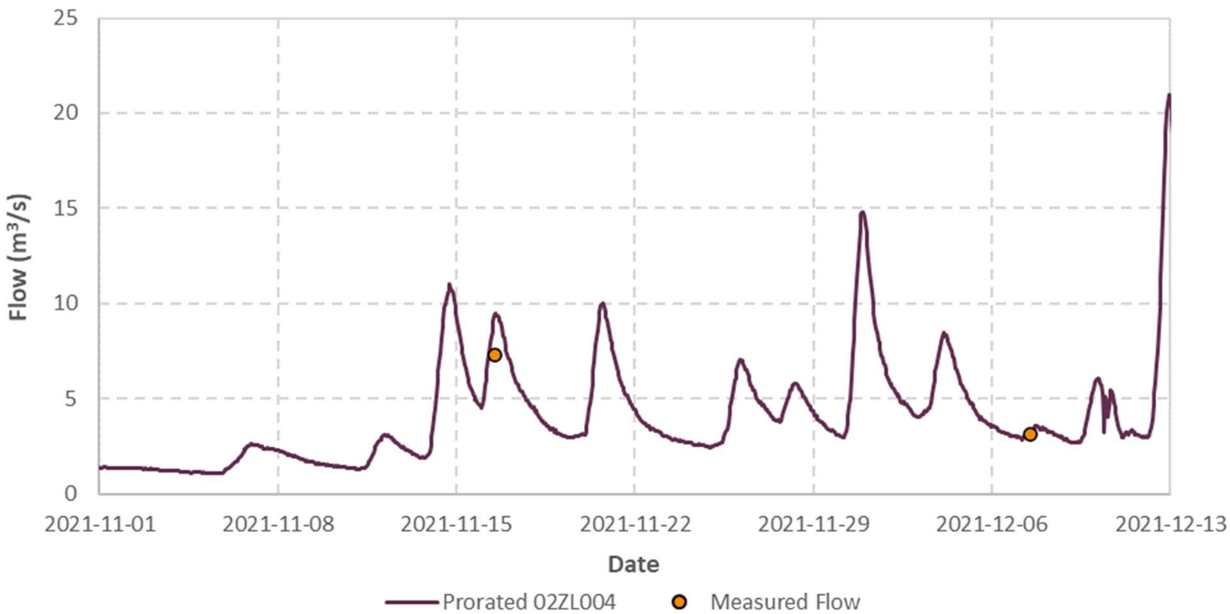
The two flow measurement trips took place between November 15 and 18, 2021, and December 6 and 9, 2021. Flows were measured using either a Teledyne River Ray 600 kHz Acoustic Doppler Current Profiler (ADCP) or a Sontek FlowTracker Acoustic Doppler Velocimeter (ADV), depending on flow conditions at each site. Flow measurements are completed by recording the flow velocity passing through a given cross section at a single point in time, and when combined with the below-water flow area, provides an estimate of the flow rate at the time of the measurement. The flow measurements are summarized in Table 3.

### TABLE 3: SUMMARY OF FLOW MEASUREMENTS

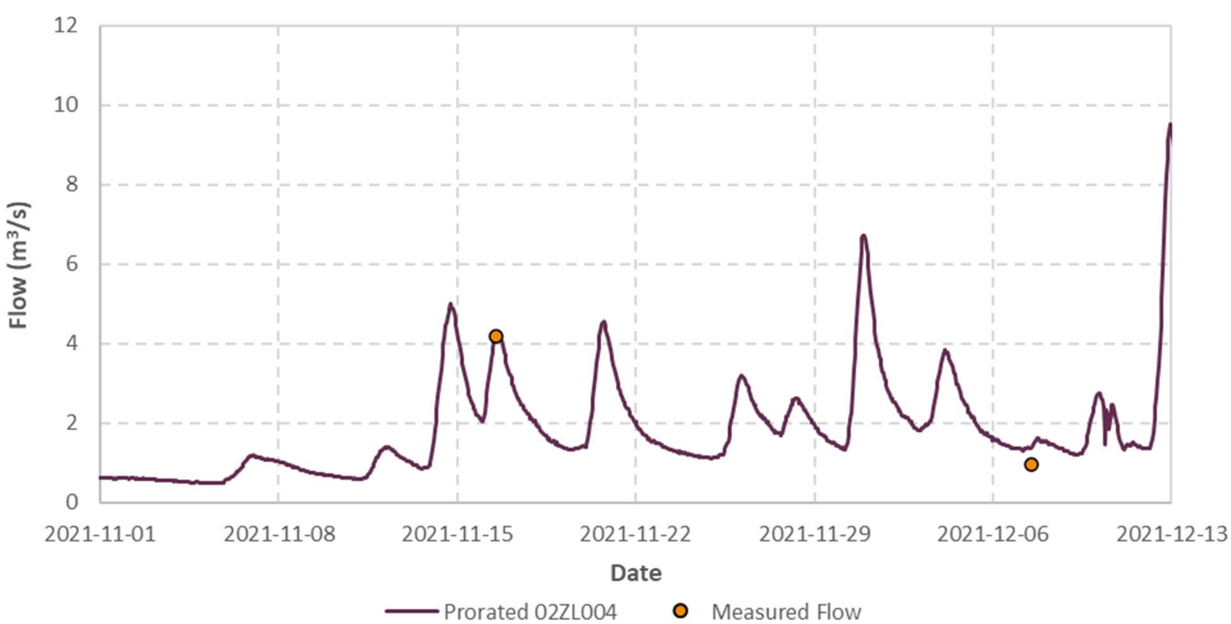
| Location | Nov. 15 – 18 Flow ($m^3/s$) | Dec. 6 – 9 Flow ($m^3/s$) |
|---|---|---|
| Salmon Cove River at Highway 70 (Salmon Cove) | 7.3 | 3.1 |
| Salmon Cove River at Highway 70 (Victoria) | 4.2 | 1.0 |
| Powells Brook at Highway 70 | 0.9 | 0.2 |
| Island Pond Brook at Highway 70 | 3.0 | 1.8 |
| Southeast River at Long Hill Road | 8.5 | 2.8 |
| Freshwater local creek at Kelly's Lane | 0.1 | 0.1 |
| Smelt Brook at Highway 91 | 0.6 | 0.2 |

The flow metering data was used to evaluate the relative accuracy of prorated flows from nearby gauged rivers to the ungauged rivers being considered in the study area. As well, the flow measurement on Smelt Brook was used to estimate the portion of flow from Glennon's Cove River that is conveyed into Smelt Brook from the river bifurcation south of Placentia. Based on prorated flows from the Northeast River gauge and the measured flow on Smelt Brook, it is estimated that approximately 25% of the flow from Glennon's Cove River upstream of the bifurcation is conveyed to Smelt Brook, with the remaining 75% being conveyed on Glennon's Cove River to the ocean. Comparisons of the prorated gauged flows to the measured flows, including the 25% contribution from Glennon's Cove River to Smelt Brook, are shown on Figure 16 to Figure 22.

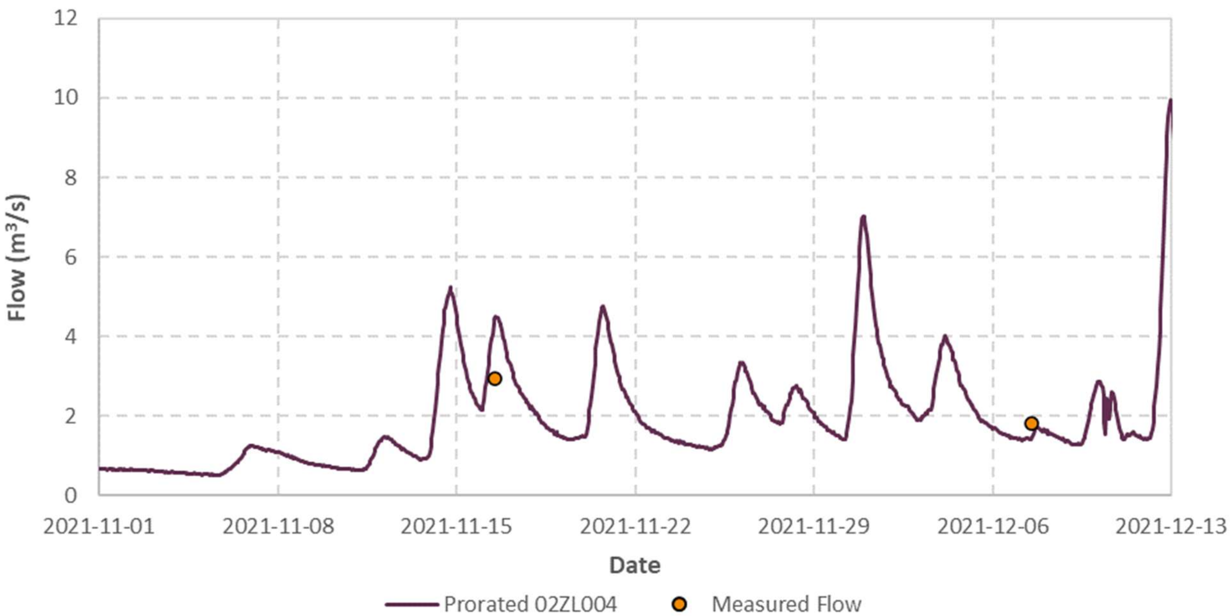
### FIGURE 16: COMPARISON OF PRORATED AND MEASURED SALMON COVE RIVER FLOWS AT HIGHWAY 70 (SALMON COVE)




### FIGURE 17: COMPARISON OF PRORATED AND MEASURED SALMON COVE RIVER FLOWS AT HIGHWAY 70 (VICTORIA)



### FIGURE 18: COMPARISON OF PRORATED AND MEASURED ISLAND POND BROOK FLOWS AT HIGHWAY 70




### FIGURE 19: COMPARISON OF PRORATED AND MEASURED POWELLS BROOK FLOWS AT HIGHWAY 70

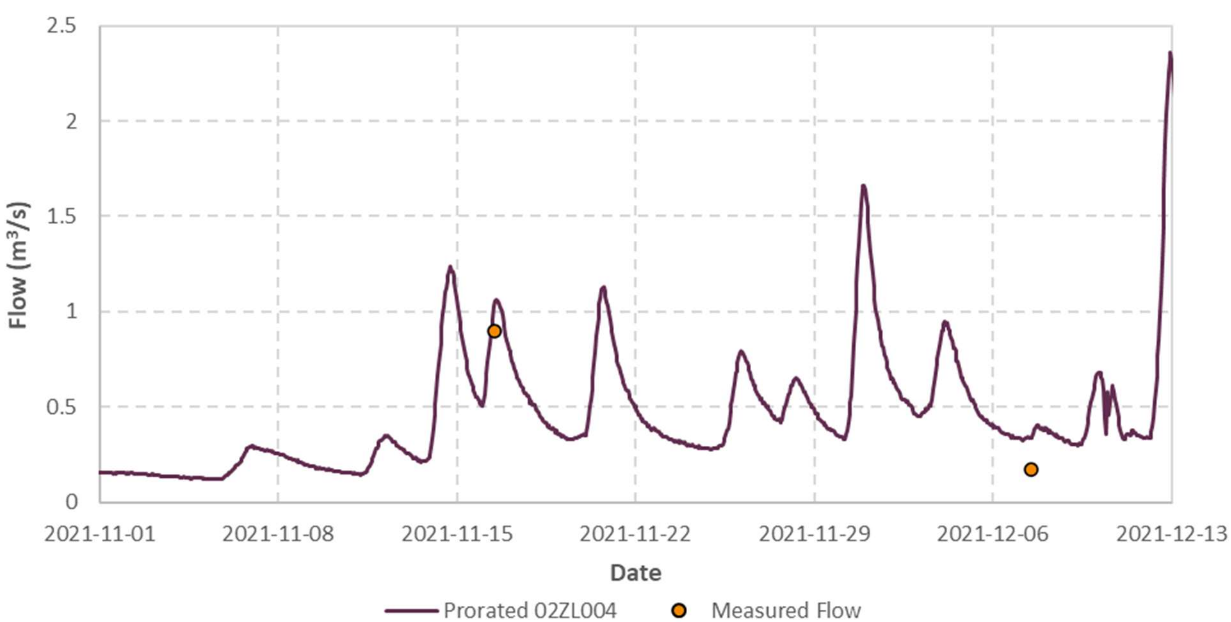


FIGURE 20: COMPARISON OF PRORATED AND MEASURED SOUTHEAST RIVER FLOW AT LONG HILL ROAD

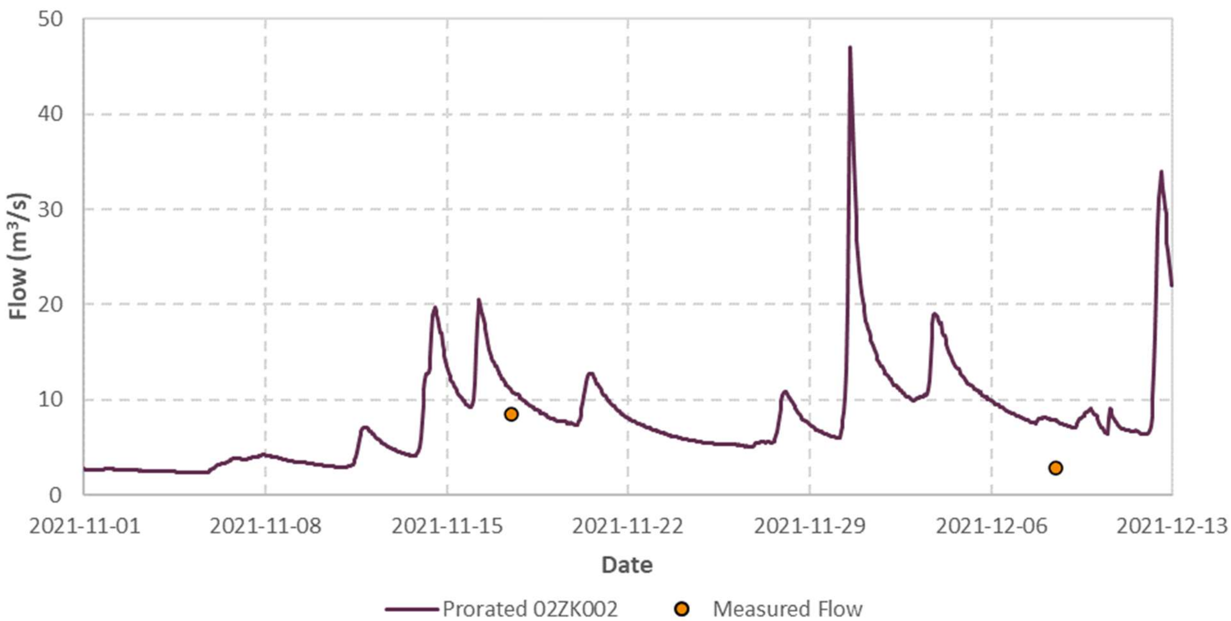



FIGURE 21: COMPARISON OF PRORATED AND MEASURED FRESHWATER LOCAL CREEK FLOW AT KELLY'S LANE

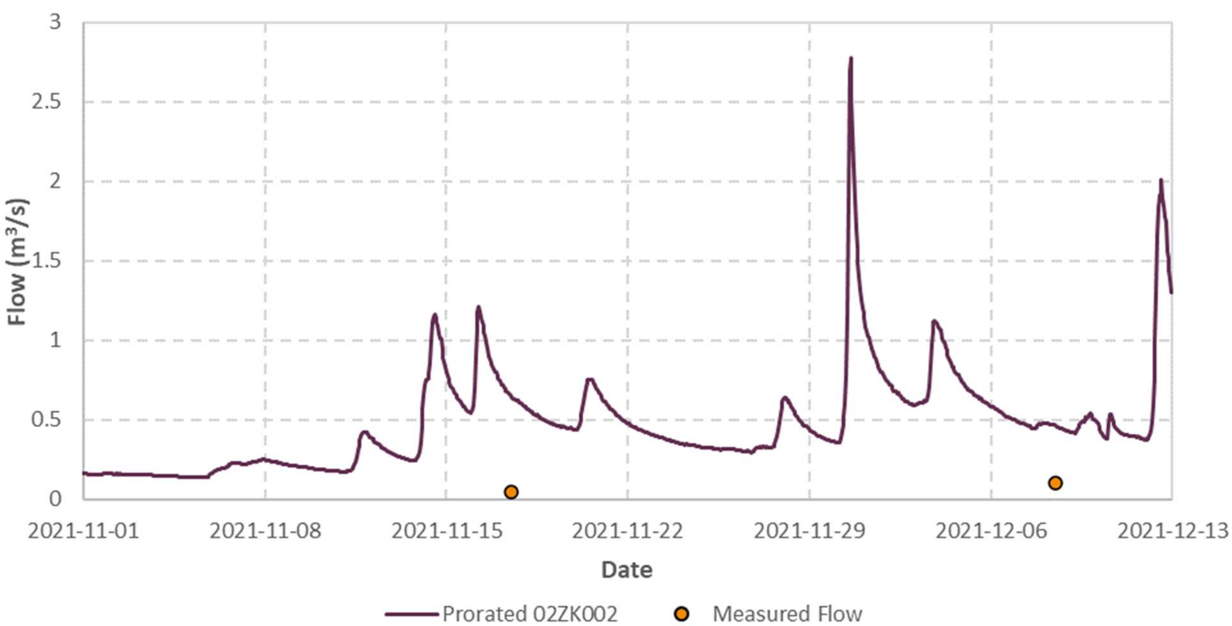
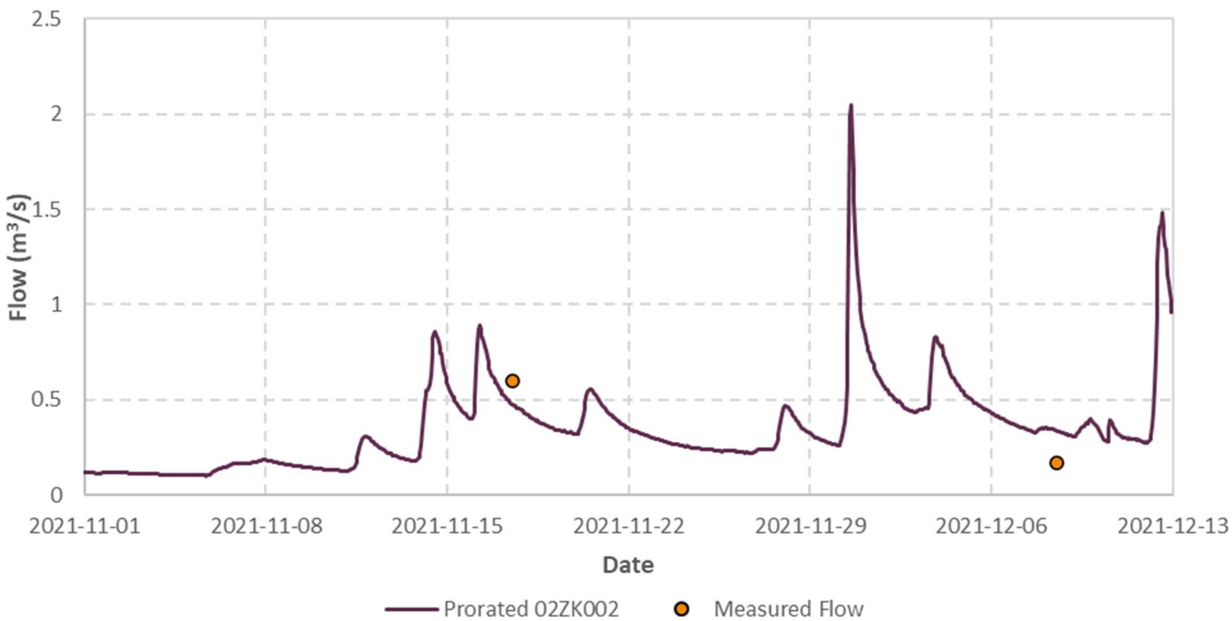


FIGURE 22: COMPARISON OF PRORATED AND MEASURED SMELT BROOK FLOWS AT HIGHWAY 91




The comparison of prorated and measured flows generally showed good agreement, with the exception of the local creek in Freshwater (Figure 21). However, flows on that creek may have been attenuated by Clarkes Pond and Larkins Pond that is not accounted for in the prorated flows. Given the good agreement between the prorated flows on Smelt Brook that include a 25% contribution from Glennon's Cove River, a 25% contribution of flow from Glennon's Cove River upstream of the bifurcation was assumed and included in subsequent hydraulic analyses.

## 3.4 HRDEM Quality Control

KGS Group obtained a digital elevation model (DEM) from the Federal government for the project area. The DEM is a 1 m grid and is the primary data source for all topography data and hydraulic modelling. NEPSL collected GPS/RTK survey data that was used by KGS Group to validate and confirm the accuracy of the DEM. This survey data was compared to the HRDEM at the same location to ascertain the vertical accuracy of the HRDEM. Comparisons were made at 1,475 locations in Carbonear, Salmon Cove and Victoria, with 36 locations located on firm or flat ground (i.e. at bridge and culvert crossings) and the remaining 1,439 located in vegetated areas (i.e. ground and bank shots at surveyed cross section locations). In Placentia, comparisons were made at 1,149 locations, with 58 of those located on flat and firm ground and the remaining 1,091 located in vegetated areas. The results fell within acceptable tolerances of 0.2 m for hard surface returns and 0.5 m for the remaining data set respectively. The results are summarized in Table 4.

TABLE 4: HRDEM SURFACE STATISTICS

| Monument Name | Count | Minimum Difference (m) | Maximum Difference (m) | Sum of Differences (m) | Mean Difference (m) | Standard Deviation of Differences (m) |
|---|---|---|---|---|---|---|
| Carbonear Firm/Flat Ground Stats. | 36 | -0.195 | 0.199 | 0.804 | 0.022 | 0.081 |
| Carbonear Remaining Ground Stats. | 1439 | -0.483 | 0.493 | -14.841 | -0.010 | 0.133 |
| Placentia Firm/Flat Ground Stats. | 58 | -0.160 | 0.187 | -0.185 | -0.003 | 0.068 |
| Placentia Remaining Ground Stats. | 1091 | -0.499 | 0.479 | -49.099 | -0.045 | 0.169 |

The validation of the LiDAR data is also described in our separate LiDAR Validation Report, which is included in Appendix D.

## 3.5 Field Verification

The DEM and flood risk maps were verified based on a combination of input from representatives from the Towns of Placentia, Carbonear, Salmon Cove and Victoria, as described in Section 2.4, and the various field survey points that were collected to evaluate the accuracy of the HRDEM data, as described in Section 3.4. Very good agreement was noted between the flood maps and historical flooding by the representatives of the Towns. Similarly, there was very good agreement between the field survey points and HRDEM. Accordingly, the DEM and subsequent flood maps were found to be free of anomalies, deviations, or obvious issues.

# 4.0 AERIAL PHOTOGRAPHY AND DIGITAL ELEVATION MODEL DEVELOPMENT

## 4.1 Overview

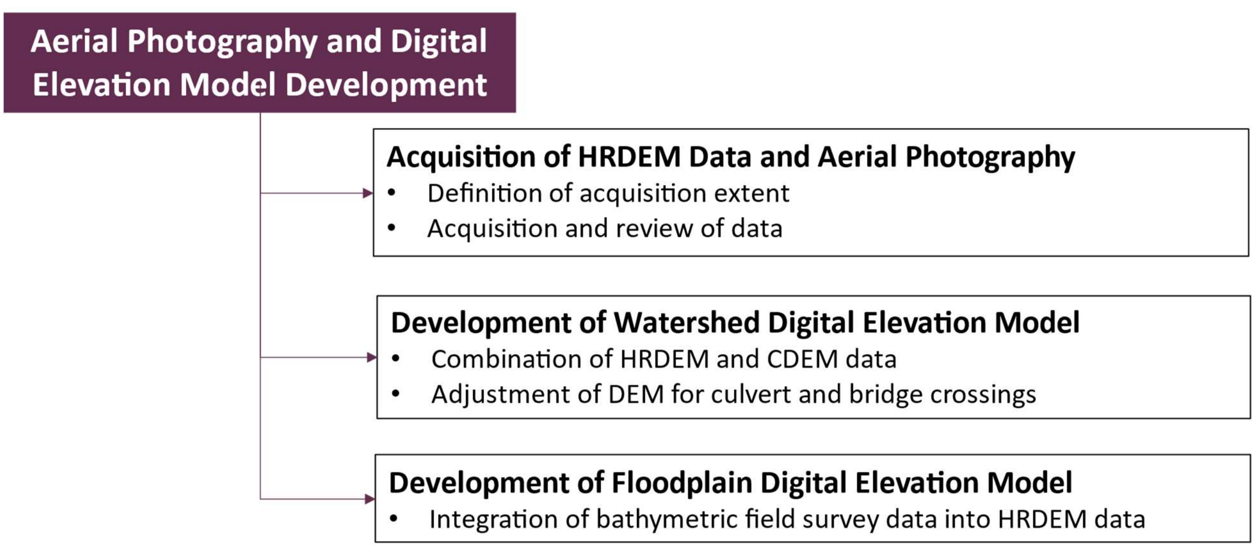
Existing aerial photography data was acquired from the Government of Newfoundland and Labrador, while an existing high-resolution model representing the above-water ground surface was acquired from Natural Resources Canada (NRCan), known as the High Resolution Digital Elevation Model (HRDEM). The HRDEM data acquired from NRCan is used to represent the ground surface elevation throughout the study area, while the aerial imagery acquired from the Government of Newfoundland and Labrador is used as a high-resolution imagery background in the flood risk and flood hazard maps.

The HRDEM data, in combination with below-water survey information, was used to make a ground elevation model of both the above and below-water ground surface throughout the study areas. This ground elevation model was then used to define the physical characteristics for the hydraulic models, and served as the ground surface representation in the development of the flood risk and flood hazard maps.

In addition to the ground elevation model used for the hydraulic model and flood mapping, a larger scale ground elevation model was built based on a combination of the HRDEM data and lower resolution data, known as the Canadian Digital Elevation Model (CDEM), also developed by NRCan. This information was used to represent the physical characteristics for the hydrologic models of the watersheds used to estimate the flows on the various rivers evaluated as part of this study.

The tasks completed as part of the Aerial Photography and Digital Elevation Model Development are shown on Figure 23.

FIGURE 23: OVERVIEW OF AERIAL PHOTOGRAPHY AND DEM DEVELOPMENT



## 4.2 Acquisition of HRDEM Data and Aerial Photography

Existing orthophotography was acquired from the Government of Newfoundland and Labrador throughout the study areas of interest. The orthoimagery data available from the Government of Newfoundland and Labrador was provided as a set of imagery tiles that consisted of mosaicked orthorectified aerial photos. The acquisition area for the orthoimagery was set to extend beyond the drainage basins for the rivers and creeks being considered in the study to ensure that there was adequate imagery cover.

An initial review of the orthoimagery showed that in Carbonear, Salmon Cove and Victoria, the imagery was generally well colour balanced and consistent. However, in Placentia, some tiles required further colour balancing to ensure a consistent backdrop for the flood maps.

HRDEM data was similarly acquired from NRCan throughout the study area. HRDEM is derived from Light Detection and Ranging (LiDAR) data and includes both Digital Terrain Models (DTM), which represents the bare ground without any plants and buildings, and Digital Surface Models (DSM), which includes all objects on the ground surface. For this project, the DTM was acquired for use in the development of the models and maps. The LiDAR data that the HRDEM is based on was collected during June and July 2020. The resulting HRDEM has a spatial resolution of 1 m by 1 m. The HRDEM data is provided by NRCan in the UTM NAD83 (CSRS) coordinate system and CGVD2013 vertical datum. For this flood risk mapping study, the HRDEM data was reprojected into the NAD83 (CSRS) MTM Zone 1 coordinate system, consistent with project requirements.

Quality control of the HRDEM data was completed by comparing HRDEM ground elevations with corresponding ground elevations captured as part of the field survey, as described in Section 3.4. As noted in that section, the HRDEM data was found to be appropriate for use in the flood risk mapping study.

## 4.3 Development of Watershed Digital Elevation Model

Two DEMs of the various watersheds considered as part of the study were developed. These DEMs were used to assist in the development of the hydrologic models in HEC-HMS, and to define various model components and parameters, including the definition of sub-basins, sub-basin slopes, and sub-basin lengths.

The DEMs were developed based on a combination of the HRDEM data described in Section 4.2, and the Canadian Digital Elevation Model (CDEM). The CDEM was developed by NRCan 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 CDED provides elevations at 5 m intervals, resulting elevations in the DEM being interpolated in between the 5 m elevation intervals from the CDED dataset. The CDEM is provided by NRCan in the UTM NAD83 (CSRS) coordinate system, and the CGVD28 vertical datum. Accordingly, the CDEM data was reprojected to the NAD83 (CSRS) coordinate system and corrected to the CGVD 2013 vertical datum based on the difference between CGVD2013 and CGVD28 at a number of control points throughout the study area. The vertical datum differences at each control point were interpolated to generate continuous surfaces representative of the differences between the CGVD28 and CGVD2013 datums throughout the study areas, which were then applied to the CDEM data to convert it to the CGVD2013 datum.

Since the watershed DEMs were going to be used in the development of the hydrologic models, it was crucial that hydrologic connectivity be defined along the waterways of interest to ensure that the basin extents were correctly delineated. In support of this, modifications were made throughout the DEMs to cut through road and railway embankments crossing the waterways.

The watershed DEMs developed for the Carbonear and Placentia areas are shown on Figure 24 and Figure 25. The footprints of the HRDEM data are shown in the black hatched areas, with the remaining data being defined by the CDEM.

## FIGURE 24: CARBONEAR AREA WATERSHED DEM

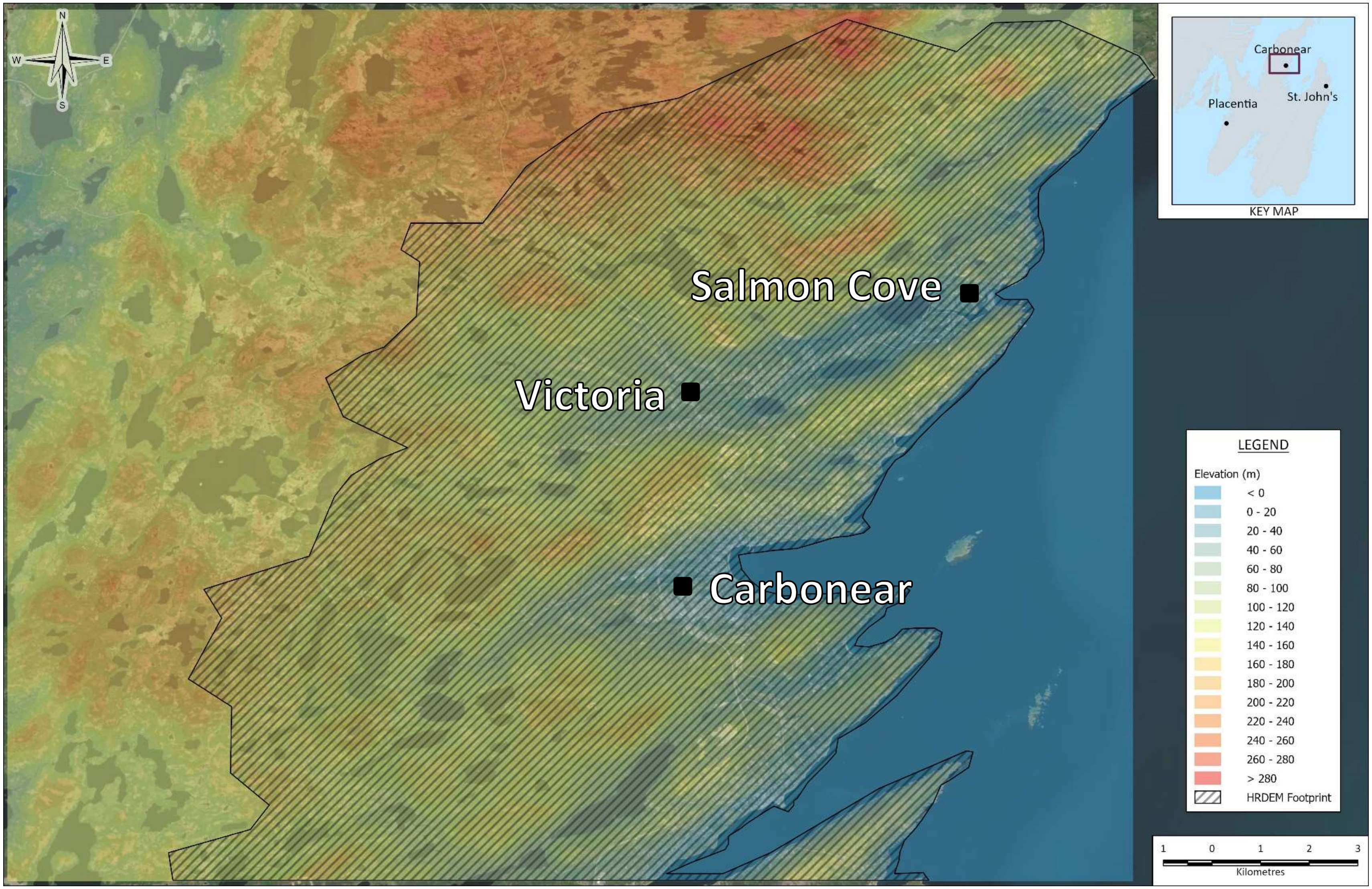
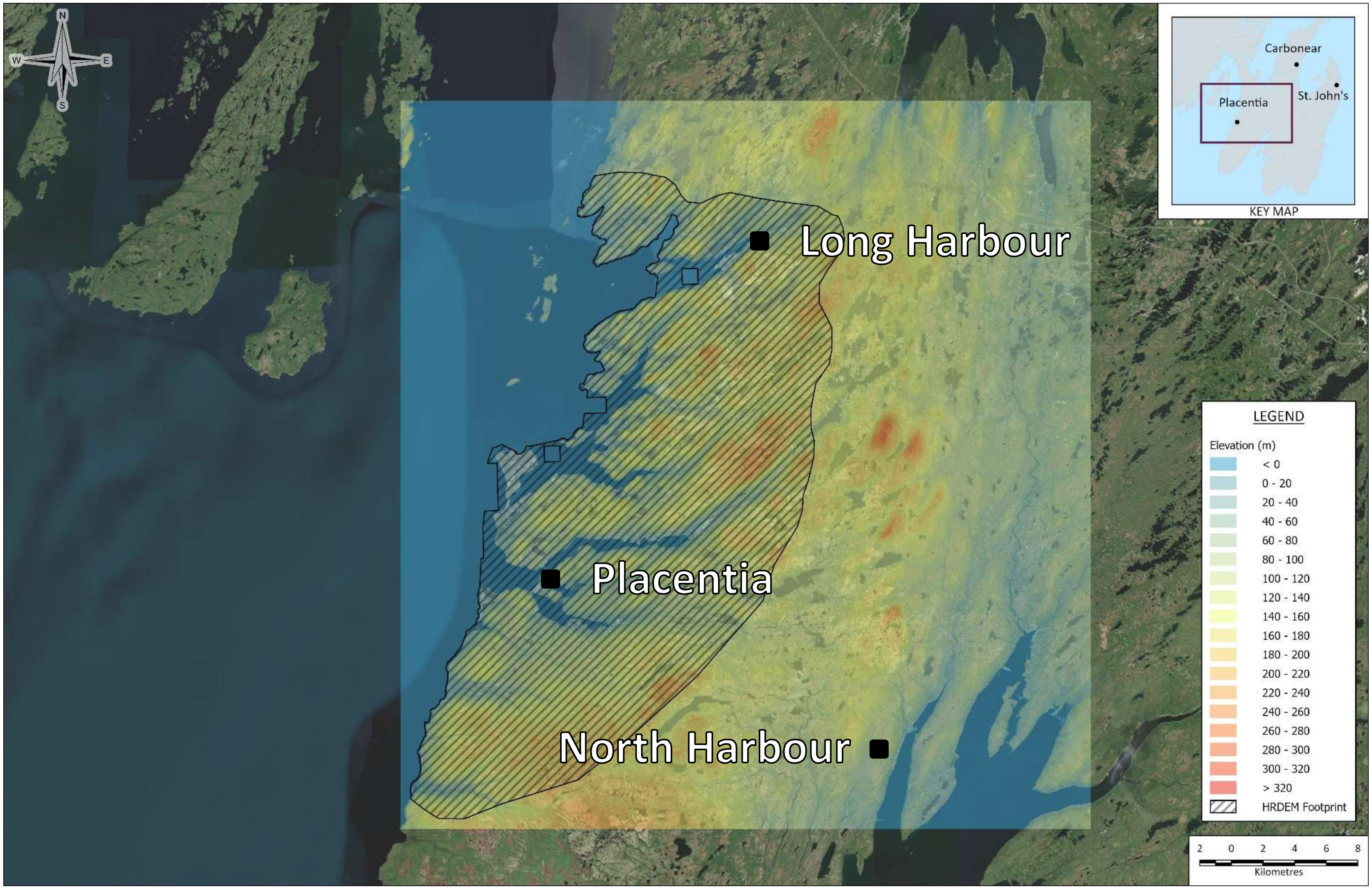


FIGURE 25: PLACENTIA AREA WATERSHED DEM



## 4.4 Development of Flood Plain Digital Elevation Model

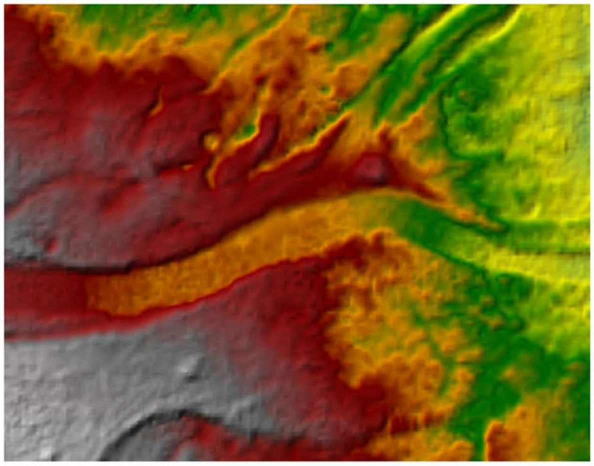
The flood plain DEMs that served as the basis for the hydraulic models and the subsequent flood maps were developed based on a combination of the surveyed bathymetry data and the HRDEM data that was acquired for this study. The HRDEM provided a representation of the above-water ground surface throughout the study area, but provided no information below the water surface that was present in the DEM. Coastal and riverine bathymetry were integrated into the HRDEM data to define the flood plain DEM based on different methodologies due to the different resolution of the data that was available for each aspect.

The coastal bathymetry through the Northeast Arm, Swan Arm, and Southeast Arm in Placentia was developed using interpolated breaklines that were created to help define the bathymetry between the surveyed bathymetric cross sections. 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. Nearshore breaklines were then created to help establish proper slopes along the shoreline. The shoreline breaklines defined based on the LiDAR data helped seamlessly merge the coastal bathymetry DEM into the HRDEM to infill the below-water portion of the HRDEM in Placentia, representative of 2021 conditions.

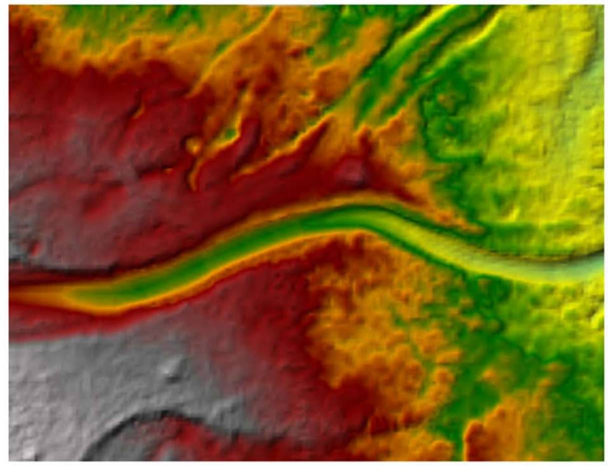
Riverine bathymetry was defined based on a combination of field survey data, HRDEM data, aerial imagery and observations from the field survey crew. River channel inverts were estimated by calculating the depth between the water surface elevation apparent in the HRDEM data and the surveyed channel invert at surveyed cross section locations. This calculated depth was then interpolated between cross section locations along the river centreline, resulting in continuous estimates of the river invert elevations throughout the study area for all the rivers and creeks considered in the study.

Polygons delineating the approximate extent of the water surface in the HRDEM were developed to identify the required extents of the bathymetric DEMs. The water surface polygons were then used in combination with the continuous estimated channel invert and interpolated breaklines to define bathymetric DEMs for each of the rivers, which were then merged seamlessly with the HRDEM data to infill the below-water portion of the HRDEMs in the Placentia and Carbonear areas. An example of this infilling is shown on Figure 26, while the bare earth DEMs for the Carbonear Area and Placentia Area are shown on Figure 27 and Figure 28.

## FIGURE 26: EXAMPLE OF BATHYMETRIC INFILLING



HRDEM



Bare Earth

## FIGURE 27: CARBONEAR AREA BARE EARTH DEM

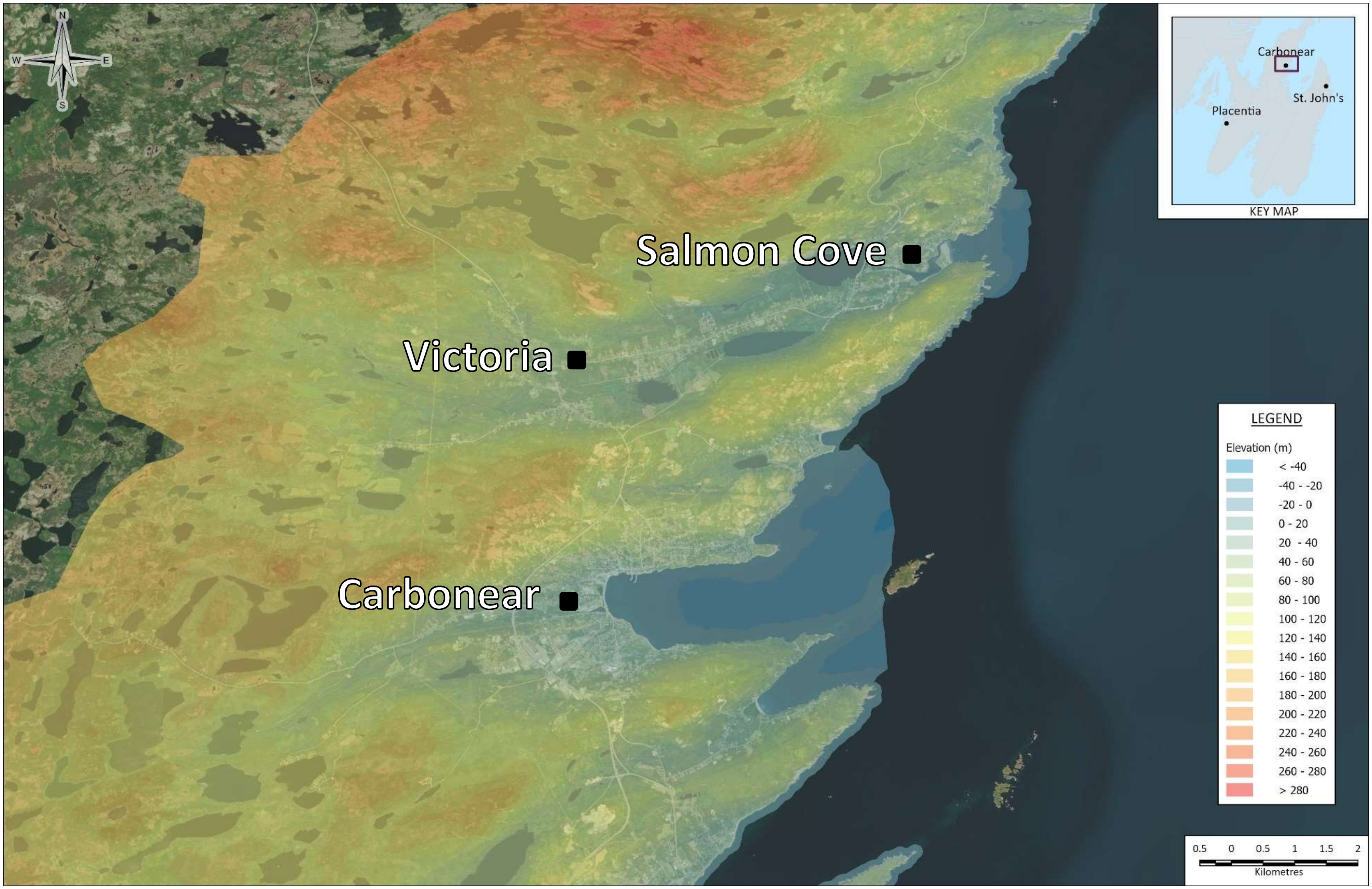
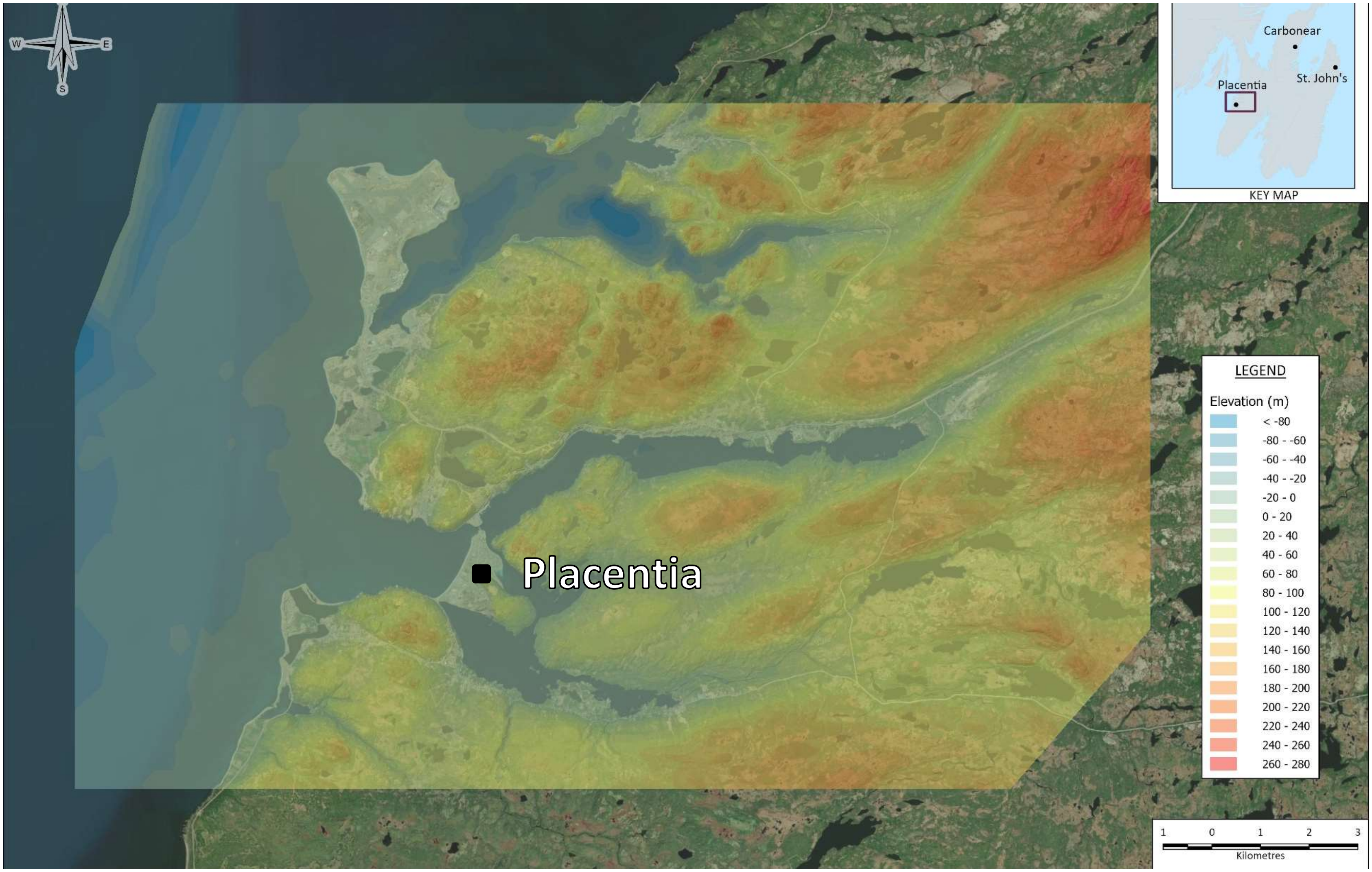


FIGURE 28: PLACENTIA AREA BARE EARTH DEM



# 5.0 REMOTE SENSING AND LAND USE CLASSIFICATION

## 5.1 Overview

Land use throughout the study areas was classified using high resolution satellite imagery collected by the European Space Agency's (ESA) SPOT-6 satellites. The SPOT-6 satellites collect images using different sensors to capture different portions of the light spectrum, and capture high resolution imagery over large swaths of land. The imagery that was used to classify the land use within the study area was from August 10 and 16, 2020.

The land use of the satellite imagery within the study area was classified using a supervised, automated process using GIS software. As part of the classification, training datasets were prepared by KGS Group personnel. The automated process used the training datasets to automatically classify different land uses throughout the full SPOT-6 imagery data. Maps showing the land use classification in Placentia, Carbonear, Salmon Cove and Victoria were developed.

Soil classification data were acquired from the National Soils Database (NSDB) developed by the Government of Canada. Soils data was acquired across the Avalon Peninsula, and was converted from the soil types defined by the Government of Canada to a different classification scheme used in hydrologic modelling. Maps of the soil classifications were developed.

The final land use classification and soils classification data were used to define separate maps 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. These maps of Curve Numbers were used in the hydrologic modelling to model how rainfall is translated to flow within a river basin.

The tasks completed as part of the remote sensing and land use classification task are summarized on Figure 29.

FIGURE 29: OVERVIEW OF REMOTE SENSING AND LAND USE CLASSIFICATION

**Remote Sensing and Land Use Classification**

- **Acquisition and Processing of Remote Sensing Imagery**
  - Collection of ESA SPOT-6 satellite imagery
  - Processing of imagery
- **Land Use Classification**
  - Supervised automated classification
  - Review and adjustment of classification
- **Soils Classification**
  - Acquisition of Canadian Soil Database soil classification data
  - Conversion of soils classification to NRCS soil types
- **Curve Number Mapping**
  - Integration of land use and soils classification to define Curve Number maps

## 5.2 Acquisition and Processing of Remote Sensing Imagery

SPOT-6 satellite imagery was downloaded from the European Space Agency (ESA), specifically captures of the Carbonear, Salmon Cove and Victoria area completed on August 10, 2020, and the Placentia area capture completed on August 16, 2020. The SPOT-6 imagery target acquisition area extended 1.5 km beyond the drainage basins defined for the study to ensure that no gaps would be present for the development of the Curve Number maps.

The SPOT-6 satellite captures a 60 km swath per suite of sensors. Using both identical suites of sensors, the SPOT-6 satellite is capable of capturing data at up to 1.5 m spatial resolution for panchromatic and multispectral imagery. The SPOT-6 satellite completes an orbit approximately every 98 m, resulting in a repeating capture cycle every 26 days. The spectral bands that SPOT-6 captures are summarized in Table 5.

TABLE 5: SPOT-6 BAND WAVELENGTHS

| Band | Wavelength (µm) |
|---|---|
| Panchromatic | 0.45 – 0.75 |
| Blue | 0.45 – 0.52 |
| Green | 0.53 – 0.60 |
| Red | 0.62 – 0.69 |
| Near Infrared | 0.76 – 0.89 |

Considerable processing is completed by ESA to correct radiometric and sensor distortions, including optical and instrument distortions and atmospheric effects. Since each of the Carbonear, Salmon Cove, Victoria and Placentia area captures were completed during one pass, corrections were not required for temporal effects that would otherwise be required if captures from separate dates were to be used.

The SPOT-6 imagery was provided to KGS Group as two tiles covering the acquisition areas (i.e. one tile covering Placentia, and one tile covering Carbonear, Salmon Cove and Victoria). A review was completed to ensure that the SPOT-6 imagery aligned well with the Digital Elevation Model (DEM) that was used in the study, as well as the orthoimagery data. The review included a visual comparison of the orthoimagery and SPOT-6 satellite imagery, as well as visual comparisons of topographic features that were apparent in both the SPOT-6 imagery and DEM, such as roads and waterbodies. The SPOT-6 satellite imagery was found to be in good agreement with the DEM and orthoimagery.

The acquisition and processing of the remote sensing imagery is described separately in our Remote Sensing Report, which is provided for reference in Appendix E.

## 5.3 Land Use Classification

Land use classification of the SPOT-6 imagery was completed using the Land Class Wizard tool in ArcGIS Pro developed by Esri. The Land Class Wizard tool automatically splits the SPOT-6 imagery into a large number of discrete classification polygons. These classification polygons are then manually assigned to the land use classes defined by WRMD in the terms of reference, which are summarized in Table 6.

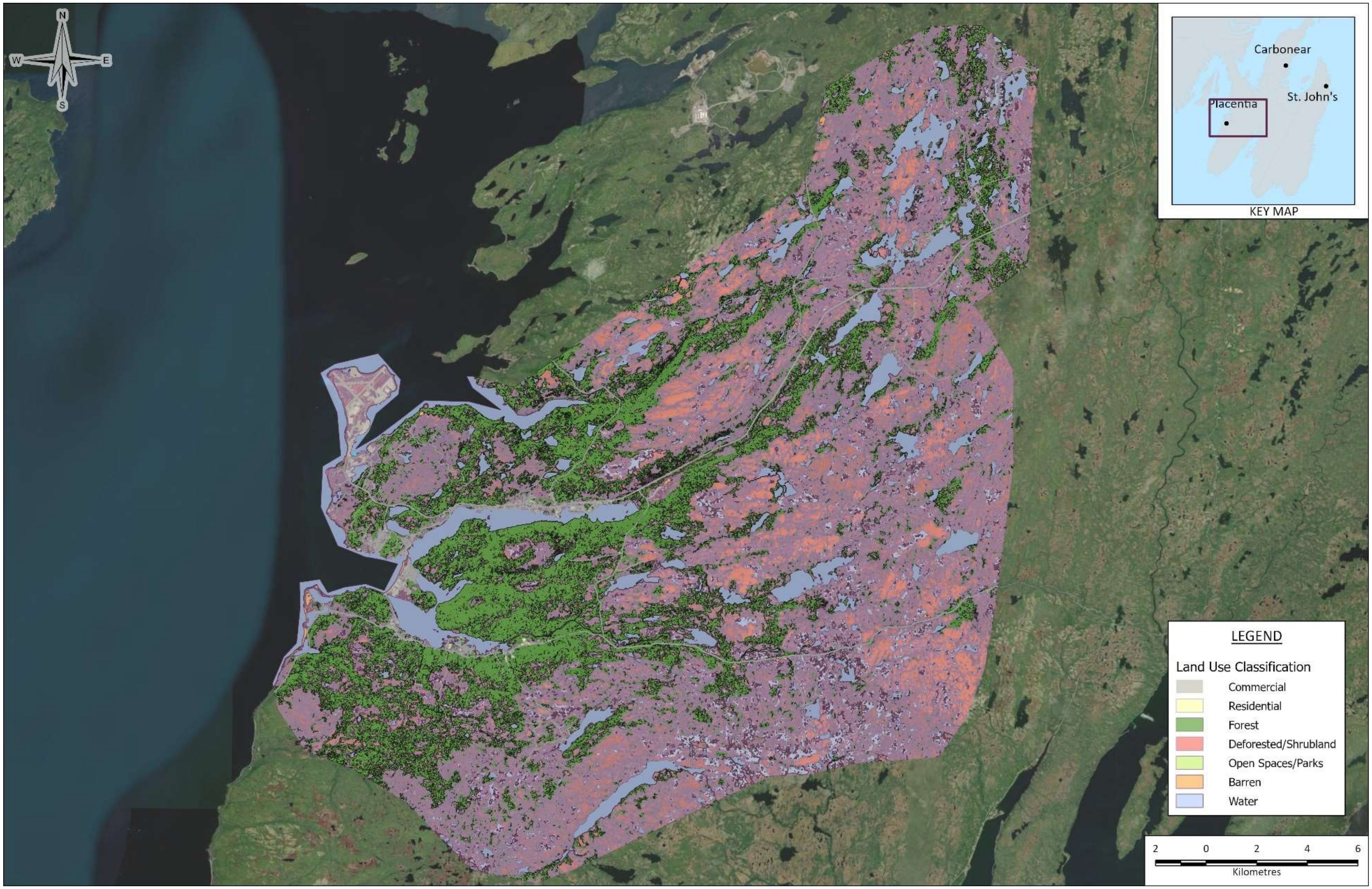
TABLE 6: WRMD LAND USE CLASSES

| WRMD Land Cover | Examples |
|---|---|
| Forest | Forests |
| Residential | Small homes and subdivisions. |
| Commercial | Large buildings 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 spaces | Agricultural areas, farmer fields; parks, cemeteries, golf courses, etc. within urban areas, low lying grass areas near airports, vegetated areas. |
| Swamps/wetlands/waterbodies | Swamps, wetlands, lakes, ponds and rivers |
| Unclassified | No data, cloud, shadow, snow/ice |

The resulting land use classification map for Carbonear, Victoria and Salmon Cove are shown on Figure 30, while the classification map for Placentia is shown on Figure 31.

## FIGURE 30: CARBONEAR, SALMON COVE AND VICTORIA LAND USE CLASSIFICATION MAP

## FIGURE 31: PLACENTIA LAND USE CLASSIFICATION MAP



## 5.4 Soils Classification

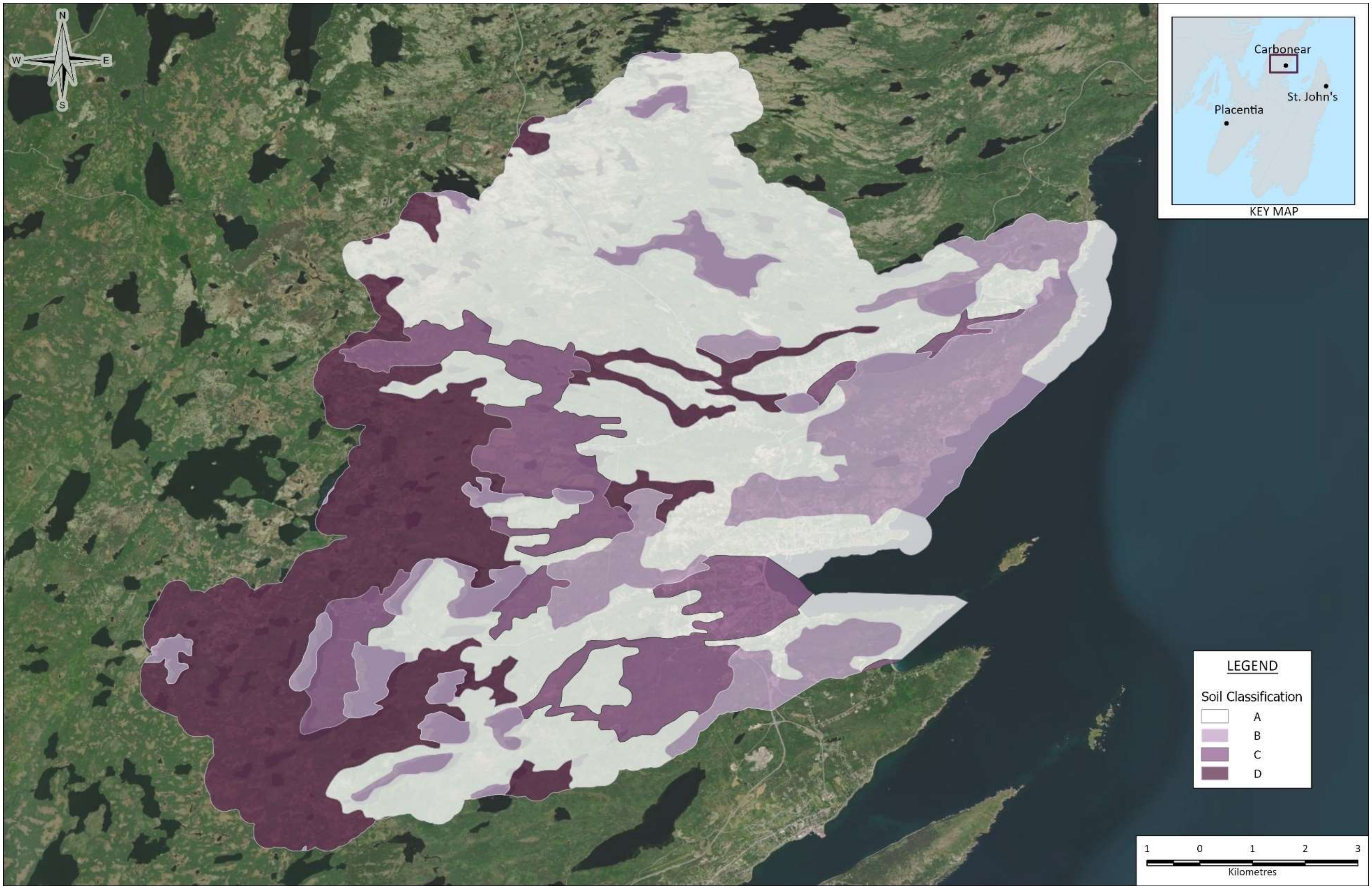
Available soil classification data included in the National Soils Database (NSDB) Version 2 were acquired for the study areas, matching the extents of the SPOT-6 satellite imagery. The NSDB data was processed to convert the soil classification scheme from the NSDB scheme to the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) soil classes. The soil classification schemes in both the NSDB and NRCS represent how each soil classification drains water, ranging from very rapidly to very poorly. The conversion of the NSDB soil classes to NRCS soil classes enabled the combination of the soils classification data with the land use classification data to develop Soil Conservation Service (SCS) Curve Number mapping data for use in the hydrologic modelling. The conversion of NSDB soil classes to NRCS soil classes are summarized in Table 7.

TABLE 7: CORRELATION OF NSDB TO NRCS SOIL CLASSES

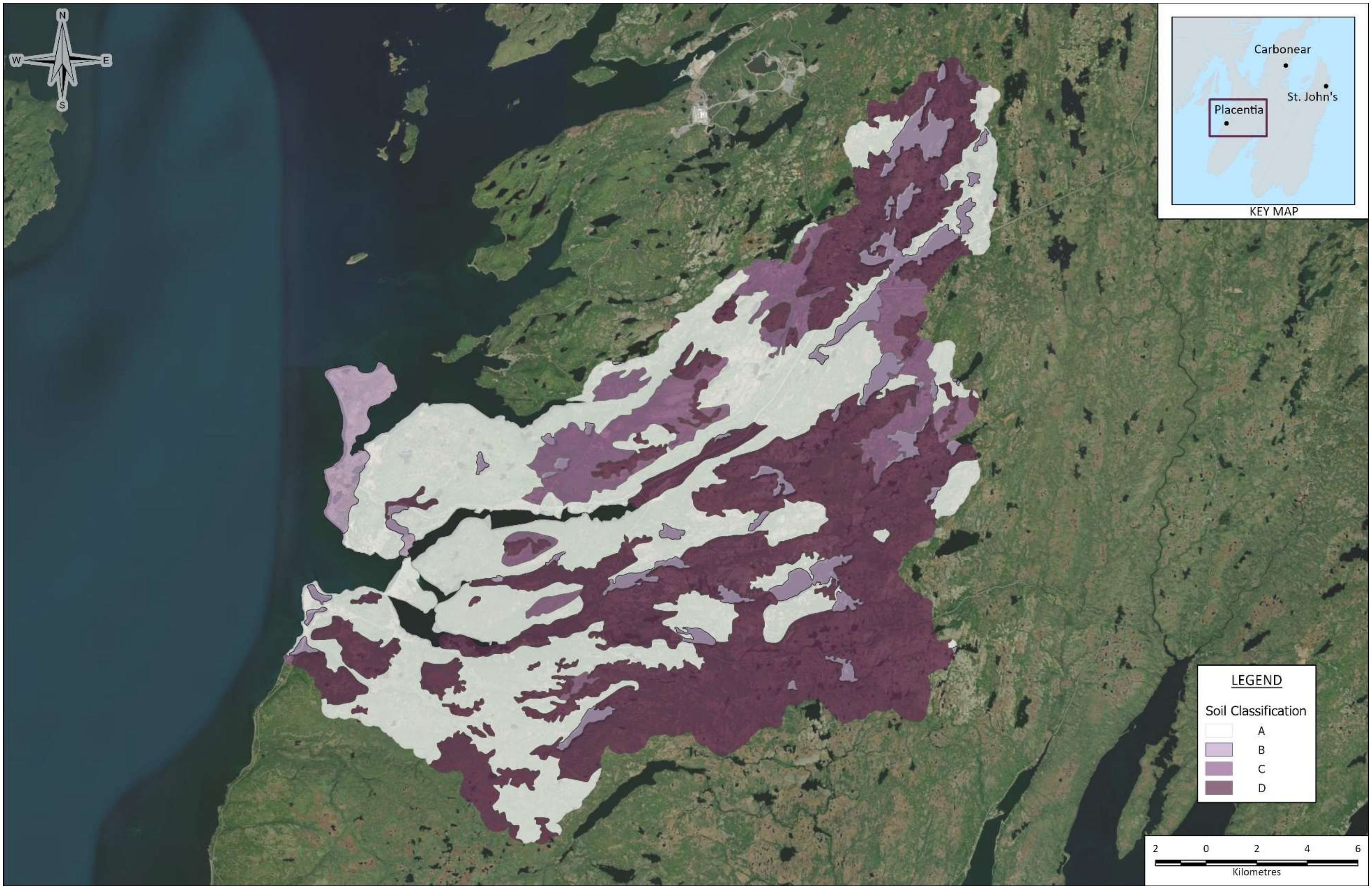
| NSDB Soil Class | NRCS Soil Class |
|---|---|
| Very Rapidly | A |
| Rapidly | A |
| Well | A |
| Moderately Well | A |
| Imperfectly | B |
| Poorly | C |
| Very Poorly | D |

The resulting soil classification map for Carbonear, Victoria and Salmon Cove is shown on Figure 32, while the soils classification map for Placentia is shown on Figure 33.

# FIGURE 32: CARBONEAR, SALMON COVE AND VICTORIA SOIL CLASSIFICATION MAP



## FIGURE 33: PLACENTIA SOIL CLASSIFICATION MAP



## 5.5 Curve Number Mapping

The land use classification data and NRCS soil classification data were combined based on the array provided by WRMD in the terms of reference to generate SCS Curve Number maps for Placentia, Carbonear, Salmon Cove and Victoria. The array relates the WRMD land use classes with the NRCS soil classes to define a Curve Number, which is used to translate rainfall to runoff in hydrologic models. The conversion table defined in the terms of reference is shown on Table 8.

**TABLE 8: CURVE NUMBER DEFINITION TABLE**

| Land Cover | NRCS Soil Type | | | |
|---|---|---|---|---|
| | A | B | C | D |
| Forest | 50 | 74 | 85 | 89 |
| Residential | 78 | 88 | 94 | 96 |
| Commercial | 96 | 97 | 98 | 98 |
| Deforested Areas | 75 | 87 | 92 | 94 |
| Barren Land | 89 | 94 | 97 | 98 |
| Fields/Pastures/Open Spaces | 59 | 78 | 88 | 91 |
| Swamps/Wetlands/Waterbodies | 100 | 100 | 100 | 100 |
| Unclassified | NA | NA | NA | NA |

The resulting Curve Number map for Carbonear, Salmon Cove and Victoria are shown on Figure 34, while the Curve Number map for Placentia is shown on Figure 35.

FIGURE 34: CARBONEAR, SALMON COVE AND VICTORIA CURVE NUMBER MAP

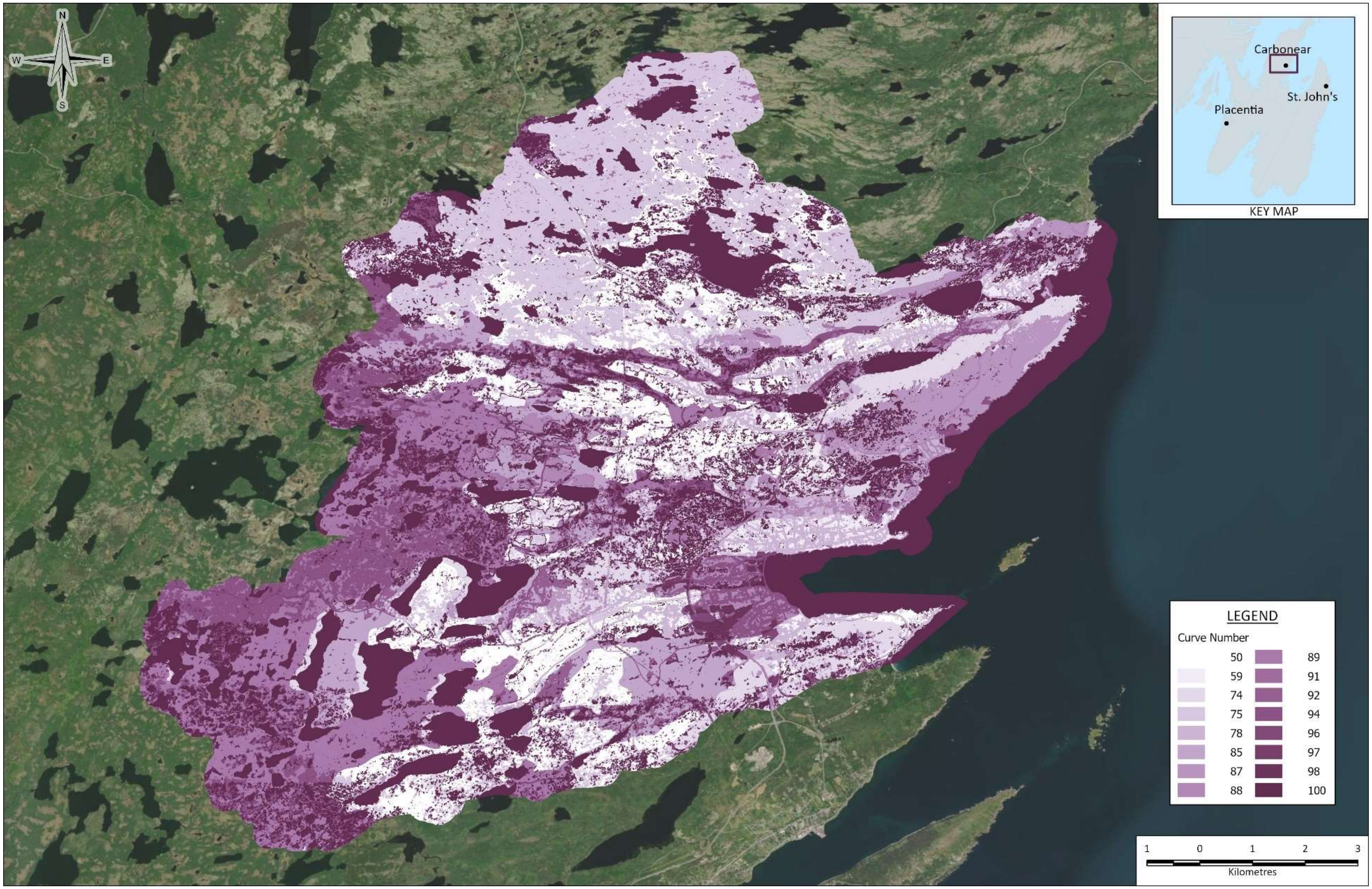
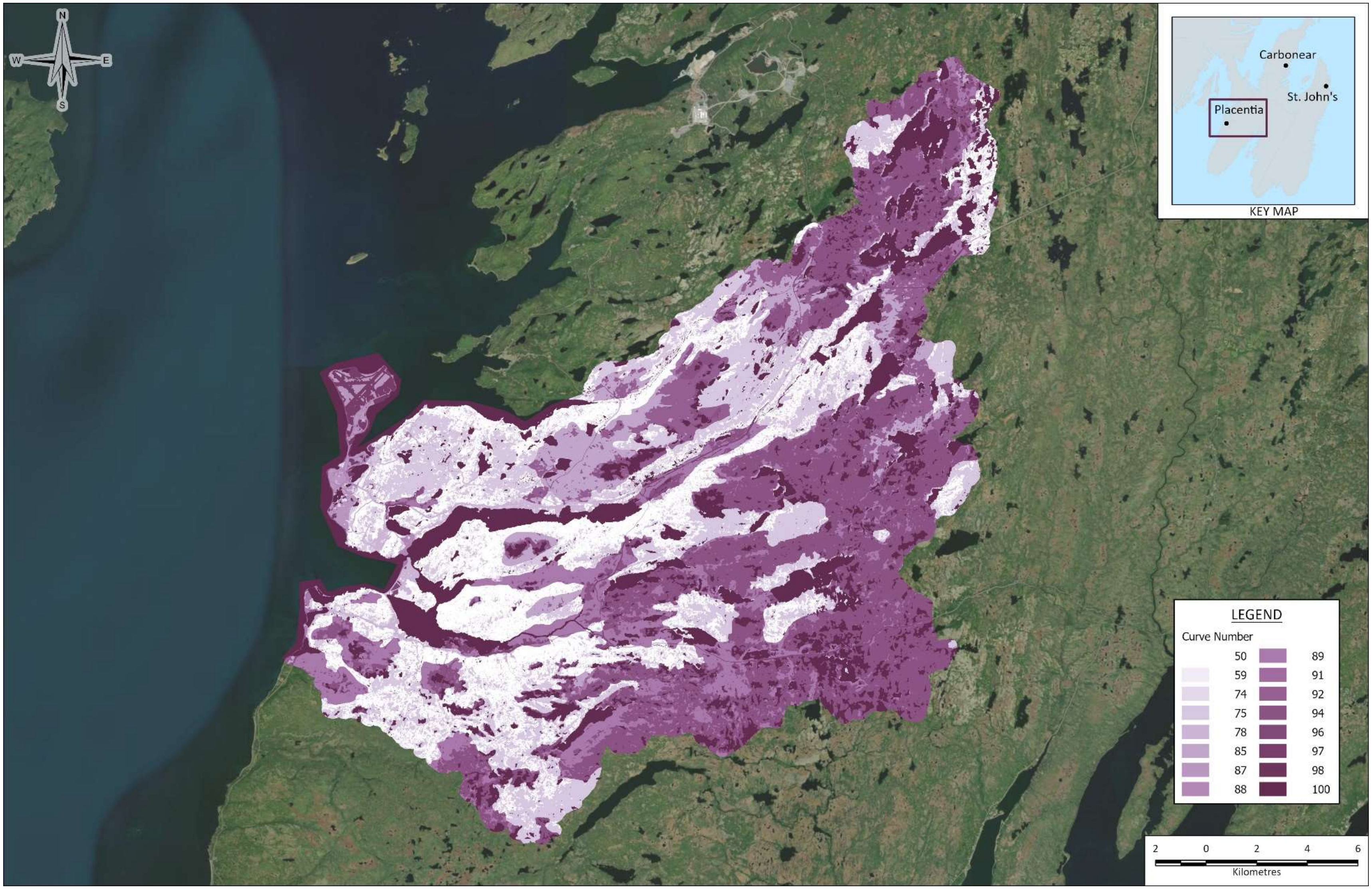


FIGURE 35: PLACENTIA CURVE NUMBER MAP



# 6.0 HYDROLOGIC INVESTIGATIONS AND MODELLING

## 6.1 Overview

Flood flows on the various rivers and creeks considered in this study were estimated using three separate methods, specifically by completing a statistical analysis of available recorded flows, completing a statistical analysis of recorded flows on rivers throughout Newfoundland, and by developing a computer model of the various rivers and creek basins to simulate storm events.

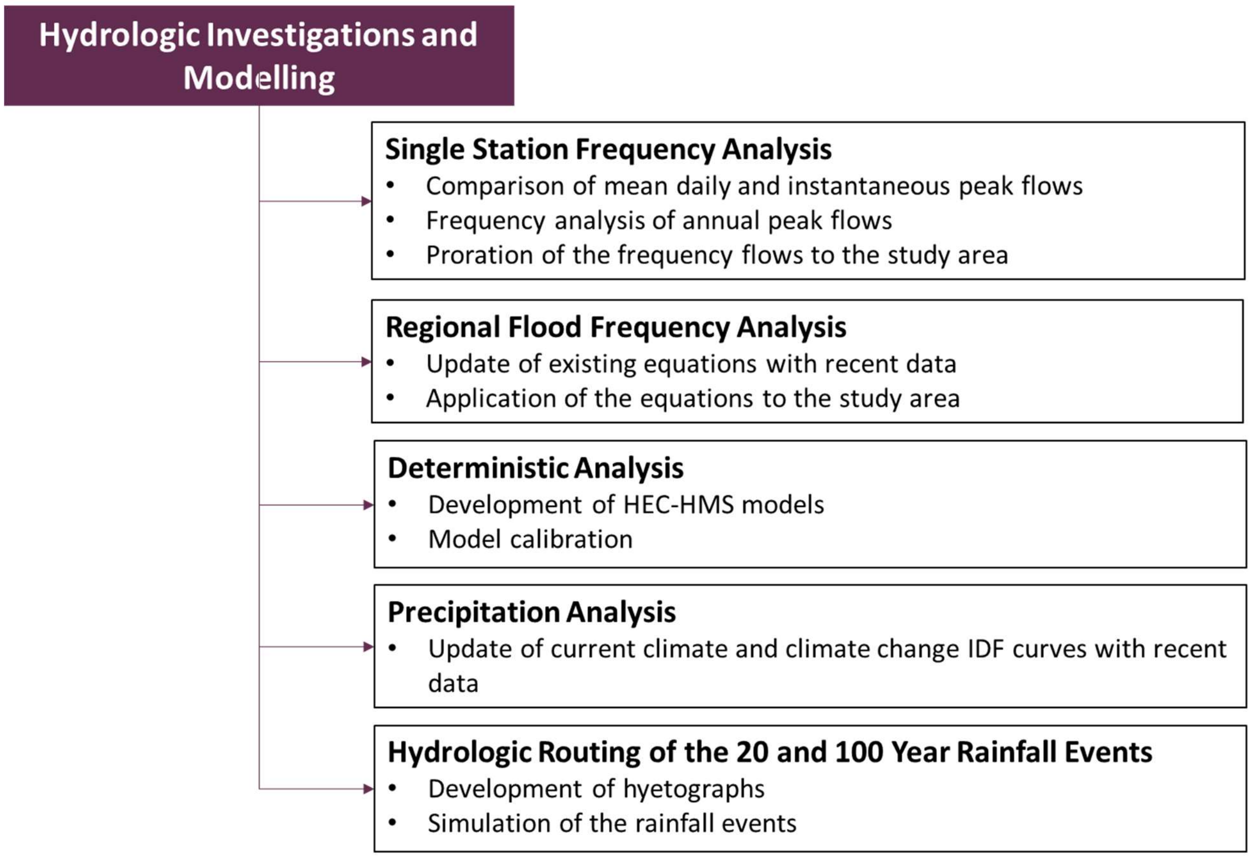
The statistical analysis of recorded flows was based on flows recorded by Water Survey of Canada on the Northeast River near Placentia, and on Shearstown Brook at Shearstown. The analyses considered recorded flows that were available, and fit a statistical distribution to the yearly maximum flows. This statistical fit was then used to estimate the flow rate for 20 and 100-year AEP floods.

A similar analysis was completed for various rivers throughout select regions of Newfoundland where recorded flows are available. By fitting statistical distributions to the yearly maximum flows for each river, a dataset of 20 and 100-year AEP 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 parameters representing lake and swamp effects, a set of equations was developed to estimate the 20 and 100-year AEP flood flows for any ungauged river within select regions of Newfoundland.

Computer models of the various rivers and creeks (i.e. hydrological models) were developed to model flows on those rivers for 20 and 100-year AEP rainfall events. Hydrological models are used to represent the various meteorological processes that occur within a river's drainage area, including rainfall and groundwater losses by representing rivers and tributaries, as well as their drainage areas, numerically. The models were adjusted to represent recorded flows, where available, and were found to accurately represent the historical observed flows. The models were then used to estimate the flows on the rivers in the study area for 20 and 100-year AEP rainfall events.

The tasks completed as part of the hydrologic investigations and modelling are shown on Figure 36.

**FIGURE 36: OVERVIEW OF HYDROLOGIC INVESTIGATIONS AND MODELLING**




## 6.2 Stochastic Analyses

### 6.2.1 SINGLE STATION FREQUENCY ANALYSES

Single station frequency analyses (SSFA) were completed for the WSC gauges 02ZK002 (i.e. Northeast River near Placentia) and 02ZL004 (i.e. Shearstown Brook at Shearstown), which are shown on Figure 37 and Figure 38 along with the watersheds that were assessed as part of the study. The 02ZK002 and 02ZL004 WSC gauges measure natural (i.e. unregulated) flows on the rivers, and as such are appropriate for estimating return period flows on natural waterways with similar physiographic characteristics. The available hydrometric data at WSC gauge 02ZK002 extended from 1979 to 2019, while the period of record for WSC gauge 02ZL004 was from 1983 to 2020. Instantaneous peak flow data were available from 1983 to 2020 for WSC gauge 02ZL004, with data missing only for 1994 and 1996. Similarly, instantaneous peak flow data were available from 1979 to 2019 for WSC gauge 02ZK002, with data missing only for 2002, 2004, 2016 and 2018. To estimate the missing instantaneous peak flow data, regressions were developed to relate the annual instantaneous peak flows to the mean daily flow that occurred on the same date as the instantaneous peak flow. From these regressions, the missing instantaneous peak flow data could be estimated based on the annual mean daily peak flow.

FIGURE 37: LOCATION OF WSC STATION 02ZK002 RELATIVE TO PLACENTIA DRAINAGE BASINS

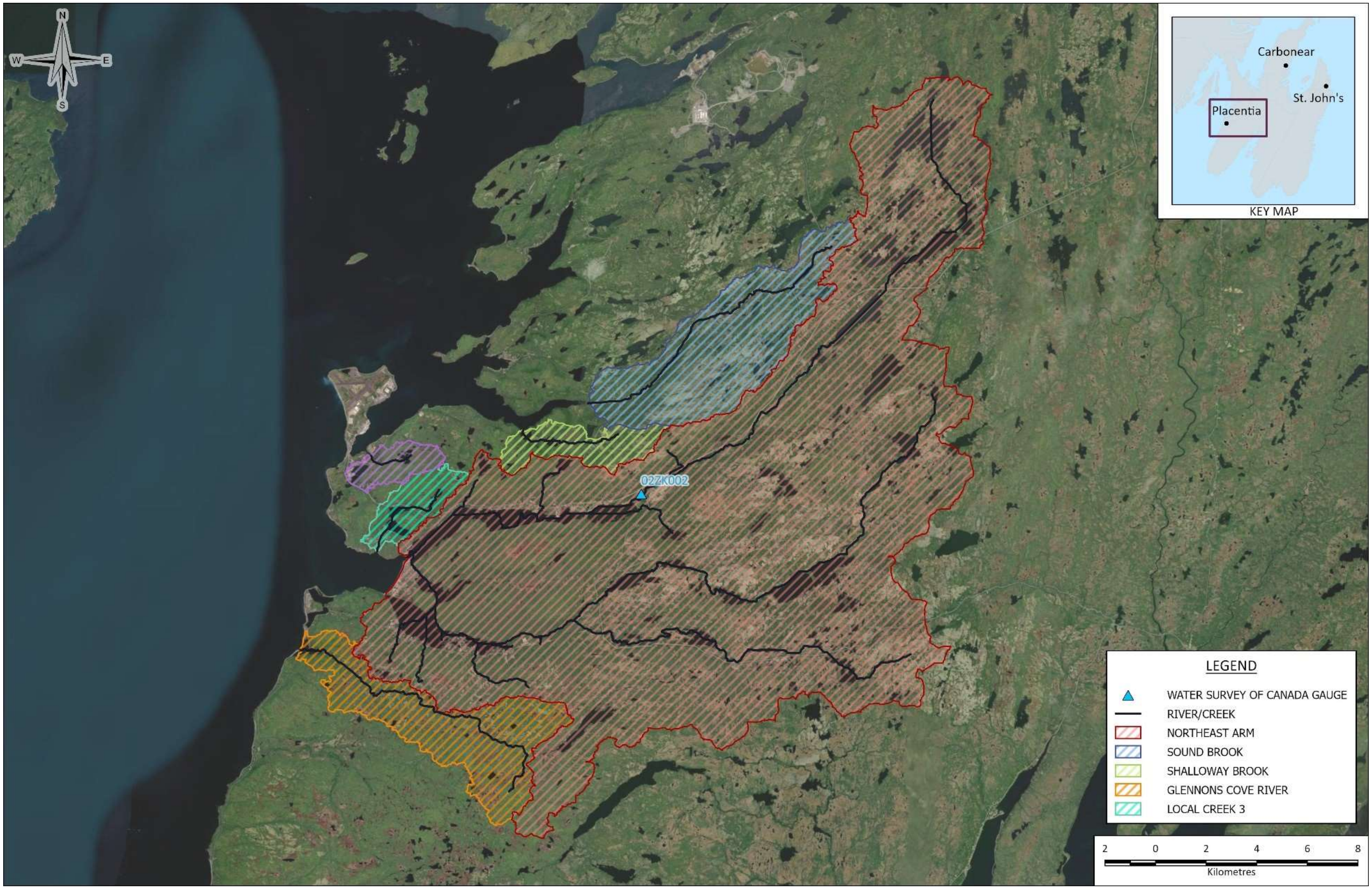
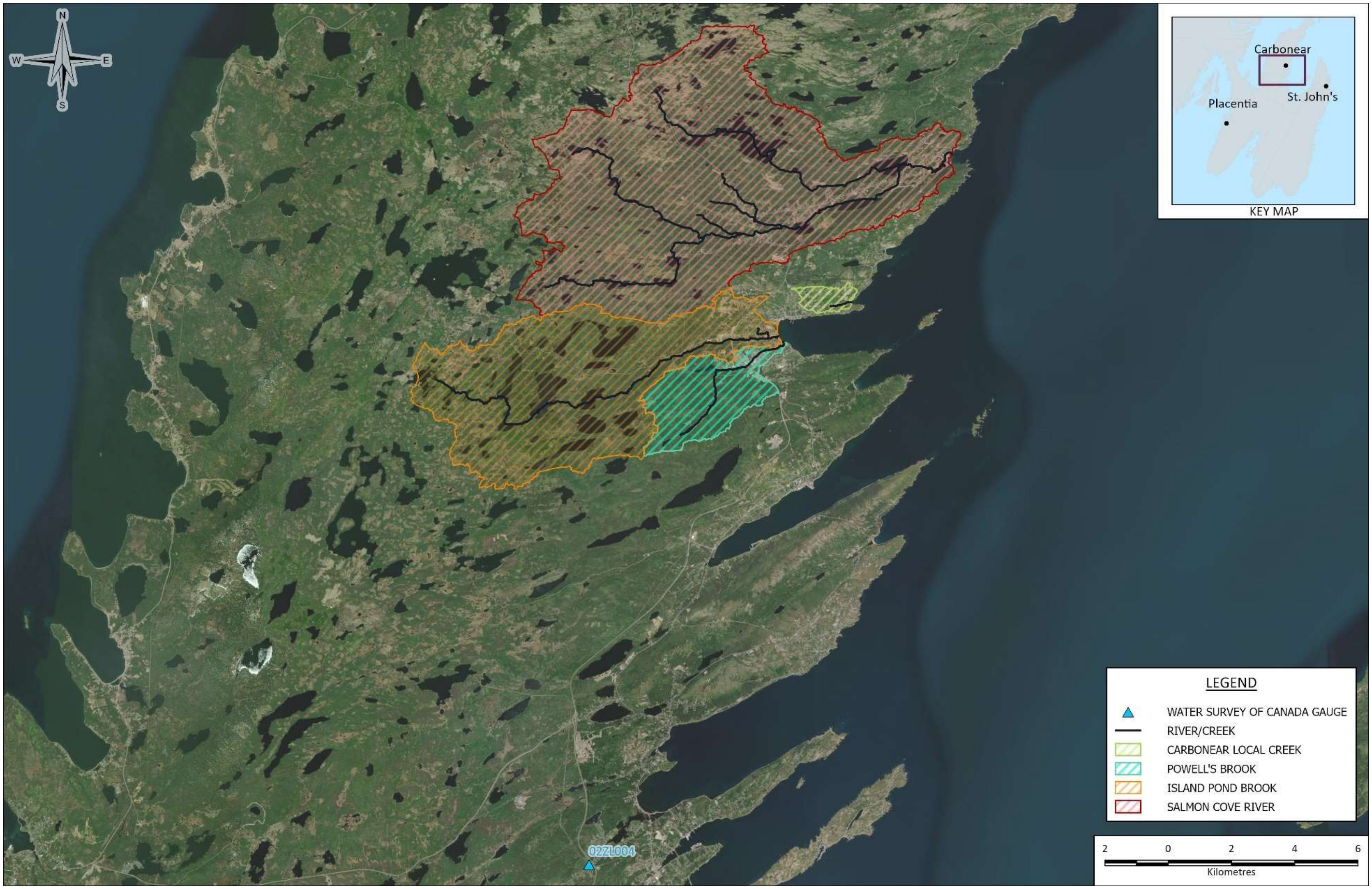


FIGURE 38: LOCATION OF WSC STATION 02ZL004 RELATIVE TO CARBONEAR AREA DRAINAGE BASINS



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, specifically the Wald-Wolfowitz test for independence, the Kendall test for stationarity, and the Wilcoxon test for homogeneity. The results of these statistical tests are summarized in Table 9.

### TABLE 9: SSFA STATISTICAL TESTS

| Station | Independence | Stationarity | Homogeneity |
|---|---|---|---|
| **Northeast River near Placentia** | Pass | Fail | Pass (1%) |
| **Shearstown Brook at Shearstown** | Pass | Pass | Pass |

The statistical tests in the HYFRAN statistical hydrology software showed that the datasets were independent, and that the datasets were homogenous. However, the Northeast River near Placentia dataset did not pass the statistical test for stationarity. This is likely attributed to the lower than average annual peak flows that have occurred on the river from 2011 to 2019. While these flows could have been removed from the analysis to satisfy the statistical test, the resulting estimate of the 100-year flow would have been less accurate given the shorter period of record used to estimate the flow. Accordingly, the full period of record was used in the analysis.

A review of peak flows was carried out to determine if it was appropriate to separate the peak flows into snowmelt and rainfall events. The review showed that the majority of annual peak flows occurred between December and May, although the timing of the majority of the high flow events did not correspond with the typical spring freshet, as they occurred during winter. The review found that the typical cause of the annual peak flows were large rainfall events during winter storms. Accordingly, the peak flow datasets were not subdivided into snowmelt and rainfall events for the SSFA.

The SSFA of the annual instantaneous peak flows were 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,
- Generalized Extreme-Value (GEV) distribution, and
- Log Pearson Type 3 distribution.

As indicated in the terms of reference, the maximum likelihood method for distribution parameter estimation was used to fit the distributions. The GEV distribution was found to provide the best fit to the Northeast River dataset, while the 3-Parameter Lognormal distribution was found to be most appropriate for the Shearstown dataset. The appropriateness of the frequency curves was assessed considering the p-value and chi statistic from the Chi-squared test, as well as a visual inspection of the frequency curves. Frequency flows based on these distributions are summarized in Table 10, with the frequency curves for the Northeast River and Shearstown Brook shown on Figure 39 and Figure 40.

### TABLE 10: FREQUENCY CURVE FLOWS

| Return Period (Years) | Shearstown Brook Flow ($m^3/s$) | Northeast River Flow ($m^3/s$) |
|---|---|---|
| **100** | 62.6 | 265.0 |
| **50** | 51.4 | 206.0 |
| **20** | 38.5 | 146.0 |
| **10** | 30.1 | 110.0 |
| **5** | 22.7 | 80.9 |
| **2** | 14.0 | 48.4 |

### FIGURE 39: NORTHEAST RIVER NEAR PLACENTIA FREQUENCY CURVE

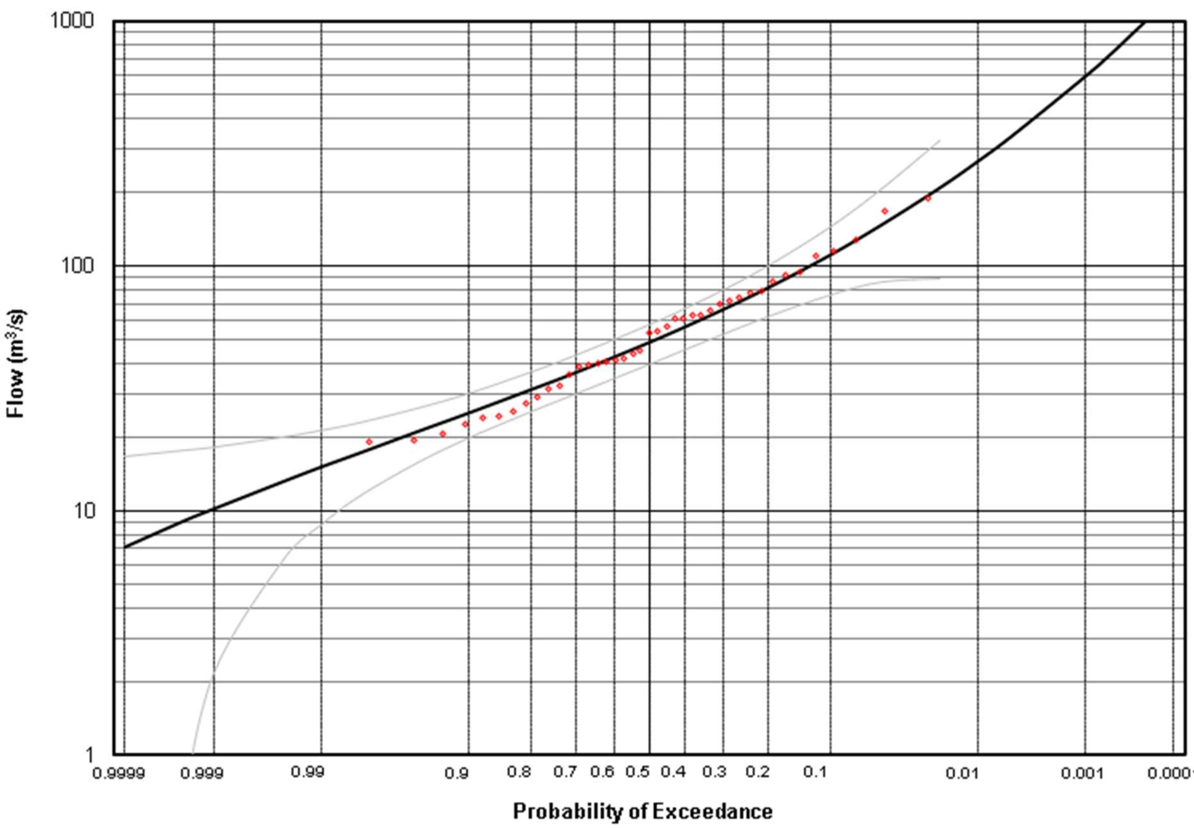
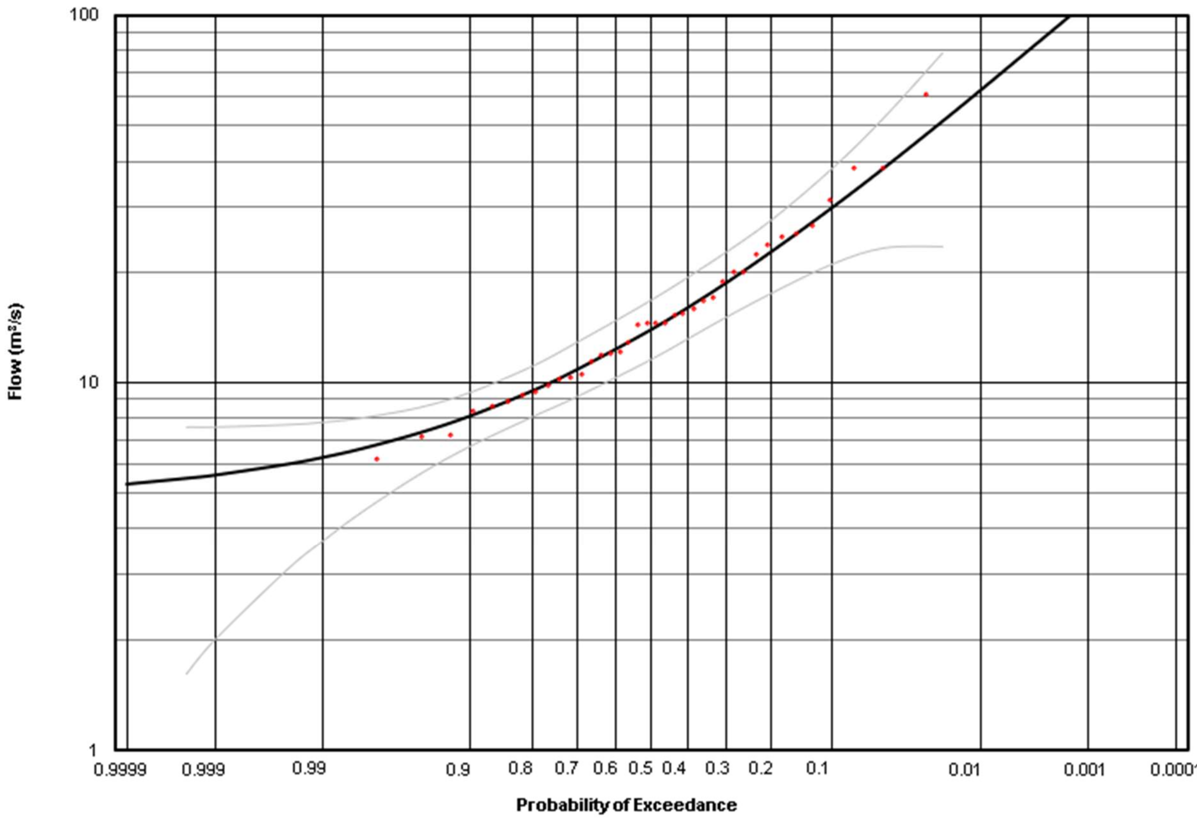


**FIGURE 40: SHEARSTOWN BROOK AT SHEARSTOWN FREQUENCY CURVE**




The 20 and 100-year AEP frequency flows from the Northeast River were prorated to the rivers that were considered as part of the flood risk mapping study in the Placentia Area, while the 20 and 100-year AEP frequency flows from the Shearstown Brook were prorated to the rivers considered in the study in Carbonear, Salmon Cove and Victoria. The flow proration was completed on the basis of ratio of the drainage area of a particular river or creek to the index station (i.e. either the Northeast River or Shearstown Brook WSC stations), and included the regional coefficient for each of the 20 and 100-year AEP flood flows as an exponent to the drainage area ratio. However, the appropriateness of frequency flow proration is generally limited by the difference in drainage basin sizes and physiographic similarities between basins. Given the size of the Northeast River basin area at WSC gauge 02ZK002 (i.e. 89.6 $km^2$) and the Shearstown Brook basin area at WSC gauge 02ZL004 (i.e. 28.9 $km^2$), the prorated flows are inappropriate for many of the smaller tributaries and rivers in the study area. The prorated flows for the Carbonear and Placentia areas are summarized in Table 11 and Table 12.

## TABLE 11: CARBONEAR, SALMON COVE AND VICTORIA SSFA FLOWS

| Location | Drainage Area ($km^2$) | 20-Year Flow ($m^3/s$) | 100-Year Flow ($m^3/s$) |
|---|---|---|---|
| Salmon Cove River at U/S Model Boundary | 13.4 | 20.7 | 33.2 |
| Big Brook above Salmon Cove River | 14.5 | 22.1 | 35.4 |
| Local Creek 5 above Salmon Cove River | 1.3 | 3.2 | 4.8 |
| Clark Brook above Double Brook | 2.2 | 4.8 | 7.5 |
| Double Brook above Local Creek 4 | 1.1 | 2.8 | 4.2 |
| Local Creek 4 above Double Brook | 0.9 | 2.4 | 3.6 |
| Local Creek 3 above Salmon Cove River | 0.6 | 1.7 | 2.6 |
| Spout Brook | 22.9 | 31.9 | 51.7 |
| Local Creek 2 above Salmon Cove River | 0.5 | 1.5 | 2.2 |
| Local Creek 1 above Salmon Cove River | 0.4 | 1.2 | 1.8 |
| Salmon Cove River Outlet | 70.3 | 78.7 | 130.5 |
| Carbonear Local Creek Outlet | 1.2 | 3.0 | 4.5 |
| Island Pond Brook above Local Creek 1 | 37.2 | 47.2 | 77.1 |
| Island Pond Brook Local Creek 2 above Local Creek 1 | 0.1 | 0.4 | 0.6 |
| Island Pond Brook Local Creek 1 above Island Pond Brook | 0.5 | 1.5 | 2.2 |
| Island Pond Brook Outlet | 37.8 | 47.8 | 78.1 |

### TABLE 12: PLACENTIA AREA SSFA FLOWS

| Location | Drainage Area (km2) | 20-Year Flow ($m^3/s$) | 100-Year Flow ($m^3/s$) |
|---|---|---|---|
| **Southeast River Outlet** | 137.9 | 177.2 | 315.2 |
| **Northeast River Outlet** | 90.6 | 146.7 | 266.2 |
| **Rattling Brook Outlet** | 5.6 | 42.0 | 86.9 |
| **Smelt Brook Outlet** | 3.8 | 35.3 | 74.4 |
| **Local Creek 1 Outlet** | 1.3 | 21.8 | 48.3 |
| **Baldwins Brook Outlet** | 5.6 | 42.0 | 86.9 |
| **Local Creek 2 Outlet** | 2.5 | 29.3 | 62.9 |
| **Little Salmonier River Outlet** | 4.5 | 38.1 | 79.6 |
| **Local Creek 3 Outlet** | 6.4 | 44.6 | 91.7 |
| **Local Creek 4 Outlet** | 3.2 | 32.7 | 69.4 |
| **Mill Brook Outlet** | 3.4 | 33.6 | 71.1 |
| **Local Creek 5 Outlet** | 6.8 | 45.9 | 94.0 |
| **Shalloway Brook Outlet** | 8.2 | 49.9 | 101.3 |
| **Sound Brook Outlet** | 33.8 | 94.2 | 179.1 |

### 6.2.2 REGIONAL FLOOD FREQUENCY ANALYSES

As part of this project KGS Group updated the Regional Flood Frequency Analysis (RFFA) for the Southeast and Southwest hydrological regions of Newfoundland. The updated regression equations were then used to estimate the 20 and 100-year AEP events on ungauged rivers and creeks within the study area. The methodology implemented for this analysis was based on the methodology described in the *Regional Flood Frequency Analysis for Newfoundland and Labrador – 2014 Update* (AMEC, 2014). In short, SSFA are completed for stations that meet statistical screening requirements in the regions of interest, and the resulting data for each return period is used to develop regional regression equations to estimate return period flows considering relevant physiographic parameters.

All WSC streamflow gauges within the Southeast and Southwest regions on Newfoundland were identified using the HYDAT database available in the Environment Canada Data Explorer. An initial screening found 58 stations located in the Southeast or Southwest regions, both active and discontinued. Recent (i.e. 2019 and 2020) data for active stations was available for most stations. Initial screening was completed to identify stations that were suitable for a SSFA, specifically excluding stations that measured regulated flows or had a period of record shorter than 10 years. Of the initial 58 stations, 39 stations passed the initial screening, as 9 stations measured regulated flow and an additional 10 stations had less than 10 years of data.

For each of the stations that satisfied the initial screening, gaps in the annual maximum instantaneous flow data were identified and, where possible, infilled based on a regression analysis of the instantaneous and mean daily discharges. The WSC stations that passed the statistical screening, as well as key data for those stations, are summarized in Appendix F.

Further statistical screening was completed using the HYFRAN statistical hydrology software, specifically tests for independence, trend, and homogeneity. The results of those statistical tests are summarized in Table 13. All results are for a significance level of 5% unless a significance level of 1% is indicated. Gauges that failed the independence, homogeneity, or the trend tests were not used in the subsequent SSFA analyses. A total of four gauges were excluded from subsequent analyses.

### TABLE 13: STATISTICAL SCREENING RESULTS

| Station Number | Station Name | Region | Sample Size | Independence | Trend | Homogeneity | Passed Statistical Screening |
|---|---|---|---|---|---|---|---|
| **02YJ001** | HARRYS RIVER BELOW HIGHWAY BRIDGE | SW | 51 | Pass | Pass | Pass | Yes |
| **02YJ003** | PINCHGUT BROOK AT OUTLET OF PINCHGUT LAKE | SW | 11 | Pass | Pass | Pass | Yes |
| **02YK002** | LEWASEECHJEECH BROOK AT LITTLE GRAND LAKE | SW | 58 | Fail | Pass (1%) | Pass (1%) | No |
| **02YN002** | LLOYDS RIVER BELOW KING GEORGE IV LAKE | SW | 40 | Pass | Pass | Pass | Yes |
| **02ZA001** | LITTLE BARACHOIS BROOK NEAR ST. GEORGE'S | SW | 18 | Pass | Pass | Pass | Yes |
| **02ZA002** | HIGHLANDS RIVER AT TRANS-CANADA HIGHWAY | SW | 37 | Pass | Pass | Pass | Yes |
| **02ZA003** | LITTLE CODROY RIVER NEAR DOYLES | SW | 15 | Pass | Pass | Pass | Yes |
| **02ZB001** | ISLE AUX MORTS RIVER BELOW HIGHWAY BRIDGE | SW | 57 | Pass | Pass | Pass | Yes |
| **02ZC002** | GRANDY BROOK BELOW TOP POND BROOK | SW | 33 | Pass (1%) | Pass | Pass | Yes |
| **02ZD002** | GREY RIVER NEAR GREY RIVER | SW | 42 | Pass | Pass | Pass | Yes |
| **02ZE001** | SALMON RIVER AT LONG POND | SW | 16 | Pass | Pass | Pass | Yes |
| **02ZE004** | CONNE RIVER AT OUTLET OF CONNE RIVER POND | SW | 32 | Pass | Pass | Pass | Yes |
| **02ZF001** | BAY DU NORD RIVER AT BIG FALLS | SW | 68 | Pass | Pass | Pass | Yes |
| **02ZG001** | GARNISH RIVER NEAR GARNISH | SE | 61 | Pass | Pass | Pass | Yes |
| **02ZG002** | TIDES BROOK BELOW FRESHWATER POND | SE | 19 | Pass | Pass | Pass | Yes |
| **02ZG003** | SALMONIER RIVER NEAR LAMALINE | SE | 40 | Pass | Pass | Pass | Yes |
| **02ZG004** | RATTLE BROOK NEAR BOAT HARBOUR | SE | 40 | Pass | Pass | Pass | Yes |
| **02ZH002** | COME BY CHANCE RIVER NEAR GOOBIES | SE | 50 | Pass | Pass | Pass | Yes |
| **02ZK001** | ROCKY RIVER NEAR COLINET | SE | 72 | Pass | Pass | Pass | Yes |
| **02ZK002** | NORTHEAST RIVER NEAR PLACENTIA | SE | 40 | Pass | Pass (1%) | Pass | Yes |
| **02ZK003** | LITTLE BARACHOIS RIVER NEAR PLACENTIA | SW | 36 | Pass (1%) | Fail | Fail | No |
| **02ZK004** | LITTLE SALMONIER RIVER NEAR NORTH HARBOUR | SW | 36 | Pass | Fail | Pass (1%) | No |
| **02ZK005** | TROUT BROOK NEAR BELLEVUE | SE | 11 | Pass | Pass | Pass | Yes |
| **02ZK006** | RATTLING BROOK BELOW BRIDGE | SE | 14 | Pass | Pass (1%) | Pass (1%) | Yes |
| **02ZL003** | SPOUT COVE BROOK NEAR SPOUT COVE | SE | 18 | Pass | Pass | Pass | Yes |
| **02ZL004** | SHEARSTOWN BROOK AT SHEARSTOWN | SE | 37 | Pass | Pass | Pass | Yes |
| **02ZL005** | BIG BROOK AT LEAD COVE | SE | 36 | Pass | Pass | Pass | Yes |

| Station Number | Station Name | Region | Sample Size | Independence | Trend | Homogeneity | Passed Statistical Screening |
|---|---|---|---|---|---|---|---|
| **02ZM006** | NORTHEAST POND RIVER AT NORTHEAST POND | SE | 50 | Pass | Pass (1%) | Pass (1%) | Yes |
| **02ZM008** | WATERFORD RIVER AT KILBRIDE | SE | 46 | Pass | Pass | Pass | Yes |
| **02ZM009** | SEAL COVE BROOK NEAR CAPPAHAYDEN | SE | 40 | Pass | Fail | Pass (1%) | No |
| **02ZM010** | WATERFORD RIVER AT MOUNT PEARL | SE | 15 | Pass | Pass | Pass | Yes |
| **02ZM016** | SOUTH RIVER NEAR HOLYROOD | SE | 36 | Pass | Pass | Pass | Yes |
| **02ZM017** | LEARY BROOK AT ST. JOHN'S | SE | 16 | Pass | Pass | Pass | Yes |
| **02ZM018** | VIRGINIA RIVER AT PLEASANTVILLE | SE | 36 | Pass | Pass | Pass | Yes |
| **02ZM019** | VIRGINIA RIVER AT CARTWRIGHT PLACE | SE | 14 | Pass | Pass | Pass | Yes |
| **02ZM020** | LEARYS BROOK AT PRINCE PHILIP DRIVE | SE | 33 | Pass | Pass | Pass | Yes |
| **02ZM021** | SOUTH BROOK AT PEARL TOWN ROAD | SE | 0 | Pass | Pass | Pass | Yes |
| **02ZN001** | NORTHWEST BROOK AT NORTHWEST POND | SE | 30 | Pass | Pass (1%) | Pass | Yes |
| **02ZN002** | ST. SHOTTS RIVER NEAR TREPASSEY | SE | 34 | Pass | Pass | Pass | Yes |

In total 35 gauge stations were found to be suitable for the SSFA, and were used to develop RFFA equations for the SE and SW regions. A total of 23 gauge stations were in the Southeast region, and 12 stations were in the Southwest region.

The HYFRAN statistical hydrology software was used to estimate the 2, 5, 10, 20, 50, and 100-year AEP flows for each of the gauge stations that passed the statistical screening. An initial analysis of different distributions was performed to determine which distribution best fits the data. This analysis considered:

- Extreme Value Distribution (EV-1).
- Lognormal Distribution (LN).
- Three-Parameter Lognormal Distribution (3PLN).
- Generalized Extreme-Value Distribution (GEV).
- Log Pearson Type 3 Distribution (LP3).

For each distribution, the maximum likelihood solution was chosen. If no maximum likelihood solution was found, then a method of moments (MOM) solution was used. No distributions were found to be more appropriate than others, and therefore the 3PLN distribution was used in this study as it had previously been used in the 1999 and the 2014 RRFA updates. The AEP flows for the 35 gauge stations are summarized in Table 14. The *Q100 Upper Limit* column in Table 14 represents the percentage by which the upper limit of the 95% confidence interval for the 100-year AEP flow exceeds the estimated value of the 100-year AEP flow, where the 95% confidence interval is the range where there is 95% certainty that the true value of the 100-year AEP flow is within that range.

## TABLE 14: SSFA RESULTS

| Station Number | Station Name | Region | Return Period Flows (cms) | | | | | | Q100 Upper Limit | Distribution used |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Q2 | Q5 | Q10 | Q20 | Q50 | Q100 | | |
| **02YJ001** | HARRYS RIVER BELOW HIGHWAY BRIDGE | SW | 291.9 | 396.1 | 465.6 | 532.5 | 619.8 | 686.0 | 25% | 3PLN (Max Likelihood) |
| **02YJ003** | PINCHGUT BROOK AT OUTLET OF PINCHGUT LAKE | SW | 29.50 | 36.20 | 40.0 | 43.30 | 47.30 | 50.00 | N/D | 3PLN (MOM) |
| **02YN002** | LLOYDS RIVER BELOW KING GEORGE IV LAKE | SW | 163.6 | 224.9 | 268.4 | 311.9 | 370.9 | 417.2 | 32% | 3PLN (Max Likelihood) |
| **02ZA001** | LITTLE BARACHOIS BROOK NEAR ST. GEORGE'S | SW | 118.2 | 159.3 | 183.2 | 204.1 | 229.3 | 246.9 | 34% | 3PLN (MOM) |
| **02ZA002** | HIGHLANDS RIVER AT TRANS-CANADA HIGHWAY | SW | 48.16 | 79.99 | 110.4 | 147.4 | 208.0 | 264.1 | 61% | 3PLN (Max Likelihood) |
| **02ZA003** | LITTLE CODROY RIVER NEAR DOYLES | SW | 152.9 | 212.3 | 249.1 | 282.9 | 325.1 | 355.9 | N/D | 3PLN (MOM) |
| **02ZB001** | ISLE AUX MORTS RIVER BELOW HIGHWAY BRIDGE | SW | 332.0 | 503.4 | 635.3 | 774.7 | 973.6 | 1137 | 34% | 3PLN (Max Likelihood) |
| **02ZC002** | GRANDY BROOK BELOW TOP POND BROOK | SW | 361.5 | 470.3 | 541.8 | 610.2 | 698.6 | 765.2 | 28% | 3PLN (Max Likelihood) |
| **02ZD002** | GREY RIVER NEAR GREY RIVER | SW | 855.0 | 1202 | 1426 | 1638 | 1909 | 2111 | 27% | 3PLN (Max Likelihood) |
| **02ZE001** | SALMON RIVER AT LONG POND | SW | 852.0 | 1199 | 1424 | 1637 | 1911 | 2115 | 27% | 3PLN (Max Likelihood) |
| **02ZE004** | CONNE RIVER AT OUTLET OF CONNE RIVER POND | SW | 40.84 | 58.56 | 72.86 | 88.42 | 111.3 | 130.6 | 46% | 3PLN (Max Likelihood) |
| **02ZF001** | BAY DU NORD RIVER AT BIG FALLS | SW | 194.7 | 266.1 | 314.5 | 361.7 | 423.8 | 471.4 | 22% | 3PLN (Max Likelihood) |
| **02ZG001** | GARNISH RIVER NEAR GARNISH | SE | 55.27 | 84.17 | 109.0 | 137.2 | 180.4 | 218.1 | 39% | 3PLN (Max Likelihood) |
| **02ZG002** | TIDES BROOK BELOW FRESHWATER POND | SE | 218.2 | 319.6 | 407.7 | 508.4 | 663.8 | 800.2 | N/D | 3PLN (Max Likelihood) |
| **02ZG003** | SALMONIER RIVER NEAR LAMALINE | SE | 65.18 | 89.94 | 106.0 | 121.2 | 140.8 | 155.4 | 27% | 3PLN (Max Likelihood) |
| **02ZG004** | RATTLE BROOK NEAR BOAT HARBOUR | SE | 31.69 | 47.91 | 61.16 | 75.68 | 97.21 | 115.4 | 44% | 3PLN (Max Likelihood) |
| **02ZH002** | COME BY CHANCE RIVER NEAR GOOBIES | SE | 30.99 | 43.42 | 51.38 | 58.86 | 68.37 | 75.45 | 24% | 3PLN (Max Likelihood) |
| **02ZK001** | ROCKY RIVER NEAR COLINET | SE | 142.1 | 198.4 | 238.3 | 278.3 | 332.5 | 375.1 | 24% | 3PLN (Max Likelihood) |
| **02ZK005** | TROUT BROOK NEAR BELLEVUE | SE | 27.15 | 40.51 | 50.13 | 59.87 | 73.19 | 83.74 | N/D | 3PLN (Max Likelihood) |
| **02ZK006** | RATTLING BROOK BELOW BRIDGE | SE | 9.552 | 17.98 | 27.16 | 39.36 | 61.16 | 82.85 | N/D | 3PLN (Max Likelihood) |
| **02ZL003** | SPOUT COVE BROOK NEAR SPOUT COVE | SE | 8.516 | 12.07 | 14.34 | 16.47 | 19.19 | 21.2 | 41% | 3PLN (Max Likelihood) |
| **02ZL004** | SHEARSTOWN BROOK AT SHEARSTOWN | SE | 13.67 | 20.99 | 26.86 | 33.22 | 42.54 | 50.36 | 45% | 3PLN (Max Likelihood) |
| **02ZL005** | BIG BROOK AT LEAD COVE | SE | 5.14 | 7.46 | 9.129 | 10.82 | 13.13 | 14.95 | 37% | 3PLN (Max Likelihood) |
| **02ZM006** | NORTHEAST POND RIVER AT NORTHEAST POND | SE | 3.515 | 4.826 | 5.729 | 6.617 | 7.798 | 8.71 | 27% | 3PLN (Max Likelihood) |
| **02ZM008** | WATERFORD RIVER AT KILBRIDE | SE | 44.75 | 60.09 | 70.02 | 79.40 | 91.43 | 100.4 | 30% | 3PLN (MOM) |
| **02ZM010** | WATERFORD RIVER AT MOUNT PEARL | SE | 15.3 | 23.34 | 31.43 | 41.64 | 58.96 | 75.45 | N/D | 3PLN (Max Likelihood) |
| **02ZM016** | SOUTH RIVER NEAR HOLYROOD | SE | 10.25 | 13.99 | 16.57 | 19.12 | 22.51 | 25.14 | 32% | 3PLN (Max Likelihood) |
| **02ZM017** | LEARY BROOK AT ST. JOHN'S | SE | 12.70 | 16.20 | 18.34 | 20.29 | 22.72 | 24.48 | 33% | 3PLN (Max Likelihood) |

| Station Number | Station Name | Region | Return Period Flows (cms) | | | | | | Q100 Upper Limit | Distribution used |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Q2 | Q5 | Q10 | Q20 | Q50 | Q100 | | |
| **02ZM018** | VIRGINIA RIVER AT PLEASANTVILLE | SE | 8.891 | 11.66 | 13.46 | 15.18 | 17.40 | 19.06 | 28% | 3PLN (Max Likelihood) |
| **02ZM019** | VIRGINIA RIVER AT CARTWRIGHT PLACE | SE | 3.363 | 4.466 | 5.267 | 6.082 | 7.203 | 8.095 | N/D | 3PLN (Max Likelihood) |
| **02ZM020** | LEARYS BROOK AT PRINCE PHILIP DRIVE | SE | 18.83 | 25.71 | 30.39 | 34.96 | 40.99 | 45.63 | 32% | 3PLN (Max Likelihood) |
| **02ZM021** | SOUTH BROOK AT PEARL TOWN ROAD | SE | 10.59 | 13.4 | 15.01 | 16.42 | 18.09 | 19.26 | N/D | 3PLN (MOM) |
| **02ZN001** | NORTHWEST BROOK AT NORTHWEST POND | SE | 38.23 | 47.41 | 52.49 | 56.85 | 61.92 | 65.40 | 18% | 3PLN (Max Likelihood) |
| **02ZN002** | ST. SHOTTS RIVER NEAR TREPASSEY | SE | 8.861 | 13.59 | 17.39 | 21.52 | 27.59 | 32.69 | 48% | 3PLN (Max Likelihood) |
| **02ZK002** | NORTHEAST RIVER NEAR PLACENTIA | SE | 52.69 | 86.78 | 114.6 | 145.1 | 190.4 | 228.8 | 47% | 3PLN (Max Likelihood) |

Single parameter and multiple parameter log regression analyses were completed on the AEP flows for each return period in both the Southeast and Southwest regions. The log regression equation is given by:

$$log_{10}(Q_T) = log_{10}(c) + a_1\, log_{10}(var_1) + a_2 log_{10}(var_2) + a_3 log_{10}(var_3) + \cdots \qquad \text{[Eq.1]}$$

where $Q_T$ is the estimated flow for return period, $c$ and $a_i$ are the regression coefficients, and $var_i$ are the regression parameters. Equation 1 can be manipulated to return the estimated return period flows directly, as follows:

$$Q_T = c(var_1)^{a_1}(var_2)^{a_2}(var_3)^{a_3} \ldots \qquad \text{[Eq.2]}$$

The WSC stations were divided into two groups based on the percentage that the upper 95% confidence interval of the 100-year AEP flow exceeds the estimate of the 100-year AEP flow (i.e. *Q100 Upper* in Table 14), with stations with the highest ratio retained for the verification group. However, some values for the 95% confidence interval could not be determined. These values were prioritized over the high ratio values to be in the verification group. Three quarters of gauge stations were used to develop the regression equations, with the remaining stations used as verification for both regions.

Consistent with previous RFFA studies for Newfoundland and Labrador, three regression parameters were considered for this study, specifically drainage area (DA), lake attenuation factor (LAF), and lakes and swamp factor (LSF). The single parameter log regression analyses only considered DA. The multiple log regression analyses considered DA and LAF in the Southeast region and DA and LSF in the Southwest region., where LAF is given by:

$$LAF = \sum_{i=1}^{n} [(100\frac{L_{areai}}{DA})\,(100\frac{C_{areai}}{DA})] \qquad \text{[Eq.3]}$$

where $n$ is the number of lakes with surface area greater than 1% of the gauge DA in which they reside, $L_{areai}$ is the area of lake $i$, $DA$ is the drainage area of the gauge station, and $C_{areai}$ is the drainage area of lake $i$. LSF is defined as:

$$LSF = (1 + FACLS) - \frac{FLSAR}{(1 + FACLS)} \qquad \text{[Eq.4]}$$

where *FACLS* is the fraction of the watershed area controlled by lakes and swamps, and *FLSAR* is the fraction of watershed area occupied by lakes and swamps.

The LAF values used in this study were taken from the 2014 RFFA study. Where no value was provided the LAF was determined through similar GIS processes as the DA's. Due to the nature of the log regression equation (Eq. 1) LAF values of zero will result in the regression equation going to infinity. Similar to the 1999 and 2014 RFFA studies, a value of 50 was used in place of those stations with LAF values of zero.

All values for the LSF were taken from the 2014 RFFA study. The values of the regression parameters for each gauge station are summarized in Table 15.

### TABLE 15: RFFA REGRESSION ANALYSIS PARAMETERS

| Station Number | Station Name | Region | DA ($km^2$) | LAF | LSF |
|---|---|---|---|---|---|
| **02YJ001** | HARRYS RIVER BELOW HIGHWAY BRIDGE | SW | 618 | | 1.67 |
| **02YJ003** | PINCHGUT BROOK AT OUTLET OF PINCHGUT LAKE | SW | 116 | | 1.95 |
| **02YN002** | LLOYDS RIVER BELOW KING GEORGE IV LAKE | SW | 481 | | 1.91 |
| **02ZA001** | LITTLE BARACHOIS BROOK NEAR ST. GEORGE'S | SW | 337 | | 1.78 |
| **02ZA002** | HIGHLANDS RIVER AT TRANS-CANADA HIGHWAY | SW | 70 | | 1.39 |
| **02ZA003** | LITTLE CODROY RIVER NEAR DOYLES | SW | 128 | | 1.66 |
| **02ZB001** | ISLE AUX MORTS RIVER BELOW HIGHWAY BRIDGE | SW | 204 | | 1.52 |
| **02ZC002** | GRANDY BROOK BELOW TOP POND BROOK | SW | 252 | | 1.3 |
| **02ZD002** | GREY RIVER NEAR GREY RIVER | SW | 4588 | | 1.51 |
| **02ZE001** | SALMON RIVER AT LONG POND | SW | 5921 | | 1.92 |
| **02ZE004** | CONNE RIVER AT OUTLET OF CONNE RIVER POND | SW | 100 | | 1.81 |
| **02ZF001** | BAY DU NORD RIVER AT BIG FALLS | SW | 1172 | | 1.84 |
| **02ZG001** | GARNISH RIVER NEAR GARNISH | SE | 211 | 202 | |
| **02ZG002** | TIDES BROOK BELOW FRESHWATER POND | SE | 164 | 588 | |
| **02ZG003** | SALMONIER RIVER NEAR LAMALINE | SE | 116 | 43 | |
| **02ZG004** | RATTLE BROOK NEAR BOAT HARBOUR | SE | 44 | 123 | |
| **02ZH002** | COME BY CHANCE RIVER NEAR GOOBIES | SE | 35 | 21 | |
| **02ZK001** | ROCKY RIVER NEAR COLINET | SE | 296 | 9 | |
| **02ZK005** | TROUT BROOK NEAR BELLEVUE | SE | 47 | 92 | |
| **02ZK006** | RATTLING BROOK BELOW BRIDGE | SE | 34 | 469 | |
| **02ZL003** | SPOUT COVE BROOK NEAR SPOUT COVE | SE | 11 | 319 | |
| **02ZL004** | SHEARSTOWN BROOK AT SHEARSTOWN | SE | 30 | 50 | |
| **02ZL005** | BIG BROOK AT LEAD COVE | SE | 11 | 272 | |
| **02ZM006** | NORTHEAST POND RIVER AT NORTHEAST POND | SE | 4 | 265 | |
| **02ZM008** | WATERFORD RIVER AT KILBRIDE | SE | 53 | 50 | |
| **02ZM010** | WATERFORD RIVER AT MOUNT PEARL | SE | 18 | 50 | |

| Station Number | Station Name | Region | DA ($km^2$) | LAF | LSF |
|---|---|---|---|---|---|
| **02ZM016** | SOUTH RIVER NEAR HOLYROOD | SE | 17 | 148 | |
| **02ZM017** | LEARY BROOK AT ST. JOHN'S | SE | 7 | 50 | |
| **02ZM018** | VIRGINIA RIVER AT PLEASANTVILLE | SE | 12 | 21 | |
| **02ZM019** | VIRGINIA RIVER AT CARTWRIGHT PLACE | SE | 5 | 105 | |
| **02ZM020** | LEARYS BROOK AT PRINCE PHILIP DRIVE | SE | 15 | 50 | |
| **02ZM021** | SOUTH BROOK AT PEARL TOWN ROAD | SE | 10 | 50 | |
| **02ZN001** | NORTHWEST BROOK AT NORTHWEST POND | SE | 90 | 132 | |
| **02ZN002** | ST. SHOTTS RIVER NEAR TREPASSEY | SE | 16 | 512 | |
| **02ZK002** | NORTHEAST RIVER NEAR PLACENTIA | SE | 93 | 250 | |

The one-parameter and two-parameter regression equations were developed for the Southeast and Southwest regions of Newfoundland for the 2, 5, 20, 50, and 100-year return periods. The regression correlation coefficient (SMR) and the standard error of the estimate (SEE) are summarized in Table 16. SMR values represents the variance in the dependant variable that can be explained by the regression parameters, where 1 is a perfect correlation and 0 shows no correlation. The SEE values, which measure the variation of the actual values to the computed values, measures the accuracy of the regression equation with a lower value depicting more accurate results.

### TABLE 16: REGRESSION EQUATION STATISTICS

| | SE Region | | | SW Region | | |
|---|---|---|---|---|---|---|
| | AEP Return Period | SMR | SEE | AEP Return Period | SMR | SEE |
| Two Parameter | 2 Year | 0.920 | 0.133 | 2 Year | 0.774 | 0.219 |
| | 5 Year | 0.922 | 0.133 | 5 Year | 0.776 | 0.211 |
| | 10 Year | 0.921 | 0.135 | 10 Year | 0.772 | 0.207 |
| | 20 Year | 0.918 | 0.139 | 20 Year | 0.764 | 0.205 |
| | 50 Year | 0.912 | 0.146 | 50 Year | 0.747 | 0.206 |
| | 100 Year | 0.906 | 0.153 | 100 Year | 0.729 | 0.209 |
| One Parameter | 2 Year | 0.883 | 0.156 | 2 Year | 0.650 | 0.253 |
| | 5 Year | 0.898 | 0.147 | 5 Year | 0.637 | 0.249 |
| | 10 Year | 0.904 | 0.143 | 10 Year | 0.618 | 0.248 |
| | 20 Year | 0.907 | 0.143 | 20 Year | 0.595 | 0.249 |
| | 50 Year | 0.906 | 0.146 | 50 Year | 0.557 | 0.252 |
| | 100 Year | 0.902 | 0.150 | 100 Year | 0.525 | 0.256 |

The regression equations for the Southeast region provided more accurate estimations of the return period flows than the regression equations developed for the Southwest region considering both the one-parameter and two-parameter equations. For the Southeast region, DA accounted for 88% to 90% of the variation in flows. The addition of the LAF only provides a marginal increase in the correlation and accuracy relative to considering DA alone. The impact of DA in the Southwest region accounts for 52% to 65% of the variation in the flows. This is consistent with the findings of the 2014 RFFA. The addition of LSF for the Southwest region increased the SMR values to 73% to 78%.

The regression equations developed as part of this study were compared to the results of the previous two RFFA results for Newfoundland and Labrador completed in 1999 and 2014, specifically comparing the SMR and SEE. The comparison is summarized in Table 17.

### TABLE 17: COMPARISON BETWEEN THE 1999, 2014 AND 2021 RFFA

| Study | Region | Parameters | Range of SMR | Range of SEE |
|---|---|---|---|---|
| **2021** | SE | DA, LAF | 0.906 - 0.920 | 0.133 - 0.153 |
| | SW | DA, LSF | 0.729 - 0.774 | 0.209 - 0.219 |
| **2014** | SE | DA, LAF | 0.929 - 0.942 | 0.120 - 0.132 |
| | SW | DA, LSF | 0.835 - 0.887 | 0.164 - 0.215 |
| **1999** | SE | DA, LAF | 0.929 - 0.967 | 0.088 - 0.129 |
| | SW | DA, LSF | 0.829 - 0.924 | 0.140 - 0.237 |

The comparison shows that the RFFA completed as part of this study (i.e. 2021 RFFA) has comparably accurate regression equations to the 1999 and 2014 studies, albeit with somewhat lower SMR values and somewhat higher SEE values. Some of the differences in SMR and SEE can be attributed to different statistical hydrology software being used in fitting the distributions as part of the SSFA of each station, as well as differences in the data available for the RFFA.

The one- and two-parameter regression equations developed as part of the RFFA completed for this project for the Southeast region are summarized in Table 18 and Table 19, while those defined for the Southwest region are summarized in Table 20 and Table 21.

### TABLE 18: ONE-PARAMETER EQUATIONS FOR THE SOUTHEAST REGION

| One Parameter Equations | SMR | SEE |
|---|---|---|
| $Q_2 = 1.447(DA^{0.770})$ | 0.883 | 0.156 |
| $Q_5 = 1.946(DA^{0.785})$ | 0.898 | 0.147 |
| $Q_{10} = 2.265(DA^{0.795})$ | 0.904 | 0.143 |
| $Q_{20} = 2.565(DA^{0.805})$ | 0.907 | 0.143 |
| $Q_{50} = 2.947(DA^{0.817})$ | 0.906 | 0.146 |
| $Q_{100} = 3.231(DA^{0.826})$ | 0.902 | 0.150 |

### TABLE 19: TWO-PARAMETER EQUATIONS FOR THE SOUTHEAST REGION

| Two Parameter Equations | SMR | SEE |
|---|---|---|
| $Q_2 = 3.904(DA^{0.718})(LAF^{-0.181})$ | 0.920 | 0.133 |
| $Q_5 = 4.344(DA^{0.742})(LAF^{-0.146})$ | 0.922 | 0.133 |
| $Q_{10} = 4.447(DA^{0.760})(LAF^{-0.123})$ | 0.921 | 0.135 |
| $Q_{20} = 4.478(DA^{0.776})(LAF^{-0.102})$ | 0.918 | 0.139 |
| $Q_{50} = 4.460(DA^{0.796})(LAF^{-0.076})$ | 0.912 | 0.146 |
| $Q_{100} = 4.424(DA^{0.810})(LAF^{-0.057})$ | 0.906 | 0.153 |

### TABLE 20: ONE-PARAMETER EQUATIONS FOR THE SOUTHWEST REGION

| One Parameter Equations | SMR | SEE |
|---|---|---|
| $Q_2 = 9.534(DA^{0.513})$ | 0.650 | 0.253 |
| $Q_5 = 15.455(DA^{0.491})$ | 0.637 | 0.249 |
| $Q_{10} = 21.326(DA^{0.470})$ | 0.618 | 0.248 |
| $Q_{20} = 28.600(DA^{0.449})$ | 0.595 | 0.249 |
| $Q_{50} = 40.758(DA^{0.422})$ | 0.557 | 0.252 |
| $Q_{100} = 42.234(DA^{0.402})$ | 0.525 | 0.256 |

### TABLE 21: TWO-PARAMETER RFFA EQUATIONS FOR THE SOUTHWEST REGION

| Two Parameter Equations | SMR | SEE |
|---|---|---|
| $Q_2 = 15.062(DA^{0.643})(LSF^{-2.633})$ | 0.774 | 0.219 |
| $Q_5 = 24.696(DA^{0.625})(LSF^{-2.699})$ | 0.776 | 0.211 |
| $Q_{10} = 34.4423(DA^{0.607})(LSF^{-2.757})$ | 0.772 | 0.207 |
| $Q_{20} = 46.645(DA^{0.588})(LSF^{-2.817})$ | 0.764 | 0.205 |
| $Q_{50} = 67.330(DA^{0.565})(LSF^{-2.890})$ | 0.747 | 0.206 |
| $Q_{100} = 87.094(DA^{0.548})(LSF^{-2.944})$ | 0.729 | 0.209 |

Similar to the SSFA, the appropriateness of the RFFA equations is dependent on the physiographic parameters (i.e. basin size, slope, land cover, etc.) of ungauged basins relative to those considered in the RFFA. Given that the smallest basin areas of 70 km$^2$ for the Southwest region and 4 km$^2$, the RFFA equations should be considered inappropriate to use for basin sizes smaller than the smallest basins considered in each of the RFFA equation sets. The 20 and 100-year AEP flows defined by the RFFA equations for the rivers and creeks considered in the Carbonear, Salmon Cove and Victoria area are summarized in Table 22, while the 20 and 100-year AEP flows defined by the RFFA equations for the Placentia area are summarized in Table 23.

### TABLE 22: RFFA FLOWS FOR CARBONEAR, SALMON COVE AND VICTORIA

| Location | RFFA – 1 Parameter | | RFFA – 2 Parameter | |
|---|---|---|---|---|
| | 20-Year Flow (m$^3$/s) | 100-Year Flow (m$^3$/s) | 20-Year Flow (m$^3$/s) | 100-Year Flow (m$^3$/s) |
| Salmon Cove River at U/S Model Boundary | 20.7 | 27.6 | 21.2 | 28.0 |
| Big Brook above Salmon Cove River | 22.1 | 29.4 | 22.6 | 29.9 |
| Local Creek 5 above Salmon Cove River | 3.2 | 4.0 | 3.2 | 4.1 |
| Clark Brook above Double Brook | 4.8 | 6.2 | 4.9 | 6.3 |
| Double Brook above Local Creek 4 | 2.8 | 3.5 | 2.8 | 3.6 |
| Local Creek 4 above Double Brook | 2.4 | 3.0 | 2.4 | 3.0 |
| Local Creek 3 above Salmon Cove River | 1.7 | 2.1 | 1.7 | 2.2 |
| Spout Brook | 31.9 | 42.9 | 32.6 | 43.6 |
| Local Creek 2 above Salmon Cove River | 1.5 | 1.8 | 1.5 | 1.9 |
| Local Creek 1 above Salmon Cove River | 1.2 | 1.5 | 1.3 | 1.5 |
| Salmon Cove River Outlet | 78.7 | 108.4 | 80.5 | 110.2 |
| Carbonear Local Creek Outlet | 3.0 | 3.8 | 3.5 | 4.1 |
| Island Pond Brook above Local Creek 1 | 47.1 | 64.1 | 43.6 | 61.6 |
| Local Creek 2 above Local Creek 1 | 0.4 | 0.5 | 0.4 | 0.5 |
| Local Creek 1 above Island Pond Brook | 1.5 | 1.8 | 1.4 | 1.8 |
| Island Pond Brook Outlet | 47.7 | 64.9 | 44.2 | 62.4 |
| Powells Brook Outlet | 14.6 | 19.3 | 16.1 | 20.4 |

TABLE 23: RFFA FLOWS FOR PLACENTIA

| Location | RFFA – 1 Parameter | | RFFA – 2 Parameter | |
|---|---|---|---|---|
| | 20-Year Flow ($m^3/s$) | 100-Year Flow ($m^3/s$) | 20-Year Flow ($m^3/s$) | 100-Year Flow ($m^3/s$) |
| Southeast River Outlet | 261.2 | 313.3 | 206.2 | 296.6 |
| Northeast River Outlet | 216.4 | 264.6 | 188.6 | 278.0 |
| Rattling Brook Outlet | 62.0 | 86.4 | 258.6 | 465.2 |
| Smelt Brook Outlet | 52.1 | 73.9 | 290.9 | 539.7 |
| Local Creek 1 Outlet | 32.2 | 48.0 | 31.1 | 56.0 |
| Baldwins Brook Outlet | 62.0 | 86.4 | 196.5 | 349.0 |
| Local Creek 2 Outlet | 43.2 | 62.5 | 98.1 | 178.2 |
| Little Salmonier River Outlet | 56.2 | 79.1 | 35.4 | 59.0 |
| Local Creek 3 Outlet | 65.8 | 91.2 | 29.7 | 48.0 |
| Local Creek 4 Outlet | 48.2 | 69.0 | 63.9 | 112.0 |
| Mill Brook Outlet | 49.5 | 70.7 | 33.6 | 57.0 |
| Local Creek 5 Outlet | 67.6 | 93.4 | 70.3 | 117.7 |
| Shalloway Brook Outlet | 73.6 | 100.7 | 24.9 | 39.2 |
| Sound Brook Outlet | 138.9 | 178.0 | 120.2 | 185.3 |
| Glennon's Cove River Outlet | 124.8 | 161.7 | 507.5 | 848.4 |

## 6.3 Deterministic Analyses

### 6.3.1 MODEL DEVELOPMENT

Hydrologic models of the Carbonear, Salmon Cove and Victoria area and Placentia area were developed using the Hydrologic Engineering Centre's Hydrologic Modelling System (HEC-HMS) version 4.9 (U.S. Army Corps of Engineers, 2018). The Geospatial Hydrologic Modelling (HEC-GeoHMS) extension was used to develop the HEC-HMS models in Esri ArcMap 10.8. 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.

Two HEC-HMS models developed as sub-basin models, one for the Placentia area, and one that represented the Carbonear, Salmon Cove and Victoria area. Sub-basins within the models were defined based on the watershed DEM, as described in Section 4.3, using HEC-GeoHMS in ArcMap. Sub-basins were defined throughout all of the creeks and rivers being considered as part of this study, as well as local sources of flow between major tributaries. The delineated sub-basins for the Carbonear, Salmon Cove, and Victoria area model are shown on Figure 41, while the sub-basins for the Placentia area model are shown on Figure 42.

## FIGURE 41: CARBONEAR, SALMON COVE AND VICTORIA AREA MODEL SUB-BASINS

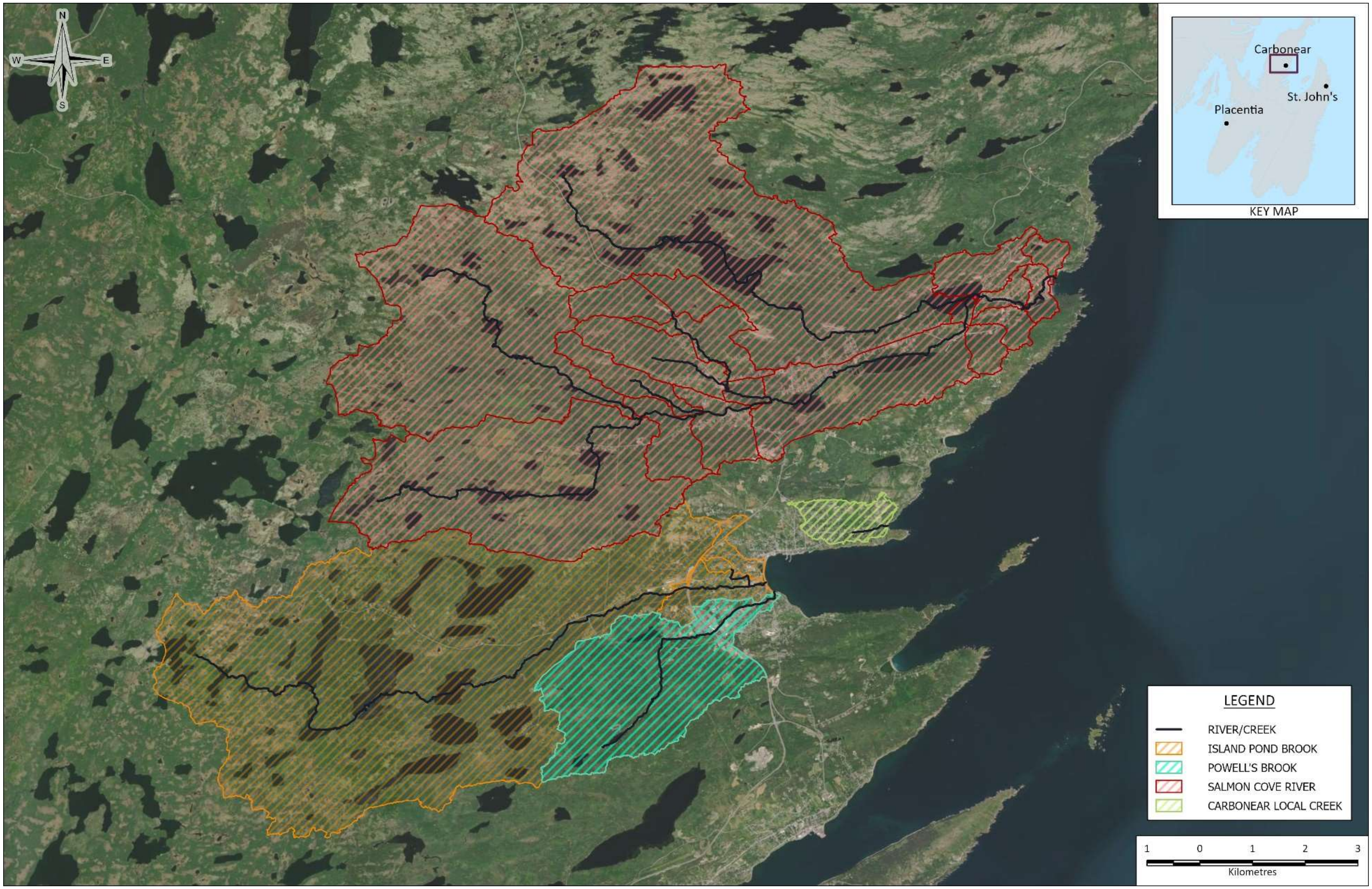
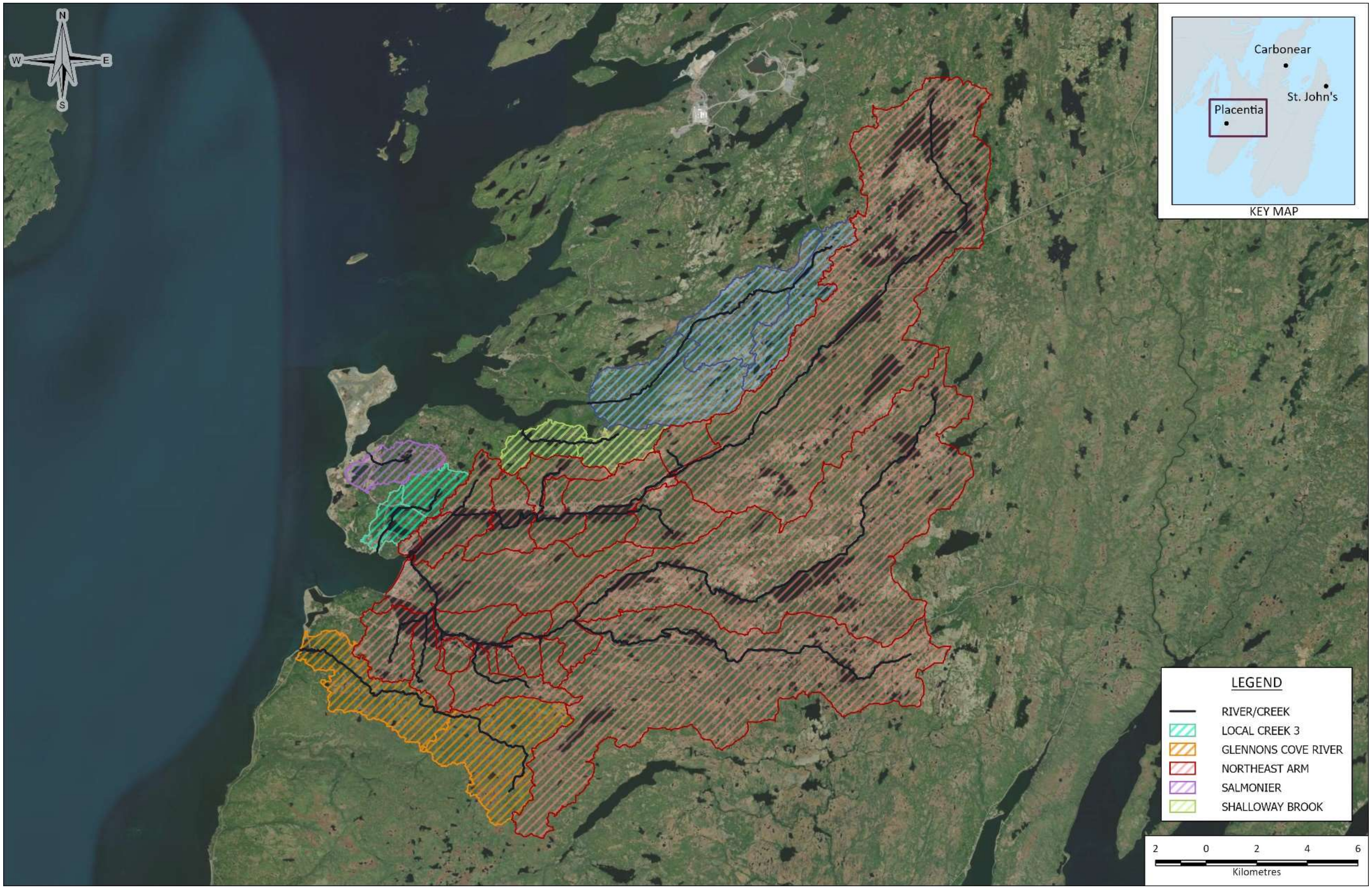


FIGURE 42: PLACENTIA AREA MODEL SUB-BASINS



Following the sub-basin delineation, terrain pre-processing was completed to fill surface depressions within the watershed DEM, define flow directions within the DEM, and the generation of the stream networks within the models. Physical characteristics of the watersheds, such as stream characteristics, curve numbers, and basin lag times were estimated from the watershed DEM and CN maps described in Section 5.5. The parameterization of the HEC-HMS models was subsequently adjusted during the model calibration process.

The physical processes that were included in the HEC-HMS model were defined using standard hydrologic methods included in the modelling software. Snowmelt was not considered in the model, as only rainfall-only events were considered in the calibration and implementation of the model. These processes, as well as the hydrologic method incorporated into the model to describe them, are summarized in Table 24.

### TABLE 24: HEC-HMS REPRESENTATION OF PHYSICAL PROCESSES

| Physical Process | Modelling Method |
|---|---|
| **Transform** | Clark Unit Hydrograph |
| **Infiltration** | SCS Curve Number |
| **Baseflow** | Recession |
| **Routing** | Muskingum-Cunge |

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 25, as well as the minimum, maximum and recommended values for each parameter, where available.

## TABLE 25: OVERVIEW OF MODEL PROCESSES

| 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 |
| **Loss** | Initial Abstraction | mm | Amount of precipitation that must fall before surface excess results | 0 | N/A | N/A |
| **Loss** | Curve Number | unitless | Composite Curve Number for the sub-basin | 0 | 100 | 30 - 100 |
| **Loss** | Impervious | % | Percentage of the subbasin that is impervious | 0 | 100 | 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** | Ratio to Peak | unitless | Ratio from the peak flow at which baseflow will be reset on the receding limb | 0 | 1 | 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 |

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

As previously noted, the HEC-HMS models were set up as sub basin models. Sub basin models require meteorological inputs from point locations, which are used to drive runoff responses. While there is a precipitation station near Placentia at Argentia, there are considerable gaps in the available precipitation data, and the station is no longer active. In Carbonear, Salmon Cove, and Victoria, the nearest precipitation stations are either in St. John's or near Shearstown. In light of these gaps in the available precipitation data, precipitation time series were defined based on precipitation data from the Canadian Precipitation Analysis (CaPA) product.

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 on the Avalon peninsula, as well as the sharp gradients in precipitation that can occur, would introduce considerable uncertainty into any interpolation method. Furthermore, Environment Canada gauge data suffers from well documented systematic biases including wind driven undercatch, 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. Accordingly, CaPA data was used as the precipitation input for the hydrologic modelling.

The HEC-HMS models were developed with the intention of single-event simulations, for which the SCS Curve Number method is appropriate. Furthermore, given that the model was ultimately to be used to simulate rainfall events, it was conservatively assumed that none of the precipitation would accumulate into snowpack and would fall strictly as rainfall. Based on this conservative assumption, no temperature inputs were required for the model.

### 6.3.2 MODEL CALIBRATION

The HEC-HMS models were calibrated to two recent rainfall events and validated to a third, separate event. In the Carbonear, Salmon Cove and Victoria area, the model was calibrated to precipitation events on June 26, 2018, and January 30, 2022, and validated to the rainfall that occurred on November 31, 2021. The rainfall intensity associated with those events are shown on Figure 43 to Figure 45.

**FIGURE 43: CARBONEAR, SALMON COVE AND VICTORIA AREA MODEL JUNE 2018 RAINFALL**

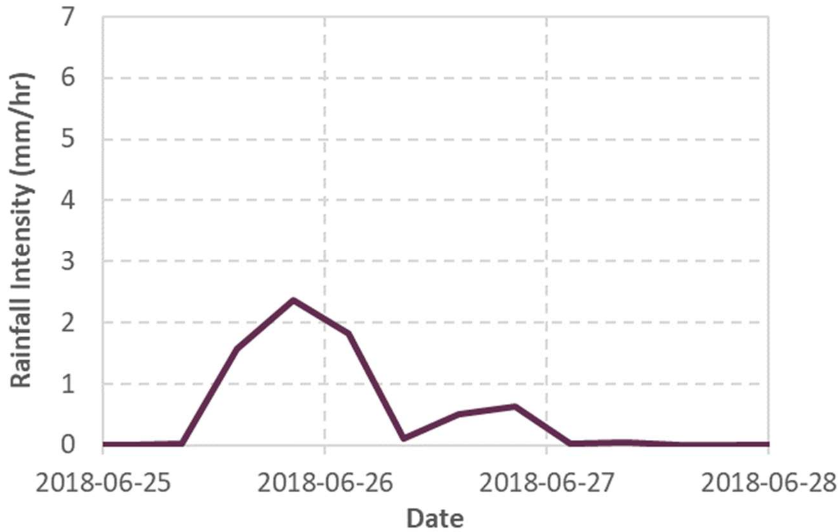



**FIGURE 44: CARBONEAR, SALMON COVE AND VICTORIA AREA MODEL JANUARY 2022 RAINFALL**

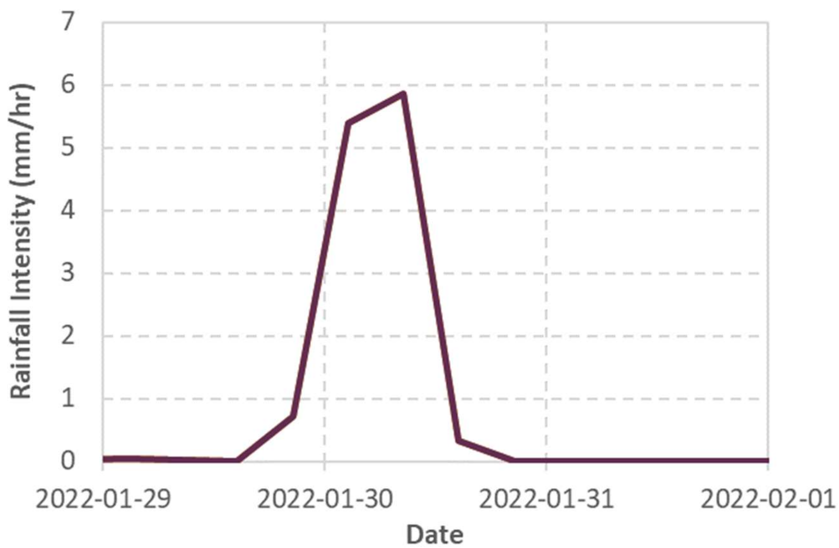
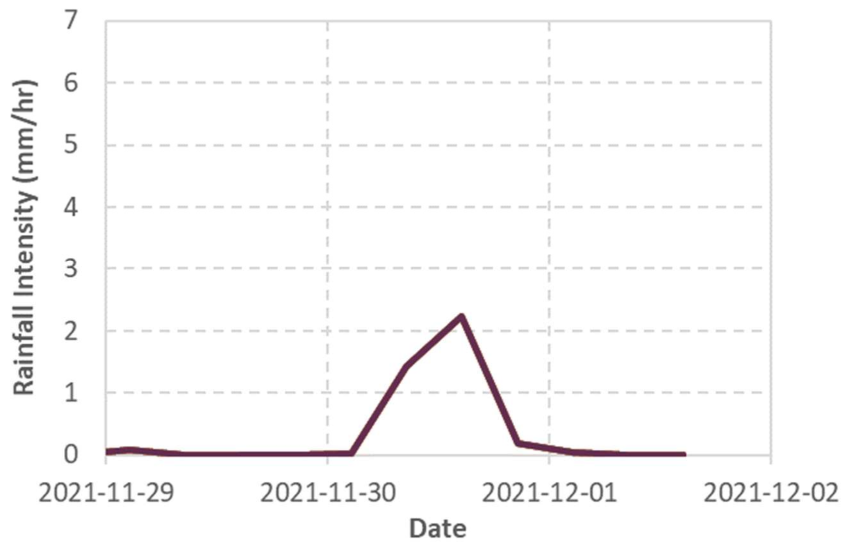
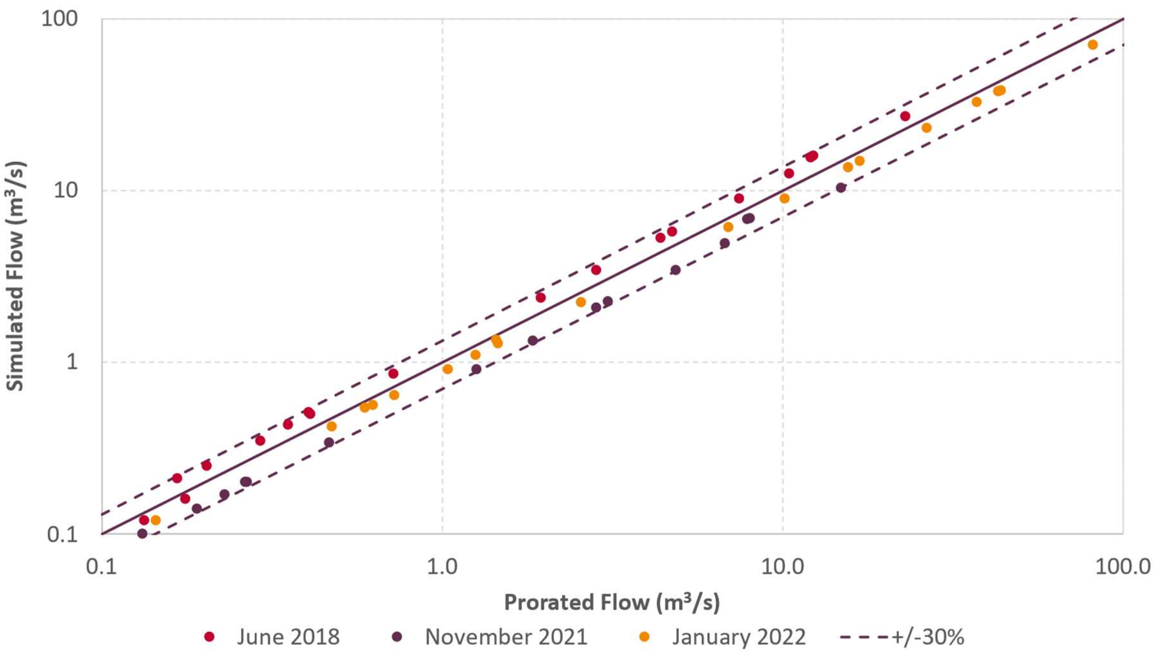


**FIGURE 45: CARBONEAR, SALMON COVE AND VICTORIA AREA MODEL NOVEMBER 2021 RAINFALL**




Since gauged flows were not available on any of the rivers being considered in the flood mapping study in this area, it was not possible to directly compare recorded and simulated flows. Instead, peak flows from the WSC gauge 02ZL004 (i.e. Shearstown Brook at Shearstown) were prorated to areas of interest to provide an estimate of the peak flows on the ungauged rivers. The model parameters in each basin were adjusted to provide an accurate representation of the prorated peak flows for each of the calibration events, and were then confirmed via the validation simulation. A comparison of the simulated peak flows at the various sub-basins in the Carbonear, Salmon Cove, and Victoria HEC-HMS model to the corresponding prorated peak flows are shown on Figure 46.

### FIGURE 46: COMPARISON OF SIMULATED AND PRORATED PEAK FLOWS IN THE CARBONEAR, SALMON COVE AND VICTORIA AREA MODEL




The comparison of the simulated and prorated peak flows showed good agreement between the flows defined by the HEC-HMS model and the prorated flows, with all peak flows being within +/- 30%.

Similar to the HEC-HMS model for the Carbonear, Salmon Cove and Victoria, the Placentia area HEC-HMS model was calibrated and validated considering three separate rainfall events. Specifically, the model was calibrated to the rainfall events on April 4, 2016, and September 20, 2020, and validated to the rainfall that occurred on November 31, 2021. The rainfall intensity associated with those events is shown on Figure 47 to Figure 49.

FIGURE 47: PLACENTIA AREA MODEL APRIL 2016 RAINFALL

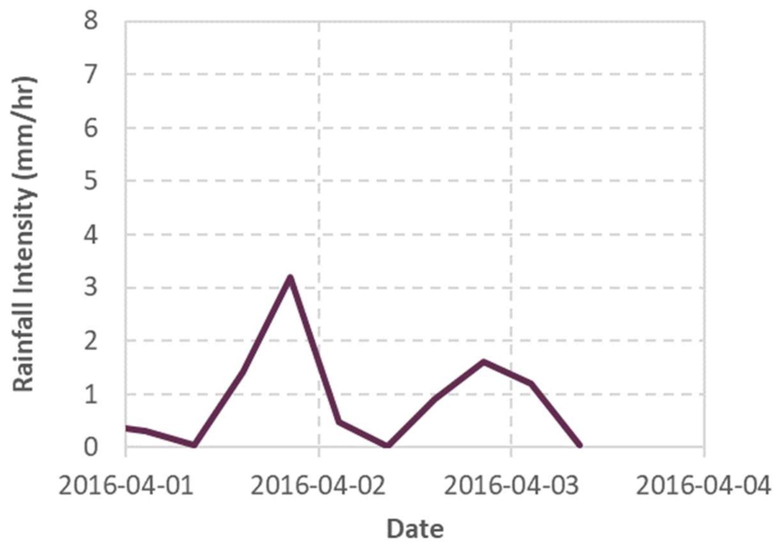



FIGURE 48: PLACENTIA AREA MODEL SEPTEMBER 2020 RAINFALL

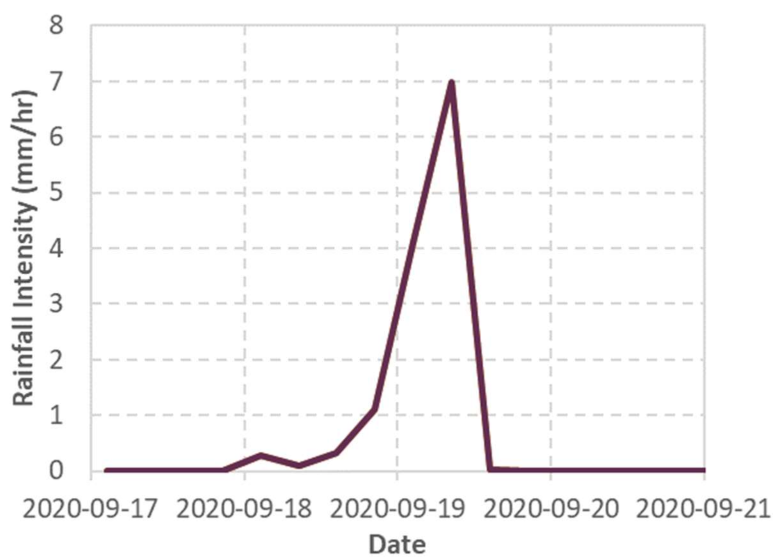
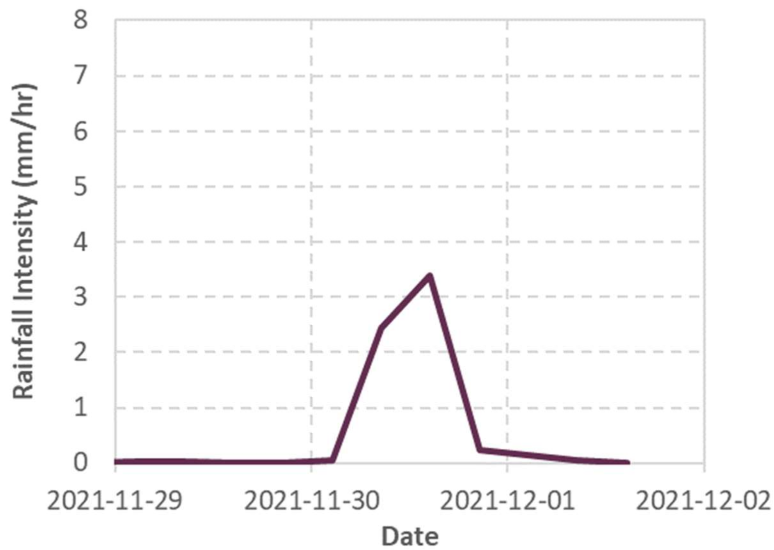
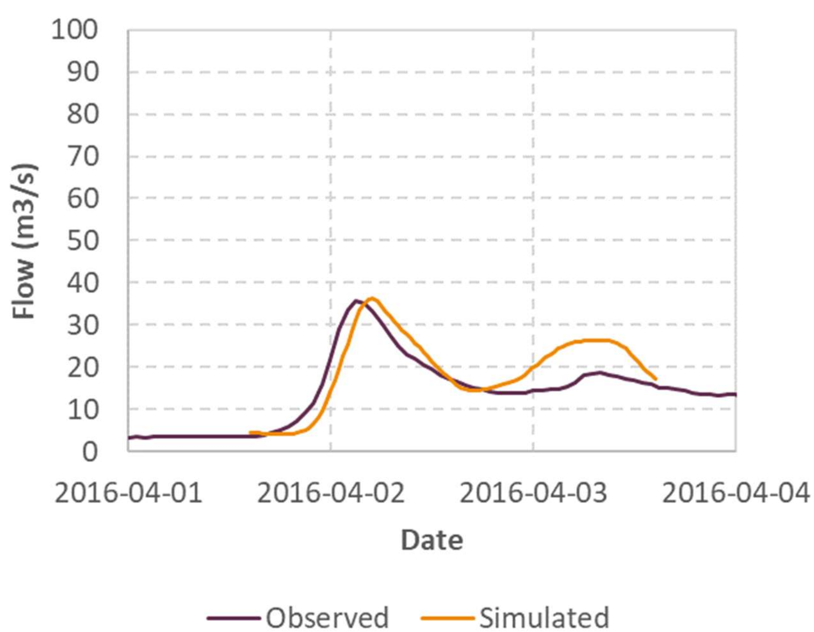


FIGURE 49: PLACENTIA AREA MODEL NOVEMBER 2021 RAINFALL

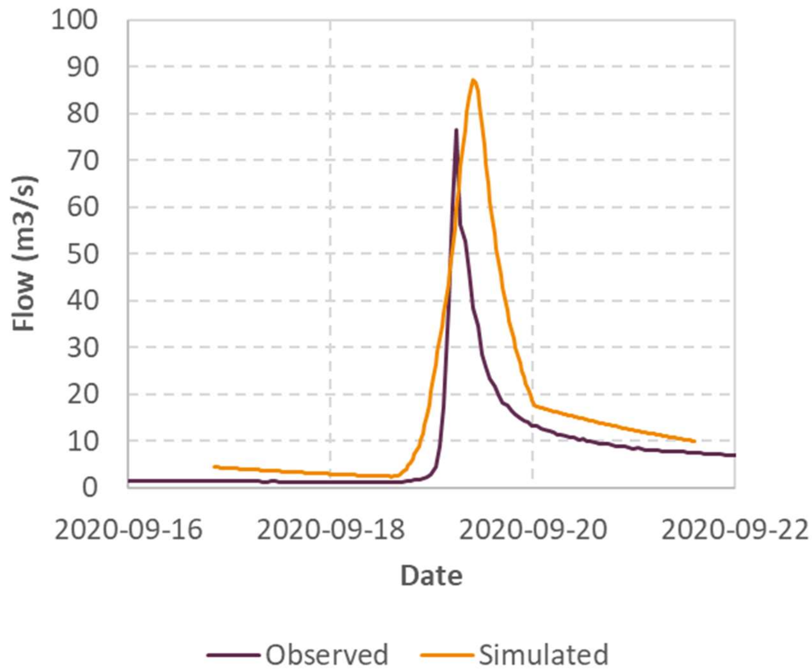



Unlike the Carbonear, Salmon Cove and Victoria HEC-HMS model, recorded flows were available within the Placentia HEC-HMS model domain on the Northeast River. This allowed for the direct comparison of the simulated flows for the calibration and validation flood events on the Northeast River, providing a much clearer picture of the model performance. Comparisons of the simulated and observed flows on the Northeast River for the April 2016, September 2020, and November 2021 rainfall events are shown on Figure 50 to Figure 52.

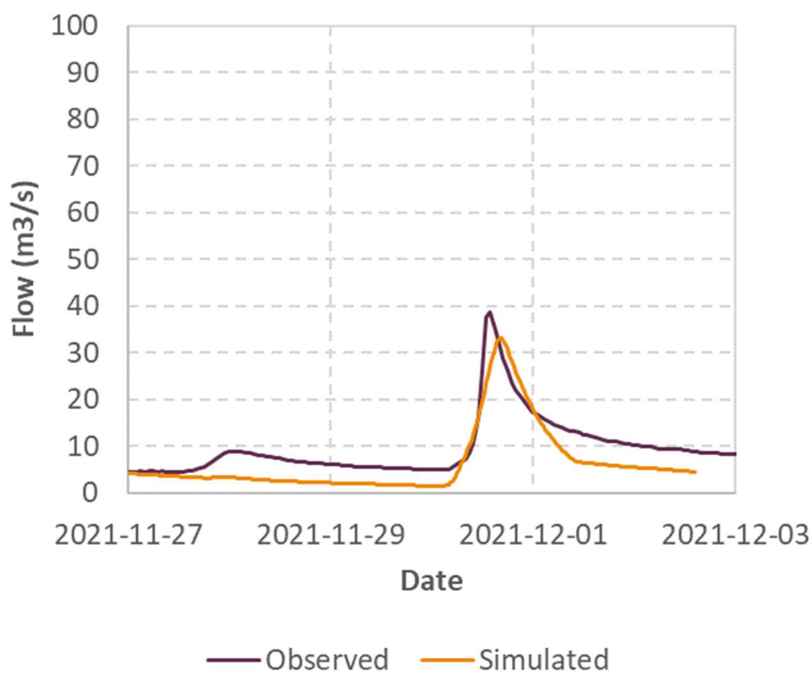
FIGURE 50: NORTHEAST RIVER SIMULATED AND OBSERVED FLOWS FOR APRIL 2016



## FIGURE 51: NORTHEAST RIVER SIMULATED AND OBSERVED FLOWS FOR SEPTEMBER 2020



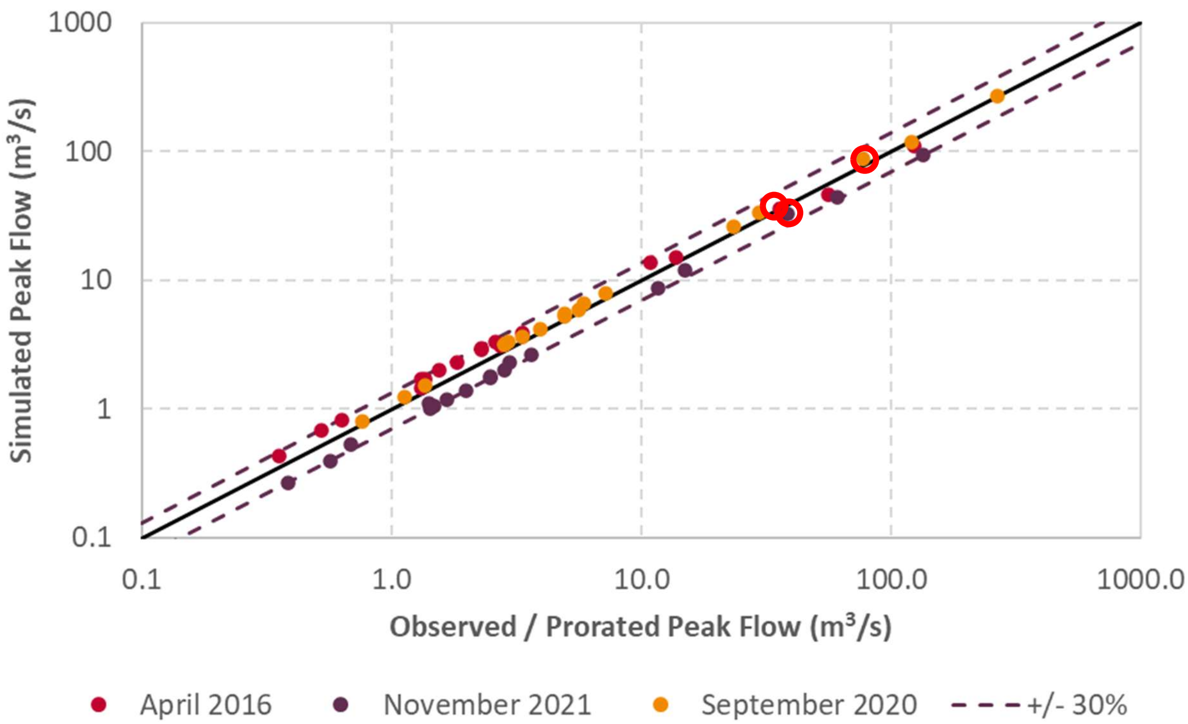

## FIGURE 52: NORTHEAST RIVER SIMULATED AND OBSERVED FLOWS FOR NOVEMBER 2021



The simulated flows on the Northeast River were found to be in good agreement with the observed flows, with the simulated peak flows within 15% of the observed peak flows and the timing of the simulated peaks within hours of the observed peaks.

Similar to the Carbonear area model, for ungauged basins, the observed peak flow rates from the calibration and validation simulations were prorated to the ungauged basins on the basis of drainage area to serve as a basis for adjusting the ungauged basins in the HEC-HMS model. A comparison of the simulated peak flows at the various sub-basins in the Placentia HEC-HMS model to the corresponding prorated peak flows are shown on Figure 53, with the recorded peaks at the Northeast River highlighted in red.

FIGURE 53: COMPARISON OF SIMULATED AND PRORATED FLOWS IN THE PLACENTIA AREA MODEL




The comparison of the simulated and prorated peak flows showed good agreement between the flows defined by the HEC-HMS model and the prorated flows, with all peak flows being within +/- 30%.

The HEC-HMS models were considered to be reasonably calibrated and suitable for use in defining the flows on the various rivers and creeks associated with the 20 and 100-year AEP rainfall events.

## 6.4 Precipitation Analysis

### 6.4.1 EXISTING CONDITIONS IDF CURVES

An update was completed for IDF curves at Argentia and St. John's for inclusion in the hydrologic model to define flow rates on the various rivers and creeks within the study area for the 20 and 100-year AEP rainfall events. These stations were selected for updating as they are the closest stations to the study areas. Precipitation records were reviewed for each of the stations. The status of each station, as well as the data available for each station are summarized in Table 26.

TABLE 26: SUMMARY OF ECCC IDF CURVE STATIONS

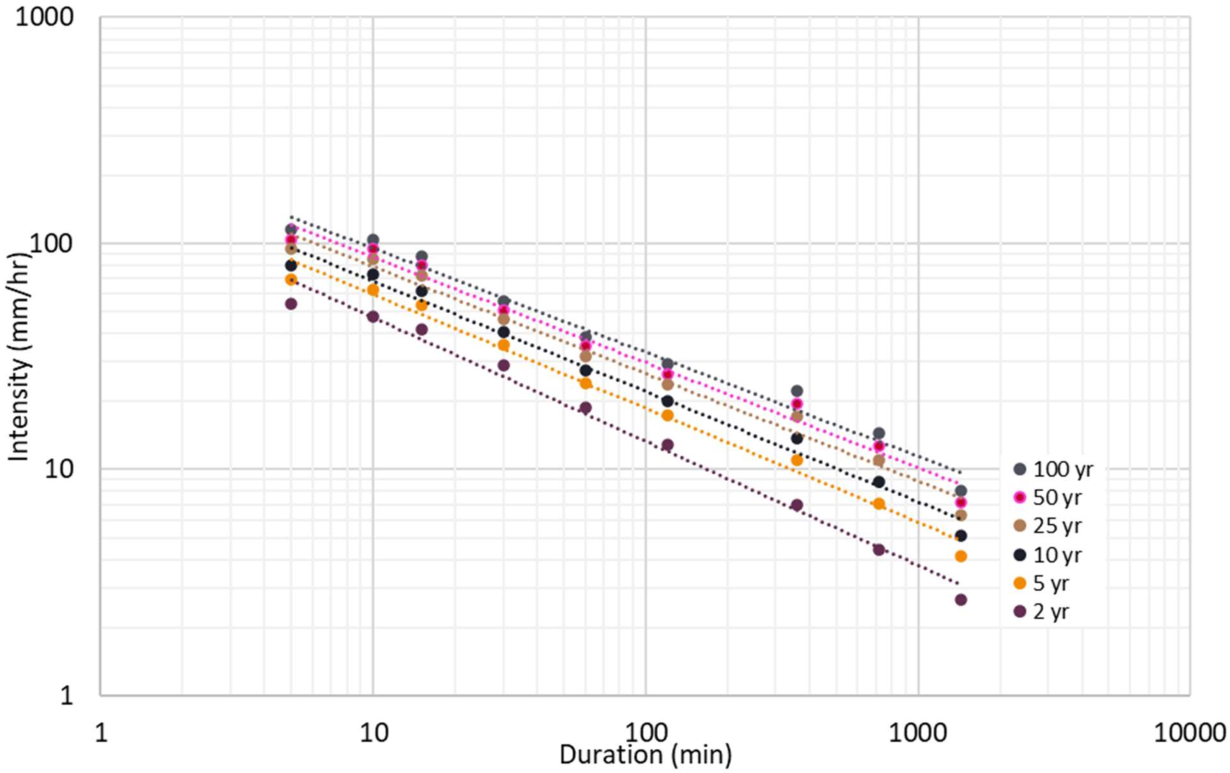
| Station Name | Station ID | Duration of Data in IDF Curve | Number of Years of Data | Status of Station |
|---|---|---|---|---|
| **Argentia (AUT)** | 8400104 | 1980 - 2013 | 17 | Inactive (as of 2017) |
| **St. John's A** | 8403506 | 1949-1996 | 35 | Inactive (as of 2012) |

The IDF curves were updated based on available precipitation data in the region. As most stations record precipitation year-round and record "total precipitation", the data was separated into solid precipitation (i.e. snow) versus liquid (i.e. rain). Snow was classified when the mean air temperature was less than zero degrees Celsius (<0˚C), whereas rainfall was classified when the mean air temperature was greater than or equal to zero degrees Celsius.

Statistical analysis was completed using the HYFRAN statistical software package. This software is widely used in hydrologic analyses, providing the ability to fit numerous statistical distributions and verify statistical hypothesis for independence and homogeneity. For the stations in this analysis, the Gumbel Method of Moments distribution was used to represent the distribution of the annual maximum rainfall amounts. This method follows procedures documented in the update Report on the IDF curves for the Province of Newfoundland and Labrador by Conestoga-Rovers and Associates (2015).

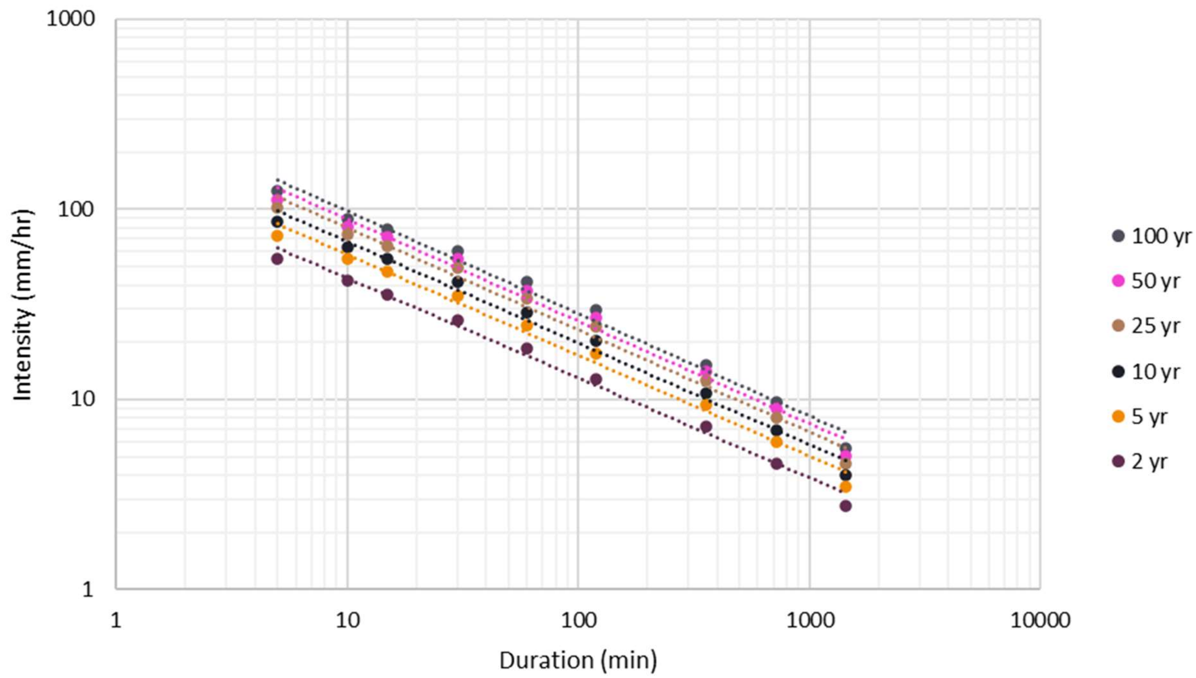
The IDF curve for Argentia (AUT) was updated by using the more recently available 15-min and 1-hr precipitation data at the Argentia (AUT) station from 2013 to 2017. Precipitation data at the station was recorded up to April 10, 2017. All duration precipitation events, excluding the 5-min and 10-min durations, were updated to include the more recent data. Due to the sparse monitoring in the region, there were no nearby stations to supplement or extend the dataset. The resulting updated IDF curve is shown on Figure 54.

FIGURE 54: UPDATED IDF CURVE FOR ARGENTIA (AUT)

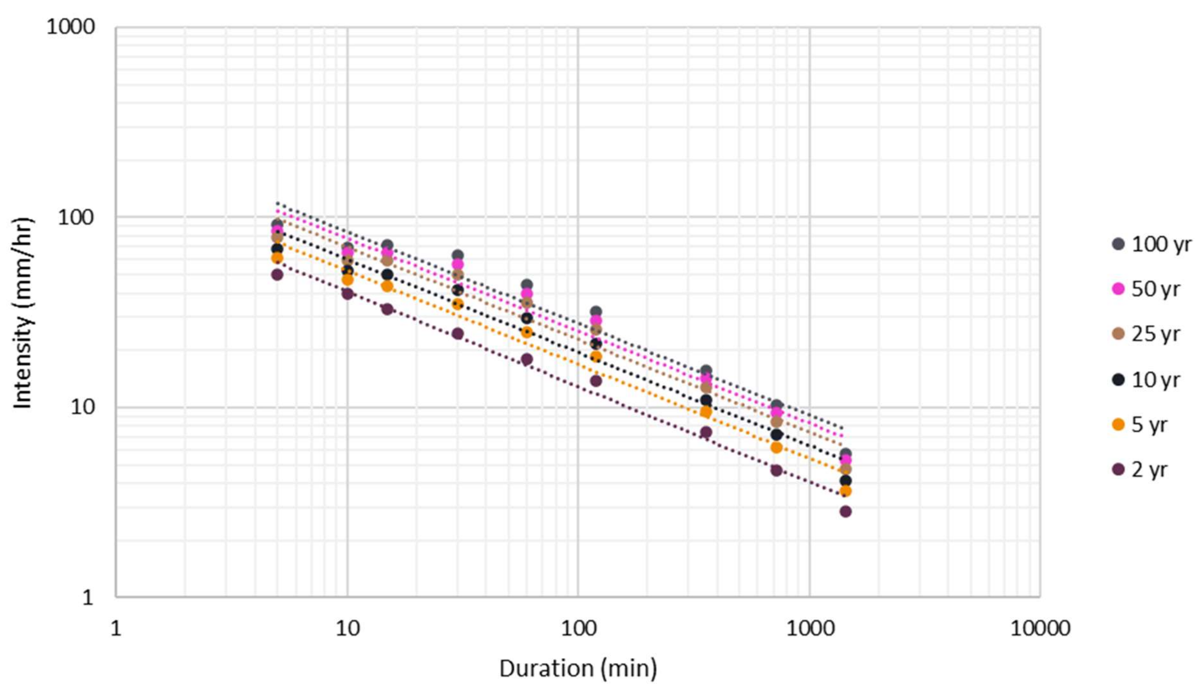



Two IDF curves were updated for St. John's, specifically the St. John's A IDF curve developed by ECCC, as well as the St. John's Ruby Line IDF curve developed as part of the 2015 IDF Curve Update for Newfoundland and Labrador completed by Conestoga-Rovers and Associates (2015). Both IDF curves were updated using additional data from 2015 to 2021 data from the ECCC St. John's West Climate station (i.e. ID 8403603), as this is the only readily available precipitation in the area. The updated IDF curves for St. John's A and St. John's Ruby Line IDF curve are shown on Figure 55 and Figure 56. Rainfall hyetographs developed using the St. John's Ruby Line IDF curve were found to result in greater river flows, and as such the Ruby Line IDF curve was conservatively adopted for the subsequent development of rainfall hyetographs for inclusion in the hydrologic modelling.

## FIGURE 55: UPDATED IDF CURVE FOR ST. JOHN'S A




## FIGURE 56: UPDATED IDF CURVE FOR ST. JOHN'S RUBY LINE



The updated IDF curve for the St. John's Ruby Line station was found to define hyetographs that resulted in higher flows than those defined using the updated St. John's A IDF curve, and was as such adopted for subsequent analyses in the study.

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 G. The updated IDF curves for Argentia (AUT) and St. John's A are also included in a tabular format in Appendix H, for reference.

### 6.4.2 CLIMATE CHANGE IDF CURVES

Future climate change due to increased carbon dioxide emissions is expected to increase global temperatures and result in increased precipitation. The Government of Newfoundland and Labrador recently commissioned a study to assess the anticipated impacts of climate change on IDF curves within Newfoundland and Labrador (Finnis, 2018), which includes IDF curves that have been affected by climate change for a number of Representation Concentration Pathway (RCP) scenarios, and projected to the 2041 – 2070 and 2071 – 2100 timeframes. For this study, the median 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. The 2071 – 2100 timeframe IDF curves were also adopted. The climate change IDF curves for Argentia and St. John's are shown on Figure 57 and Figure 58.

FIGURE 57: CLIMATE CHANGE IDF CURVE FOR ARGENTIA

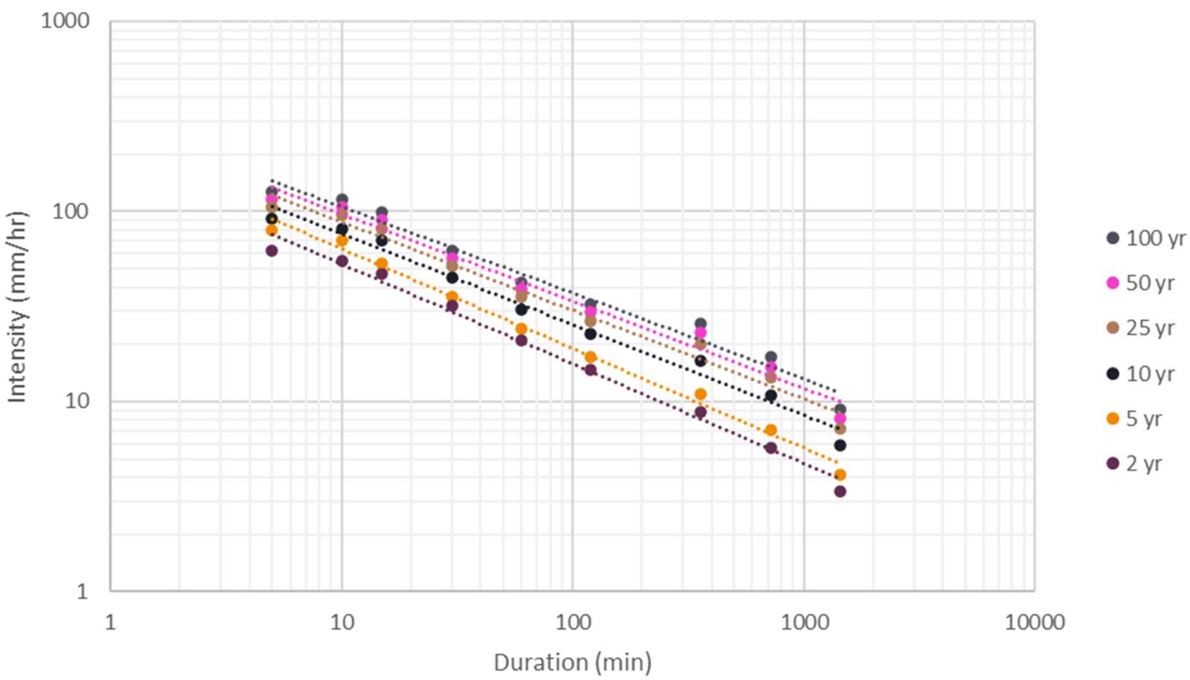
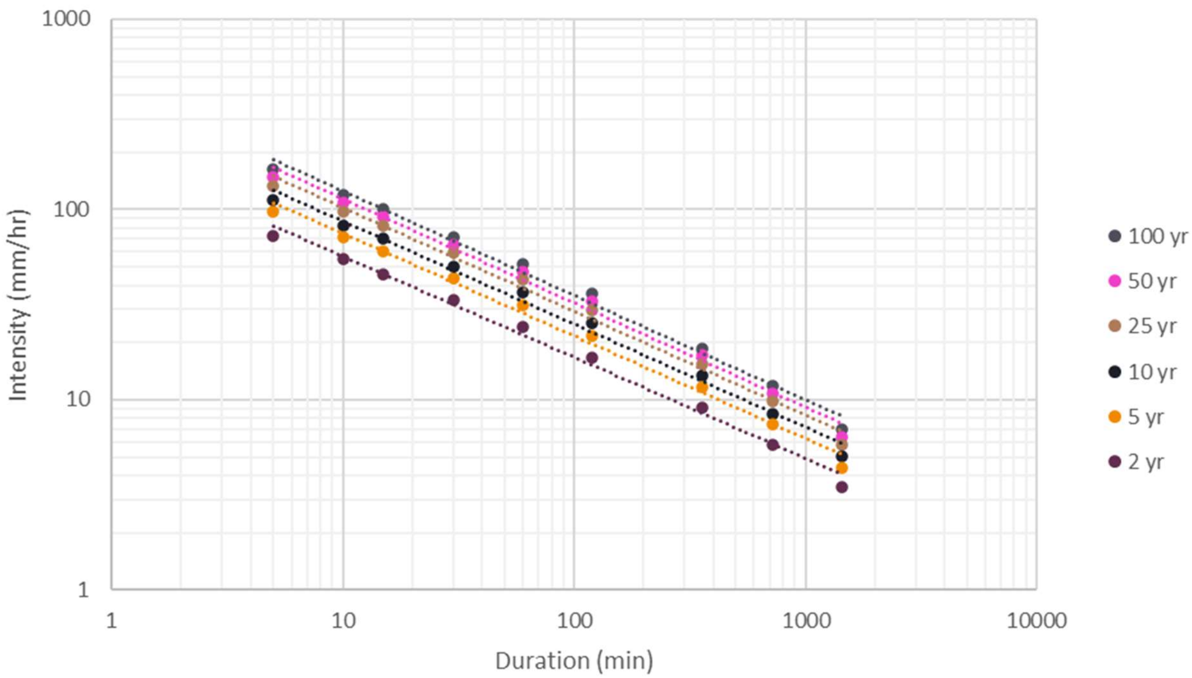


FIGURE 58: CLIMATE CHANGE IDF CURVE FOR ST. JOHN'S




The climate change IDF curves defined by Finnis (2018) were used to develop hyetographs for inclusion in the hydrologic routing of the 20 and 100-year AEP rainfall events to evaluate the impact of climate change on river flows.

## 6.5 Definition and 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 AEP design storms at the Argentia and St. John's stations. The synthetic hyetographs were defined using both 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, and the mass curve method defined by WRMD in the terms of reference. The 6, 12 and 24 hour hyetographs were developed for the Carbonear area based on the St. John's IDF curve to evaluate whether the alternating block or mass curve method was more appropriate for use in the study, and to determine the most appropriate storm duration. The 6, 12, and 24 hour hyetographs developed for the Carbonear area are shown on Figure 59 to Figure 64.

FIGURE 59: 6-HOUR HYETOGRAPH (ALTERNATING BLOCK)

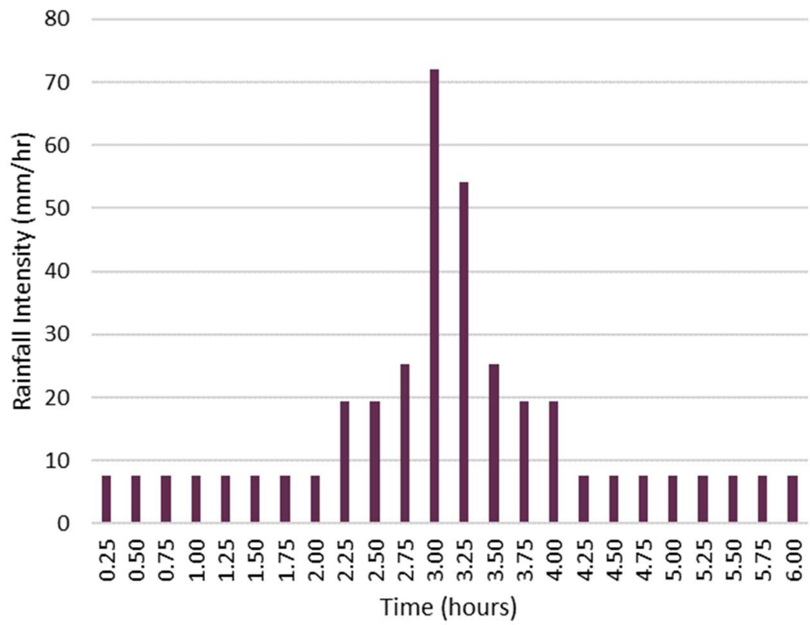



FIGURE 60: 12-HOUR HYETOGRAPH (ALTERNATING BLOCK)

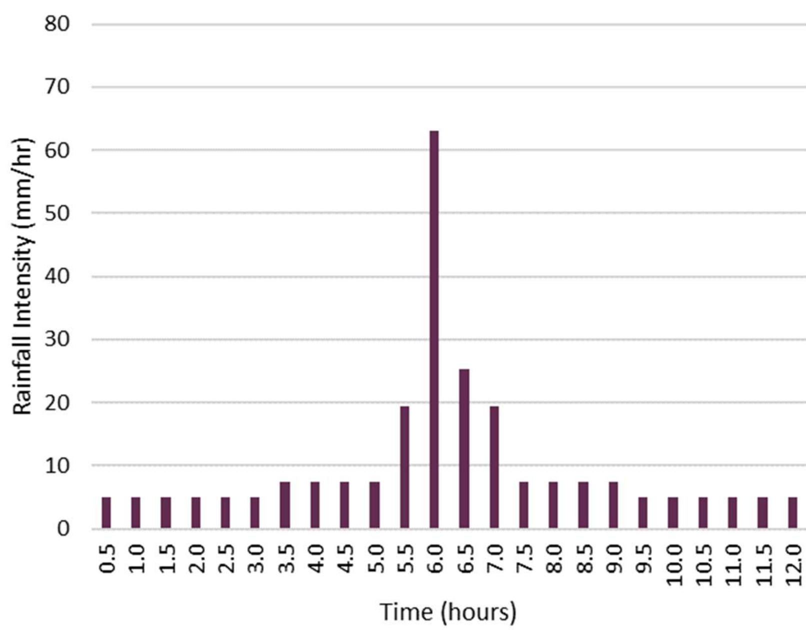


FIGURE 61: 24-HOUR HYETOGRAPH (ALTERNATING BLOCK)

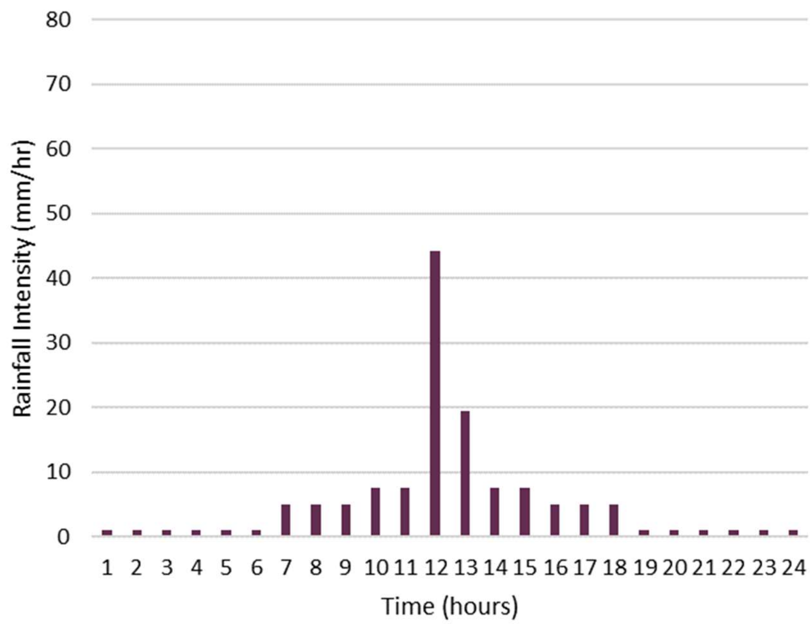



FIGURE 62: 6-HOUR HYETOGRAPH (MASS CURVE)

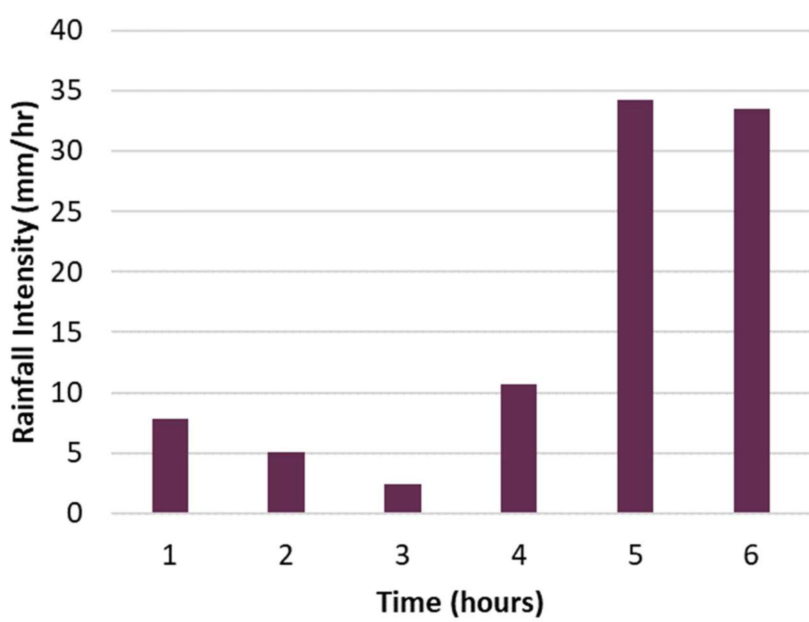


FIGURE 63: 12-HOUR HYETOGRAPH (MASS CURVE)

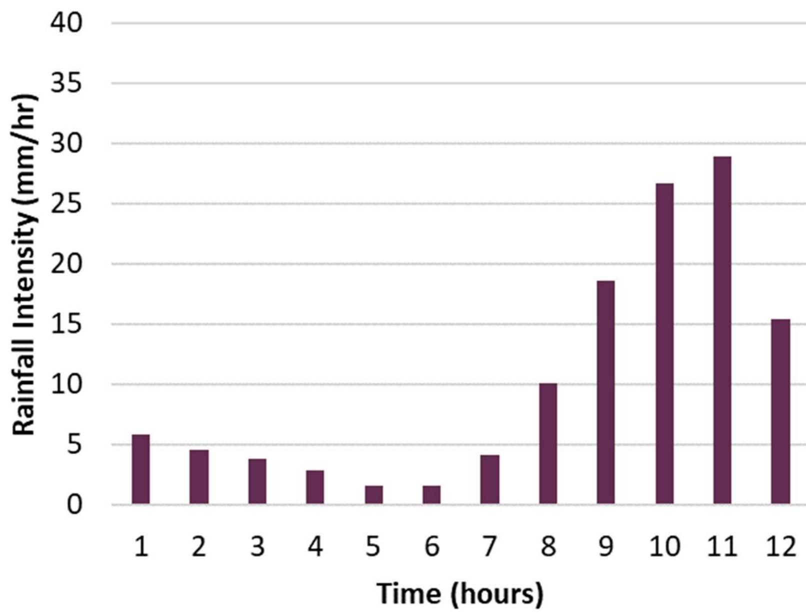
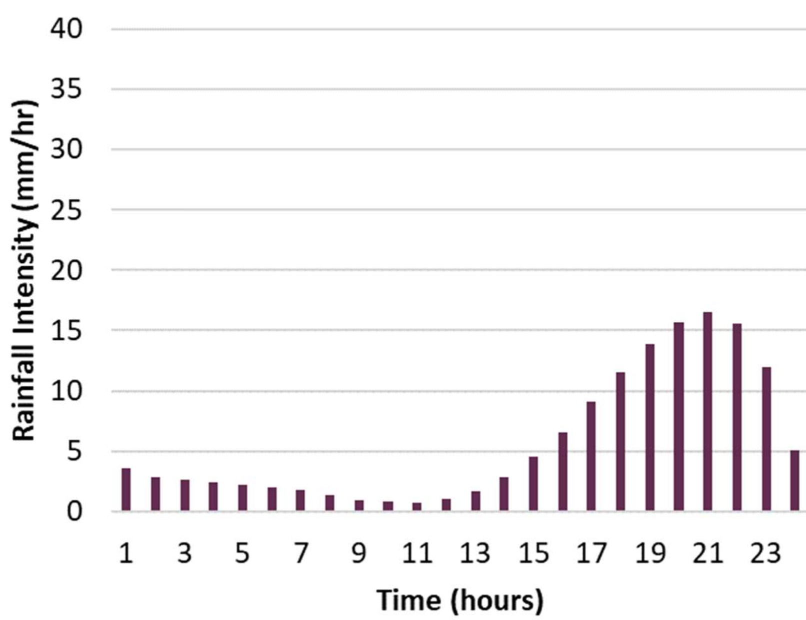



FIGURE 64: 24-HOUR HYETOGRAPH (MASS CURVE)




The hyetographs were simulated on the Salmon Cove River, and flows at the model outlet were extracted for comparison. Comparisons of the resulting flows for the Alternating Block method are shown on Figure 65, while a comparison of the resulting flows associated with the Mass Curve method are shown on Figure 66.

FIGURE 65: ALTERNATING BLOCK FLOWS

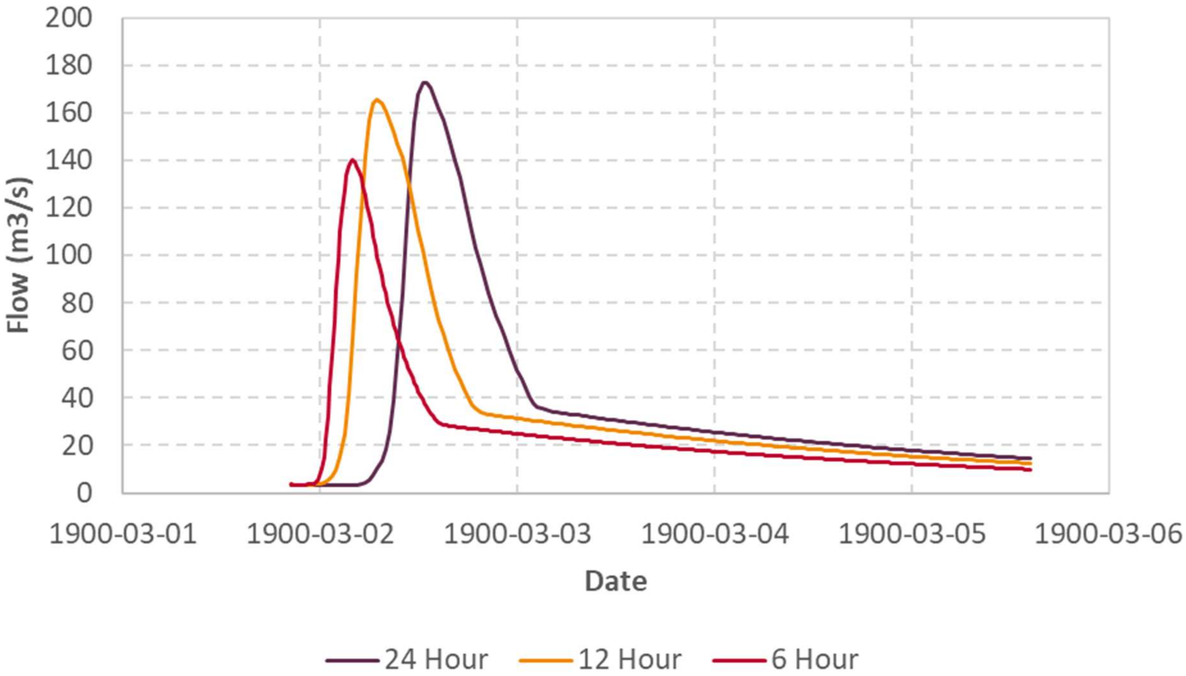
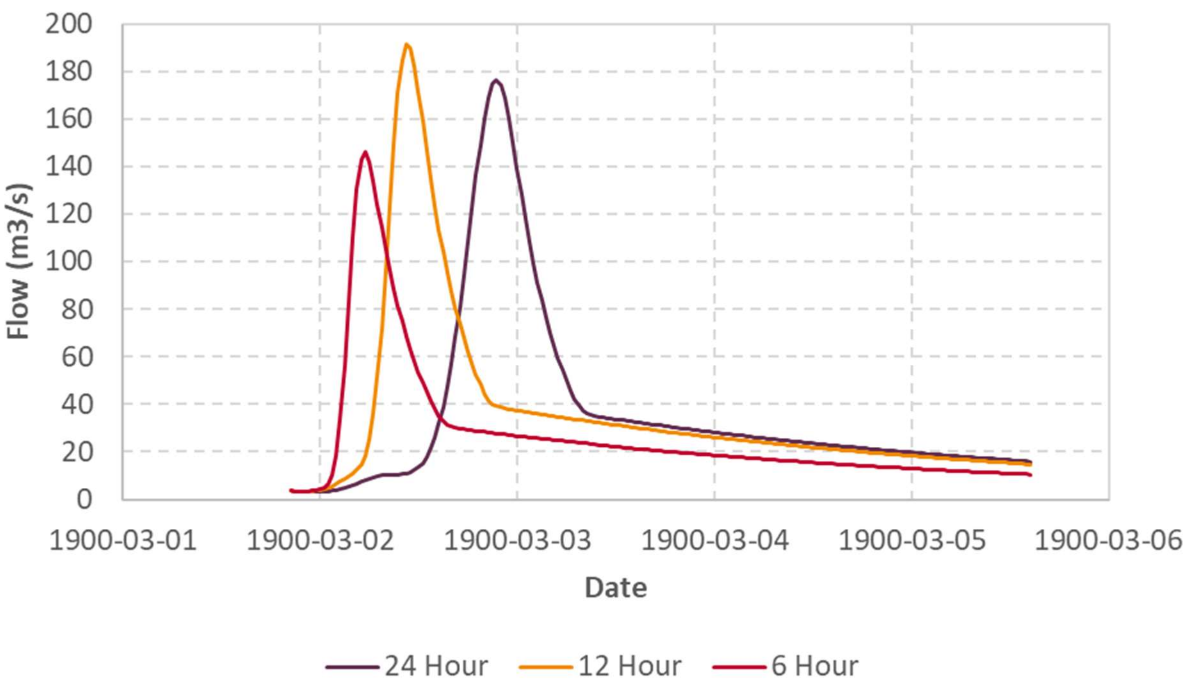



FIGURE 66: MASS CURVE FLOWS




The comparison of flows showed that in general, longer duration storm events resulted in larger flows than shorter duration events, with the exception of the flows associated with the 12 hour Mass Curve hyetograph, which was higher than the 24 hour hyetograph. This can be attributed to how the rainfall intensity is distributed throughout the 12-hour hyetograph. The Alternating Block and Mass Curve hyetographs resulted in similar flows for the 6 and 24 hour durations. Given that it is an industry standard and produced a somewhat more conservative peak flow relative to the majority of the other hyetographs, the 100-year AEP Alternating Block was adopted for subsequent analyses.

The 20 and 100-year AEP rainfall events were integrated into the calibrated HEC-HMS models for the Carbonear and Placentia area models. The resulting flows associated with those 20 and 100-year AEP rainfall events defined by the HEC-HMS models for the rivers and creeks considered in the Carbonear, Salmon Cove and Victoria area are summarized in Table 27, while the flows defined by the HEC-HMS model for the Placentia area are summarized in Table 28.

TABLE 27: HEC-HMS FLOWS FOR CARBONEAR AREA

| Location | 20-Year AEP Rainfall Flow ($m^3/s$) | 100-Year AEP Rainfall Flow ($m^3/s$) |
|---|---|---|
| Salmon Cove River at U/S Model Boundary | 25.2 | 33.8 |
| Big Brook above Salmon Cove River | 27.4 | 36.9 |
| Local Creek 5 above Salmon Cove River | 2.4 | 3.2 |
| Clark Brook above Double Brook | 4.1 | 5.5 |
| Double Brook above Local Creek 4 | 2.0 | 2.7 |
| Local Creek 4 above Double Brook | 1.7 | 2.3 |
| Local Creek 3 above Salmon Cove River | 1.2 | 1.6 |
| Spout Brook | 42.6 | 57.6 |
| Local Creek 2 above Salmon Cove River | 1.0 | 1.4 |
| Local Creek 1 above Salmon Cove River | 0.8 | 1.0 |
| Salmon Cove River Outlet | 128.9 | 172.7 |
| Carbonear Local Creek Outlet | 2.6 | 3.4 |
| Island Pond Brook above Local Creek 1 | 65.7 | 86.5 |
| Island Pond Brook Local Creek 2 above Local Creek 1 | 0.2 | 0.3 |
| Island Pond Brook Local Creek 1 above Island Pond Brook | 1.0 | 1.4 |
| Island Pond Brook Outlet | 67.0 | 88.2 |
| Powells Brook Outlet | 16.4 | 22.1 |

TABLE 28: PLACENTIA AREA HEC-HMS FLOWS

| Location | 20-Year AEP Rainfall Flow ($m^3/s$) | 100-Year AEP Rainfall Flow ($m^3/s$) |
|---|---|---|
| Southeast River Outlet | 251.4 | 354.5 |
| Northeast River Outlet | 192.6 | 271.4 |
| Rattling Brook Outlet | 11.6 | 16.1 |
| Smelt Brook Outlet | 8.2 | 11.3 |
| Local Creek 1 Outlet | 2.9 | 4.0 |
| Baldwins Brook Outlet | 12.4 | 17.2 |
| Local Creek 2 Outlet | 1.8 | 2.5 |
| Little Salmonier River Outlet | 9.2 | 12.8 |
| Local Creek 3 Outlet | 13.1 | 18.1 |
| Local Creek 4 Outlet | 7.4 | 10.3 |
| Mill Brook Outlet | 7.6 | 10.6 |
| Local Creek 5 Outlet | 15.0 | 21.1 |
| Shalloway Brook Outlet | 18.3 | 25.7 |
| Sound Brook Outlet | 75.1 | 105.5 |
| Glennon's Cove River Outlet | 57.9 | 80.5 |

## 6.6 Adopted 1:20 and 1:100 AEP Flows

As noted in Sections 6.2.1, the proration of SSFA flows to basins considerably larger or smaller than the index station, or to basins with different physiographic characteristics can result in significant errors in estimated AEP flows. Similarly, as noted in Section 6.2.2, considerable errors can occur while using the RFFA equations to estimate AEP flows in basins that are beyond of the physiographic characteristics of the basins that were considered in the development of the RFFA equations. Accordingly, the proration of SSFA flows and use of RFFA equations for small basins within the study areas is inappropriate and prone to error. A comparison of the estimated flows based on the SSFA, RFFA, and HEC-HMS model for the Carbonear, Salmon Cove, and Victoria area are summarized in Table 29, and the Placentia area in Table 30. Locations where the application of a specific method is considered inappropriate are highlighted in orange.

## TABLE 29: COMPARISON OF FLOWS IN CARBONEAR AREA

| Location | 20-Year AEP Flow ($m^3/s$) | | | | 100-Year AEP Flow ($m^3/s$) | | | |
|---|---|---|---|---|---|---|---|---|
| | SSFA | RFFA 1-Param. | RFFA 2-Param. | HEC-HMS | SSFA | RFFA 1-Param. | RFFA 2-Param. | HEC-HMS |
| Salmon Cove River at U/S Model Boundary | 20.7 | 20.7 | 21.2 | 25.2 | 33.2 | 27.6 | 28.0 | 33.8 |
| Big Brook above Salmon Cove River | 22.1 | 22.1 | 22.6 | 27.4 | 35.4 | 29.4 | 29.9 | 36.9 |
| Local Creek 5 above Salmon Cove River | 3.2 | 3.2 | 3.2 | 2.4 | 4.8 | 4.0 | 4.1 | 3.2 |
| Clark Brook above Double Brook | 4.8 | 4.8 | 4.9 | 4.1 | 7.5 | 6.2 | 6.3 | 5.5 |
| Double Brook above Local Creek 4 | 2.8 | 2.8 | 2.8 | 2.0 | 4.2 | 3.5 | 3.6 | 2.7 |
| Local Creek 4 above Double Brook | 2.4 | 2.4 | 2.4 | 1.7 | 3.6 | 3.0 | 3.0 | 2.3 |
| Local Creek 3 above Salmon Cove River | 1.7 | 1.7 | 1.7 | 1.2 | 2.6 | 2.1 | 2.2 | 1.6 |
| Spout Brook | 31.9 | 31.9 | 32.6 | 42.6 | 51.7 | 42.9 | 43.6 | 57.6 |
| Local Creek 2 above Salmon Cove River | 1.5 | 1.5 | 1.5 | 1.0 | 2.2 | 1.8 | 1.9 | 1.4 |
| Local Creek 1 above Salmon Cove River | 1.2 | 1.2 | 1.3 | 0.8 | 1.8 | 1.5 | 1.5 | 1.0 |
| Salmon Cove River Outlet | 78.7 | 78.7 | 80.5 | 128.9 | 130.5 | 108.4 | 110.2 | 172.7 |
| Carbonear Local Creek Outlet | 3.0 | 3.0 | 3.5 | 2.6 | 4.5 | 3.8 | 4.1 | 3.4 |
| Island Pond Brook above Local Creek 1 | 47.2 | 47.1 | 43.6 | 65.7 | 77.1 | 64.1 | 61.6 | 86.5 |
| Island Pond Brook Local Creek 2 above Local Creek 1 | 0.4 | 0.4 | 0.4 | 0.2 | 0.6 | 0.5 | 0.5 | 0.3 |
| Island Pond Brook Local Creek 1 above Island Pond Brook | 1.5 | 1.5 | 1.4 | 1.0 | 2.2 | 1.8 | 1.8 | 1.4 |
| Island Pond Brook Outlet | 47.8 | 47.7 | 44.2 | 67.0 | 78.1 | 64.9 | 62.4 | 88.2 |
| Powells Brook Outlet | 14.6 | 14.6 | 16.1 | 16.4 | 23.2 | 19.3 | 20.4 | 22.1 |

### TABLE 30: COMPARISON OF PLACENTIA AREA FLOWS

| Location | 20-Year Flow ($m^3/s$) | | | | 100-Year Flow ($m^3/s$) | | | |
|---|---|---|---|---|---|---|---|---|
| | SSFA | RFFA 1-Param. | RFFA 2-Param | HEC-HMS | SSFA | RFFA 1-Param. | RFFA 2-Param. | HEC-HMS |
| **Southeast River Outlet** | 177.2 | 261.2 | 206.2 | 251.4 | 315.2 | 313.3 | 296.6 | 354.5 |
| **Northeast River Outlet** | 146.7 | 216.4 | 188.6 | 192.6 | 266.2 | 264.6 | 278.0 | 271.4 |
| **Rattling Brook Outlet** | 42.0 | 62.0 | 258.6 | 11.6 | 86.9 | 86.4 | 465.2 | 16.1 |
| **Smelt Brook Outlet** | 35.3 | 52.1 | 290.9 | 8.2 | 74.4 | 73.9 | 539.7 | 11.3 |
| **Local Creek 1 Outlet** | 21.8 | 32.2 | 31.1 | 2.9 | 48.3 | 48.0 | 56.0 | 4.0 |
| **Baldwins Brook Outlet** | 42.0 | 62.0 | 196.5 | 12.4 | 86.9 | 86.4 | 349.0 | 17.2 |
| **Local Creek 2 Outlet** | 29.3 | 43.2 | 98.1 | 1.8 | 62.9 | 62.5 | 178.2 | 2.5 |
| **Little Salmonier River Outlet** | 38.1 | 56.2 | 35.4 | 9.2 | 79.6 | 79.1 | 59.0 | 12.8 |
| **Local Creek 3 Outlet** | 44.6 | 65.8 | 29.7 | 13.1 | 91.7 | 91.2 | 48.0 | 18.1 |
| **Local Creek 4 Outlet** | 32.7 | 48.2 | 63.9 | 7.4 | 69.4 | 69.0 | 112.0 | 10.3 |
| **Mill Brook Outlet** | 33.6 | 49.5 | 33.6 | 7.6 | 71.1 | 70.7 | 57.0 | 10.6 |
| **Local Creek 5 Outlet** | 45.9 | 67.6 | 70.3 | 15.0 | 94.0 | 93.4 | 117.7 | 21.1 |
| **Shalloway Brook Outlet** | 49.9 | 73.6 | 24.9 | 18.3 | 101.3 | 100.7 | 39.2 | 25.7 |
| **Sound Brook Outlet** | 94.2 | 138.9 | 120.2 | 75.1 | 179.1 | 178.0 | 185.3 | 105.5 |
| **Glennon's Cove River Outlet** | 84.6 | 124.8 | 507.5 | 57.9 | 162.6 | 161.7 | 848.4 | 80.5 |

For locations where the prorated SSFA and calculated RFFA flows are appropriate, there is generally good agreement between the flows estimated by the SSFA, RFFA, and HEC-HMS model. However, given that the prorated SSFA and calculated RFFA flows are inappropriate for many locations in both the Carbonear and Placentia areas, the flows defined by the HEC-HMS model were adopted for subsequent analyses in this study. The final adopted flows for the Carbonear and Placentia areas are summarized in Table 31 and Table 32.

### TABLE 31: ADOPTED FLOWS FOR THE CARBONEAR AREA

| Location | 20-Year Rainfall Flow ($m^3/s$) | 100-Year Rainfall Flow ($m^3/s$) |
|---|---|---|
| Salmon Cove River at U/S Model Boundary | 25.2 | 33.8 |
| Big Brook above Salmon Cove River | 27.4 | 36.9 |
| Local Creek 5 above Salmon Cove River | 2.4 | 3.2 |
| Clark Brook above Double Brook | 4.1 | 5.5 |
| Double Brook above Local Creek 4 | 2.0 | 2.7 |
| Local Creek 4 above Double Brook | 1.7 | 2.3 |
| Local Creek 3 above Salmon Cove River | 1.2 | 1.6 |
| Spout Brook | 42.6 | 57.6 |
| Local Creek 2 above Salmon Cove River | 1.0 | 1.4 |
| Local Creek 1 above Salmon Cove River | 0.8 | 1.0 |
| Salmon Cove River Outlet | 128.9 | 172.7 |
| Carbonear Local Creek Outlet | 2.6 | 3.4 |
| Island Pond Brook above Local Creek 1 | 65.7 | 86.5 |
| Island Pond Brook Local Creek 2 above Local Creek 1 | 0.2 | 0.3 |
| Island Pond Brook Local Creek 1 above Island Pond Brook | 1.0 | 1.4 |
| Island Pond Brook Outlet | 67.0 | 88.2 |
| Powells Brook Outlet | 16.4 | 22.1 |

### TABLE 32: ADOPTED FLOWS FOR THE PLACENTIA AREA

| Location | 20-Year AEP Rainfall Flow ($m^3/s$) | 100-Year AEP Rainfall Flow ($m^3/s$) |
|---|---|---|
| Southeast River Outlet | 251.4 | 354.5 |
| Northeast River Outlet | 192.6 | 271.4 |
| Rattling Brook Outlet | 11.6 | 16.1 |
| Smelt Brook Outlet | 8.2 | 11.3 |
| Local Creek 1 Outlet | 2.9 | 4.0 |
| Baldwins Brook Outlet | 12.4 | 17.2 |
| Local Creek 2 Outlet | 1.8 | 2.5 |
| Little Salmonier River Outlet | 9.2 | 12.8 |
| Local Creek 3 Outlet | 13.1 | 18.1 |
| Local Creek 4 Outlet | 7.4 | 10.3 |
| Mill Brook Outlet | 7.6 | 10.6 |
| Local Creek 5 Outlet | 15.0 | 21.1 |
| Shalloway Brook Outlet | 18.3 | 25.7 |
| Sound Brook Outlet | 75.1 | 105.5 |
| Glennon’s Cove River Outlet | 57.9 | 80.5 |

# 7.0 CLIMATE CHANGE AND FUTURE DEVELOPMENT

## 7.1 Overview

To account for the projected impacts associated with climate change, a review and assessment was completed of the projected impacts to precipitation, the potential for ice growth, and sea level rise, and how these impacts could affect flooding throughout Carbonear, Salmon Cove, Victoria and Placentia.

The anticipated impacts to flows on the rivers and creeks due to climate change was assessed considering the anticipated impacts to rainfall. The assessment compared the simulated river flows associated with the 20 and 100-year AEP events under current climate and climate change conditions using the hydrologic model. The assessment showed flow increases of between 21% and 50% in the Carbonear area, and by between 14% and 18% in the Placentia area on the various rivers and creeks due to the projected climate change impacts.

Another key climate change consideration is sea level rise. This change was accounted for based on projected sea level rise changes defined in 2021 by NRCan (James et at., 2021). While the Government of Newfoundland and Labrador has previously commissioned a study to define the expected sea level rise relative to ground elevation, resulting 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), more recent studies, such as that completed by NRCan in 2021, provide updated estimates of sea level rise and are considered to be the most appropriate data source for assessing sea level rise as part of this project. In short, it is anticipated that the sea level will rise by 0.62 m in Placentia and 0.63 m in Salmon Cove and Carbonear relative to the ground elevation by the end of the century.

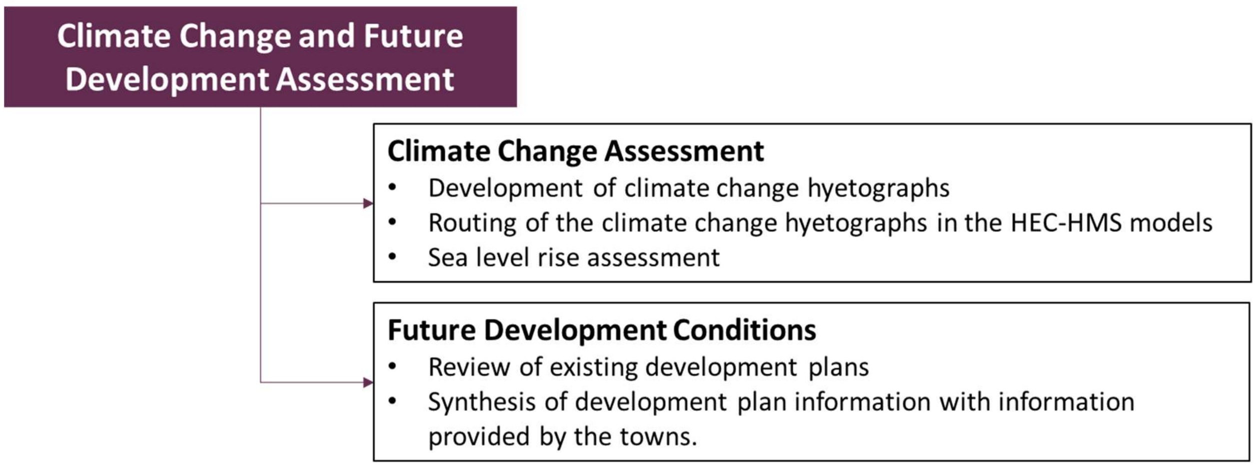
Ice processes, including the potential for ice jamming, are expected to be affected by climate change due to the projected rising temperatures. The current state of research regarding climate change impacts on ice jams suggests that, given the relatively rare occurrence of ice jamming in Carbonear, Salmon Cove and Victoria, the increase in air temperature could reduce the occurrence of winter ice, or alternatively result in a thinner ice cover, that could result in fewer and less severe ice jam floods. Conversely, an increase in winter and spring precipitation could lead to more mid-winter ice breakup events, potentially leading to an increase in the occurrence of mid-winter ice jams.

A review of the proposed development plans for Carbonear, Salmon Cove, Victoria and Placentia was completed to identify potential large developments within the communities that could affect the hydrology on the rivers and creeks being considered as part of this study. Discussions were similarly held with the towns to further identify any significant developments. Any developments identified by the towns were either minor and not anticipated to impact the hydrology within the study area, or were located outside of the drainage basins of the rivers and creeks considered in the study. However, given the potential impact on the hydrology that could occur should large developments occur within the drainage basins of the rivers and creeks considered in this study, policies should be adopted by the towns to ensure that future developments result in no net increase in flow on the rivers and creeks.

The river flows and raised sea levels associated with the climate change rainfall events were integrated into the hydraulic models to define the anticipated water levels associated with the climate change conditions.

The tasks completed as part of the climate change and future development assessment are shown on Figure 67.

FIGURE 67: OVERVIEW OF CLIMATE CHANGE AND FUTURE DEVELOPMENT ASSESSMENT

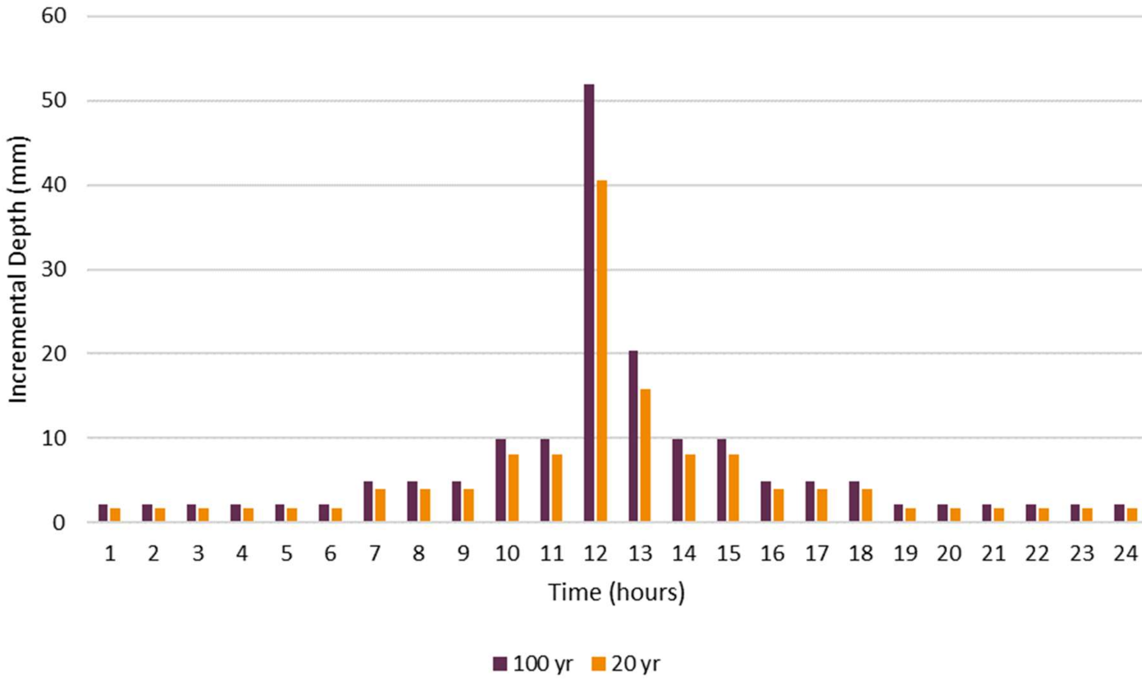



## 7.2 Climate Change Assessment

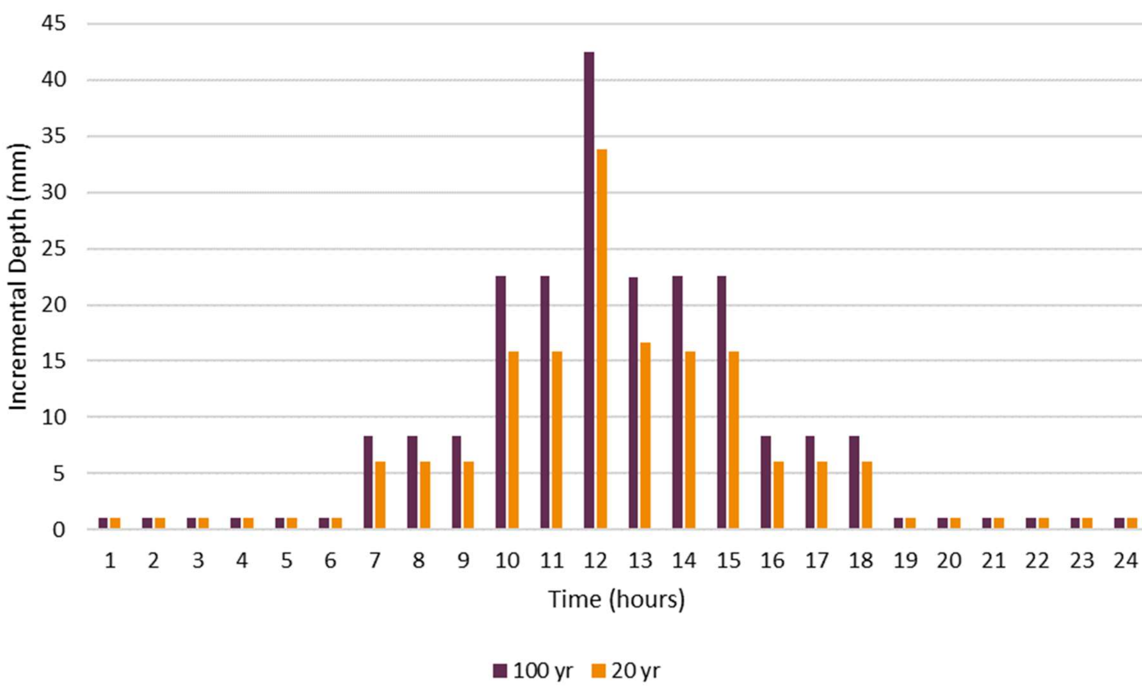
### 7.2.1 RIVER AND CREEK FLOWS

Climate change impacts to the flows on the rivers and creeks considered in the study were assessed by developing hyetographs representative of climate change conditions from the climate change IDF curves, and simulating those hyetographs in the HEC-HMS models. The 20 and 100-year AEP rainfall hyetographs for the Carbonear and Placentia areas are shown on Figure 68 and Figure 69.

## FIGURE 68: CLIMATE CHANGE HYETOGRAPHS FOR THE CARBONEAR AREA




## FIGURE 69: CLIMATE CHANGE HYETOGRAPHS FOR THE PLACENTIA AREA



The climate change hyetographs were simulated in the HEC-HMS model to assess the impacts to flows on the rivers. The resulting river flows for current climate and climate change conditions are summarized for the Carbonear area in Table 33, and the Placentia area in Table 34.

### TABLE 33: CARBONEAR AREA CURRENT CLIMATE AND CLIMATE CHANGE FLOWS

| Location | Current Climate Flow ($m^3/s$) | | Climate Change Flow ($m^3/s$) | |
|---|---|---|---|---|
| | 20-Year AEP | 100-Year AEP | 20-Year AEP | 100-Year AEP |
| Salmon Cove River at U/S Model Boundary | 25.2 | 33.8 | 31.4 | 42.1 |
| Big Brook above Salmon Cove River | 27.4 | 36.9 | 34.2 | 45.9 |
| Local Creek 5 above Salmon Cove River | 2.4 | 3.2 | 3.0 | 4.0 |
| Clark Brook above Double Brook | 4.1 | 5.5 | 5.1 | 6.9 |
| Double Brook above Local Creek 4 | 5.4 | 7.3 | 6.8 | 9.0 |
| Local Creek 4 above Double Brook | 1.7 | 2.3 | 2.1 | 2.8 |
| Local Creek 3 above Salmon Cove River | 1.2 | 1.6 | 1.5 | 2.0 |
| Spout Brook | 42.6 | 57.2 | 53.1 | 71.3 |
| Local Creek 2 above Salmon Cove River | 1.0 | 1.4 | 1.3 | 1.7 |
| Local Creek 1 above Salmon Cove River | 0.8 | 1.0 | 1.0 | 1.3 |
| Salmon Cove River Outlet | 128.9 | 172.7 | 161.0 | 215.4 |
| Carbonear Local Creek Outlet | 2.6 | 3.4 | 3.2 | 4.2 |
| Island Pond Brook above Local Creek 1 | 65.7 | 86.5 | 80.7 | 106.3 |
| Island Pond Brook Local Creek 2 above Local Creek 1 | 0.2 | 0.3 | 0.3 | 0.4 |
| Island Pond Brook Local Creek 1 above Island Pond Brook | 1.0 | 1.4 | 1.3 | 1.7 |
| Island Pond Brook Outlet | 67.0 | 88.2 | 82.3 | 108.4 |
| Powells Brook Outlet | 16.4 | 22.1 | 20.5 | 27.5 |

### TABLE 34: PLACENTIA AREA CURRENT CLIMATE AND CLIMATE CHANGE FLOWS

| Location | Current Climate Flow ($m^3/s$) | | Climate Change Flow ($m^3/s$) | |
|---|---|---|---|---|
| | 20-Year AEP | 100-Year AEP | 20-Year AEP | 100-Year AEP |
| Southeast River Outlet | 251.4 | 354.5 | 295.9 | 415.5 |
| Northeast River Outlet | 192.6 | 271.4 | 225.7 | 316.9 |
| Rattling Brook Outlet | 11.6 | 16.1 | 13.6 | 18.8 |
| Smelt Brook Outlet | 8.2 | 11.3 | 9.5 | 13.2 |
| Local Creek 1 Outlet | 2.9 | 4.0 | 3.3 | 4.6 |
| Baldwins Brook Outlet | 12.4 | 17.2 | 14.5 | 20.1 |
| Local Creek 2 Outlet | 1.8 | 2.5 | 2.1 | 2.9 |
| Little Salmonier River Outlet | 9.2 | 12.8 | 10.7 | 14.8 |
| Local Creek 3 Outlet | 13.1 | 18.1 | 15.2 | 21.0 |
| Local Creek 4 Outlet | 7.4 | 10.3 | 8.6 | 12.0 |
| Mill Brook Outlet | 7.6 | 10.6 | 8.9 | 12.4 |
| Local Creek 5 Outlet | 15.0 | 21.1 | 17.6 | 24.7 |
| Shalloway Brook Outlet | 18.3 | 25.7 | 21.5 | 30.1 |
| Sound Brook Outlet | 75.1 | 105.5 | 88.2 | 123.7 |
| Glennon's Cove River Outlet | 57.9 | 80.5 | 67.7 | 93.9 |

The relative impacts that climate change are anticipated to have on the peak precipitation and total precipitation volume in the Carbonear and Placentia areas, as well as the 20 and 100-year AEP flood flows on the various rivers and creeks within those communities are summarized in Table 35 and Table 36.

### TABLE 35: CARBONEAR AREA CLIMATE CHANGE IMPACTS ON PRECIPITATION AND FLOW

| Location | Increase in Peak Precipitation (%) | | Increase in Total Precipitation Volume (%) | | Increase in River Flow (%) | |
|---|---|---|---|---|---|---|
| | 20-Year AEP | 100-Year AEP | 20-Year AEP | 100-Year AEP | 20-Year AEP | 100-Year AEP |
| Salmon Cove River at U/S Model Boundary | 19.0 | 17.6 | 20.3 | 21.9 | 24.6 | 24.6 |
| Big Brook above Salmon Cove River | 19.0 | 17.6 | 20.3 | 21.9 | 24.8 | 24.4 |
| Local Creek 5 above Salmon Cove River | 19.0 | 17.6 | 20.3 | 21.9 | 25.0 | 25.0 |
| Clark Brook above Double Brook | 19.0 | 17.6 | 20.3 | 21.9 | 24.4 | 25.5 |
| Double Brook above Local Creek 4 | 19.0 | 17.6 | 20.3 | 21.9 | 25.9 | 23.3 |
| Local Creek 4 above Double Brook | 19.0 | 17.6 | 20.3 | 21.9 | 23.5 | 21.7 |
| Local Creek 3 above Salmon Cove River | 19.0 | 17.6 | 20.3 | 21.9 | 25.0 | 25.0 |
| Spout Brook | 19.0 | 17.6 | 20.3 | 21.9 | 24.6 | 24.7 |
| Local Creek 2 above Salmon Cove River | 19.0 | 17.6 | 20.3 | 21.9 | 30.0 | 21.4 |
| Local Creek 1 above Salmon Cove River | 19.0 | 17.6 | 20.3 | 21.9 | 25.0 | 30.0 |
| Salmon Cove River Outlet | 19.0 | 17.6 | 20.3 | 21.9 | 24.9 | 24.7 |
| Carbonear Local Creek Outlet | 19.0 | 17.6 | 20.3 | 21.9 | 23.1 | 23.5 |
| Island Pond Brook above Local Creek 1 | 19.0 | 17.6 | 20.3 | 21.9 | 22.8 | 22.9 |
| Island Pond Brook Local Creek 2 above Local Creek 1 | 19.0 | 17.6 | 20.3 | 21.9 | 50.0 | 33.3 |
| Island Pond Brook Local Creek 1 above Island Pond Brook | 19.0 | 17.6 | 20.3 | 21.9 | 30.0 | 21.4 |
| Island Pond Brook Outlet | 19.0 | 17.6 | 20.3 | 21.9 | 22.8 | 22.9 |
| Powells Brook Outlet | 19.0 | 17.6 | 20.3 | 21.9 | 25.0 | 24.4 |

### TABLE 36: PLACENTIA AREA CLIMATE CHANGE IMPACTS ON PRECIPITATION AND FLOW

| Location | Increase in Peak Precipitation (%) | | Increase in Total Precipitation Volume (%) | | Increase in River Flow (%) | |
|---|---|---|---|---|---|---|
| | 20-Year AEP | 100-Year AEP | 20-Year AEP | 100-Year AEP | 20-Year AEP | 100-Year AEP |
| Southeast River Outlet | 9.7 | 11.0 | 12.6 | 12.3 | 17.7 | 17.2 |
| Northeast River Outlet | 9.7 | 11.0 | 12.6 | 12.3 | 17.2 | 16.8 |
| Rattling Brook Outlet | 9.7 | 11.0 | 12.6 | 12.3 | 17.2 | 16.8 |
| Smelt Brook Outlet | 9.7 | 11.0 | 12.6 | 12.3 | 15.9 | 16.8 |
| Local Creek 1 Outlet | 9.7 | 11.0 | 12.6 | 12.3 | 13.8 | 15.0 |
| Baldwins Brook Outlet | 9.7 | 11.0 | 12.6 | 12.3 | 16.9 | 16.9 |
| Local Creek 2 Outlet | 9.7 | 11.0 | 12.6 | 12.3 | 17.6 | 15.5 |
| Little Salmonier River Outlet | 9.7 | 11.0 | 12.6 | 12.3 | 16.3 | 15.6 |
| Local Creek 3 Outlet | 9.7 | 11.0 | 12.6 | 12.3 | 16.0 | 16.0 |
| Local Creek 4 Outlet | 9.7 | 11.0 | 12.6 | 12.3 | 16.2 | 16.5 |
| Mill Brook Outlet | 9.7 | 11.0 | 12.6 | 12.3 | 17.1 | 17.0 |
| Local Creek 5 Outlet | 9.7 | 11.0 | 12.6 | 12.3 | 17.3 | 17.1 |
| Shalloway Brook Outlet | 9.7 | 11.0 | 12.6 | 12.3 | 17.5 | 17.1 |
| Sound Brook Outlet | 9.7 | 11.0 | 12.6 | 12.3 | 17.4 | 17.3 |

### 7.2.2 SEA LEVEL RISE

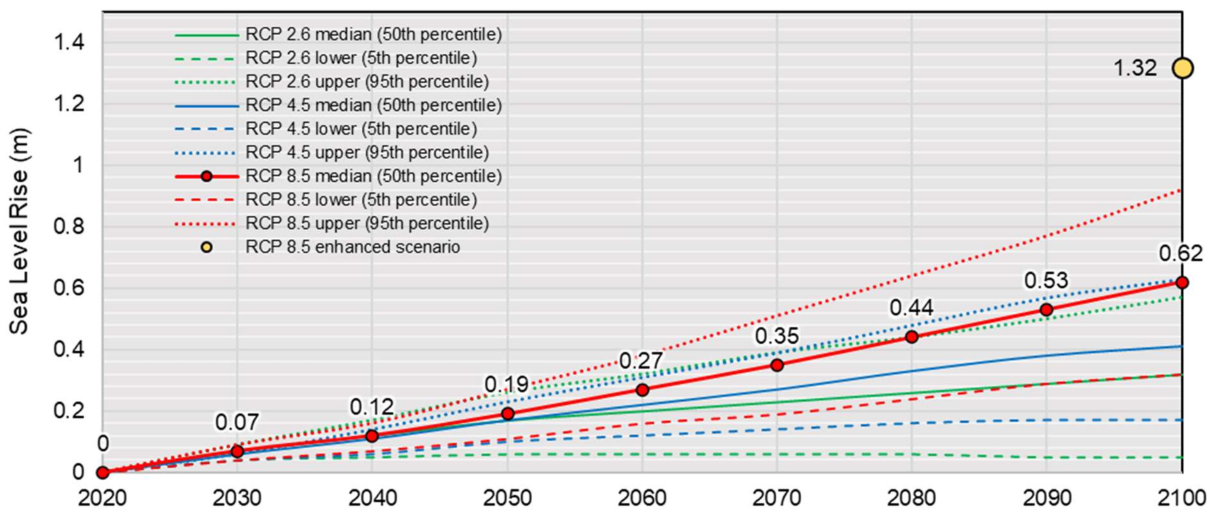
To help Canadians plan, prepare for, and remain resilient to projected sea-level changes, NRCan has developed a new state-of-the-art dataset of present and future relative sea-levels (James et al., 2021). The dataset provides projections for relative sea-level change, which is the change in ocean height relative to land and is the apparent sea-level change experienced by coastal communities and ecosystems. It is a combined measure of both changes to ocean levels due to climate change and vertical land movements. While the Government of Newfoundland and Labrador has previously commissioned a study to assess the relative impacts of sea level rise (M. Batterson and D. Liverman, 2010), the dataset provided by NRCan is more recent and representative of the current state of research into projected relative sea level rise.

Sea level rise projections are available at a resolution of 0.1° (i.e. approximately 11 km latitude and 2 to 8 km longitude), and for 2006 and every subsequent decade from 2010-2100, relative to 1986-2005 conditions. The data is available for the three RCP emissions scenarios (i.e. RCP 2.6, RCP 4.5, RCP 8.5) and an enhanced scenario. The enhanced scenario adds a further 65 cm of global sea-level rise to the median projection of the highest (RCP8.5) climate scenario at 2100. This 65 cm reflects a potential additional contribution from the Antarctic Ice Sheet and is still considered to be unlikely.

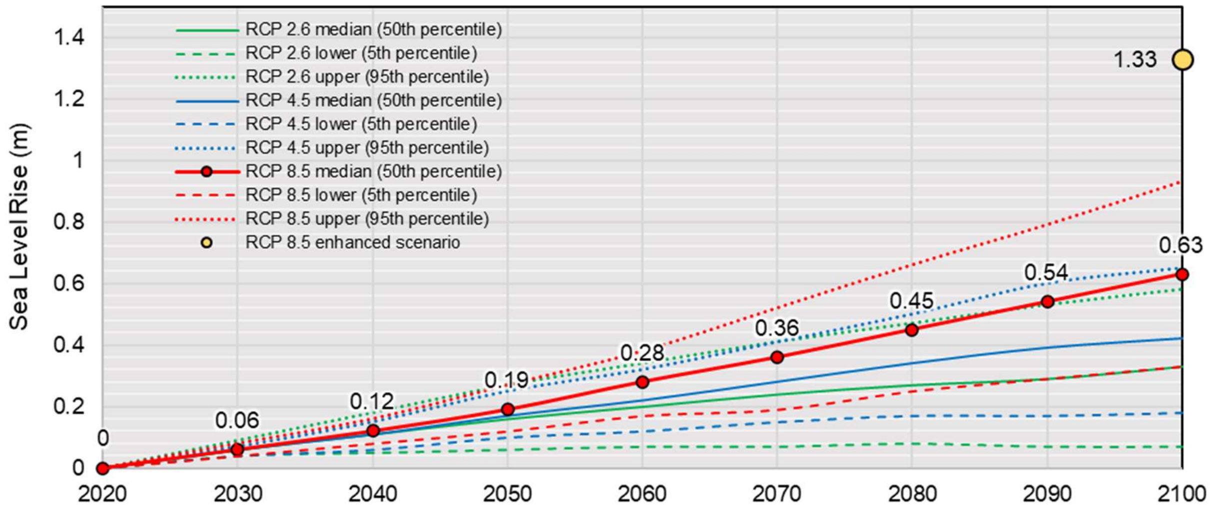
Projected sea-level changes in the NRCan dataset include the effects of changes in glacier and ice-sheet mass loss, thermal expansion of the oceans, changing ocean circulation conditions, and human-caused changes in land water storage, as summarized in IPCC AR5. A new land motion model developed by the Canadian Geodetic Survey (Robin et al., 2020; Canadian Geodetic Survey, 2019) was also incorporated into the data to replace less-accurate land motion values utilized by the IPCC AR5. Vertical land movements in Canada are largely driven by loading and unloading of the Earth's surface by ice sheets.

The RCP 8.5 climate scenario was adopted to define sea level rise. As well, the sea level rise was considered from present day to the year 2100. The RCP 8.5 median relative sea level rise projections, including land subsidence, that were adopted for Placentia (i.e. 0.62 m) and the Carbonear area (i.e. 0.63 m) are shown on Figure 70 and Figure 71.

FIGURE 70: PROJECTED SEA LEVEL RISE FOR PLACENTIA



## FIGURE 71: PROJECTED SEA LEVEL RISE FOR THE CARBONEAR AREA

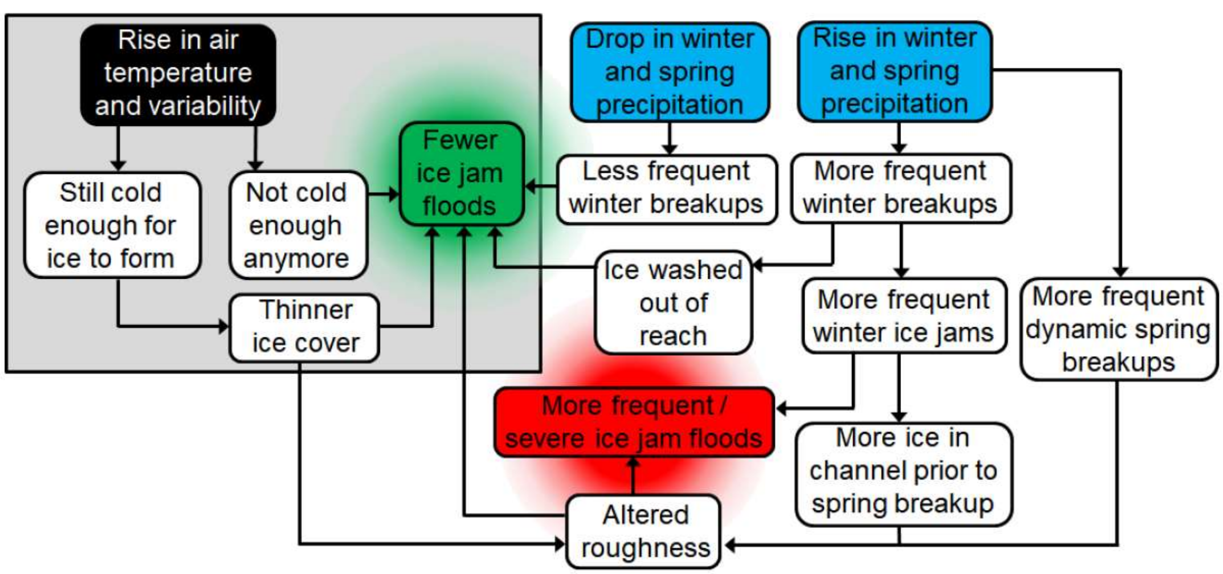



The anticipated sea level rise values were added to the current climate AEP storm surge levels to estimate the climate change AEP storm surge levels.

### 7.2.3 RIVER ICE

A high-level review of the anticipated impacts associated with climate change, and how those impacts could affect ice jamming in the study area, was completed. As noted in Turcotte et al. (2019), predicting how climate change will affect ice jamming is very difficult, varies considerably from location to location, and has a high degree of uncertainty. The pathways that climate change could affect ice jamming are shown conceptually on Figure 72.

## FIGURE 72: CLIMATE CHANGE IMPACTS ON ICE JAMMING




(Source: Turcotte et al., 2019)

Based on the anticipated climate change impacts to mean daily temperature for winter (i.e. December, January, and February) conditions documented in Finnis (2018), mean daily temperatures are projected to increase by 5.3°C in Placentia and St. John's (i.e. the nearest location to Carbonear, Salmon Cove and Victoria) by the year 2100. Precipitation in Placentia is projected to increase by 40% for winter conditions and 48% for spring (i.e. March, April and May) conditions. In St. John's, precipitation is projected to decrease slightly by 1% for winter conditions and increase by 13% for spring conditions.

Ice jamming has not been identified as an issue in Placentia, and given the considerable increase in winter temperatures, it is anticipated that ice jamming will continue to not pose an issue in the community. In Salmon Cove, Victoria and Carbonear, where ice jamming has occasionally occurred, the increase in winter temperatures could result in a thinner ice cover or no ice cover over the winter, thereby reducing the potential for and severity of ice jamming. However, should ice covers continue to form, ice jamming could occur more frequently due to increased instances of winter rainfall dislodging the ice. Given the somewhat conflicting impacts on the likelihood and severity of ice jamming due to climate change, no definitive conclusions can be drawn regarding the ultimate impacts on the likelihood and severity of future ice jamming.

## 7.3 Future Development Conditions

KGS Group completed a review of the current municipal plans in place in the towns of Carbonear, Salmon Cove, Victoria and Placentia to identify any proposed developments that could affect the hydrology of the rivers and creeks being considered as part of this study. These municipal plans included:

- The 2014 – 2024 Development Plan for the Town of Placentia,
- The Town of Salmon Cove Municipal Plan 2020 – 2030,
- The Town of Carbonear Municipal Plan 2004 – 2014, and
- The Town of Victoria Municipal Plan 2010.

In addition to the municipal plans for each of the towns, subsequent amendments to those plans were also reviewed. Discussions were held with each of the towns to discuss the anticipated development and the identification of any large developments within the towns. The proposed developments identified in the municipal plans and amendments, as well as through discussions with the town, were found to either be minor in nature, such as residential infilling in existing neighbourhoods, or in areas that are outside of the drainage basins of the rivers and creeks considered in this study. As such, these developments would not impact the hydrology of the rivers and creeks being considered in the study. However, given the potential impacts that developments could have on the hydrology, the towns should adopt policies stating that any developments within the drainage basins considered in this study should result in no net increase in flows. These policies would mitigate the potential increase in flood risk associated with extensive developments within the watersheds assessed as part of this study.

# 8.0 HYDRAULIC INVESTIGATIONS AND MODELLING

## 8.1 Overview

The Towns of Salmon Cove, Carbonear and Placentia are vulnerable coastal communities that are frequently exposed to powerful Atlantic storm systems that have the potential to cause damages to coastal infrastructure, thereby exposing these communities to flood risk. Future sea level rise, changes to coastal climate, and changes to precipitation may exacerbate these risks further, increasing exposure and impact to human health, environment, and natural and built infrastructure. To describe the flood risk, a number of computer models were developed to assess the river and costal flood processes. Specifically three separate types of models were developed:

- ***Coastal Models*** were developed to investigate local storm surge effects, and wave impacts such as run-up. The results from the modelling of coastal processes complement and feed directly into the river models.
- ***Open Water River Models*** were defined to convert the flows defined by the hydrologic modelling into water levels on the various rivers and creeks considered in this study.
- ***River Ice Jam Models*** were developed to determine the maximum potential for ice jamming in Carbonear, Salmon Cove and Victoria, as those communities had historically experienced flooding due to ice jamming.

This integrated modelling approach ensures that coastal and inland flood processes are jointly considered to quantify overall flood risk for these coastal communities.

A large, regional coastal model of the north Atlantic was developed to simulate historical storm surges on the ocean. Two smaller, more detailed models of Placentia Bay and Conception Bay were also developed to take outputs from the larger model and use those outputs to better estimate the storm surge near the Communities of Placentia, Carbonear and Salmon Cove. These models were adjusted to accurately represent historical storm surge events. Statistical analyses were completed to determine the 20 and 100-year AEP storm surge events. Separately, wind conditions were added to the model to evaluate the 20 and 100-year AEP wave heights. Calculations were then completed to evaluate how far inland the 20 and 100-year AEP waves could run up along the coast.

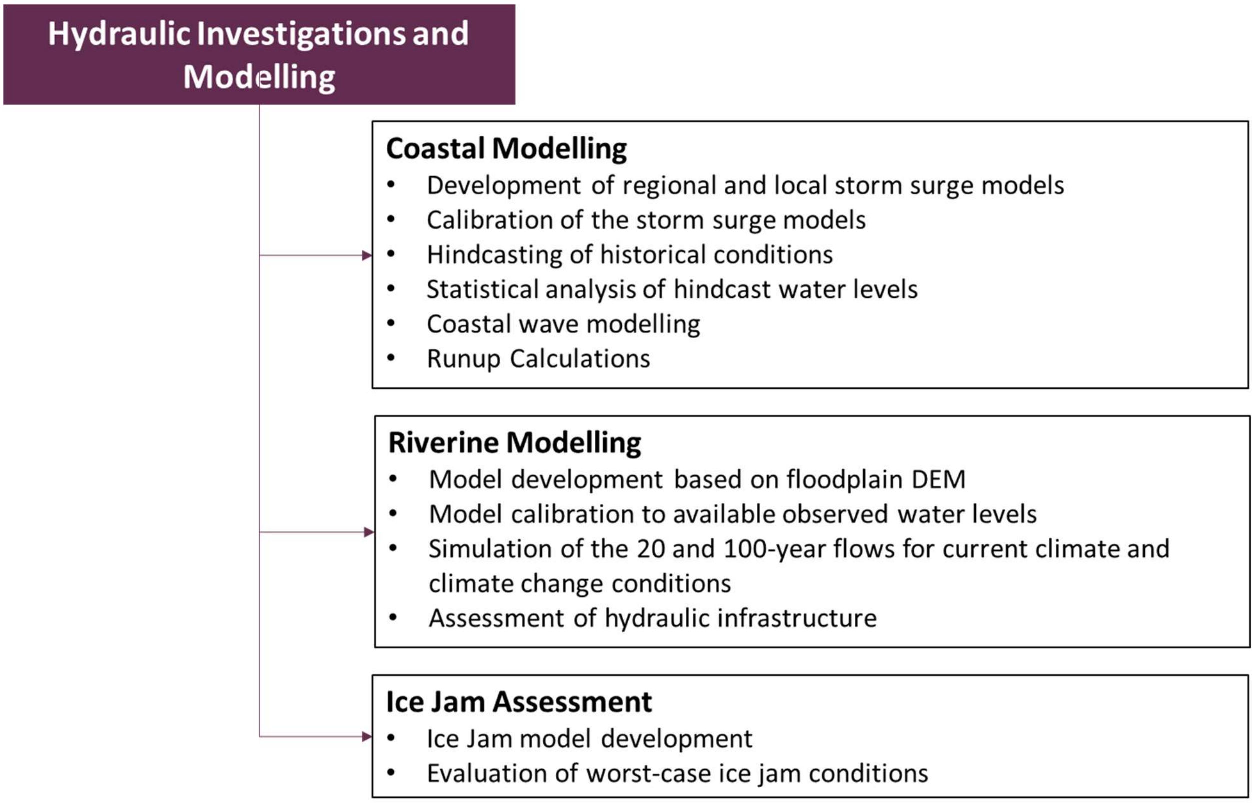
Numerous river hydraulic models were developed throughout the communities of Placentia, Carbonear, Salmon Cove and Victoria to define water levels caused by the 20 and 100-year AEP rainfall events. The models were adjusted to accurately reproduce recorded water levels, where they were available, and were found to be accurate.

Ice jam models were developed for the Salmon Cove River, Island Pond Brook, and Powells Brook to evaluate the potential for ice jamming, and to assess how the potential ice jam water levels compared to the open water flood levels on the rivers.

The water levels resulting from the coastal and riverine modelling were used to develop flood risk maps that show the extent of flooding, as well as flood hazard maps that show the depth of flooding, speed of the flood waters, and a calculated hazard within the flood extent.

An overview of the tasks completed as part of the hydraulic investigations and modelling is shown on Figure 73.

FIGURE 73: OVERVIEW OF HYDRAULIC INVESTIGATIONS AND MODELLING




## 8.2 Coastal Modelling

### 8.2.1 APPROACH TO HYDRODYNAMIC MODELLING

The shoreline of Newfoundland is a complex system of coves, inlets and fjords, with highly variable bathymetric and shoreline features that are exposed to a range of oceanographic forcings from tides, distant storms, Atlantic hurricanes, and wind or swell dominated waves. This range of variables can significantly influence locally generated storm surge over small distances. Traditionally estimates of storm surge have been completed using the analysis of historical data records at gauging stations. Often these records are incomplete, unreliable, and only available near larger urban coastal communities. Additionally, a record of sufficient length is required to reliably predict low frequency storm surge conditions, such as the 100-year AEP storm surge. According to USACE (CEM, 2006), when performing an extreme value analysis (EVA) to derive design conditions, the extrapolation beyond 3 times the data record length should be avoided if possible. Therefore, it is often challenging to predict coastal storm surge conditions in rural communities such as Salmon Cove, Carbonear and Placentia due to:

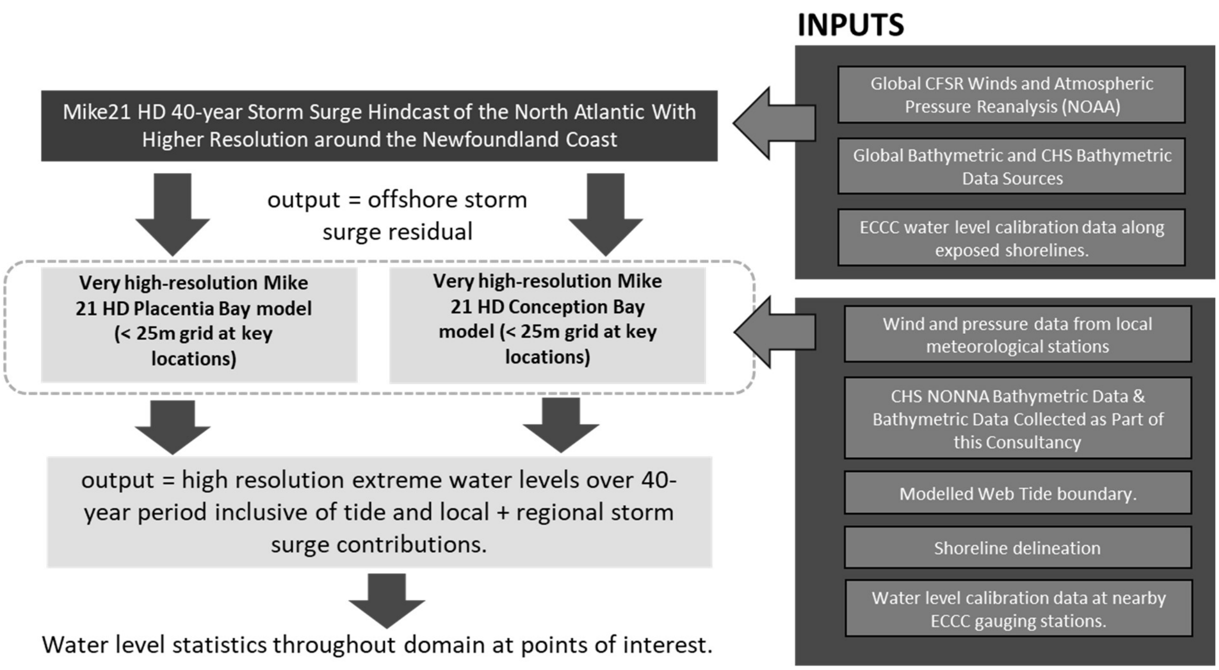
- A lack of nearby available data,

- The regional and site-specific nature of storm surge gradients that cannot be described by distant data sources, and
- Water level data records that are too short, outdated, or unreliable to derive return values for design surge events.

To resolve this data gap, numerical modelling tools were leveraged to simulate high-resolution, location specific storm surge gradients over a sufficient timespan to derive 100-year AEP storm surge elevations.

The storm surge modelling framework that was implemented to simulate a 40-year storm surge hindcast for Conception Bay and Placentia Bay, with sufficient resolution along the coastlines of Salmon Cove, Carbonear and Placentia is shown on Figure 74. The DHI MIKE21 flexible mesh (FM), hydrodynamic (HD) model was used to develop a detailed HD model of the northern Atlantic, with sufficient size and resolution to accurately replicate coastal storm surge from 1980 to 2020.

FIGURE 74: STORM SURGE MODELLING FRAMEWORK




Greater detail outlining the MIKE21 FM HD model development, input data, and calibration is provided in Section 8.2.2, and is broadly summarized by the following steps:

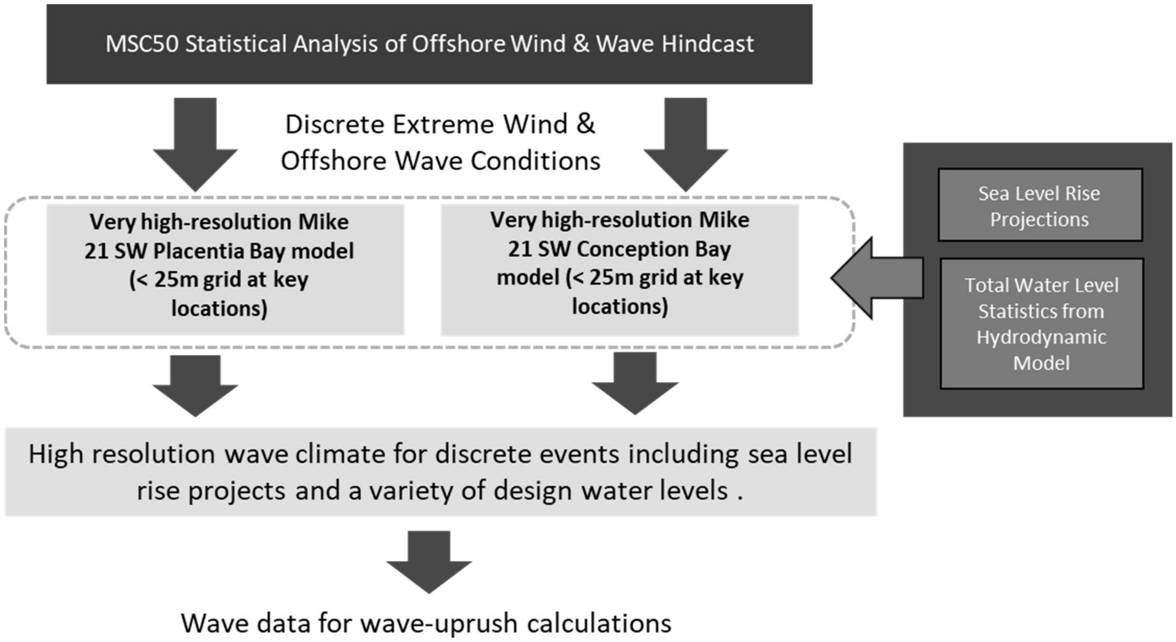
- **A regional storm surge model** has been developed for the north Atlantic, with higher resolution around the Province of Newfoundland and within Conception Bay and Placentia Bay.
- **The regional MIKE21 FM HD model** includes global spatially and temporally varying wind and pressure fields using the global Climate Forecast System Reanalysis (CFSR) model administered by the National Centre for Atmospheric Research (NCAR). The HD model water level is static and set to mean sea level (MSL), thereby only producing the storm surge residual of the total coastal water levels. Storm surge model results are then compared to regionally measured long-term records, and the model calibration is

adjusted until a satisfactory agreement between measured and modelled storm surge residuals is obtained.

- **High-resolution detailed models of Placentia Bay and Conception Bay** with a mesh resolution down to 25 m at Salmon Cove, Carbonear and Placentia have been developed in the MIKE21 FM HD model environment. Bathymetric data is sourced from the Canadian Hydrographic (CHS) non-navigational (NONNA) bathymetric data repository and complemented with locally collected bathymetric and topographic data collected as part of this consultancy.
- **Boundary conditions from the regional Atlantic HD storm surge model** are combined with 40-years of tidal boundary conditions using the Bedford Institute of Oceanography (BIO) Government of Canada WebTide model, to create a total water level signal that includes both surge and tidal components. Additionally, the local models include spatially and temporally varying wind and pressure fields to simulate local surge processes. Where possible, the local HD models are calibrated to water level observations.
- **Output from the 40-year total water level simulations** (combined tide and surge effects) are available throughout the entirety of the local HD model domains. Points have been extracted at key locations of interest and total water levels and depth averaged currents extracted as continuous, hourly timeseries over the period from 1980-2020.
- **Model data can then be interpreted** using a combination of a peak-over-threshold (POT) analysis and an extreme value analysis (EVA) to evaluate the extreme total water levels and depth averaged currents associated events ranging from a 1-year to 100-year AEP events. Assessing total water levels using an EVA is representative of the joint probability of tidal conditions and storm events occurring simultaneously and is frequently less conservative and more representative of actual conditions than considering these processes independently.
- **The extreme water level and depth averaged current** statistics at 38-points in the Placentia Bay domain and 5-points in the Conception Bay domain are interpolated for the development of flood and risk mapping products.

To calculate wave run-up along coastal reaches of the Salmon Cove, Carbonear and Placentia watersheds the industry standard MIKE21 FM spectral wave (SW) model will be used to simulate nearshore wave conditions for discrete extreme wave events, using offshore wind and wave statistics derived from the MSC50 wave hindcast product supported by ECCC. The framework for the completion of the wave run-up modelling is summarized in Figure 75.

FIGURE 75: OVERVIEW OF WAVE RUN-UP MODELLING



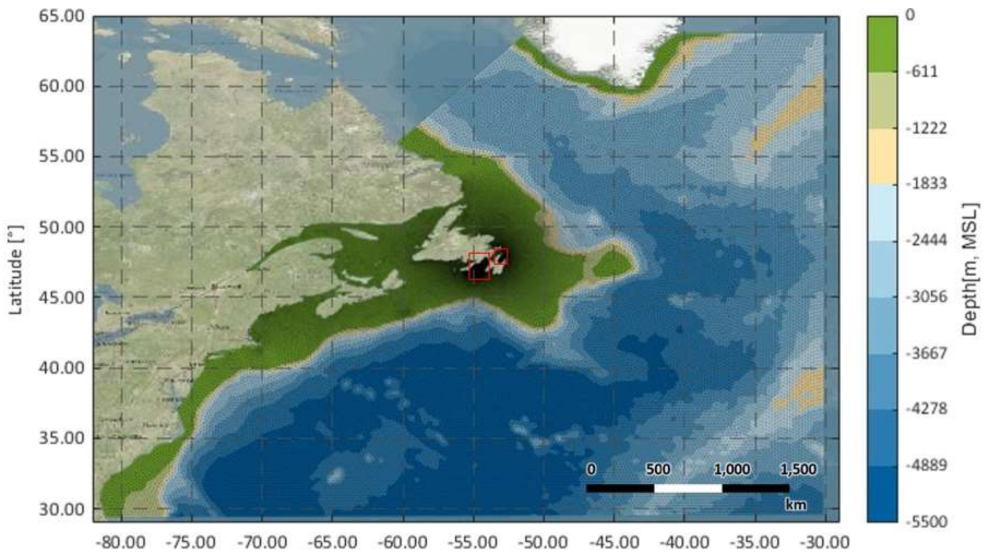

Greater detail outlining the MIKE21 FM SW model development, input data, and calibration is provided in Section 8.2.2, and is broadly summarized by the following steps:

- **The MIKE21 FM SW modelling** has been completed using the same computation grid and domain for the Placentia Bay and Conception Bay MIKE21 FM HD models. Model parameters were defined based on regionally tuned settings and parameters to simulate extreme wave conditions. It is therefore anticipated that the spectral wave model developed for this study is sufficiently robust and reliable for the purposes of calculating wave run-up.
- **The MIKE21 FM SW models integrate the MSC50 wave hindcast data.** Offshore wave and wind data spanning the period from January 1954 to December 2018 was assessed and a POT and EVA analysis performed to derive the 1 to 100-year AEP wave conditions. Water levels derived from the results of the MIKE21 FM HD storm surge model were used, in addition to sea level rise scenarios, to simulate a range of discrete multidirectional extreme wave conditions at a high resolution along the Salmon Cove, Carbonear and Placentia shoreline.
- **Outputs from the wave model along the shoreline were used to perform 1D wave run-up calculations** along a selection of coastal profiles generated in GIS, extracted from the flood plain DEM.

### 8.2.2 MODEL DEVELOPMENT

The Atlantic regional hydrodynamic model domain is shown on Figure 76, with the high-resolution Conception Bay and Placentia Bay domains shown in red. The domain was developed to capture the evolution of regional storm surge events that develop in the Atlantic at distances over 1,000 km from Newfoundland and Labrador.

### FIGURE 76: ATLANTIC REGIONAL HYDRODYNAMIC MODEL DOMAIN

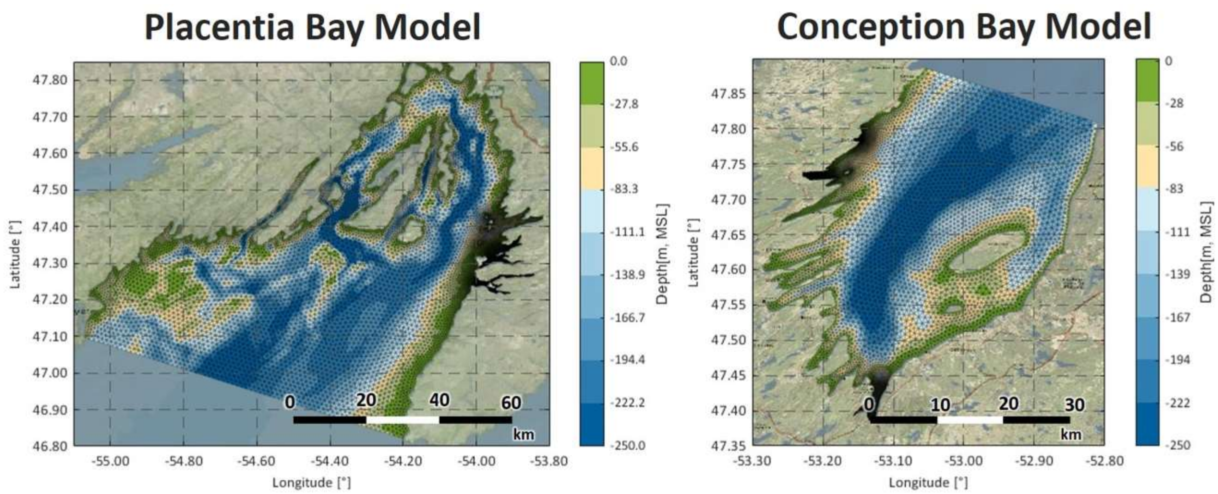



The models have been developed using MIKE21 FM, with higher resolution in nearshore regions of interest, and lower resolution in the open ocean, thereby enhancing the computational efficiency of the model, without compromising its performance. Ice cover has not been integrated into the model, as the Avalon peninsula in Newfoundland typically does not experience sustained shore fast sea ice, which could dampen or reduce storm surge potential. Model calibration has validated that the exclusion of sea ice in the model does not influence the performance of the model. It is important to note that sea ice is an important process within the Gulf of St. Lawrence and should be considered when assessing storm surge on the west coast of Newfoundland.

Two high-resolution regional models of Placentia Bay and Conception Bay, as shown on Figure 77, are nested into the regional Atlantic model, further increasing resolution in the areas of interest down to just 25 m. The high-resolution models use locally collected bathymetric data and CHS NONNA data, resolving nearshore areas in sufficient detail to describe local storm surge gradients.

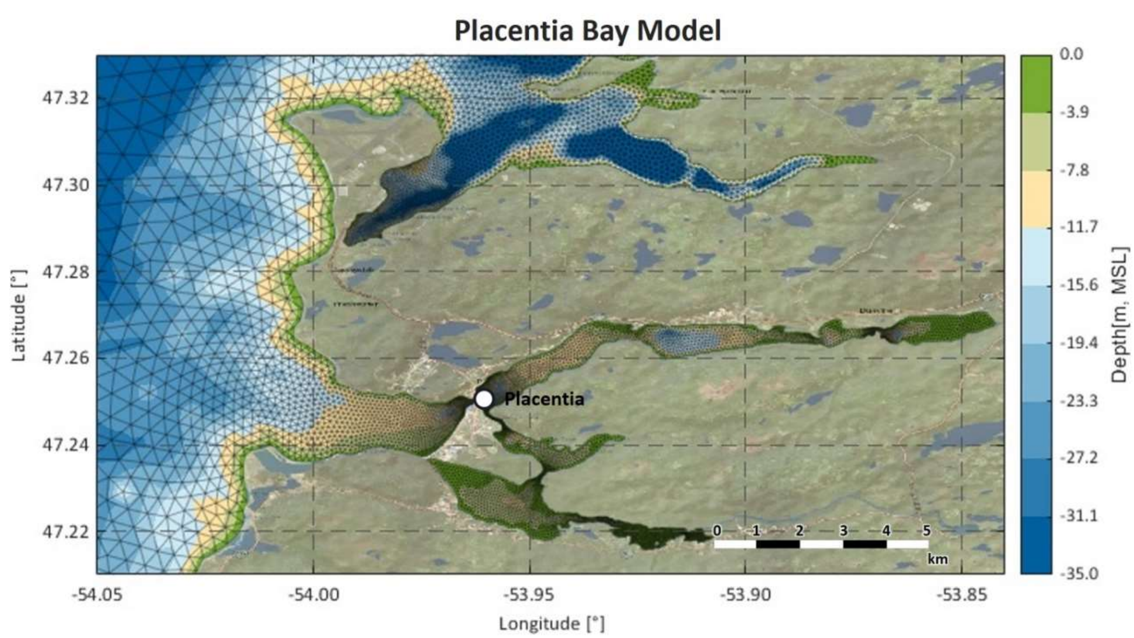
Since oceanographic bathymetric data, as well as tidal information, are defined in the MSL or CGVD28 vertical datums, which correspond to each other (i.e. MSL is equivalent to 0.0 CGVD28). Accordingly, the MIKE21 FM models were developed and implemented in the CGVD28 vertical datum, and as necessary, extracted results from the model were then converted to the CGVD2013 vertical datum. This approach minimized the conversion of geodetic data and the potential impacts of differences between the vertical datums across large areas.

### FIGURE 77: PLACENTIA BAY AND CONCEPTION BAY MODEL DOMAINS




The coastal inlets and fjords near Placentia, as shown on Figure 78, have been captured at a high resolution to resolve the current speeds and varying total water levels inland from the Placentia lift bridge, as well as within the constrictions and narrow passages of the southeast and northeast arm.

### FIGURE 78: LOCAL MODEL RESOLUTION AT PLACENTIA




A variety of input data and calibration data is required to develop the numerical wave and storm surge models. Brief summaries of the tidal, atmospheric, bathymetric, geographic, and water level monitoring data that were used in the numerical modelling investigation of coastal processes are provided below.

***Tides***

The local MIKE21 FM HD models require a continuous hourly tidal signal at the boundary, which is combined with the regional MIKE21 FM HD surge residual output. Tidal boundary conditions for the model were generally at hourly intervals using the NRCan Bedford Institute of Oceanography (BIO) Northwest Atlantic WebTide model, as described by Dupont, F. et. Al (2002).

As noted above, water levels in the model were simulated relative to MSL or CGVD28, which was consistent with the vertical datum of the MIKE21 model. To convert local bathymetric data sets from chart datum (CD) to CGVD28, the tidal conditions for each location were referenced from the 2022 Canadian Tide and Current Tables, as published by the Canadian Hydrographic Service, and corrections applied to CGVD28 using the NRCAN Vertical Datum Transformations tool. The tidal range for both Argentia and Harbour Grace (i.e. applicable for Carbonear and Salmon Cove) relative to CD and CGVD28 are summarized in Table 37 and Table 38. As previously noted, this approach was taken to minimize potential differences between the vertical datums across large areas.

**TABLE 37: TIDAL CONDITIONS AT ARGENTIA**

| Tide | Tide m (CD) | Tide m (CGVD28) |
|---|---|---|
| Higher high water large tide (HHWLT) | 2.74 | 1.34 |
| Higher high water mean tide (HHWMT) | 2.24 | 0.84 |
| Mean water level (MWL) | 1.40 | 0.00 |
| Lower low water mean tide (LLWMT) | 0.69 | -0.71 |
| Lower low water large tide (LLWLT) | 0.66 | -0.74 |

**TABLE 38: TIDAL CONDITIONS AT HARBOUR GRACE**

| Tide | Tide m (CD) | Tide m (CGVD28) |
|---|---|---|
| Higher high water large tide (HHWLT) | 1.24 | 0.59 |
| Higher high water mean tide (HHWMT) | 1.08 | 0.43 |
| Mean water level (MWL) | 0.64 | 0.00 |
| Lower low water mean tide (LLWMT) | 0.30 | -0.35 |
| Lower low water large tide (LLWLT) | 0.27 | -0.38 |

***Atmospheric Data***

The storm surge model requires robust historical spatially and temporally varying wind and pressure fields across the entirety of the domain. The global Climate Forecast System Reanalysis (CFSR) hindcast model administered by NOAA's National Centre for Atmospheric Research (NCAR) is a global, high resolution, coupled atmosphere-ocean-land surface-sea ice system designed to provide the best estimate of historical winds across coupled land-ocean domains.

The CFSR data covers the period from 1979 to 2010 (i.e. 31 years), and since then the operational re-forecast data set, denoted CFSv2, has been applied, extending from 2010 to present day. Since CFSv2 is an active forecast dataset that is being regularly updated, it is possible to use it in the future to update the database in a consistent manner. The underlying model in CFSv2 is the same as in CFSR; however, the spatial resolution of wind was increased from 0.3° to 0.2°, as summarized on Table 39, while the resolution of atmospheric pressure was interpolated to the same grid as the wind speed in this project (i.e. 0.5)° for the entire period. Hereafter, 'CFSR' will refer to the combined CFSR and CFSv2 data sets.

### TABLE 39: CHARACTERISTICS OF THE CFSR WIND AND PRESSURE DATA

| Dataset (period) | Temporal resolution [hour] | Spatial resolution of wind [°] | Spatial resolution air pressure* [°] |
|---|---|---|---|
| **CFSR (1979 – 2010)** | 1 | 0.3 | 0.5 |
| **CFSv2 (2011 – 2020)** | 1 | 0.2 | 0.5 |

* Interpolated to the same grid as the wind speed data

The CFSR data used for this study were available on an hourly basis from 1 January 1979 to 31 December 2020. CFSR was included as the dataset covers this extended period, which provides confidence in the values established. DHI has previous experience using the CFSR dataset in different parts of the world with very satisfactory results when used as forcing of wave and hydrodynamic models.

The CFSR parameters applied in this study are summarised in Table 40. In CFSR, the wind speed at 10 m MSL ($U_{10}$) is calculated from the lowest level model wind speed (i.e. approximately 20 m MSL) using the surface-layer similarity theory, where the roughness length over water is updated at each time step using the Charnock relationship.

### TABLE 40: SPECIFICATIONS OF CFSR PARAMETERS

| Abbreviation | Unit | Description | Comment |
|---|---|---|---|
| **$WS_{10}$ or $U_{10}$** | m/s | Wind speed at height 10m MSL | Representative of 2-hour averages |
| **$WD_{10}$ or $D_{10}$** | °N (coming from) | Wind direction at height 10m MSL | |

CFSR wind values are instantaneous (i.e. snapshots) and may be saved at arbitrary time intervals from the model (i.e. every hour in CFSR). Hence, the model values are not inherently associated with any time-averaging period such as for instance, synoptic measurements, which are typically averaged over 10 minutes for wind data. However, the model values represent an area determined by the spatial resolution of the model grid, rather than a single point.

The model data has previously been characterized as a representative approximation of 10 minute averaged values by some providers of meteorological data. However, the models generally produce a smooth variation of the atmospheric parameters, and the fluctuations between each instantaneous model grid value are usually small compared to synoptic measurements. CFSR wind data has been validated to measured winds & atmospheric pressure records at St. Lawrence (i.e. ECCC station 8403615), Argentia (i.e. ECCC station 8400100), Cape Race (i.e. ECCC station 8401000), St. John's (i.e. ECCC station 8403506), and Grates Cove (i.e. ECCC station 840B053).

2D data was extracted across the MIKE21 FM HD Atlantic model domain from 1980 to 2020 at a 25km resolution, where wind and pressure fields varied temporally at 4-hour intervals.

***Bathymetry Data & Shoreline Delineation***

The regional Atlantic and local Placentia Bay and Conception Bay models were interpolated using a combination of the following bathymetry data sets:

- Global General Bathymetric Chart of the Oceans (GEBCO) data of the Atlantic Ocean supplied by the British Oceanographic Data Centre (BODC).
- Canadian Hydrographic Service (CHD) NONNA (non-navigational) bathymetric data along the Newfoundland coastline.
- Locally collected bathymetric data collected as part of this project in the Northeast Arm and Southeast Arm of the Placentia watershed.

The shoreline was delineated based on a combination of the flood plain DEM and GIS data from the Government of Newfoundland and Labrador Open Data.

***Measured Water Level Data***

Measured coastal water level data throughout Newfoundland and Atlantic Canada was compiled to calibrate the MIKE21 FM HD storm surge models. Total water level data, which includes tide and surge, was downloaded at gauging stations administered by the Marine Environmental Data Section (MEDS) of Fisheries and Oceans Canada for Great St. Lawrence (i.e. station 755), St. John's (i.e. station 905), Argentia (i.e. station 835), Bonavista (i.e. station 990), Holyrood (i.e. station 925) and Yarmouth (i.e. station 365).

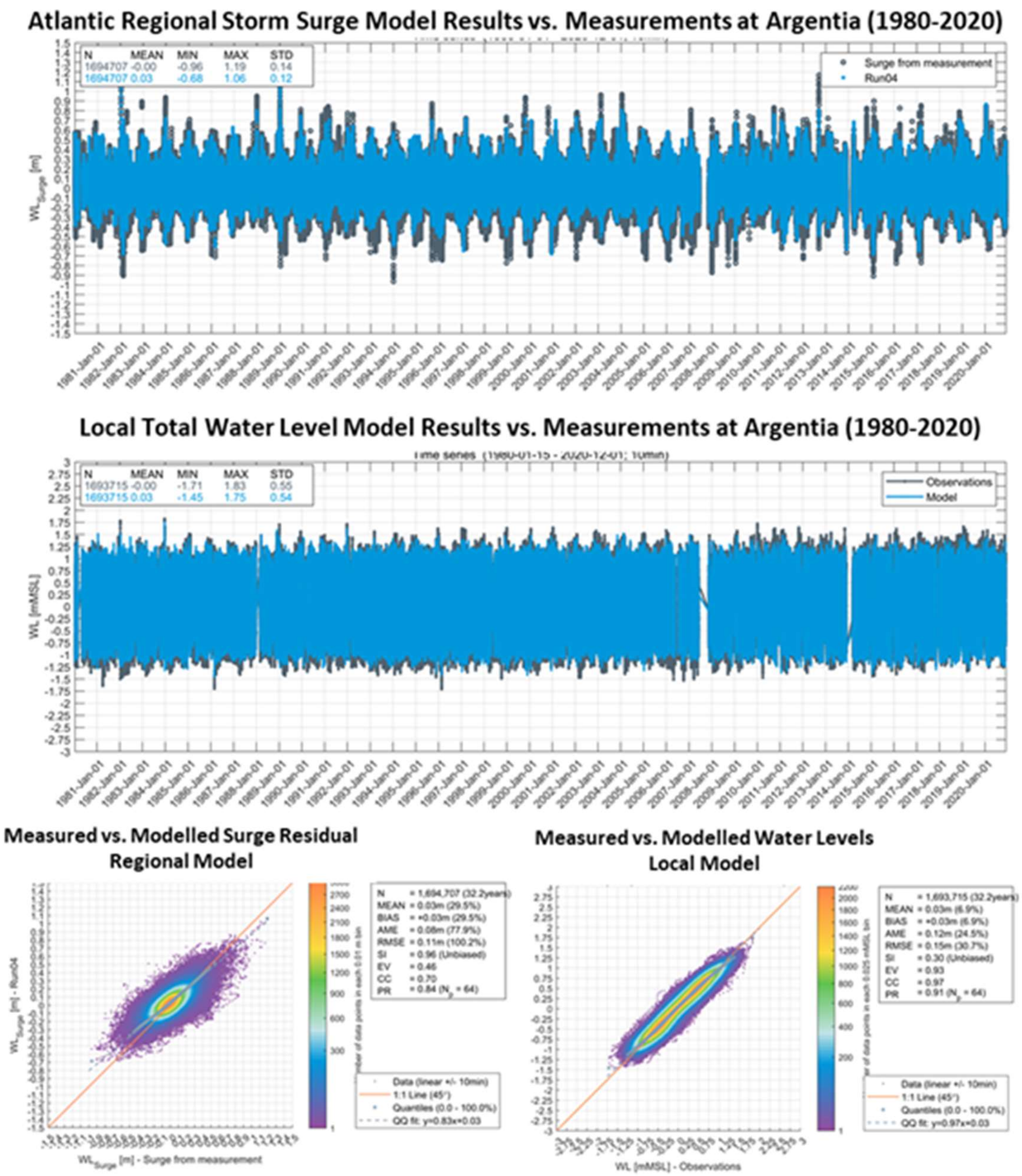
***MSC50 Hindcast data***

Wave statistics to drive the MIKE21 FM SW model were derived from the MSC50 Atlantic wave hindcast product from ECCC. This dataset spans the period January 1954 to December 2018, and contains hourly time series of wind (i.e. speed, direction) and significant waves (i.e. height, period, direction). The MSC50 hindcast was developed by Oceanweather Inc. and is distributed by ECCC (Swail et al., 2006). The MSC50 timeseries was interpreted using a POT and EVA analysis to derive the offshore wind and wave conditions for the 20-year and 100-year AEP events, which are propagated across the domain to derive spatially varying discrete wave conditions for use in the wave run-up analysis. Further details of the analysis of the MSC50 hindcast data is provided in Section 8.2.5.

### 8.2.3 MODEL CALIBRATION AND VALIDATION

Measured total water level data (i.e. surge and tide) is available at Argentia for the entire hindcast period from 1980 to 2020. The measured data was used to calibrate both the regional Atlantic HD model, as shown at the top of Figure 79, and the local regional Placentia Bay model as shown in the middle of Figure 79. Note that gaps in the data are due to missing observed total water level data.

FIGURE 79: MODEL CALIBRATION FOR THE PLACENTIA BAY DOMAIN

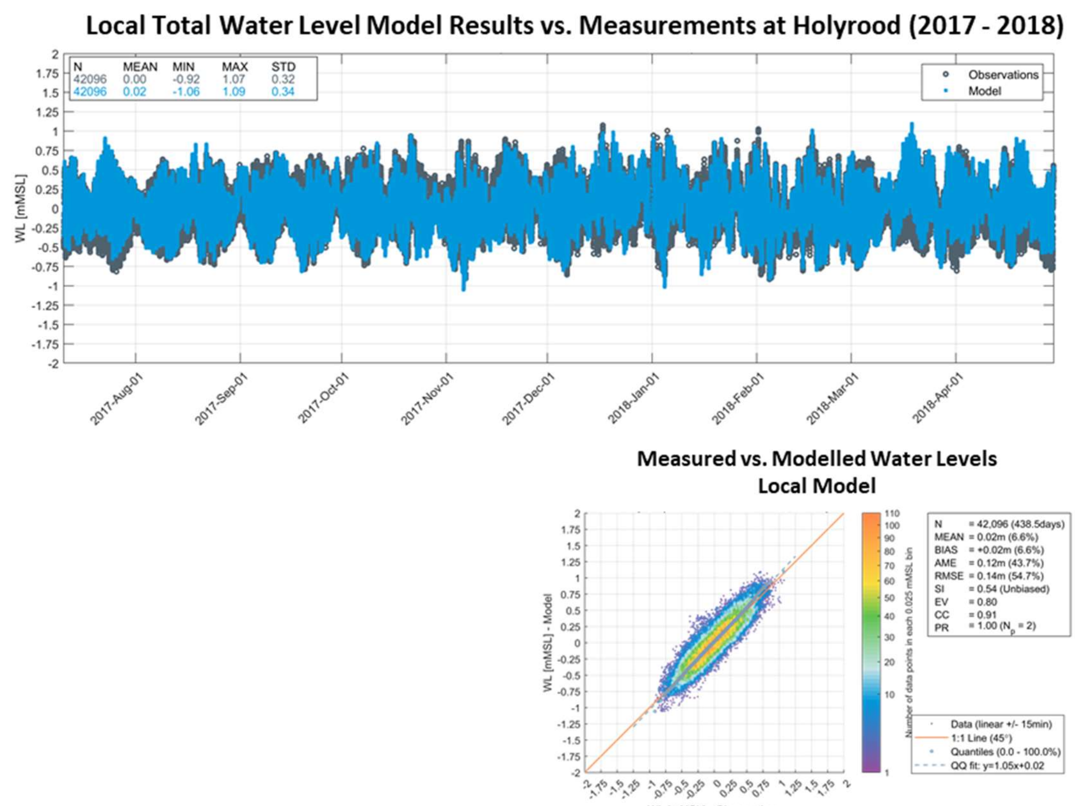



The regional Atlantic HD model simulates the storm surge residual only. The model has a relatively low resolution at the Argentia gauging station due to the size of the model domain, and the need to achieve computational efficiency. The total water level signal at Argentia was analyzed over the 40-year period from 1980 to 2020 and the tidal component was extracted from the timeseries using a harmonic analysis to isolate and extract the storm surge residual. The modelled storm surge residual, shown in blue in Figure 79, was compared to the 40-year historical measured residual, shown in grey in Figure 79, and directly as scatter data on the bottom-left of Figure 79. Given the resolution of the regional Atlantic model at Argentia, the measured versus modelled storm surge residual demonstrates satisfactory agreement.

The performance of the modelled versus measured water levels is further enhanced in the local Placentia Bay model, where the tidal component is added to the surge residual, resulting in stronger agreement between measured and modelled total water levels. The modelled total water level, shown in blue, is compared as a 40-year timeseries to the measured total water level, shown in grey, in the middle of Figure 79, and directly as scatter data at the bottom-right of Figure 79. These plots indicate a strong agreement between measurements and observations, and the model calibration can thus be considered satisfactory for an investigation of this nature.

Similarly, the Conception Bay model was calibrated to measured data at Holyrood, location in the southern end of Conception Bay. Limited measured water level data was available within Conception Bay, and the most recent record of approximately 9-months of measured total water level data was used to calibrate the total water levels within Conception Bay, as shown on Figure 80.

FIGURE 80: MODEL CALIBRATION FOR THE CONCEPTION BAY DOMAIN

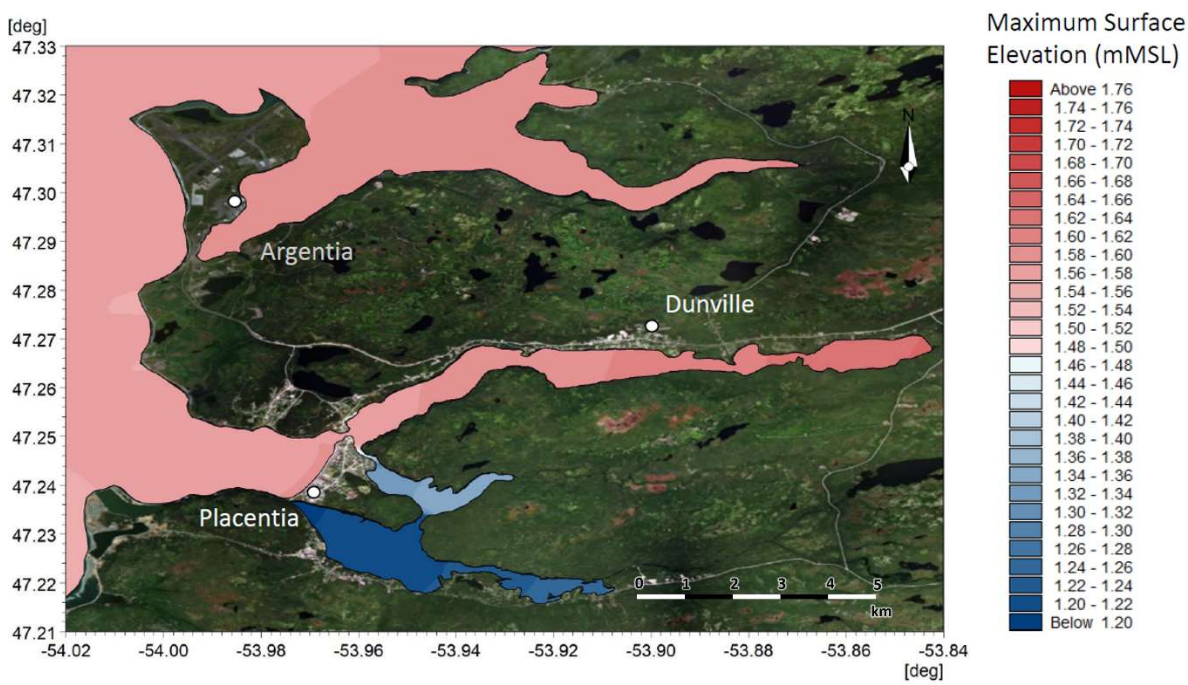


As with the Placentia Bay domain, the results in Figure 80 demonstrate a strong agreement between measurements and observations, and as such the model can be considered to be well calibrated.

### 8.2.4 DEFINITION OF THE 1:20 AND 1:100 COASTAL FLOOD LEVELS

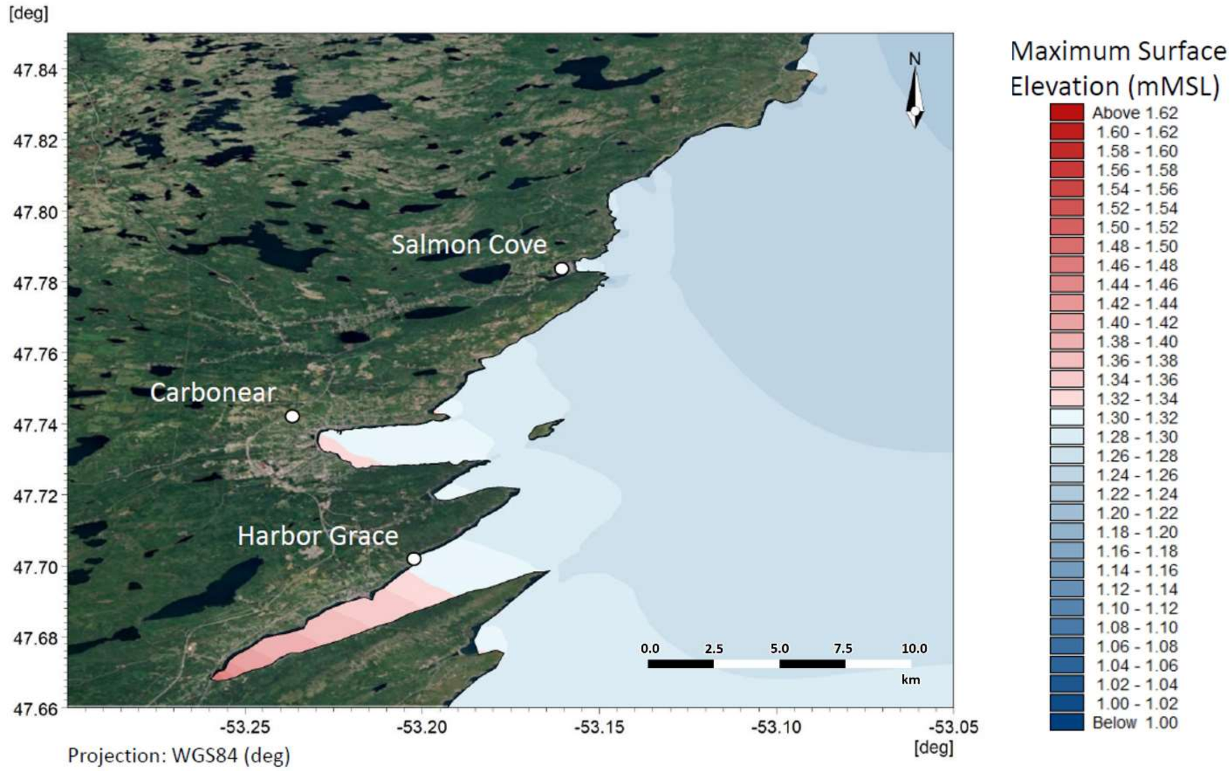
Results are available at hourly-intervals at every node in the model domain from 1980 to 2020. This large data set can be interpreted either at hourly intervals in 2D, or as timeseries at individual nodes. A sample of the maximum observed total water level in 1988 is depicted within the Placentia area of interest for reference on Figure 81. The storm surge gradient from offshore, and into the northeast, and southeast arm demonstrates the spatially varying and complex total water level gradients within the area of interest, where total water levels (relative to MSL) vary by over 0.5 m.

FIGURE 81: 1988 MAXIMUM TOTAL WATER LEVEL IN PLACENTIA BAY




Similarly, a sample of the maximum storm surge gradient for 1994 in Conception Bay at the area of interest is shown on Figure 82 to demonstrate the slight surge gradient that is possible in Harbour Grace and Carbonear relative to offshore conditions in Conception Bay itself.

### FIGURE 82: 1994 MAXIMUM TOTAL WATER LEVEL IN CONCEPTION BAY




To derive AEP storm surge flood levels, total water levels with a defined AEP are required throughout the flood mapping area of interest. Similarly, depth-averaged currents with a known AEP are also required throughout the domain. Producing AEP statistics at each node in the model is neither practical nor feasible, given that the models have several hundred thousand nodes and that total water level differences between neighboring nodes can often be negligible. Instead, a representative selection of 34 nodes have been chosen for analysis and interpretation for the Placentia Bay domain, as shown on Figure 83, and 5 nodes were selected for analysis in the Conception Bay domain, as shown on Figure 84. These number and locations of the nodes selected for further analysis were defined to accurately characterize the variation in the storm surge, particularly as it progresses inland into Northeast Arm, Swan Arm and Southeast Arm, and were based on a review of simulated storm surge events.

FIGURE 83: DATA EXTRACTION POINTS IN PLACENTIA BAY

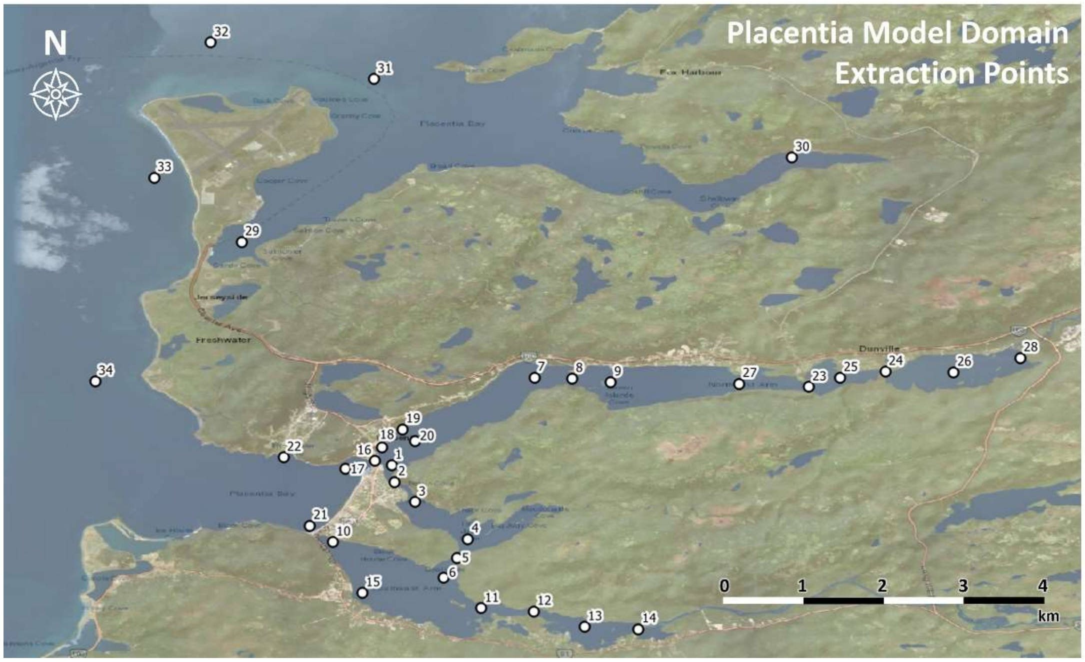
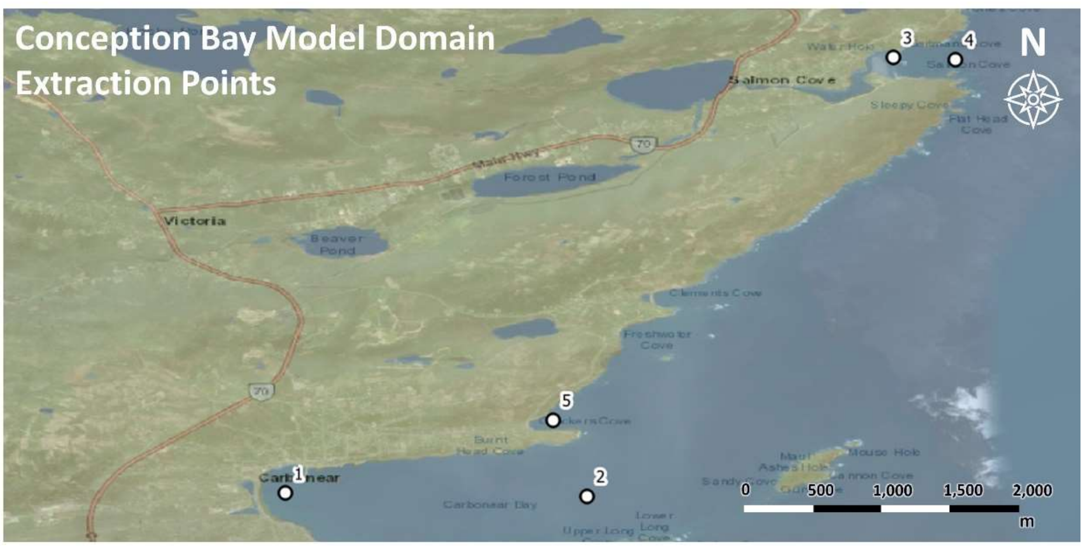



FIGURE 84: DATA EXTRACTION POINTS IN CONCEPTION BAY




At each data extraction point, timeseries of total water levels and depth-averaged velocities were extracted for integration into the flood risk and flood hazard maps. Subsequently, a POT and EVA analysis is performed for each timeseries, and the AEP for total water levels and depth averaged currents were defined by fitting representative statistical distributions to the data. The resulting AEP water levels and depth-averaged velocities are summarized in the Placentia area and Carbonear area in Table 41 and Table 42. The EVA analysis at each point is included for reference in Appendix I.

## TABLE 41: AEP WATER LEVELS AND VELOCITIES IN PLACENTIA BAY

| | Total Water Levels (m, MWL) | | | | | | Depth average currents (m/s) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Station | 100% | 20% | 10% | 5% | 2% | 1% | 100% | 20% | 10% | 5% | 2% | 1% |
| s01 | 1.4 | 1.48 | 1.53 | 1.57 | 1.65 | 1.71 | 0.17 | 0.18 | 0.18 | 0.18 | 0.19 | 0.20 |
| s02 | 1.25 | 1.33 | 1.37 | 1.42 | 1.49 | 1.55 | 1.38 | 1.45 | 1.49 | 1.52 | 1.59 | 1.63 |
| s03 | 1.15 | 1.23 | 1.27 | 1.32 | 1.40 | 1.45 | 0.37 | 0.40 | 0.41 | 0.42 | 0.44 | 0.45 |
| s04 | 1.15 | 1.23 | 1.28 | 1.33 | 1.40 | 1.45 | 0.21 | 0.23 | 0.23 | 0.23 | 0.24 | 0.25 |
| s05 | 0.93 | 1.07 | 1.14 | 1.21 | 1.30 | 1.37 | 1.94 | 2.04 | 2.07 | 2.11 | 2.14 | 2.16 |
| s06 | 0.94 | 1.08 | 1.15 | 1.21 | 1.30 | 1.37 | 0.23 | 0.26 | 0.27 | 0.28 | 0.29 | 0.31 |
| s07 | 1.40 | 1.50 | 1.55 | 1.60 | 1.66 | 1.72 | 0.24 | 0.26 | 0.27 | 0.28 | 0.29 | 0.30 |
| s08 | 1.41 | 1.50 | 1.55 | 1.61 | 1.67 | 1.72 | 0.53 | 0.56 | 0.58 | 0.59 | 0.61 | 0.62 |
| s09 | 1.41 | 1.50 | 1.55 | 1.61 | 1.67 | 1.73 | 0.09 | 0.10 | 0.11 | 0.12 | 0.12 | 0.12 |
| s10 | 0.94 | 1.08 | 1.14 | 1.22 | 1.30 | 1.37 | 0.09 | 0.10 | 0.10 | 0.10 | 0.11 | 0.11 |
| s11 | 0.94 | 1.08 | 1.15 | 1.21 | 1.31 | 1.38 | 0.06 | 0.08 | 0.08 | 0.09 | 0.09 | 0.09 |
| s12 | 0.95 | 1.09 | 1.16 | 1.22 | 1.31 | 1.39 | 0.09 | 0.11 | 0.12 | 0.12 | 0.13 | 0.14 |
| s13 | 0.95 | 1.09 | 1.16 | 1.24 | 1.32 | 1.39 | 0.14 | 0.16 | 0.17 | 0.17 | 0.19 | 0.19 |
| s14 | 0.95 | 1.10 | 1.17 | 1.24 | 1.33 | 1.40 | 0.07 | 0.08 | 0.08 | 0.08 | 0.09 | 0.09 |
| s15 | 0.94 | 1.08 | 1.14 | 1.21 | 1.30 | 1.37 | 0.15 | 0.18 | 0.19 | 0.20 | 0.21 | 0.23 |
| s16 | 1.39 | 1.47 | 1.52 | 1.57 | 1.64 | 1.70 | 1.88 | 2.04 | 2.09 | 2.14 | 2.22 | 2.28 |
| s17 | 1.40 | 1.49 | 1.54 | 1.60 | 1.66 | 1.72 | 0.56 | 0.61 | 0.63 | 0.66 | 0.70 | 0.73 |
| s18 | 1.40 | 1.48 | 1.53 | 1.58 | 1.66 | 1.72 | 0.39 | 0.42 | 0.43 | 0.44 | 0.45 | 0.46 |
| s19 | 1.40 | 1.48 | 1.53 | 1.58 | 1.66 | 1.72 | 0.39 | 0.42 | 0.44 | 0.45 | 0.46 | 0.47 |
| s20 | 1.40 | 1.48 | 1.53 | 1.58 | 1.66 | 1.72 | 0.21 | 0.23 | 0.24 | 0.25 | 0.27 | 0.28 |
| s21 | 1.40 | 1.49 | 1.54 | 1.60 | 1.66 | 1.72 | 0.26 | 0.29 | 0.3 | 0.31 | 0.32 | 0.33 |
| s22 | 1.40 | 1.49 | 1.54 | 1.59 | 1.66 | 1.71 | 0.13 | 0.15 | 0.15 | 0.16 | 0.17 | 0.17 |
| s23 | 1.42 | 1.51 | 1.56 | 1.62 | 1.69 | 1.75 | 0.50 | 0.54 | 0.55 | 0.56 | 0.58 | 0.59 |
| s24 | 1.43 | 1.52 | 1.57 | 1.63 | 1.71 | 1.77 | 0.92 | 0.99 | 1.02 | 1.04 | 1.08 | 1.10 |
| s25 | 1.42 | 1.52 | 1.57 | 1.63 | 1.70 | 1.76 | 0.19 | 0.21 | 0.21 | 0.22 | 0.23 | 0.23 |
| s26 | 1.43 | 1.53 | 1.58 | 1.64 | 1.71 | 1.77 | 0.15 | 0.17 | 0.18 | 0.19 | 0.20 | 0.21 |
| s27 | 1.41 | 1.51 | 1.56 | 1.61 | 1.68 | 1.74 | 0.22 | 0.23 | 0.24 | 0.24 | 0.25 | 0.25 |
| s28 | 1.44 | 1.53 | 1.59 | 1.64 | 1.72 | 1.78 | 0.13 | 0.16 | 0.17 | 0.17 | 0.19 | 0.21 |
| s29 | 1.40 | 1.50 | 1.55 | 1.60 | 1.67 | 1.72 | 0.09 | 0.10 | 0.11 | 0.11 | 0.12 | 0.13 |
| s30 | 1.41 | 1.50 | 1.55 | 1.60 | 1.67 | 1.73 | 0.04 | 0.04 | 0.05 | 0.05 | 0.05 | 0.05 |
| s31 | 1.40 | 1.50 | 1.55 | 1.60 | 1.67 | 1.72 | 0.2 | 0.23 | 0.24 | 0.25 | 0.26 | 0.28 |
| s32 | 1.40 | 1.50 | 1.55 | 1.59 | 1.66 | 1.72 | 0.44 | 0.50 | 0.54 | 0.57 | 0.61 | 0.64 |
| s33 | 1.40 | 1.49 | 1.54 | 1.59 | 1.66 | 1.72 | 0.39 | 0.44 | 0.46 | 0.49 | 0.52 | 0.54 |
| s34 | 1.40 | 1.49 | 1.54 | 1.59 | 1.66 | 1.71 | 0.49 | 0.57 | 0.60 | 0.63 | 0.67 | 0.70 |

### TABLE 42: AEP AT LOCATIONS IN CONCEPTION BAY

| | Total Water Levels (m, MWL) | | | | | | Depth average currents (m/s) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Station** | **100%** | **20%** | **10%** | **5%** | **2%** | **1%** | **100%** | **20%** | **10%** | **5%** | **2%** | **1%** |
| **s01** | 1.28 | 1.40 | 1.46 | 1.52 | 1.58 | 1.64 | 0.12 | 0.14 | 0.15 | 0.16 | 0.16 | 0.16 |
| **s02** | 1.28 | 1.41 | 1.46 | 1.51 | 1.59 | 1.64 | 0.12 | 0.14 | 0.15 | 0.15 | 0.17 | 0.17 |
| **s03** | 1.27 | 1.40 | 1.46 | 1.52 | 1.58 | 1.64 | 0.12 | 0.13 | 0.13 | 0.14 | 0.15 | 0.15 |
| **s04** | 1.28 | 1.40 | 1.46 | 1.52 | 1.58 | 1.64 | 0.13 | 0.15 | 0.15 | 0.15 | 0.17 | 0.17 |
| **s05** | 1.28 | 1.41 | 1.46 | 1.51 | 1.59 | 1.64 | 0.10 | 0.11 | 0.12 | 0.13 | 0.14 | 0.15 |

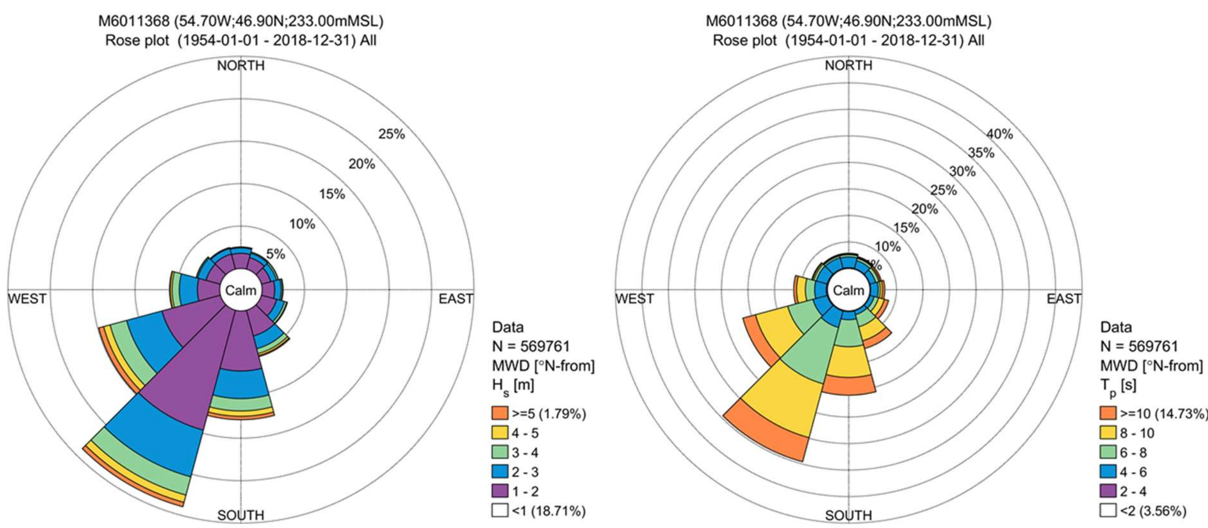
#### 8.2.5 COASTAL WAVE MODELLING

Wave statistics used to drive the MIKE21 FM SW model were derived from the MSC50 Atlantic wave hindcast product from ECCC. This dataset spans the period January 1954 to December 2018, and contains hourly time series of wind (i.e. speed, direction) and significant waves (i.e. height, period, direction). The MSC50 hindcast was developed by Oceanweather Inc. and is distributed by ECCC (Swail et al., 2006). A summary of the wave modelling completed for Placentia Bay and Conception Bay are provided below.

***Placentia Bay – MSC50 Data Point M6011368***

A summary of the wave statistics for the significant wave height (i.e. Hs, m) and the peak wave period (i.e. Tp, seconds), is provided in a rose plot format in Figure 85. Prevailing offshore waves are from the southwest, which is consistent with prevailing offshore wave conditions along the south shore of the Avalon Peninsula.

FIGURE 85: MSC50 M6011368 WAVE HEIGHT AND WAVE PERIOD




Monthly wave roses for Placentia Bay, provided in Appendix J, indicate that:

- Prevailing lower energy waves are from the southwest, during summer months (i.e. May to August), and

- The fall (i.e. September to November) and winter (i.e. December to March) months experience the highest energy waves, predominantly from south/south-west, and are typically associated with storm activity.

Other wind and wave statistics, which are provided in Appendix J, for point M6011368 include:

- Significant wave height and frequency of occurrence tables in 30° bins,
- Sustained wind speed and frequency of occurrence tables in 30° bins,
- Annual wind rose plot,
- Peak wave period and frequency of occurrence tables in 30° bins.
- A significant wave height probability distribution and a peak wave period probability distribution.
- Sustained wind speed probability distribution.
- Polar plots depicting peak wave direction relative to significant wave height and peak wave direction relative to peak wave period.

The timeseries data used for the significant wave height and prevailing winds were assessed in 30° directional bins using an EVA to assess wave and wind conditions for a 1-year to 100-year AEP range. The wave and wind conditions are summarized in Table 43 and Table 44.

### TABLE 43: AEP SIGNIFICANT WAVE HEIGHT PER DIRECTION FOR MSC50 M6011368

| AEP | Significant Wave Height (m) per Direction | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 180° | 210° | 240° | 270° | 300° | 330° | 360° | 30° | 60° | 90° | 120° | 150° |
| **100%** | 6.9 | 7.5 | 7.3 | 5.1 | 3.9 | 3.4 | 3.4 | 3.5 | 3.6 | 3.8 | 4.3 | 5.9 |
| **20%** | 8.4 | 9.3 | 8.7 | 6.0 | 4.8 | 4.4 | 4.2 | 4.3 | 4.4 | 4.7 | 5.3 | 7.3 |
| **10%** | 8.9 | 9.9 | 9.2 | 6.4 | 5.2 | 4.8 | 4.5 | 4.6 | 4.7 | 5.0 | 5.8 | 7.8 |
| **5%** | 9.4 | 10.7 | 9.7 | 6.7 | 5.5 | 5.2 | 4.7 | 5.0 | 5.1 | 5.4 | 6.4 | 8.5 |
| **2%** | 9.9 | 11.2 | 10.1 | 7.0 | 6.0 | 5.8 | 5.1 | 5.3 | 5.3 | 5.6 | 6.9 | 9.1 |
| **1%** | 10.3 | 11.7 | 10.5 | 7.2 | 6.3 | 6.2 | 5.3 | 5.5 | 5.6 | 5.8 | 7.4 | 9.6 |

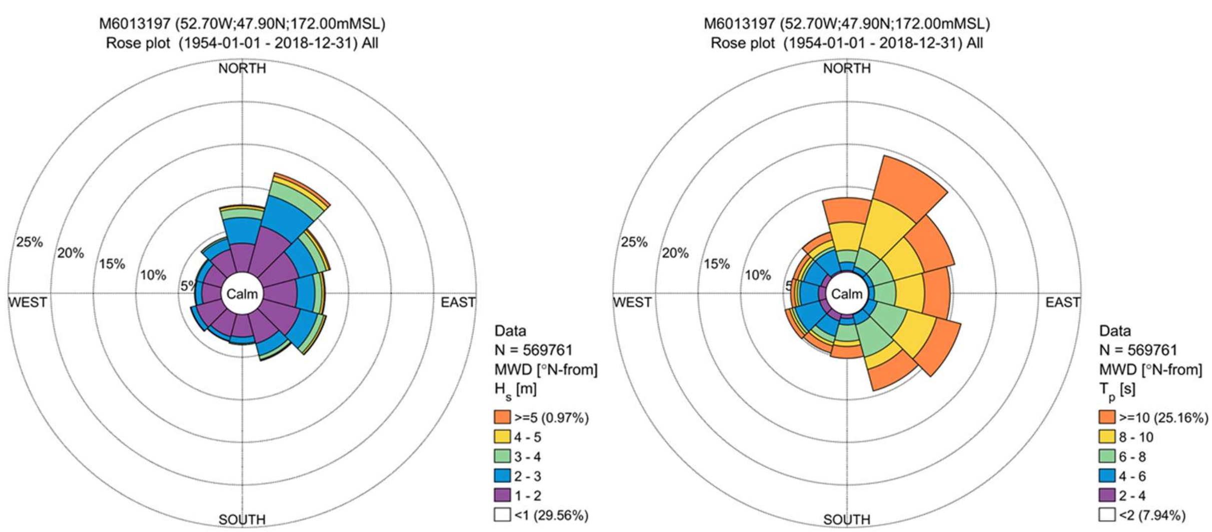
### TABLE 44: AEP WIND SPEED PER DIRECTION FOR MSC50 M6013197

| AEP | Significant Wave Height (m) per Direction | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 180° | 210° | 240° | 270° | 300° | 330° | 360° | 30° | 60° | 90° | 120° | 150° |
| **100%** | 18.8 | 19.3 | 20.8 | 21.6 | 20.2 | 18.8 | 18.0 | 18.4 | 18.9 | 18.7 | 19.5 | 19.3 |
| **20%** | 21.5 | 22.3 | 23.5 | 24.1 | 23.0 | 21.8 | 21.1 | 21.3 | 22.0 | 21.7 | 22.1 | 21.9 |
| **10%** | 24.0 | 24.6 | 26.4 | 26.4 | 25.4 | 24.0 | 23.4 | 23.6 | 24.4 | 24.2 | 24.0 | 24.3 |
| **5%** | 22.7 | 23.5 | 24.6 | 25.0 | 24.1 | 22.9 | 22.2 | 22.4 | 23.2 | 22.9 | 23.0 | 23.0 |
| **2%** | 25.6 | 26.2 | 27.1 | 27.1 | 26.6 | 25.4 | 24.9 | 24.9 | 25.7 | 25.4 | 25.1 | 25.5 |
| **1%** | 26.8 | 27.3 | 28.1 | 28.0 | 27.6 | 26.4 | 25.9 | 25.9 | 26.8 | 26.4 | 25.9 | 26.5 |

***Conception Bay – MSC50 Data Point M6013197***

A summary of the wave statistics for the significant wave height and the peak wave period for Conception Bay is provided in a rose plot format in Figure 86. Prevailing offshore waves are from the east and northeast, which is consistent with prevailing offshore wave conditions along the northeastern shore of the Avalon Peninsula.

### FIGURE 86: MSC50 M6013197 WAVE HEIGHT AND WAVE PERIOD




Monthly wave roses, included in Appendix J, indicate that:

- Prevailing lower energy waves are from the east, during summer months (i.e. May to August), and
- The fall (i.e. September to November) and winter (i.e. December to March) months experience the highest energy waves, predominantly from north, northeast, and are typically associated with storm activity.

As with point M6011368, offshore wave and wind statistics are provided in Appendix J for point M6013197. The timeseries data for the significant waver height and prevailing winds were assessed in 30° directional bins using an extreme value analysis to assess wave and wind conditions for a 1-year to 100-year AEP range. The wind and wave conditions for MSC50 M6013197 are summarized in Table 45 and Table 46.

### TABLE 45: AEP SIGNIFICANT WAVE HEIGHT PER DIRECTION FOR MSC50 M6013197

| | Significant Wave Height (m) per Direction | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **AEP** | 180° | 210° | 240° | 270° | 300° | 330° | 360° | 30° | 60° | 90° | 120° | 150° |
| **100%** | 3.8 | 3.5 | 3.3 | 3.3 | 3.3 | 3.6 | 5.1 | 6.1 | 5.1 | 4.9 | 5.1 | 4.8 |
| **20%** | 4.5 | 4.1 | 3.8 | 3.8 | 3.9 | 4.5 | 6.6 | 7.8 | 6.5 | 6.5 | 6.5 | 5.9 |
| **10%** | 4.8 | 4.3 | 4.0 | 3.9 | 4.0 | 4.8 | 7.2 | 8.4 | 7.2 | 7.2 | 7.2 | 6.3 |
| **5%** | 5.3 | 4.7 | 4.4 | 4.2 | 4.3 | 5.5 | 8.4 | 9.6 | 8.7 | 8.5 | 8.5 | 7.0 |
| **2%** | 5.5 | 4.8 | 4.5 | 4.3 | 4.4 | 5.8 | 8.9 | 10.0 | 9.3 | 9.1 | 9.1 | 7.3 |
| **1%** | 5.0 | 4.47 | 4.1 | 4.0 | 4.1 | 5.1 | 7.8 | 9.0 | 8.0 | 8.0 | 7.8 | 6.5 |

### TABLE 46: AEP WIND SPEED PER DIRECTION FOR MSC50 M6013197

| | Significant Wave Height (m) per Direction | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **AEP** | 180° | 210° | 240° | 270° | 300° | 330° | 360° | 30° | 60° | 90° | 120° | 150° |
| **100%** | 19.0 | 19.2 | 20.5 | 21.1 | 20.5 | 19.6 | 18.1 | 16.9 | 16.4 | 16.4 | 18.5 | 19.1 |
| **20%** | 21.3 | 21.8 | 22.7 | 23.6 | 23.3 | 22.6 | 20.7 | 19.4 | 19.1 | 19.4 | 20.7 | 21.9 |
| **10%** | 22.3 | 22.8 | 23.5 | 24.5 | 24.3 | 23.7 | 21.8 | 20.5 | 20.2 | 20.6 | 21.4 | 23.2 |
| **5%** | 24.5 | 25.2 | 25.1 | 26.3 | 26.6 | 26.3 | 24.0 | 22.7 | 22.6 | 23.3 | 23.1 | 26.2 |
| **2%** | 25.5 | 26.1 | 25.8 | 27.1 | 27.5 | 27.3 | 24.9 | 23.6 | 23.6 | 24.4 | 23.8 | 27.6 |
| **1%** | 23.5 | 23.8 | 24.0 | 25.4 | 25.8 | 25.0 | 22.84 | 21.3 | 21.3 | 21.8 | 22.0 | 24.6 |

Spectral wave modelling, which is used to define the growth, decay and transformation of wind-generated waves and swell in offshore and coastal areas, was completed using the state-of-the-art numerical model MIKE 21 FM SW. MIKE 21 SW includes the following physical processes:

- Wave growth by action of wind
- Non-linear wave-wave interaction
- Dissipation due to white capping

- Dissipation due to bottom friction
- Dissipation due to depth-induced wave breaking
- Refraction and shoaling due to depth variations

The model was set up with a fully spectral, quasi-stationary formulation that is suitable for wave studies of discrete extreme conditions. The model was driven with total water levels and extreme offshore wave conditions and sustained winds from the MSC50 hindcast. Summaries of the spectral wave simulations for Placentia Bay and Conception Bay are provided below.

***Placentia Bay***

Model outputs showing discrete extreme wave conditions in Placentia are shown for an illustrative case (i.e. 100-yr, 240° prevailing wind and offshore waves) at regional and local scales on Figure 87 to Figure 89.

FIGURE 87: 100-YEAR AEP SIGNIFICANT WAVE HEIGHT FOR PLACENTIA BAY

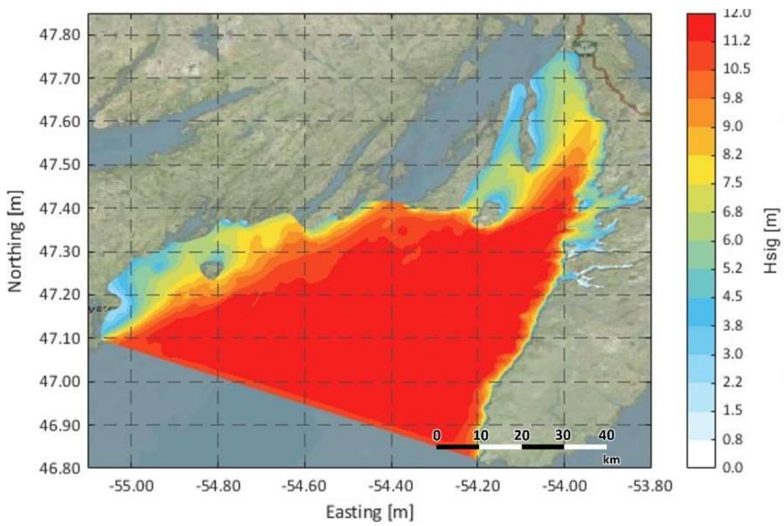
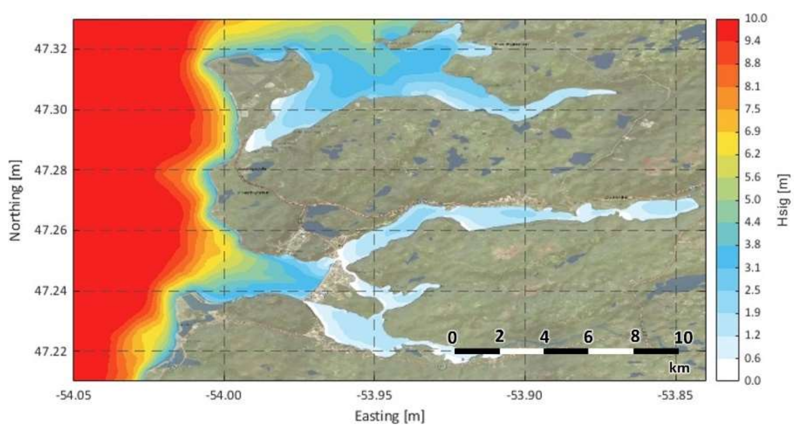
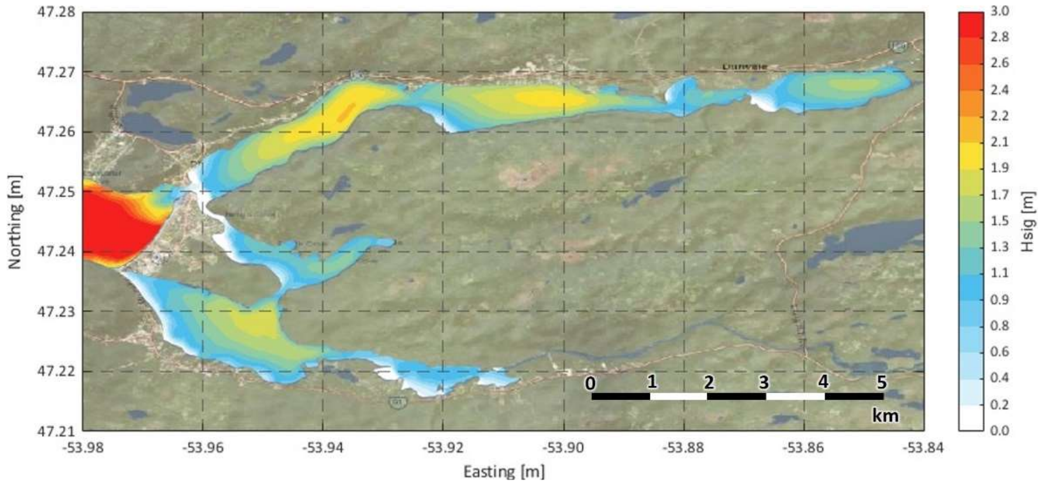



FIGURE 88: 100-YEAR AEP SIGNIFICANT WAVE HEIGHT FOR THE PLACENTIA REGION



### FIGURE 89: 100-YEAR AEP SIGNIFICANT WAVE HEIGHT IN NORTHEAST AND SOUTHEAST ARMS



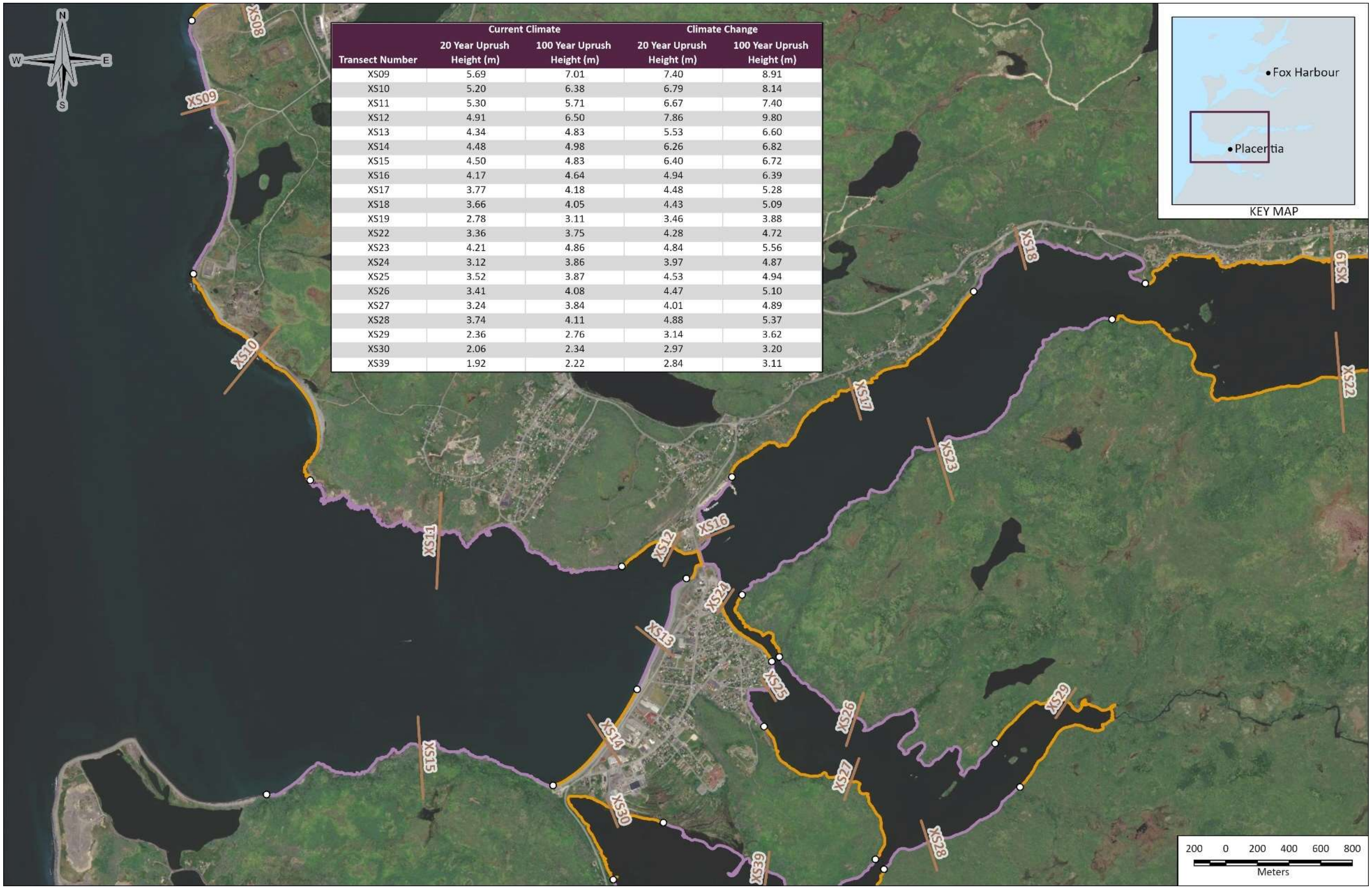

Wave model outputs for several additional directions and 20- and 100-year AEP events are included in Appendix K. The model outputs illustrate the site-specific impacts of extreme wave events throughout the model domain.

Outputs from the MIKE21 FM SW model were extracted throughout the model domains and used in combination with the storm surge, sea level rise, and coastal cross sections extracted from the DEM to complete wave uprush calculations following the methodology defined by EurOtop (2018). Coastal cross sections were extracted from the DEM at representative locations for consistent stretches of shoreline. Wave uprush heights were not integrated into the flood risk mapping due to the transient nature of the wave uprush, and that the wave uprush only affects a limited region near the coastline. Figure 90 to Figure 93 summarize wave uprush heights, which are summarized in tables embedded in the figures, as well as the location of the representative cross sections that were used for the uprush calculations, as shown in brown, for a given section of coastline, which are shown alternatingly in yellow and purple.

## FIGURE 90: PLACENTIA AREA WAVE UPRUSH HEIGHTS (SHEET 1)

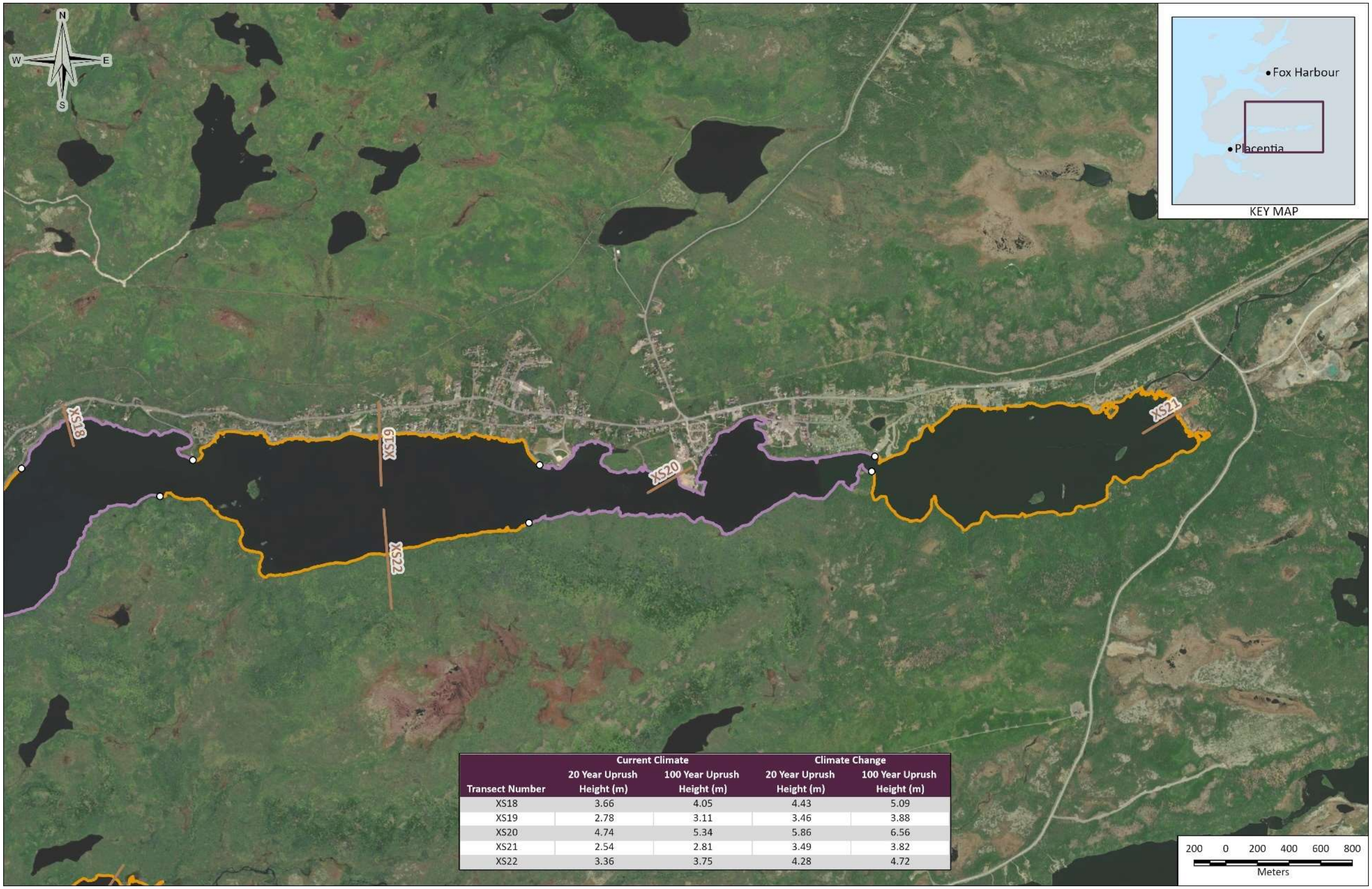

| Transect Number | Current Climate 20 Year Uprush Height (m) | Current Climate 100 Year Uprush Height (m) | Climate Change 20 Year Uprush Height (m) | Climate Change 100 Year Uprush Height (m) |
|---|---|---|---|---|
| XS01 | 3.87 | 5.14 | 4.42 | 5.80 |
| XS02 | 2.12 | 2.80 | 2.47 | 3.13 |
| XS03 | 5.05 | 5.40 | 6.67 | 6.39 |
| XS04 | 5.26 | 6.65 | 6.18 | 7.96 |
| XS05 | 4.42 | 5.73 | 5.28 | 6.80 |
| XS06 | 3.26 | 4.98 | 3.67 | 5.44 |
| XS07 | 4.37 | 6.19 | 4.83 | 6.68 |
| XS08 | 4.10 | 5.59 | 4.49 | 6.21 |
| XS09 | 5.69 | 7.01 | 7.40 | 8.91 |

## FIGURE 91: PLACENTIA AREA WAVE UPRUSH HEIGHTS (SHEET 2)



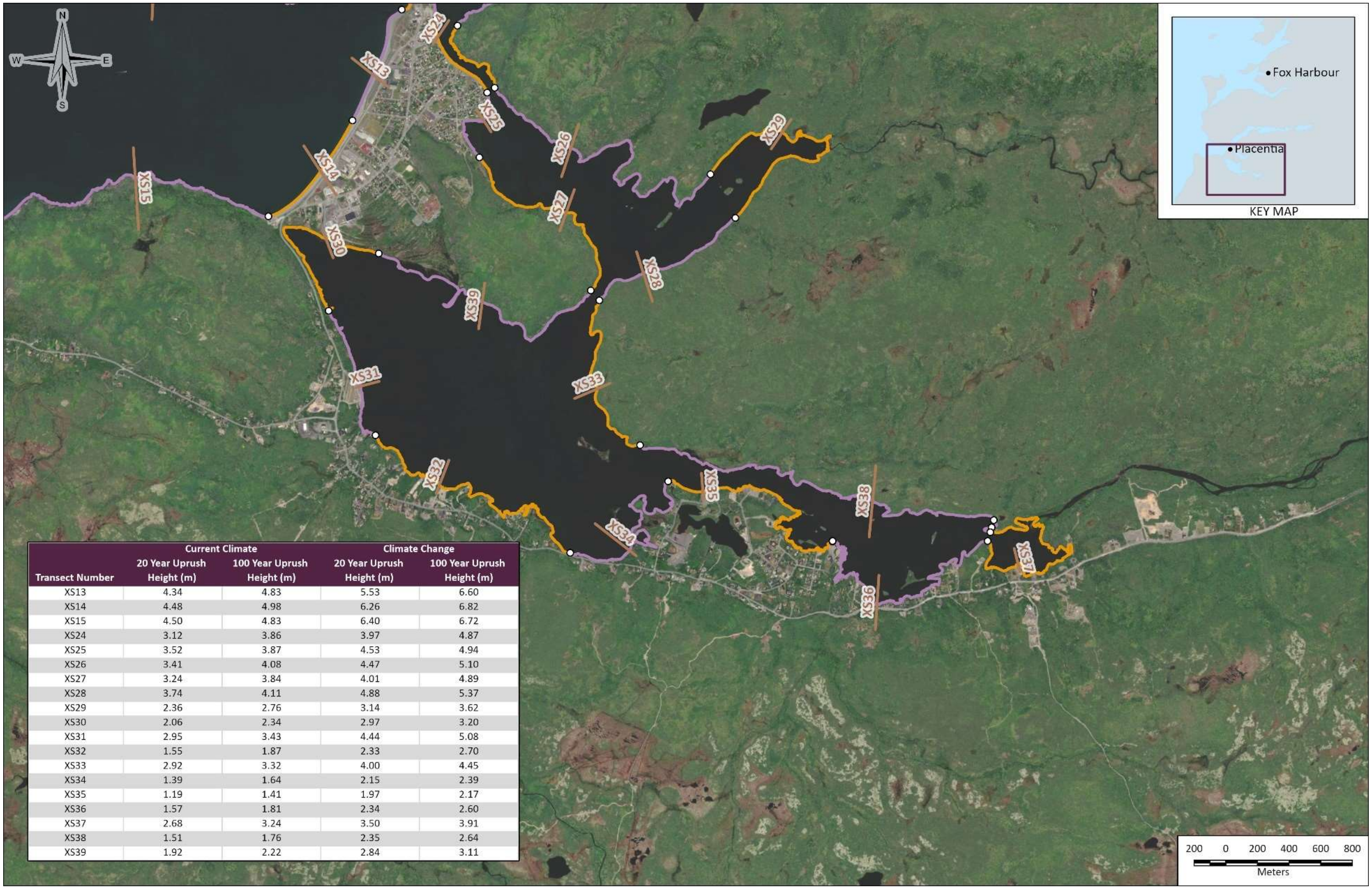

| Transect Number | Current Climate: 20 Year Uprush Height (m) | Current Climate: 100 Year Uprush Height (m) | Climate Change: 20 Year Uprush Height (m) | Climate Change: 100 Year Uprush Height (m) |
|---|---|---|---|---|
| XS09 | 5.69 | 7.01 | 7.40 | 8.91 |
| XS10 | 5.20 | 6.38 | 6.79 | 8.14 |
| XS11 | 5.30 | 5.71 | 6.67 | 7.40 |
| XS12 | 4.91 | 6.50 | 7.86 | 9.80 |
| XS13 | 4.34 | 4.83 | 5.53 | 6.60 |
| XS14 | 4.48 | 4.98 | 6.26 | 6.82 |
| XS15 | 4.50 | 4.83 | 6.40 | 6.72 |
| XS16 | 4.17 | 4.64 | 4.94 | 6.39 |
| XS17 | 3.77 | 4.18 | 4.48 | 5.28 |
| XS18 | 3.66 | 4.05 | 4.43 | 5.09 |
| XS19 | 2.78 | 3.11 | 3.46 | 3.88 |
| XS22 | 3.36 | 3.75 | 4.28 | 4.72 |
| XS23 | 4.21 | 4.86 | 4.84 | 5.56 |
| XS24 | 3.12 | 3.86 | 3.97 | 4.87 |
| XS25 | 3.52 | 3.87 | 4.53 | 4.94 |
| XS26 | 3.41 | 4.08 | 4.47 | 5.10 |
| XS27 | 3.24 | 3.84 | 4.01 | 4.89 |
| XS28 | 3.74 | 4.11 | 4.88 | 5.37 |
| XS29 | 2.36 | 2.76 | 3.14 | 3.62 |
| XS30 | 2.06 | 2.34 | 2.97 | 3.20 |
| XS39 | 1.92 | 2.22 | 2.84 | 3.11 |

# FIGURE 92: PLACENTIA AREA WAVE UPRUSH HEIGHTS (SHEET 3)




| Transect Number | Current Climate: 20 Year Uprush Height (m) | Current Climate: 100 Year Uprush Height (m) | Climate Change: 20 Year Uprush Height (m) | Climate Change: 100 Year Uprush Height (m) |
|---|---|---|---|---|
| XS18 | 3.66 | 4.05 | 4.43 | 5.09 |
| XS19 | 2.78 | 3.11 | 3.46 | 3.88 |
| XS20 | 4.74 | 5.34 | 5.86 | 6.56 |
| XS21 | 2.54 | 2.81 | 3.49 | 3.82 |
| XS22 | 3.36 | 3.75 | 4.28 | 4.72 |

## FIGURE 93: PLACENTIA AREA WAVE UPRUSH HEIGHTS (SHEET 4)




| Transect Number | Current Climate 20 Year Uprush Height (m) | Current Climate 100 Year Uprush Height (m) | Climate Change 20 Year Uprush Height (m) | Climate Change 100 Year Uprush Height (m) |
|---|---|---|---|---|
| XS13 | 4.34 | 4.83 | 5.53 | 6.60 |
| XS14 | 4.48 | 4.98 | 6.26 | 6.82 |
| XS15 | 4.50 | 4.83 | 6.40 | 6.72 |
| XS24 | 3.12 | 3.86 | 3.97 | 4.87 |
| XS25 | 3.52 | 3.87 | 4.53 | 4.94 |
| XS26 | 3.41 | 4.08 | 4.47 | 5.10 |
| XS27 | 3.24 | 3.84 | 4.01 | 4.89 |
| XS28 | 3.74 | 4.11 | 4.88 | 5.37 |
| XS29 | 2.36 | 2.76 | 3.14 | 3.62 |
| XS30 | 2.06 | 2.34 | 2.97 | 3.20 |
| XS31 | 2.95 | 3.43 | 4.44 | 5.08 |
| XS32 | 1.55 | 1.87 | 2.33 | 2.70 |
| XS33 | 2.92 | 3.32 | 4.00 | 4.45 |
| XS34 | 1.39 | 1.64 | 2.15 | 2.39 |
| XS35 | 1.19 | 1.41 | 1.97 | 2.17 |
| XS36 | 1.57 | 1.81 | 2.34 | 2.60 |
| XS37 | 2.68 | 3.24 | 3.50 | 3.91 |
| XS38 | 1.51 | 1.76 | 2.35 | 2.64 |
| XS39 | 1.92 | 2.22 | 2.84 | 3.11 |

### *Carbonear Area*

Model outputs for discrete extreme wave conditions in Conception Bay for an illustrative case (i.e. 100-yr, 30° prevailing wind and offshore waves) are shown for regional and local scales on Figure 94 and Figure 95. As with the Placentia domain, the Carbonear model outputs for several additional directions and 20- and 100-year AEP events are included in Appendix K.

FIGURE 94: 100-YEAR AEP SIGNIFICANT WAVE HEIGHT FOR CONCEPTION BAY

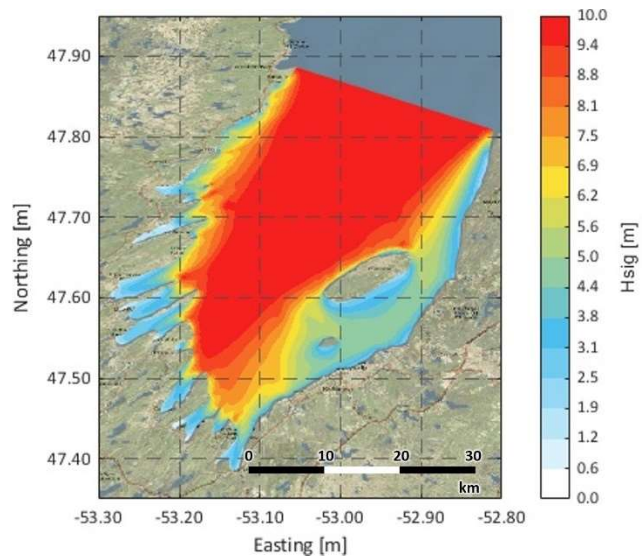
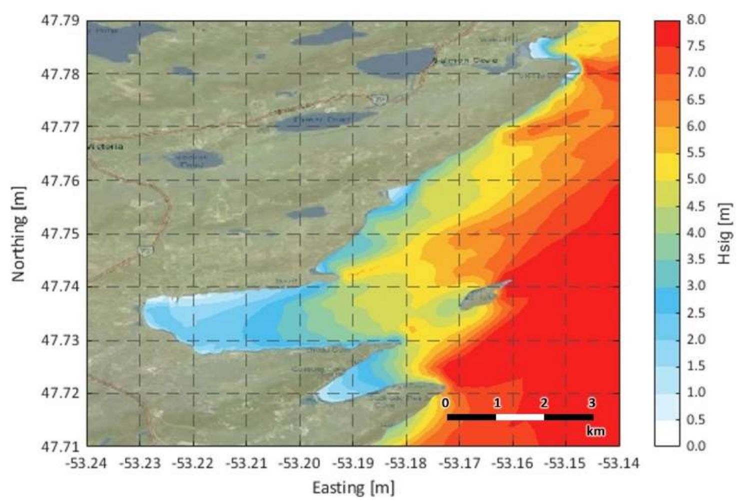
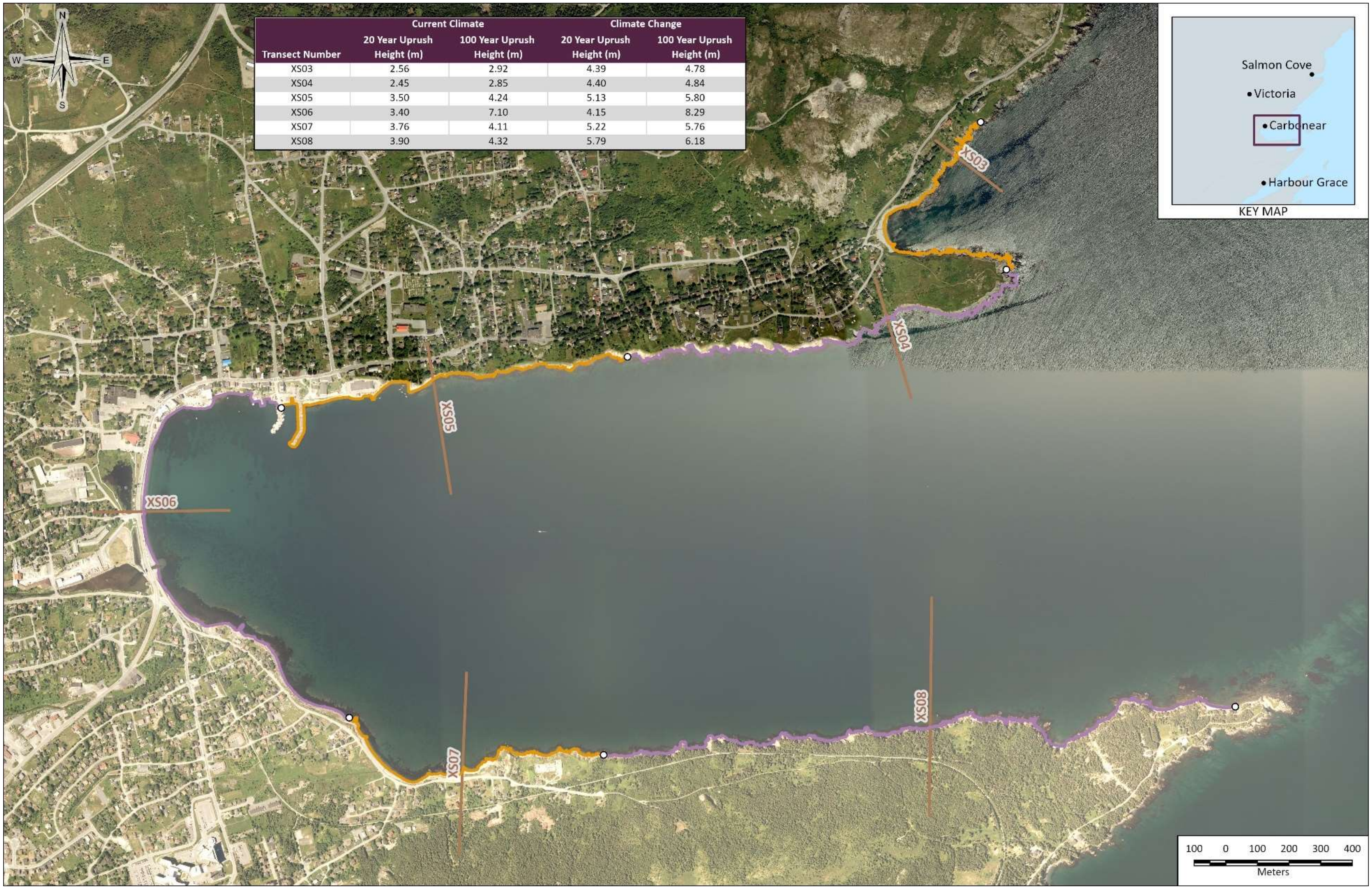



FIGURE 95: 100-YEAR AEP SIGNIFICANT WAVE HEIGHT FOR CARBONEAR AND SALMON COVE



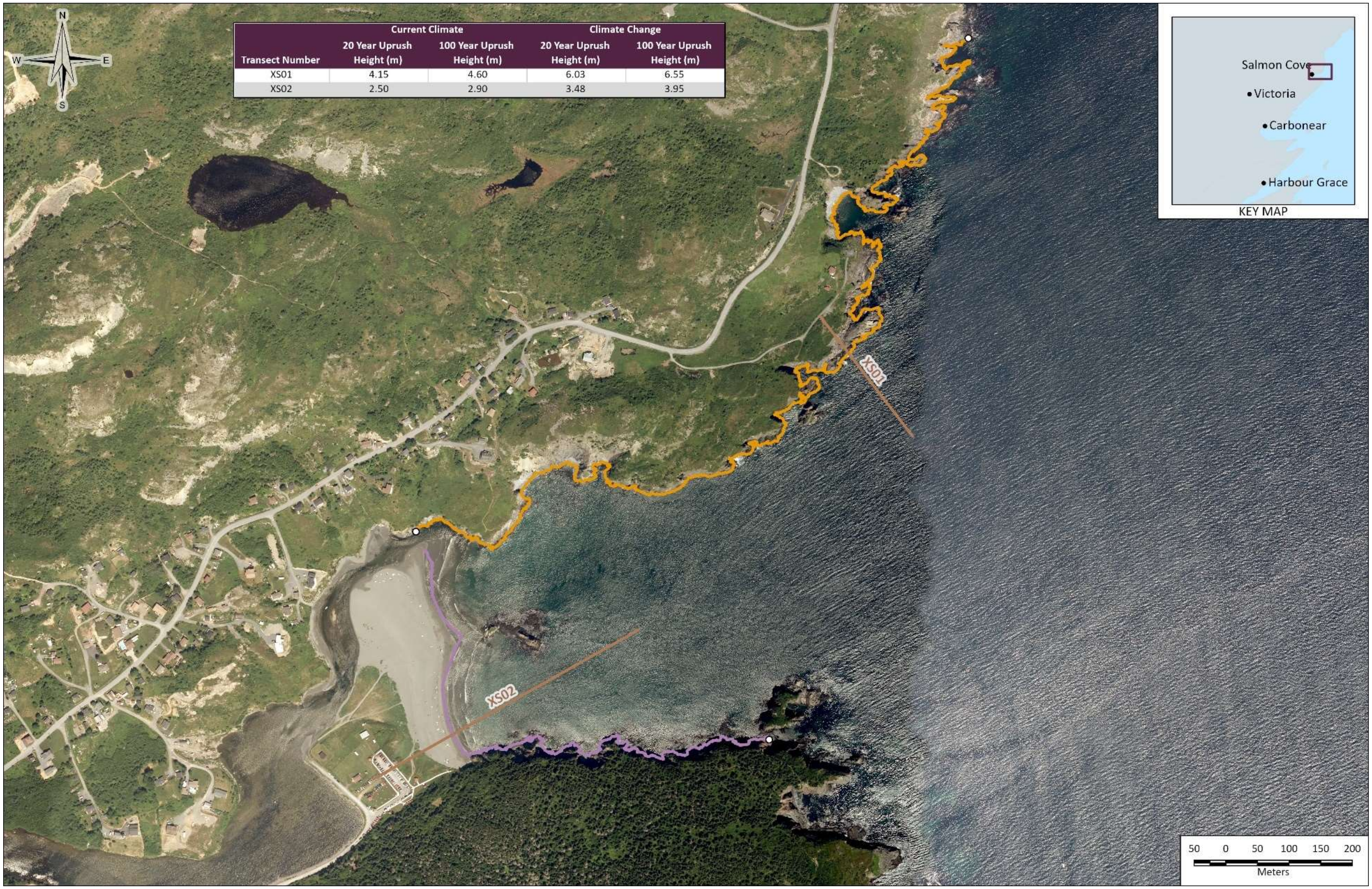

Similar to the Placentia area, outputs from the MIKE21 FM SW model were extracted throughout the model domain for wave uprush calculations. The wave uprush heights, as well as the location of the representative cross sections that were used for the uprush calculations for a given section of coastline are shown on Figure 96 and Figure 97.

# FIGURE 96: CARBONEAR AREA WAVE UPRUSH HEIGHTS




| | Current Climate | | Climate Change | |
|---|---|---|---|---|
| Transect Number | 20 Year Uprush Height (m) | 100 Year Uprush Height (m) | 20 Year Uprush Height (m) | 100 Year Uprush Height (m) |
| XS03 | 2.56 | 2.92 | 4.39 | 4.78 |
| XS04 | 2.45 | 2.85 | 4.40 | 4.84 |
| XS05 | 3.50 | 4.24 | 5.13 | 5.80 |
| XS06 | 3.40 | 7.10 | 4.15 | 8.29 |
| XS07 | 3.76 | 4.11 | 5.22 | 5.76 |
| XS08 | 3.90 | 4.32 | 5.79 | 6.18 |

## FIGURE 97: SALMON COVE WAVE UPRUSH HEIGHTS




| | Current Climate | | Climate Change | |
|---|---|---|---|---|
| Transect Number | 20 Year Uprush Height (m) | 100 Year Uprush Height (m) | 20 Year Uprush Height (m) | 100 Year Uprush Height (m) |
| XS01 | 4.15 | 4.60 | 6.03 | 6.55 |
| XS02 | 2.50 | 2.90 | 3.48 | 3.95 |

## 8.3 Riverine Modelling

### 8.3.1 MODEL DEVELOPMENT

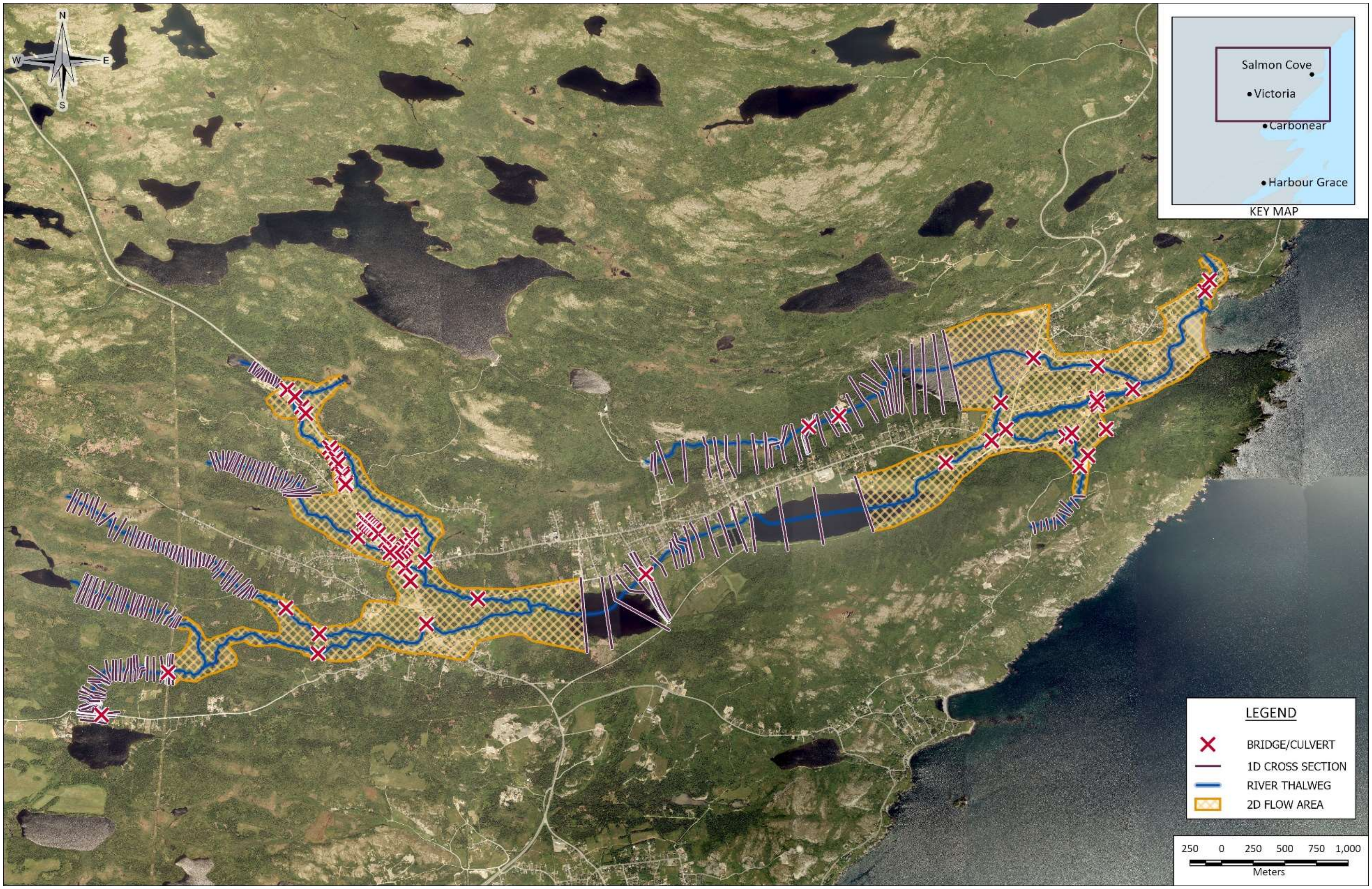
Hydraulic models for the rivers and creeks considered in the study were developed using the USACE Hydraulic Engineering Center's River Analysis System (HEC-RAS) (U.S. Army Corps of Engineers, 2021) software version 6.1. The ArcGIS HEC-GeoRAS extension was not used for this project, as the majority of the functionality has been integrated into the RAS Mapper module in HEC-RAS.

HEC-RAS is a river analysis software capable of completing steady and unsteady state hydraulic modelling in 1-dimensional (1D), 2-dimensional (2D) and coupled 1D/2D domains by applying an iterative solution procedure to energy equations for steady state conditions. HEC-RAS has frequently and successfully been applied to flood risk mapping studies.

The models developed throughout Carbonear, Salmon Cove, Victoria and Placentia were developed as either 1D models, 2D models, or coupled 1D/2D models, depending on the hydraulic characteristics of each river. The model geometries were defined based on the flood plain DEMs, as described in Section 4.4. Key bridge and culvert crossings were defined in the models based on field survey data, with the exception of the Sound Brook culvert on Highway 102, which was defined based on design drawings provided by WRMD. Additional minor culvert crossings, such as those in small ditches in 2D areas, were integrated into the models as required to maintain hydraulic connectivity. These culverts were only integrated into the model if they could be estimated from available imagery, including Google Street View.

The layouts of the hydraulic models for the various rivers and creeks considered in the study area are shown on Figure 98 to Figure 113.

# FIGURE 98: SALMON COVE RIVER MODEL LAYOUT



## FIGURE 99: CARBONEAR LOCAL CREEK MODEL LAYOUT

## FIGURE 100: ISLAND POND BROOK AND POWELLS BROOK MODEL LAYOUT (CARBONEAR)

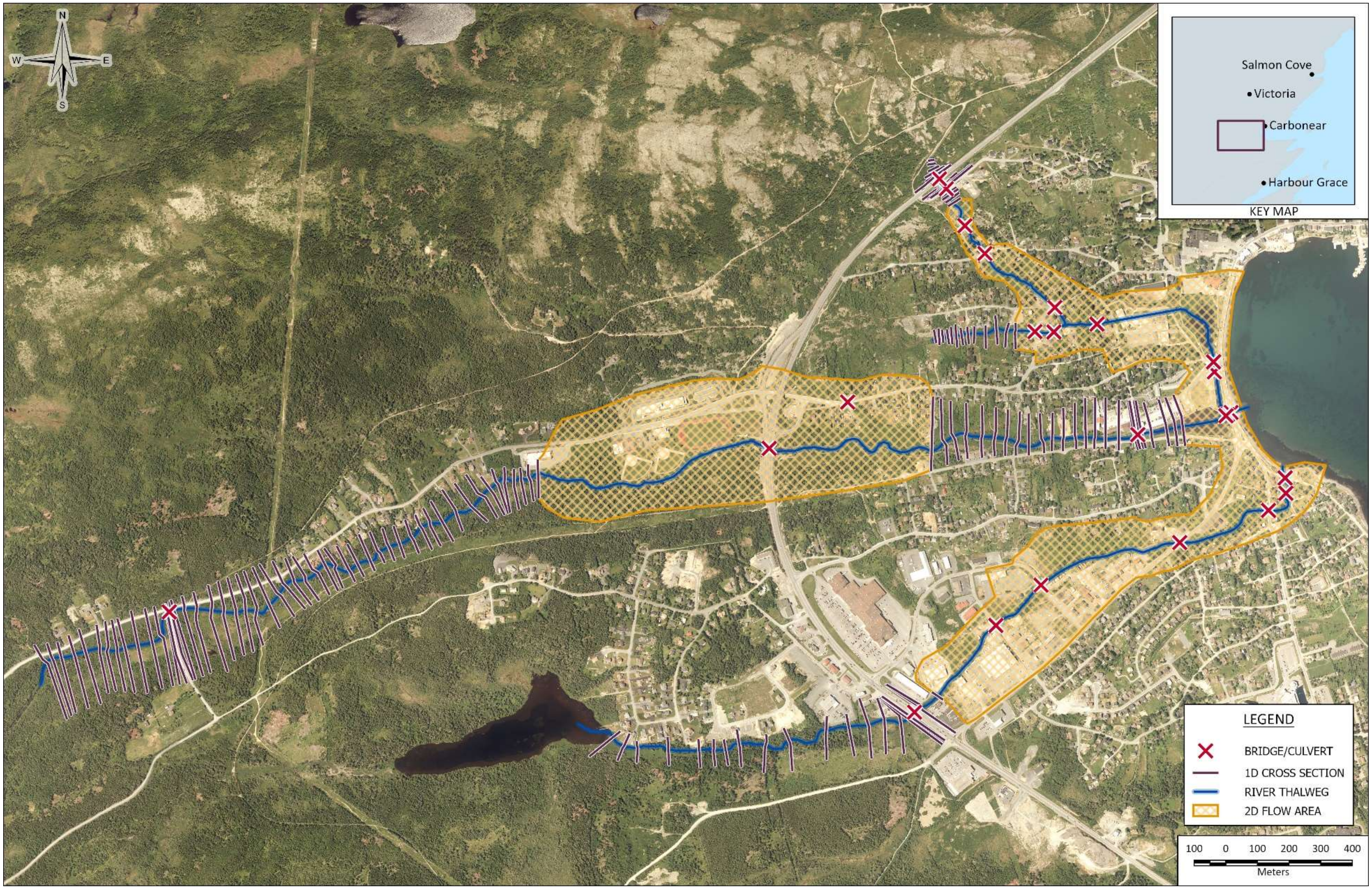


FIGURE 101: RATTLING BROOK MODEL LAYOUT (PLACENTIA)

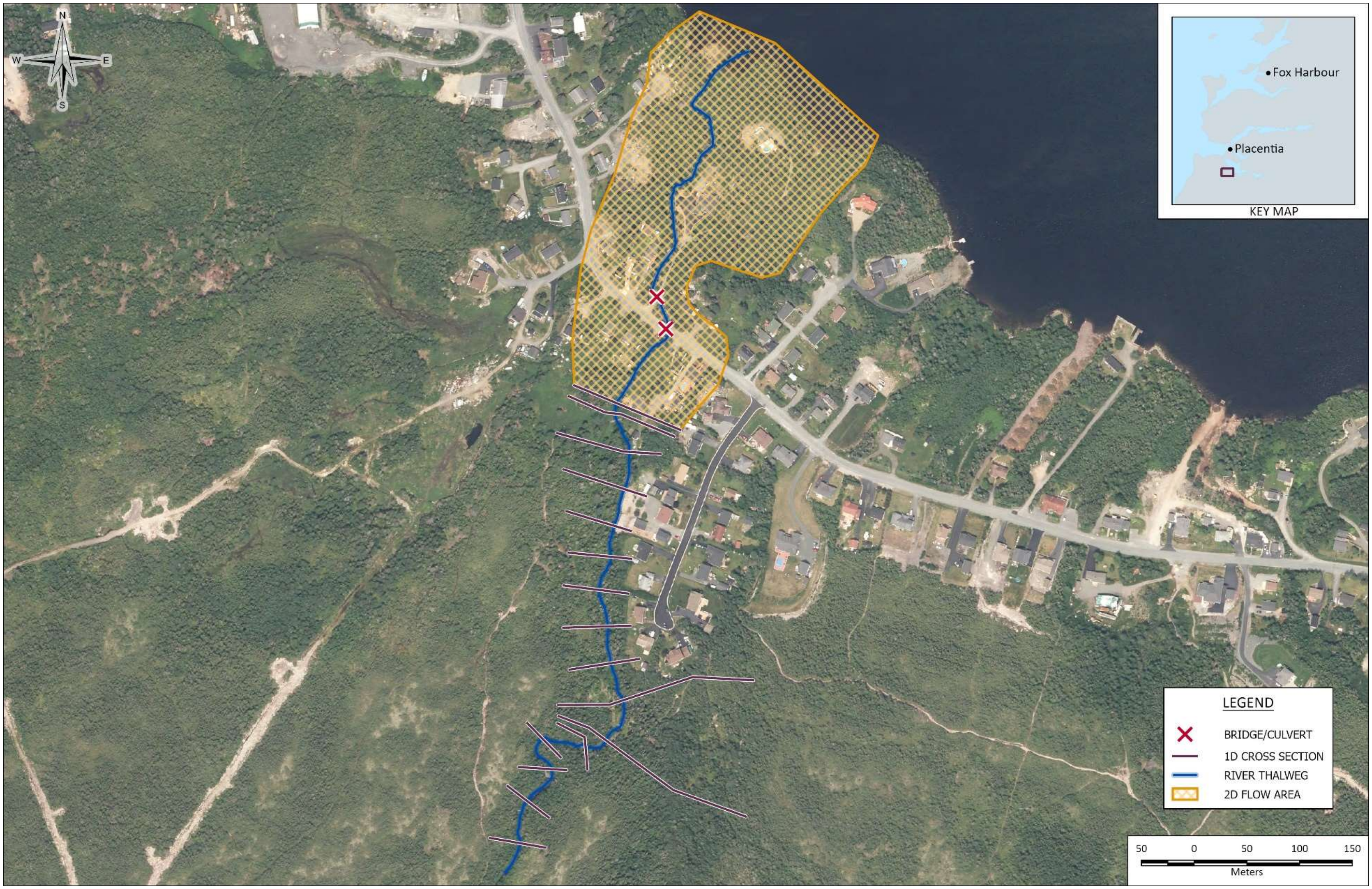
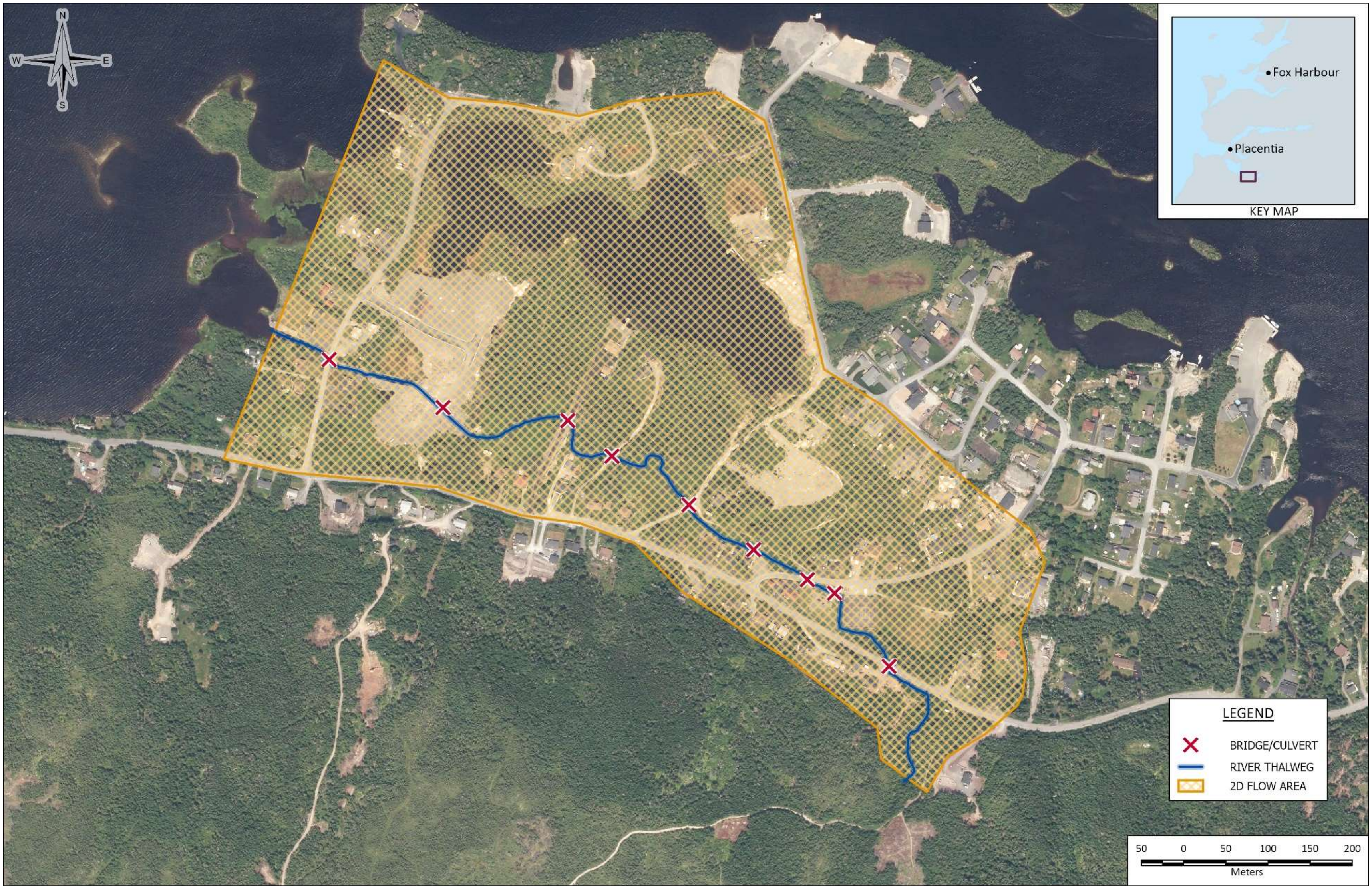


FIGURE 102: SMELT BROOK MODEL LAYOUT (PLACENTIA)

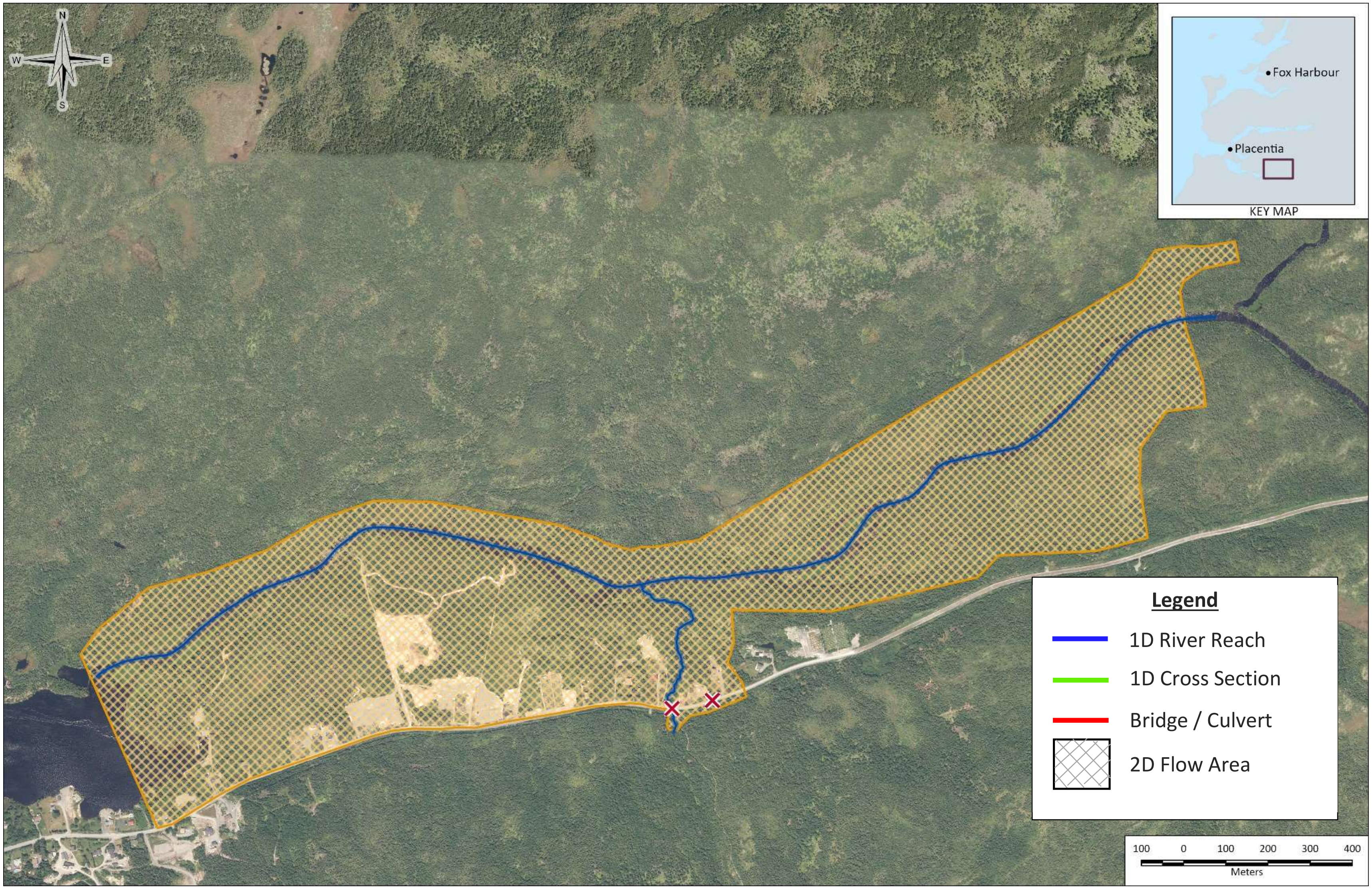
## FIGURE 103: PLACENTIA LOCAL CREEK 1 MODEL LAYOUT (PLACENTIA)



## FIGURE 104: BALDWINS BROOK MODEL LAYOUT (PLACENTIA)

## FIGURE 105: PLACENTIA LOCAL CREEK 2 MODEL LAYOUT (PLACENTIA)

FIGURE 106: SOUTHEAST RIVER MODEL LAYOUT (PLACENTIA)



# FIGURE 107: PLACENTIA LOCAL CREEK 3 MODEL LAYOUT (PLACENTIA)

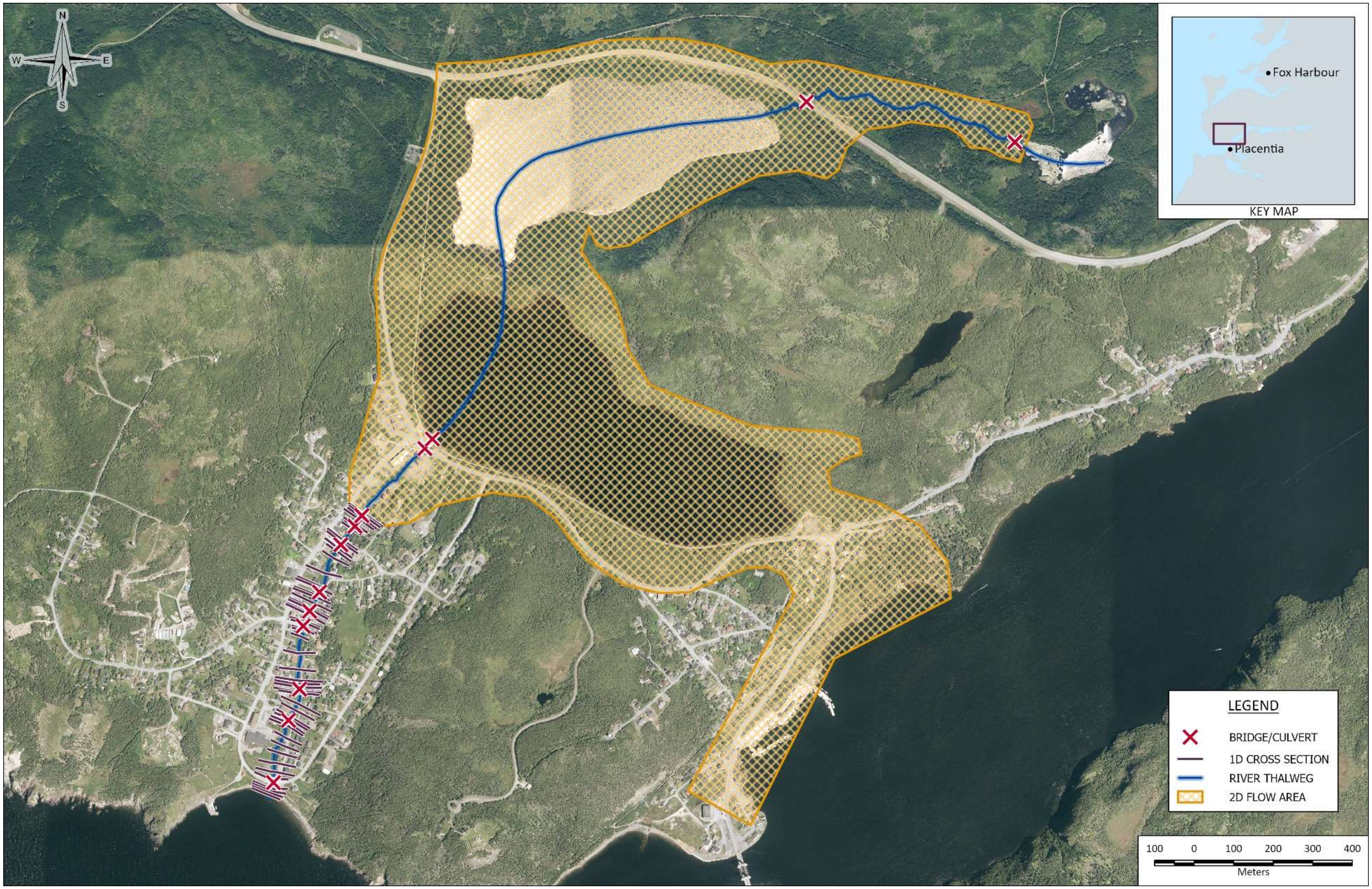
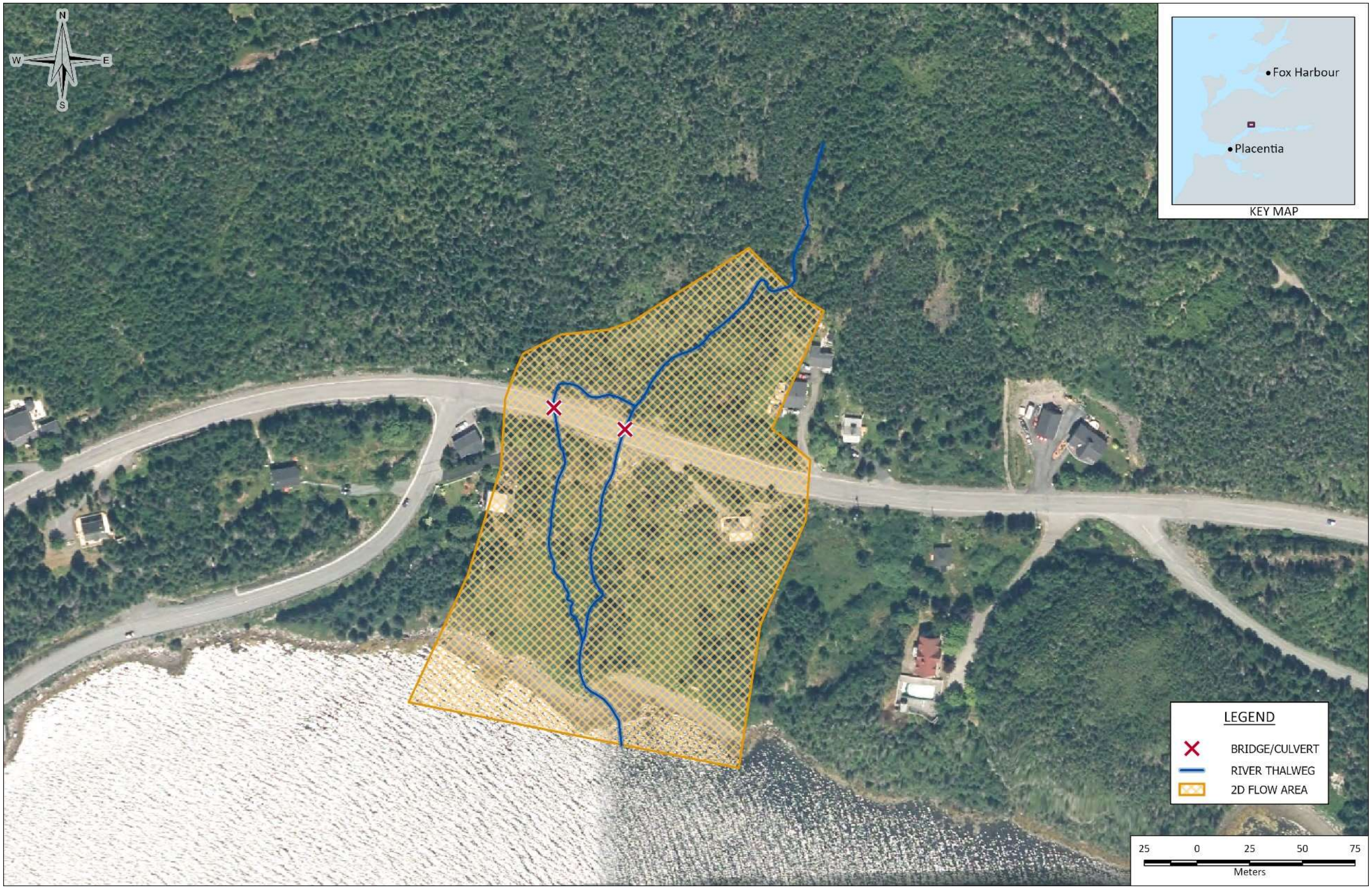
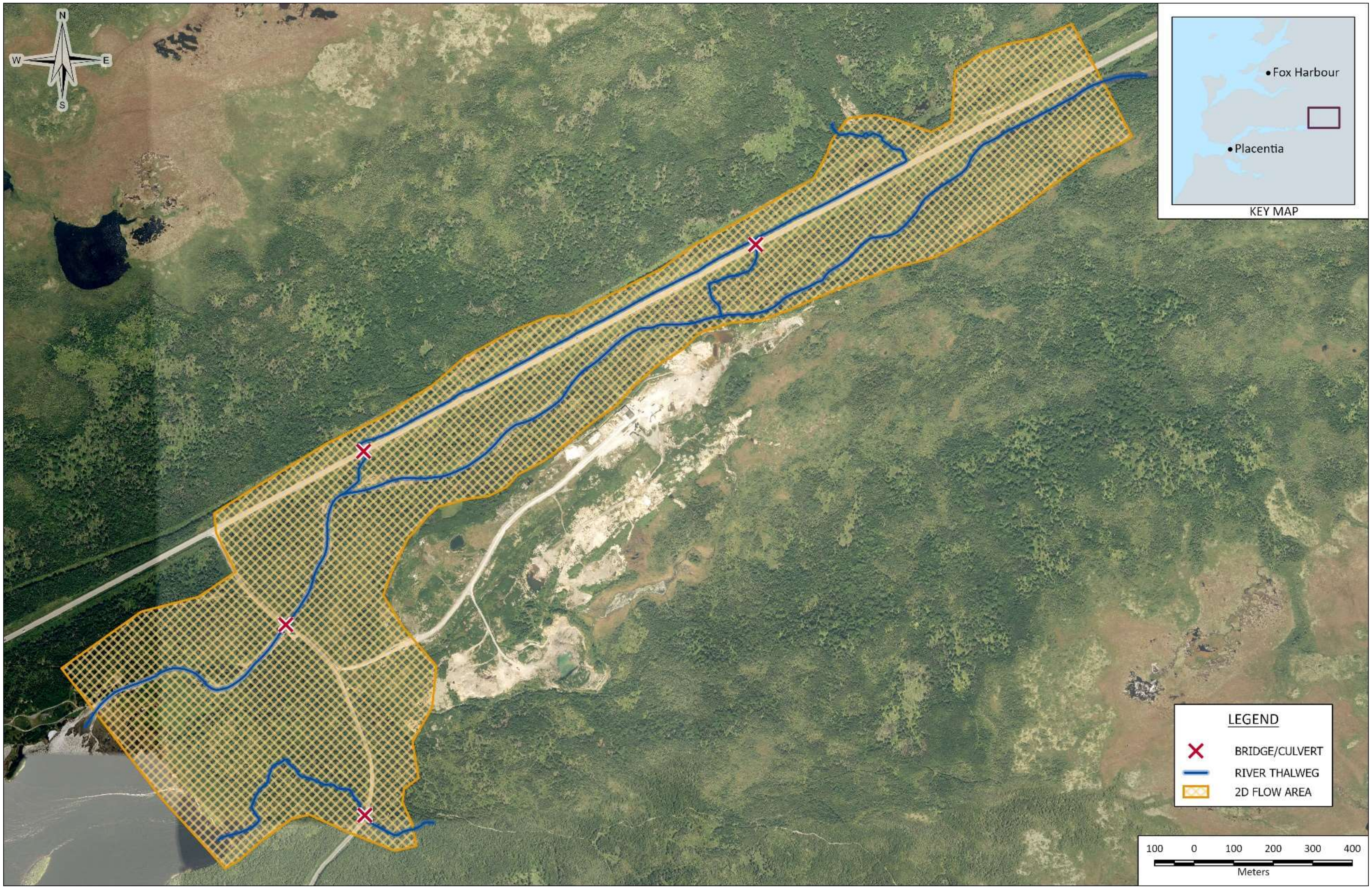


FIGURE 108: PLACENTIA LOCAL CREEK 4 MODEL LAYOUT (PLACENTIA)



## FIGURE 109: MILL BROOK MODEL LAYOUT (PLACENTIA)

FIGURE 110: NORTHEAST RIVER MODEL LAYOUT (PLACENTIA)



## FIGURE 111: LITTLE SALMONIER RIVER MODEL LAYOUT (PLACENTIA)

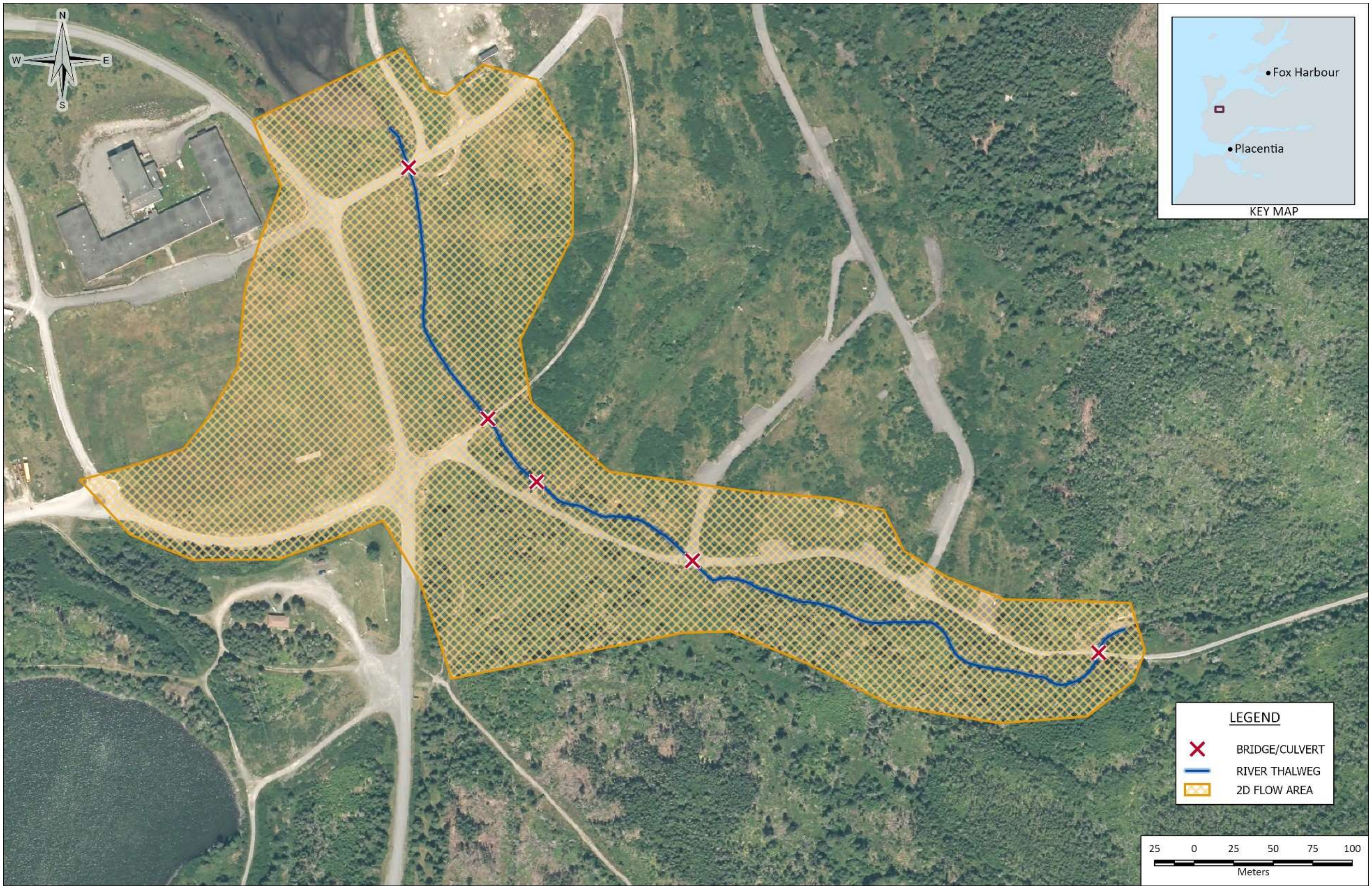


FIGURE 112: SHALLOWAY BROOK MODEL LAYOUT (PLACENTIA)

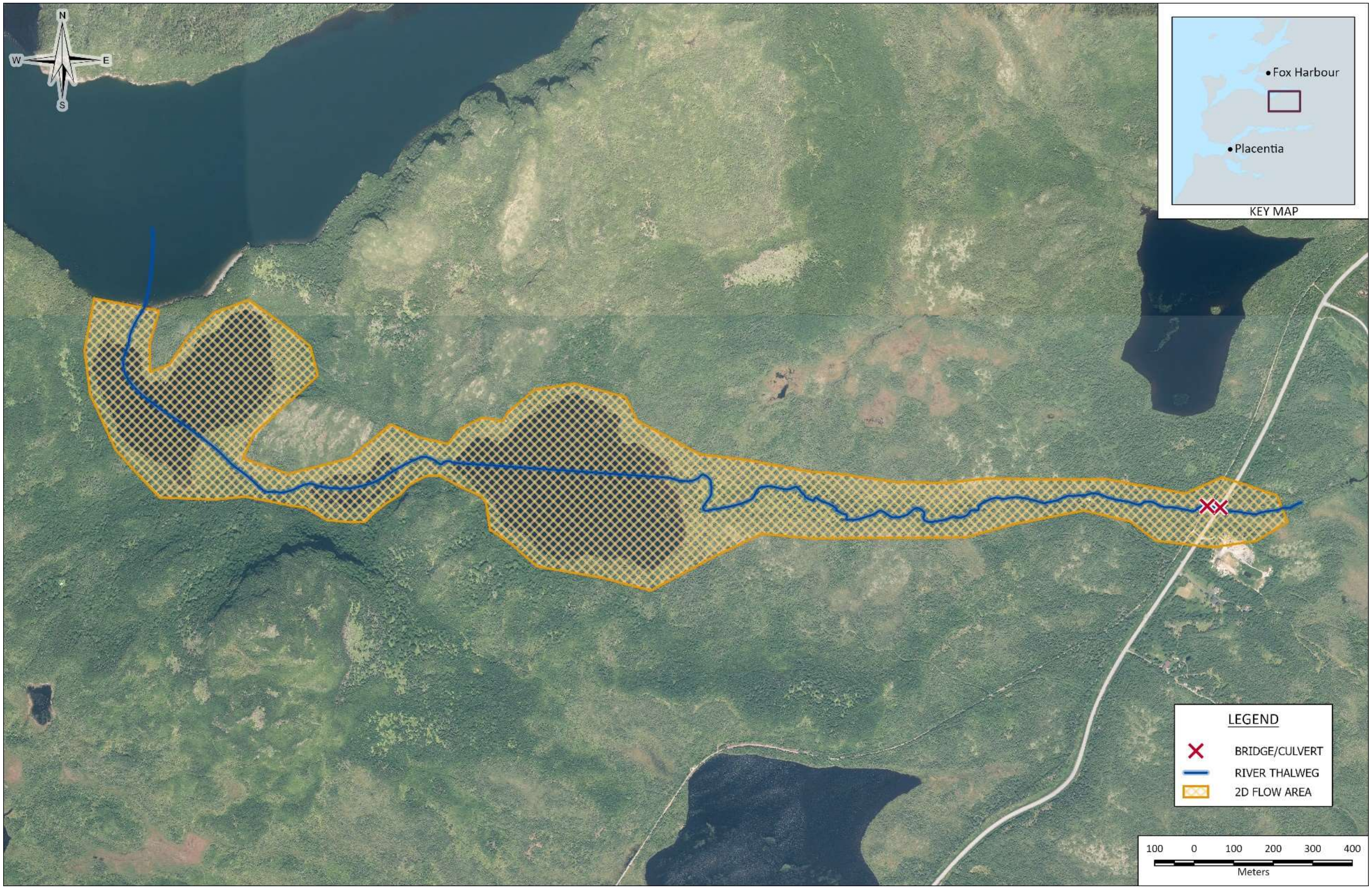
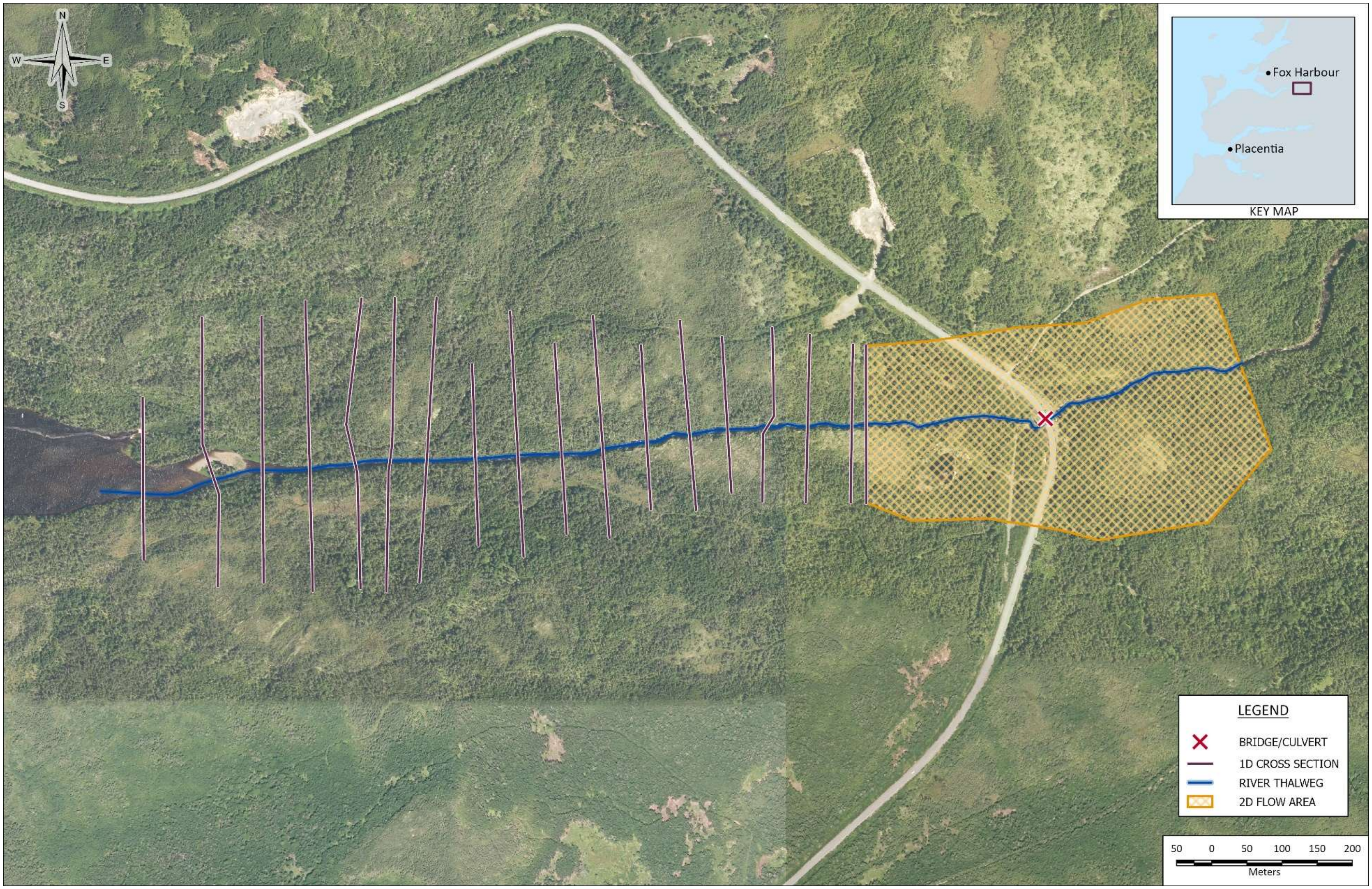


FIGURE 113: SOUND BROOK MODEL LAYOUT (PLACENTIA)



Breaklines were integrated into the 2D model domains to ensure the accurate representation of key linear features, such as trails, ridges, river centrelines, and roads, as required. Cell sizes in the 2D model domain ranged from 0.25 $m^2$ to 16 $m^2$, with higher resolution areas in the model being defined at locations with very fast, shallow moving flow using refinement regions.

Roughness coefficients were defined in the model based on the land use classification described in Section 5.3. However, the resolution of the land use classification was downscaled to a lower resolution to enable its integration into the HEC-RAS model. Since the water land use class defined by the land use classification also included wetlands and swamps, which have significantly different hydraulic roughness than riverbeds, additional polygons were developed to represent the main channel on each of the rivers and creeks. The riverbed roughness coefficients were further adjusted for select rivers as part of the model calibration, and a representative roughness coefficient from the calibration was implemented to the uncalibrated rivers. The initial roughness coefficients adopted as part of the model development, which are consistent with standard values defined by USACE, are summarized in Table 47.

### TABLE 47: INITIAL ROUGHNESS COEFFICIENTS

| Land Use Classification | Manning's n |
|---|---|
| **Commercial** | 0.140 |
| **Residential** | 0.120 |
| **Forest** | 0.120 |
| **Shrubland** | 0.080 |
| **Open Spaces** | 0.040 |
| **Barren** | 0.026 |
| **Wetlands and Swamps** | 0.110 |
| **Riverbed** | 0.035 |

Inflows to the models were defined based on outflows from the HEC-HMS models, while water levels at the downstream model boundaries were defined based on the storm surge modelling. While the models were run using the unsteady state solver, constant flows and water levels were integrated into the models to represent steady state conditions. This approach was taken as the unsteady state solver is required for 2D and coupled 1D/2D models. The boundary conditions included in the models are summarized in Table 48 for the Carbonear area hydraulic models, while the boundary conditions for the Placentia area models are summarized in Table 49 .

### TABLE 48: CARBONEAR AREA HYDRAULIC MODEL BOUNDARY CONDITIONS

| Geometry | Location | Boundary Type | Current Climate | | Climate Change | |
|---|---|---|---|---|---|---|
| | | | 20 Year | 100 Year | 20 Year | 100 Year |
| Salmon Cove River | Salmon Cove River at U/S Model Boundary | Flow ($m^3/s$) | 25.2 | 33.8 | 31.4 | 42.1 |
| | Big Brook at U/S Model Boundary | Flow ($m^3/s$) | 27.4 | 36.9 | 34.2 | 45.9 |
| | Local Creek 5 at U/S Model Boundary | Flow ($m^3/s$) | 2.4 | 3.2 | 3.0 | 4.0 |
| | Clark Brook at U/S Model Boundary | Flow ($m^3/s$) | 4.1 | 5.5 | 5.1 | 6.9 |
| | Double Brook at U/S Model Boundary | Flow ($m^3/s$) | 5.4 | 7.3 | 6.8 | 9.0 |
| | Local Creek 4 at U/S Model Boundary | Flow ($m^3/s$) | 1.7 | 2.3 | 2.1 | 2.8 |
| | Local Inflow | Flow ($m^3/s$) | 4.2 | 5.9 | 5.4 | 7.7 |
| | Local Inflow | Flow ($m^3/s$) | 8.6 | 11.9 | 11.0 | 15.1 |
| | Local Creek 3 at U/S Model Boundary | Flow ($m^3/s$) | 1.2 | 1.6 | 1.5 | 2.0 |
| | Spout Brook | Flow ($m^3/s$) | 42.6 | 57.2 | 53.1 | 71.3 |
| | Local Creek 2 at U/S Model Boundary | Flow ($m^3/s$) | 1.0 | 1.4 | 1.3 | 1.7 |
| | Local Creek 1 at U/S Model Boundary | Flow ($m^3/s$) | 0.8 | 1.0 | 1.0 | 1.3 |
| | Local Inflow | Flow ($m^3/s$) | 3.6 | 4.7 | 4.3 | 6.2 |
| | Salmon Cove River at D/S Boundary | Level (m) | 1.1 | 1.2 | 1.7 | 1.9 |
| Carbonear Local Creek | Carbonear Local Creek at U/S Boundary | Flow ($m^3/s$) | 2.6 | 3.4 | 3.2 | 4.2 |
| | Carbonear Local Creek at D/S Boundary | Level (m) | 1.1 | 1.2 | 1.7 | 1.8 |
| Island Pond Brook and Powells Brook | Island Pond Brook at U/S Model Boundary | Flow ($m^3/s$) | 65.7 | 86.5 | 80.7 | 106.3 |
| | Local Creek 2 at U/S Model Boundary | Flow ($m^3/s$) | 0.2 | 0.3 | 0.3 | 0.4 |
| | Local Creek 1 at U/S Model Boundary | Flow ($m^3/s$) | 1.0 | 1.4 | 1.3 | 1.7 |
| | Powells Brook at U/S Model Boundary | Flow ($m^3/s$) | 16.4 | 22.1 | 20.5 | 27.5 |
| | Island Pond Brook and Powells Brook at D/S Model Boundary | Level (m) | 1.1 | 1.2 | 1.7 | 1.8 |

TABLE 49: PLACENTIA AREA HYDRAULIC MODEL BOUNDARY CONDITIONS

| Geometry | Location | Boundary Type | Current Climate | | Climate Change | |
|---|---|---|---|---|---|---|
| | | | 20 Year | 100 Year | 20 Year | 100 Year |
| Northeast River | Northeast River U/S Boundary | Flow ($m^3/s$) | 185.5 | 261.3 | 217.3 | 305.1 |
| | Northeast River Tributary U/S Boundary | Flow ($m^3/s$) | 7.2 | 10.1 | 8.4 | 11.8 |
| | Local Creek 5 U/S Boundary | Flow ($m^3/s$) | 15.0 | 21.1 | 17.6 | 24.7 |
| | Northeast River D/S Boundary | Level (m) | 1.2 | 1.4 | 1.9 | 2.0 |
| Southeast River | Southeast River U/S Boundary | Flow ($m^3/s$) | 248.0 | 349.7 | 291.9 | 409.9 |
| | Southeast River Tributary U/S Boundary | Flow ($m^3/s$) | 3.5 | 4.8 | 4.1 | 5.6 |
| | Southeast River D/S Boundary | Level (m) | 0.8 | 1.0 | 1.5 | 1.6 |
| Rattling Brook | Rattling Brook U/S Boundary | Flow ($m^3/s$) | 11.6 | 16.1 | 13.6 | 18.8 |
| | Rattling Brook D/S Boundary | Level (m) | 0.8 | 1.0 | 1.4 | 1.6 |
| Smelt Brook | Smelt Brook U/S Boundary | Flow ($m^3/s$) | 16.8 | 23.2 | 19.5 | 27.1 |
| | Smelt Brook D/S Boundary | Level (m) | 0.8 | 1.0 | 1.4 | 1.6 |
| Local Creek 1 | Local Creek 1 U/S Boundary | Flow ($m^3/s$) | 2.9 | 4.0 | 3.3 | 4.6 |
| | Local Creek 1 D/S Boundary | Level (m) | 0.8 | 1.0 | 1.4 | 1.6 |
| Baldwins Brook | Baldwins Brook U/S Boundary | Flow ($m^3/s$) | 12.4 | 17.2 | 14.5 | 20.1 |
| | Baldwins Brook D/S Boundary | Level (m) | 0.8 | 1.0 | 1.5 | 1.6 |
| Local Creek 2 | Local Creek 2 U/S Boundary | Flow ($m^3/s$) | 5.1 | 7.1 | 6.0 | 8.2 |
| | Local Creek 2 D/S Boundary | Level (m) | 0.8 | 1.0 | 1.5 | 1.6 |
| Local Creek 3 | Local Creek 3 U/S Boundary | Flow ($m^3/s$) | 13.1 | 18.1 | 15.2 | 21.0 |
| | Local Creek 3 Overflow D/S Boundary | Flow ($m^3/s$) | 1.2 | 1.3 | 1.8 | 1.9 |
| | Local Creek 3 D/S Boundary | Level (m) | 1.2 | 1.3 | 1.8 | 1.9 |
| Local Creek 4 | Local Creek 4 U/S Boundary | Flow ($m^3/s$) | 7.4 | 10.3 | 8.6 | 12.0 |
| | Local Creek 4 D/S Boundary | Level (m) | 1.2 | 1.3 | 1.8 | 1.9 |
| Mill Brook | Mill Brook U/S Boundary | Flow ($m^3/s$) | 7.6 | 10.6 | 8.9 | 12.4 |
| | Mill Brook D/S Boundary | Level (m) | 1.2 | 1.3 | 1.8 | 2.0 |
| Little Salmonier River | Little Salmonier River U/S Boundary | Flow ($m^3/s$) | 9.2 | 12.8 | 10.7 | 14.8 |
| | Little Salmonier River D/S Boundary | Level (m) | 1.2 | 1.3 | 1.8 | 1.9 |
| Shalloway Brook | Shalloway Brook U/S Boundary | Flow ($m^3/s$) | 9.3 | 13.1 | 10.9 | 15.3 |
| | Shalloway Downstream Local Inflow | Flow ($m^3/s$) | 9.0 | 12.6 | 10.6 | 14.9 |
| | Shalloway Brook D/S Boundary | Level (m) | 1.2 | 1.3 | 1.8 | 1.9 |
| Sound Brook | Sound Brook U/S Boundary | Flow ($m^3/s$) | 75.1 | 105.5 | 88.2 | 123.7 |
| | Sound Brook D/S Boundary | Level (m) | 1.2 | 1.3 | 1.8 | 1.9 |

### 8.3.2 MODEL CALIBRATION

Hydraulic model calibration was completed on select rivers that were either gauged by WSC within the study area, or on rivers where water level loggers were deployed by KGS Group. Accordingly, the only rivers with data available for calibration were:

- Northeast River,
- Southeast River,
- Salmon Cove River,
- Island Pond Brook, and
- Powells Brook.

Model calibration was achieved by adjusting the channel roughness associated with the riverbed roughness class described in Section 8.3.1 such that the simulated water levels accurately replicated observed water levels. On the Northeast River, inflows were defined directly from WSC gauge 02ZK002 (i.e. Northeast River near Placentia). Flows on the Southeast River were defined by prorating the WSC 02ZK002 flows on the basis of drainage area, while the flows on the Salmon Cove River, Island Pond Brook and Powells Brook were defined by prorating the 02ZL004 (i.e. Shearstown Brook at Shearstown) flows on the basis of drainage area. The Carbonear area hydraulic models were calibrated to the highest water level conditions that were recorded by the water level loggers, which occurred on December 13, 2021. Similarly, the Northeast and Southeast River models were calibrated to the high flow conditions that occurred on November 31, 2021.

The final riverbed roughness coefficients for the calibrated creeks are summarized in Table 50.

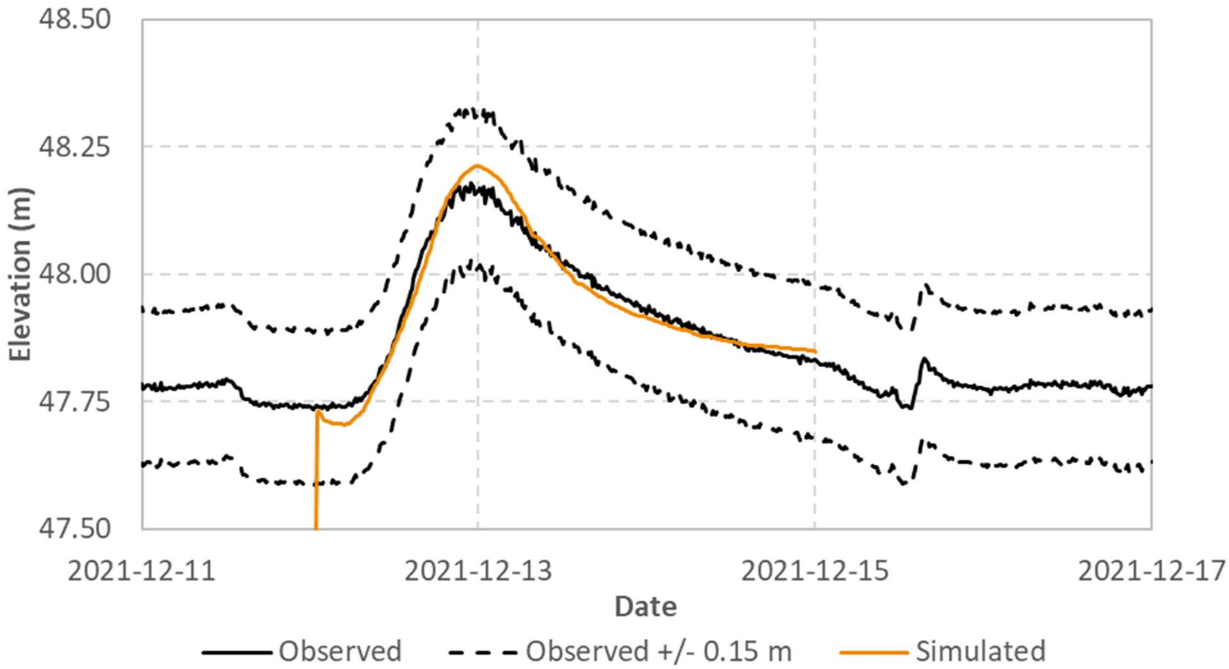
TABLE 50: FINAL CALIBRATED RIVERBED ROUGHNESS COEFFICIENTS

| River | Final Manning's n |
|---|---|
| Northeast River | 0.037 |
| Southeast River | 0.030 |
| Salmon Cove River | 0.032 |
| Island Pond Brook | 0.035 |
| Powells Brook | 0.035 |

Based on the range of calibrated roughness coefficients, a riverbed roughness value of 0.035 was adopted for the uncalibrated rivers. This value was an appropriately conservative estimate given the typical riverbed characteristics, and was within both the range of calibrated roughness values and industry standard values.

The model representations of the recorded water levels are summarized on Figure 114 to Figure 119.

## FIGURE 114: SALMON COVE RIVER CALIBRATION AT HIGHWAY 70 (VICTORIA)




## FIGURE 115: SALMON COVE RIVER CALIRBATION AT HIGHWAY 70 (SALMON COVE)

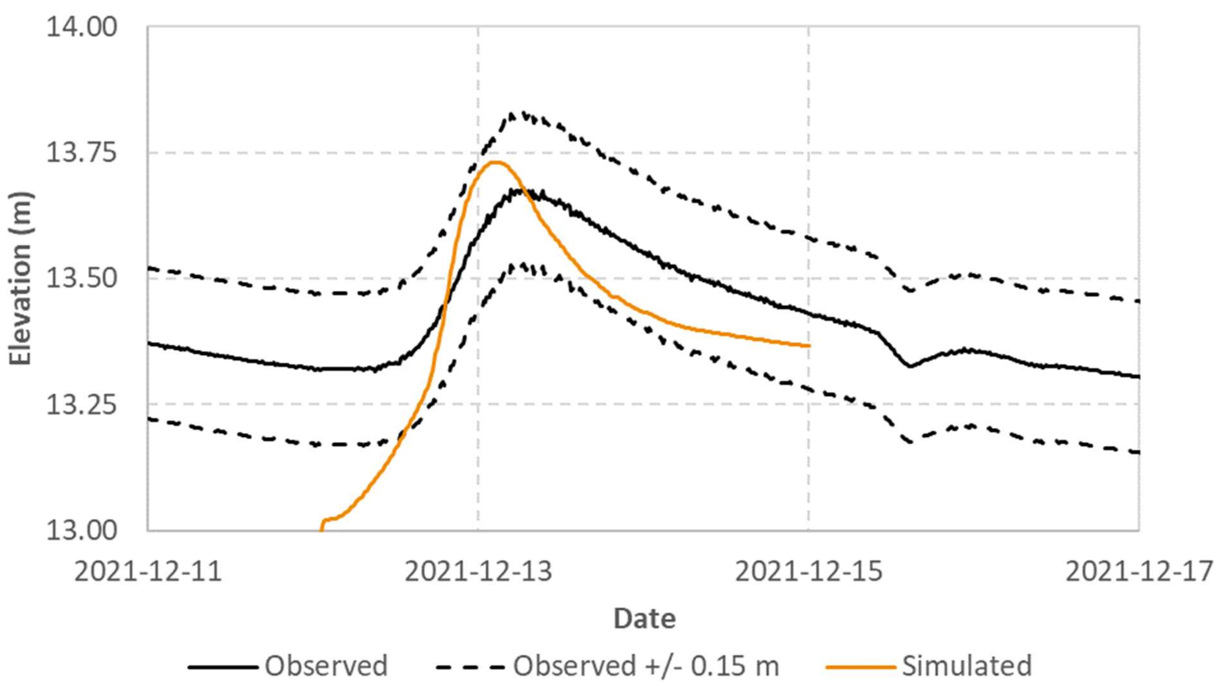


FIGURE 116: ISLAND POND BROOK CALIBARATION AT HIGHWAY 70 (CARBONEAR)

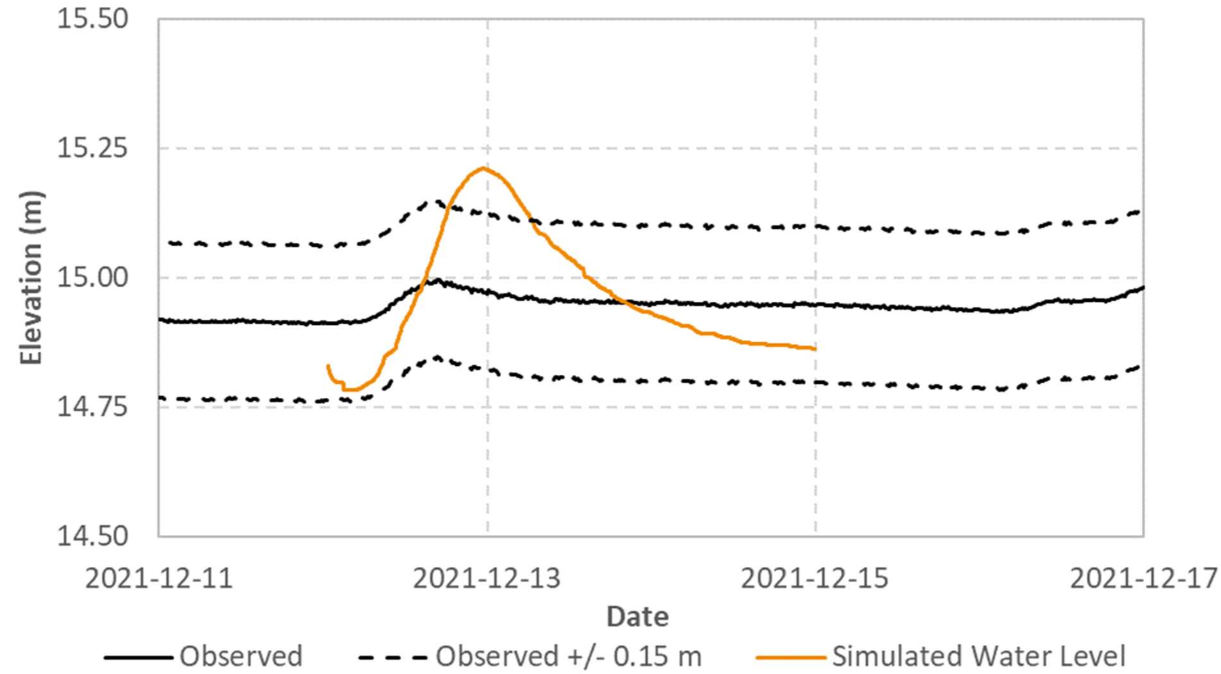



FIGURE 117: POWELLS BROOK CALIBRATION (CARBONEAR)

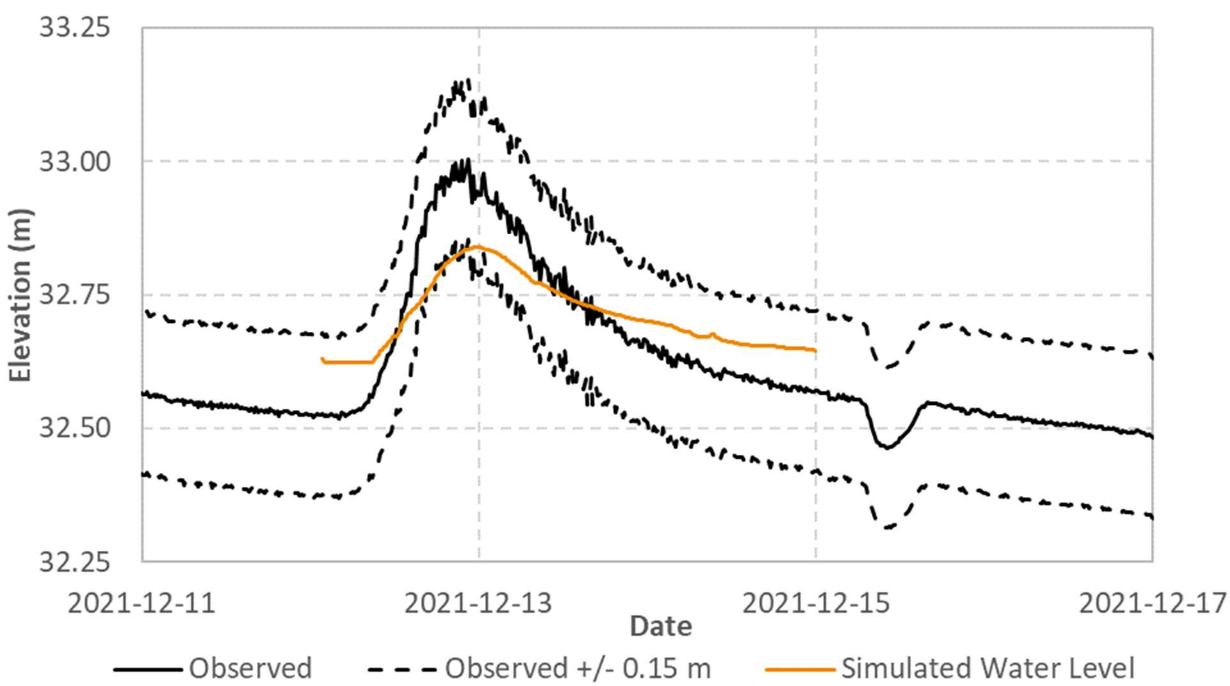


FIGURE 118: NORTHEAST RIVER CALIBRATION (PLACENTIA)

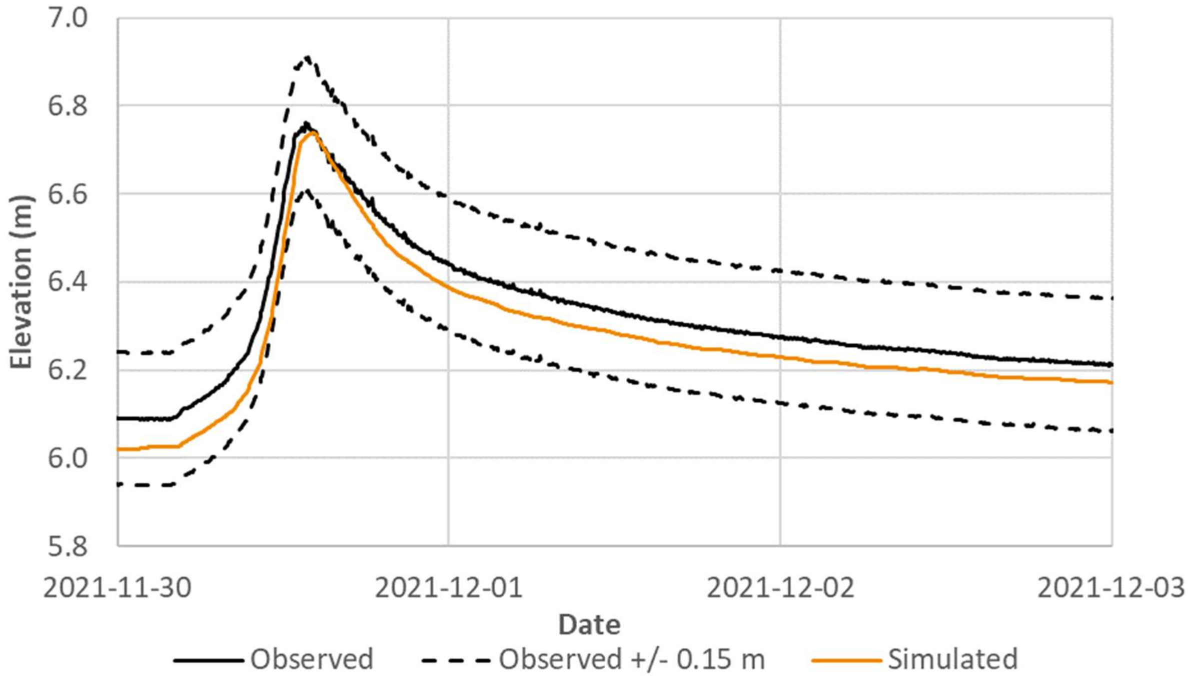
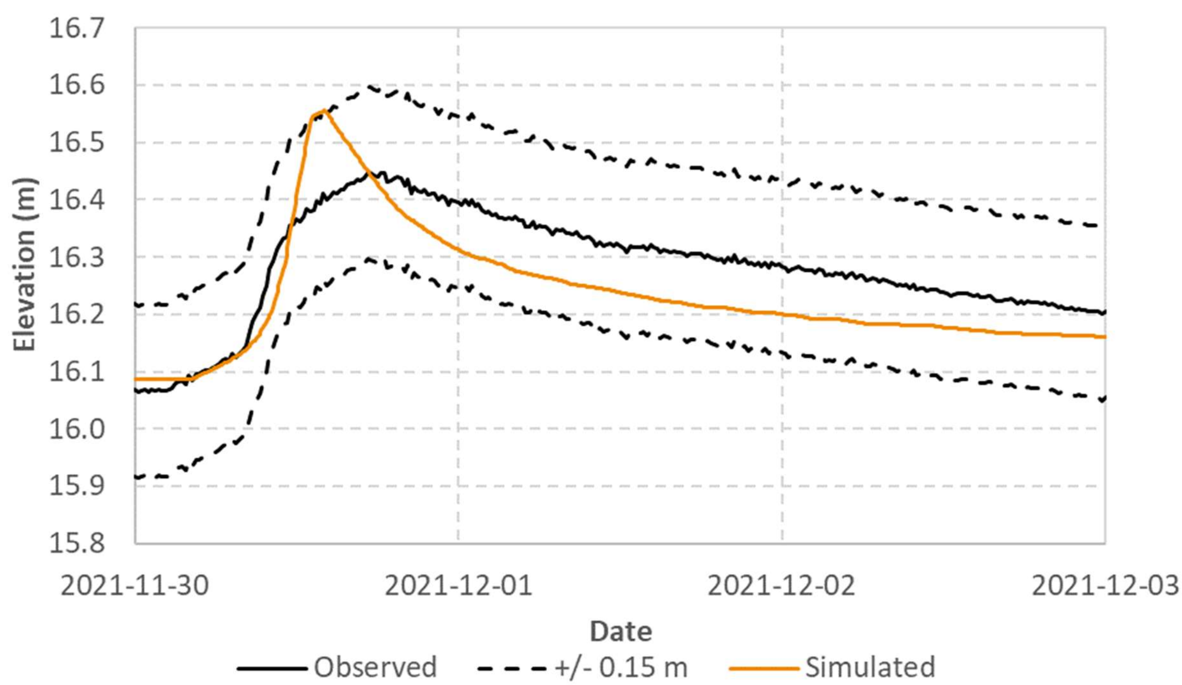



FIGURE 119: SOUTHEAST RIVER CALIBRATION (PLACENTIA)




The hydraulic models were found to generally be well calibrated, with the simulated peak water levels being within 0.15 m of the observed peak water level, with the exception of the Island Pond Brook. While the Island

Pond Brook matched the water levels before and after the peak accurately, the observed water levels on Island Pond Brook did not exhibit the same response as the other rivers in the area. This could be attributed to the rainfall missing a large portion of the Island Pond Brook watershed, resulting in a smaller response. Similarly, while the Southeast River HEC-RAS model was found to reproduce the observed peak water level within 0.15 m, the hydrograph did not perfectly represent the observed hydrograph. This suggests that the hydrologic response of the Southeast River basin is somewhat different than the Northeast River basin, as the peak on the Southeast River was somewhat attenuated relative to the Northeast River. Nonetheless, the models generally matched the observed water levels well and were considered to be well calibrated for the development of the flood mapping.

### 8.3.3 HYDRAULIC MODELLING OF THE 1:20 AND 1:100 AEP FLOODS

Following the development of the hydraulic models, the flows associated with the 20 and 100-year AEP rainfall events were simulated in each model. The models were run under unsteady state conditions, with the various inflows to the models representative of the peak flows defined by the HEC-HMS model and downstream boundaries set to match the 20 and 100-year AEP storm surge levels defined by the coastal modelling. The simulations were completed considering mixed flow conditions to allow for the transition between subcritical and supercritical flow conditions, as required. Initial conditions in the models were established by including a warm-up period in each simulation, which gradually increases flows within the model domain for a portion of the warm-up period until the flow reaches the initial flow in the simulation. The initial flow is then maintained for the remainder of the warm-up period, allowing for the model to establish appropriate initial water levels and flows throughout the model domain before the commencement of the simulation. This process minimizes the potential for numerical instabilities associated with defining constant initial elevations throughout the model domain, which can result in large surges of flow once the simulation commences.

The boundary conditions included inflow hydrographs at the upstream boundary conditions representing the peak flow associated with the 20 and 100-year AEP rainfall events, while the downstream boundaries in the models were set to water level boundaries representative of the storm surge water levels. For the model of the Salmon Cove River, local inflows were included in the model to account for local runoff not captured by any of the simulated tributaries. The boundary conditions included in the HEC-RAS models are summarized in Table 51.

### TABLE 51: HYDRAULIC MODEL BOUNDARY CONDITIONS

| Model | Town | Geometry | Boundary Condition | Unit | Current Climate 20-Year AEP | Current Climate 100-Year AEP | Climate Change 20-Year AEP | Climate Change 100-Year AEP |
|---|---|---|---|---|---|---|---|---|
| Carbonear, Victoria and Salmon Cove | Victoria | Salmon Cove River 2D | Salmon Cove River Upstream Inflow | m³/s | 25.2 | 33.8 | 31.4 | 42.1 |
| | | | Big Brook Upstream Inflow | m³/s | 27.4 | 36.9 | 34.2 | 45.9 |
| | | | Local Creek 5 Upstream Inflow | m³/s | 2.4 | 3.2 | 3.0 | 4.0 |
| | | | Clark Brook Upstream Inflow | m³/s | 4.1 | 5.5 | 5.1 | 6.9 |
| | | | Double Brook Upstream Inflow | m³/s | 5.4 | 7.3 | 6.8 | 9.0 |
| | | | Local Creek 4 Upstream Inflow | m³/s | 1.7 | 2.3 | 2.1 | 2.8 |
| | | | Salmon Cove River Local Inflow 1 | m³/s | 4.2 | 5.9 | 5.4 | 7.7 |
| | | | Salmon Cove River Local Inflow 2 | m³/s | 8.6 | 11.9 | 11.0 | 15.1 |
| | | | Spout Brook Upstream Inflow | m³/s | 42.6 | 57.2 | 53.1 | 71.3 |
| | Salmon Cove | | Local Creek 3 Upstream Inflow | m³/s | 1.2 | 1.6 | 1.5 | 2.0 |
| | | | Local Creek 2 Upstream Inflow | m³/s | 1.0 | 1.4 | 1.3 | 1.7 |
| | | | Local Creek 1 Upstream Inflow | m³/s | 0.8 | 1.0 | 1.0 | 1.3 |
| | | | Salmon Cove River Local Inflow 3 | m³/s | 3.6 | 4.7 | 4.3 | 6.2 |
| | | | Salmon Cove River Downstream Water Level | m | 1.1 | 1.2 | 1.7 | 1.9 |
| | Carbonear | Carbonear Local Creek 2D | Carbonear Local Creek Upstream Inflow | m³/s | 2.6 | 3.4 | 3.2 | 4.2 |
| | | | Carbonear Local Creek Downstream Water Level | m | 1.1 | 1.2 | 1.7 | 1.8 |
| | | Island Pond Brook and Powells Brook | Island Pond Brook Upstream Inflow | m³/s | 65.7 | 86.5 | 80.7 | 106.3 |
| | | | Local Creek 2 Upstream Inflow | m³/s | 0.2 | 0.3 | 0.3 | 0.4 |
| | | | Local Creek 1 Upstream Inflow | m³/s | 1.0 | 1.4 | 1.3 | 1.7 |
| | | | Powells Brook Upstream Inflow | m³/s | 16.4 | 22.1 | 20.5 | 27.5 |
| | | | Island Pond Brook and Powells Brook Downstream Water Level | m | 1.1 | 1.2 | 1.7 | 1.8 |
| Placentia | Placentia | Northeast River | Northeast River Upstream Inflow | m³/s | 185.5 | 261.3 | 217.3 | 305.1 |
| | | | Northeast River Tributary Upstream Inflow | m³/s | 7.2 | 10.1 | 8.4 | 11.8 |
| | | | Placentia Area Local Creek 5 Upstream Inflow | m³/s | 15.0 | 21.1 | 17.6 | 24.7 |
| | | | Northeast River Downstream Water Level | m | 1.2 | 1.4 | 1.9 | 2.0 |
| | | Southeast River | Southeast River Upstream Inflow | m³/s | 248.0 | 349.7 | 291.9 | 409.9 |
| | | | Southeast River Tributary Upstream Inflow | m³/s | 3.5 | 4.8 | 4.1 | 5.6 |
| | | | Southeast River Downstream Water Level | m | 0.8 | 1.0 | 1.5 | 1.6 |
| | | Rattling Brook | Rattling Brook Upstream Inflow | m³/s | 11.6 | 16.1 | 13.6 | 18.8 |
| | | | Rattling Brook Downstream Water Level | m | 0.8 | 1.0 | 1.4 | 1.6 |
| | | Smelt Brook | Smelt Brook Upstream Inflow | m³/s | 16.8 | 23.2 | 19.5 | 27.1 |
| | | | Smelt Brook Downstream Water Level | m | 0.8 | 1.0 | 1.4 | 1.6 |
| | | Placentia Area Local Creek 1 | Placentia Area Local Creek 1 Upstream Inflow | m³/s | 2.9 | 4.0 | 3.3 | 4.6 |
| | | | Placentia Area Local Creek 1 Downstream Water Level | m | 0.8 | 1.0 | 1.4 | 1.6 |
| | | Baldwins Brook | Baldwins Brook Upstream Inflow | m³/s | 12.4 | 17.2 | 14.5 | 20.1 |
| | | | Baldwins Brook Downstream Water Level | m | 0.8 | 1.0 | 1.5 | 1.6 |
| | | Placentia Area Local Creek 2 | Placentia Area Local Creek 2 Upstream Inflow | m³/s | 1.8 | 2.5 | 2.1 | 2.9 |
| | | | Placentia Area Local Creek 2 Downstream Water Level | m | 0.8 | 1.0 | 1.5 | 1.6 |
| | | Placentia Area Local Creek 3 | Placentia Area Local Creek 3 Upstream Inflow | m³/s | 13.1 | 18.1 | 15.2 | 21.0 |
| | | | Placentia Area Local Creek 3 Overflow Downstream Water Level | m | 1.2 | 1.3 | 1.8 | 1.9 |
| | | | Placentia Area Local Creek 3 Downstream Water Level | m | 1.2 | 1.3 | 1.8 | 1.9 |
| | | Placentia Area Local Creek 4 | Placentia Area Local Creek 4 Upstream Inflow | m³/s | 7.4 | 10.3 | 8.6 | 12.0 |
| | | | Placentia Area Local Creek 4 Downstream Water Level | m | 1.2 | 1.3 | 1.8 | 1.9 |
| | | Mill Brook | Mill Brook Upstream Inflow | m³/s | 7.6 | 10.6 | 8.9 | 12.4 |
| | | | Mill Brook Downstream Water Level | m | 1.2 | 1.3 | 1.8 | 2.0 |
| | | Little Salmonier River | Little Salmonier River Upstream Inflow | m³/s | 9.2 | 12.8 | 10.7 | 14.8 |
| | | | Little Salmonier River Downstream Water Level | m | 1.2 | 1.3 | 1.8 | 1.9 |
| | | Shalloway Brook | Shalloway Brook Upstream Inflow | m³/s | 9.3 | 13.1 | 10.9 | 15.3 |
| | | | Shalloway Downstream Local Inflow | m³/s | 9.0 | 12.6 | 10.6 | 14.9 |
| | | | Shalloway Brook Downstream Water Level | m | 1.2 | 1.3 | 1.8 | 1.9 |
| | | Sound Brook | Sound Brook Upstream Inflow | m³/s | 75.1 | 105.5 | 88.2 | 123.7 |
| | | | Sound Brook Downstream Water Level | m | 1.2 | 1.3 | 1.8 | 1.9 |

The 1D cross sections included in the hydraulic models are shown in Appendix L. Water levels and flows at each 1D cross section for each flood condition (i.e. 20 and 100-year AEP floods for current climate and climate change conditions) are summarized in Appendix M.

### 8.3.4 ASSESSMENT OF HYDRAULIC STRUCTURE CAPACITIES

The capacity of the culvert and bridge crossings included in the hydraulic models were assessed for each of the flood events. This assessment 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 AEP flood events for current climate and climate change conditions, as well as the road crest elevation for each culvert crossing are summarized in Table 52. Water levels that exceed the road crest elevation are shown in red.

### TABLE 52: HYDRAULIC STRUCTURE CAPACITY

| Town | River | Crossing Name | Structure Configuration | Top of Road Elevation (m) | Current Climate Water Level (m) | | Climate Change Water Level (m) | |
|---|---|---|---|---|---|---|---|---|
| | | | | | 20-Year AEP | 100-Year AEP | 20-Year AEP | 100-Year AEP |
| Victoria | Clark Brook | VSC_CB_C001 | 1.1 m H x 6.3 m W arch CMP | 52.2 | 51.4 | 51.6 | 51.6 | 51.8 |
| Victoria | Clark Brook | VSC_CB_B002 | 11 m span wood bridge | 51.6 | **51.8** | **52.0** | **51.9** | **52.1** |
| Victoria | Clark Brook | VSC_CB_C003 | 2.2 m H x 3.2 m W arch CMP | 60.3 | 58.8 | 59.0 | 59.0 | 59.2 |
| Victoria | Double Brook | VSC_DB_B001 | 3 m span wood bridge | 42.4 | **42.5** | **42.6** | **42.6** | **42.7** |
| Victoria | Double Brook | VSC_DB_B002 | 5.2 m span concrete bridge | 53.4 | 51.6 | 51.7 | 51.6 | 51.8 |
| Victoria | Double Brook | VSC_DB_C003 | 1.0 m H x 1.9 m W arch CMP | 80.0 | 78.7 | 78.8 | 78.8 | 78.9 |
| Victoria | Double Brook | VSC_DB_C004 | 1.5m dia. circular CMP | 102.0 | 101.8 | 101.9 | 101.9 | 101.9 |
| Salmon Cove | Local Creek 1 | VSC_LC1_C001 | 2 x 0.7 m dia. circular CMP | 19.0 | 17.8 | 17.9 | 17.8 | 18.0 |
| Salmon Cove | Local Creek 1 | VSC_LC1_C002 | 0.9 m dia. circular CMP | 35.0 | 34.9 | **35.0** | 35.0 | **35.0** |
| Salmon Cove | Local Creek 2 | VSC_LC2_C001 | 0.6 m dia. circular CMP | 0.8 | **1.4** | **1.6** | **1.9** | **2.1** |
| Salmon Cove | Local Creek 2 | VSC_LC2_C002 | 0.6 m dia. circular CMP | 2.0 | **2.2** | **2.2** | **2.2** | **2.2** |
| Salmon Cove | Local Creek 3 | VSC_LC3_C001 | 1.4 m H x 2.1 m W arch CMP | 9.5 | 8.5 | 8.6 | 8.6 | 8.7 |
| Salmon Cove | Local Creek 3 | VSC_LC3_C002 | 0.5 m dia. circular CMP | 11.6 | 11.3 | 11.3 | 11.3 | 11.4 |
| Salmon Cove | Local Creek 3 | VSC_LC3_C003 | 2 x 0.9 m dia. circular CMP | 12.3 | 12.1 | 12.2 | 12.1 | 12.3 |
| Salmon Cove | Local Creek 3 | VSC_LC3_C004 | 2 x 0.45 m dia. circular CMP | 69.6 | **69.8** | **69.8** | **69.8** | **69.8** |
| Victoria | Local Creek 4 | VSC_LC4_C001 | 1 x 1.0 m dia. circular CMP | 97.7 | 97.0 | 97.3 | 97.2 | 97.7 |
| Victoria | Local Creek 4 | VSC_LC4_C002 | 1 x 0.8 m dia. circular CMP | 99.7 | 98.7 | 98.7 | 98.7 | 98.8 |
| Victoria | Local Creek 5 | VSC_LC5_C001 | 2 x 0.3 m dia. circular CMP | 57.5 | **57.8** | **57.8** | **57.8** | **57.9** |
| Victoria | Local Creek 5 | VSC_LC5_C002 | 2 x 0.3 m dia. circular CMP | 76.0 | **76.4** | **76.4** | **76.4** | **76.5** |
| Salmon Cove | Spout Brook | VSC_SB_B001 | 8.3 m span wood bridge | 11.4 | **11.9** | **12.0** | **12.0** | **12.1** |
| Salmon Cove | Spout Brook | VSC_SB_B002 | 6.3 m span wood bridge | 14.5 | **14.7** | **14.8** | **14.8** | **14.9** |
| Salmon Cove | Salmon Cove River | VSC_SCR_B001 | 19.6 m span concrete bridge | 1.7 | **2.4** | **2.6** | **2.6** | **2.8** |
| Salmon Cove | Salmon Cove River | VSC_SCR_B002 | 21.4 m span concrete bridge | 4.0 | 2.8 | 3.1 | 3.0 | 3.6 |
| Salmon Cove | Salmon Cove River | VSC_SCR_B003 | 15 m span wood bridge | 2.9 | **3.0** | **3.2** | **3.1** | **3.6** |
| Salmon Cove | Salmon Cove River | VSC_SCR_B004 | 14 m span concrete bridge | 9.4 | **9.9** | **10.1** | **10.0** | **10.2** |
| Salmon Cove | Salmon Cove River | VSC_SCR_B005 | 16.2 m span concrete bridge | 17.9 | 15.3 | 15.6 | 15.6 | 15.8 |
| Victoria | Salmon Cove River | VSC_SCR_B006 | 10 m span wood bridge | 38.1 | 38.0 | **38.7** | **38.6** | **39.1** |
| Victoria | Salmon Cove River | VSC_SCR_B007 | 19 m span concrete bridge | 50.9 | 49.3 | 49.6 | 49.5 | 49.8 |
| Victoria | Salmon Cove River | VSC_SCR_B008 | 18.3 m span wood bridge | 58.2 | **58.3** | **58.5** | **58.4** | **58.6** |
| Victoria | Salmon Cove River | VSC_SCR_B009 | 5.6 m span wood bridge | 74.5 | **74.7** | **74.8** | **74.8** | **74.8** |
| Victoria | Salmon Cove River | VSC_SCR_C010 | 2 x 0.65 m dia. circular CMP<br>1.2 m circular concrete culvert | 97.1 | **97.2** | **97.2** | **97.2** | **97.3** |
| Carbonear | Island Pond Brook | CB_IPB_B001 | 10.9 m span concrete bridge | 1.7 | **2.0** | **2.2** | **2.3** | **2.4** |
| Carbonear | Island Pond Brook | CB_IPB_B002 | 10.6 m span wood bridge | 1.6 | **2.1** | **2.3** | **2.3** | **2.4** |
| Carbonear | Island Pond Brook | CB_IPB_B003 | 8.9 m span wood bridge | 1.5 | **2.1** | **2.3** | **2.3** | **2.4** |
| Carbonear | Island Pond Brook | CB_IPB_B004 | 10.1 m span bridge | 2.4 | **3.6** | **3.6** | **3.6** | **3.5** |
| Carbonear | Island Pond Brook | CB_IPB_C005 | 3 x 3.5 m H x 5.0 m W arch CMP | 21.0 | 17.9 | 18.3 | 18.2 | 18.4 |
| Carbonear | Island Pond Brook | CB_IPB_C006 | 4 x 1.2 m dia. circular CMP | 58.5 | **58.8** | **58.9** | **58.9** | **59.0** |
| Carbonear | Local Creek 1 | CB_IPB_LC1_B001 | 2.9 m span wood bridge | 1.5 | **2.1** | **2.3** | **2.3** | **2.4** |

| Town | River | Crossing Name | Structure Configuration | Top of Road Elevation (m) | Current Climate Water Level (m) | | Climate Change Water Level (m) | |
|---|---|---|---|---|---|---|---|---|
| | | | | | 20-Year AEP | 100-Year AEP | 20-Year AEP | 100-Year AEP |
| Carbonear | Local Creek 1 | CB_IPB_LC1_C002 | 1.5 m dia. circular CMP | 1.6 | **2.1** | **2.3** | **2.3** | **2.4** |
| Carbonear | Local Creek 1 | CB_IPB_LC1_C003 | 0.7 m dia. circular CMP | 7.8 | **8.0** | **8.0** | **8.0** | **8.0** |
| Carbonear | Local Creek 1 | CB_IPB_LC1_C004 | 0.6 m dia. circular CMP | 12.0 | **12.1** | **12.2** | **12.2** | **12.2** |
| Carbonear | Local Creek 1 | CB_IPB_LC1_C005 | 0.75 m dia. circular CMP | 34.3 | **34.6** | **34.6** | **34.6** | **34.6** |
| Carbonear | Local Creek 1 | CB_IPB_LC1_C006 | 0.9 m dia. circular CMP | 43.5 | **43.6** | **43.7** | **43.7** | **43.7** |
| Carbonear | Local Creek 1 | CB_IPB_LC1_C007 | 1.0 m dia. circular CMP | 64.5 | 63.2 | 63.4 | 63.3 | 63.6 |
| Carbonear | Local Creek 1 | CB_IPB_LC1_C007 | 1.1 m dia. circular CMP | 72.7 | 68.5 | 68.5 | 68.5 | 68.6 |
| Carbonear | Local Creek 2 | CB_IPB_LC2_C001 | 0.5 m dia. circular CMP | 12.1 | 10.6 | 10.7 | 10.6 | 10.6 |
| Carbonear | Local Creek 2 | CB_IPB_LC2_C002 | 0.5 m dia. circular CMP | 12.4 | 11.8 | 12.1 | 12.0 | 12.1 |
| Carbonear | Powells Brook | CB_PB_C001 | 2.5 m H x 5.0 m W CMP arch | 3.5 | 2.3 | 2.7 | 2.6 | 2.8 |
| Carbonear | Powells Brook | CB_PB_B002 | 10.5 m span wood bridge | 6.5 | 4.5 | 4.7 | 4.7 | 4.8 |
| Carbonear | Powells Brook | CB_PB_C003 | 2.0 m H x 5.3 m W CMP arch | 9.0 | 8.1 | 8.5 | 8.4 | 8.7 |
| Carbonear | Powells Brook | CB_PB_C004 | 2.5 m H x 6.1 m W CMP arch | 14.6 | 12.8 | 13.2 | 13.1 | 13.4 |
| Carbonear | Powells Brook | CB_PB_C005 | 1.3 m H x 8.2 m W CMP arch | 19.5 | 19.0 | 19.4 | 19.2 | **19.7** |
| Carbonear | Powells Brook | CB_PB_C006 | 2.0 m H x 8.9 m W CMP arch | 24.9 | 23.6 | 23.9 | 23.8 | 24.2 |
| Carbonear | Powells Brook | CB_PB_C007 | 1 x 2.0 m dia. circular CMP<br>2.4 m dia. circular CMP | 35.5 | 34.4 | 35.1 | 34.9 | **35.6** |
| Carbonear | Carbonear Local Creek | CB_LC_C001 | 1.6 m H x 3.1 m W CMP arch | 4.5 | 3.3 | 3.6 | 3.5 | 3.8 |
| Carbonear | Carbonear Local Creek | CB_LC_C002 | 1.2 m H x 1.8 m W elliptical CMP | 11.7 | 11.1 | 11.5 | 11.4 | 11.7 |
| Carbonear | Carbonear Local Creek | CB_LC_C003 | 1.6 m dia. circular corrugated plastic | 12.3 | 11.7 | 12.0 | 11.9 | 12.2 |
| Carbonear | Carbonear Local Creek | CB_LC_C004 | 2 x 1.0 m dia. circular CMP | 14.6 | 14.4 | **14.7** | 14.6 | **14.7** |
| Carbonear | Carbonear Local Creek | CB_LC_C005 | 1.7 m dia. c circular corrugated plastic | 16.8 | 16.2 | 16.5 | 16.4 | 16.7 |
| Carbonear | Carbonear Local Creek | CB_LC_C006 | 1.5 m dia. circular CMP | 18.8 | 17.6 | 17.8 | 17.8 | 18.1 |
| Carbonear | Carbonear Local Creek | CB_LC_C007 | 1.1 m H x 1.6 m W CMP arch | 36.1 | 35.6 | 36.0 | 35.9 | **36.2** |
| Carbonear | Carbonear Local Creek | CB_LC_C008 | 1.5 m dia. circular CMP | 63.5 | 62.8 | 62.8 | 62.8 | 62.9 |
| Placentia | Baldwins Brook | PL_BB_B001 | 6.4 m long span concrete bridge | 9.9 | 8.1 | 8.4 | 8.2 | 8.6 |
| Placentia | Baldwins Brook | PL_BB_B002 | 6.4 m long span concrete bridge | 9.8 | 8.2 | 8.4 | 8.3 | 8.6 |
| Placentia | Local Creek 1 | PL_LC1_C001 | 1.0 m H x 1.4 m W pipe arch CMP | 1.2 | 0.8 | 1.0 | **1.4** | **1.6** |
| Placentia | Local Creek 1 | PL_LC1_C002 | 3 x 0.9 m dia. circular CMP | 2.7 | 1.0 | 1.2 | 1.5 | 1.7 |
| Placentia | Local Creek 1 | PL_LC1_C003 | 0.6 m dia. circular corrugated plastic pipe | 3.8 | 2.1 | 2.7 | 2.7 | 2.7 |
| Placentia | Local Creek 1 | PL_LC1_C004 | 0.7 m dia. CMP<br>0.6 m dia. CMP | 2.0 | **2.1** | **2.7** | **2.7** | **2.7** |
| Placentia | Local Creek 1 | PL_LC1_C005 | 0.9 m H x 1.1 m W elliptical CMP | 2.6 | **2.7** | **2.9** | **2.8** | **2.9** |
| Placentia | Local Creek 1 | PL_LC1_C006 | 0.9 m dia. circular CMP | 3.8 | 3.7 | 3.8 | 3.7 | 3.8 |
| Placentia | Local Creek 1 | PL_LC1_C007 | 2 x 0.6 m dia. circular CMP | 4.6 | **5.0** | **5.1** | **5.0** | **5.1** |
| Placentia | Local Creek 1 | PL_LC1_C008 | 2 x 0.6 m dia. circular CMP | 5.3 | **5.6** | **5.6** | **5.6** | **5.7** |
| Placentia | Local Creek 1 | PL_LC1_C009 | 2 x 0.6 m dia. circular CMP | 11.2 | **11.8** | **11.9** | **11.8** | **11.9** |
| Placentia | Local Creek 2 | PL_LC2_C001 | 1.5m H x 2.1 m W pipe arch CMP | 5.2 | 4.5 | 4.7 | 4.6 | 4.8 |
| Placentia | Local Creek 2 | PL_LC2_C002 | 0.8 m H x 1.0 m W pipe arch CMP | 17.5 | **17.7** | **17.8** | **17.8** | **17.8** |
| Placentia | Local Creek 3 | PL_LC3_C001 | 2 x 1.3 m dia. circular CMP | 5.8 | **6.0** | **6.1** | **6.1** | **6.2** |
| Placentia | Local Creek 3 | PL_LC3_C002 | 2 x 1.3 m H x 1.8 m W pipe arch CMP | 12.8 | 12.5 | 12.6 | 12.6 | 12.7 |

| Town | River | Crossing Name | Structure Configuration | Top of Road Elevation (m) | Current Climate Water Level (m) | | Climate Change Water Level (m) | |
|---|---|---|---|---|---|---|---|---|
| | | | | | 20-Year AEP | 100-Year AEP | 20-Year AEP | 100-Year AEP |
| Placentia | Local Creek 3 | PL_LC3_C003 | 2 x 1.4 m H x 1.9 m W pipe arch CMP | 15.1 | **15.4** | **15.5** | **15.5** | **15.6** |
| Placentia | Local Creek 3 | PL_LC3_C004 | 2 x 1.5 m dia. circular concrete pipe | 26.2 | **26.3** | **26.5** | **26.4** | **26.6** |
| Placentia | Local Creek 3 | PL_LC3_B005 | 4 m long span wood bridge | 27.6 | **28.2** | **28.3** | **28.2** | **28.3** |
| Placentia | Local Creek 3 | PL_LC3_C006 | 2 x 1.1 m H x 1.65 m W pipe arch CMP | 28.9 | **29.3** | **29.5** | **29.4** | **29.5** |
| Placentia | Local Creek 3 | PL_LC3_C007 | 2 x 1.3 m dia. circular concrete pipe | 36.3 | **36.5** | **36.5** | **36.5** | **36.6** |
| Placentia | Local Creek 3 | PL_LC3_B008 | 5 m long span wood bridge | 37.3 | **37.9** | **38.0** | **37.9** | **38.1** |
| Placentia | Local Creek 3 | PL_LC3_C009 | 1.4 m H x 1.9 m W pipe arch CMP | 38.3 | **38.9** | **38.9** | **38.9** | **38.9** |
| Placentia | Local Creek 3 | PL_LC3_C010 | 2 x 1.6 m dia. circular CMP | 41.2 | **41.5** | **41.6** | **41.6** | **41.6** |
| Placentia | Local Creek 3 | PL_LC3_B011 | 3.8 m long span wood bridge | 41.2 | **41.6** | **41.6** | **41.6** | **41.7** |
| Placentia | Local Creek 3 | PL_LC3_C012 | 2.2 m dia. circular CMP | 47.6 | 45.5 | 47.0 | 46.1 | **47.7** |
| Placentia | Local Creek 3 | PL_LC3_C013 | 2 x 1.0 m dia. circular CMP | 61.0 | **61.4** | **61.5** | **61.5** | **61.6** |
| Placentia | Local Creek 4 | PL_LC4_C001A | 1.5 m dia. circular CMP | 22.4 | 20.7 | 21.2 | 20.9 | 21.6 |
| Placentia | Local Creek 4 | PL_LC4_C001B | 1.7 m dia. circular CMP | 22.4 | 21.6 | 21.9 | 21.7 | 22.0 |
| Placentia | Little Salmonier River | PL_LSR_C001 | 1.6 m H x 2.3 m W concrete box culvert | 4.2 | 3.6 | **4.4** | 3.9 | **4.5** |
| Placentia | Little Salmonier River | PL_LSR_C002 | 1.4 m H x 2.4 m W concrete box culvert | 6.8 | 5.9 | 5.9 | 5.9 | 6.0 |
| Placentia | Little Salmonier River | PL_LSR_C003 | 6 x 0.5 m dia. circular concrete pipe | 8.2 | **8.5** | **8.5** | **8.5** | **8.5** |
| Placentia | Little Salmonier River | PL_LSR_C004 | 2 x 1.1 m dia. circular concrete pipe | 12.4 | **13.1** | **13.2** | **13.1** | **13.2** |
| Placentia | Little Salmonier River | PL_LSR_C005 | 2 x 1.0 m H x 1.4 m W pipe arch CMP | 31.8 | **32.2** | **32.3** | **32.3** | **32.4** |
| Placentia | Mill Brook | PL_MB_C001 | 2 x 1.5 m H x 2.4 m W pipe arch CMP | 18.4 | 17.8 | 18.1 | 17.9 | 18.3 |
| Placentia | Northeast River | PL_NER_B001 | 22.97 m long span concrete bridge | 8.2 | 7.6 | 8.0 | 7.8 | 8.1 |
| Placentia | Local Creek 5 | PL_LC5_C001 | 2 x 1.5 m H x 2.0 m W CMP Arch | 21.1 | **22.0** | **22.2** | **22.1** | **22.3** |
| Placentia | Northeast River Local Creek | PL_NER_LC_C001 | 0.9 m dia. circular CMP | 16.6 | **16.7** | **16.7** | **16.7** | **16.7** |
| Placentia | Northeast River Local Creek | PL_NER_LC_C002 | 0.9 m dia. circular CMP | 25.9 | 25.3 | 25.4 | 25.3 | 25.4 |
| Placentia | Rattling Brook | PL_RB_C001 | 3.0 m dia. circular CMP | 14.3 | **14.7** | **15.0** | **14.9** | **15.1** |
| Placentia | Rattling Brook | PL_RB_B002 | 4.0 m long span concrete bridge | 16.7 | **17.3** | **17.4** | **17.4** | **17.4** |
| Placentia | Southeast River Local Creek | PL_SER_LC_C001 | 1.7 m H x 2.4 m pipe arch CMP | 38.5 | 37.8 | 38.0 | 37.9 | 38.1 |
| Placentia | Southeast River Local Creek | PL_SER_LC_C002 | 0.9 m dia. circular CMP | 39.3 | 38.1 | 38.2 | 38.1 | 38.2 |
| Placentia | Shalloway Brook | PL_SHB_C001 | 2.2 m dia. circular CMP | 80.0 | **80.4** | **80.5** | **80.4** | **80.6** |
| Placentia | Shalloway Brook | PL_SHB_rail | 0.7 m dia. circular CMP<br>0.7 m dia. circular concrete pipe | 80.8 | 80.3 | 80.5 | 80.4 | 80.5 |
| Placentia | Smelt Brook | PL_SMB_B001 | 7.6 m long span concrete bridge | 8.3 | 6.2 | 7.8 | 7.6 | 8.0 |
| Placentia | Smelt Brook | PL_SMB_B002 | 4.0 m long span concrete bridge | 7.8 | 6.2 | **8.0** | 7.7 | **8.2** |
| Placentia | Sound Brook | PL_SOB_C001 | 3.0 m H x 6 m W arch CMP | 42.9 | 40.1 | **43.2** | 41.4 | **43.5** |

The culvert and bridge crossings were also reviewed to identify instances where the limited culvert or bridge capacity resulted in nearby sections of roadway being overtopped due to the inadequate culvert or bridge capacity. These locations include:

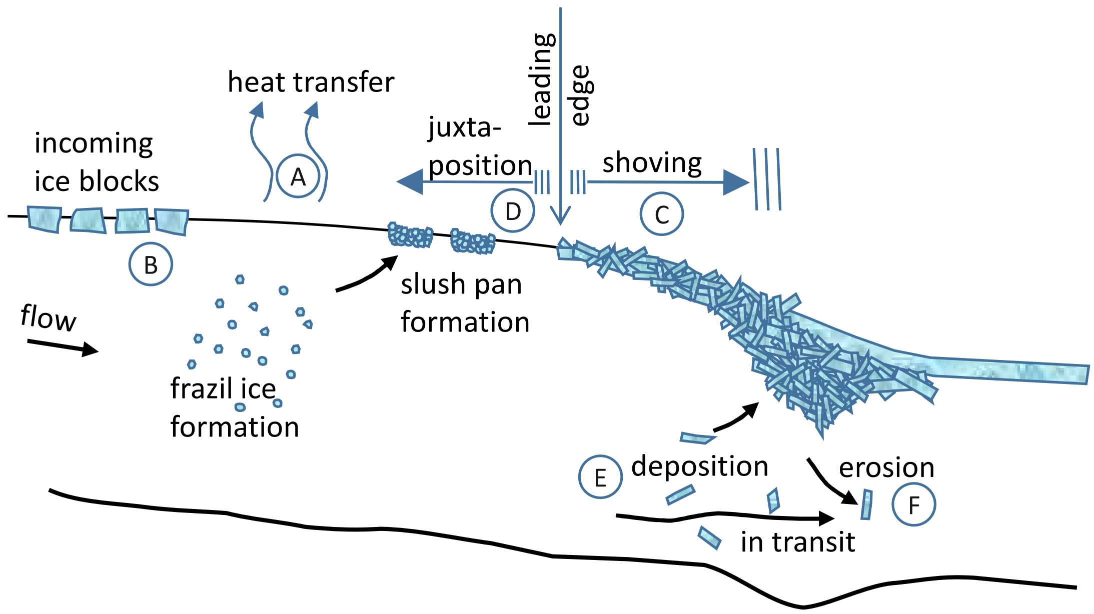
- Highway 74 northwest of the Clark Brook crossing (i.e. VSC_CB_001),
- Highway 70 north of Salmon Cove River in Salmon Cove (i.e. VSC_SCR_B002),
- Highway 70 east of Salmon Cove River in Salmon Cove (i.e. VSC_SCR_B005),
- Adelaide St. south of Local Creek 2 in Carbonear (i.e. CB_IPB_LC2_C002),
- Morrissey Lane north of Local Creek 1 in Placentia (i.e. PL_LC1_C001),
- Highway 91 west of Local Creek 2 in Placentia (i.e. PL_LC2_C001),
- Brook Lane east of Local Creek 3 in Placentia at multiple culverts (i.e. PL_LC3_B005, PL_LC3_C006, PL_LC3_B008, and PL_LC3_C009),
- The intersection of Marquis Ave., Snelling Ave., and Argentia Pond Road is overtopped south of the crossing on Little Salmonier River (i.e. PL_LSR_C002),
- Argentia Pond Road is overtopped next to the culvert crossing on Little Salmonier River (i.e. PL_LSR_C003),
- Old Placentia Road is overtopped southeast of the crossing on the Northeast River (i.e. PL_NER_B001),
- Highway 100 is overtopped both northeast and southwest of the Northeast River tributary crossing (i.e. PL_NER_LC_C002),
- Fox Harbour Road is overtopped south of the Shalloway Brook crossing (i.e. PL_SHB_Rail).

## 8.4 Assessment of Potential Impacts due to River Ice

### 8.4.1 OVERVIEW OF ICE PROCESSES

To evaluate the potential for ice jam flooding and the water levels associated with ice jamming, RIVICE models were developed for Island Pond Brook, Powells Brook, and three sections of the Salmon Cove River. Ice jam models were not developed for Placentia, as ice jamming was not identified as an issue in the community. The key river ice processes simulated in RIVICE that are relevant to this study are shown on Figure 120.

## FIGURE 120: RIVER ICE 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 120, 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 formation of ice jams due to frazil ice accumulation was not considered as part of this assessment. The second source is the volume of inflowing ice per time step, represented as ‘B’ in Figure 120, 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 120 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 riverbanks (i.e. $F_F$), given by the equation:

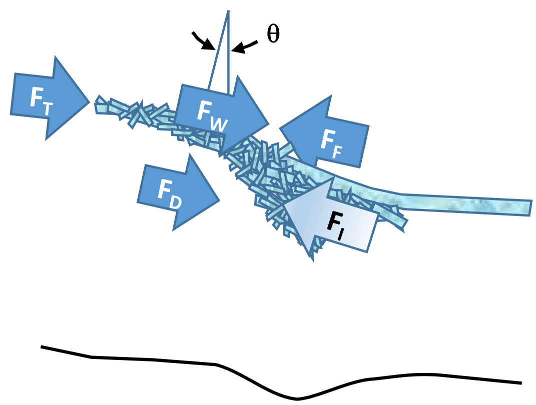
$$F_T + F_W + F_D > F_I + F_F \qquad \text{(Eq. 5)}$$

The second process is the progression of the ice cover upstream through juxtapositioning of the ice cover, represented as ‘D’ in Figure 120, 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:

$$F_T + F_W + F_D < F_I + F_F \quad \text{(Eq. 6)}$$

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 121 and summarized in Table 53.

### FIGURE 121: FORCES APPLIED TO AN ICE-JAM COVER




Source: Sheikholeslami et al. (2017)

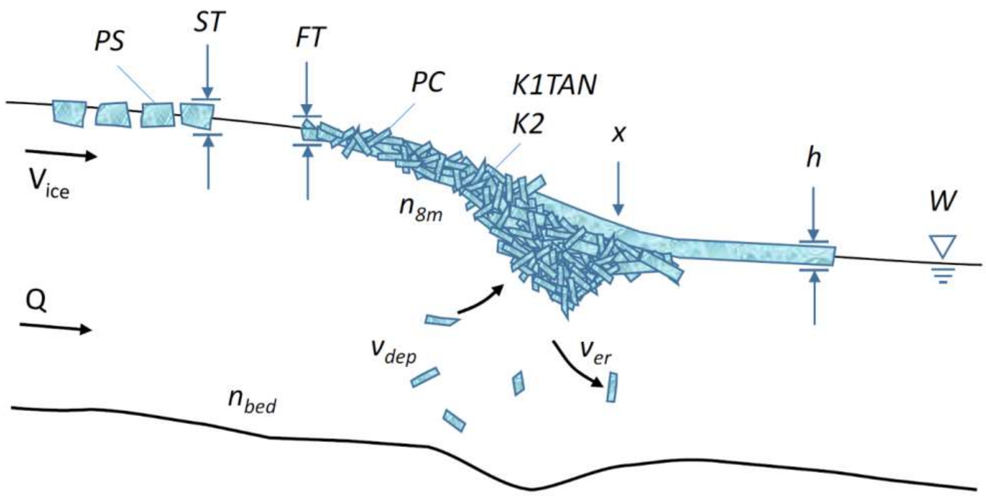
### TABLE 53: FORCES APPLIED TO AN ICE-JAM COVER

| 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 riverbanks |
| $F_I$ | 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 120. 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 120.

These processes are represented using parameters specific to the processes in RIVICE, as shown on Figure 122 and summarized in Table 54.

### FIGURE 122: PARAMETERS USED TO DESCRIBE THE ICE PROCESSES IN RIVICE




Source: Sheikholeslami et al. (2017)

### TABLE 54: 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 | Riverbed Roughness Coefficient |
| K1TAN | Ice Strength Parameter |
| K2 | Ice Strength Parameter |
| Q | 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, which was not considered as part of this assessment.

The ice cover front has a thickness of *FT* and a porosity of *PC*. The width of the river at the front is known 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:

$$length = \frac{V_{ice}}{widt \ \ \times ice\ thickness \times ice\ porosity} \qquad \text{(Eq. 7)}$$

Coefficients for the roughness of the riverbed (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 riverbank, 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 $v_{er}$.

Since there was very limited information relating to the locations where historical ice jams have occurred, ice jams were allowed to form at the downstream end of the river reach being modelled, and supplied with enough volume of ice for the jam to proceed to the upstream end of the model. This approach allowed for the definition of the maximum envelope of ice jam water levels, as it considers an ice jam along the full reach of the river. However, this represents a very conservative assumption, as it assumes both that ice jams occur at all locations at once, without dislodging from the riverbanks, and that there is a sufficient volume of incoming ice for the jam to aggregate to the upstream extent of the model.

The RIVICE model parameters, as well as the acceptable range of values adopted for the RIVICE models, are summarized in Table 55. Note that for different rivers, the acceptable range of parameters would be different.

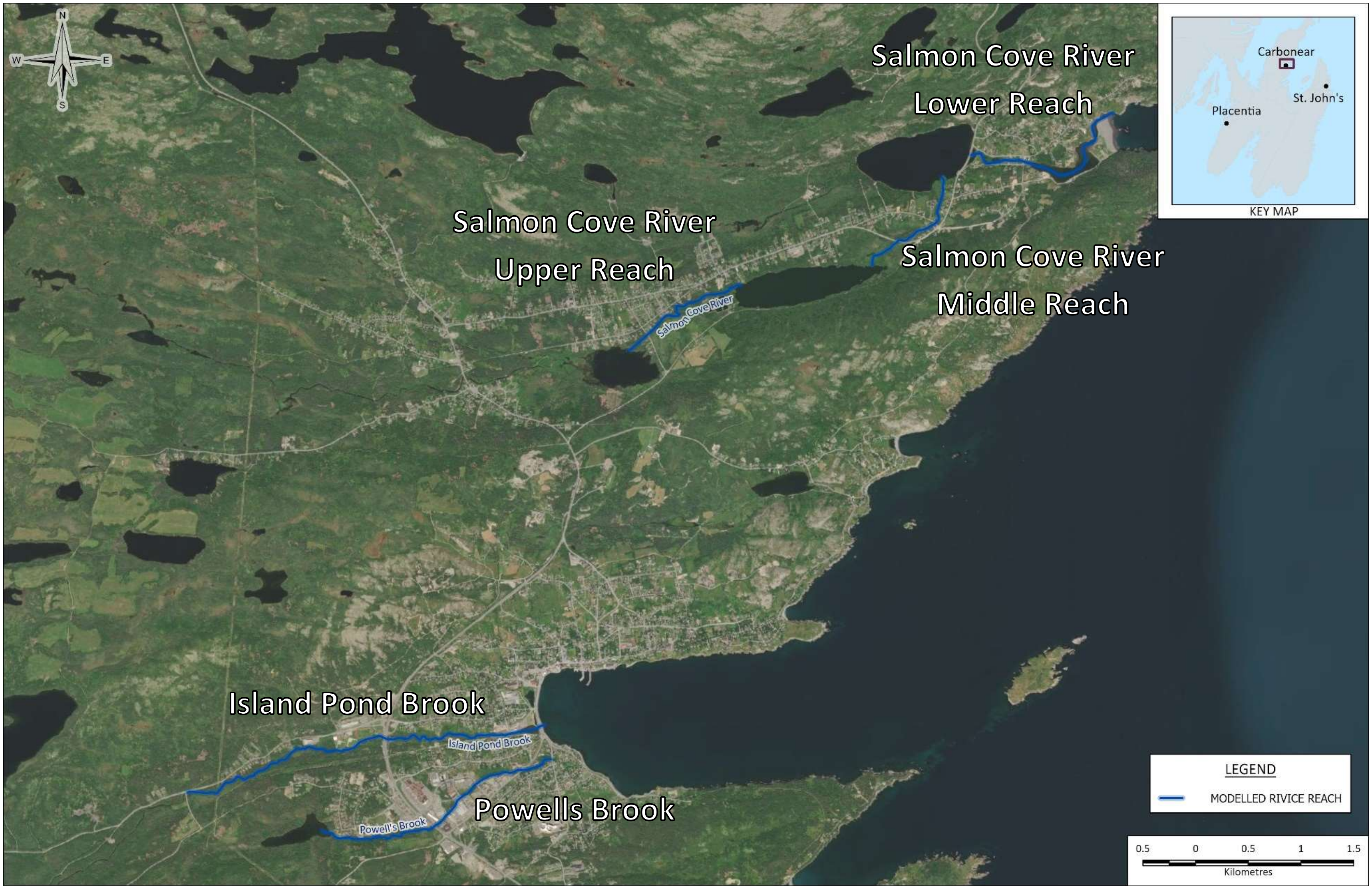
### TABLE 55: RIVICE MODEL PARAMETERS AND RANGES

| 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 |
| $n_{bed}$ | Riverbed 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 | River Flow | Function of River Flows | Function of River Flows | $m^3/s$ |
| W | Downstream Water Level | Function of Tidal or River Levels | Function of Tidal or River Levels | m |
| x | Ice Jam Toe Cross Section Number | At River Outlet | At River Outlet | Unitless |
| $T_A$ | Air Temperature | Function of Air Temperature | Function of Air Temperature | °C |
| H | Heat Transfer Coefficient | 15 | 25 | $W/m^2/°C$ |

### 8.4.2 RIVICE MODEL DEVELOPMENT

RIVICE models of the Salmon Cove River, Island Pond Brook and Powells Brook were developed based on cross sections extracted from the bare earth DEM. Due to limitations of RIVICE, the areas outside of the main channels (i.e. overbank areas) were removed from the cross sections. As well, culvert and bridge crossings were not integrated into the RIVICE models, as the software presently is unable to represent those crossings. Cross sections were extracted along the DEM at 100 m increments, and then interpolated as required within RIVICE to maintain numerical stability. The river reaches modelled in RIVICE are shown on Figure 123.

## FIGURE 123: RIVER REACHES MODELLED IN RIVICE



### 8.4.3 RIVICE MODEL CALIBRATION

Prior to simulating ice jam conditions, the RIVICE models were calibrated to open water conditions. The RIVICE model calibration was completed by adjusting the Manning's bed roughness coefficient. The basis for the calibration of the RIVICE models was open water profiles corresponding to the 100-year AEP ice affected flows that were simulated in a simplified 1D version of the HEC-RAS models developed for the Salmon Cove River, Island Pond Brook and Powells Brook. Channel bed roughness coefficients were used in the 1D model that were consistent with the calibrated 2D model.

The 100-year AEP ice affected flows on Salmon Cove River, Powells Brook and Island Pond Brook were estimated by completing a frequency analysis of the annual peak ice-affected flow rates from WSC gauge 02ZL004 (i.e. Shearstown Brook at Shearstown). Ice-affected flows can be discerned from open water flows in WSC flow data, as they are indicated with a 'B' code, which denotes the presence of river ice. The location of the 02ZL004 gauge relative to Powells Brook, Island Pond Brook and Salmon Cove River is shown on Figure 38. A 3-parameter lognormal distribution was found to be most suitable distribution, and was fit to the annual peak ice-affected flows. The frequency analysis indicated a 100-year AEP ice-affected flow of 11.3 $m^3/s$ on the Shearstown Brook at Shearstown. This flow was then prorated to Powells Brook, Island Pond Brook and the three river reaches of the Salmon Cove River that were considered in the analysis on the basis of drainage area. The resulting estimated 100-year AEP ice-affected flows are summarized in Table 56.

TABLE 56: ICE-AFFECTED 100-YEAR AEP FLOWS

| River | Drainage Area ($km^2$) | 100-Year AEP Flow ($m^3/s$) |
|---|---|---|
| Island Pond Brook | 37.8 | 14.8 |
| Powells Brook | 8.7 | 3.4 |
| Salmon Cove River (Upper) | 39.9 | 16.7 |
| Salmon Cove River (Middle) | 42.8 | 15.6 |
| Salmon Cove River (Lower) | 67.8 | 11.3 |

Comparisons of the calibrated RIVICE water levels to the HEC-RAS levels models are shown on Figure 124 to Figure 128.

**FIGURE 124: ISLAND POND BROOK RIVICE CALIBRATION**

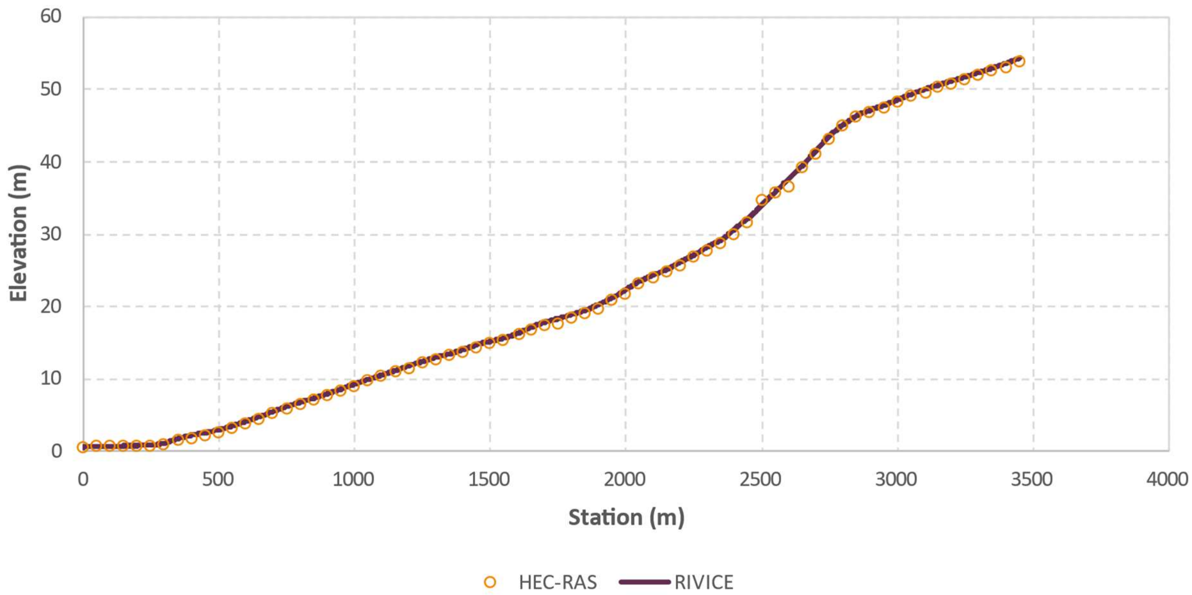
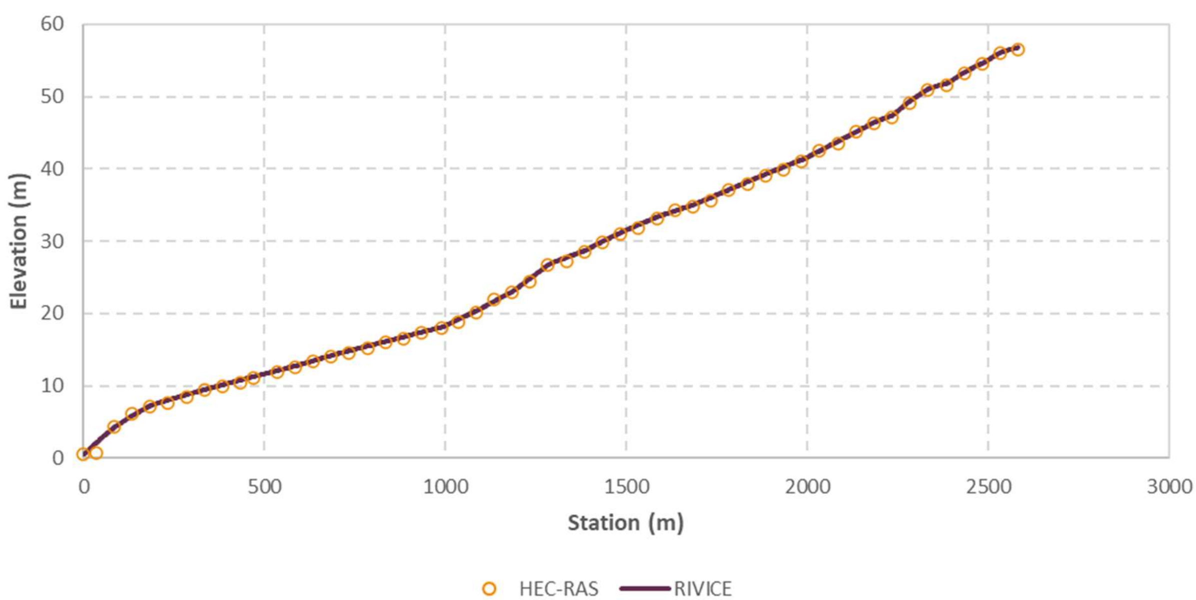
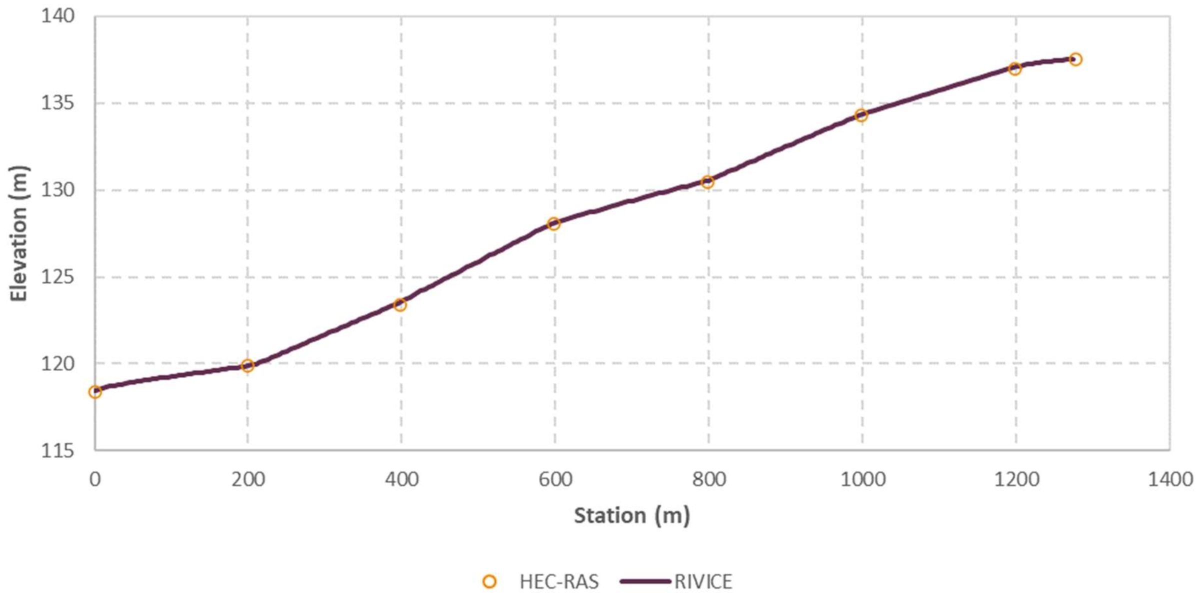



**FIGURE 125: POWELLS BROOK RIVICE CALIBRATION**



### FIGURE 126: SALMON COVE RIVER UPPER REACH RIVICE CALIBRATION




### FIGURE 127: SALMON COVE RIVER MIDDLE REACH RIVICE CALIBRATION

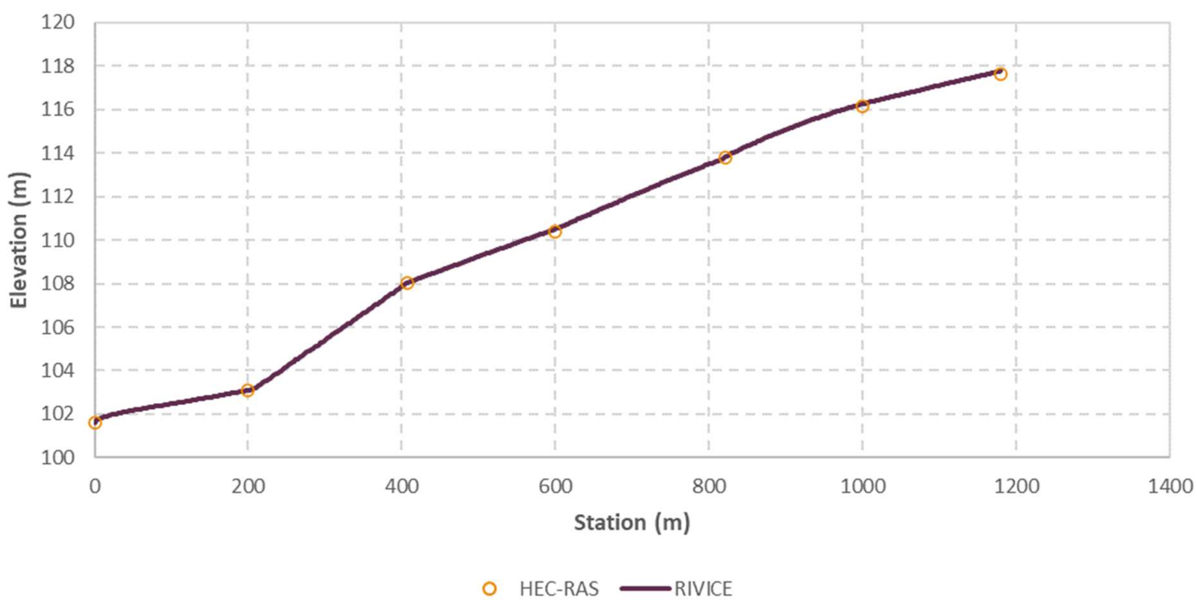
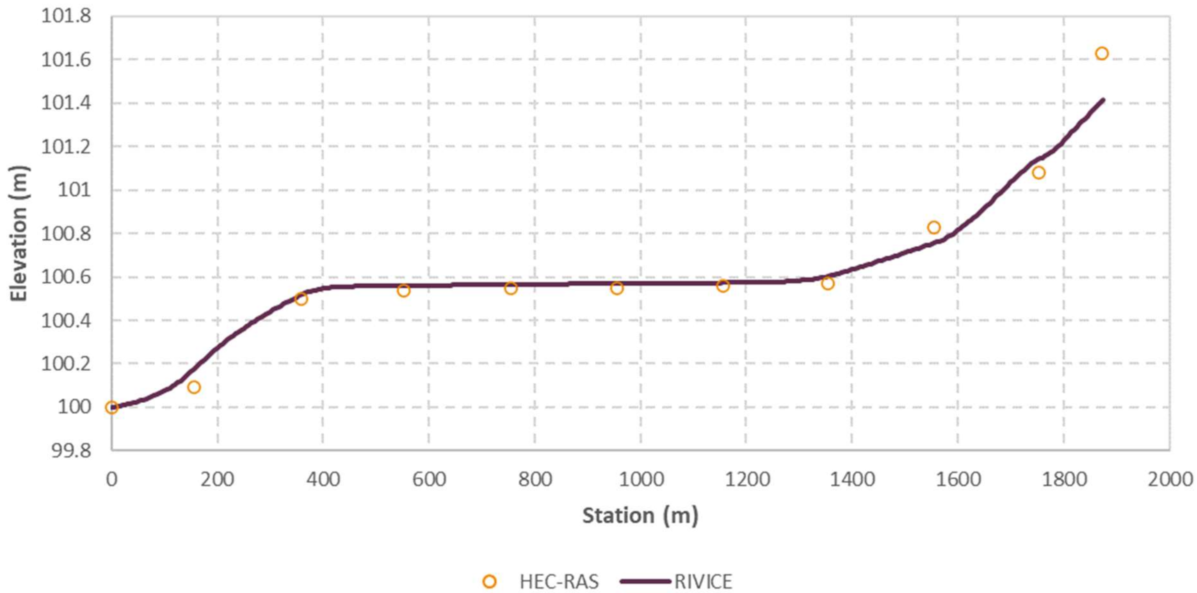


FIGURE 128: SALMON COVE RIVER LOWER REACH RIVICE CALIBRATION




The calibration of the RIVICE models required high Manning's roughness coefficients for most of the river reaches to accurately reproduce the HEC-RAS water levels, well above the calibrated roughness coefficients included in the HEC-RAS models. This was in part due to another limitation of RIVICE, specifically that the software cannot model supercritical flows. Accordingly, higher roughness coefficients were required to ensure that flows in the model remained subcritical. The calibrated roughness coefficients for the RIVICE model are summarized in Table 57, with the open water roughness coefficients shown for reference.

TABLE 57: CALIBRATED RIVICE ROUGHNESS COEFFICIENTS

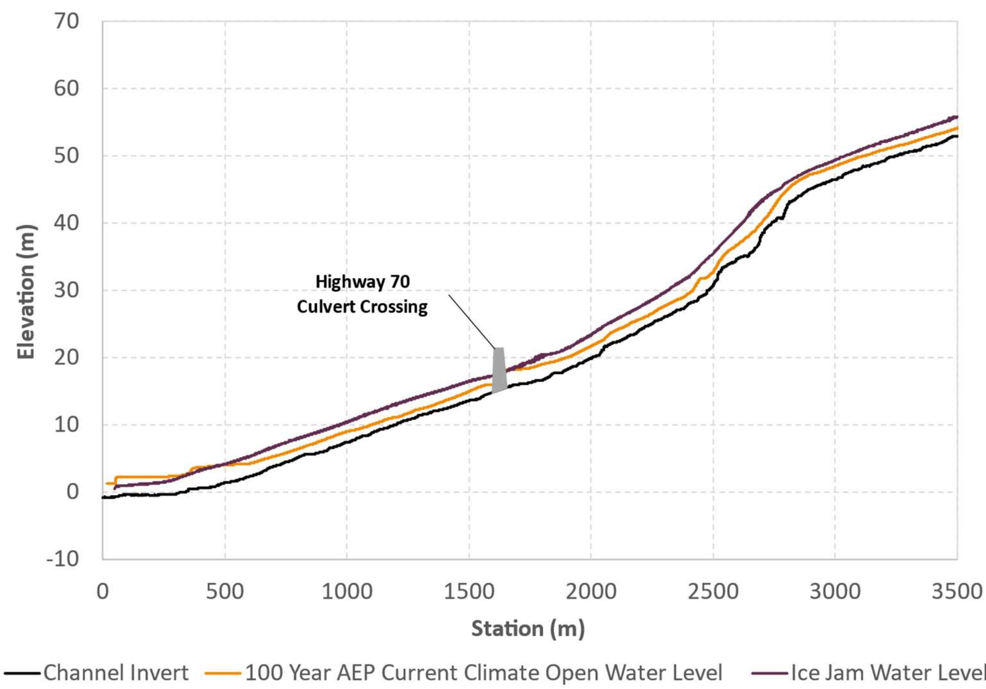
| River Reach | Open Water Roughness Coefficient | RIVICE Roughness Coefficient |
|---|---|---|
| Island Pond Brook | 0.035 | 0.095 |
| Powells Brook | 0.035 | 0.075 |
| Salmon Cove River Upper | 0.032 | 0.045 |
| Salmon Cove River Middle | 0.032 | 0.045 |
| Salmon Cove River Lower | 0.032 | 0.030 |

### 8.4.4 ICE-AFFECTED HYDRAULIC MODEL SIMULATIONS

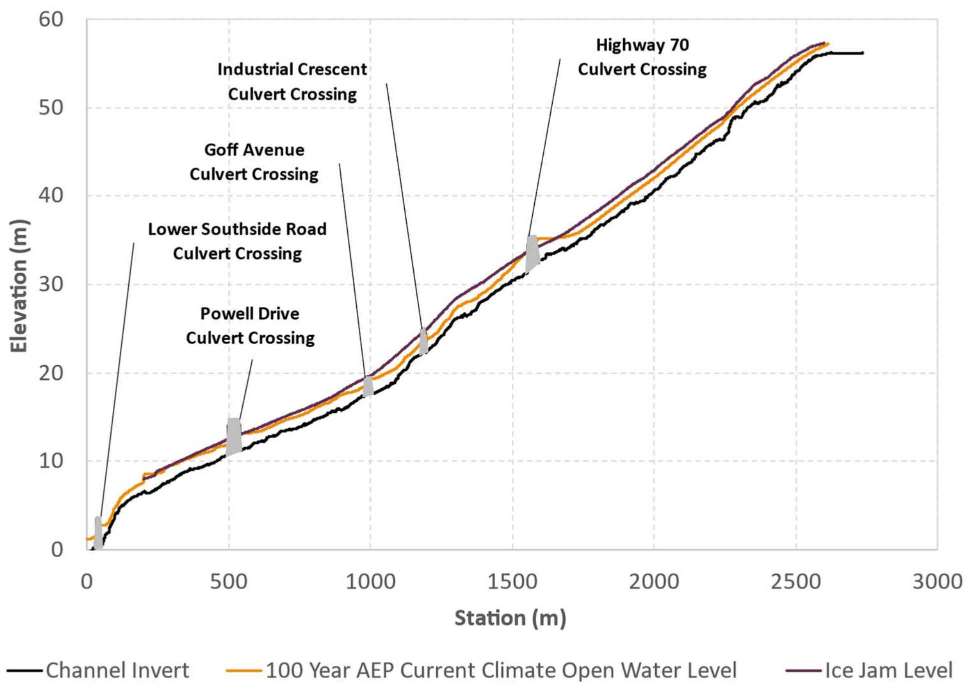
Following the calibration of the RIVICE model to open water conditions, the RIVICE models were used to estimate the maximum ice jam elevations along the rivers associated with the 100-year AEP ice affected flows. As noted in Section 8.4.1, the assessments assumed the initiation of the ice jam occurring at the downstream model extent, with sufficiently high volumes of incoming ice to allow for the aggregation of the ice jam upstream through the full river reach length considered in the model. This conservative approach mitigated uncertainty in the potential ice jam locations, as it assumed that an ice jam would form along the entire reach of the river, and provided an upper limit of the ice jam water levels on the rivers that could occur during the passage of the 100-year AEP ice-affected flow with the occurrence of an ice jam at any location along the river. Furthermore, additional adjustments to the RIVICE model parameterization were required both to maintain numerical stability, and to allow for ice jams to aggregate fully to the upstream model boundaries.

Comparisons of the ice jam water levels to the open water levels on Island Pond Brook, Powells Brook and Salmon Cove River are shown on Figure 129 to Figure 133.

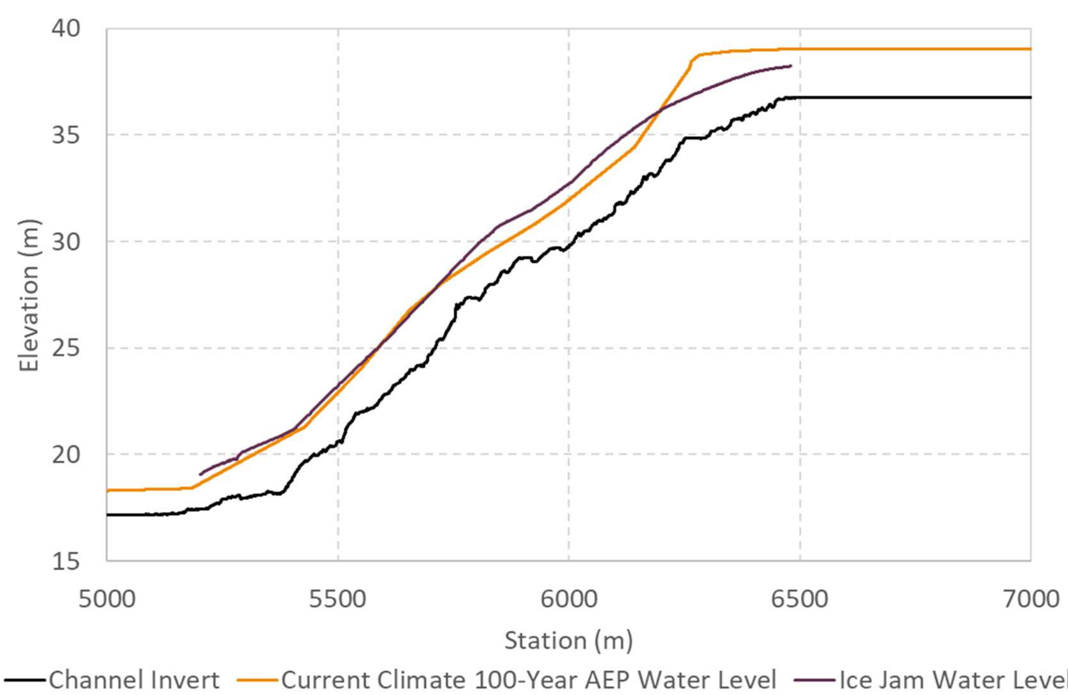
FIGURE 129: COMPARISON OF ICE JAM AND OPEN WATER LEVELS ON ISLAND POND BROOK



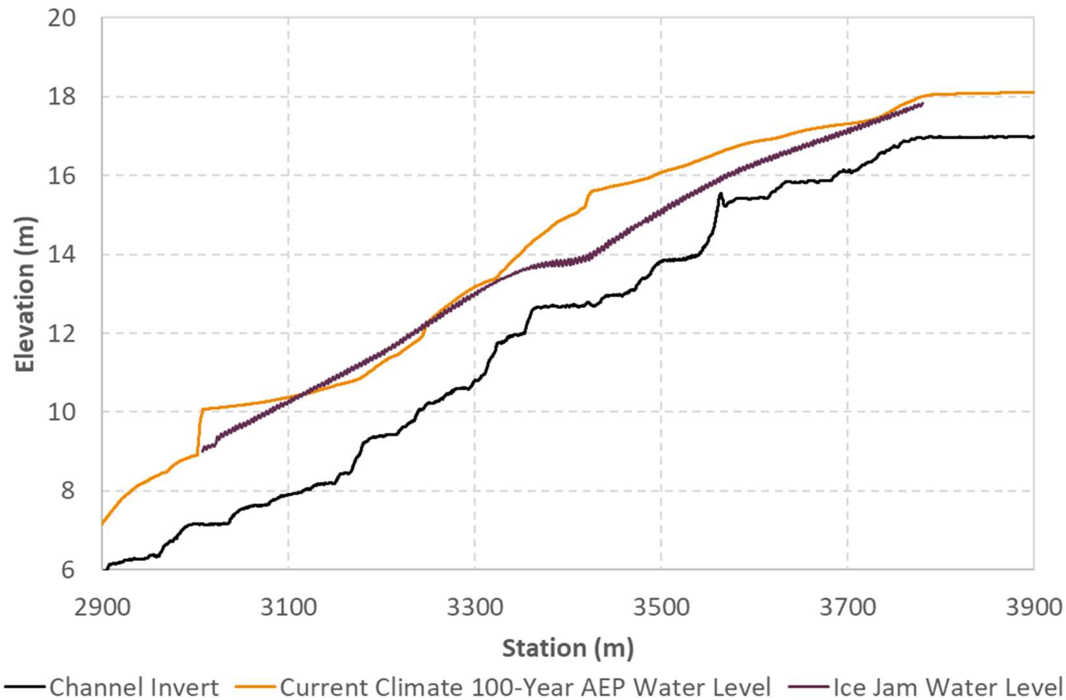
## FIGURE 130: COMPARISON OF ICE JAM AND OPEN WATER LEVELS ON POWELLS BROOK



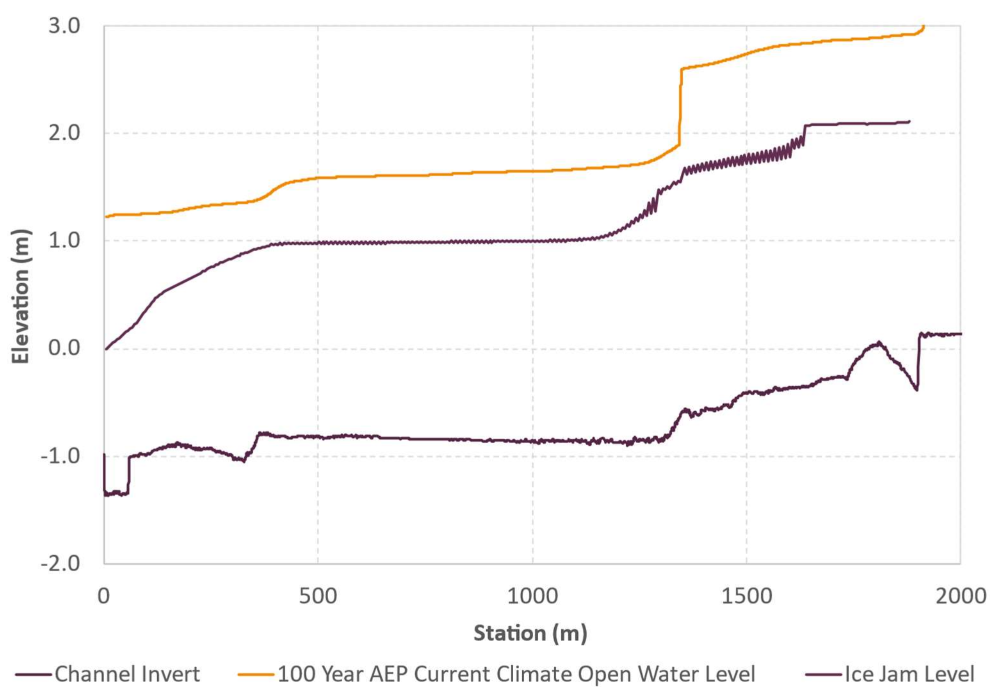

## FIGURE 131: COMPARISON OF ICE JAM AND OPEN WATER LEVELS ON THE UPPER REACH OF SALMON COVE RIVER



## FIGURE 132: COMPARISON OF ICE JAM AND OPEN WATER LEVELS ON THE MIDDLE REACH OF SALMON COVE RIVER




## FIGURE 133: COMPARISON OF ICE JAM AND OPEN WATER LEVELS ON THE LOWER REACH OF SALMON COVE RIVER



On the Salmon Cove River, the 100-year AEP open water levels were generally higher than or comparable to the ice jam levels defined by the RIVICE model, particularly on the lower reach of the Salmon Cove River, as shown on Figure 133. On the middle reach of the Salmon Cove River, as shown on Figure 132, the model results show that for a short reach of the river extending from station 3100 to 3250, the ice jam water levels could exceed the open water 100-year AEP flood level by up to 0.38 m.

On the upper reach of the Salmon Cove River, as shown on Figure 131, ice jam levels could be higher than the open water 100-year AEP levels associated with the current climate by up to 0.45 m between station 5200 to 5600, including a potential ice jam level of 22.70 m along the western edge of the wastewater lagoon, which based on the LiDAR data has a crest elevation ranging from 22.71 to 22.90 m. It should again be noted, however, that the ice jam levels are based on a number of conservative assumptions and adjustments to maintain numerical stability in the RIVICE model, and as such represent a condition less likely than a 100-year AEP ice jam. Nonetheless, the crest of the wastewater lagoon dike should be surveyed to confirm the crest elevation and evaluate whether there is adequate freeboard.

The comparison of open water and ice jam levels also shows higher ice jam levels between station 5700 and 6200, however additional adjustments were required to allow for further ice aggregation upstream of station 5700, and as such the ice jam levels are likely unrealistic.

On both Island Pond Brook and Powells Brook, as shown on Figure 129 and Figure 130, ice jam levels are consistently higher than the 100-year AEP levels under current climate conditions. However, given the significant increase in bed roughness that was required to maintain numerical stability, and that RIVICE can only represent the main channel of the river, these levels are likely unrealistic.

Given the combination of the conservative assumptions that were made in the ice jam assessment, the simplifications that were made in the RIVICE modelling, and that on certain reaches, the ice jam levels were comparable to the open water flood levels, while on others the ice jam levels were considered to be unrealistic, the ice jam levels were not integrated into the flood risk maps. Instead, the flood risk mapping was developed based on the results of the open water hydraulic modelling.

# 9.0 SENSITIVITY ANALYSES OF THE HYDROLOGIC AND HYDRAULIC MODEL INPUTS

## 9.1 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 key model parameters for each simulation to see how the change affects the model results.

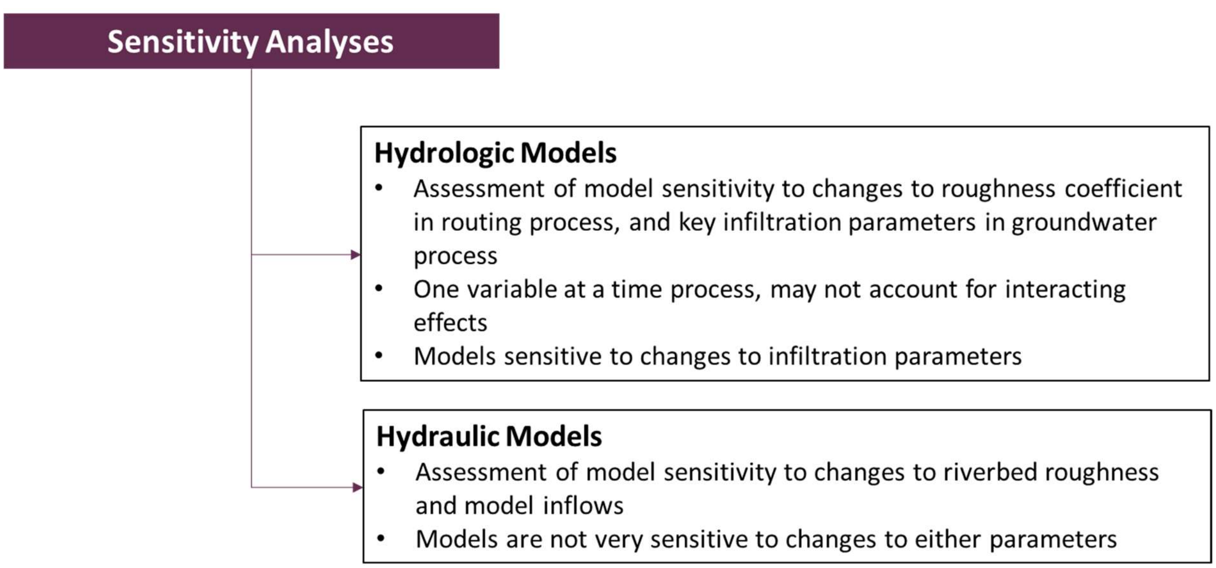
For the hydrological model, the sensitivity test checked how sensitive the model was to the parameters that represent channel roughness included in the hydrologic routing function of the model, as well as the parameters that represent how much rainfall gets absorbed by the ground during rain and melt 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 downstream end of each river or creek. The tests showed that the model was sensitive to the ground absorption model parameters.

Similar tests were completed for the hydraulic models. The tests considered the model sensitivity to changes to the inflow on each river, and to the parameter that represents the riverbed roughness. The sensitivity was checked by comparing the modelled water levels along each river. The sensitivity tests showed that the model is not very sensitive to changes to either parameter.

Based on the results of the model sensitivity tests, it was considered that the adopted model results described in Sections 6.0 and 8.0 are considered appropriate for developing the flood mapping.

An overview of the sensitivity analysis task is shown on Figure 134.

FIGURE 134: OVERVIEW OF SENSITIVITY ANALYSES TASKS



## 9.2 Hydrologic Model Sensitivity

A sensitivity analysis was completed for the HEC-HMS models to assess the model sensitivity to changes to key model parameters, specifically the SCS Curve Number and the Manning's roughness coefficient included in the routing function. These parameters were adjusted from -30% to +30% in the HEC-HMS model, which was then used to simulate the 100-year AEP rainfall event under current climate conditions.

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 sensitivities were assessed at the outlets of each of the rivers and creeks that were evaluated for mapping in this study. The sensitivity analysis results for both the Placentia area model and Carbonear area model, which includes Carbonear, Salmon Cove and Victoria, are summarized in Table 58.

## TABLE 58: HYDROLOGIC MODEL SENSITIVITY ANALYSIS RESULTS

| Model | Town | Location | Peak Flow Percent Difference (%) | | | | | | Peak Flow Percent Difference (%) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | CN-30% | CN-20% | CN-10% | CN+10% | CN+20% | CN+30% | n-30% | n-20% | n-10% | n+10% | n+20% | n+30% |
| Placentia Area | Placentia | Southeast River Outlet | -45.9% | -30.9% | -15.2% | 9.8% | 9.9% | 10.0% | 0.0% | 0.0% | 0.0% | -0.1% | -0.4% | -0.4% |
| | | Northeast River Outlet | -46.2% | -30.9% | -15.1% | 10.5% | 12.1% | 12.6% | -0.1% | -0.1% | -0.1% | -0.1% | -0.1% | -0.1% |
| | | Rattling Brook Outlet | -44.9% | -29.6% | -14.3% | 5.0% | 5.0% | 5.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| | | Smelt Brook Outlet | -44.9% | -29.4% | -14.1% | 6.4% | 6.4% | 6.4% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| | | Local Creek 1 Outlet | -45.1% | -29.5% | -14.4% | 7.3% | 7.3% | 7.3% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| | | Baldwins Brook Outlet | -45.0% | -29.9% | -14.4% | 6.0% | 6.0% | 6.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| | | Local Creek 2 Outlet | -44.8% | -30.0% | -14.4% | 5.6% | 5.6% | 5.6% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| | | Little Salmonier River Outlet | -44.8% | -29.6% | -14.6% | 5.3% | 5.3% | 5.3% | --- | --- | --- | --- | --- | --- |
| | | Local Creek 3 Outlet | -44.7% | -29.8% | -14.5% | 4.9% | 4.9% | 4.9% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| | | Local Creek 4 Outlet | -45.0% | -30.1% | -14.6% | 7.0% | 7.0% | 7.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| | | Mill Brook Outlet | -45.3% | -29.9% | -14.8% | 8.6% | 8.6% | 8.6% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| | | Local Creek 5 Outlet | -45.5% | -30.0% | -14.8% | 9.5% | 9.5% | 9.5% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| | | Shalloway Brook Outlet | -45.7% | -30.0% | -14.5% | 8.1% | 8.1% | 8.1% | 0.1% | 0.1% | 0.0% | 0.0% | -0.1% | -0.1% |
| | | Sound Brook Outlet | -45.6% | -30.2% | -14.6% | 9.3% | 9.3% | 9.3% | -0.4% | 0.0% | -0.3% | 0.0% | 0.0% | 0.0% |
| | | Glennons Cove River Outlet | -44.9% | -30.0% | -14.5% | 6.1% | 6.1% | 6.1% | 0.0% | 0.0% | 0.1% | 0.0% | 0.0% | 0.0% |
| Carbonear Area | Salmon Cove & Victoria | Salmon Cove River at U/S Model Boundary | -61.1% | -43.4% | -22.8% | 22.5% | 26.4% | 26.4% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| | | Big Brook above Salmon Cove River Confluence | -61.1% | -43.4% | -22.8% | 22.6% | 26.6% | 26.6% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| | | Local Creek 5 above Salmon Cove River Confluence | -61.0% | -43.4% | -22.6% | 22.6% | 26.4% | 26.4% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| | | Clark Brook above Double Brook Confluence | -61.1% | -43.5% | -22.8% | 22.6% | 27.0% | 27.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| | | Double Brook above Local Creek 4 Confluence | -61.2% | -43.4% | -22.9% | 22.6% | 26.4% | 26.4% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| | | Local Creek 4 above Double Brook Confluence | -60.9% | -43.1% | -22.7% | 23.1% | 27.1% | 27.1% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| | | Local Creek 3 above Salmon Cove River | -61.4% | -43.7% | -22.8% | 22.8% | 26.6% | 26.6% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| | | Spout Brook above Salmon Cove River | -61.1% | -43.3% | -22.7% | 22.9% | 27.7% | 27.7% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| | | Local Creek 2 above Salmon Cove River | -60.9% | -43.5% | -22.5% | 22.5% | 26.8% | 26.8% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| | | Local Creek 1 above Salmon Cove River | -61.2% | -43.7% | -23.3% | 22.3% | 26.2% | 26.2% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| | | Salmon Cove River Outlet | -60.5% | -42.9% | -22.5% | 22.7% | 27.4% | 27.4% | 1.1% | 0.7% | 0.3% | -0.1% | -0.4% | -0.6% |
| | Carbonear | Carbonear Local Creek Outlet | -62.2% | -44.0% | -23.2% | 21.7% | 23.8% | 23.8% | --- | --- | --- | --- | --- | --- |
| | | Island Pond Brook above Local Creek 1 Confluence | -59.3% | -42.1% | -22.0% | 18.3% | 18.3% | 18.3% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| | | Local Creek 2 above Local Creek 1 Confluence | -62.5% | -43.8% | -25.0% | 21.9% | 31.3% | 31.3% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| | | Local Creek 1 above Island Pond Brook Confluence | -61.3% | -43.8% | -22.6% | 21.9% | 26.3% | 26.3% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| | | Island Pond Brook Outlet | -59.4% | -42.2% | -22.1% | 18.4% | 18.5% | 18.5% | 0.1% | 0.1% | 0.1% | -0.1% | -0.1% | 0.0% |
| | | Powells Brook Outlet | -61.1% | -43.4% | -22.8% | 22.6% | 26.8% | 26.8% | --- | --- | --- | --- | --- | --- |

The sensitivity analysis showed that the Placentia area and Carbonear area hydrologic models are sensitive to changes to the SCS curve number, with a 30% reduction to the curve number resulting in a reduction in flow of up to 46% in Placentia and up to 61% in Carbonear, Salmon Cove, or Victoria. An increase of 30% to the SCS curve number results in increases to flow rates of up to 13% in Placentia, and up to 31% in Carbonear, Salmon Cove, and Victoria. The greater model sensitivity to reductions to the curve number relative to the model sensitivity to increases to the curve number is due to the calibrated curve number values being closer to the maximum curve number value (i.e. 99) in HEC-HMS than the minimum (i.e. 50). Accordingly, most basin curve numbers can be increased by between 10% and 20% before hitting the upper curve number limit in HEC-HMS, with no sensitivity for further increases. However, the basin curve numbers can be decreased by up to 30% without hitting the lower curve number of 50.

The HEC-HMS models were found to not be sensitive to changes to the Manning's roughness coefficients included in the routing process.

Given the high model sensitivity to changes to the SCS curve number, and the limited information available for calibration, specifically nearby precipitation, water level and flow gauges, additional hydrometric and meteorological monitoring stations could be deployed to further enhance the understanding of the hydrology in Placentia, Carbonear, Salmon Cove, and Victoria. In Placentia, there is a WSC gauging station on the Northeast River that provides good information on the hydrological response on larger basins, however there is limited information to assess the hydrologic response of small (i.e. less than 10 km$^2$) basins. Accordingly, the installation of a flow and water level monitoring station near the outlet of a smaller basin, such as Rattling Brook or Baldwins Brook, could further enhance the understanding of the hydrologic response for the smaller basins in the area. Similarly, with the discontinuation of the ECCC Argentia meteorological station, there is limited gauged precipitation data available in the area, and the installation of a new meteorological monitoring station either at Argentia or in Placentia would allow for ongoing precipitation monitoring and a better understanding of the precipitation that does fall in the Placentia region.

In Carbonear, Salmon Cove and Victoria, there is a similar dearth of hydrological and meteorological monitoring, with the nearest gauged river (i.e. Shearstown Brook at Shearstown) located approximately 17 km from Carbonear and 24 km from Salmon Cove and Victoria. Similarly, the nearest ECCC meteorological station is located in St. John's, approximately 45 km to the southeast. Accordingly, the deployment of a hydrometric monitoring station on either Island Pond Brook or the Salmon Cove River, with a meteorological station located nearby, would serve to greatly enhance the understanding of the hydrology in the area. Potential hydrometric monitoring locations could include Island Pond Brook upstream of Highway 70 near Carbonear Collegiate, as there would be good access to the river, and flood flows are confined to the channel south of the collegiate, or on Salmon Cove River north of Old Neck Road, where again there is reasonable river access and flood flows are fully channelized.

## 9.3 Hydraulic Model Sensitivity

A sensitivity analysis was completed to assess the sensitivity of the HEC-RAS models to changes to the Manning's roughness coefficients of the main channels, as well as to the flows on each of the rivers and creeks. For the sensitivity analysis of the model to changes to the Manning's roughness coefficients, the roughness coefficients of the main channels of the various rivers and creeks were adjusted by +/- 10%, 20%

and 30%, and the models were then used to simulate the 100-year AEP flood under current climate conditions. For the sensitivity analysis of the model to changes to the flows considered in the models, the 100-year AEP, current climate flood discharges were adjusted by +/- 10%, 20% and 30% and simulated in the models. The results of these simulations were then compared to the simulated 100-year AEP flood conditions using the unadjusted models, with water levels extracted along each of the rivers and creeks at 100 m spacing.

The results of the sensitivity analysis for the Placentia area model are summarized in Table 59, while the sensitivity analysis results for the Carbonear area model is summarized in Table 60. The minimum and maximum water level changes associated with the changes to Manning's roughness coefficient and flow on each river and creek are summarized in Table 59 and Table 60. Water level changes at each of the water level extraction locations are included in Appendix N.

### TABLE 59: PLACENTIA AREA HEC-RAS MODEL SENSITIVITY

| Region | River | Change | Water Level Difference (m) | | | | | | Water Level Difference (m) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | n - 30% | n - 20% | n - 10% | n + 10% | n + 20% | n + 30% | Q - 30% | Q - 20% | Q - 10% | Q + 10% | Q + 20% | Q + 30% |
| Placentia | Rattling Brook | Minimum Change | -0.01 | -0.01 | 0.00 | 0.00 | 0.00 | 0.00 | -0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Maximum Change | -0.20 | -0.14 | -0.07 | 0.07 | 0.14 | 0.20 | -0.32 | -0.19 | -0.09 | 0.08 | 0.15 | 0.22 |
| | Smelt Brook | Minimum Change | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Maximum Change | -0.18 | -0.11 | -0.05 | 0.05 | 0.10 | 0.14 | -0.46 | -0.30 | -0.15 | 0.13 | 0.24 | 0.33 |
| | Local Creek 1 | Minimum Change | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Maximum Change | -0.12 | -0.08 | -0.04 | 0.04 | 0.07 | 0.10 | -0.12 | -0.08 | -0.04 | 0.04 | 0.07 | 0.10 |
| | Baldwins Brook | Minimum Change | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Maximum Change | -0.43 | -0.17 | -0.08 | 0.08 | 0.15 | 0.21 | -0.27 | -0.17 | -0.08 | 0.08 | 0.15 | 0.23 |
| | Local Creek 2 | Minimum Change | -0.01 | -0.01 | 0.00 | 0.00 | 0.01 | 0.01 | -0.02 | -0.02 | -0.02 | -0.33 | -0.31 | -0.28 |
| | | Maximum Change | -0.12 | -0.07 | -0.03 | 0.03 | 0.06 | 0.09 | -0.45 | -0.42 | -0.39 | -0.02 | -0.02 | -0.01 |
| | Local Creek 3 | Minimum Change | 0.00 | 0.00 | 0.00 | -0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Maximum Change | -0.24 | -0.17 | -0.12 | 0.05 | 0.10 | 0.15 | -1.52 | -1.10 | -0.56 | 0.61 | 0.78 | 0.85 |
| | Mill Brook | Minimum Change | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Maximum Change | -0.17 | -0.11 | -0.05 | 0.05 | 0.09 | 0.14 | -0.11 | -0.11 | -0.05 | 0.05 | 0.09 | 0.13 |
| | Little Salmonier River | Minimum Change | -0.02 | -0.01 | -0.01 | 0.01 | 0.01 | 0.02 | -0.02 | -0.01 | -0.01 | 0.01 | 0.02 | 0.03 |
| | | Maximum Change | -0.18 | -0.12 | -0.06 | 0.06 | 0.11 | 0.16 | -0.78 | -0.58 | -0.31 | 0.11 | 0.17 | 0.21 |
| | Shalloway Brook | Minimum Change | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Maximum Change | -0.21 | -0.13 | -0.06 | 0.07 | 0.13 | 0.18 | -0.21 | -0.13 | -0.06 | 0.07 | 0.12 | 0.18 |
| | Sound Brook | Minimum Change | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Maximum Change | -0.76 | -0.50 | -0.25 | 0.22 | 0.43 | 0.62 | -3.17 | -2.18 | -1.09 | 0.27 | 0.42 | 0.60 |
| | Local Creek 4 Reach 1 | Minimum Change | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Maximum Change | -0.12 | -0.08 | -0.04 | 0.03 | 0.07 | 0.10 | -0.09 | -0.06 | -0.03 | 0.03 | 0.05 | 0.08 |
| | Local Creek 4 Reach 2 | Minimum Change | -0.05 | -0.03 | -0.01 | 0.01 | 0.02 | 0.03 | -0.10 | -0.06 | -0.03 | 0.03 | 0.06 | 0.09 |
| | | Maximum Change | -0.10 | -0.07 | -0.03 | 0.03 | 0.06 | 0.09 | -0.22 | -0.13 | -0.06 | 0.05 | 0.09 | 0.13 |
| | Southeast River | Minimum Change | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.26 | 0.32 | 0.37 | 0.06 | 0.12 | 0.17 |
| | | Maximum Change | -0.39 | -0.25 | -0.12 | 0.11 | 0.22 | 0.32 | -0.39 | -0.25 | -0.12 | 0.46 | 0.50 | 0.54 |
| | Southeast River Tributary | Minimum Change | -0.07 | -0.04 | -0.02 | 0.02 | 0.04 | 0.06 | -0.07 | -0.04 | -0.02 | 0.02 | 0.04 | 0.06 |
| | | Maximum Change | -0.36 | -0.23 | -0.11 | 0.10 | 0.20 | 0.30 | -0.36 | -0.23 | -0.11 | 0.10 | 0.20 | 0.30 |
| | Northeast River | Minimum Change | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | -0.02 | -0.02 | -0.01 | -1.37 | -1.37 | -1.37 |
| | | Maximum Change | -0.41 | -0.26 | -0.13 | 0.12 | 0.23 | 0.33 | -1.37 | -1.37 | -1.37 | 0.13 | 0.24 | 0.35 |
| | Northeast River Tributary Reach 1 | Minimum Change | 0.05 | 0.04 | 0.02 | -0.02 | -0.04 | -0.07 | -0.01 | -0.01 | 0.01 | 0.00 | 0.01 | 0.01 |
| | | Maximum Change | -0.32 | -0.21 | -0.10 | 0.10 | 0.19 | 0.27 | -0.32 | -0.21 | -0.10 | 0.10 | 0.19 | 0.27 |
| | Northeast River Tributary Reach 2 | Minimum Change | -0.26 | -0.17 | -0.08 | 0.08 | 0.15 | 0.22 | -0.25 | -0.16 | -0.08 | 0.08 | 0.15 | 0.22 |
| | | Maximum Change | -0.32 | -0.21 | -0.10 | 0.09 | 0.18 | 0.27 | -0.32 | -0.21 | -0.10 | 0.09 | 0.18 | 0.27 |
| | Local Creek 5 | Minimum Change | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.02 |
| | | Maximum Change | -0.22 | -0.14 | -0.07 | 0.06 | 0.12 | 0.17 | -0.23 | -0.15 | -0.07 | 0.07 | 0.13 | 0.19 |

### TABLE 60: CARBONEAR AREA HEC-RAS MODEL SENSITIVITY

| Region | River | Change | Water Level Difference (m) | | | | | | Water Level Difference (m) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | n - 30% | n - 20% | n - 10% | n + 10% | n + 20% | n + 30% | Q - 30% | Q - 20% | Q - 10% | Q + 10% | Q + 20% | Q + 30% |
| Salmon Cove and Victoria | Big Brook | Minimum Change | -0.12 | -0.08 | -0.04 | 0.04 | 0.07 | 0.11 | -0.12 | -0.08 | -0.04 | 0.04 | 0.07 | 0.11 |
| | | Maximum Change | -0.27 | -0.18 | -0.09 | 0.08 | 0.15 | 0.22 | -0.29 | -0.19 | -0.09 | 0.08 | 0.16 | 0.22 |
| | Clark Brook | Minimum Change | 0.00 | -0.01 | 0.00 | 0.00 | 0.01 | 0.01 | -0.01 | -0.01 | 0.00 | 0.00 | 0.01 | 0.01 |
| | | Maximum Change | -0.10 | -0.07 | -0.03 | 0.03 | 0.06 | 0.09 | -0.23 | -0.17 | -0.07 | 0.07 | 0.14 | 0.20 |
| | Double Brook | Minimum Change | -0.02 | -0.01 | 0.00 | 0.00 | 0.01 | 0.01 | -0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Maximum Change | -0.14 | -0.09 | -0.04 | 0.05 | 0.09 | 0.13 | -0.29 | -0.19 | -0.04 | 0.05 | 0.15 | 0.21 |
| | Local Creek 1 | Minimum Change | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | -0.01 | 0.00 | 0.00 | 0.01 | 0.01 | 0.02 |
| | | Maximum Change | -0.07 | -0.04 | -0.02 | 0.02 | 0.03 | 0.04 | -0.08 | -0.04 | -0.19 | 0.03 | 0.05 | 0.06 |
| | Local Creek 2 | Minimum Change | -0.02 | -0.01 | 0.00 | 0.01 | 0.01 | 0.02 | -0.02 | -0.01 | 0.00 | 0.01 | 0.01 | 0.02 |
| | | Maximum Change | -0.18 | -0.12 | -0.06 | 0.06 | 0.12 | 0.18 | -0.18 | -0.12 | -0.06 | 0.06 | 0.12 | 0.18 |
| | Local Creek 3 | Minimum Change | -0.03 | -0.02 | -0.01 | 0.00 | 0.01 | 0.02 | -0.02 | -0.01 | 0.00 | 0.00 | 0.01 | 0.02 |
| | | Maximum Change | -0.29 | -0.19 | -0.09 | 0.09 | 0.17 | 0.25 | -0.30 | -0.19 | -0.10 | 0.09 | 0.17 | 0.26 |
| | Local Creek 4 | Minimum Change | 0.02 | 0.01 | 0.01 | -0.01 | -0.01 | -0.01 | -0.02 | -0.01 | 0.00 | 0.01 | 0.01 | 0.02 |
| | | Maximum Change | -0.08 | -0.05 | -0.02 | 0.03 | 0.05 | 0.07 | -0.32 | -0.22 | -0.11 | 0.14 | 0.31 | 0.39 |
| | Local Creek 5 | Minimum Change | -0.02 | -0.01 | 0.00 | 0.01 | 0.02 | 0.02 | -0.03 | -0.01 | 0.00 | 0.01 | 0.02 | 0.02 |
| | | Maximum Change | -0.23 | -0.15 | -0.07 | 0.07 | 0.13 | 0.19 | -0.25 | -0.16 | -0.08 | 0.07 | 0.14 | 0.20 |
| | Salmon Cove River | Minimum Change | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Maximum Change | -0.33 | -0.22 | -0.13 | 0.10 | 0.19 | 0.25 | -0.86 | -0.76 | -0.63 | 0.18 | 0.36 | 0.55 |
| | Spout Brook | Minimum Change | -0.03 | -0.02 | -0.01 | 0.01 | 0.02 | 0.03 | -0.09 | -0.05 | -0.02 | 0.02 | 0.05 | 0.07 |
| | | Maximum Change | -0.18 | -0.14 | -0.07 | 0.08 | 0.17 | 0.25 | -0.44 | -0.28 | -0.14 | 0.18 | 0.36 | 0.55 |
| Carbonear | Carbonear Local Creek | Minimum Change | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 |
| | | Maximum Change | -0.16 | -0.10 | -0.05 | 0.04 | 0.08 | 0.11 | -0.28 | -0.19 | -0.09 | 0.09 | 0.19 | 0.28 |
| | Local Creek 1 | Minimum Change | -0.01 | -0.01 | 0.00 | 0.00 | 0.00 | 0.01 | -0.02 | -0.01 | -0.01 | 0.01 | 0.01 | 0.02 |
| | | Maximum Change | -0.06 | -0.04 | -0.02 | 0.02 | 0.03 | 0.05 | -0.26 | -0.16 | -0.07 | 0.06 | 0.10 | 0.15 |
| | Local Creek 2 | Minimum Change | -0.01 | -0.01 | -0.01 | 0.00 | 0.00 | 0.01 | -0.01 | 0.00 | 0.01 | 0.00 | 0.01 | 0.01 |
| | | Maximum Change | -0.05 | -0.04 | -0.02 | 0.01 | 0.02 | 0.03 | -0.05 | -0.03 | -0.02 | 0.01 | 0.02 | 0.02 |
| | Island Pond Brook | Minimum Change | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | -0.05 | 0.00 |
| | | Maximum Change | -0.31 | -0.19 | -0.09 | 0.09 | 0.16 | 0.22 | -0.49 | -0.33 | -0.16 | 0.15 | 0.30 | 0.40 |
| | Powells Brook | Minimum Change | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Maximum Change | -0.29 | -0.19 | -0.11 | 0.08 | 0.16 | 0.23 | -0.79 | -0.59 | -0.33 | 0.29 | 0.42 | 0.50 |

The HEC-RAS sensitivity analyses showed that the models were generally not very sensitive to changes to roughness coefficients or flows, with water level changes generally less than 0.3 m in most locations associated with changes to roughness or flow of 30%. While there are areas with greater changes, these are generally located upstream of culvert or bridge crossings that are close to their maximum conveyance at the 100-year AEP flood. At these locations, small changes to the hydraulic conditions can result in the conveyance capacity of bridges or culverts being exceeded, causing water to back up until the road above the culverts or bridge is overtopped. Conversely, for culvert or bridge crossings that are slightly overtopped, small changes to the hydraulic conditions can result in the culvert or bridge conveyance not being exceeded, leading to a considerable reduction in water level upstream of the crossing.

In addition to the modest sensitivity of the HEC-RAS models to changes to either Manning's roughness coefficients or flow, it should be noted that changes to the flood levels by +/- 0.3 m generally do not have a significant impact on the flood extents, due to how steep the river valleys are in the study area. Accordingly, while the HEC-HMS models were found to be sensitive to changes to the SCS curve numbers, the sensitivity of those models are tempered by the relatively limited sensitivity of the HEC-RAS models to changes to flows. The potential impacts of the HEC-HMS model sensitivity are then further reduced by the mitigating nature of the steep river valley walls.

# 10.0 FLOOD RISK MAPPING

## 10.1 Overview

Once water levels on the various rivers and creeks were estimated for the 20 and 100-year AEP 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 within HEC-RAS 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 created within HEC-RAS 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 135.

FIGURE 135: OVERVIEW OF FLOOD RISK MAPPING

**Flood Risk Mapping**

**Flood Risk Maps**
- Mapping of flood extents defined by HEC-RAS
- Careful review and adjustment of flooded areas to remove hydraulically isolated areas
- Maps provided to communities for review on March 29 and March 30, 2022

**Flood Hazard Maps**
- Calculation of depth of flooding and mapping of velocities
- Application of adjustments made to flood risk maps to depth and velocity maps
- Calculation of flood hazard using a depth-velocity-hazard matrix

**Flooded Infrastructure Maps**
- Cursory assessment of flooded buildings based on available information

## 10.2 Flood Risk Maps

The calibrated hydraulic models described in Section 8.0 were used to simulate the 20 and 100-year AEP floods for the current climate and climate change conditions.

In the HEC-RAS extension RAS Mapper, water levels from the 1D portions of the hydraulic models were linearly interpolated between each cross section in the model to define a smooth, continuous surface, while water levels defined in 2D areas were output directly by the software. The RAS Mapper extension then overlays the 1D water levels on top of the bare earth DEM, as described in Section 4.4, to define the flooded areas within the 1D areas. The 1D flood extents are then merged seamlessly with the 2D flood extents.

The initial flooded areas output by RAS Mapper were carefully reviewed to identify any areas that are shown as flooded but hydraulically disconnected from the main flooded area. Any hydraulically isolated areas were removed from the mapping. The flood zones for the current climate and climate change conditions were then overlain on top of the detailed orthoimagery acquired from WRMD. Draft flood risk maps were provided to the Towns of Carbonear, Salmon Cove, Victoria and Placentia, as well as WRMD, for review. The maps were provided to the towns and WRMD digitally using Esri's ArcGIS Online tool to facilitate review, as it enables users to pan and zoom to any areas of interest.

Subsequent to the review of the maps by WRMD and the towns, the maps were updated based on comments received from WRMD and the towns. Hard copy and digital versions of the flood risk maps were also developed for dissemination to Placentia, Carbonear, Salmon Cove and Victoria. Each set of flood risk maps showed both the 20-year and 100-year flood zones, and consisted of 14 map sheets in Carbonear, 22 map sheets in Victoria and Salmon Cove, and 71 map sheets in Placentia showing the flood zones in developed areas. These maps are included in Appendix O. Maps showing the comparison between the historical flood risk with the flood risk defined as part of this study for the 20 and 100-year AEP floods are included in Appendix P.

The total flooded area in each community for each flood condition is summarized in Table 61. These flooded areas do not include areas beyond the present-day coastal shorelines, as those would not change under future conditions.

TABLE 61: COMPARISON OF FLOODED AREAS

| Climate Condition | AEP | Flooded Area (ha) Placentia | Carbonear | Victoria | Salmon Cove |
|---|---|---|---|---|---|
| Current Climate | 20-Year | 297.4 | 54.6 | 171.2 | 108.9 |
| Current Climate | 100-Year | 337.6 | 63.0 | 189.9 | 115.7 |
| Climate Change | 20-Year | 376.0 | 63.0 | 186.0 | 115.9 |
| Climate Change | 100-Year | 464.8 | 73.8 | 202.8 | 122.6 |

Shapefiles showing the extent of flooding for the 20 and 100-year AEP floods under current climate and climate change conditions have been provided separately to WRMD to facilitate the comparison of current climate and climate change conditions.

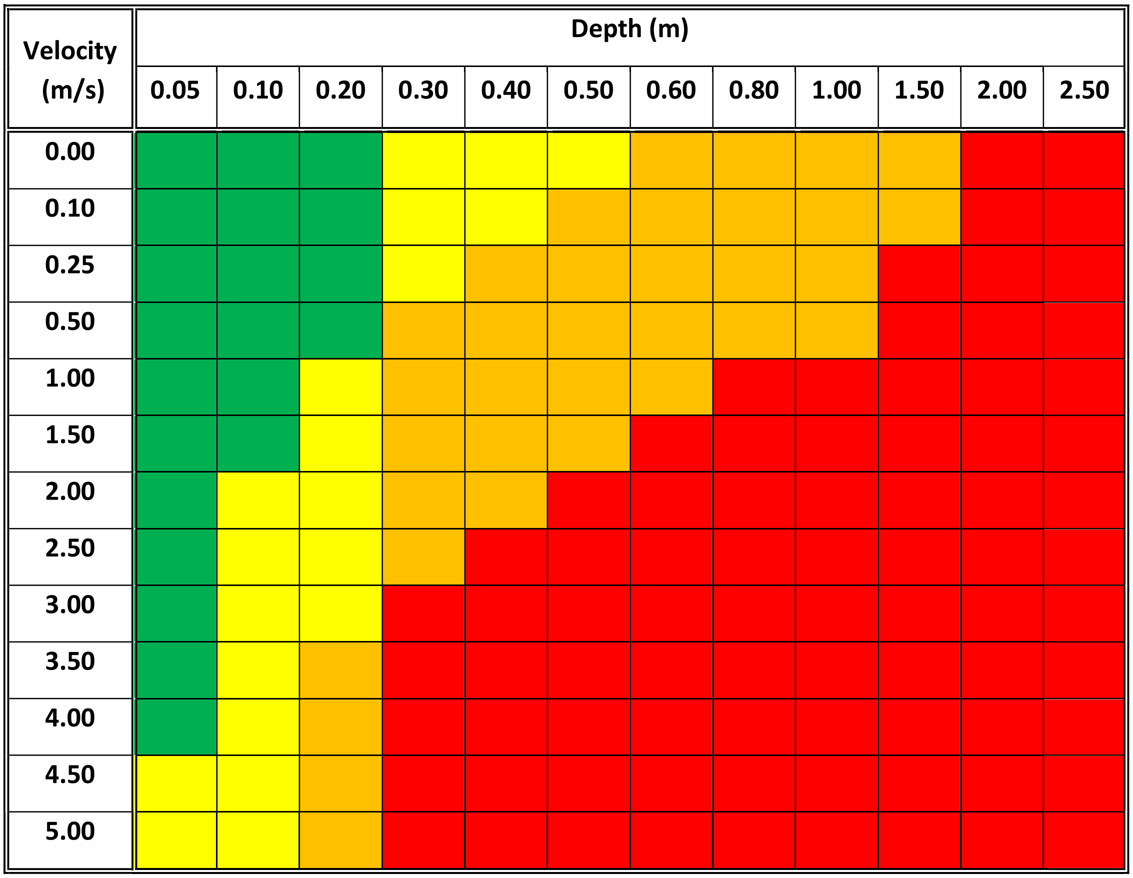
## 10.3 Flood Hazard Maps

In addition to the flood risk maps showing the total inundated area, digital mapping data were developed for the depth of flooding, velocity, and flood hazard for the 20 and 100-year AEP floods under current climate and climate change conditions. Any adjustments made to the flooding extents shown on the flood risk maps were similarly incorporated into the depth of flooding, velocity, and flood hazard maps.

The depth of flooding mapping data was generated directly by HEC-RAS in RASMapper. The software automatically subtracts the DEM elevation from the simulated water surface, producing a seamless, continuous raster of depth data. The velocity data was developed based on a combination of velocities in 2D areas directly output by HEC-RAS in RASMapper, and interpolated velocities within 1D areas of the models. In the 1D areas, velocities at cross sections were exported in the left overbank, main channel, and right overbank, which were then interpolated along the river reach. Breaklines were developed along the channel banks to differentiate between the channel and overbank velocities in the interpolation. The interpolated 1D velocities and directly output 2D velocities were then merged into a seamless, continuous surface.

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 and 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 136.

FIGURE 136: FLOOD HAZARD CLASSIFICATION




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

The depth of flooding, velocity, and flood hazard mapping data for the 20 and 100-year AEP floods for current climate and climate change conditions were provided separately to WRMD in a digital format. Overview maps showing the depth of flooding, velocity and flood hazard for the 20 and 100-year AEP floods for current climate and climate change conditions are included in Appendix Q.

## 10.4 Flooded Infrastructure

KGS Group completed a cursory assessment of buildings affected by the 20 and 100-year AEP floods in Placentia, Carbonear, Salmon Cove and Victoria. An initial assessment was completed by visually inspecting the flood risk maps and identifying any residences affected by the 20 and 100-year AEP floods for the current climate and climate change conditions.

Based on the assessment, the total number of flooded buildings that could be flooded for the 20 and 100-year AEP floods for current climate and climate change conditions are summarized in Table 62.

### TABLE 62: SUMMARY OF FLOODED BUILDINGS

| Town | Number of Flooded Buildings | | | |
|---|---|---|---|---|
| | Current Climate | | Climate Change | |
| | 20-Year AEP | 100-Year AEP | 20-Year AEP | 100-Year AEP |
| Placentia | 40 | 66 | 136 | 452 |
| Carbonear | 34 | 39 | 42 | 54 |
| Salmon Cove | 24 | 34 | 32 | 39 |
| Victoria | 7 | 15 | 12 | 25 |

In addition to the buildings impacted by flooding, there are two additional pieces of infrastructure that were identified as critical by both the representatives from the towns, as well as WRMD. Specifically, these include the flood wall in Placentia, and the wastewater lagoon dike in Victoria.

In Placentia, the flood wall was found to be high enough to provide protection to the community for the 20 and 100-year AEP storm surge under current climate conditions, and the 20-year AEP storm surge under climate change conditions. However, the flood levels associated with the 100-year AEP storm surge exceeded the height of the flood wall, resulting in flooding in the community. The level of freeboard associated with the 20 and 100-year AEP storm surge floods under current climate conditions, as well as the 20-year AEP storm surge under climate change conditions, should be reviewed to determine if an acceptable level of freeboard is provided. Enhancements to the flood wall should be made in the future to continue protecting the community under climate change conditions. Similarly, a study should be undertaken to evaluate the potential benefits associated with the construction of flood protection measures along the southern side of Placentia to prevent flooding from the Southeast Arm.

In Victoria, the crest of the wastewater lagoon dike, as estimated from the LiDAR data, is higher than the 20 and 100-year AEP flood levels under current climate and climate change conditions. However, there is potential for ice jam levels to nearly exceed the wastewater lagoon dike crest. While it is difficult to attribute a likelihood to the ice jam levels, they would be less likely than a 100-year AEP event. However, given the high consequences associated with overtopping of the dike, the dike crest should be surveyed, and the level of freeboard evaluated for the open water flood conditions to ensure that there is sufficient freeboard. Consideration should also be given to the potential impacts of ice jamming in the vicinity of the wastewater lagoon.

# 11.0 DEVELOPMENT OF A FLOOD FORECASTING STRATEGY

## 11.1 Overview

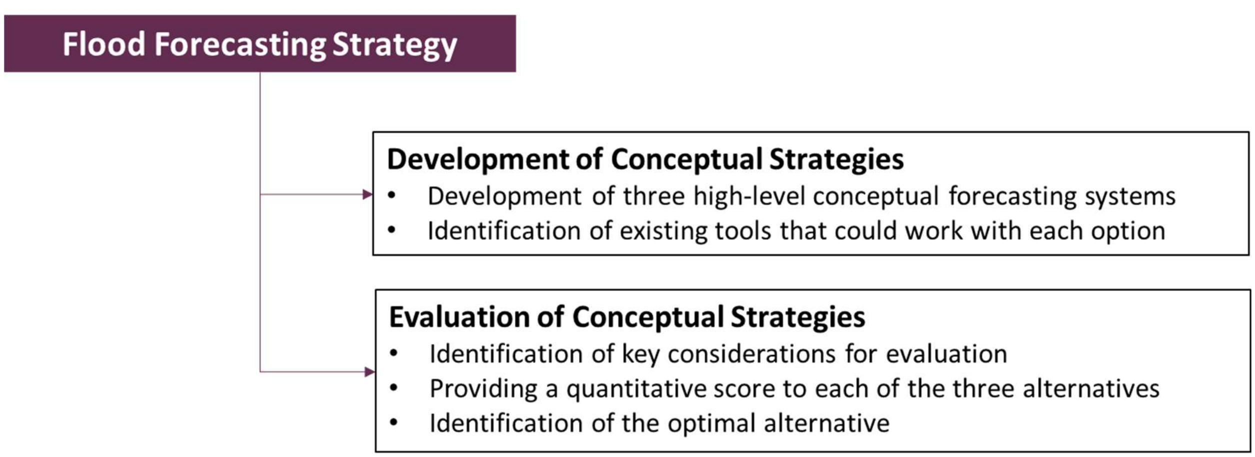
To support any future development and implementation of a flood forecasting service in Placentia, Carbonear, Salmon Cove and Victoria, a series of high-level conceptual flood forecasting strategies were developed and evaluated. The conceptual flood forecasting strategies included:

- ***Option 1 –*** Leveraging and monitoring existing meteorological forecasting tools, storm surge prediction tools, and the Government of Newfoundland and Labrador's Hurricane Early Warning System.
- ***Option 2 –*** The development of a system to automatically monitor existing forecasting tools and systems, and to compare those forecast values to threshold values defined as part of this flood risk mapping study. The system would automatically send warnings to the Government of Newfoundland and Labrador if any of the forecast values exceed the threshold values.
- ***Option 3 –*** A fully integrated and automated forecasting system that would generate hydrologic, hydraulic, and storm surge forecasts based on existing meteorological forecasts. In addition to generating the hydrologic, hydraulic, and storm surge forecasts, the system would compare forecast values to threshold values, and would automatically alert the Government of Newfoundland and Labrador if those forecast values exceed the thresholds.

Following the development of the conceptual options, each option was evaluated based on a set of considerations that would be required to implement each system, such as costs and the effort to maintain and operate each system.

An overview of the forecasting strategy development task is shown on Figure 137.

FIGURE 137: OVERVIEW OF THE FLOOD FORECASTING STRATEGY TASKS



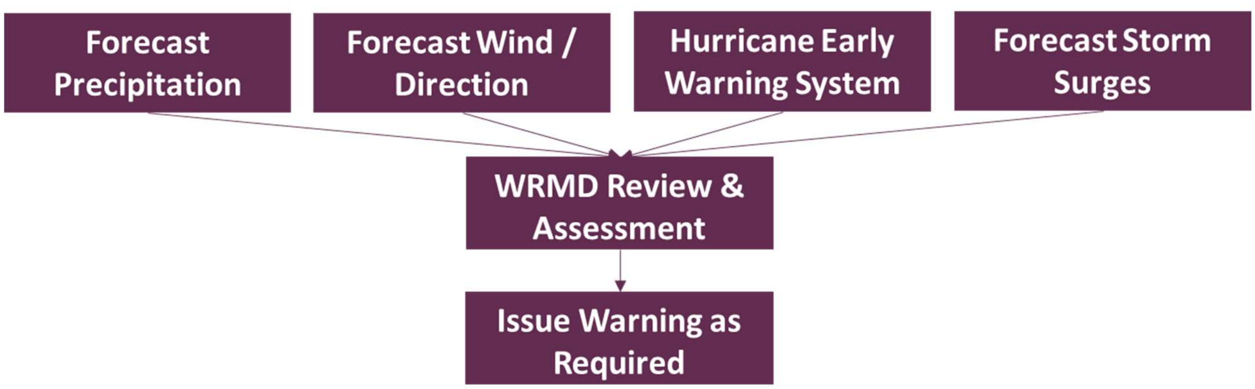
## 11.2 Development of Conceptual Strategies

Three high-level conceptual flood forecasting strategies were developed for the communities of Placentia, Carbonear, Salmon Cove and Victoria, ranging in complexity from manual monitoring of existing meteorological and storm surge forecasts generated by other governmental agencies to a fully automated forecasting system that processes forecast meteorological data to generate flood levels throughout each community. These three conceptual flood forecasting strategies are described further, below.

### 11.2.1 FORECASTING STRATEGY OPTION 1

The first forecasting strategy option consists of supplementing the current forecast monitoring completed by the Government of Newfoundland and Labrador to leverage additional forecasting tools developed by other agencies, such as ECCC. This option requires that government personnel manually acquire and review precipitation, wind, and storm surge forecasts. These forecast values can then be compared to reference values defined as part of this flood risk mapping study, such as the 20 or 100-year AEP rainfall volumes, to identify any forecast conditions that could result in flooding. This option is represented conceptually on Figure 138.

FIGURE 138: FORECASTING STRATEGY OPTION 1



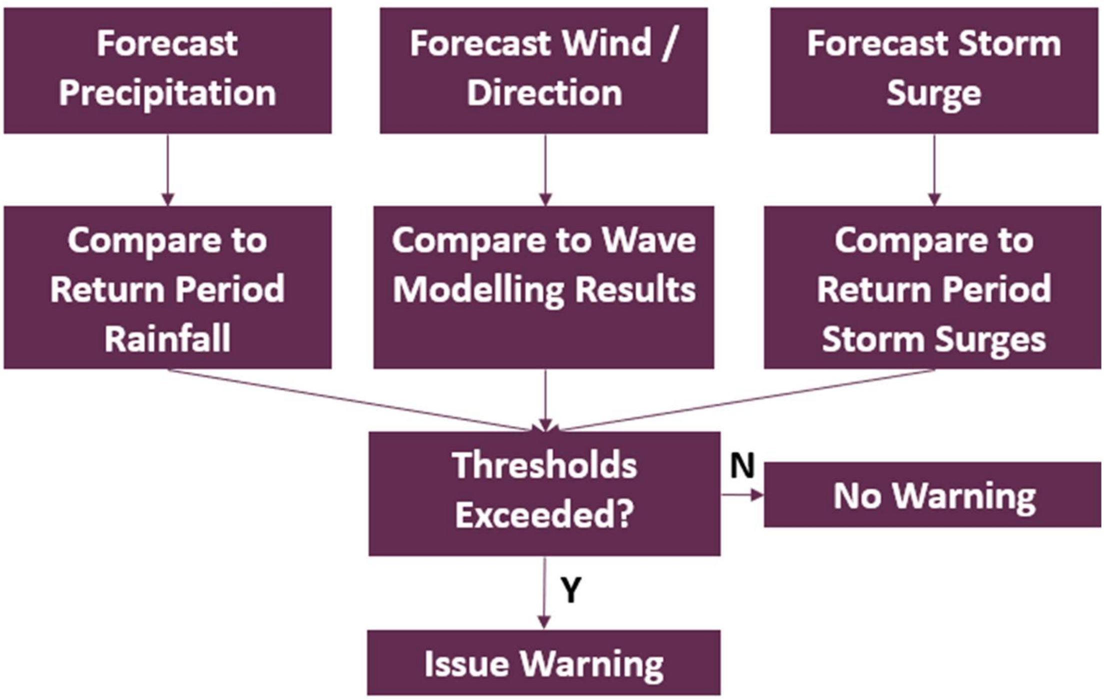

As well, this option would continue to leverage the Government of Newfoundland and Labrador's Hurricane Early Warning System, which provides monitoring and forecasting of post-tropical depressions and hurricanes as they are forecast to pass through Newfoundland and Labrador during the north Atlantic hurricane season. Given that the majority of flooding in Placentia, Carbonear, Salmon Cove and Victoria result from storm surges and/or significant precipitation events, the Hurricane Early Warning System can provide early warning for a number of events that could result in flooding in the communities. Additional tools that could be monitored by government personnel include:

- ECCC forecast storm surge data, including from the Global Deterministic Storm Surge Prediction System and the Regional Ensemble Storm Surge Prediction System,
- ECCC forecast meteorological data, including the Global Deterministic Prediction System and Numerical Weather Prediction data, and
- Forecast hurricane and cyclone paths developed by the U.S. National Oceanic and Atmospheric Administration's National Hurricane Center.

### 11.2.2 FORECASTING STRATEGY OPTION 2

The second forecasting strategy consists of developing an automated system to automatically retrieve and process forecast storm surge, precipitation and wind data. This would require the custom development of software to automatically retrieve the data from the various forecast sources, such as ECCC, as well as means to process those forecasts such that they could automatically be compared to threshold storm surges and precipitation values that are anticipated to result in flooding, as identified as part of this study. In the event that any of the forecasts exceed thresholds at which flooding would be expected, the system would automatically notify Government of Newfoundland and Labrador personnel of the potential for flooding. This option is represented conceptually on Figure 139.

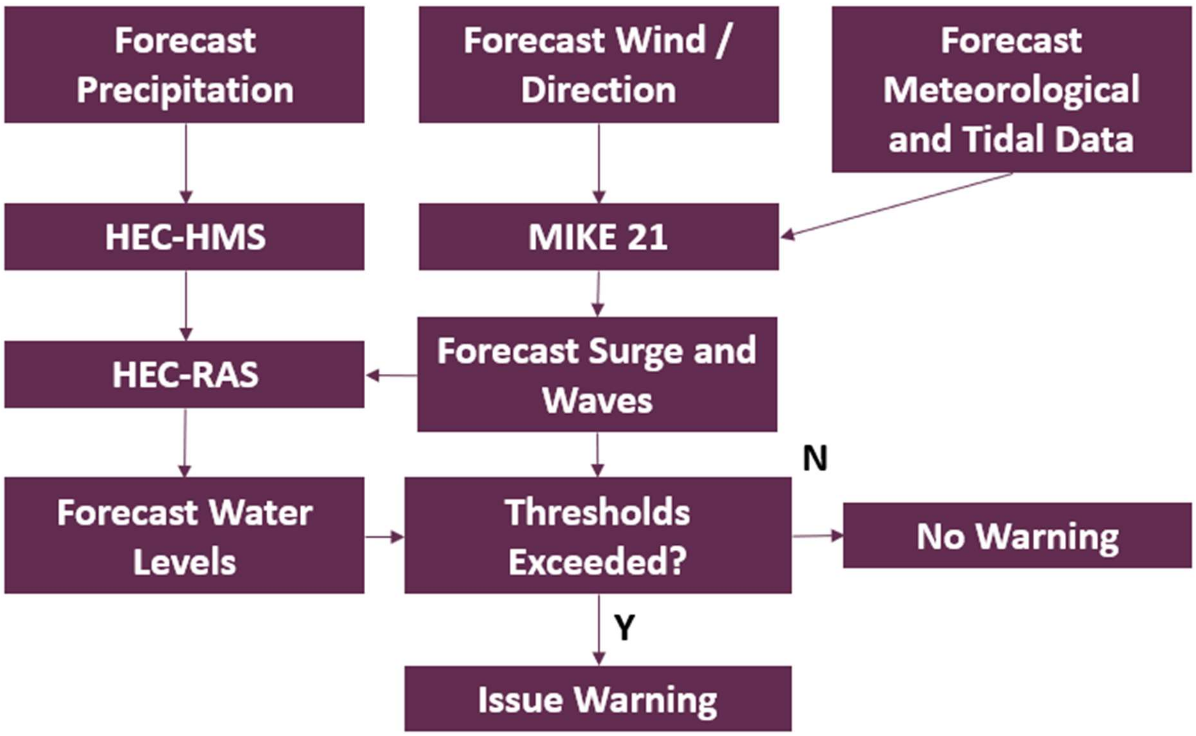
FIGURE 139: FORECASTING STRATEGY OPTION 2




### 11.2.3 FORECASTING STRATEGY OPTION 3

The third and most complex forecasting strategy consists of the adjustment of the hydrologic and hydraulic models to work in a forecasting capacity, and the integration of those systems into an automated framework that acquires forecast meteorological data, processes it into a format suitable for the hydrologic and hydraulic models, and then runs the models to generate river flows, river levels, and storm surge levels. Specifically, this would require acquiring and processing precipitation data from ECCC for use in the hydrologic model to generate forecast river flows, the acquisition of forecast atmospheric pressure data, wind data, and forecast tidal data for inclusion in the MIKE 21 model to generate forecast storm surge levels, and the integration of the forecast river flow and storm surge levels into the HEC-RAS models. Customized software would be required to integrate these separate models into one seamless package. As well, some adjustments to the models would be warranted both to ensure that they work as expected in a forecasting capacity, as well as potential simplifications to the models to ensure a feasible model run time. Regardless of model simplification, considerable computational power would be required to simulate and process all of the models in a reasonable timeframe, as both the coastal and riverine hydraulic models contain considerable 2D areas, which can be computationally expensive. Further software development would be required to extract results from the simulations for presentation and comparison to threshold storm surge and river flood levels, such that if the thresholds are exceeded, an automated warning is issued to government personnel. This option is shown conceptually on Figure 140.

FIGURE 140: FORECASTING STRATEGY OPTION 3




## 11.3 Evaluation of Conceptual Strategies

A qualitative evaluation of the three flood forecasting strategies was completed. As part of the evaluation, the following criteria were considered:

- Development costs,
- Maintenance costs,
- WRMD operational effort,
- Computational cost, and
- Forecast level of detail.

Each of the three conceptual flood forecasting strategies were compared for each category to identify which option performed best, which performed worst, and which was neither best nor worst.

The development costs associated with Option 3 were found to be most substantial, as considerable development work would be required to develop the various forecasting models, as well as a system to automatically acquire and process inputs to the models, and process the forecast simulation results. Option 1 was found to require the least amount of development cost, as it leverages existing forecasting tools and systems. Option 2 would require more cost than Option 1, but less cost than Option 3, as the system would only monitor existing forecasting systems.

Similar to development costs, Option 3 was found to require the most maintenance costs, which are ongoing expenses to ensure that the system and subsystems are accurate and up to date. Considerable effort would be required to monitor the performance of the various models generating forecasts, as well as the automated system that acquires data and generates the forecasts. Option 1 would require no maintenance costs, as the system relies on manual review of existing forecasting tools developed and maintained by others. Option 2 would require some maintenance costs to ensure that the automated monitoring systems work consistently and as expected.

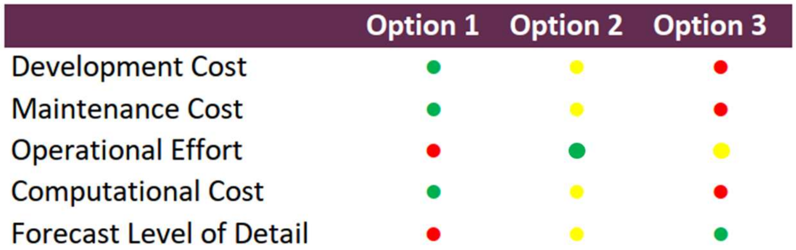
The operational effort associated with each of the options, which consists of the time spent by Government of Newfoundland and Labrador personnel in the day-to-day operation of the system, would be least with Option 2, as the system would automatically monitor existing forecasts and automatically warn government personnel as required. Option 1 would require the most effort, as government personnel would be responsible for acquiring and reviewing forecasts on an ongoing basis. Option 3 would require moderate effort, as more effort would be required reviewing and scrutinizing the results of the system to ensure that they are reasonable.

Computational cost, which represents the complexity of the calculations being completed by the forecasting system options, would be least with Option 1, as government personnel would be manually reviewing existing forecasts and forecasting tools. Option 3 would be most computationally expensive, as the system would need to complete a number of hydrologic, hydraulic, and storm surge simulations in a short period of time. Option 2 would require a moderate level of computational cost to acquire and process existing forecast results, and compare them to key threshold values.

Lastly, the forecast level of detail would be greatest with Option 3, as the system would generate flood levels at all locations assessed as part of this study. With Option 1, the level of detail would be relatively low, instead providing government personnel with forecast information on anticipated rainfall volumes and rates, forecast storm surge, and forecast winds. Option 2 would provide more detail than Option 1, and considerably less than Option 3, as forecast values could be automatically compared to key threshold values from this study to estimate levels at key locations. However, a high level of forecast detail may only provide limited benefit relative to lower levels of detail, as flooding in Placentia, Carbonear, Salmon Cove and Victoria are largely driven by large rainfall events, post-tropical depressions, and high wind conditions, all of which are relatively well forecast.

The resulting evaluation of the three conceptual options is shown schematically on Figure 141.

**FIGURE 141: QUALITATIVE EVALUATION OF FLOOD FORECASTING STRATEGIES**




Based on the evaluation of the alternatives, Option 1, which consisted of leveraging and monitoring existing forecasting tools, was found to be the best strategy. The options and evaluation were reviewed with WRMD, whom concurred that Option 1 was most suitable.

# 12.0 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***

- The Island Pond Brook, Powells Brook, Salmon Cove River, and Salmon Cove River tributary watersheds would experience similar hydrologic responses to rainfall as the Shearstown Brook watershed. Similarly, the various watersheds near Placentia considered as part of this study would experience similar hydrologic responses as the Northeast River watershed.
- Evapotranspiration, surface storage, and canopy storage were assumed to have a negligible impact on short (i.e. 24-hour or less) rainfall events.
- Twenty five percent of the Glennons Cove River is conveyed to Smelt Brook at the bifurcation of the river.
- The 20 and 100-year AEP rainfall events based off on the IDF curve at Argentia would be representative throughout the various watersheds that drain into Placentia. Similarly, the 20 and 100-year AEP rainfall events based on the IDF curve at St. John's would be representative of rainfall in Carbonear, Salmon Cove and Victoria.

***Assumptions in Climate Change and Future Development Assessment***

- Future climate conditions will match those defined by the RCP 8.5 climate change scenario.
- Changes in future land use were assumed based on available development plans. It has been assumed that any future developments will be completed within a 'no net increase to flow' framework.

***Assumptions in Hydraulic Modelling***

- Channel bathymetry below the water surface in the LiDAR was interpolated assuming an interpolated depth of water between the LiDAR surface and the surveyed channel invert between surveyed cross sections.
- The depth of the ponds on Salmon Cove River, Island Pond Brook and Local Creek 3 in Placentia were assumed based on nearby surveyed cross sections.
- Water taken for municipal use were considered to be negligible relative to the 20 and 100-year AEP flows.
- The size of a number of culverts located outside of the main flow paths in 2D areas were estimated based on available imagery. Similarly, the inverts of those culverts were estimated from the LiDAR data.
- The riverine hydraulic models assumed steady state conditions, with the peak flows defined by the hydrologic models being held at a steady state.
- The 20 and 100-year river flows were assumed to occur concurrently with the 20 and 100-year storm surge levels in coastal areas.
- Sufficient ice volumes were assumed to allow for ice jamming on Island Pond Brook, Powells Brook and Salmon Cove River to accumulate to the upstream boundaries of those models.

- The ice jams on Island Pond Brook, Powells Brook and Salmon Cove River were assumed to occur during the passage of the 100-year ice-affected flow.

***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.
- The flood wall in Placentia will continue to be in place as-is under climate change conditions.

# 13.0 CONCLUSIONS

The following conclusions can be made from the climate change flood risk mapping study for Placentia, Carbonear, Salmon Cove and Victoria:

- Flows on the various rivers and creeks representative of the 20 and 100-year AEP floods were estimated using SSFA, RFFA, and hydrologic modelling methods.
- Hydrologic models were developed for the watersheds that drain into Placentia, Carbonear, Salmon Cove and Victoria. Initial model parameters were defined based on available physiographic data, and were adjusted to represent estimated flows from nearby gauged rivers.
- The 20 and 100-year AEP flows defined via hydrologic modelling were found to be the most appropriate, and were adopted for inclusion in the hydraulic modelling.
- Impacts to flows and water levels were estimated for the end of the century based on available climate change studies. The 20 and 100-year AEP flood flows are anticipated to increase by between 15% to 50% under climate change conditions. Sea levels are anticipated to rise by 0.62 m in Placentia and 0.63 m in Salmon Cove and Carbonear.
- Riverine hydraulic models were developed for the various rivers and creeks assessed as part of this study. The models consisted of 1D flow areas, 2D flow areas, and coupled 1D/2D flow areas. Where available, models were calibrated to water levels recorded by either WSC or as part of the field program completed as part of this project. The calibrated models were then used to simulate the 20 and 100-year AEP flood flows to define the 20 and 100-year AEP flood levels under current climate and climate change conditions.
- Ice jam models were developed for Salmon Cove River, Island Pond Brook and Powells Brook based on extracted cross sections from the bare earth DEM. The models were initially calibrated to open water conditions. Unrealistically high Manning's roughness coefficients were required in many of the models to maintain numerical stability, as RIVICE is unable to represent critical or supercritical flow. The models were then used to simulate the aggradation of ice jams throughout the model domain under the passage of the 100-year AEP ice affected flow. The ice jam levels exceeded open water levels in certain locations, however on Island Pond Brook and Powells Brook these levels were considered to be unrealistic.
- Coastal modelling was completed at two scales, one representative of the north Atlantic region, and the other representing highly detailed areas in Placentia Bay and Conception Bay. The regional coastal model was calibrated and validated to available historical tidal gauge data, and used as inputs to the Placentia Bay and Conception Bay models, which were similarly calibrated and validated to available historical tidal data.
- The calibrated coastal models were used to complete hindcast simulations of the coastal environment from 1980 to 2020. Storm surge data were extracted at key locations throughout the study domain, and statistical analyses were completed to define the 20 and 100-year AEP storm surge heights.
- Wave modelling was completed in Placentia, Carbonear and Salmon Cove considering the MSC50 offshore wave and wind conditions. Representative sections of coastline were extracted, and in combination with the wave model results, were used to calculate wave uprush heights throughout the study areas.

- Flood risk maps were developed for current climate and climate change conditions in Placentia, Carbonear, Salmon Cove and Victoria. The mapping deliverables included 142 map sheets in Placentia, 28 map sheets in Carbonear, and 44 map sheets in Victoria and Salmon Cove, as well as digital data showing the depth of flooding, flow velocities, and flood hazard in each of the communities.
- Several buildings are affected by flooding in Placentia, Carbonear, Salmon Cove and Victoria under current climate conditions.
  - In Placentia, there are 40 and 66 buildings that are flooded by the 20 and 100-year AEP floods under current climate conditions, which increase to 136 and 452 buildings flooded by the 20 and 100-year AEP floods under climate change conditions. The significant increase in flooded buildings associated with the 100-year AEP flood under climate change conditions is due to the flood wall in Placentia being overtopped.
  - In Carbonear, there are 34 and 39 buildings that are flooded by the 20 and 100-year AEP floods under current climate conditions, which increase to 42 and 54 buildings flooded by the 20 and 100-year AEP floods under climate change conditions.
  - In Salmon Cove, there are 24 and 34 buildings that are flooded by the 20 and 100-year AEP floods under current climate conditions, which increase to 32 and 39 buildings flooded by the 20 and 100-year AEP floods under climate change conditions.
  - In Victoria, there are 7 and 15 buildings that are flooded by the 20 and 100-year AEP floods under current climate conditions, which increase to 12 and 25 buildings flooded by the 20 and 100-year AEP floods under climate change conditions.
- The flood wall in Placentia was found to provide protection to the town for the 20 and 100-year AEP floods under current climate conditions, as well as the 20-year AEP flood under climate change conditions. However, the 100-year AEP flood under climate change conditions was found to exceed the height of the flood wall and flood the community.
- The wastewater lagoon in Victoria was found to have a sufficiently high dike to protect the lagoon from the 20 and 100-year AEP floods under current climate and climate change conditions. However, the simulated ice jam levels at the wastewater lagoon are very close to the dike crest apparent in the LiDAR data, although the ice jam levels represent a condition less likely than a 100-year AEP ice jam.
- Three high-level conceptual flood forecasting strategies were developed for the communities of Placentia, Carbonear, Salmon Cove and Victoria, ranging from enhanced manual monitoring of existing forecasts to a fully integrated and automated forecasting system. It was found that enhancing the Government of Newfoundland and Labrador's existing monitoring with additional existing forecasting services was the optimal solution.

# 14.0 RECOMMENDATIONS

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

- The community of Placentia has expressed a desire to hold a meeting with the Government of Newfoundland and Labrador to review the potential policy implications associated with the updated flood maps. The Government of Newfoundland and Labrador should organize and attend this meeting with representatives from Placentia to review the policy implications of the updated flood maps.
- The communities of Placentia, Carbonear, Salmon Cove and Victoria should adopt development policies to ensure that any developments do not result in net increases in flow on the rivers and creeks near the proposed developments.
- The vertical datum for WSC station 02ZK002 (i.e. Northeast River near Placentia) is currently a local datum, which has been adjusted to a geodetic datum for this study based on surveyed benchmarks for the gauge. The hydrometric station should be updated to report the water levels in the CGVD 2013 datum.
- The rainfall station at Argentia was taken out of service in 2017, and as such there are no ongoing precipitation measurements being collected in Placentia. A new meteorological station should be installed in Argentia or Placentia to enable the collection of meteorological data in the region.
- Limited meteorological data is available in Carbonear, Salmon Cove and Victoria. A meteorological station should be installed in one of the communities to enhance the understanding of the hydrology in the area.
- In the Placentia area, there is limited information available regarding the hydrology of small creeks, as the only gauged river in the area is Northeast River. Accordingly, a hydrometric monitoring station should be installed on a smaller creek in the region, such as Rattling Brook or Baldwins Brook.
- There are no hydrometric gauging stations on any of the rivers and creeks in Carbonear, Salmon Cove and Victoria. To further enhance the understanding of the hydrology in the area, a hydrometric monitoring station should be installed on either Island Pond Brook near Carbonear Collegiate or on Salmon Cove River north of Old Neck Road.
- The flood wall in Placentia was found to be high enough to provide protection for the 20 and 100-year AEP flood levels under current climate conditions, and the 20-year AEP flood under climate change conditions. However, the flood wall crest is exceeded by the 100-year AEP flood under climate change conditions. Accordingly, an evaluation of the flood wall elevation, including considerations for freeboard, should be completed considering the acceptable level of risk and consequences associated with the flood wall being overtopped, and any proposed upgrades to the flood wall from that evaluation should be implemented to continue to protect the community into the future.
- A study should be completed to identify and evaluate the potential costs and benefits associated with providing flood protection along the southern extent of Placentia along Southeast Arm to provide protection to the community from high storm surge levels intruding into the town.
- The dike surrounding the wastewater lagoon in Victoria should be surveyed to confirm the dike crest elevation relative to the flood levels described in this study, as well as an evaluation of the level of freeboard and acceptable level of risk. Considerations in that study should also consider the potential

for ice jam levels higher than open water flood levels, although care should be given to the acceptable level of risk associated with ice jamming.

# 15.0 REFERENCES

1. AMEC Environment & Infrastructure (2014). *Regional Flood Frequency Analysis for Newfoundland and Labrador*. Burlington, ON: AMEC Environment & Infrastructure.

2. Batterson, M. and Liverman, D. (2010). Past and Future Sea-Level Change in Newfoundland and Labrador: Guidelines for Policy and Planning. *Current Research. Newfoundland and Labrador, Department of Natural Resources, Geological Survey 10*(1), 129-141. DOI: 10.13140/RG.2.2.23283.07209

3. Canadian Geodetic Survey. (2019). NAD83(CSRS) v7. Retrieved from https://webapp.geod.nrcan.gc.ca/geod/tools-outils/nad83-docs.php

4. USACE (2006). *Coastal Engineering Manual.* Washington, D.C.: U.S. Army Corps of Engineers. Retrieved from http://app.knovel.com/hotlink/toc/id:kpCEM0000P/coastal-engineering-manual.

5. Conestoga-Rovers & Associates (2015). *Intensity-Duration-Frequency Curve Update for Newfoundland and Labrador.* Mount Pearl, NFLD: Conestoga-Rovers & Associates.

6. Dupont, F., Hannah, C. G., Greenberg, D. A., Cherniawsky, J. Y., & Naimie, C. E. (2002). *Modelling system for tides for the Northwest Atlantic coastal ocean* (Vol. 221, pp. vii+-72). Fisheries & Oceans Canada, Maritimes Region, Ocean Sciences Division, Coastal Ocean Science Section, Bedford Institute of Oceanography.

7. Finnis, J. and Daraio, J. (2018). *Projected Impacts of Climate Change for the Province of Newfoundland and Labrador:* 2018 Update. St. John's, NL: Memorial University of Newfoundland.

8. James, T. S., Robin, C., Henton, J., & Craymer, M. (2021). Relative sea-level projections for Canada based on the IPCC Fifth Assessment Report and the NAD83v70VG national crustal velocity model. *Geological Survey of Canada: Ottawa, ON, Canada*.

9. Rollings, K. (1999). *Regional Flood Frequency Analysis for the Island of Newfoundland*. Government of Newfoundland and Labrador, Department of Environment and Labour, Water Resources Management Division, Hydrologic Modelling Section.

10. Sheikholeslami, R., Yassin, F., Lindenschmidt, K.-E. and Razavi, S. (2017). Improved Understanding of River Ice Processes Using Global Sensitivity Analysis Approaches. *Journal of Hydrologic Engineering* 22(11): 04017048. DOI: 10.1061/(ASCE)HE.1943-5584.0001574

11. Swail, V. R., Cardone, V. J., Ferguson, M., Gummer, D. J., Harris, E. L., Orelup, E. A., & Cox, A. T. (2006, September). The MSC50 wind and wave reanalysis. In *Proceedings of the 9th International Workshop on Wave Hindcasting and Forecasting* (Vol. 25, p. 29). Victoria, BC, Canada.

12. Turcotte, B., Burrell, B., and Beltaos, S. (2019). The Impact of Climate Change on Breakup Ice Jams in Canada: State of Knowledge and Research Approaches. In Proceedings of the 20th Workshop on the Hydraulics of Ice Covered Rivers 2019. Ottawa, Ontario: Committee on River Ice Processes and the Environment.

13. Uden, M. and Hall, H. (2007). Application of Remote Sensing (Digital Terrain Models) in Flood Risk Assessments. *Proceedings of the National Hydrology Seminar 2007: GIS in Hydrology* (1 – 8). Tullamore, Ireland: Irish National Committees, International Hydrological Programme, International Commission on Irrigation & Drainage.

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