



GOVERNMENT OF NEWFOUNDLAND AND LABRADOR

Climate Change Flood Risk Mapping Study for Ferryland, Brigus, Heart's Delight-Islington, Winterton and Hant's Harbour

Revision:
Final / Rev 0

KGS Group Project:
22-3217-002

Date:
December 19, 2025



Government
of Canada

KGS
GROUP

PREPARED BY:

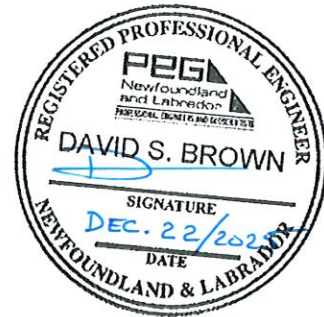


Andrew Weiss, M.Sc., P.Eng.
Water Resources Modelling Lead

APPROVED BY:



David S. Brown, M.Eng., P.Eng.
Principal – Water Management



PROVINCE OF NEWFOUNDLAND AND LABRADOR



PERMIT HOLDER
This Permit Allows

KONTZAMANIS GRAUMANN SMITH MACMILLAN
MIRC WINNIPEG WATER RESOURCES - 07361

To practice Professional Engineering
In Newfoundland and Labrador.
Permit No. as issued by PENGL N0687
which is valid for the year 2025

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 Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour. The engineering study included the development of detailed hydraulic and hydrologic models to serve as the basis for the flood risk mapping. This project was funded in part by the Government of Canada.

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 Trinity Bay, Conception Bay, and the eastern coast of the Avalon Peninsula, 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 Ferryland, Brigus, Heart's Delight – Islington, Hant's Harbour, and Winterton. N.E. Parrott 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.

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 Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour. 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 Ferryland, Brigus, Heart's Delight – Islington,

Winterton and Hant's Harbour. 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 Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour.
- **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 Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour 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 Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour. 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 Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour were added to the inventory.

Field Program

A detailed field program was completed to capture critical topographic and bathymetric data in Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour, 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 fifty-four river cross sections were surveyed in the study area, with an additional 33 bathymetric cross sections surveyed along the shoreline in Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour. Culvert and bridge details were surveyed for 92 crossings throughout the study area. Water level monitoring equipment was deployed at five locations throughout the study area, specifically on Quarry River in Ferryland, Lambes Brook in Brigus, Heart's Delight Brook in Heart's Delight – Islington, Western Pond Brook in Winterton, and Shorts Brook in Hant's Harbour. Flow measurements were collected on those 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 Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour 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, leveraging a recently completed regional flood frequency analysis for the southeast region of Newfoundland, and the development and calibration of detailed hydrologic models of the Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour areas. Recently completed analyses of precipitation in the study area were and updated existing intensity-duration-frequency curves representative of the current climate, as well climate change intensity-duration-frequency curves, were used to define the 20 and 100-year AEP rainfall events in the study area. These rainfall events 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 27% to 30% in Ferryland, 23% to 31% in Brigus, 30% to 36% in Heart's Delight – Islington, 17% to 21% in Winterton, and 21% to 25% in Hant's Harbour by the end of the 21st century. Similarly, coastal water levels are projected to increase by 0.63 m in Brigus, Heart's Delight – Islington, Winterton, and Hant's Harbour, and by 0.66 m in Ferryland due to the anticipated sea level rise.

Hydraulic Investigations and Modelling

Coastal and riverine hydraulic models were developed in Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour using MIKE 21 and HEC-RAS. The coastal models, which were developed to simulate storm surge and near-shore wave conditions, consisted of a large, north Atlantic region model, as well as three high resolution models of Trinity Bay, Conception Bay, and the eastern coast of the Avalon Peninsula. 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. Wave models were used to define near-shore wave conditions, which were then translated to wave uprush heights at a number of locations in each community.

Riverine hydraulic models were developed for the various rivers and creeks assessed as part of this study, and consisted two-dimensional hydrodynamic 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 Western Pond Brook in Winterton, Heart's Delight Brook in Heart's Delight – Islington, and Halfway Brook in Hant's Harbour using RIVICE. The models were calibrated to open water conditions, but historical ice jam data was unavailable to calibrate the model to ice jam conditions. 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. The RIVICE models were unable to define a stable ice cover for Halfway Brook and Western Pond Brook due to the very steep and narrow nature of those rivers, suggesting that the potential for ice jamming may be limited. On Heart's Delight Brook, the resulting ice jam profile was higher than the 100-year AEP open water profile. However, the ice jam levels were considered to be unrealistic given a number of assumptions required to maintain the numerical stability of the model, as well as the assumed volume of ice available to form a jam, and as such was not integrated into the resulting flood hazard maps.

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 in Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour 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 risk 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 risk 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 in Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour. 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.

TABLE OF CONTENTS

1.0 INTRODUCTION	1
1.1 Background	1
1.2 Study Goals and Objectives.....	2
1.3 Scope of Work.....	8
2.0 BACKGROUND INFORMATION REVIEW	9
2.1 Overview	9
2.2 Data Collection.....	9
2.3 Data Analysis.....	10
2.4 Community Meetings.....	10
2.5 Analysis of Historical Flooding	12
3.0 FIELD PROGRAM.....	14
3.1 Overview	14
3.2 Field Survey	15
3.2.1 Projections and Survey Control.....	15
3.2.2 Topographic and Bathymetric Survey.....	22
3.2.3 Survey of Water Crossings	28
3.2.4 Survey Processing.....	33
3.3 Flow and Water Level Monitoring Program.....	33
3.4 HRDEM Quality Control.....	41
3.5 Field Verification	42
4.0 AERIAL PHOTOGRAPHY AND DIGITAL ELEVATION MODEL DEVELOPMENT	43
4.1 Overview	43
4.2 Acquisition of HRDEM Data and Aerial Photography	44
4.3 Development of Watershed Digital Elevation Model	44
4.4 Development of Flood Plain Digital Elevation Model	47
5.0 REMOTE SENSING AND LAND USE CLASSIFICATION.....	51
5.1 Overview	51
5.2 Acquisition and Processing of Remote Sensing Imagery	52

5.3 Land Use Classification.....	53
5.4 Soils Classification	58
5.5 Curve Number Mapping.....	63
6.0 HYDROLOGIC INVESTIGATIONS AND MODELLING.....	68
6.1 Overview	68
6.2 Stochastic Analyses	69
6.2.1 Single Station Frequency Analyses.....	69
6.2.2 Regional Flood Frequency Analyses.....	78
6.3 Rational Method Analyses	89
6.4 Deterministic Analyses.....	91
6.4.1 Model Development	91
6.4.2 Model Calibration	98
6.5 Precipitation Analysis.....	102
6.5.1 Existing Conditions IDF Curves.....	102
6.5.2 Climate Change IDF Curves	104
6.6 Definition and Routing of the 1:20 and 1:100 AEP Rainfall Events.....	105
6.7 Adopted 1:20 and 1:100 AEP Flows	110
7.0 CLIMATE CHANGE AND FUTURE DEVELOPMENT.....	113
7.1 Overview	113
7.2 Climate Change Assessment	114
7.2.1 River and Creek Flows	114
7.2.2 Sea Level Rise	118
7.2.3 Storm Surge and Waves	120
7.2.4 River Ice.....	126
7.3 Future Development Conditions.....	127
8.0 HYDRAULIC INVESTIGATIONS AND MODELLING	128
8.1 Overview	128
8.2 Coastal Modelling	129
8.2.1 Approach to Hydrodynamic Modelling.....	129
8.2.2 Available Data	133
8.2.3 Computational Mesh and Bathymetry.....	138

8.2.4 Hydrodynamic Model Setup and Validation	144
8.2.5 Definition of the 1:20 and 1:100 Coastal Flood Levels	159
8.2.6 Offshore Wave Conditions	174
8.2.7 Coastal Wave Modelling	181
8.2.8 Wave Uprush Calculation	188
8.3 Riverine Modelling	197
8.3.1 Model Development	197
8.3.2 Model Calibration	205
8.3.3 Hydraulic Modelling of the 1:20 and 1:100 AEP Floods	209
8.3.4 Assessment of Hydraulic Structure Capacities	211
8.4 Assessment of Potential Impacts due to River Ice	217
8.4.1 RIVICE Model Development	223
8.4.2 RIVICE Model Calibration	225
8.4.3 Ice-Affected Hydraulic Model Simulations	228
9.0 SENSITIVITY ANALYSES OF THE HYDROLOGIC AND HYDRAULIC MODEL INPUTS	230
9.1 Overview	230
9.2 Hydrologic Model Sensitivity	231
9.3 Hydraulic Model Sensitivity	233
10.0 FLOOD HAZARD MAPPING	237
10.1 Overview	237
10.2 Flood Hazard Maps	238
10.3 Flood Risk Maps	239
10.4 Flooded Infrastructure	241
11.0 DEVELOPMENT OF A FLOOD FORECASTING STRATEGY ...	242
11.1 Overview	242
11.2 Development of Conceptual Strategies	243
11.2.1 Forecasting Strategy Option 1	243
11.2.2 Forecasting Strategy Option 2	244
11.2.3 Forecasting Strategy Option 3	244
11.3 Evaluation of Conceptual Strategies	245

12.0 REGIONAL ASSESSMENT OF STORM SURGE AND WAVES. 248

13.0 LIST OF ASSUMPTIONS 251

14.0 CONCLUSIONS 253

15.0 RECOMMENDATIONS 255

16.0 REFERENCES 256

List of Figures

- Figure 1: Rivers and Creeks Considered in Ferryland
- Figure 2: Rivers and Creeks Considered in Brigus
- Figure 3: Rivers and Creeks Considered in Heart's Delight - Islington
- Figure 4: Rivers and Creeks Considered in Winterton
- Figure 5: Rivers and Creeks Considered in Hant's Harbour
- Figure 6: Overview of Background Information Review
- Figure 7: Overview of Field Program
- Figure 8: Ferryland Survey Control Points
- Figure 9: Brigus Survey Control Points
- Figure 10: Heart's Delight – Islington Survey Control Points
- Figure 11: Winterton and Hant's Harbour Survey Control Points
- Figure 12: Topographic and Bathymetric Survey Data in Ferryland
- Figure 13: Topographic and Bathymetric Survey Data in Brigus
- Figure 14: Topographic and Bathymetric Survey Data in Heart's Delight - Islington
- Figure 15: Topographic and Bathymetric Survey Data in Winterton and Hant's Harbour
- Figure 16: Ferryland Structure Survey
- Figure 17: Brigus Structure Survey
- Figure 18: Heart's Delight – Islington Structure Survey
- Figure 19: Winterton and Hant's Harbour Structure Survey
- Figure 20: Logger Locations
- Figure 21: Quarry River (Ferryland) Recorded Water Levels
- Figure 22: Lambes Brook (Brigus) Recorded Water Levels
- Figure 23: Heart's Delight Brook (Heart's Delight - Islington) Recorded Water Levels
- Figure 24: Western Pond Brook (Winterton) Recorded Water Levels
- Figure 25: Short's Brook (Hant's Harbour) Recorded Water Levels
- Figure 26: Comparison of Prorated and Observed Flows on Quarry River (Ferryland)
- Figure 27: Comparison of Prorated and Measured Flows on Lambes Brook (Brigus)
- Figure 28: Comparison of Prorated and Observed Flows on Heart's Delight Brook (Heart's Delight - Islington)
- Figure 29: Comparison of Prorated and Measured Flows on Short's Brook (Hant's Harbour)
- Figure 30: Comparison of Prorated and Measured Flows on Western Pond Brook (Winterton)
- Figure 31: Overview of Aerial Photography and DEM Development
- Figure 32: Ferryland Watershed DEM
- Figure 33: Brigus Watershed DEM
- Figure 34: Heart's Delight - Islington Watershed DEM
- Figure 35: Winterton and Hant's Harbour Watershed DEM
- Figure 36: Comparison of Original and Modified HRDEM
- Figure 37: Ferryland Flood Plain DEM
- Figure 38: Brigus Flood Plain DEM
- Figure 39: Heart's Delight - Islington Flood Plain DEM
- Figure 40: Winterton and Hant's Harbour Flood Plain DEM

Figure 41: Overview of Remote Sensing and Land Use Classification
Figure 42: Ferryland Land Use Classification Map
Figure 43: Brigus Land Use Classification Map
Figure 44: Heart's Delight – Islington Land Use Classification Map
Figure 45: Winterton and Hant's Harbour Land Use Classification Map
Figure 46: Ferryland Soil Classification Map
Figure 47: Brigus Soil Classification Map
Figure 48: Heart's Delight – Islington Soil Classification Map
Figure 49: Winterton and Hant's Harbour Soil Classification Map
Figure 50: Ferryland Curve Number Map
Figure 51: Brigus Curve Number Map
Figure 52: Heart's Delight - Islington Curve Number Map
Figure 53: Winterton and Hant's Harbour Curve Number Map
Figure 54: Overview of Hydrologic Investigations and Modelling
Figure 55: Location of WSC Station 02ZM009 Relative to Ferryland Drainage Basins
Figure 56: Location of WSC Station 02ZL004 Relative to Brigus and Heart's Delight – Islington Area Drainage Basins
Figure 57: Location of WSC Station 02ZL005 Relative to Winterton and Hant's Harbour Area Drainage Basins
Figure 58: Seal Cove Brook near Cappahayden Frequency Curve
Figure 59: Shearstown Brook at Shearstown Frequency Curve
Figure 60: Big Brook at Lead Cove Frequency Curve
Figure 61: Ferryland Model Sub-Basins
Figure 62: Brigus Model Sub-Basins
Figure 63: Heart's Delight - Islington Model Sub-Basins
Figure 64: Winterton and Hant's Harbour Model Sub-Basins
Figure 65: Comparison of Simulated and Prorated Peak Flows in Ferryland
Figure 66: Comparison of Simulated and Prorated Peak Flows in Brigus
Figure 67: Comparison of Simulated and Prorated Peak Flows in Heart's Delight - Islington
Figure 68: Comparison of Simulated and Prorated Peak Flows in Winterton
Figure 69: Comparison of Simulated and Prorated Peak Flows in Hant's Harbour
Figure 70: Updated IDF Curve for St. John's A
Figure 71: Updated IDF Curve for St. John's Ruby Line
Figure 72: Climate Change IDF Curve for St. John's
Figure 73: 6-Hour Hyetograph (Alternating Block)
Figure 74: 12-Hour Hyetograph (Alternating Block)
Figure 75: 24-Hour Hyetograph (Alternating Block)
Figure 76: 6-Hour Hyetograph (Mass Curve)
Figure 77: 12-Hour Hyetograph (Mass Curve)
Figure 78: 24-Hour Hyetograph (Mass Curve)
Figure 79: Comparison of Alternating Block and Dimensionless Mass Curve Flows
Figure 80: Overview of Climate Change and Future Development Assessment
Figure 81: Comparison of Current Climate and Climate Change 20-Year AEP Hyetographs

Figure 82: Comparison of Current Climate and Climate Change 100-Year AEP Hyetographs
Figure 83: Projected Sea Level Rise for Trinity Bay
Figure 84: Projected Sea Level Rise for Conception Bay
Figure 85: Projected Sea Level Rise for Ferryland
Figure 86: Representative Climate Change Atlas Output Point for Ferryland Community
Figure 87: Representative Climate Change Atlas Output Point for Brigus Community
Figure 88: Representative Climate Change Atlas Output Point for Hant's Harbour and Winterton Communities
Figure 89: Representative Climate Change Atlas Output Point for Heart's Delight – Islington Community
Figure 90: Climate Change Impacts on Ice Jamming
Figure 91: Overview of Hydraulic Investigations and Modelling
Figure 92: Storm Surge Modelling Framework
Figure 93: Wave Modelling Framework
Figure 94: Locations of the Water Level Gauges
Figure 95: North-Atlantic Regional Model Domain
Figure 96: Trinity Bay Model Domain and Computational Mesh
Figure 97: Zoom on Heart's Delight – Islington Community
Figure 98: Zoom on Winterton (Upper) and Hant's Harbour (Lower) Communities
Figure 99: Conception Bay Model Domain and Computational Mesh (Upper) and Zoom on Brigus Community (Lower)
Figure 100: Ferryland Model Domain and Computational Mesh (Upper) and Zoom on the Community (Lower)
Figure 101: Regional Model Validation St. John's – Surge Residual
Figure 102: Regional Model Validation at Bonavista – Surge Residual
Figure 103: Model Calibration at Long Cove (Trinity Bay) – Total Water Level
Figure 104: Model Calibration at Long Cove (Trinity Bay) – Surge Residual
Figure 105: Model Calibration at Heart's Content (Trinity Bay) – Predicted Tides
Figure 106: Model Calibration at Holyrood Bay (Conception Bay model) – Total Water Level
Figure 107: Model Calibration at Holyrood Bay (Conception Bay model) – Surge Residual
Figure 108: Model Calibration at Long Pond (Conception Bay Model) – Total Water Level
Figure 109: Model Calibration at Long Pond (Conception Bay Model) – Surge Residual
Figure 110: Model Calibration at Bell Island (Conception Bay Model) – Total Water Level
Figure 111: Model Calibration at Bell Island (Conception Bay model) – Surge Residual
Figure 112: Model Calibration at Lance Cove (Ferryland model) – Predicted Tides
Figure 113: 2010 Maximum Total Water Level in Hant's Harbour (Upper) and Winterton (Lower)
Figure 114: 2010 Maximum Total Water Level near Heart's Delight – Islington
Figure 115: EVA Locations in Hant's Harbour
Figure 116: EVA Locations in Winterton
Figure 117: EVA Locations in Heart's Delight – Islington
Figure 118: 2010 Maximum Total Water Level near Brigus
Figure 119: EVA Locations in Brigus
Figure 120: 2010 Maximum Total Water Level near Ferryland
Figure 121: EVA Locations in Ferryland
Figure 122: MSC50 M6013845 Location Relative to Model Grid

Figure 123: MSC50 M6013845 Wave Height and Wave Period
Figure 124: MSC50 M6013197 Location Relative to Model Grid
Figure 125: MSC50 M6013197 Wave Height and Wave Period
Figure 126: MSC50 M6011567 Location Relative to Model Grid
Figure 127: MSC50 M6011567 Wave Height and Wave Period
Figure 128: 100-Year, 60° Prevailing Winds and Offshore Waves AEP Significant Wave Height at Trinity Bay
Figure 129: 100-Year 30° Prevailing Winds and Offshore Waves AEP Significant Wave Height near Heart's Delight – Islington
Figure 130: 100-Year 30° Prevailing Winds and Offshore Waves Significant Wave Height near Winterton
Figure 131: 100-Year 30° prevailing winds and offshore waves Significant Wave Height Near Hant's Harbour
Figure 132: 100-Year, 30° Prevailing Winds and Offshore Waves AEP Significant Wave Height at Conception Bay
Figure 133: 100-Year, 30° Prevailing Winds and Offshore Waves AEP Significant Wave Height at Brigus
Figure 134: 100-Year, 150° Prevailing Winds and Offshore Waves AEP Significant Wave Height at Ferryland
Figure 135: 100-Year, 150° Prevailing Winds and Offshore Waves AEP Significant Wave Height at Ferryland
Figure 136: Flowchart of the methodology applied for estimation of wave uprush
Figure 137: Decision Diagram for Wave runup – Modified from Eurotop 2018
Figure 138: Wave Uprush Calculation Locations in Ferryland
Figure 139: Wave Uprush Calculation Locations in Brigus
Figure 140: Wave Uprush Calculation Locations in Heart's Delight - Islington
Figure 141: Wave Uprush Calculation Locations in Hant's Harbour
Figure 142: Wave Uprush Calculation Locations in Winterton
Figure 143: Ferryland HEC-RAS Model Domain
Figure 144: Brigus HEC-RAS Model Domain
Figure 145: Heart's Delight - Islington HEC-RAS Model Domain
Figure 146: Winterton HEC-RAS Model Domain
Figure 147: Hant's Harbour HEC-RAS Model Domain
Figure 148: Short's Brook Calibration near Critch's Lane (Hant's Harbour)
Figure 149: Western Pond Brook Calibration near Highway 80 (Winterton)
Figure 150: Heart's Delight Brook Calibration near Highway 80 (Heart's Delight - Islington)
Figure 151: Lambes Brook Calibration near North St. (Brigus)
Figure 152: Quarry Brook Calibration near Highway 10 (Ferryland)
Figure 153: River Ice Processes Simulated in the RIVICE Model
Figure 154: Forces Applied to an Ice-Jam Cover
Figure 155: Parameters Used to Describe the Ice Processes in RIVICE
Figure 156: RIVICE Model in Heart's Delight – Islington
Figure 157: RIVICE Model in Hant's Harbour
Figure 158: RIVICE Model in Winterton
Figure 159: Halfway Brook RIVICE Calibration
Figure 160: Heart's Delight Brook RIVICE Calibration
Figure 161: Western Pond Brook RIVICE Calibration
Figure 162: Heart's Delight Brook Maximum Ice Jam Elevations

Figure 163: Overview of Sensitivity Analyses Tasks

Figure 164: Overview of Flood Risk Mapping

Figure 165: Flood Risk Classification

Figure 166: Overview of the Flood Forecasting Strategy Tasks

Figure 167: Forecasting Strategy Option 1

Figure 168: Forecasting Strategy Option 2

Figure 169: Forecasting Strategy Option 3

Figure 170: Qualitative Evaluation of Flood Forecasting Strategies

Figure 171: Output Locations for the Metocean Parameters along the Coasts of Newfoundland and Labrador (Upper) and Overview of Raster Maps Tiles for Storm Surge Statistics Covering the Entire Province

List of Tables

Table 1: Primary Survey Control Points

Table 2: Secondary Survey Control Points

Table 3: Summary of Flow Measurements

Table 4: Hydrometric Index Stations

Table 5: HRDEM Surface Statistics

Table 6: SPOT-6 Band Wavelengths

Table 7: WRMD Land Use Classes

Table 8: Correlation of NSDB to NRCS Soil Classes

Table 9: Curve Number Definition Table

Table 10: SSFA Statistical Tests

Table 11: Frequency Curve Flows

Table 12: Summary of SSFA Flows

Table 13: Statistical Screening Results

Table 14: SSFA Results

Table 15: RFFA Regression Analysis Parameters

Table 16: Regression Equation Statistics

Table 17: Comparison Between the 1999, 2014 and 2021 RFFA

Table 18: One-Parameter RFFA Equations

Table 19: Two-Parameter RFFA Equations

Table 20: Summary of RFFA Flows

Table 21: Summary of Rational Method Flows

Table 22: HEC-HMS Representation of Physical Processes

Table 23: Overview of Model Processes

Table 24: Calibration and Validation Events

Table 25: Summary of ECCC IDF Curve Stations

Table 26: Summary of HEC-HMS Flows

Table 27: Comparison of Flows

Table 28: Adopted AEP Flows

Table 29: Comparison of Current Climate and Climate Change Flows
Table 30: Relative Impact of Climate Change on River Flows
Table 31: Absolute Projected Change for Storm Surge and Significant Wave Height Statistics for the 5 Communities of Interest (Brigus, Winterton, Hant's Harbour, Heart's Delight – Islington and Ferryland)
Table 32: Percentage of Projected Change for Storm Surge and Significant Wave Height Statistics for the 5 Communities of Interest (Brigus, Winterton, Hant's Harbour, Heart's Delight – Islington and Ferryland)
Table 33: Conversion Between Chart Datum and CGVD2013 for Three Representative Stations
Table 34: Tidal Conditions at Heart's Content Station (Trinity Bay High-Resolution Domain)
Table 35: Tidal Conditions at Holyrood Bay Station (Conception Bay High-Resolution Domain)
Table 36: Tidal Conditions at Lance Cove Station (Ferryland High-Resolution Domain)
Table 37: Characteristics of the CFSR Wind and Pressure Data
Table 38: Specifications of CFSR Parameters
Table 39: Key Characteristics of the Water Level Gauges
Table 40: Regional Storm Surge Model Configuration
Table 41: Local High-Resolution Hydrodynamic Model Configuration
Table 42: Local High-Resolution Models Validation Summary
Table 43: AEP Water Levels and Velocities in Hant's Harbour
Table 44: AEP Water Levels and Velocities in Winterton
Table 45: AEP Water Levels and Velocities in Heart's Delight – Islington
Table 46: AEP Water Levels and Velocities in Brigus
Table 47: AEP Water Levels and Velocities in Ferryland
Table 48: AEP Significant Wave Height per Direction for MSC50 M6013845
Table 49: AEP Wind Speed per Direction for MSC50 M6013845
Table 50: AEP Significant Wave Height per Direction for MSC50 M6013197
Table 51: AEP Wind Speed per Direction for MSC50 M6013197
Table 52: AEP Significant Wave Height per Direction for MSC50 M6011567
Table 53: AEP Wind Speed per Direction for MSC50 M6011567
Table 54: Coastal Wave Model Setup
Table 55: AEP Wave Uprush in Ferryland
Table 56: AEP Wave Uprush in Brigus
Table 57: AEP Wave Uprush in Heart's Delight – Islington
Table 58: AEP Wave Uprush in Hant's Harbour
Table 59: AEP Wave Uprush in Winterton
Table 60: Initial Roughness Coefficients
Table 61: HEC-RAS Boundary Conditions
Table 62: Calibrated Roughness Coefficients
Table 63: 1:20 and 1:100 AEP Boundary Conditions
Table 64: Hydraulic Structure Capacity
Table 65: Forces Applied to an Ice-Jam Cover
Table 66: Parameters Used to Describe the Ice Processes in RIVICE
Table 67: RIVICE Model Parameters and Ranges
Table 68: Ice-Affected 100-Year AEP Flows

Table 69: Calibrated RIVICE Roughness Coefficients

Table 70: HEC-HMS Model Sensitivity

Table 71: Brigus HEC-RAS Model Sensitivity (Water Level Change)

Table 72: Brigus HEC-RAS Model Sensitivity (Percent Change in Depth)

Table 73: Comparison of Flooded Areas

Table 74: Summary of Flooded Buildings

List of Appendices

Appendix A – Summary of Background Data

Appendix B – Historical Flood Event Inventory

Appendix C – Survey Processing Reports

Appendix D – Culvert and Bridge Crossing Details

Appendix E – RFFA Statistical Screening Tests

Appendix F – Annual Maximum Precipitation Data

Appendix G – IDF Curve Data

Appendix H – EVA Analysis Results

Appendix I – Monthly Wave Rose Data

Appendix J – Wave Model Outputs

Appendix K – HEC-RAS Sensitivity Analysis Results

Appendix L – Flood Hazard Maps

Appendix M – Comparison of Historical and Updated Flood Hazard Maps

Appendix N – Flood Depth, Velocity, and Risk Overview Maps

Appendix O – Newfoundland and Labrador Atlas of Storm Surge and Wave Climates

List of Abbreviations

1D	1-dimensional
2D	2-dimensional
3PLN	Three-Parameter Lognormal Distribution
AAM	Average Annual Maximum
ADV	Acoustic Doppler Velocimeter
AEP	Annual Exceedance Probability
AHCDD	Adjusted and Homogenized Climate Change Data
AR5	Fifth Assessment Report
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
CMIP6	Coupled Model Intercomparison Project (Phase 6)
CN	Curve Number
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
FHIMP	Flood Hazard Identification and Mapping Program
FM	Flexible Mesh
GCM	Global Climate Model
GEBCO	Global General Bathymetric Chart of the Oceans
GEV	Generalized Extreme Value
GPS	Global Positioning System
HD	Hydrodynamic
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
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
SEE	Standard Error of the Estimate
SMR	Regression Correlation Coefficient
SSFA	Single Station Frequency Analysis
SSP	Shared Socioeconomic Pathway
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.

This report is based on information made available to KGS Group by the Government of Newfoundland and Labrador. Unless stated otherwise, KGS Group has not verified the accuracy, completeness or validity of such information, makes no representation regarding its accuracy and hereby disclaims any liability in connection therewith. KGS Group shall not be responsible for conditions/issues it was not authorized or able to investigate or which were beyond the scope of its work. The information and conclusions provided in this report apply only as they existed at the time of KGS Group’s work.

Third Party Use of Report

Any use a third party makes of this report or any reliance on or decisions made based on it, are the responsibility of such third parties. KGS Group accepts no responsibility for damages, if any, suffered by any third party as a result of decisions made or actions undertaken based on this report.

1.0 INTRODUCTION

1.1 Background

As part of the Federal Damage Reduction Program (FDRP), the Government of Newfoundland and Labrador completed flood hazard mapping projects for a number of communities where flooding had historically occurred. These flood hazard mapping projects were completed between 1981, when the Government of Newfoundland and Labrador joined the FDRP, and 1996, including the completion of flood hazard mapping studies for Gould's, Petty Harbour, and Ferryland in 1996, for the communities of Carbonear, Victoria, Salmon Cove, Whitbourne, Heart's Delight - Islington, Winterton and Hant's Harbour in 1996, and for Brigus in 1997. Subsequent to the completion of the FDRP, the Government of Newfoundland and Labrador announced a new Climate Change Adaptation initiative to update existing flood hazard mapping studies and complete new flood hazard 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 hazard mapping studies until March 31, 2022. Following the completion of the NDMP, the Government of Canada initiated the Flood Hazard Identification and Mapping Program (FHIMP), which provided extensive funding to provincial and territorial governments in support of the development or updating of flood hazard maps. Through FHIMP, this project has been funded in part by the Government of Canada.

In light of their ongoing efforts to update existing flood hazard maps and develop new flood hazard maps for at-risk communities, the Government of Newfoundland and Labrador retained KGS Group to develop updated flood hazard maps for the communities of Ferryland, Brigus, Heart's Delight - Islington, Winterton and Hant's Harbour. The updated flood hazard 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. Brigus), Trinity Bay (i.e. Heart's Delight - Islington, Winterton and Hant's Harbour), and along the eastern coast of the Avalon Peninsula (i.e. Ferryland). In the communities where flood hazard mapping was developed, historical flooding was found to have been caused by abnormally high tides, heavy seas, high winds, wave runup, and storm surge. Furthermore, potential for riverine flooding caused by heavy rainfall or rain on snow events exists within many of the communities. Ice jamming has also been noted in Heart's Delight - Islington, Winterton, and Hant's Harbour. Flooding due to coastal processes was found to worsen under the anticipated climate change-affected conditions due to the sea level rise relative to the crustal rebound in Newfoundland. Riverine flooding was also found to worsen due to the anticipated increased temperatures and precipitation events associated with climate change.

Given the broad range of environmental factors that can contribute to flooding in Ferryland, Brigus, Heart's Delight - Islington, Winterton and Hant's Harbour, a clear understanding of each mechanism and how to best incorporate considerations for each in the resulting flood hazard mapping is a critical component of this project.

The composition of the Project Team that completed the flood hazard mapping, and the roles of each of those project team members, 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 hazard mapping and the development of the flood hazard 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 Trinity Bay and Conception Bay, and along the eastern coast of the Avalon peninsula, 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 Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour. N.E. Parrott Surveys (NEPSL) 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.

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 hazard 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 to Figure 5.

The flood hazard maps developed as part of this project enhance the Water Resource Management Division's (WRMD) understanding of the potential for flooding in Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour 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.

FIGURE 1: RIVERS AND CREEKS CONSIDERED IN FERRYLAND



FIGURE 2: RIVERS AND CREEKS CONSIDERED IN BRIGUS



FIGURE 3: RIVERS AND CREEKS CONSIDERED IN HEART'S DELIGHT - ISLINGTON

FIGURE 4: RIVERS AND CREEKS CONSIDERED IN WINTERTON



FIGURE 5: RIVERS AND CREEKS CONSIDERED IN HANT'S HARBOUR



1.3 Scope of Work

The Scope of Work for this study included:

- 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 hazard maps associated with the 1:20 and 1:100 AEP floods under current climate and climate change conditions for current development conditions, and fully developed conditions, as appropriate, including 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 risk 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 hazard maps.
- Development and evaluation of a conceptual flood forecasting strategy for the communities of Ferryland, Brigus, Heart's Delight – Islington, Winterton, and Hant's Harbour.
- 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.
- Completion of current climate and climate change storm surge and wave modelling for the Province of Newfoundland and Labrador, including the development of community-level, plain language guidance materials on how to interpret those simulation results.

2.0 BACKGROUND INFORMATION REVIEW

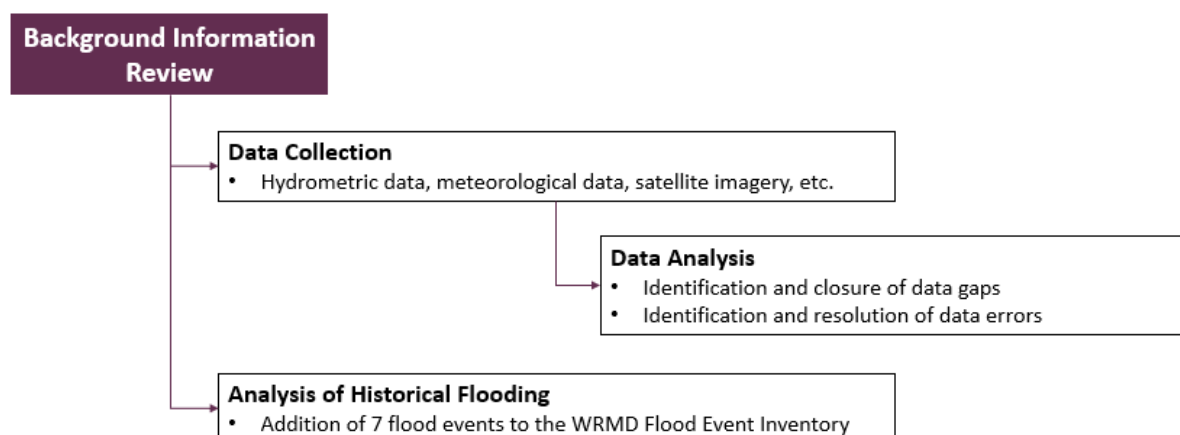
2.1 Overview

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 Ferryland, Brigus, Heart's Delight - Islington, Winterton and Hant's Harbour. 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, satellite imagery, water level and flow data, meteorological data, and reports documenting the previously completed flood hazard mapping studies for the communities. This data was collected from a variety of sources, including representatives from the Towns of Ferryland, Brigus, Heart's Delight-Islington, Winterton and Hant's Harbour, the Government of Newfoundland and Labrador, Water Survey of Canada (WSC), Environment and Climate Change Canada (ECCC), and Natural Resources Canada (NRCan).

As part of the background information review, a review of previous flood events in Ferryland, Brigus, Heart's Delight-Islington, Winterton and Hant's Harbour was completed for inclusion in the Government of Newfoundland and Labrador's Flood Event Inventory. The review identified six 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 6.

FIGURE 6: 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 Ferryland, Brigus, Heart's Delight-Islington, Winterton and Hant's Harbour. 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 Ferryland, Brigus, Heart's Delight-Islington, Winterton and Hant's Harbour,
- Satellite and remote sensing imagery,
- 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, and
- Bridge and culvert crossing information.

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. A key 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. in St. John's or 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. The data is available from January 1, 2002, to present, and provides estimated 6-hour cumulative precipitation totals throughout Canada.

2.4 Community Meetings

KGS Group held a number of meetings over the course of the project with representatives from the communities of Ferryland, Brigus, Heart's Delight-Islington, Winterton and Hant's Harbour to provide context for the flood hazard 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 hazard 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, included:

- ***Town of Brigus (December 5, 2022)*** – Representatives from the town noted that there were numerous issues due to coastal flooding and high waters over the past several months, particularly due to storm

surge. In particular, the town noted that there were 4 consecutive days over the preceding month with high water overtopping the riverbanks near the coast. River flooding was not flagged as a typical cause of flooding, but noted that the town experienced challenges with receiving environmental approvals to complete regular maintenance on the waterways in town. Representatives from the town noted that there was coastal flooding in town due to both Hurricane Igor and Larry.

- **Town of Ferryland (December 12, 2022)** – Representatives from the Town of Ferryland noted that there were numerous issues with coastal flooding and high waters, highlighting 4 or 5 recent consecutive days of strong eastern winds that resulted in high water overtopping the breakwater and beach, resulting in some damages to properties and flooding to the archaeology site. The Town also indicated that there were several instances of severe winds from the south and southeast in 2021 that resulted in coastal flooding. This took place roughly weekly for approximately 6 weeks. In short, it was noted that the Town was particularly susceptible to coastal flooding, as winds from the south, east, and north can all cause flood issues. The Town also noted flooding that occurred during 2019 on Quarry River, where the main bridge on the river was washed out. Coastal erosion was also flagged by representatives of the Town. While it was acknowledged that this was beyond the scope of this study, a future study should be completed to evaluate coastal erosion at Ferryland, including the development of mitigation to reduce future coastal erosion. Representatives from the Town also noted that offshore earthquakes could trigger tsunamis, as occurred in 1929, and result in coastal flooding. While it was acknowledged that this was outside of the scope of work for this project, a future study could evaluate flood potential associated with tsunamis.
- **Town of Winterton (December 14, 2022)** – KGS Group reviewed the proposed waterways to be included in the mapping study, with which the town concurred. Representatives from the town noted that there had not been many recent instances of flooding, with the exception of occasionally high water by the wharf. It was noted, however, that Hurricane Igor was the most significant recent event that resulted in flooding, specifically with flooding in the parking lot near the town office, and overtopping of a nearby road due to the culvert through that road being overwhelmed.
- **Town of Heart's Delight-Islington (February 15, 2023)** – The Mayor of Heart's Delight-Islington noted that flooding is typically due to a combination of storm surge, high tides, and high winds, although there have been floods due to high river flows. In particular, it was noted that three or four houses near Town Hall can become encircled by flood waters. The Mayor also indicated that one of the bridge crossings in town has been overtopped two or three times over approximately 60 years.
- **Town of Hant's Harbour (February 21, 2023)** – The proposed rivers and creeks to be included in the study were reviewed with representatives of the Town of Hant's Harbour, who concurred that the proposed rivers and creeks seemed reasonable. The Town noted that Hurricane Igor resulted in a lot of water on Short's Brook, resulting in damaged culverts that were replaced following the flood. The Town noted that Short's Brook is the main source of riverine flooding in town. High tides also cause problems with flooding, and that they can occur independently from large storm events.

Subsequent to the completion of the preparation of the draft flood hazard maps for this study, KGS held review meetings Ferryland, Brigus, and Winterton. A meeting was not held with the Town of Hant's Harbour, as it was noticed that upon review, council noted that the maps were consistent with their expectations, while a meeting was not held with the Town of Heart's Delight – Islington, as no response was received from

the town. Key points of discussions during the review meetings with each of the towns, as well as the date that the meetings occurred, include:

- ***Town of Ferryland (December 12, 2024)*** – Representatives from the Town of Ferryland noted that the flood hazard maps were in good agreement with historical flooding in the area, particularly at areas threatened by coastal flooding and at roadway crossings where the mapping showed overtopping of those crossings. Representatives from the Town also noted that some residents within the 100-year AEP flood zone regularly experience basement flooding, suggesting that under severe flood conditions, they would be at risk. Representatives from Ferryland noted that since the highway is at risk due to wave runup, and is a key transportation link for the region, erosion protection will likely be required to mitigate risks associated with wave-driven erosion.
- ***Town of Winterton (January 16, 2025)*** – Representatives from the Town of Winterton found the maps to be in good agreement with their historical flood experience. Representatives from the Town noted that the flooding resulting from Hurricane Igor largely remained within the river banks, which was noted to be in good agreement with the 20-year flood zone.
- ***Town of Brigus (February 26, 2025)*** – Representatives from the Town of Brigus found the maps to be in good agreement with their recent historical flood experiences, noting that there was considerable flooding in downtown Brigus in January 2025 due to high seas and waves.

2.5 Analysis of Historical Flooding

A thorough review was completed of the available information pertaining to flood events in Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour, 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 high storm surge and waves. Flooding was also noted due high river flows, as well as ice jamming. However, six additional flood events were identified and included in the Historical Flood Event Inventory, specifically:

- ***September 21, 2010 (Winterton)*** – High rainfall from Hurricane Igor resulted in high flows on the waterways in Winterton, resulting in a culvert crossing being overwhelmed and the roadway being overtopped by approximately 0.3 m for over an hour.
- ***September 21, 2010 (Brigus)*** – High tides and storm surge from Hurricane Igor resulted in flooding along the coast.
- ***September 21, 2010 (Hant's Harbour)*** – High rainfall associated with Hurricane Igor resulted in high flows on Short's Brook, resulting in damage to those culverts that were replaced following the storm.
- ***June 4, 2019 (Ferryland)*** – Unprecedentedly high water levels near Merrymeeting Road were observed following heavy rains. Local residents allege that construction activities taking place upstream of Merrymeeting Road were responsible for the high water levels, but the cause of the high levels is unresolved.
- ***September 11, 2021 (Brigus)*** – Coastal flooding occurred in Brigus due to a combination of high tides and storm surge from Hurricane Larry.

- **October 9, 2021 (Ferryland)** – The Colony of Avalon archaeological site experienced flooding due to high seas caused by intense winds.
- **January 5, 2025 (Brigus)** – Coastal flooding occurred in Brigus due to storm surge and heavy seas.

Historical flood events that occurred in Ferryland, Brigus, Hant’s Harbour, Winterton, and Heart’s Delight – Islington 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 fifty-four river cross sections were surveyed. Surveys of ninety-two 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. Thirty-three cross sections were also surveyed along the shoreline in Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour. A dedicated bathymetric survey was not conducted in Ferryland, as the spatial resolution and coverage of the Canadian Hydrographic Service (CHS) Non-Navigational (NONNA) dataset were assessed to be adequate to support the objectives of the assessment.

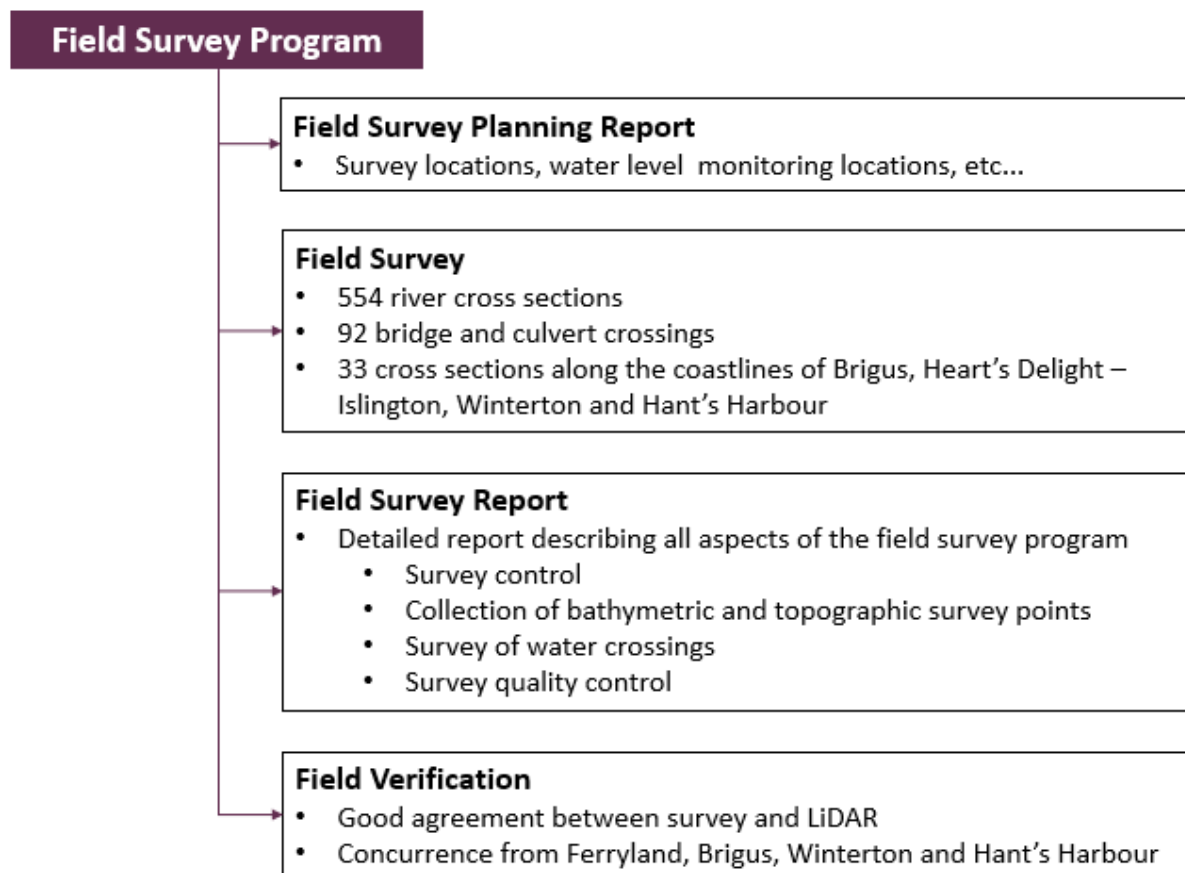
Ground elevations were surveyed throughout the study area to confirm the accuracy of the HRDEM data, and to ensure that the HRDEM data accurately represents the ground elevation throughout the study area.

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 hazard mapping products.

The tasks completed as part of the field survey are shown on Figure 7.

FIGURE 7: OVERVIEW OF FIELD 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 Canadian Geodetic Vertical Datum of 1928 (CGVD28) vertical datum. Therefore, to coincide with the project requirements, the vertical datum for the points was processed to vertical datum CGVD2013. The control processing reports are provided in Appendix C. The absolute confidence levels for the data were 3mm horizontally and 2mm vertically.

Secondary control points were established in Ferryland by NEPSL. These control points were established and used as base reference points and helped reduce baseline distances between base and rover receivers.

A list of the primary and secondary 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 8 to Figure 11.

TABLE 1: PRIMARY SURVEY CONTROL POINTS

MONUMENT ID	NORTHING (m)	EASTING (m)	ELEVATION (m)	DESCRIPTION	SITE	TYPE	NOTE	AGENCY
81G2255	5265990.580	288934.358	25.416	BRASS PLUG CONV	BRIGUS	PRIMARY HORIZONTAL	NL GEODETIC NETWORK	NL GOVT
81G2256	5266113.396	289296.670	21.096	BRASS PLUG FO	BRIGUS	PRIMARY HORIZONTAL	NL GEODETIC NETWORK	NL GOVT
81G2257	5266210.226	290061.707	15.844	BRASS PLUG CONV	BRIGUS	PRIMARY HORIZONTAL	NL GEODETIC NETWORK	NL GOVT
83G3403	5213278.578	312258.398	54.888	BRASS PLUG GPS	BRIGUS	PRIMARY HORIZONTAL	NL GEODETIC NETWORK	NL GOVT
83G3405	5209789.943	313684.565	11.123	CONC PILLAR	BRIGUS	PRIMARY HORIZONTAL	NL GEODETIC NETWORK	NL GOVT
630350	5319387.357	285124.993	30.857	BRASS PLUG CONV	HANT'S HARBOUR	PRIMARY HORIZONTAL	NL GEODETIC NETWORK	NL GOVT
944601	5319695.668	285386.209	4.816	BRASS PLUG FO	HANT'S HARBOUR	PRIMARY HORIZONTAL	NL GEODETIC NETWORK	NL GOVT
85G5504	5320302.158	285753.783	8.576	BRASS PLUG	HANT'S HARBOUR	PRIMARY HORIZONTAL	NL GEODETIC NETWORK	NL GOVT
85G5505	5319781.481	284968.707	37.526	BRASS PLUG GPS	HANT'S HARBOUR	PRIMARY HORIZONTAL	NL GEODETIC NETWORK	NL GOVT
85G5534	5293638.760	269963.725	8.026	BRASS PLUG CONV	HEART'S DELIGHT - ISLINGTON	PRIMARY HORIZONTAL	NL GEODETIC NETWORK	NL GOVT
85G5535	5293229.576	269118.830	8.692	BRASS PLUG CONV	HEART'S DELIGHT - ISLINGTON	PRIMARY HORIZONTAL	NL GEODETIC NETWORK	NL GOVT
85G5538	5292443.573	270083.890	6.551	BRASS PLUG CONV	HEART'S DELIGHT - ISLINGTON	PRIMARY HORIZONTAL	NL GEODETIC NETWORK	NL GOVT
85G5539	5292298.418	269284.301	13.021	BRASS PLUG CONV	HEART'S DELIGHT - ISLINGTON	PRIMARY HORIZONTAL	NL GEODETIC NETWORK	NL GOVT
85G5542	5291250.924	268536.174	13.071	BRASS PLUG CONV	HEART'S DELIGHT - ISLINGTON	PRIMARY HORIZONTAL	NL GEODETIC NETWORK	NL GOVT
85G5509	5312822.607	280274.539	26.944	BRASS PLUG CONV	WINTERTON	PRIMARY HORIZONTAL	NL GEODETIC NETWORK	NL GOVT
85G5510	5313015.790	279724.540	33.094	BRASS PLUG GPS	WINTERTON	PRIMARY HORIZONTAL	NL GEODETIC NETWORK	NL GOVT
85G5511	5312445.408	280366.473	39.187	BRASS PLUG CONV	WINTERTON	PRIMARY HORIZONTAL	NL GEODETIC NETWORK	NL GOVT
85G5512	5312125.965	280737.364	41.098	BRASS PLUG FO	WINTERTON	PRIMARY HORIZONTAL	NL GEODETIC NETWORK	NL GOVT
81G2248	5265577.237	287023.087	24.203	BRASS PLUG GPS	BRIGUS	PRIMARY VERTICAL	FIRST ORDER VERTICAL	CACS - PASSIVE
81G2253	5265978.624	288617.110	15.051	BRASS PLUG CONV	BRIGUS	PRIMARY VERTICAL	FIRST ORDER VERTICAL	CACS - PASSIVE
83G3404	5211607.385	313067.840	57.219	BRASS PLUG CONV	BRIGUS	PRIMARY VERTICAL	FIRST ORDER VERTICAL	CACS - PASSIVE
83G3406	5208158.220	310544.195	88.447	83G3406	FERRYLAND	PRIMARY VERTICAL	FIRST ORDER VERTICAL	CACS - PASSIVE

TABLE 2: SECONDARY SURVEY CONTROL POINTS

MONUMENT ID	NORTHING (m)	EASTING (m)	ELEVATION (m)	DESCRIPTION	SITE	TYPE	NOTE	AGENCY
19046	5210631.593	313775.196	9.024	19046	FERRYLAND	SECONDARY 3D	PROJECT CONTROL	NEPSL
23428	5212820.779	313795.757	45.015	23428	FERRYLAND	SECONDARY 3D	PROJECT CONTROL	NEPSL
CP-FERRY	5209189.950	313372.949	6.954	CP-FERRY	FERRYLAND	SECONDARY 3D	PROJECT CONTROL	NEPSL
TCP HILL	5209755.478	311746.577	57.621	TCP HILL	FERRYLAND	SECONDARY 3D	PROJECT CONTROL	NEPSL
TCP RCMP	5208770.080	312112.063	47.557	TCP RCMP	FERRYLAND	SECONDARY 3D	PROJECT CONTROL	NEPSL

FIGURE 8: FERRYLAND SURVEY CONTROL POINTS

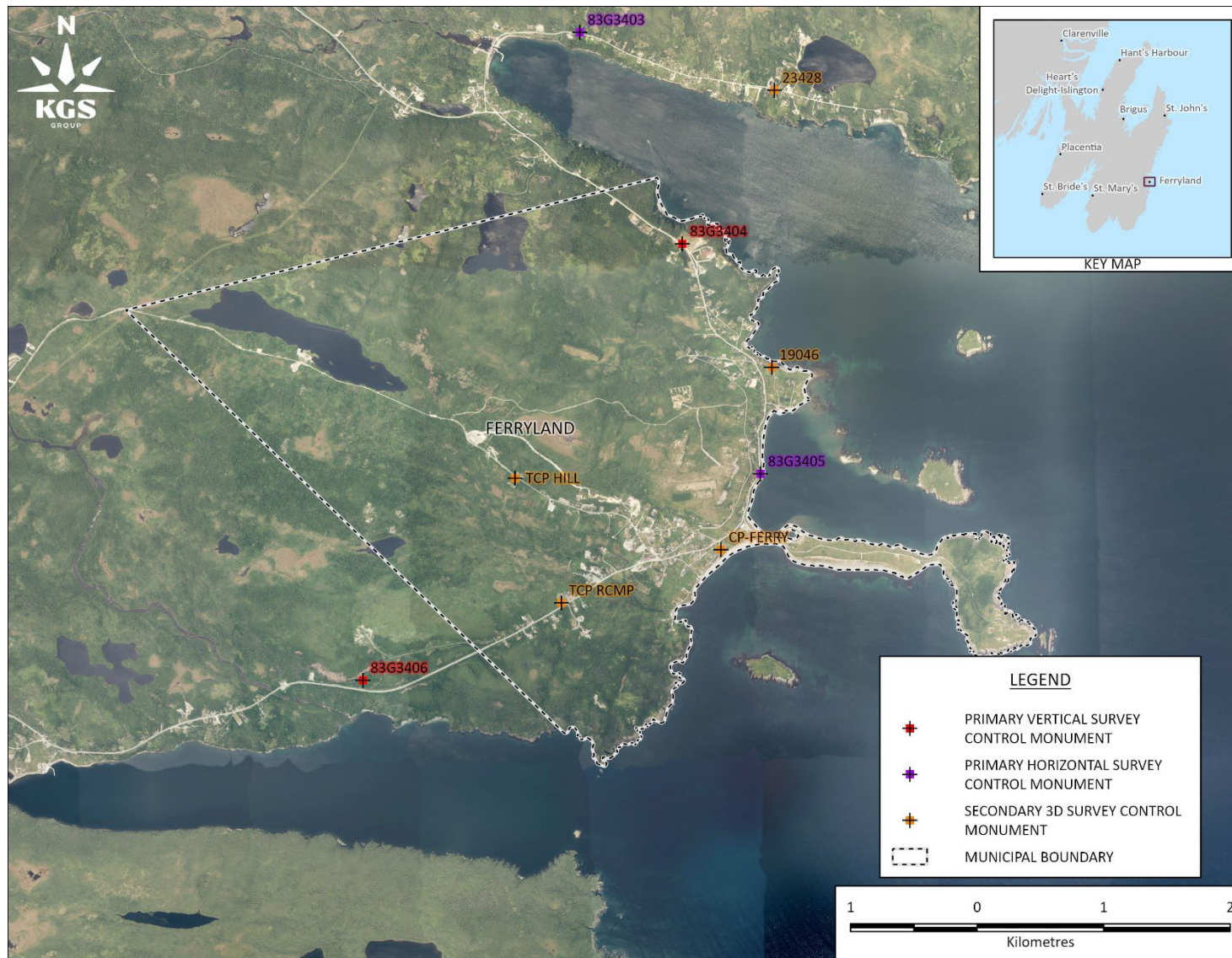


FIGURE 9: BRIGUS SURVEY CONTROL POINTS

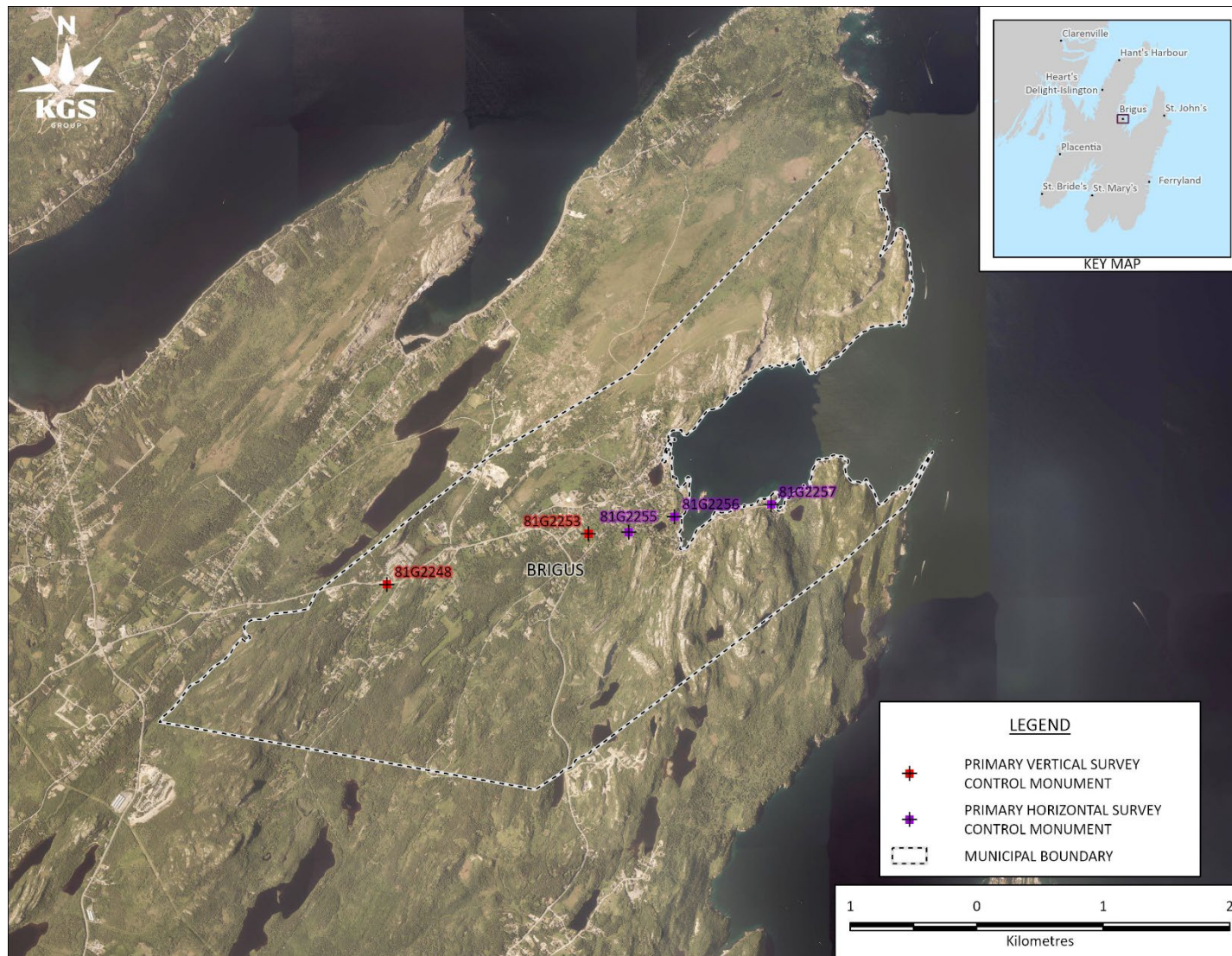


FIGURE 10: HEART'S DELIGHT – ISLINGTON SURVEY CONTROL POINTS

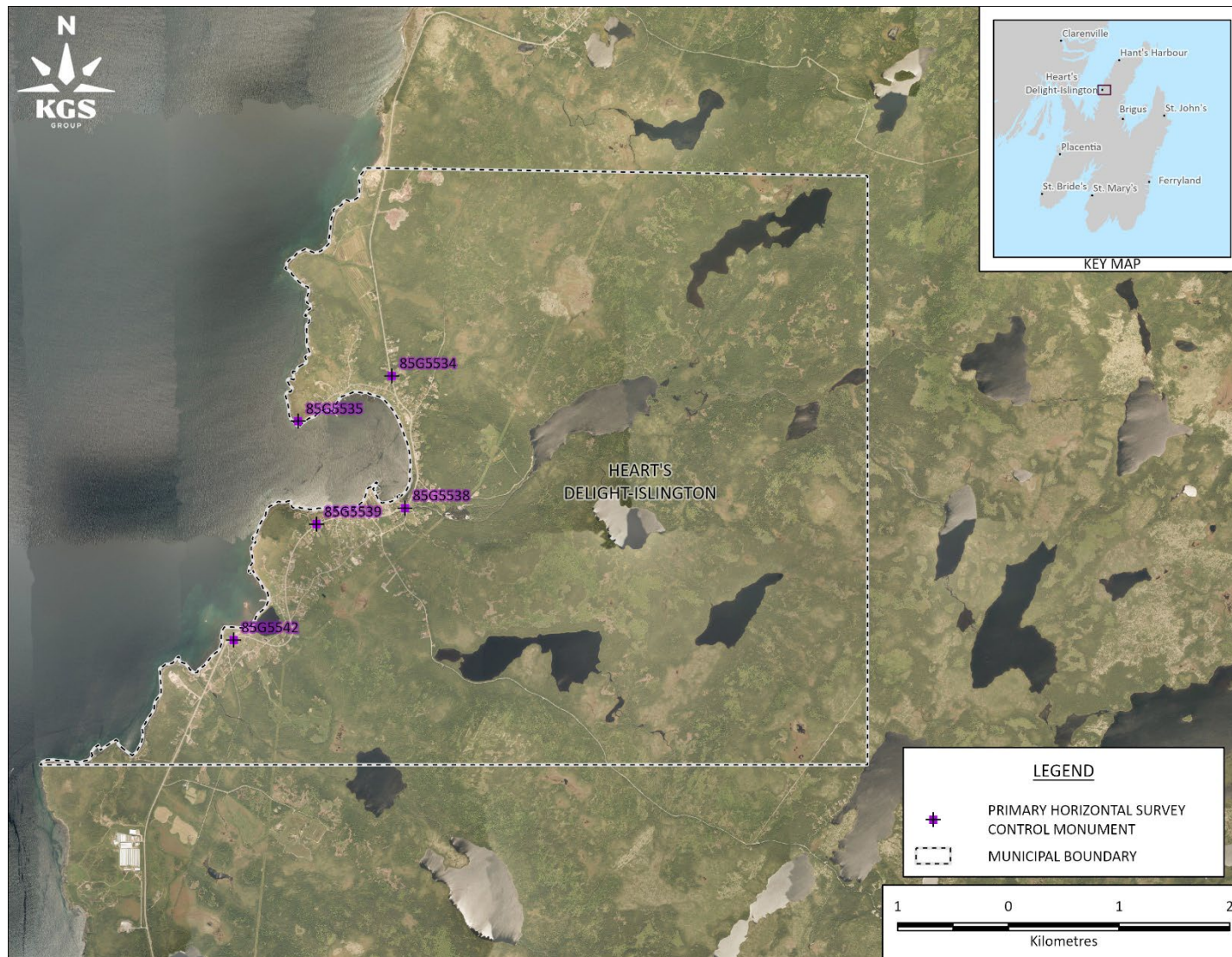
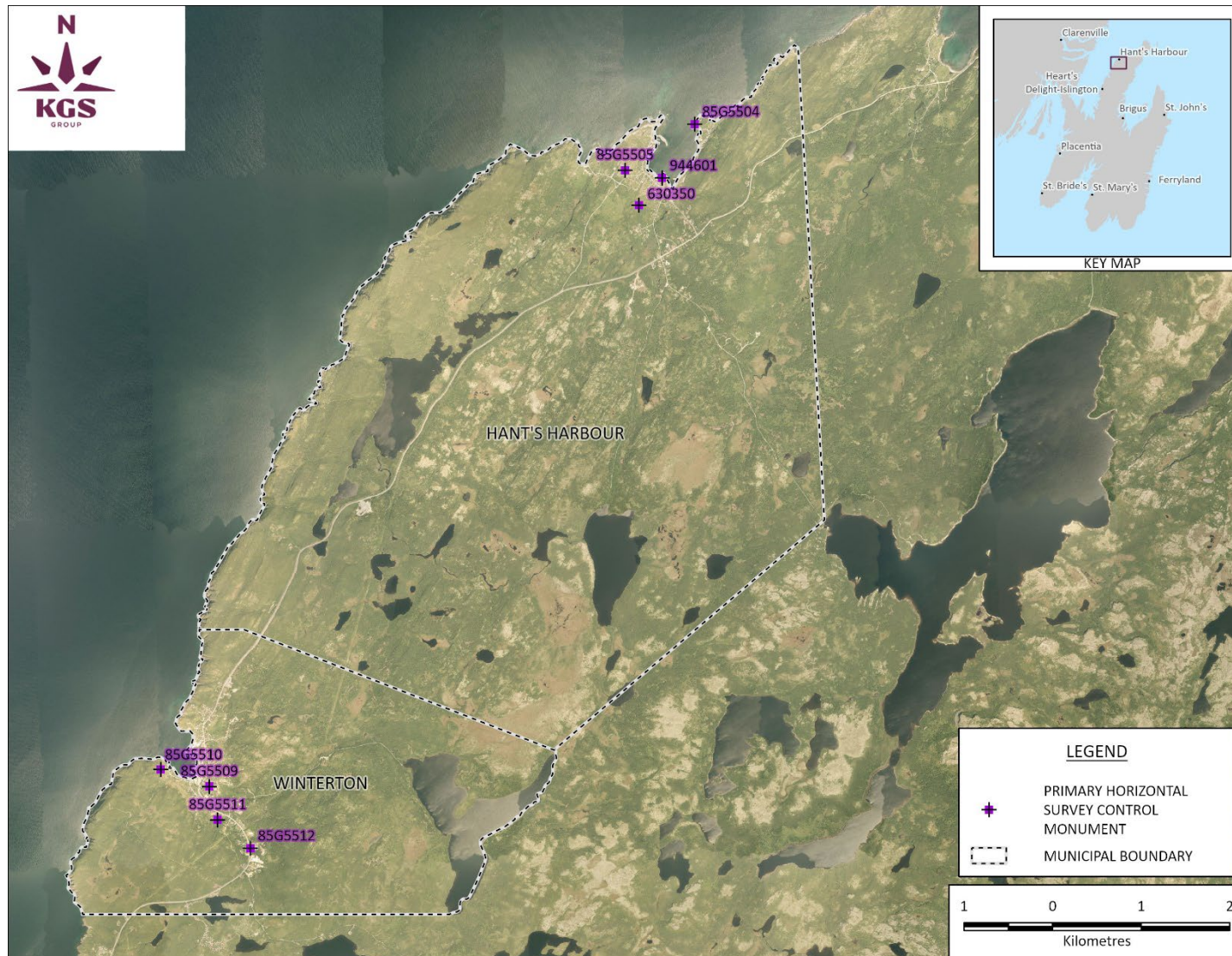


FIGURE 11: WINTERTON AND HANT'S HARBOUR SURVEY CONTROL POINTS



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, 554 river cross sections were surveyed throughout Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour.

To supplement existing coastal bathymetric data, bathymetric cross sections were collected along the coastline of Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour. A total of 33 bathymetric transects were completed throughout those communities. The proposed transect locations were selected based on criteria documented in the RFP, as well as considerations for the storm surge modelling. It should be noted that bathymetric data was not acquired throughout Ferryland, as existing high-resolution bathymetric data was available from the 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 – DFX Dual Frequency 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. These shots were completed to extend bathymetric transects into the existing HRDEM coverage and to provide more detail of existing bank geometry. Manual depth checks were completed to the water body bottom to cross validate the echosounder readings each survey day to ensure the sonar unit was accurately characterizing the waterbody bottom. As well, cross validation checks were completed through the transect lines to ensure that there was no instrument drift during the survey.

The topographic and bathymetric survey data collected in Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour are shown on Figure 12 to Figure 15.

FIGURE 12: TOPOGRAPHIC AND BATHYMETRIC SURVEY DATA IN FERRYLAND

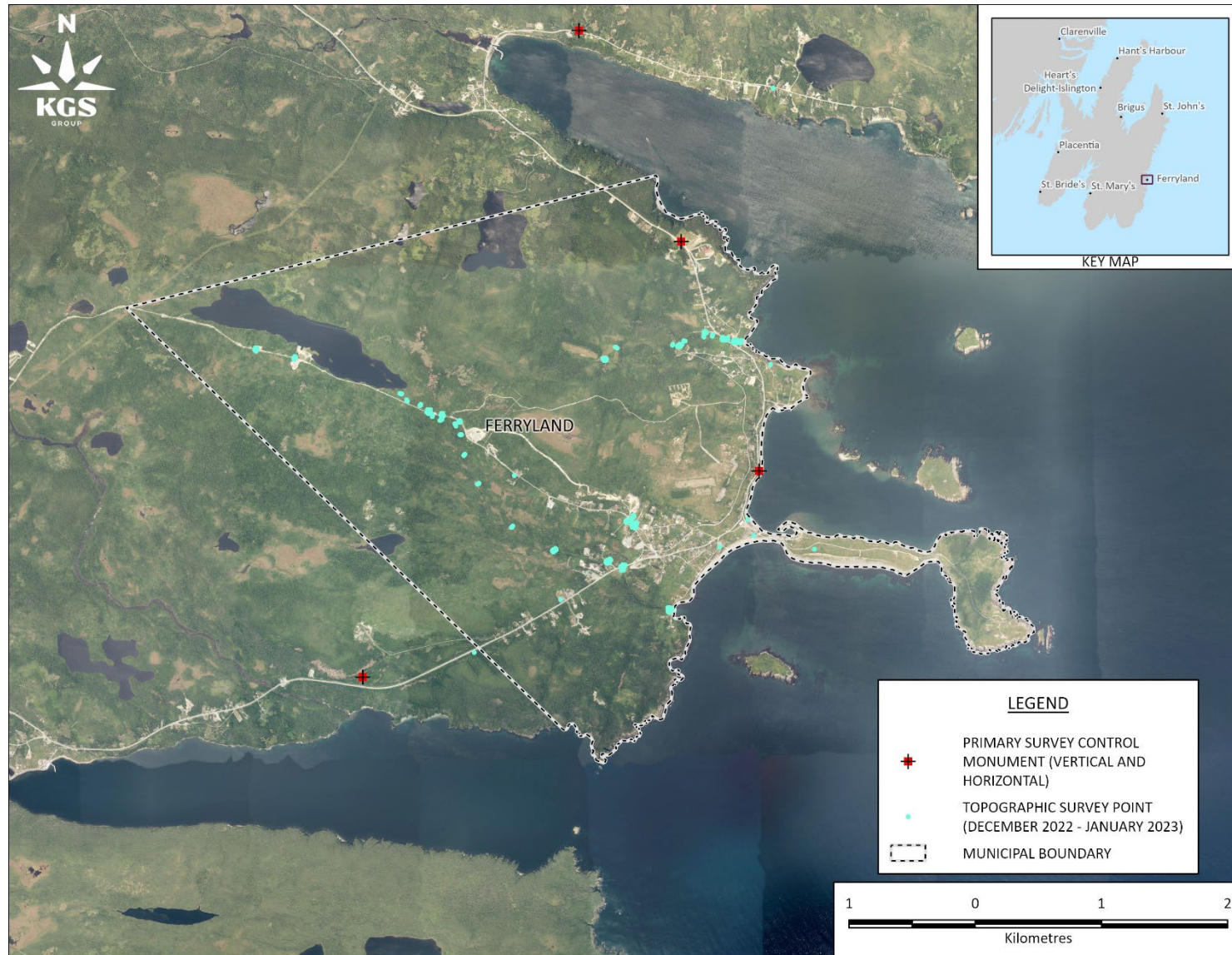


FIGURE 13: TOPOGRAPHIC AND BATHYMETRIC SURVEY DATA IN BRIGUS

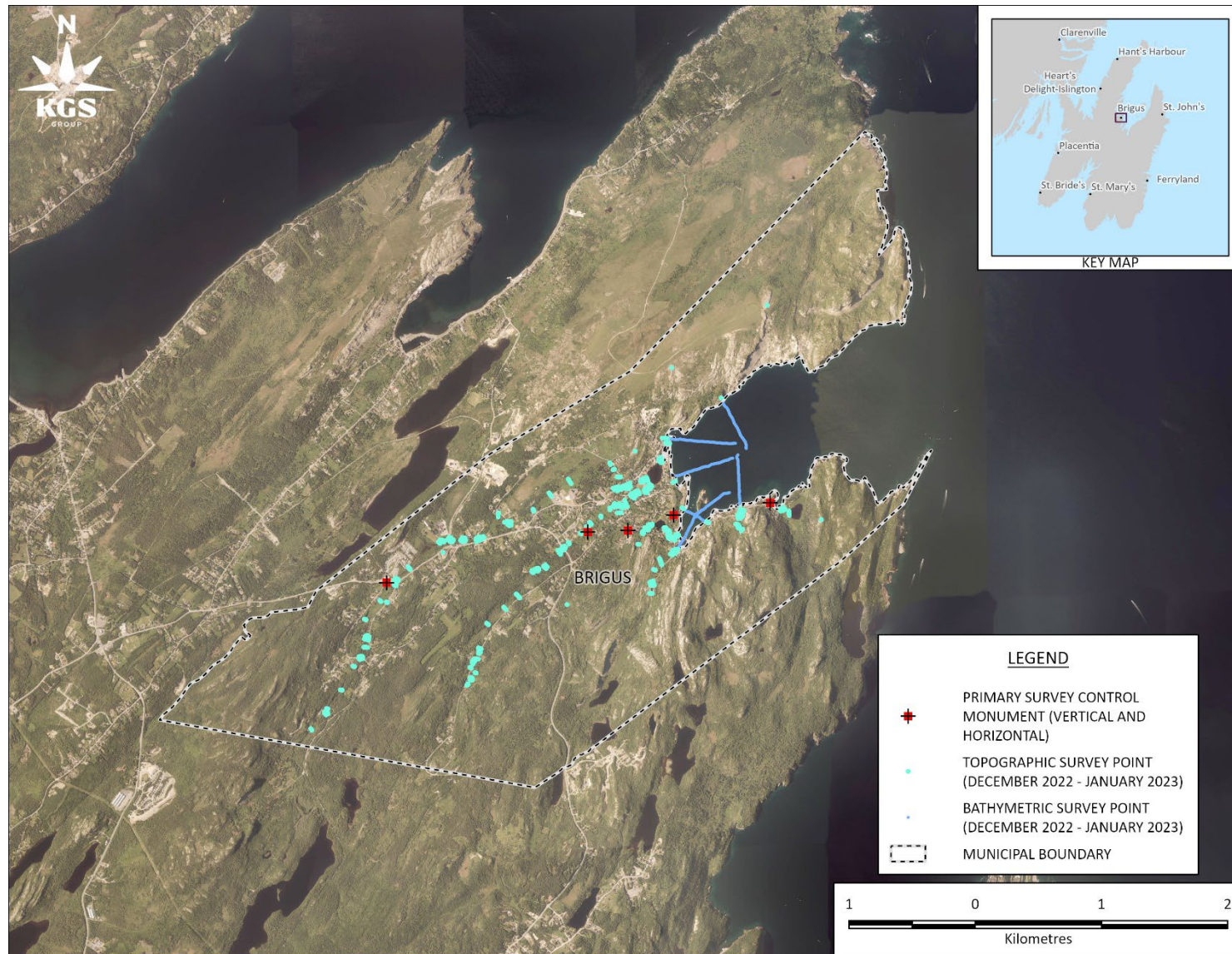


FIGURE 14: TOPOGRAPHIC AND BATHYMETRIC SURVEY DATA IN HEART'S DELIGHT - ISLINGTON

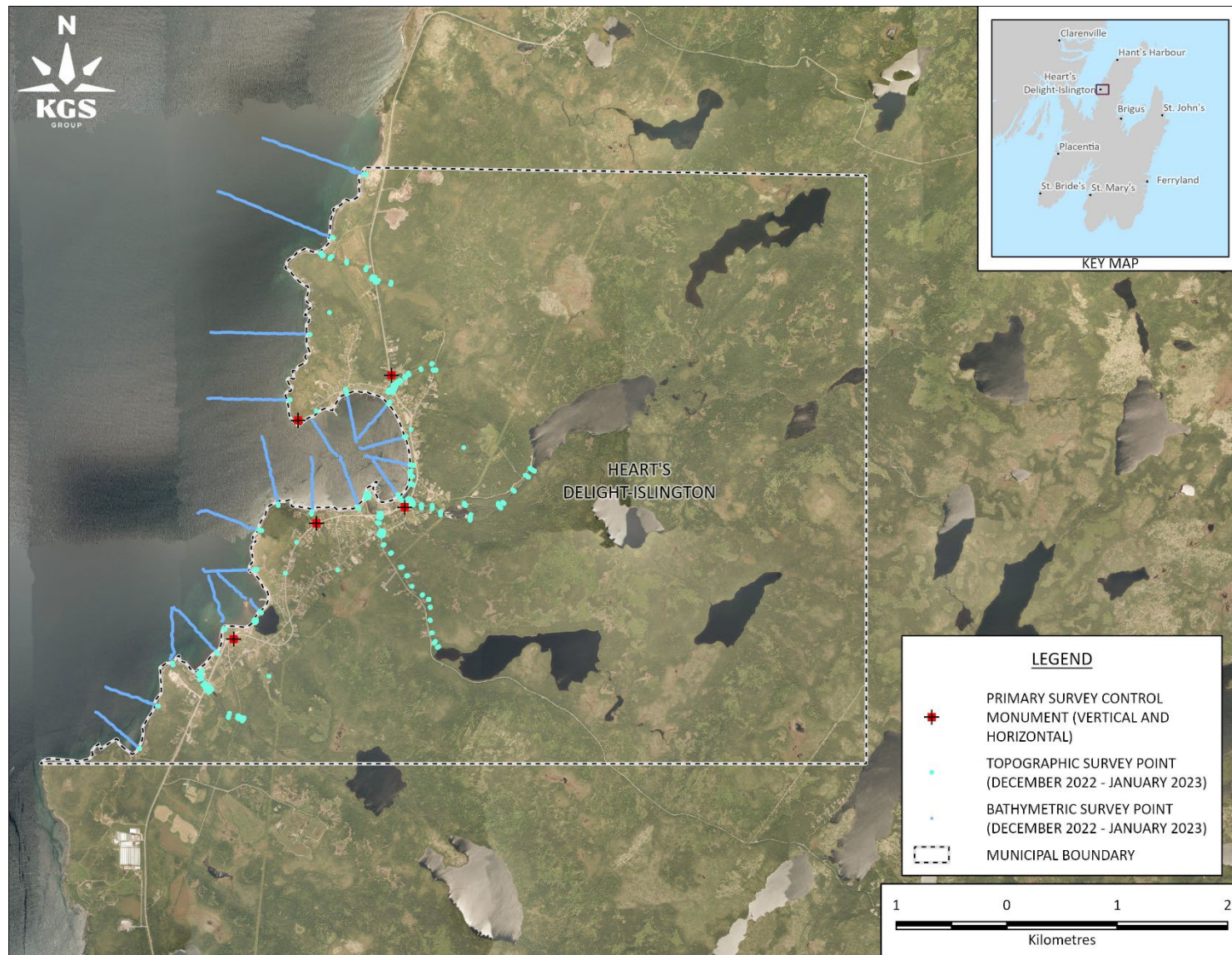
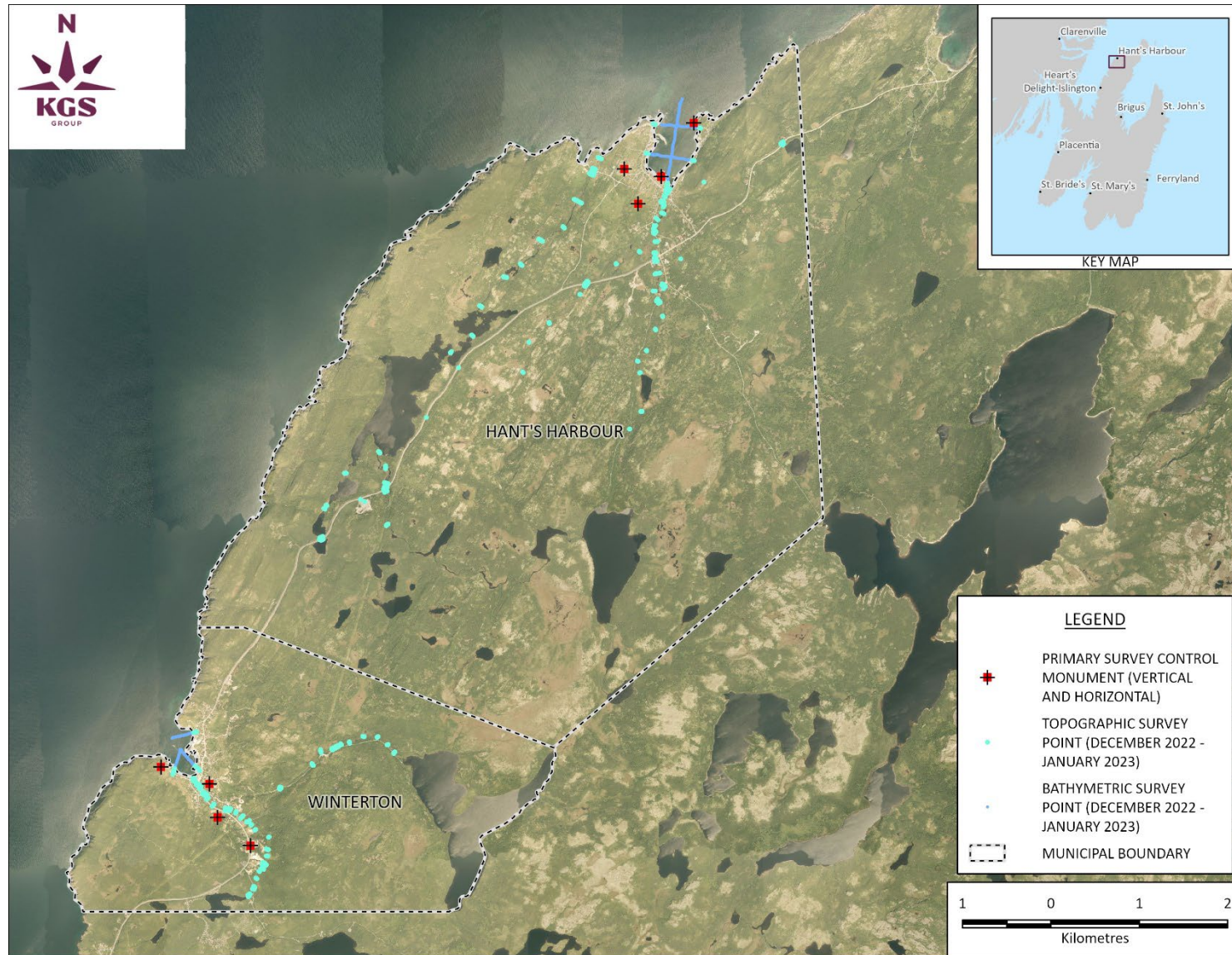


FIGURE 15: TOPOGRAPHIC AND BATHYMETRIC SURVEY DATA IN WINTERTON AND HANT'S HARBOUR



3.2.3 SURVEY OF WATER CROSSINGS

A combined total of 92 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. 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 D. Culverts that were estimated as part of subsequent hydraulic modelling are not included in Appendix D.

The locations of the bridge and culvert crossings that were surveyed are shown on Figure 16 to Figure 19.

FIGURE 16: FERRYLAND STRUCTURE SURVEY

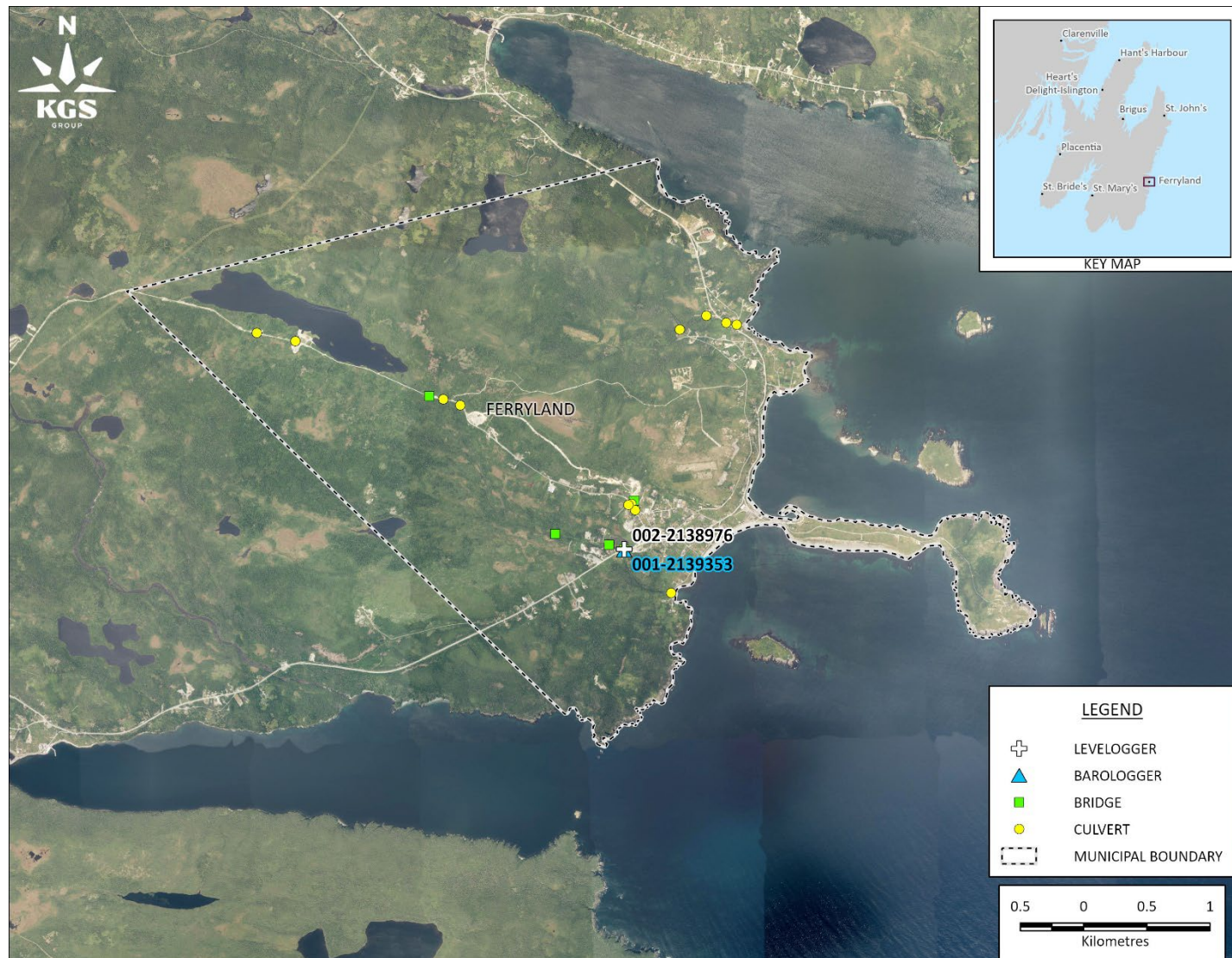


FIGURE 17: BRIGUS STRUCTURE SURVEY

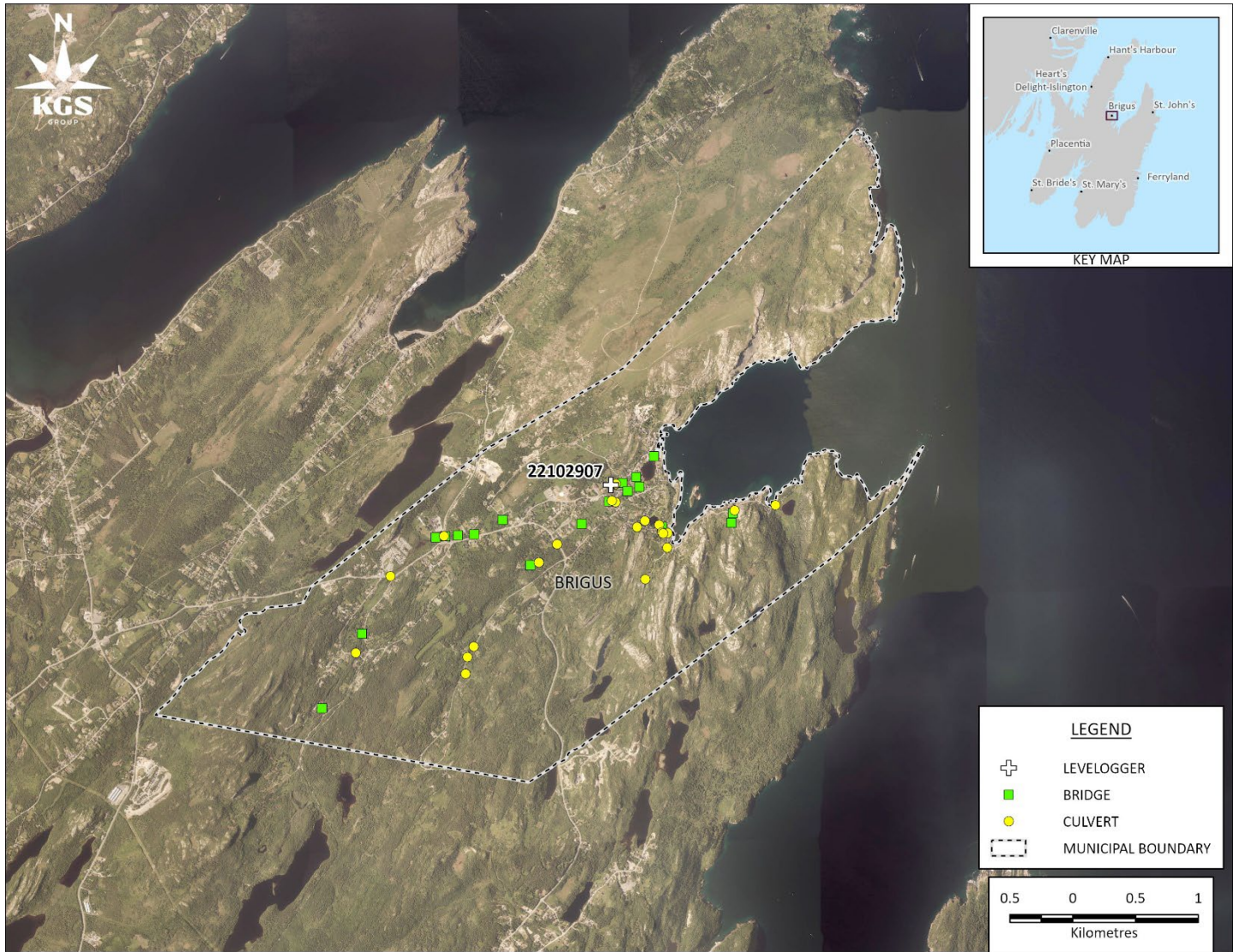


FIGURE 18: HEART'S DELIGHT – ISLINGTON STRUCTURE SURVEY

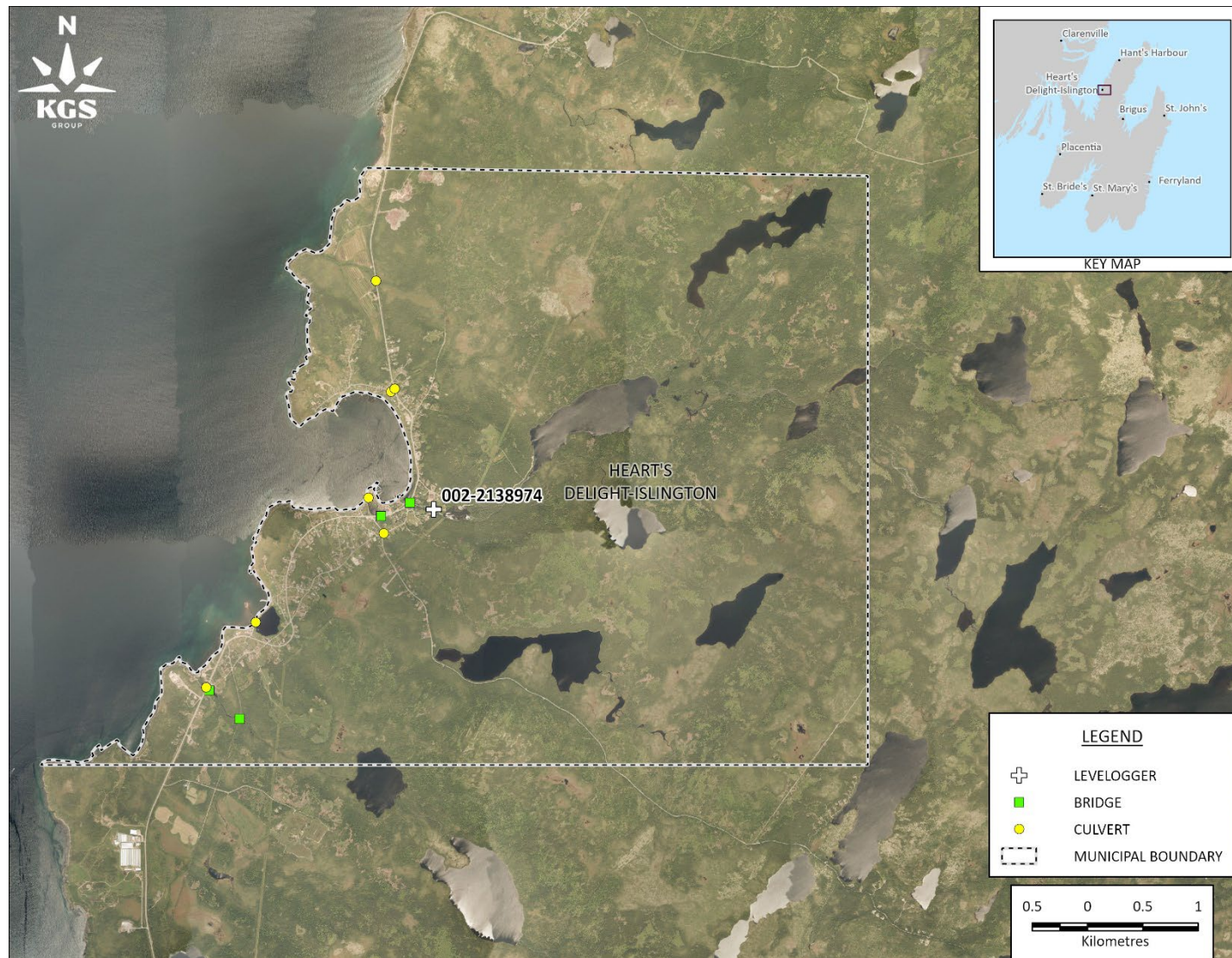
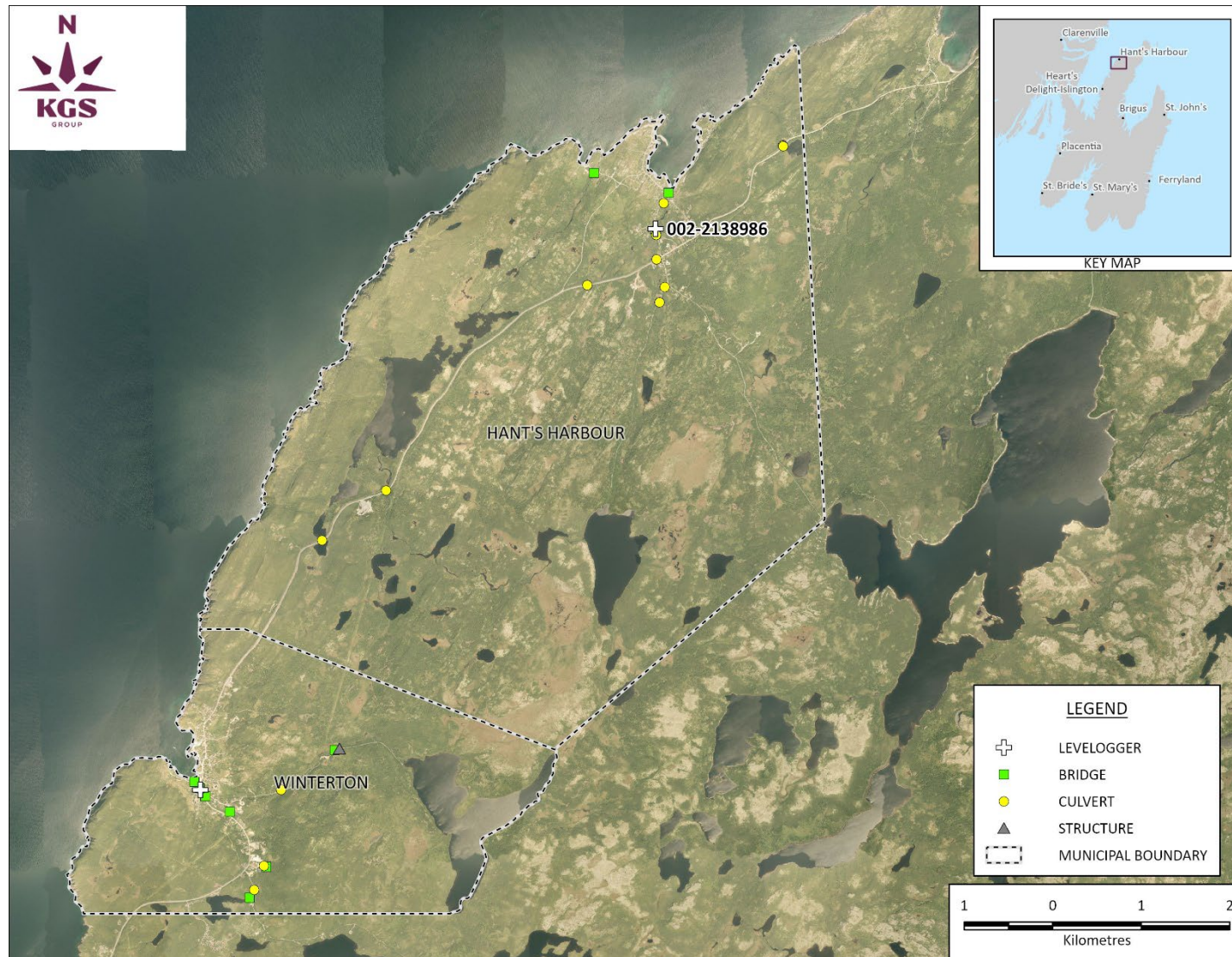


FIGURE 19: WINTERTON AND HANT'S HARBOUR STRUCTURE SURVEY



3.2.4 SURVEY PROCESSING

All surveys were processed in 3-degree NAD83 CSRS, MTM Zone 1 projection system and CGVD2013 vertical datum.

Bathymetric surveys were fixed and adjusted to control that was established at the beginning of the project. Processing of the data was cross referenced to the manual checks recorded in the field and checked to ensure residuals were within manufacturer specifications.

3.3 Flow and Water Level Monitoring Program

As part of the study, Solinst Levellogger 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 Levelloggers and Barologger were deployed and started data collection on December 13, 2022 (i.e. Ferryland and Brigus) and December 17, 2022 (Winterton, Hant's Harbour, and Heart's Delight – Islington). The loggers were removed on February 25 and 26, 2023. The loggers were setup to collect readings every 15 minutes during the 10-week installation period. Geodetic water elevations were surveyed at the time of installation and retrieval at each location of the water level loggers.

The Levelloggers were deployed at the following locations:

- Quarry River near Highway 10 in Ferryland,
- Lambes Brook near North St. in Brigus,
- Heart's Delight Brook near Highway 80 in Heart's Delight – Islington,
- Western Pond Brook near Highway 80 in Winterton, and
- Shorts Brook near Critch's Lane in Hant's Harbour.

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 in Victoria to represent atmospheric conditions in Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour, and in Ferryland to represent atmospheric conditions in Ferryland.

An overview of the deployed Barologgers and water level loggers locations throughout the study area are shown on Figure 20, while the precise locations where the levelloggers and barologgers were deployed are shown on Figure 16 and Figure 17. It should be noted, however, that a barologger was not deployed in Brigus, and as such is not shown on Figure 17.

FIGURE 20: LOGGER LOCATIONS



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. The data was compensated for real-time elevations, and 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 21 to Figure 25. It should be noted that an anomaly was observed in the recorded atmospheric pressure data around February 18, 2023, resulting in an erroneous spike in water levels in the compensated water level data. As such, the water levels on and following February 18, 2023, were not used in the model calibration.

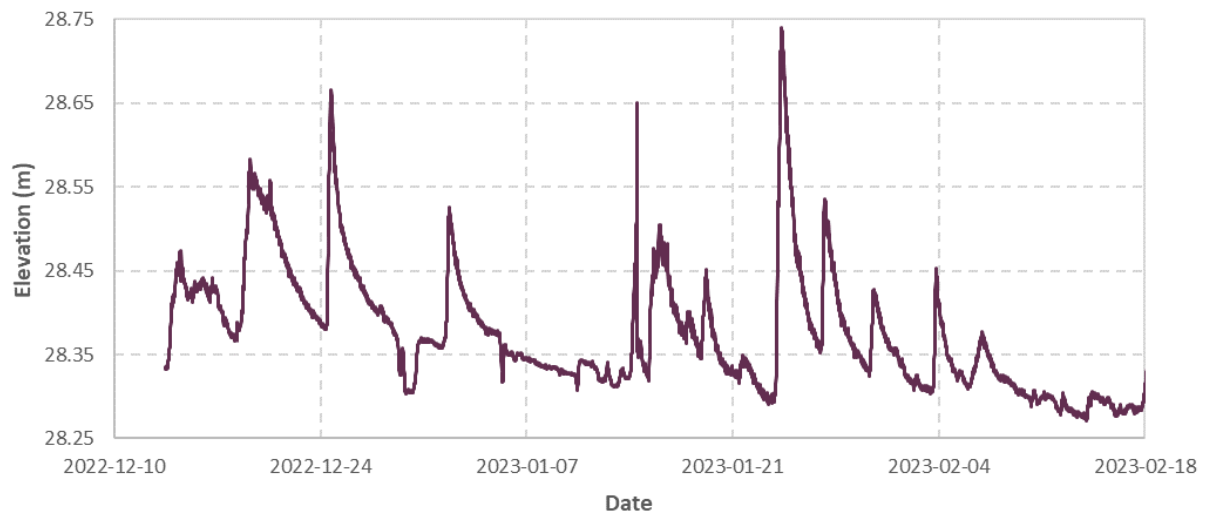
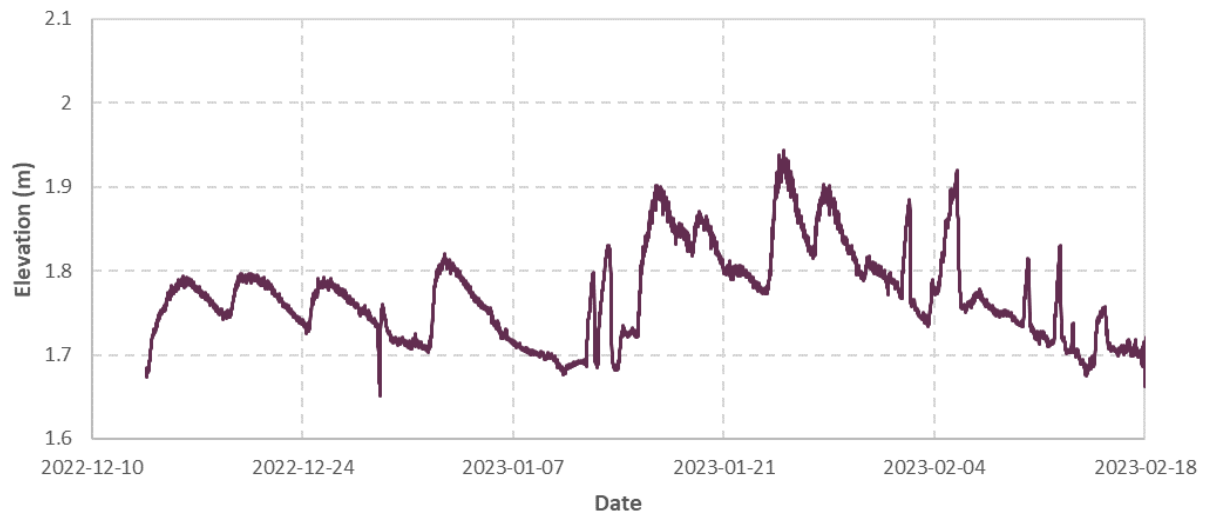
FIGURE 21: QUARRY RIVER (FERRYLAND) RECORDED WATER LEVELS**FIGURE 22: LAMBES BROOK (BRIGUS) RECORDED WATER LEVELS**

FIGURE 23: HEART'S DELIGHT BROOK (HEART'S DELIGHT - ISLINGTON) RECORDED WATER LEVELS

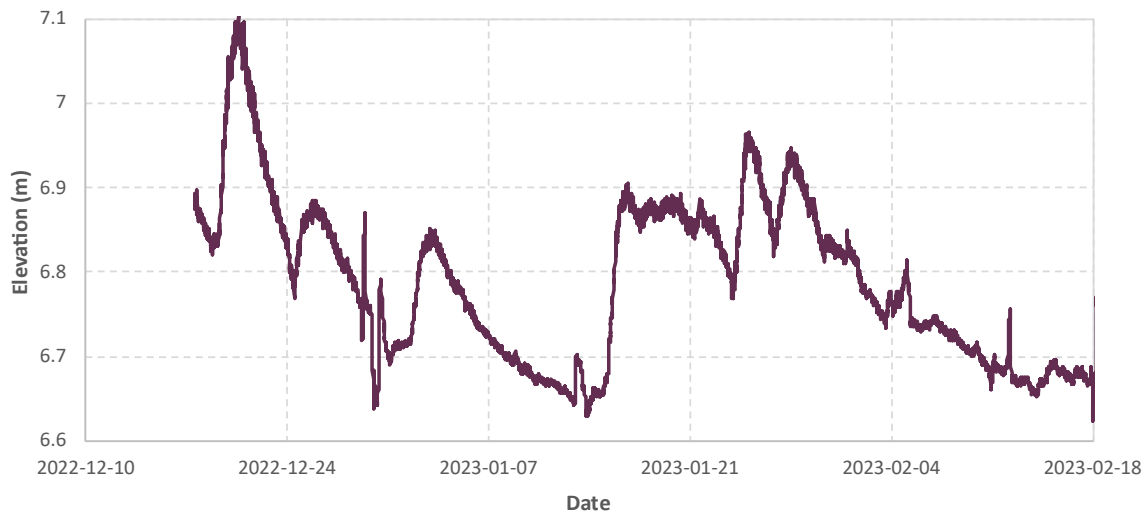


FIGURE 24: WESTERN POND BROOK (WINTERTON) RECORDED WATER LEVELS

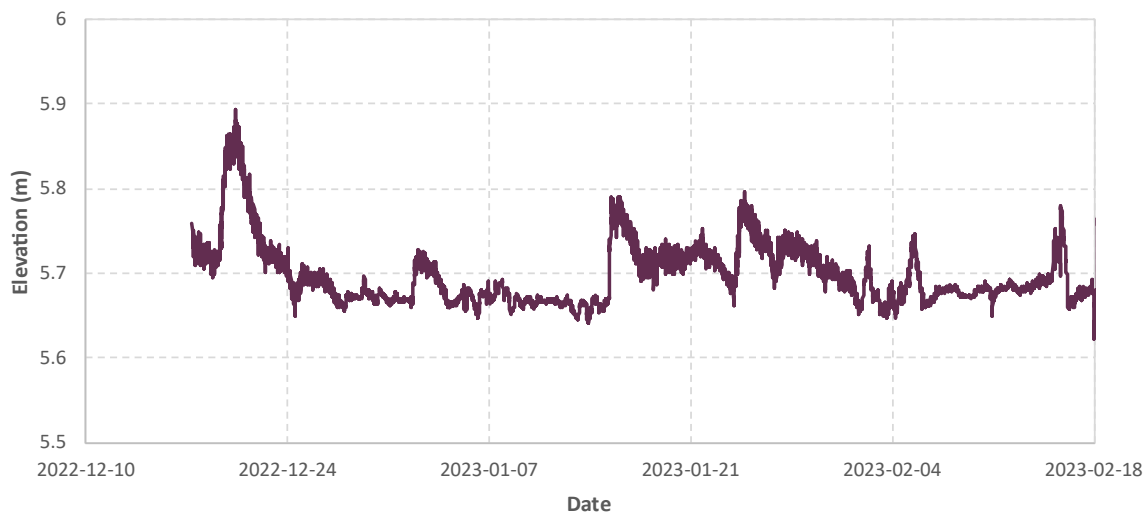
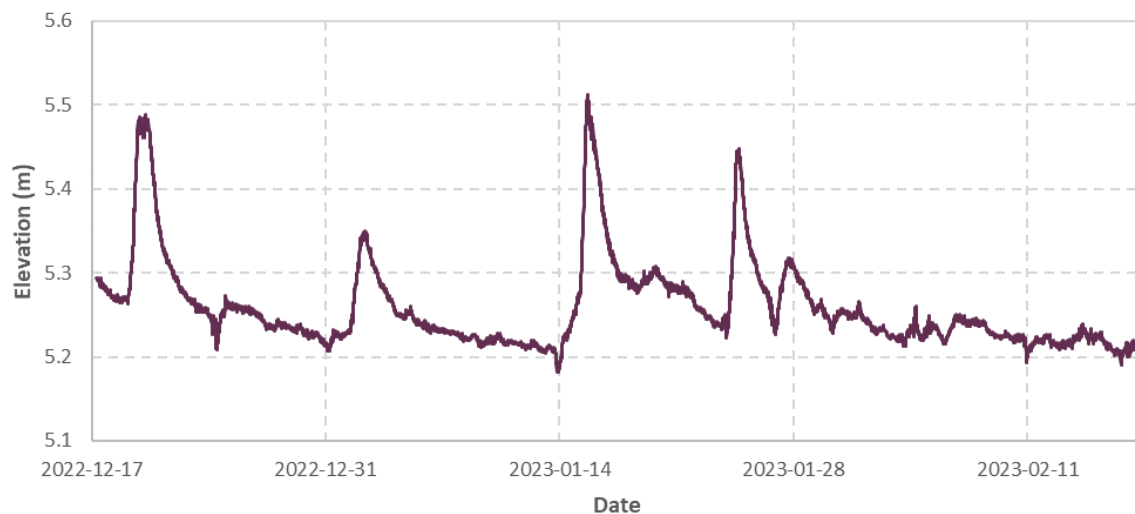


FIGURE 25: SHORT'S BROOK (HANT'S HARBOUR) RECORDED WATER LEVELS

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:

- Quarry River near Highway 10 in Ferryland,
- Lambes Brook near North St. in Brigus,
- Heart's Delight Brook near Highway 80 in Heart's Delight – Islington,
- Western Pond Brook near Highway 80 in Winterton, and
- Shorts Brook near Critch's Lane in Hant's Harbour.

The two flow measurement trips took place between December 13 - 15, 2022, and January 31 – February 2, 2023. Flows were measured using a Sontek FlowTracker Acoustic Doppler Velocimeter (ADV). 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	Dec. 13 – 15 Flow (m ³ /s)	Jan. 31 – Feb. 2 Flow (m ³ /s)
Quarry River near Highway 10 (Ferryland)	0.46	0.37
Lambes Brook near North St. (Brigus)	0.48	0.52
Heart's Delight Brook near Highway 80 (Heart's Delight – Islington)	3.9	2.9
Western Pond Brook near Highway 80 (Winterton)	2.2	0.6
Short's Brook near Critch's Lane (Hant's Harbour)	1.9	0.1

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. Details and characteristics of the hydrometric stations that were adopted as index stations are summarized in Table 4. It should be noted that these index stations were selected given their proximity and relatively comparable drainage areas to the study sites in question, as well as the reasonable agreement between the measured flows and prorated flows at each site. Comparisons of the prorated gauged flows to the measured flows are shown on Figure 26 to Figure 30.

TABLE 4: HYDROMETRIC INDEX STATIONS

Station Number	Station Name	Drainage Area (km ²)	Period of Record
02ZM009	Seal Cove Brook near Cappahayden	53.6	1979 - Present
02ZL004	Shearstown Brook at Shearstown	28.9	1983 - Present
02ZL005	Big Brook at Lead Cove	11.2	1985 - Present

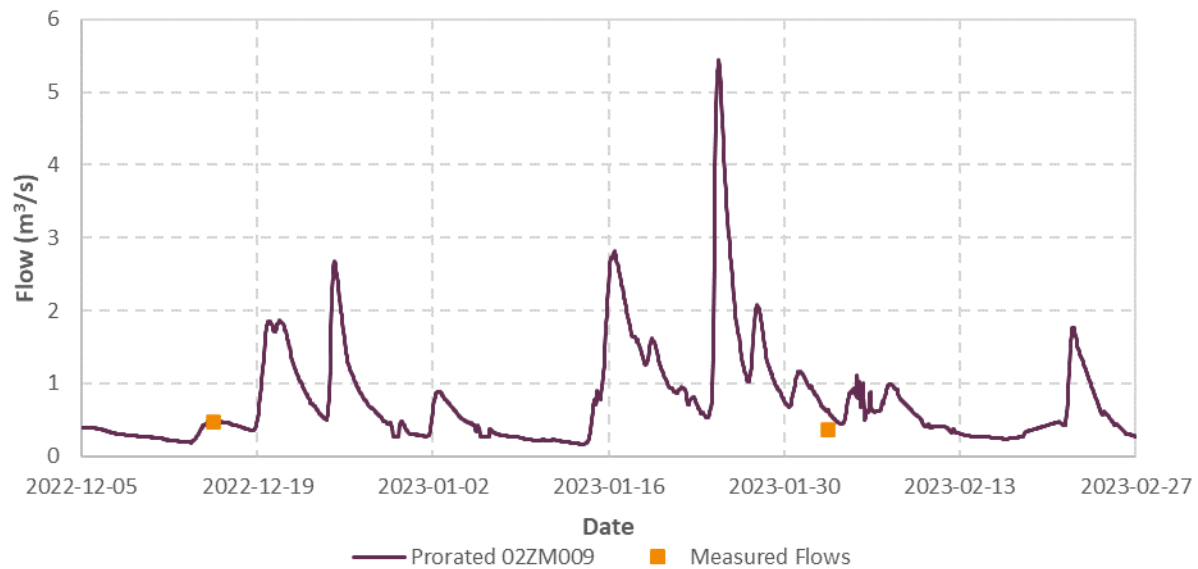
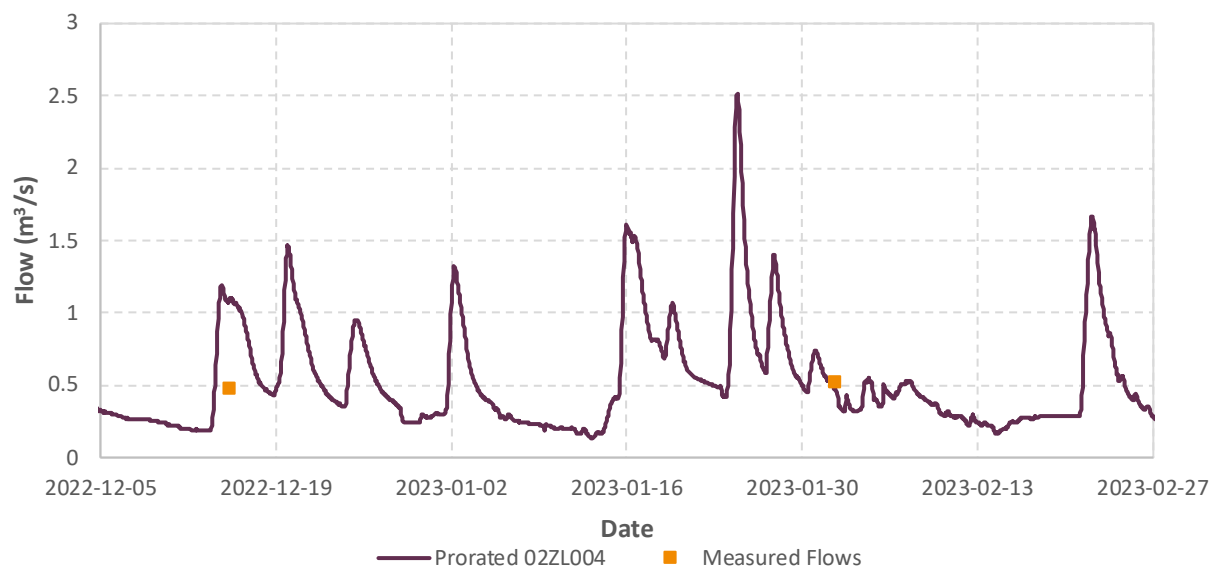
FIGURE 26: COMPARISON OF PRORATED AND OBSERVED FLOWS ON QUARRY RIVER (FERRYLAND)**FIGURE 27: COMPARISON OF PRORATED AND MEASURED FLOWS ON LAMBES BROOK (BRIGUS)**

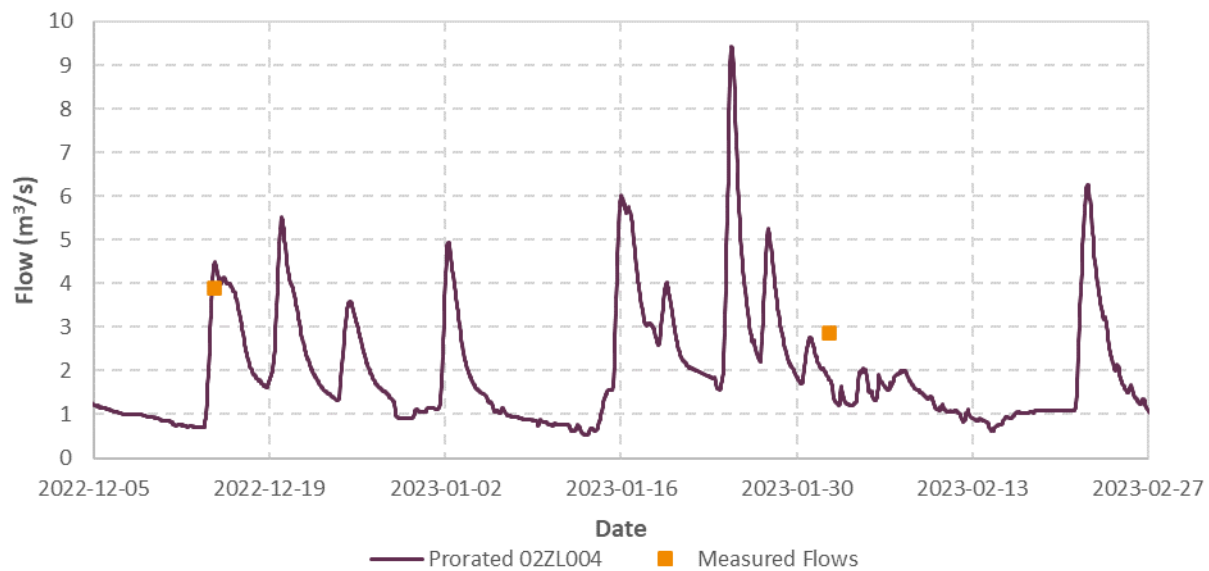
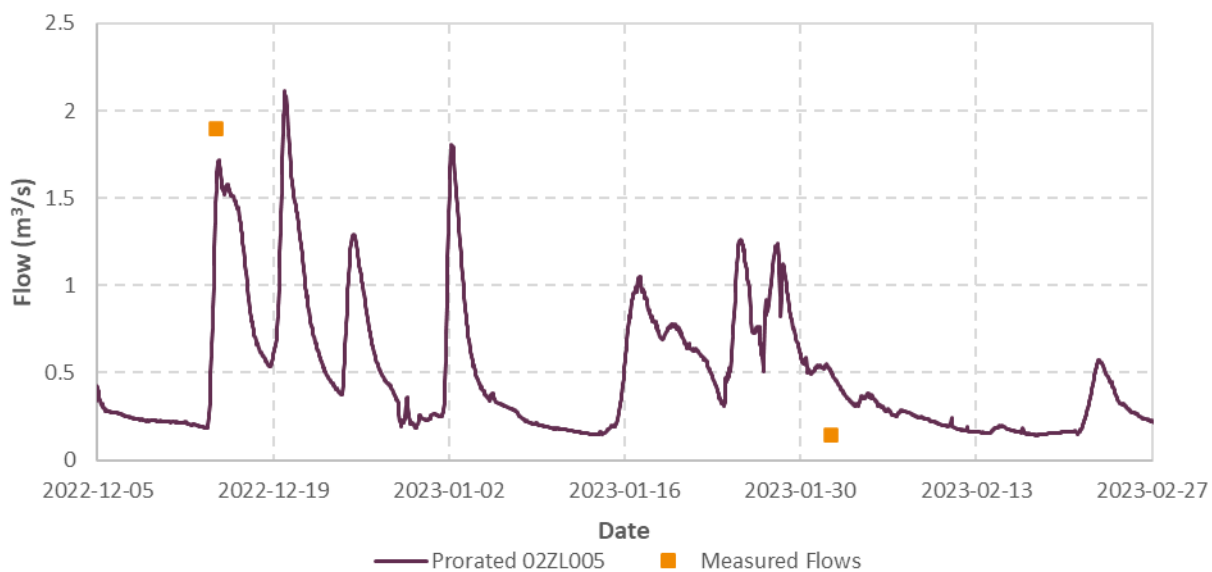
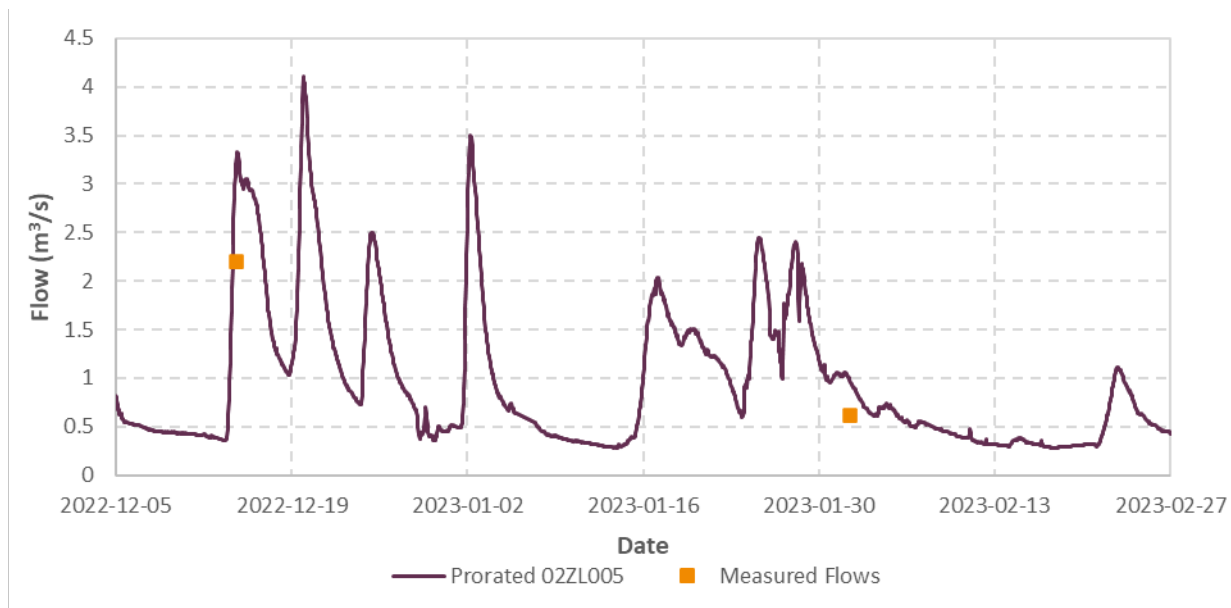
FIGURE 28: COMPARISON OF PRORATED AND OBSERVED FLOWS ON HEART'S DELIGHT BROOK (HEART'S DELIGHT - ISLINGTON)**FIGURE 29: COMPARISON OF PRORATED AND MEASURED FLOWS ON SHORT'S BROOK (HANT'S HARBOUR)**

FIGURE 30: COMPARISON OF PRORATED AND MEASURED FLOWS ON WESTERN POND BROOK (WINTERTON)



The comparison of prorated and measured flows generally showed good agreement, with the exception of the exception of the flows on December 13, 2022, in Brigus (i.e. Figure 27). However, the discrepancy between the prorated and measured flows for that day can be attributed to the different shape and size of the basin, as well as the number of relatively large ponds within each basin.

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. 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 285 locations in Ferryland, with 121 points located on firm or flat ground (i.e. at bridge and culvert crossings) and the remaining 164 located in vegetated areas (i.e. ground and bank shots at surveyed cross section locations). In Brigus, comparisons were made at 631 locations, with 385 of those located on flat and firm ground and the remaining 246 located in vegetated areas. In Heart's Delight – Islington, comparisons were made at a total of 196 locations, with 73 being located on hard surfaces, and the remaining 123 being located in vegetated areas. In Winterton and Hant's Harbour, comparisons were made at 290 locations, with 103 located on hard surfaces and 187 located on vegetated areas. The resulting calculated between surveyed points and the HRDEM surface were found to be acceptable. The results are summarized in Table 5.

TABLE 5: HRDEM SURFACE STATISTICS

Type	Location	Count	Difference			
			Mean Difference (m)	Standard Deviation (m)	Minimum Difference (m)	Maximum Difference (m)
Hard Surface	Ferryland	121	-0.010	0.076	-0.154	0.245
	Brigus	385	-0.036	0.045	-0.197	0.199
	Heart's Delight - Islington	73	-0.017	0.048	-0.130	0.154
	Winterton and Hant's Harbour	103	0.025	0.121	-0.217	0.268
Vegetated Surface	Ferryland	164	-0.073	0.202	-0.803	0.661
	Brigus	246	-0.123	0.204	-0.979	0.597
	Heart's Delight - Islington	123	0.004	0.191	-0.338	0.503
	Winterton and Hant's Harbour	187	-0.118	0.195	-0.662	0.649
Combined	Ferryland	285	-0.046	0.164	-0.804	0.661
	Brigus	631	-0.070	0.139	-0.979	0.597
	Heart's Delight - Islington	196	-0.004	0.155	-0.338	0.503
	Winterton and Hant's Harbour	290	-0.067	0.18	-0.662	0.649

It should be noted that recent advances in LiDAR capture have included the implementation of topo-bathy LiDAR, which includes collection of both above and below-water ground surface elevations. The collection of topo-bathy LiDAR should be reviewed by WRMD for future flood mapping efforts, as it may provide an efficient means of collecting bathymetric data in areas where flood mapping studies are envisioned.

3.5 Field Verification

The DEM and flood hazard maps were verified based on a combination of input from representatives from the Towns of Hant's Harbour, Brigus, and Ferryland, 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

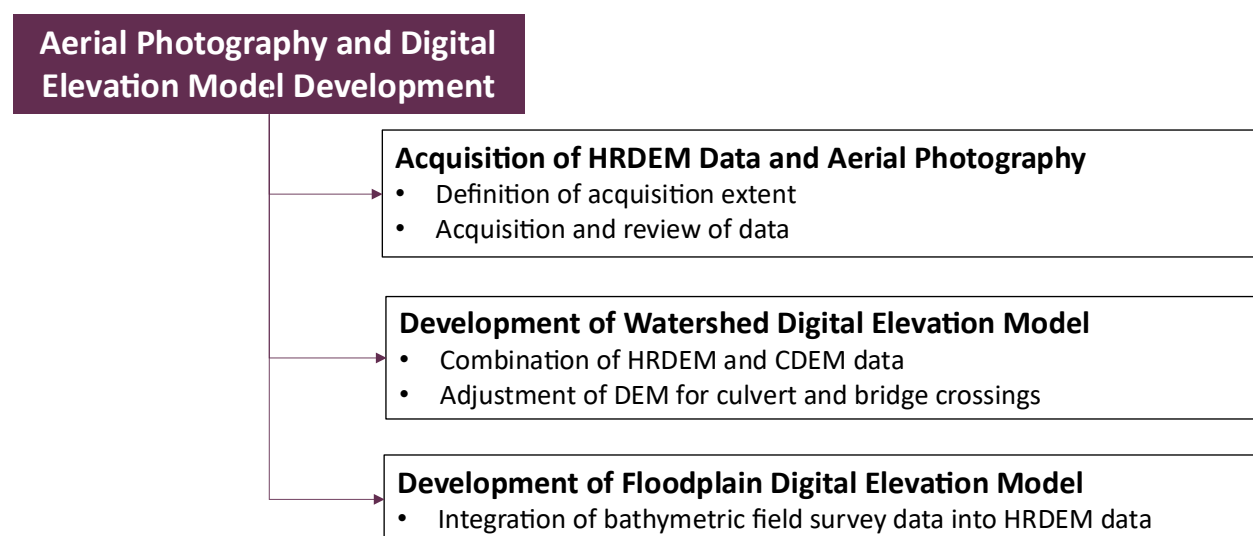
Existing aerial photography data was acquired from the Government of Newfoundland and Labrador, while an existing high-resolution model representing the above-water ground surface was acquired from Natural Resources Canada (NRCan), known as the High-Resolution Digital Elevation Model (HRDEM), described in Section 3.4. The HRDEM data acquired from NRCan was used to represent the ground surface elevation throughout the study area, while the aerial imagery acquired from the Government of Newfoundland and Labrador was used as a high resolution imagery background in the flood hazard and flood risk 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 hazard and flood risk 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 that was 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 31.

FIGURE 31: 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 orthophotos. 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 Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour, the imagery was generally well colour balanced and consistent.

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 HRDEM has a spatial resolution of 1 m by 1 m. The HRDEM data is provided by NRCan in the Universal Transverse Mercator (UTM) NAD83 (CSRS) coordinate system and CGVD2013 vertical datum. Accordingly, 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 hazard mapping study.

4.3 Development of Watershed Digital Elevation Model

Watershed DEMs were developed for the various watersheds considered as part of the study. 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 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.

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 Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour areas are shown on Figure 32 to Figure 35. The footprints of the HRDEM data are highlighted in purple, with the remaining data being defined by the CDEM.

FIGURE 32: FERRYLAND WATERSHED DEM

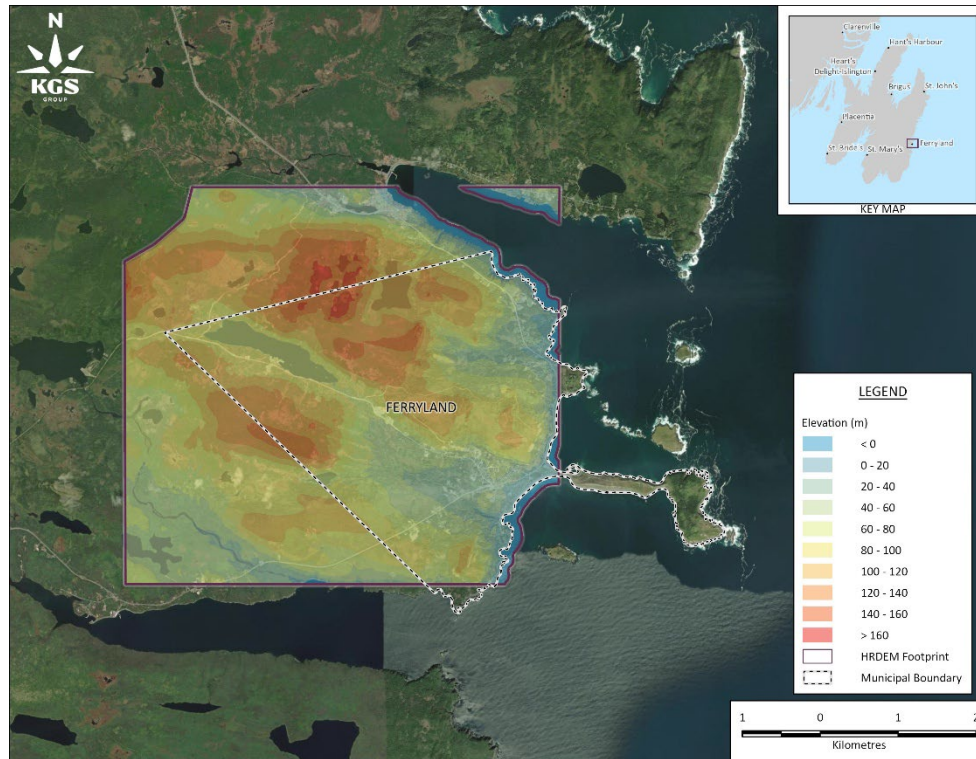


FIGURE 33: BRIGUS WATERSHED DEM

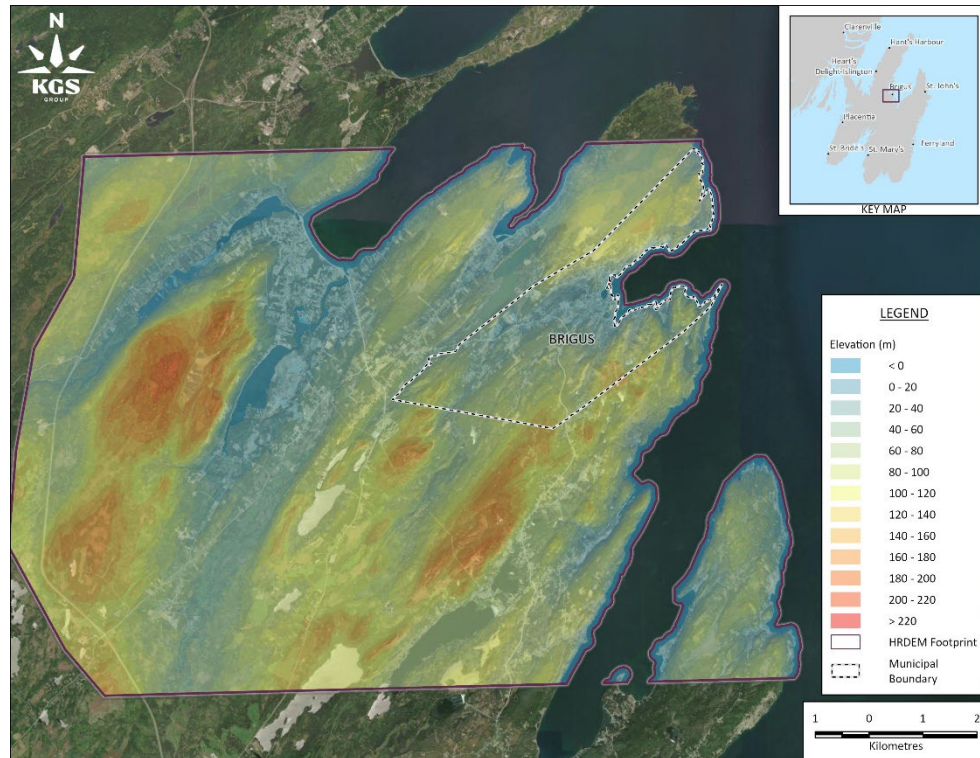


FIGURE 34: HEART'S DELIGHT - ISLINGTON WATERSHED DEM

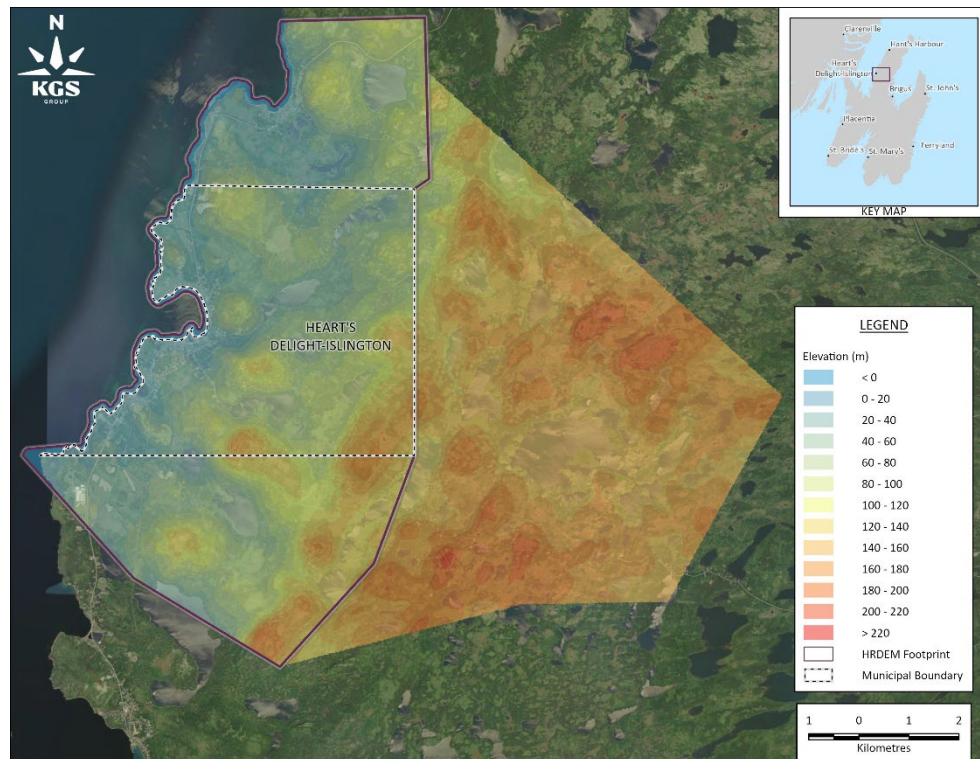
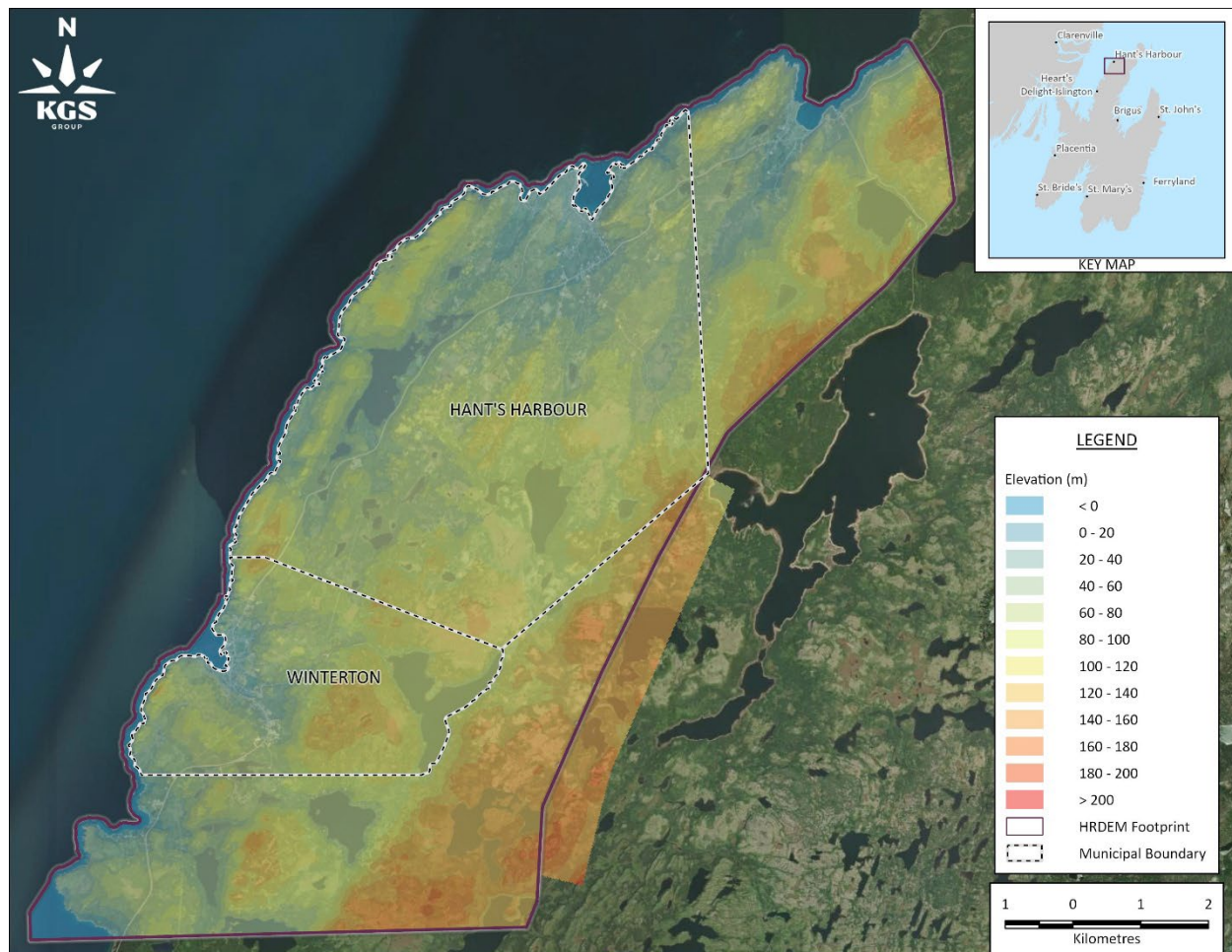


FIGURE 35: WINTERTON AND HANT'S HARBOUR WATERSHED DEM



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 along the coastline in Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour was developed based on a combination of NONNA bathymetry data from the CHS, surveyed coastal cross sections, and available nautical charts. Bathymetry in areas where no data was available was defined by interpolating between the available data. 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 were defined based on the LiDAR data to seamlessly merge the coastal bathymetry DEM into the HRDEM to infill the below-water portion of the HRDEM.

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. It should be noted that in general, the calculated depth of water in the HRDEM data that was estimated from the survey data was generally in the range of 0.3 m.

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 study areas. An example of this infilling is shown on Figure 36, while the bare earth DEMs for Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour are shown on Figure 37 to Figure 40.

FIGURE 36: COMPARISON OF ORIGINAL AND MODIFIED HRDEM

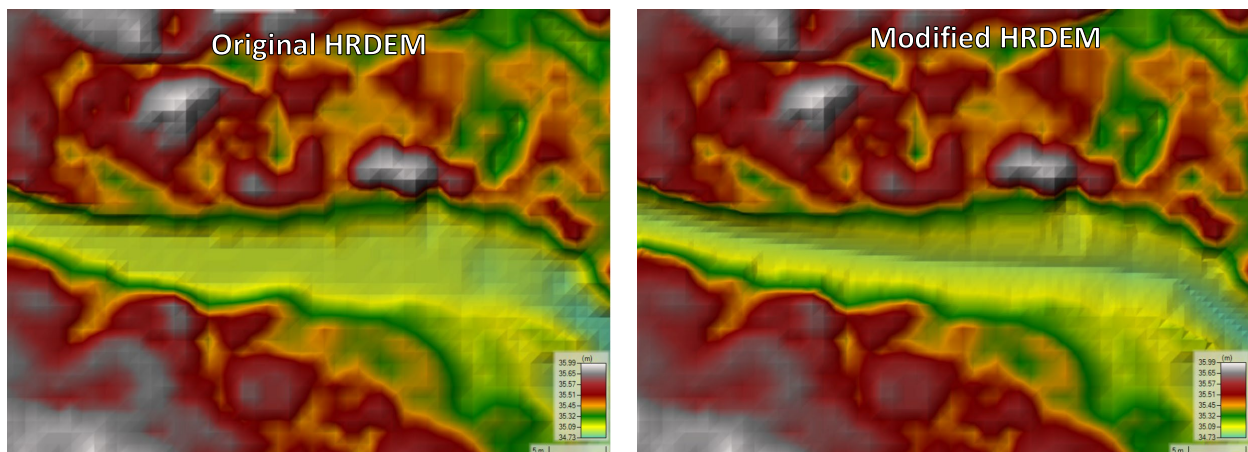


FIGURE 37: FERRYLAND FLOOD PLAIN DEM

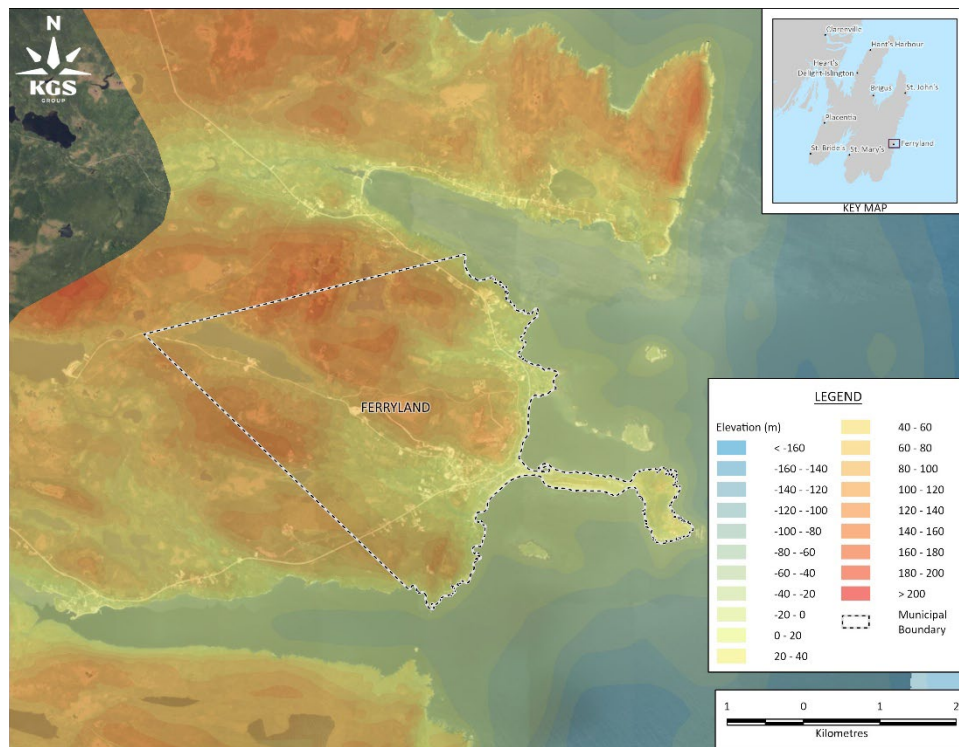


FIGURE 38: BRIGUS FLOOD PLAIN DEM

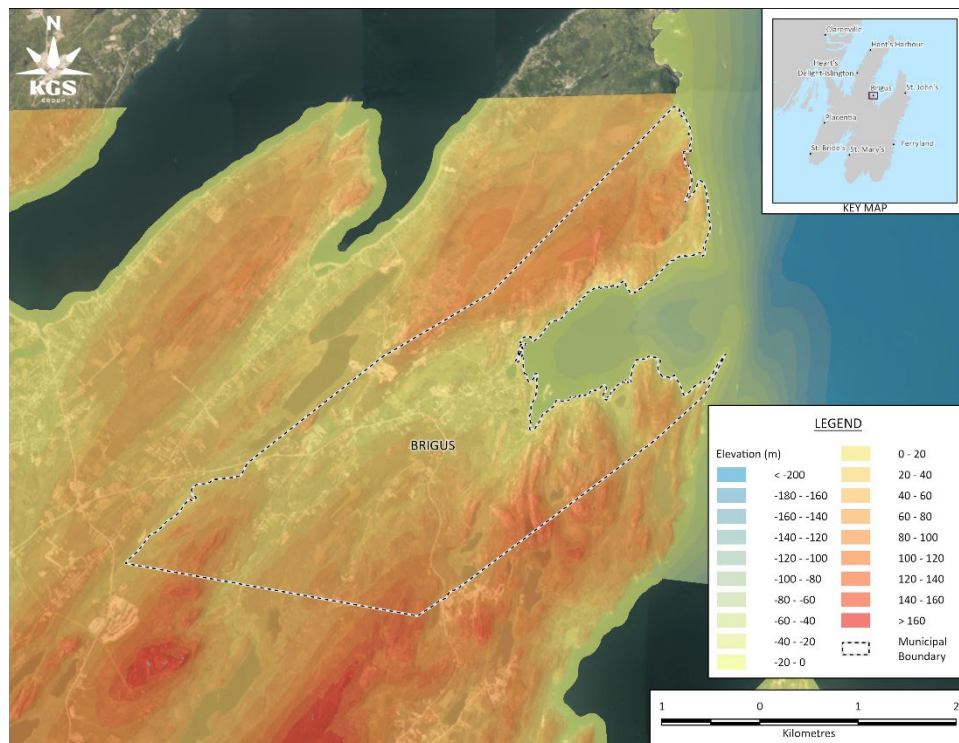


FIGURE 39: HEART'S DELIGHT - ISLINGTON FLOOD PLAIN DEM

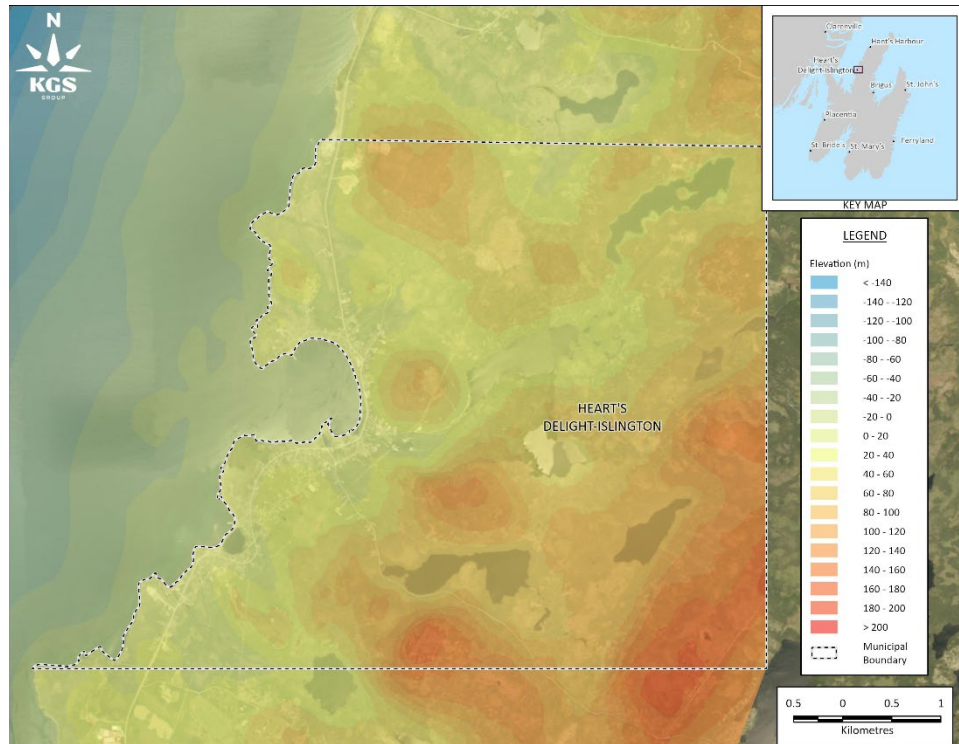
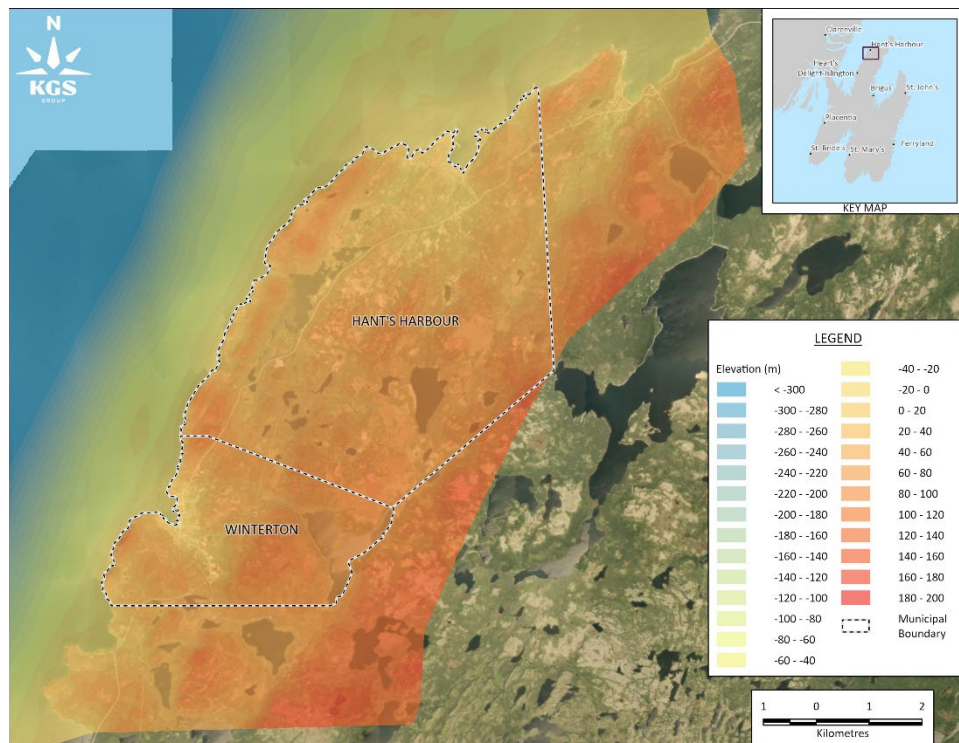


FIGURE 40: WINTERTON AND HANT'S HARBOUR FLOOD PLAIN DEM



5.0 REMOTE SENSING AND LAND USE CLASSIFICATION

5.1 Overview

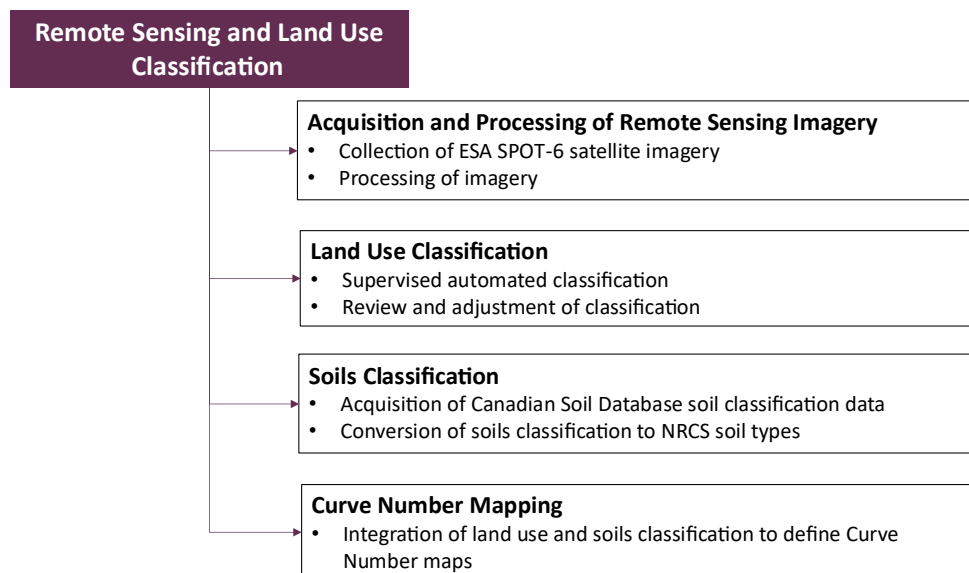
Land use throughout the study areas was classified using high resolution satellite imagery collected by the European Space Agency's (ESA) SPOT-6 satellites. The SPOT-6 satellites collect images using different sensors to capture different portions of the light spectrum, and capture high resolution imagery over large swaths of land. The imagery that was used to classify the land use within the study area was from June 25, 2021 (i.e. Ferryland and Brigus) and June 19, 2016 (i.e. Winterton, Hant's Harbour, and Heart's Delight – Islington).

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 Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour 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 41.

FIGURE 41: OVERVIEW OF REMOTE SENSING AND LAND USE CLASSIFICATION

5.2 Acquisition and Processing of Remote Sensing Imagery

SPOT-6 satellite imagery was downloaded from the ESA, specifically captures of the Ferryland and Brigus areas completed on June 25, 2021, and the Heart's Delight – Islington, Winterton and Hant's Harbour areas capture completed on June 19, 2016. 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 minutes, resulting in a repeating capture cycle every 26 days. The spectral bands that SPOT-6 captures are summarized in Table 6.

TABLE 6: 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 the Ferryland and Brigus, and Heart's Delight – Islington, Winterton and Hant's Harbour area captures were each 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 four tiles covering the acquisition areas (i.e. one tile covering Ferryland, one tile covering Brigus, one tile covering Heart's Delight - Islington, and one tile covering Winterton and Hant's Harbour). A review was completed to ensure that the SPOT-6 imagery aligned well with the 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.

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 7.

TABLE 7: 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 maps for Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour are shown on Figure 42 to Figure 45.

FIGURE 42: FERRYLAND LAND USE CLASSIFICATION MAP

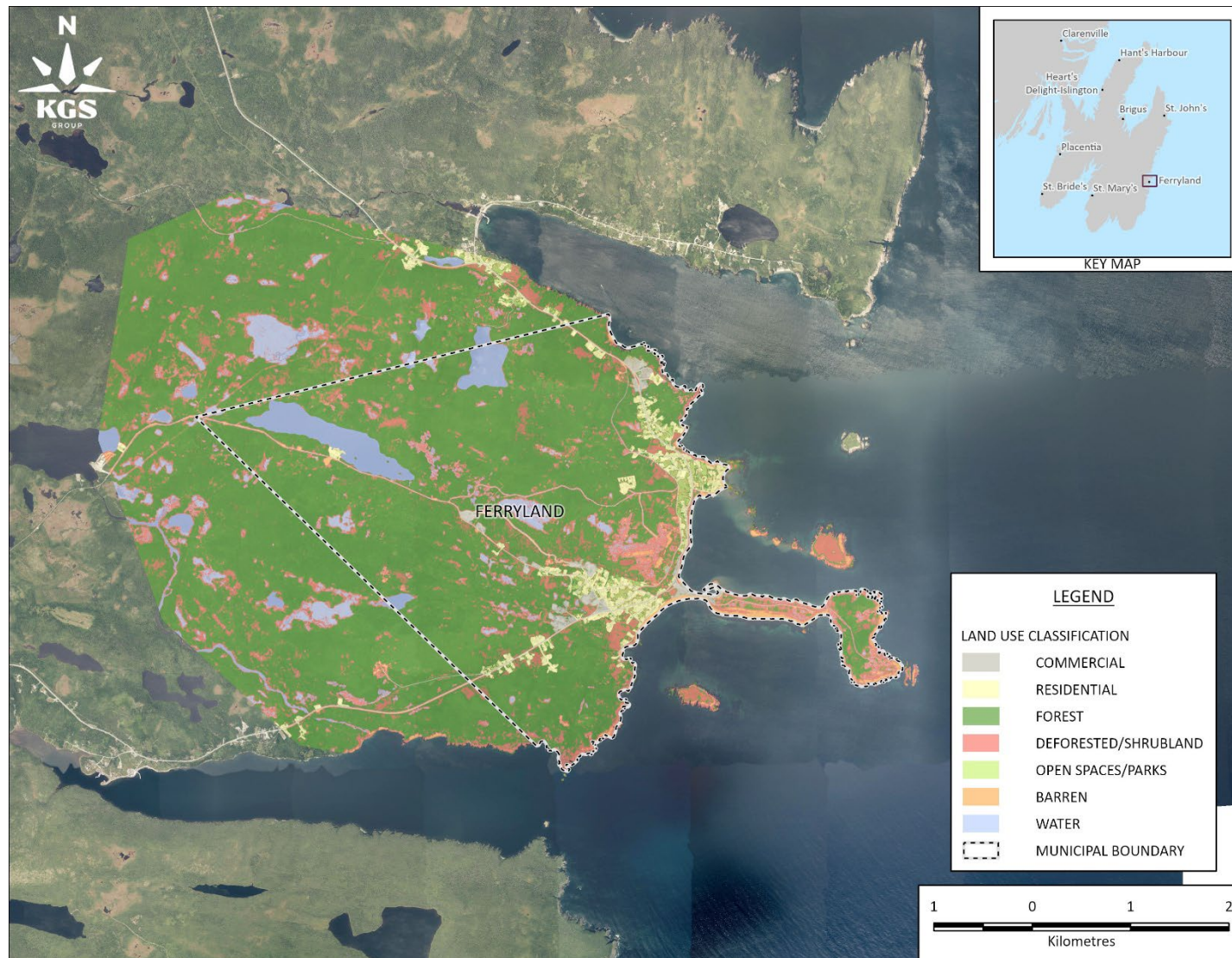


FIGURE 43: BRIGUS LAND USE CLASSIFICATION MAP

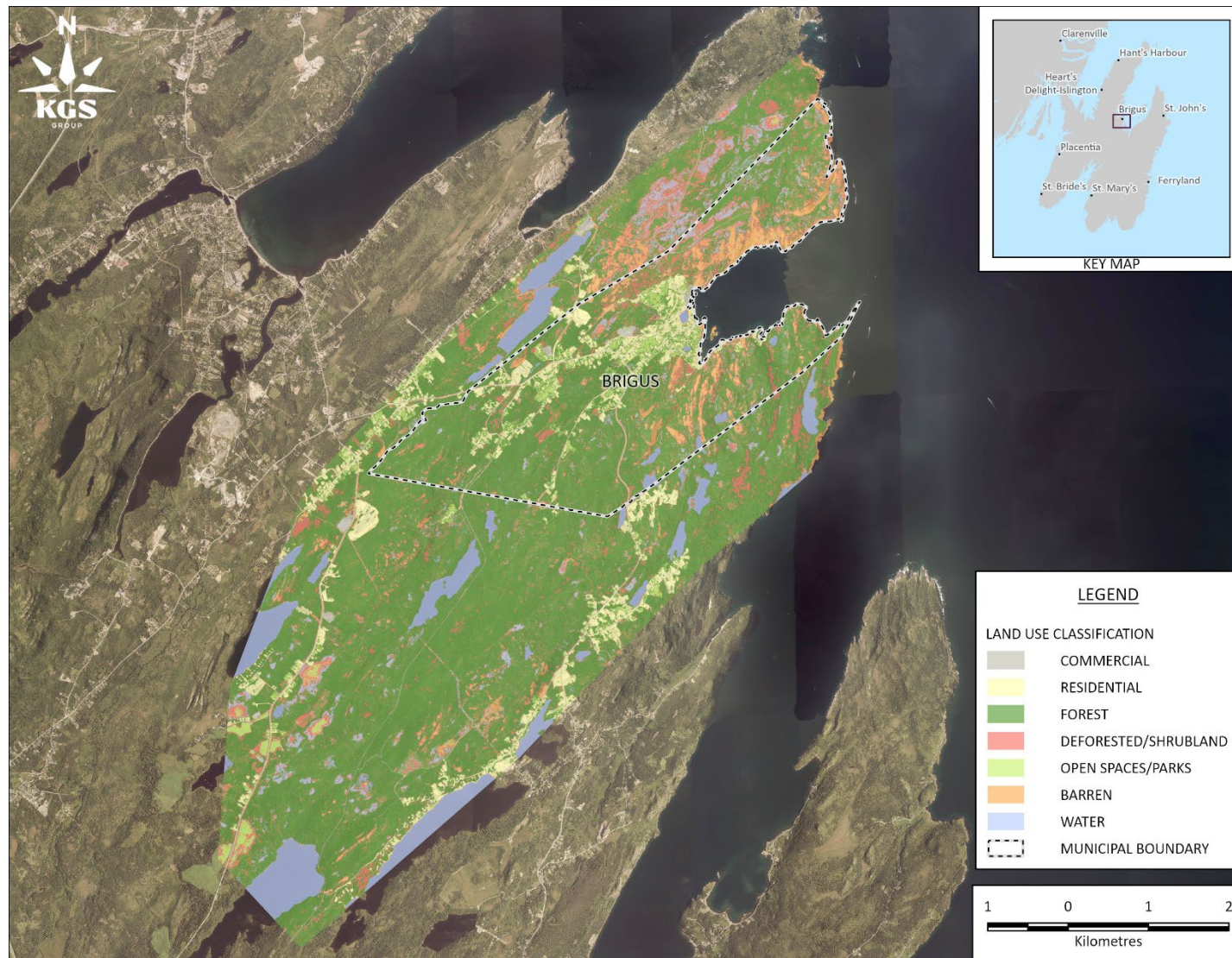


FIGURE 44: HEART'S DELIGHT – ISLINGTON LAND USE CLASSIFICATION MAP

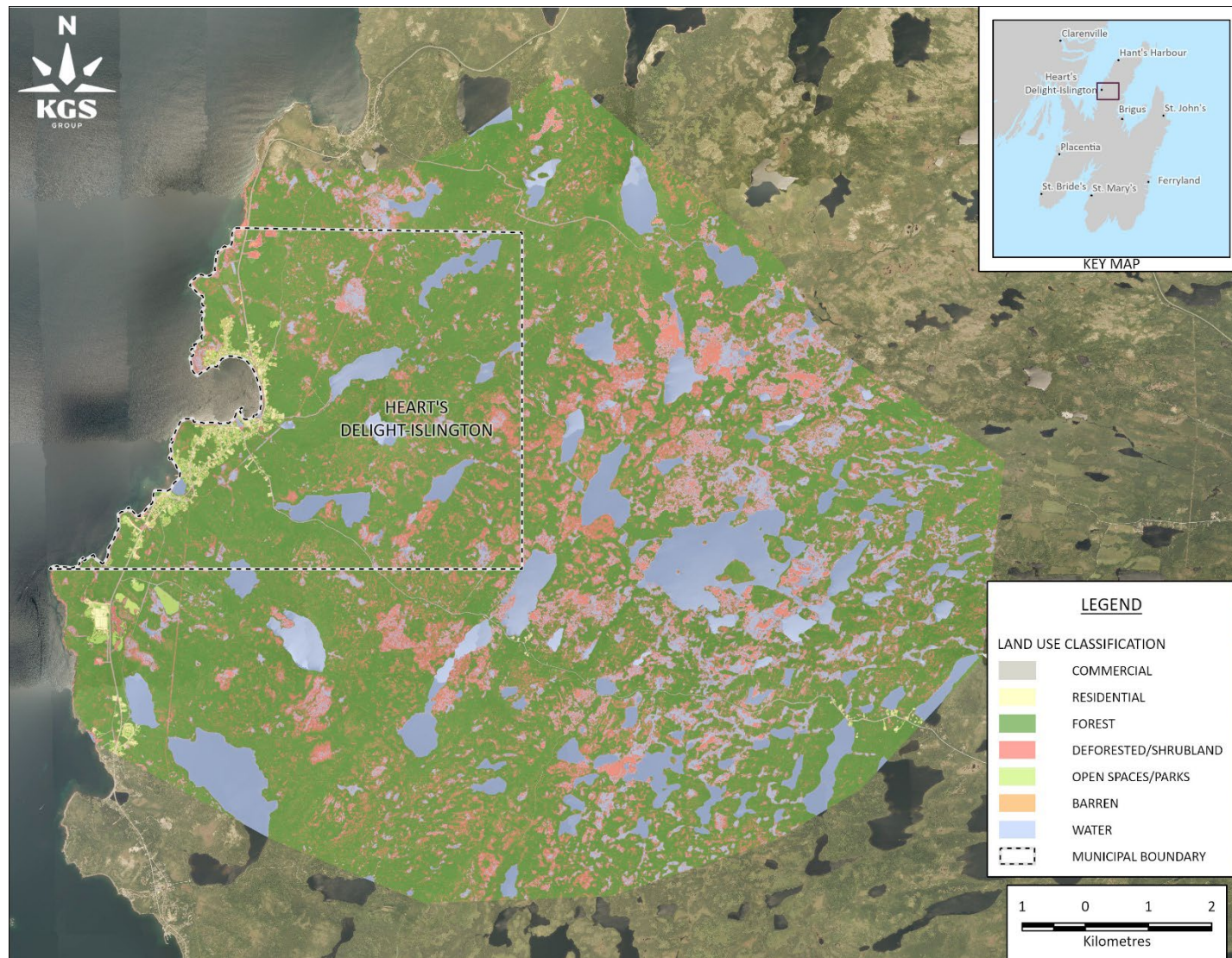
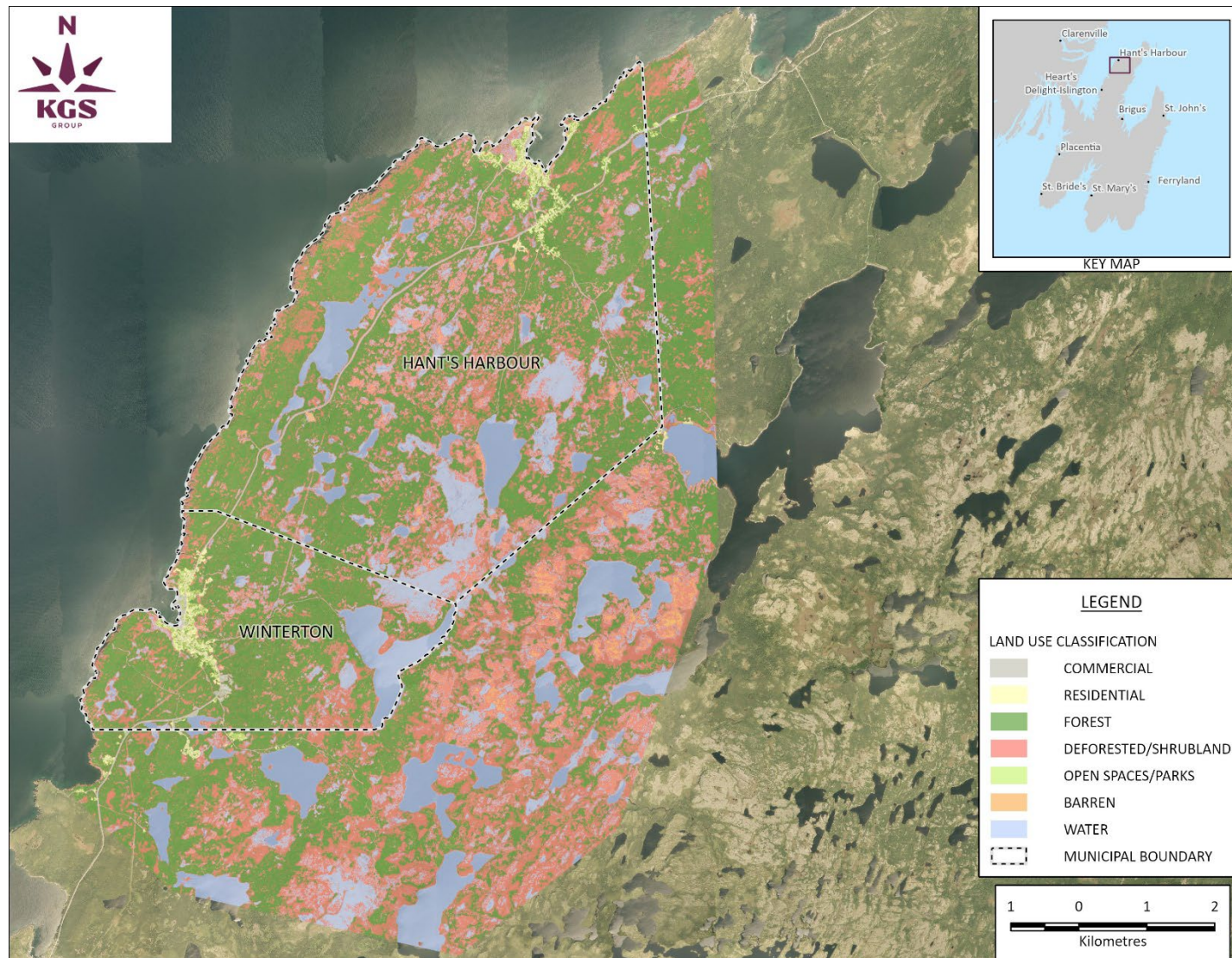


FIGURE 45: WINTERTON AND HANT'S HARBOUR LAND USE CLASSIFICATION MAP



5.4 Soils Classification

Available soil classification data included in 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. For instances where a given polygon contained more than one soil type, the soil type resulting in greater runoff was adopted for the full polygon. 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 8.

TABLE 8: 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 maps for Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour are shown on Figure 46 to Figure 49.

FIGURE 46: FERRYLAND SOIL CLASSIFICATION MAP

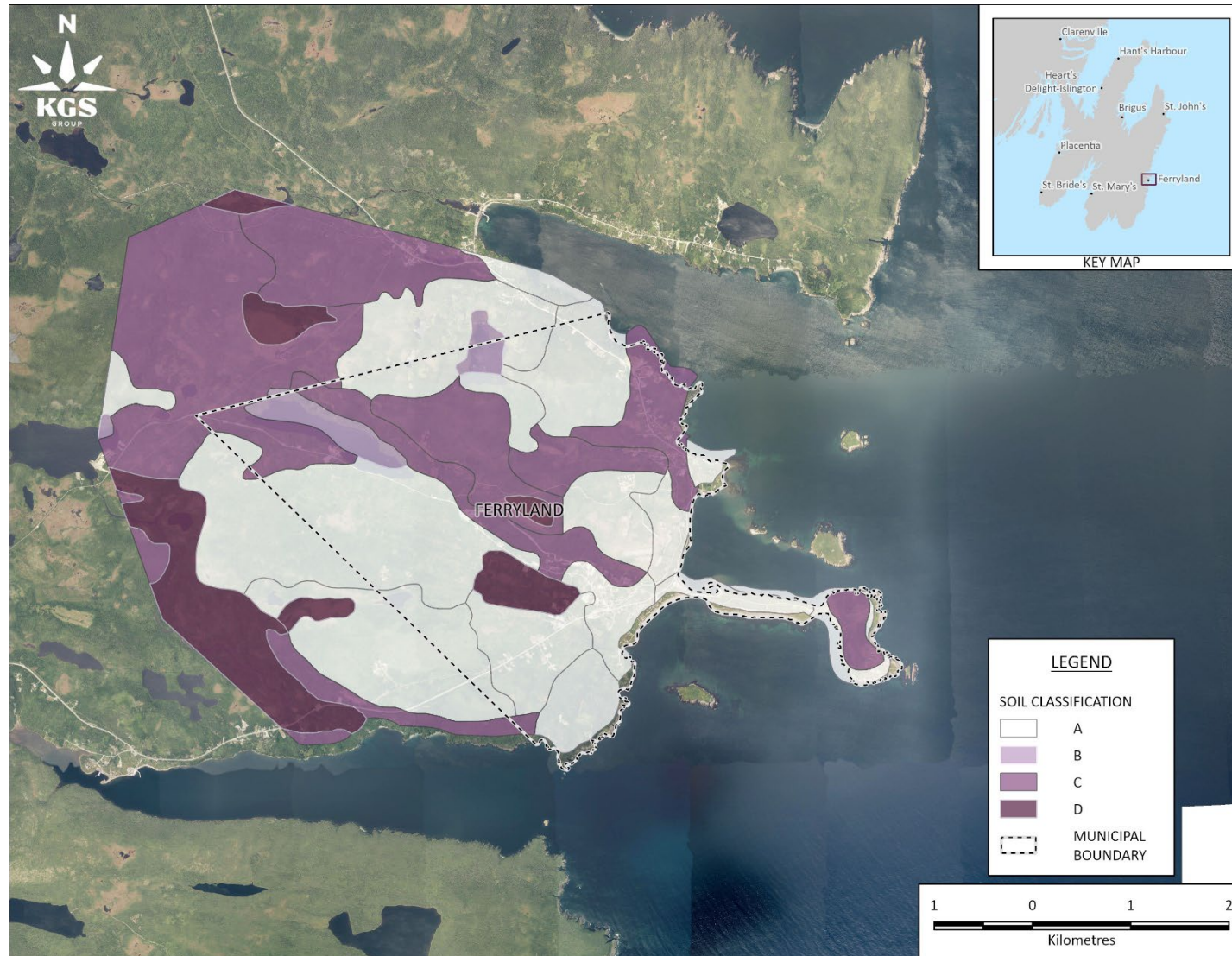


FIGURE 47: BRIGUS SOIL CLASSIFICATION MAP

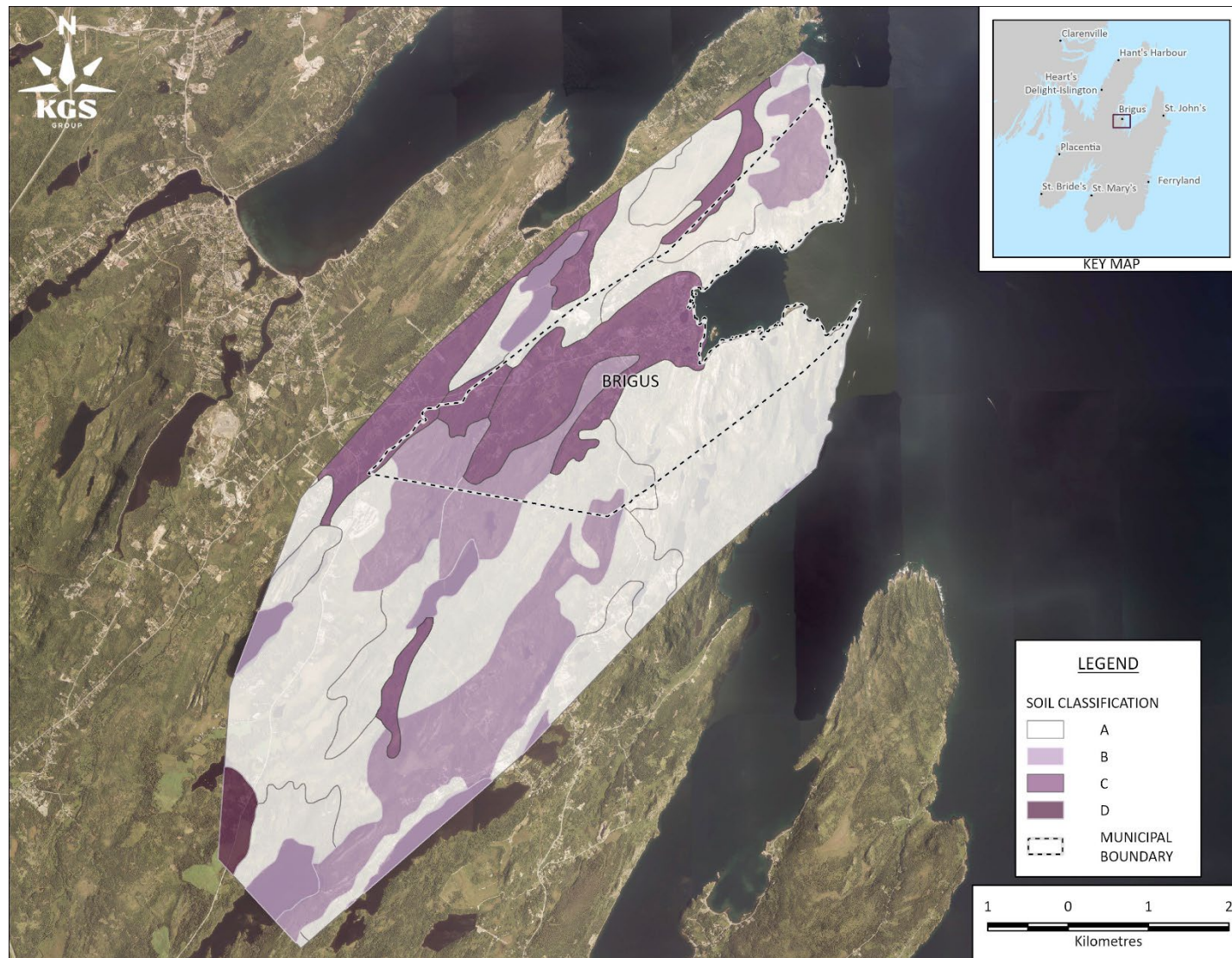


FIGURE 48: HEART'S DELIGHT – ISLINGTON SOIL CLASSIFICATION MAP

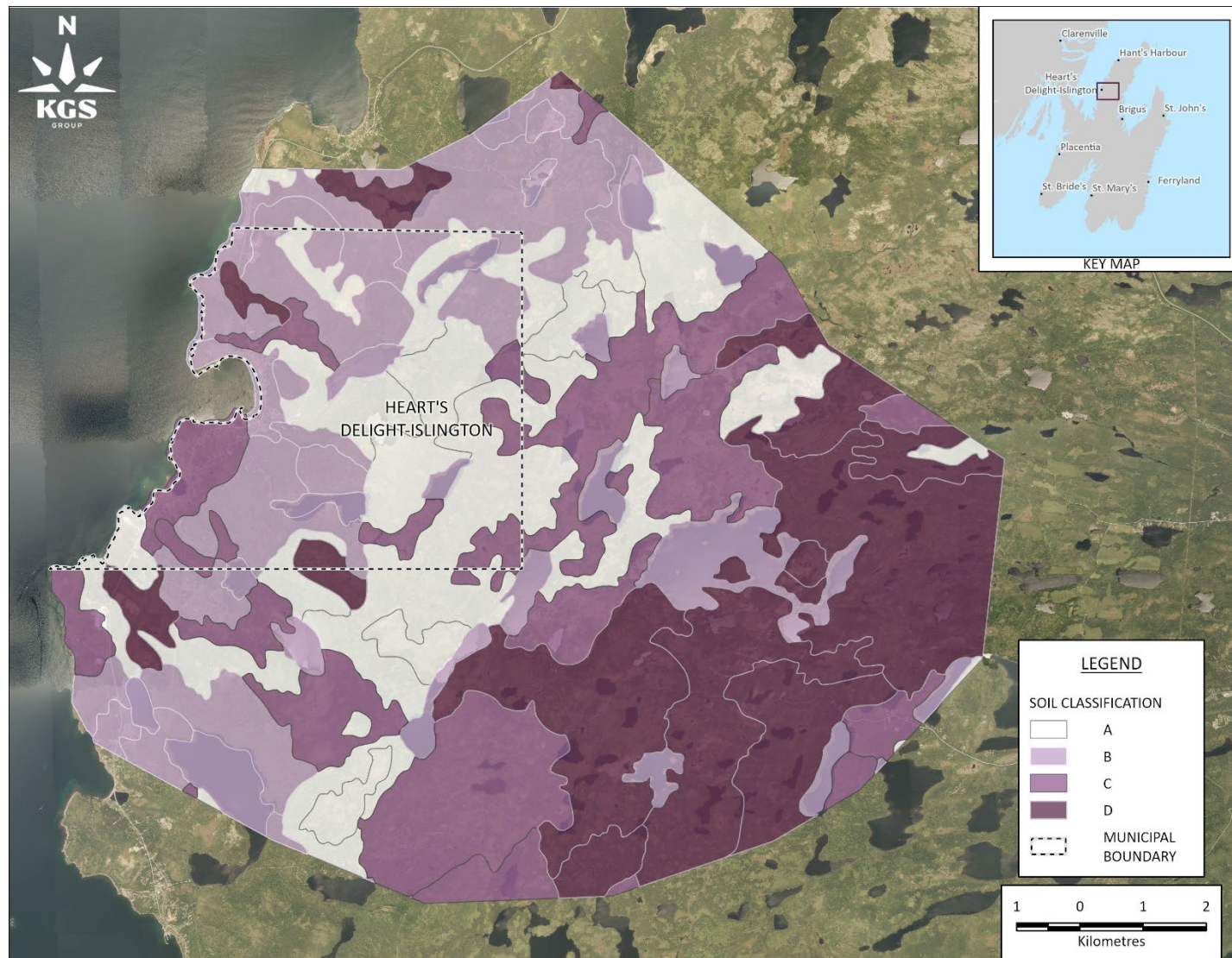
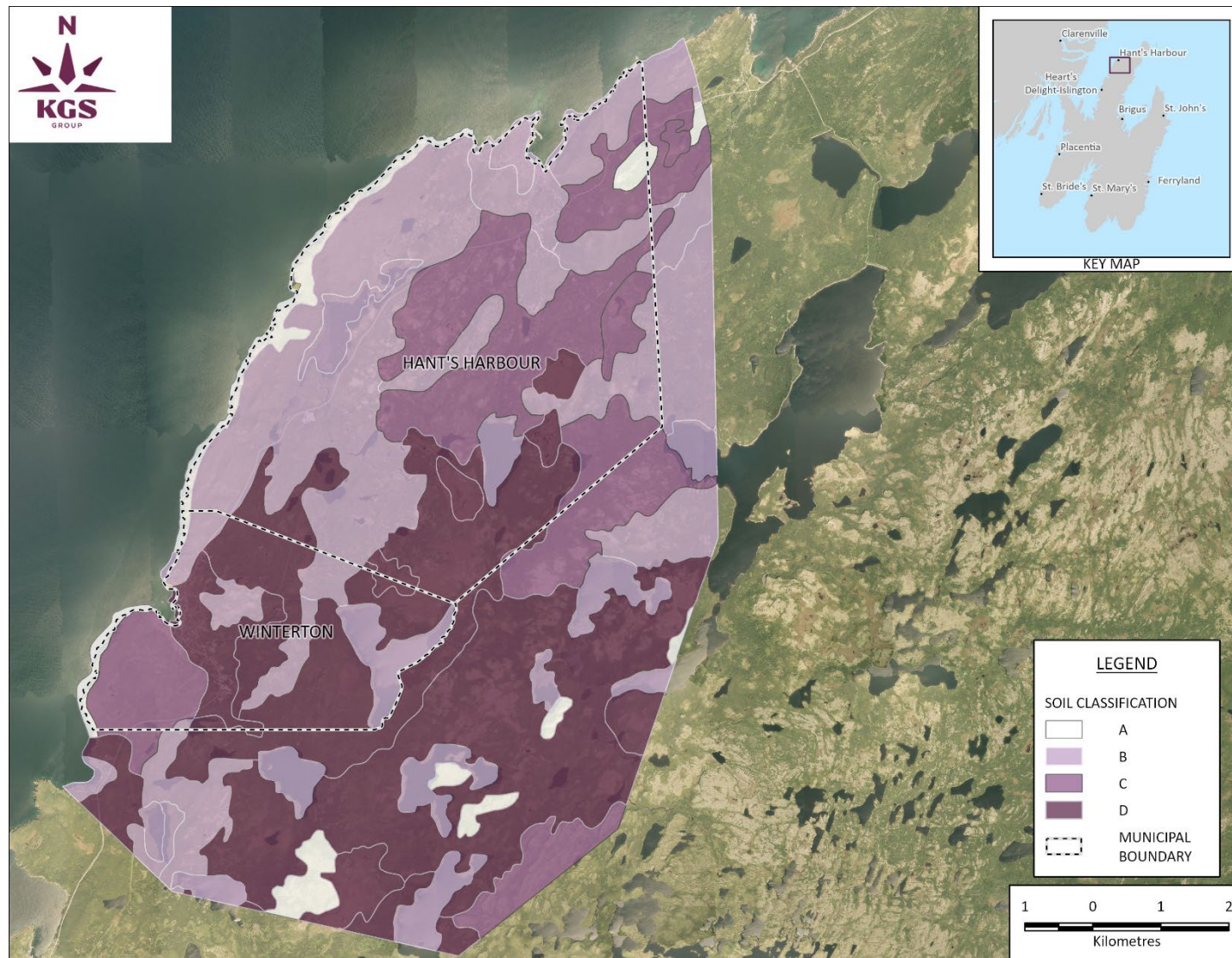


FIGURE 49: WINTERTON AND HANT'S HARBOUR SOIL CLASSIFICATION MAP



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 Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour. 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 9.

TABLE 9: 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 Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour are shown on Figure 50 to Figure 53.

FIGURE 50: FERRYLAND CURVE NUMBER MAP

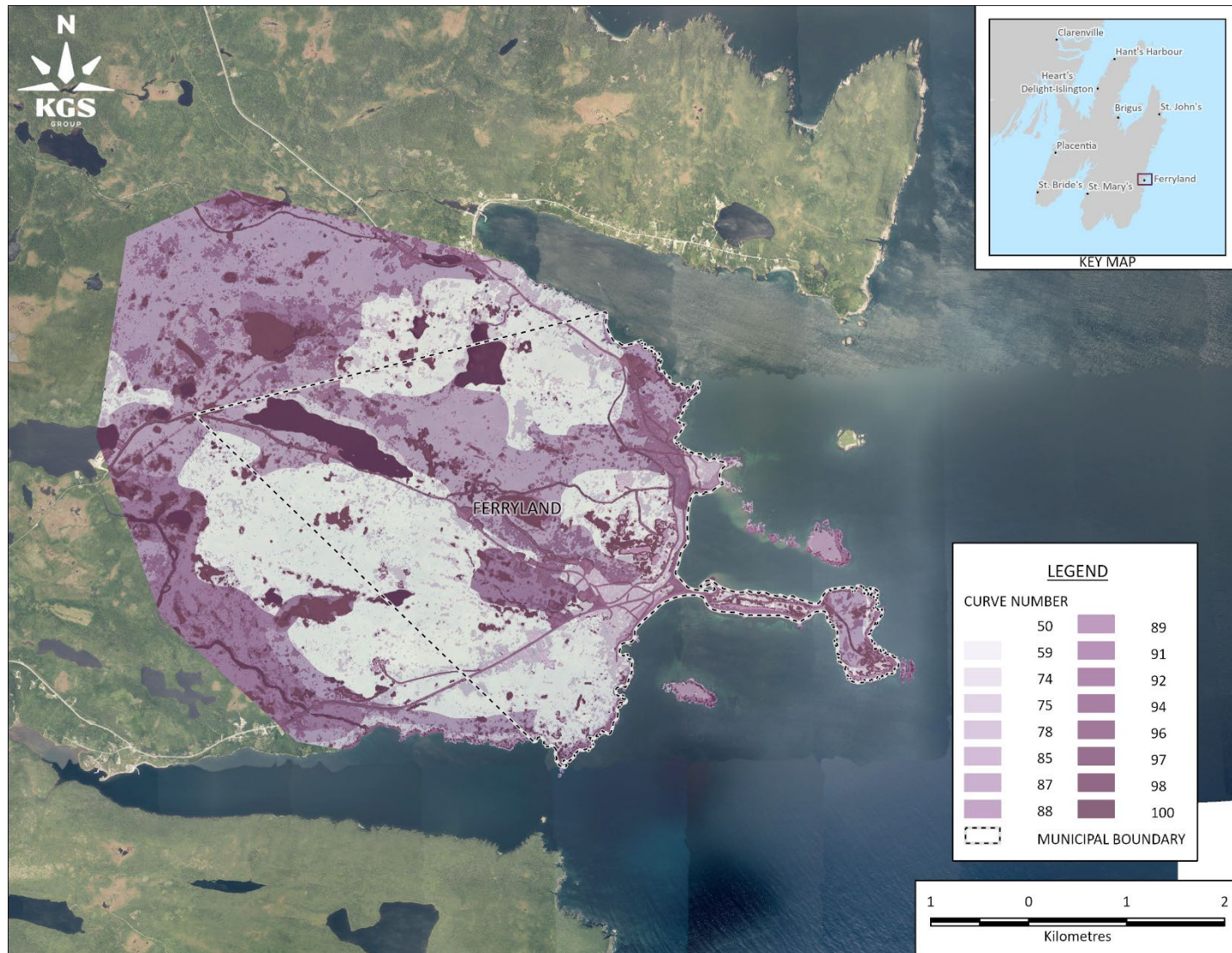


FIGURE 51: BRIGUS CURVE NUMBER MAP

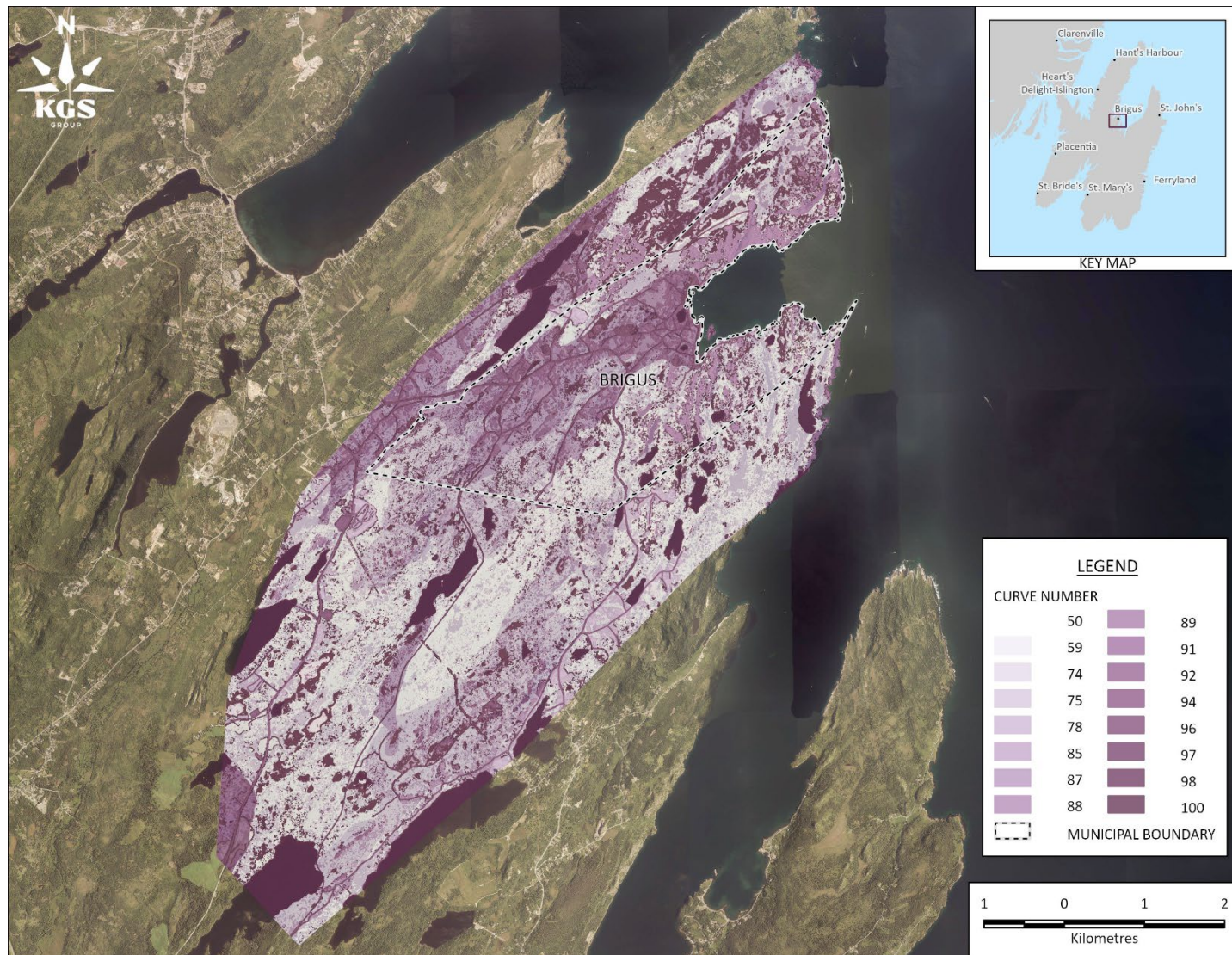


FIGURE 52: HEART'S DELIGHT - ISLINGTON CURVE NUMBER MAP

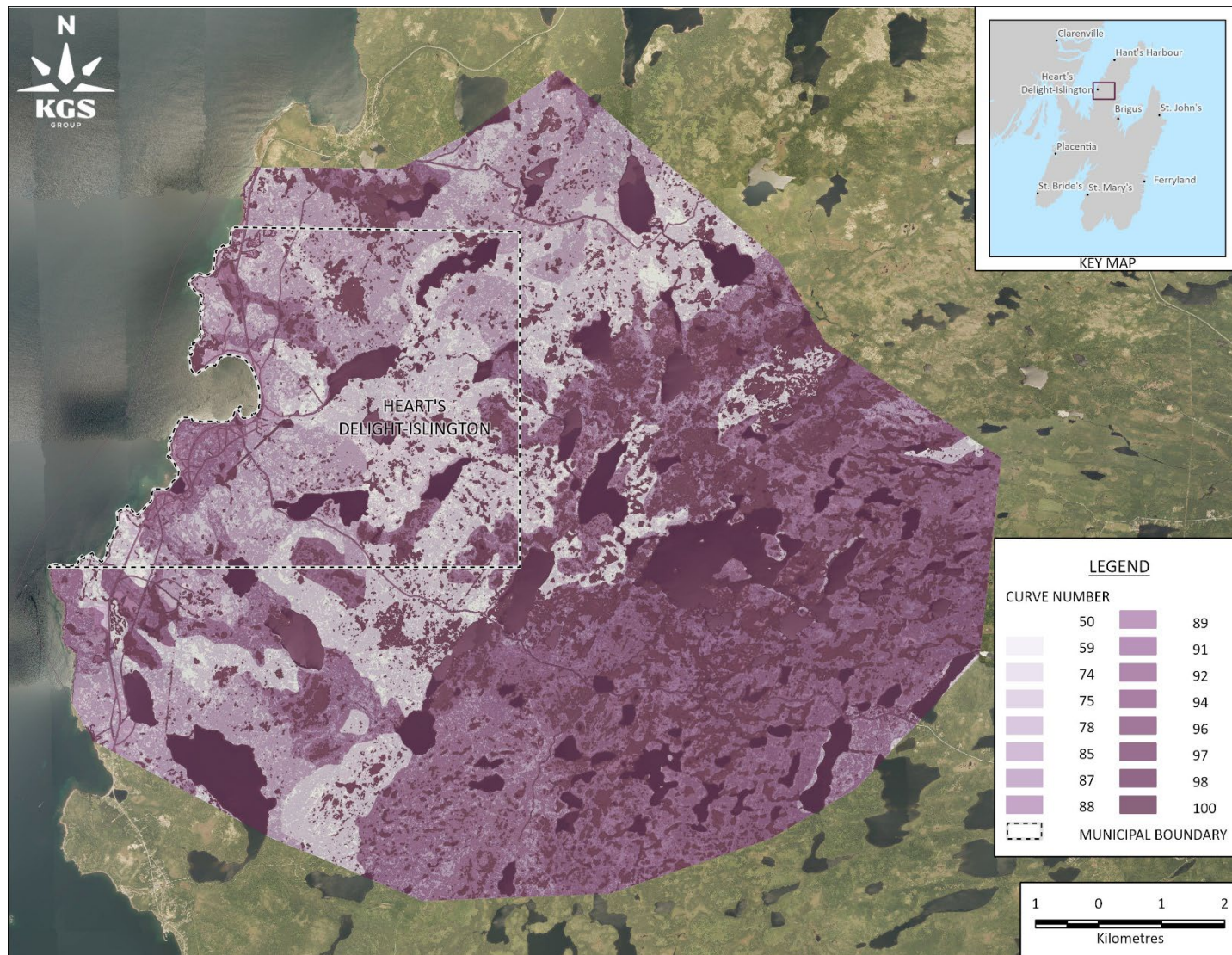
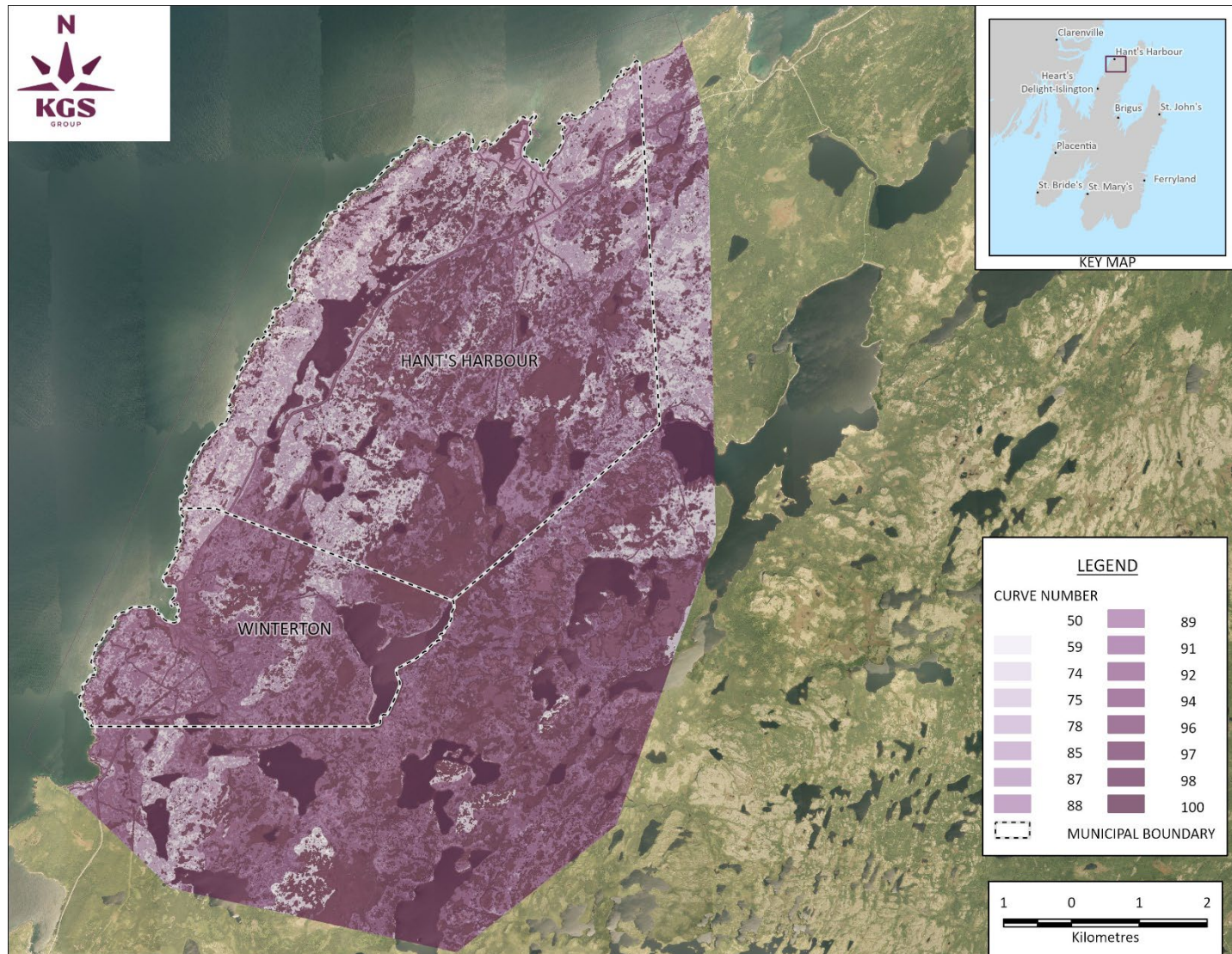


FIGURE 53: WINTERTON AND HANT'S HARBOUR CURVE NUMBER MAP



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.

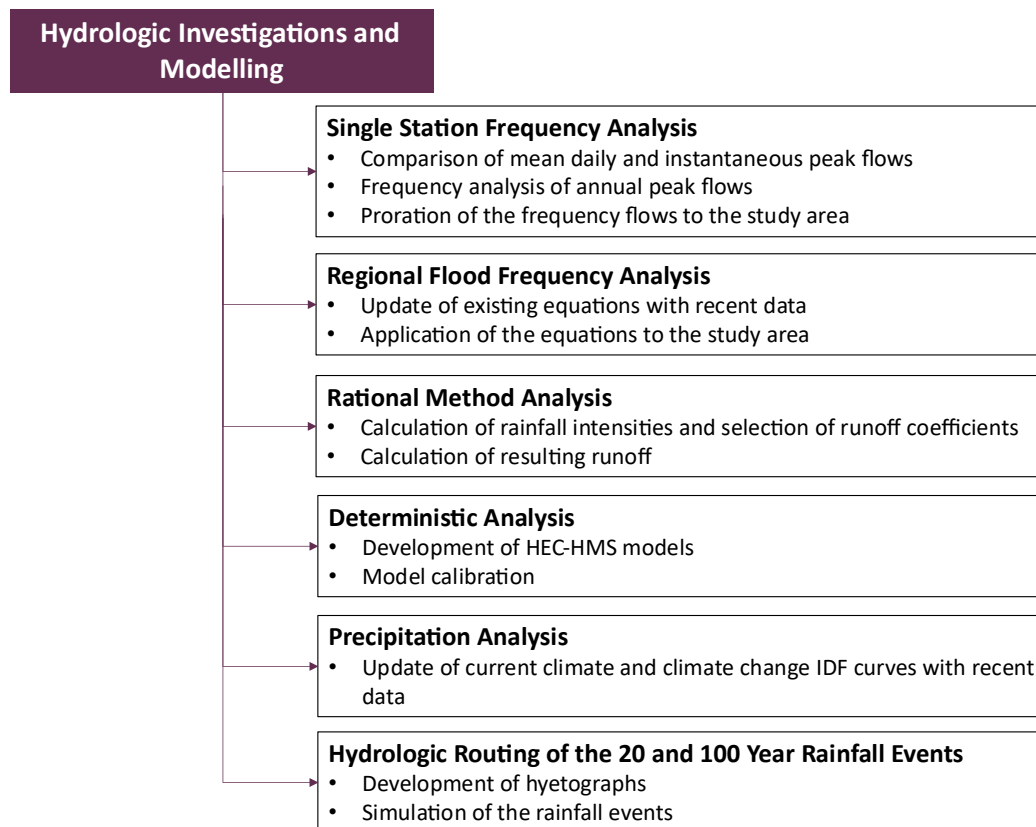
The statistical analysis of recorded flows was based on flows recorded by Water Survey of Canada on Big Brook at Lead Cove, Shearstown Brook at Shearstown, and Seal Cove Brook near Cappahayden. The analyses considered recorded flows that were available, and fit a statistical distribution to the yearly 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 effects, a set of equations was developed to estimate the 20 and 100-year AEP flood flows for any ungauged river within the southeast of Newfoundland.

Additional estimates of the 20 and 100-year AEP flood flows were estimated for each river using the Government of Newfoundland and Labrador's Rational Method, which considers rainfall intensity, the drainage area for each watershed, and a coefficient that represents how rainfall is translated to runoff for a given basin.

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 54.

FIGURE 54: 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 02ZM009 (i.e. Seal Cove Brook near Cappahayden), 02ZL004 (i.e. Shearstown Brook at Shearstown), and 02ZL005 (i.e. Big Brook at Lead Cove), which are shown on Figure 55 to Figure 57 along with the watersheds that were assessed as part of the study. Characteristics of those stations are summarized in Table 4. While other nearby stations were available for consideration in the SSFA (i.e. 02ZM004 – Horse Chops River near Cape Broyle and 02ZL003 – Spout Cove Brook near Spout Cove), those stations either had very short periods of record (i.e. 02ZM004, 1951 - 1952), or were long taken out of service (i.e. 02ZL003, 1979 - 1997). The 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 02ZM009, 02ZL004 and 02ZL005 extended from 1979 to 2021, 1983 to 2021, and 1985 to 2021, respectively. Instantaneous peak flow data were available for the full records of the gauges, with missing data in 1994 and 1996 (i.e. 02ZL004), 2014 (i.e. 02ZL005), and 2018 (i.e. 02ZM009). 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 was estimated based on the annual mean daily peak flow.

FIGURE 55: LOCATION OF WSC STATION 02ZM009 RELATIVE TO FERRYLAND DRAINAGE BASINS

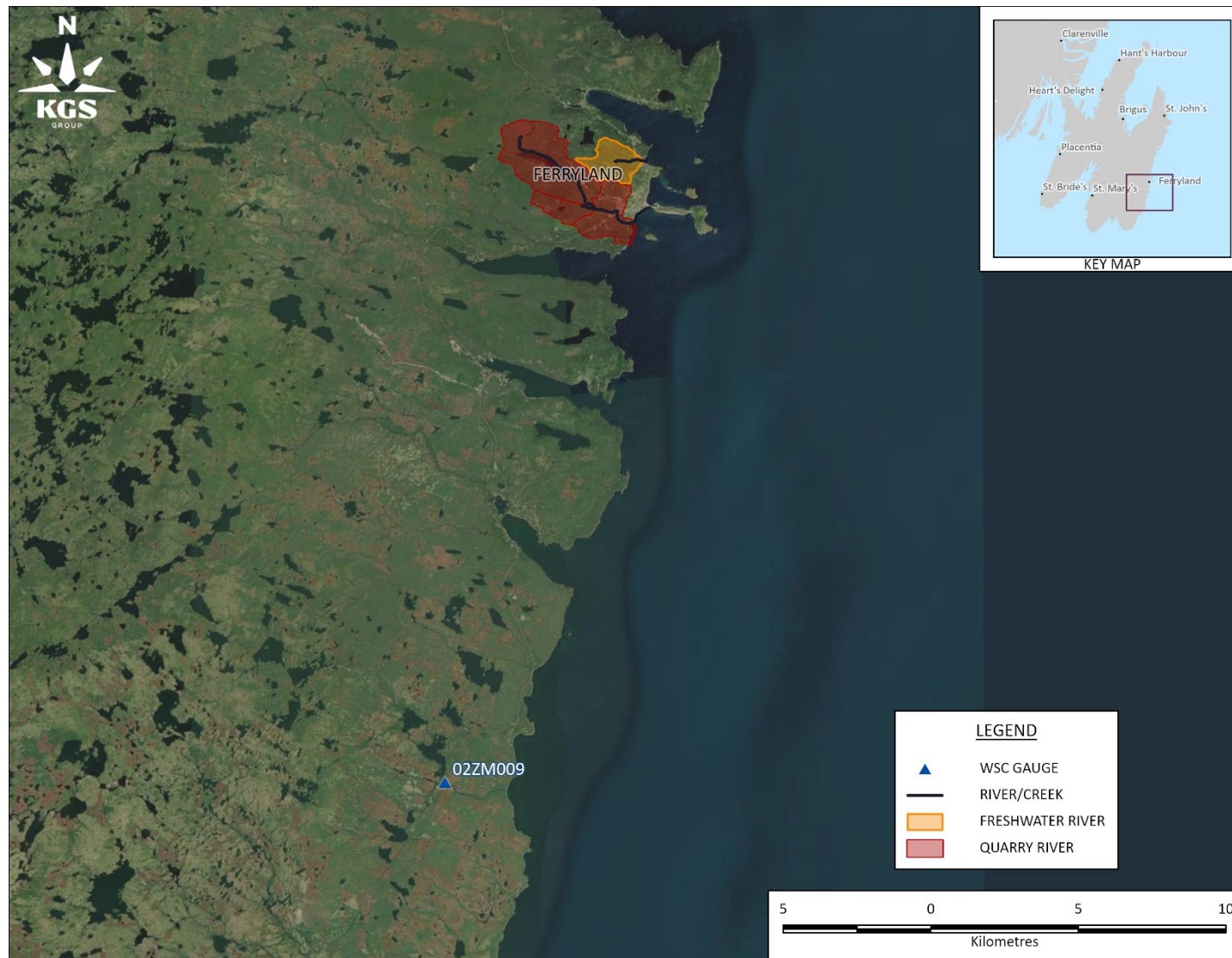


FIGURE 56: LOCATION OF WSC STATION 02ZL004 RELATIVE TO BRIGUS AND HEART'S DELIGHT – ISLINGTON AREA DRAINAGE BASINS

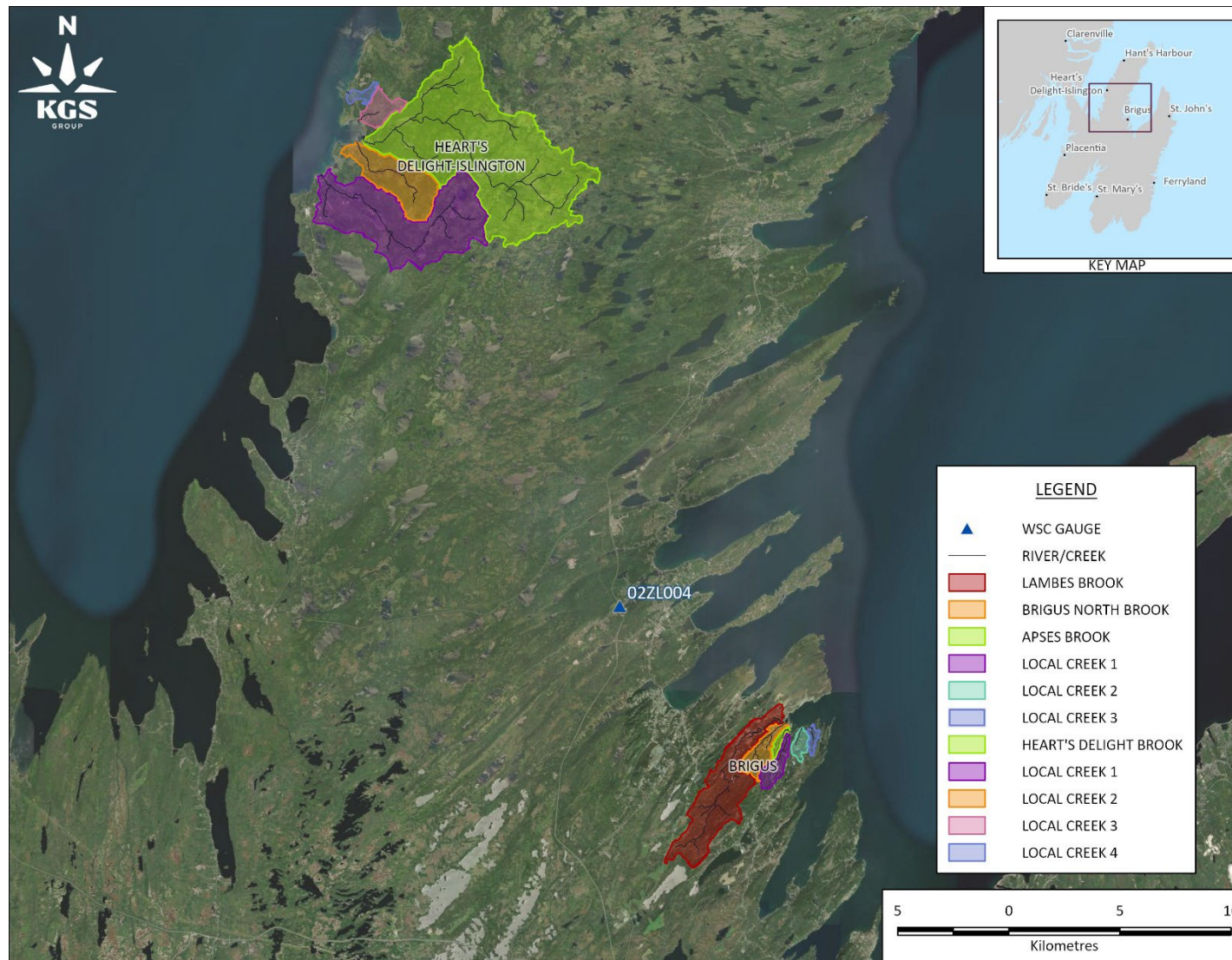
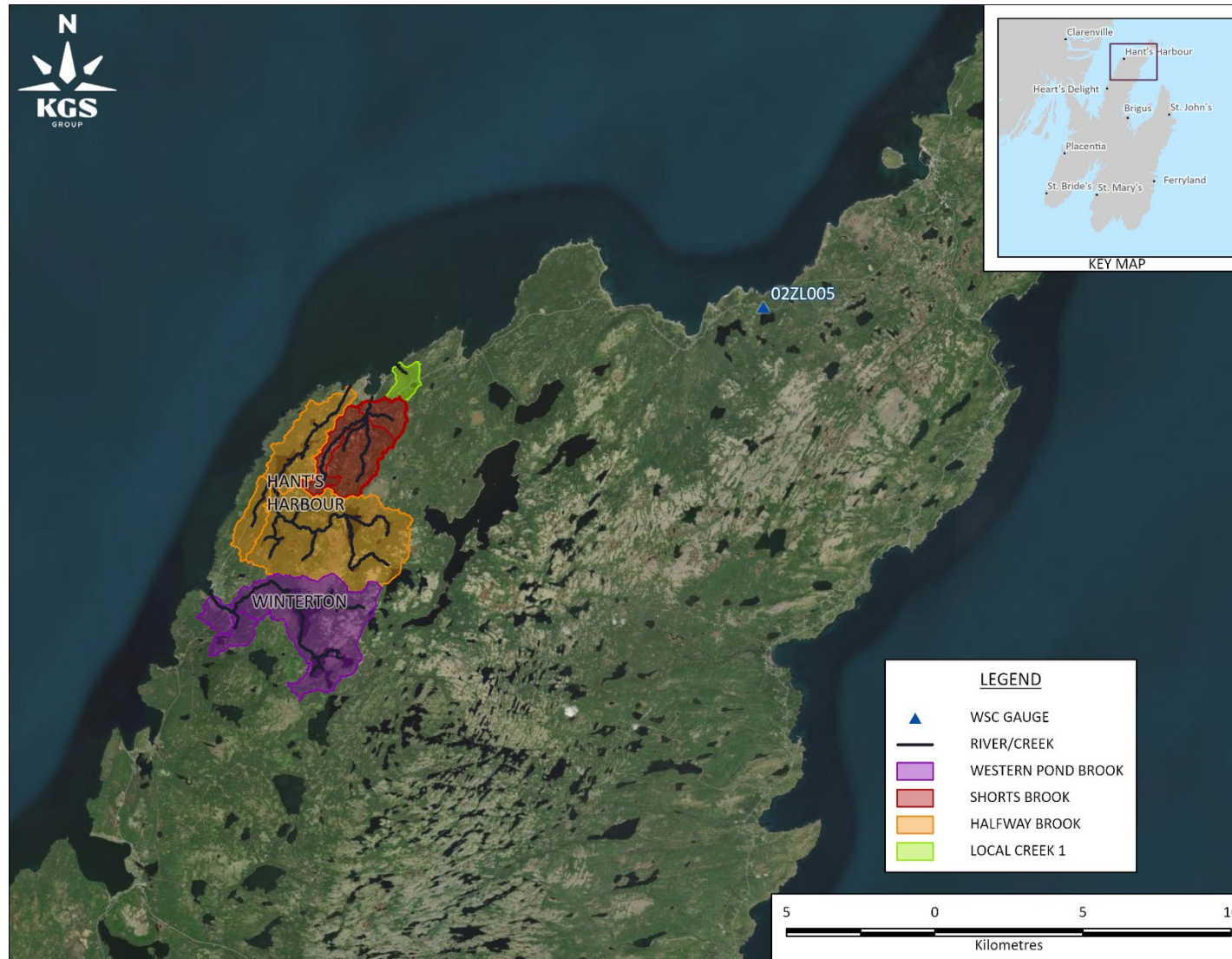


FIGURE 57: LOCATION OF WSC STATION 02ZL005 RELATIVE TO WINTERTON AND HANT'S HARBOUR AREA DRAINAGE BASINS



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. WSC gauge 02ZM009 (i.e. Seal Cove Brook near Cappahayden) was found to fail the stationarity and homogeneity tests when the full period of record was considered in the analysis, but passed both tests with data from 1979 to 1984 excluded from the analysis. Accordingly, the peak flow data from 1979 to 1984 was not considered in the analysis. The results of these statistical tests are summarized in Table 10.

TABLE 10: SSFA STATISTICAL TESTS

Station	Independence	Stationarity	Homogeneity
Seal Cove Brook near Cappahayden	Pass	Pass	Pass
Shearstown Brook at Shearstown	Pass	Pass	Pass
Big Brook at Lead Cove	Pass	Pass	Pass

The statistical tests in the HYFRAN statistical hydrology software showed that the datasets were independent, that the datasets were stationary (i.e. no trend), and that the datasets were homogenous.

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, although there were instances where the spring freshet resulted in the greatest peak flows. 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 3-Parameter Lognormal distribution was found to be most appropriate for all of the gauges. 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 11, with the frequency curves for the Seal Cove Brook, Shearstown Brook and Big Brook are shown on Figure 58 to Figure 60.

TABLE 11: FREQUENCY CURVE FLOWS

Return Period (Years)	Seal Cove Brook Flow (m ³ /s)	Shearstown Brook Flow (m ³ /s)	Big Brook Flow (m ³ /s)
100	72.9	62.6	15.3
50	63.1	51.4	13.4
20	51.8	38.5	11.0
10	44.2	30.1	9.3
5	37.5	22.7	7.6
2	29.5	14.0	5.3

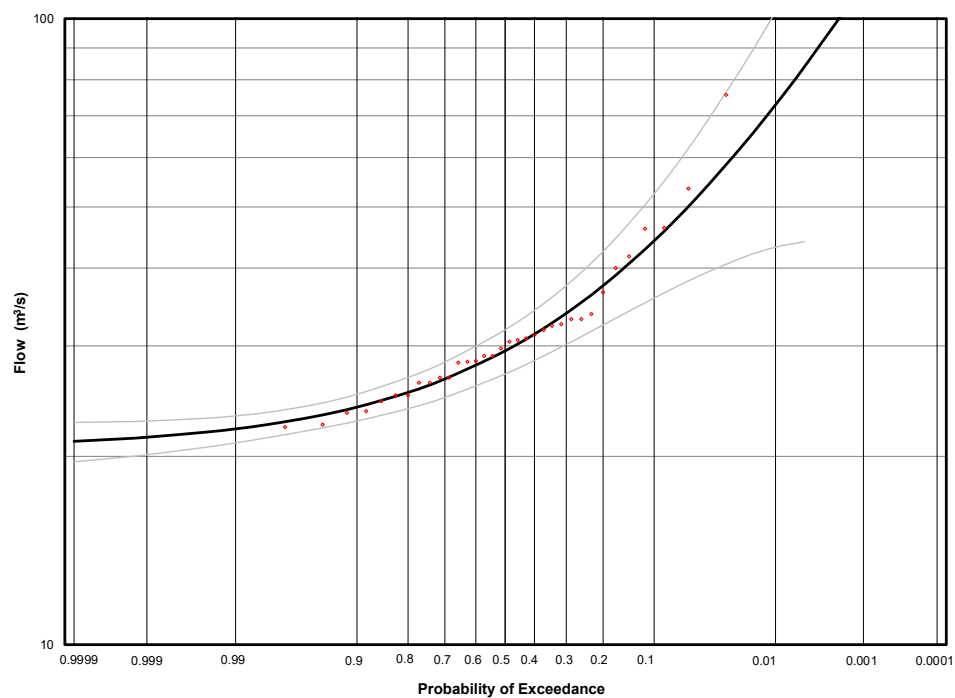
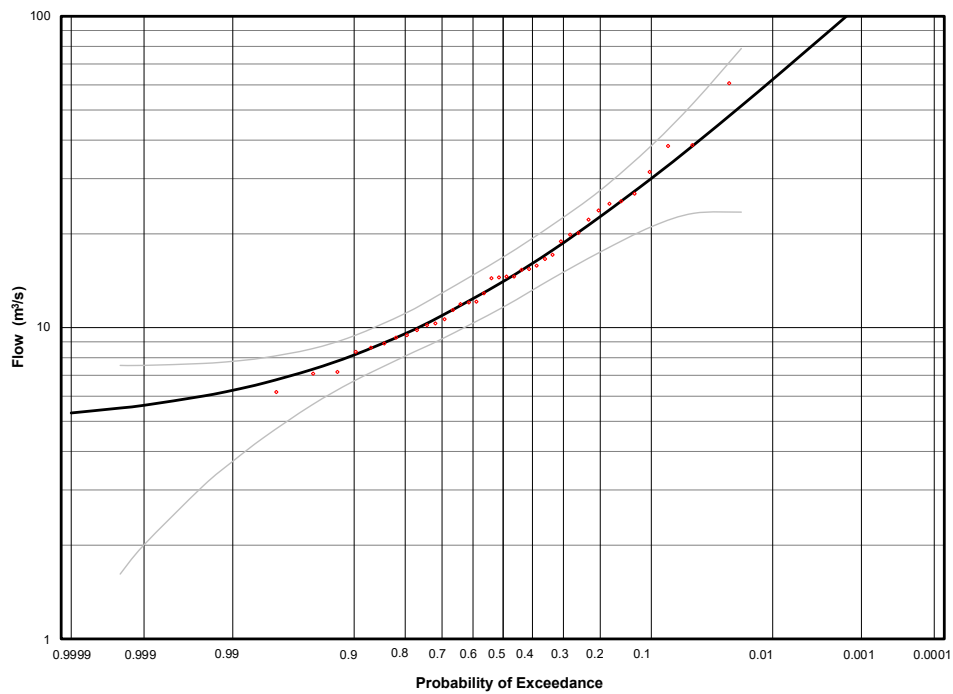
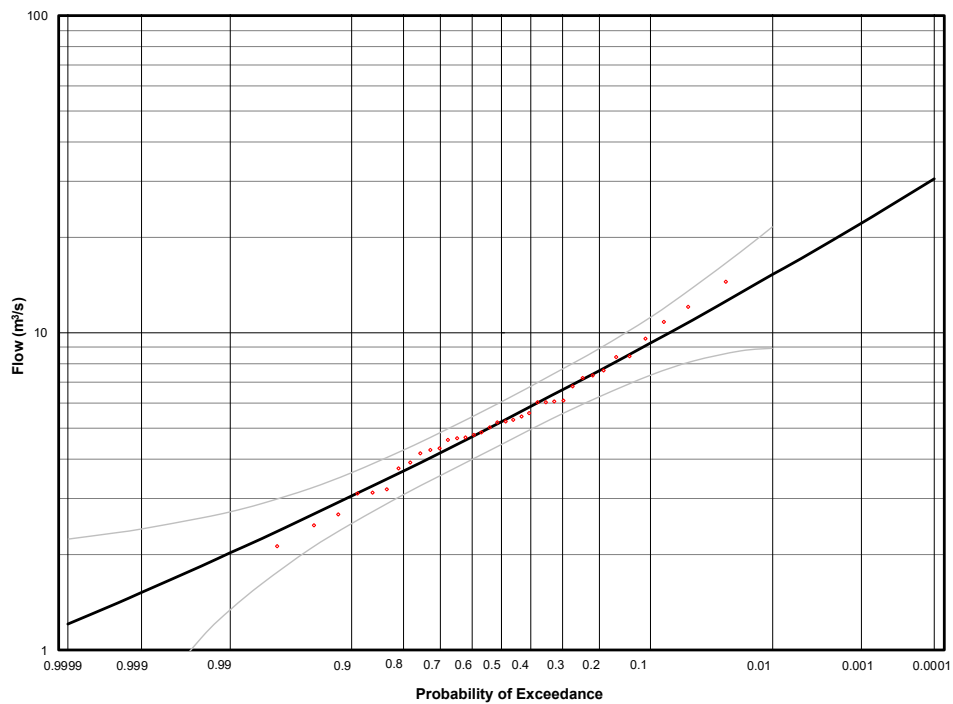
FIGURE 58: SEAL COVE BROOK NEAR CAPPAHAYDEN FREQUENCY CURVE

FIGURE 59: SHEARSTOWN BROOK AT SHEARSTOWN FREQUENCY CURVE**FIGURE 60: BIG BROOK AT LEAD COVE FREQUENCY CURVE**

The 20 and 100-year AEP frequency flows from Seal Cove Brook were prorated to the rivers considered in Ferryland, while the 20 and 100-year AEP frequency flows from the Shearstown Brook were prorated to the rivers considered Brigus and Heart's Delight – Islington. The 20 and 100-year AEP frequency flows from Big Brook were similarly prorated to the rivers and creeks considered in Winterton and Hant's Harbour. The flow proration was completed on the basis of the ratio of the drainage area of a particular river or creek to those associated with the index 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 drainage areas associated with the WSC gauges, which ranged from 11.2 km² for Big Brook at Lead Cove, 28.9 km² for Shearstown Brook at Shearstown, and 53.6 km² for Seal Cove Brook near Cappahayden, the prorated flows are inappropriate for many of the smaller tributaries and rivers in the study area. The prorated flows for the study areas are summarized in Table 12. Prorated frequency flows shaded in yellow are considered to be inappropriate given the difference in drainage area between the index station and subbasin.

TABLE 12: SUMMARY OF SSFA FLOWS

Town	Watershed	Subbasin	Drainage Area (km ²)	20-Year AEP Flow (m ³ /s)	100-Year AEP Flow (m ³ /s)
Ferryland	Freshwater River	Total	2.3	4.0	5.7
		Total	9.7	13.0	18.3
	Quarry River	Upstream North	5.8	8.6	12.2
		Upstream South	1.2	2.4	3.4
		Downstream	2.7	4.6	6.5
Brigus	Lambes Brook	Total	11.3	15.5	23.6
	Brigus North Brook	Total	2.2	4.2	6.3
	Apses Brook	Total	0.5	1.2	1.9
	Local Creek 1	Total	1.6	3.2	4.9
	Local Creek 2	Total	0.7	1.7	2.6
	Local Creek 3	Total	0.7	1.6	2.4
Heart's Delight - Islington	Heart's Delight Brook	Total	42.2	45.0	68.3
	Local Creek 1	Total	20.1	24.8	37.7
	Local Creek 2	Total	6.9	10.5	16.0
	Local Creek 3	Total	2.0	3.9	5.9
	Local Creek 4	Total	0.8	1.8	2.7
Winterton	Western Pond Brook	Total	12.9	12.1	16.5
		Upstream North	10.8	10.5	14.2
		Upstream South	1.2	1.8	2.4
		Downstream	1.0	1.5	2.1
Hant's Harbour	Halfway Brook	Total	20.1	17.4	23.5
	Halfway Brook	Upstream West	1.8	2.5	3.4
	Halfway Brook	Upstream East	14.0	13.0	17.6
	Halfway Brook	Downstream	4.3	5.0	6.8
	Shorts Brook	Total	7.1	7.5	10.2
	Shorts Brook	Upstream	3.6	4.4	5.9
	Shorts Brook	Downstream	1.5	2.2	2.9
	Shorts Brook	Southwest Brook	2.0	2.7	3.7
	Local Creek 1	Total	1.0	1.5	2.0

6.2.2 REGIONAL FLOOD FREQUENCY ANALYSES

As part of our recent Climate Change Flood Risk Mapping Study for Placentia, Carbonear, Salmon Cove and Victoria (KGS Group, 2021), the Regional Flood Frequency Analysis (RFFA) for the Southeast and Southwest hydrological regions of Newfoundland were updated with up-to-date hydrometric data. The regression equations that were updated as part of that study were then used to estimate the 20 and 100-year AEP events on ungauged rivers and creeks within the study area. The methodology that was implemented for the southeast area of Newfoundland as part of that study, which includes the majority of the Avalon Peninsula, is documented below.

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 E.

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.

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 23 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		
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)
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:

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

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:

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

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. Q_{100} 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, two regression parameters were considered for the southeast region, specifically drainage area (DA) and the lake attenuation factor (LAF). The single parameter log regression analyses only considered DA. The multiple log regression analyses considered DA and LAF, where LAF is given by:

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

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 .

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.

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
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
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 region 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

	AEP Return Period	SMR	SEE
Two Parameter	2 Year	0.920	0.133
	5 Year	0.922	0.133
	10 Year	0.921	0.135
	20 Year	0.918	0.139
	50 Year	0.912	0.146
	100 Year	0.906	0.153
One Parameter	2 Year	0.883	0.156
	5 Year	0.898	0.147
	10 Year	0.904	0.143
	20 Year	0.907	0.143
	50 Year	0.906	0.146
	100 Year	0.902	0.150

The regression equations provided accurate estimations of the return period flows, with DA accounting 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 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	Parameters	Range of SMR	Range of SEE
2021	DA, LAF	0.906 - 0.920	0.133 - 0.153
2014	DA, LAF	0.929 - 0.942	0.120 - 0.132
1999	DA, LAF	0.929 - 0.967	0.088 - 0.129

The comparison shows that the RFFA completed by KGS Group part of the Climate Change Flood Risk Mapping Study for Placentia, Carbonear, Salmon Cove and Victoria (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 are summarized in Table 18 and Table 19.

TABLE 18: ONE-PARAMETER RFFA EQUATIONS

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 RFFA EQUATIONS

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

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 area of 4 km² for the southeast region (i.e. the region containing Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour), the RFFA equations should be considered inappropriate to use for basin sizes smaller than the smallest basins considered for the development of the RFFA equations. The 20 and 100-year AEP flows defined by the RFFA equations for the rivers and creeks considered in the study areas are summarized in Table 20. Prorated frequency flows shaded in yellow are considered to be inappropriate given the drainage area for the given subbasin.

TABLE 20: SUMMARY OF RFFA FLOWS

Town	Watershed	Subbasin	Drainage Area (km ²)	20-Year AEP (m ³ /s)		100-Year AEP (m ³ /s)	
				1-Param Eq.	2-Param Eq.	1-Param Eq.	2-Param Eq.
Ferryland	Freshwater River	Total	2.3	4.9	5.6	6.3	6.8
	Quarry River	Total	9.7	15.9	15.2	21.0	20.6
		Upstream North	5.8	10.6	9.3	13.8	12.9
		Upstream South	1.2	2.9	3.4	3.7	4.1
		Downstream	2.7	5.6	6.4	7.2	7.8
Brigus	Lambes Brook	Total	11.3	18.0	17.7	23.9	23.7
	Brigus North Brook	Total	2.2	4.8	5.5	6.2	6.7
	Apses Brook	Total	0.5	1.4	1.5	1.8	1.8
	Local Creek 1	Total	1.6	3.7	3.7	4.7	4.7
	Local Creek 2	Total	0.7	2.0	2.4	2.5	2.8
	Local Creek 3	Total	0.7	1.8	1.9	2.3	2.4
Heart's Delight - Islington	Heart's Delight Brook	Total	42.2	52.2	44.9	71.1	65.6
	Local Creek 1	Total	20.1	28.8	25.2	38.6	36.0
	Local Creek 2	Total	6.9	12.2	10.7	16.0	14.9
	Local Creek 3	Total	2.0	4.5	5.2	5.8	6.3
	Local Creek 4	Total	0.8	2.1	2.5	2.6	2.9
Winterton	Western Pond Brook	Total	12.9	20.1	16.8	26.7	24.2
		Upstream North	10.8	17.4	14.0	23.0	20.5
		Upstream South	1.2	2.9	3.4	3.7	4.0
		Downstream	1.0	2.5	3.0	3.2	3.5
Hant's Harbour	Halfway Brook	Total	20.1	28.7	24.6	38.6	35.5
	Halfway Brook	Upstream West	1.8	4.1	4.7	5.3	5.7
	Halfway Brook	Upstream East	14.0	21.5	20.2	28.6	27.7
	Halfway Brook	Downstream	4.3	8.3	7.5	10.8	10.2
	Shorts Brook	Total	7.1	12.4	13.8	16.3	17.3
	Shorts Brook	Upstream	3.6	7.2	8.1	9.3	10.0
	Shorts Brook	Downstream	1.5	3.6	4.1	4.5	4.9
	Shorts Brook	Southwest Brook	2.0	4.5	5.1	5.7	6.2
	Local Creek 1	Total	1.0	2.5	2.9	3.1	3.4

6.3 Rational Method Analyses

The 20 and 100-year AEP flows on the rivers in creeks in Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour were estimated using the Rational Method. In that method, peak flow rates associated with a given return period rainfall are defined by:

$$Q = 0.278 * C * i * A \quad [\text{Eq. 4}]$$

Where Q is the peak flow in m³/s, C is the relative imperviousness of the drainage area, i is the rainfall intensity in mm/hr as defined by the IDF curve equations defined by ECCC for a given precipitation gauge, and A is the basin drainage area in km². It should be noted that the Rational Method is inappropriate for drainage areas larger than 5 km². Similarly, the Rational Method does not account for potential peak flow attenuation due to lakes and wetlands, and as such could represent a somewhat conservative estimate of peak flows. However, it should be noted that for the sub-basins where the Rational Method was appropriate (i.e. drainage areas less than 5 km²), the extents of lakes or wetlands within those sub-basins were minor, and any

potential attenuation effects were considered to be minor or negligible. Accordingly, the conservative nature of the Rational Method was considered to be reasonable.

Peak flow rates for the various rivers and creeks considered as part of this study were estimated using the ECCC precipitation gauge for St. John's A (i.e. Station 8403506), with an average relative imperviousness coefficient of 0.35 adopted for the calculations, which was found to generally be representative of soil and land use for the various watersheds. The resulting estimated flows for the various creeks and watersheds considered in this study are summarized in Table 21, with flows shaded in yellow being considered inappropriate.

TABLE 21: SUMMARY OF RATIONAL METHOD FLOWS

Town	Watershed	Subbasin	Drainage Area (km ²)	20-Year AEP Flow (m ³ /s)	AEP Flow (m ³ /s)
Ferryland	Freshwater River	Total	2.3	5.1	6.5
	Quarry River	Total	9.7	10.3	12.8
		Upstream North	5.8	8.6	10.8
		Upstream South	1.2	2.6	3.3
		Downstream	2.7	6.3	8.0
Brigus	Lambes Brook	Total	11.3	11.2	14.0
	Brigus North Brook	Total	2.2	4.0	5.0
	Apses Brook	Total	0.5	1.3	1.6
	Local Creek 1	Total	1.6	3.1	3.9
	Local Creek 2	Total	0.7	2.1	2.7
	Local Creek 3	Total	0.7	2.0	2.6
Heart's Delight - Islington	Heart's Delight Brook	Total	42.2	36.4	45.1
	Local Creek 1	Total	20.1	19.6	24.4
	Local Creek 2	Total	6.9	9.4	11.8
	Local Creek 3	Total	2.0	4.3	5.5
	Local Creek 4	Total	0.8	2.0	2.6
Winterton	Western Pond Brook	Total	12.9	14.4	18.0
		Upstream North	10.8	13.3	16.6
		Upstream South	1.2	2.7	3.5
		Downstream	1.0	2.6	3.3
Hant's Harbour	Halfway Brook	Total	20.1	17.5	21.7
	Halfway Brook	Upstream West	1.8	3.2	4.1
	Halfway Brook	Upstream East	14.0	14.8	18.4
	Halfway Brook	Downstream	4.3	6.6	8.2
	Shorts Brook	Total	7.1	9.5	11.8
	Shorts Brook	Upstream	3.6	6.5	8.2
	Shorts Brook	Downstream	1.5	3.4	4.3
	Shorts Brook	Southwest Brook	2.0	3.1	3.9
	Local Creek 1	Total	1.0	2.7	3.5

6.4 Deterministic Analyses

6.4.1 MODEL DEVELOPMENT

Hydrologic models of watersheds in Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour were developed using the Hydrologic Engineering Centre's Hydrologic Modelling System (HEC-HMS) version 4.9 (U.S. Army Corps of Engineers, 2018). Geospatial tools within the software were used to preprocess the terrain information, identify waterways, delineate drainage basins, and estimate initial model parameters. 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.

Four HEC-HMS models were developed as sub-basin models, one for the Ferryland area, one for the Brigus Area, one for the Heart's Delight – Islington area, and one for the Winterton and Hant's Harbour area. 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 using geospatial tools included in HEC-HMS. Sub-basins within the models were then defined based on the watershed DEM, as described in Section 4.3, using the geospatial tools included in HEC-HMS. Sub-basins were defined for the creeks and rivers being considered for flood mapping as part of this study, and were sub-divided to include major tributaries to those creeks and rivers within the anticipated mapping extents. The delineated sub-basins for the study areas model are shown on Figure 61 to Figure 64.

FIGURE 61: FERRYLAND MODEL SUB-BASINS

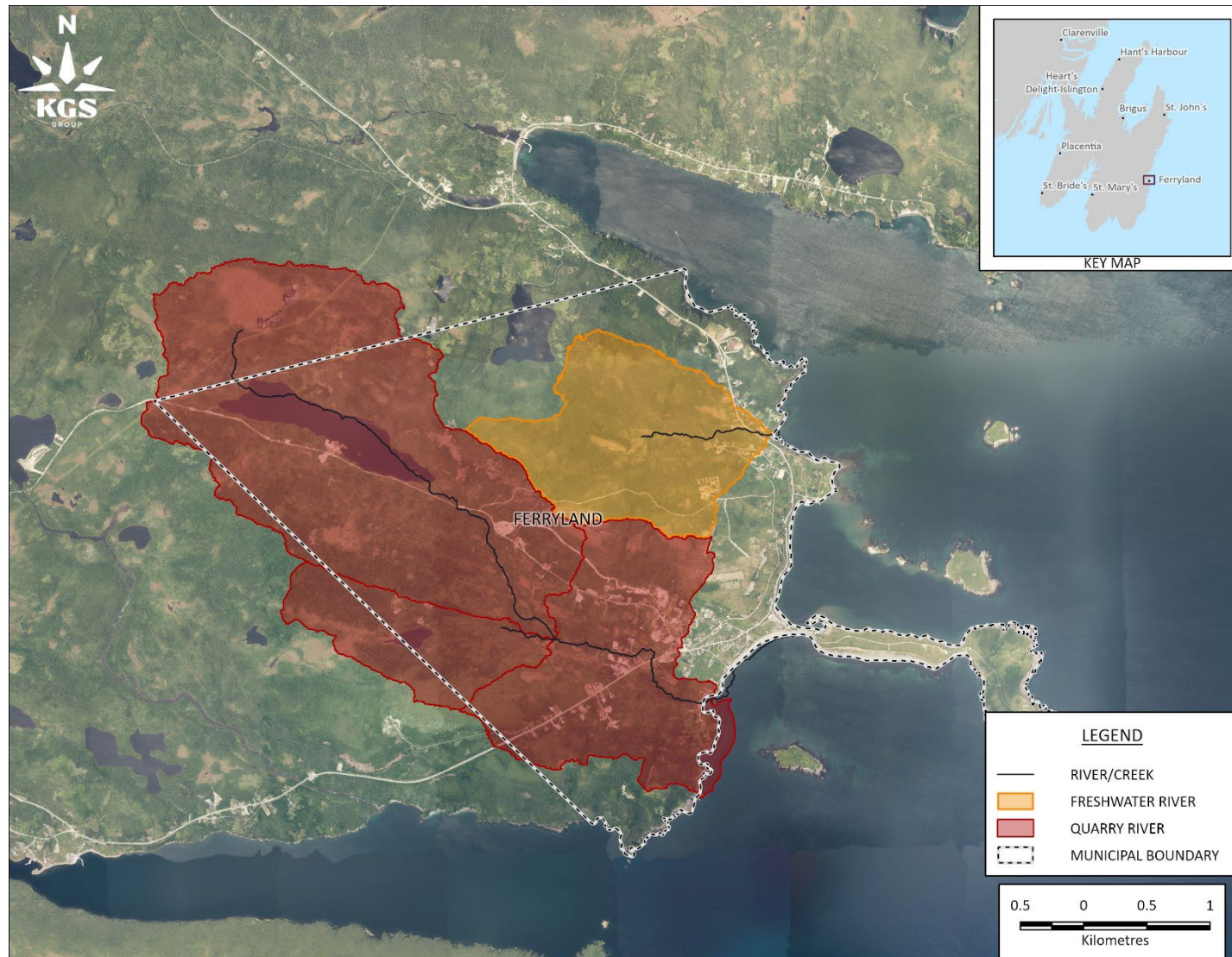


FIGURE 62: BRIGUS MODEL SUB-BASINS

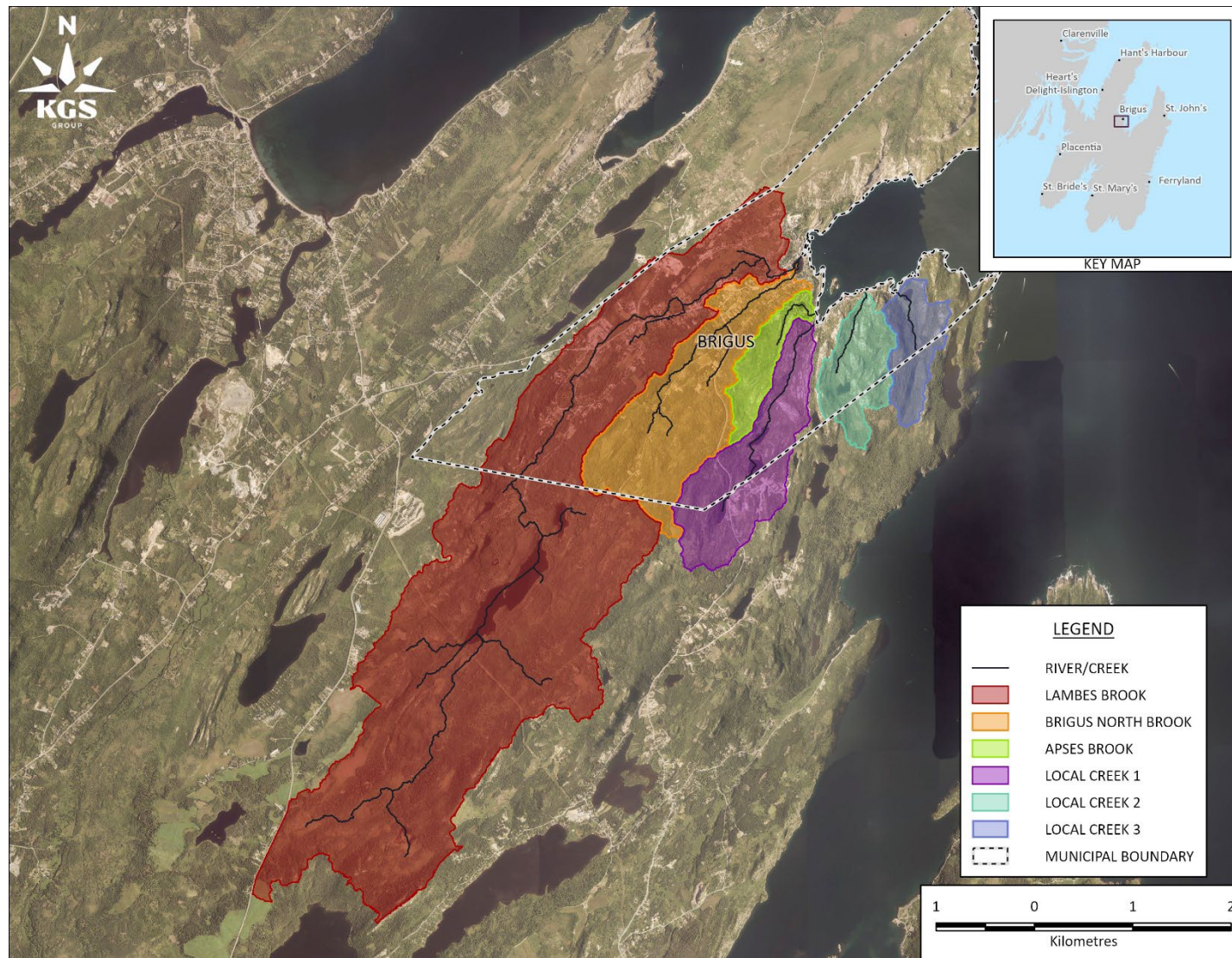


FIGURE 63: HEART'S DELIGHT - ISLINGTON MODEL SUB-BASINS

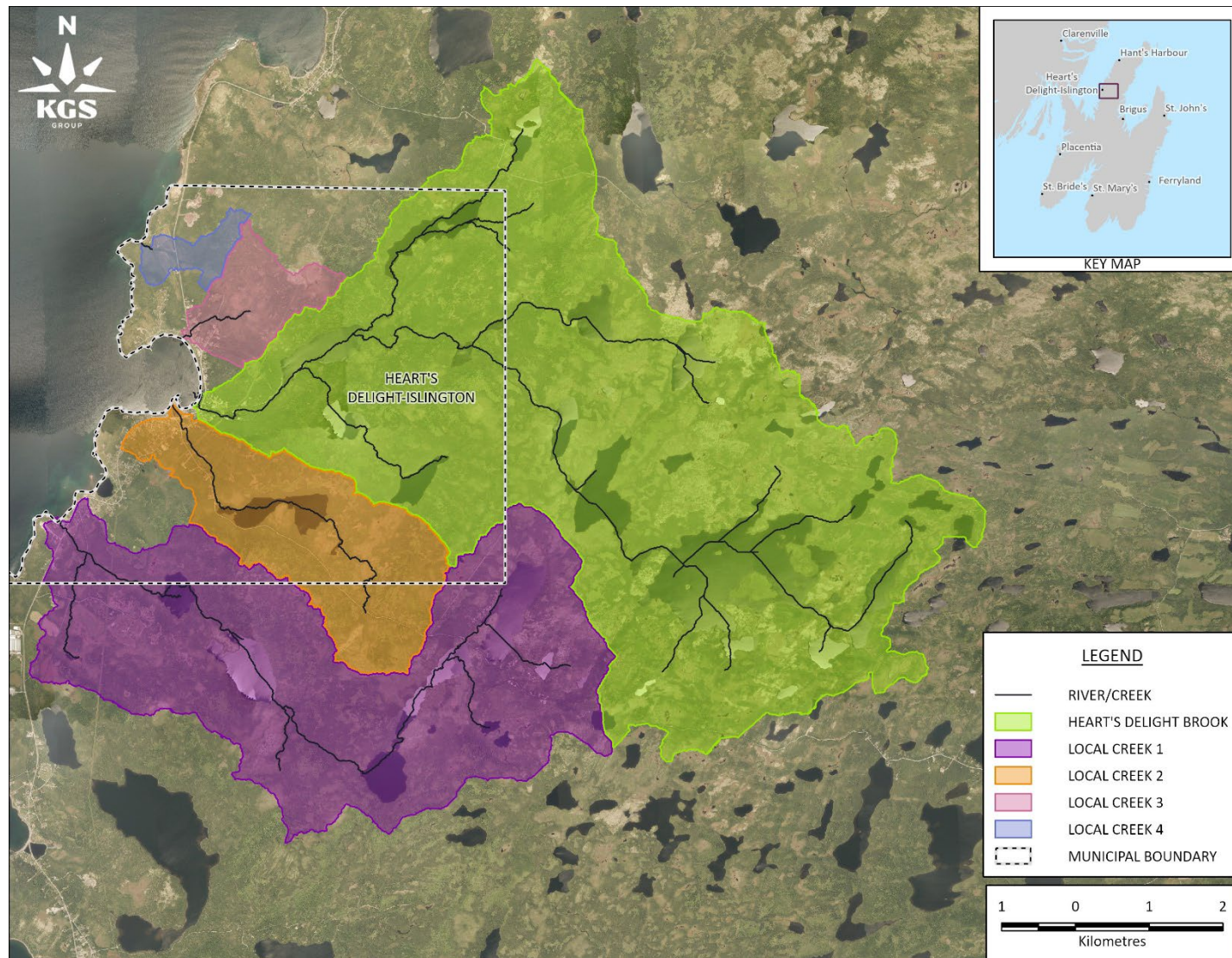
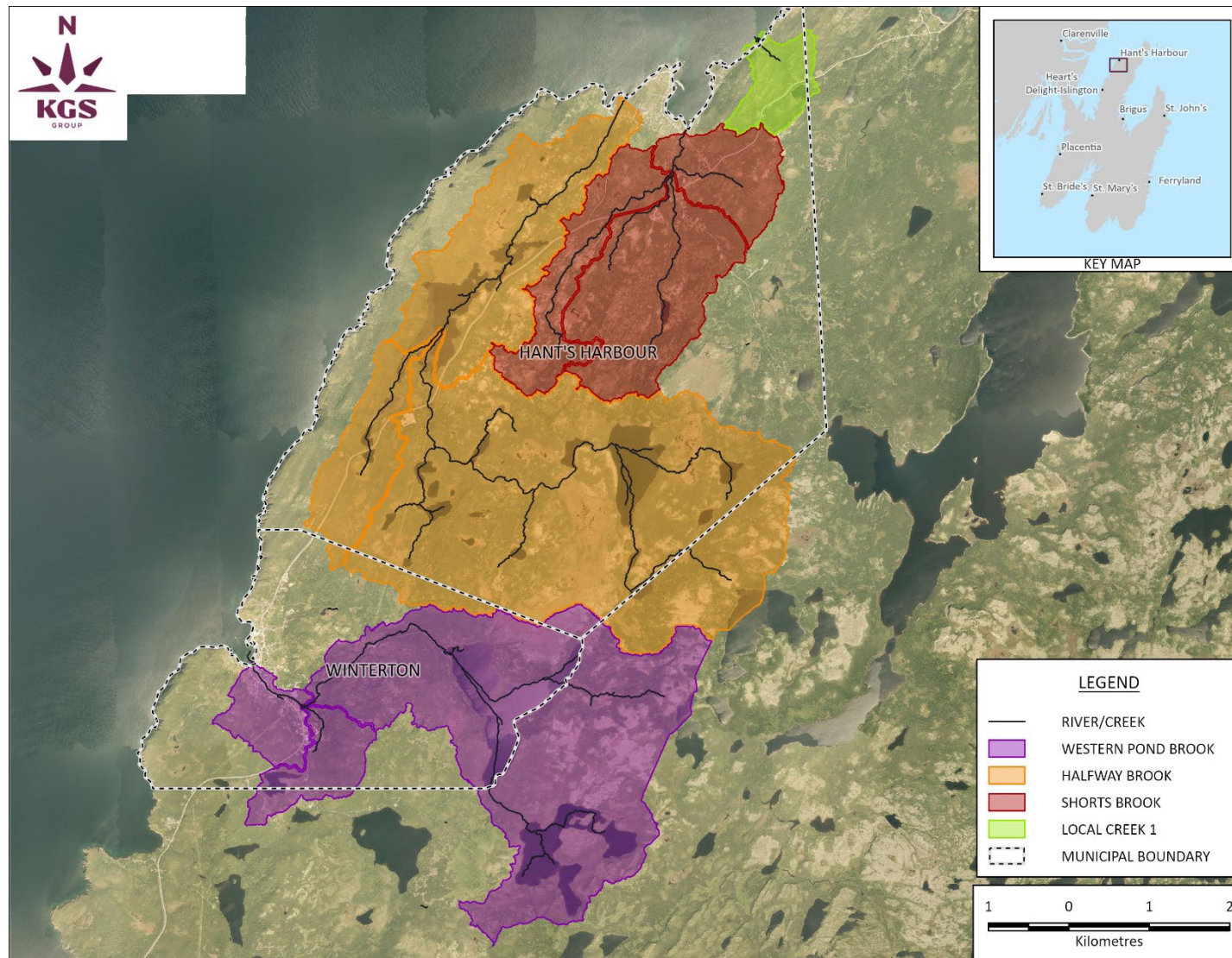


FIGURE 64: WINTERTON AND HANT'S HARBOUR MODEL SUB-BASINS



Physical characteristics of the watersheds, such as stream characteristics, curve numbers, and basin lag times were estimated from the watershed DEM and Curve Number (CN) maps described in Sections 4.4 and 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 22.

TABLE 22: 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 23, as well as the minimum, maximum and recommended values for each parameter, where available.

TABLE 23: OVERVIEW OF MODEL PROCESSES

Process	Parameter	Unit	Description	Minimum Value	Maximum Value	Recommended or Default Value
Sub-basin	Basin Area	km ²	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	m ³ /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 in St. John's, there can be significant spatial variability in rainfall intensity throughout the Avalon Peninsula, and as such calibrating the models using precipitation from St. John's was considered impractical. In light of the spatial paucity in the available precipitation data, precipitation time series were defined based on precipitation data from the 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.

6.4.2 MODEL CALIBRATION

Each of the HEC-HMS models were adjusted to two recent rainfall events and validated to a third, separate event. To calibrate the models, instantaneous peak flows from nearby gauged rivers were prorated to the rivers and creeks being considered as part of this study and used as the basis for adjusting the HEC-HMS models. Careful consideration was given to the calibration and validation events to ensure that the precipitation data defined by CaPA, and the streamflow data defined by the proration of nearby gauged flows are generally in good agreement, and seem reasonable given the scale of the event. As CaPA is a reanalysis product with a somewhat coarse resolution, there is potential for certain historical rainfall events to be inaccurately represented. Similarly, due to differences in basin shape and size, as well as the spatial variability of precipitation on the Avalon peninsula, rainfall events may not contribute equally to nearby watersheds, resulting in different flow conditions on the gauged and ungauged rivers. The rainfall events considered for the model calibration and validation are summarized in Table 24.

TABLE 24: CALIBRATION AND VALIDATION EVENTS

Location	Calibration		Validation
	Event 1	Event 2	
Ferryland	05-Dec-22	13-Feb-12	30-Jan-08
Brigus	02-Jan-23	04-Mar-13	01-Aug-07
Heart's Delight - Islington	02-Jan-23	30-May-18	20-Sep-04
Winterton	02-Jan-23	30-May-18	30-Jan-08
Hant's Harbour	02-Jan-23	30-May-18	30-Jan-08

Peak instantaneous flows from the WSC gauge 02ZL004 (i.e. Shearstown Brook at Shearstown) were prorated to the basins and subbasins in Brigus and Heart's Delight – Islington to provide an estimate of the peak flows on those ungauged basins. Similarly, instantaneous peak flows from WSC gauge 02ZL005 (i.e. Big Brook in Lead Cove) were used to define flows for the subbasins in Winterton and Hant's Harbour, while instantaneous peak flows from WSC gauge 02ZM009 (i.e. Seal Cove Brook near Cappahayden) were used to define flows for the subbasins in Ferryland. Model parameters in each area 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 Ferryland, Brigus, Heart's Delight – Islington, Winterton, and Hant's Harbour HEC-HMS models to the corresponding prorated peak flows are shown on Figure 65 to Figure 69.

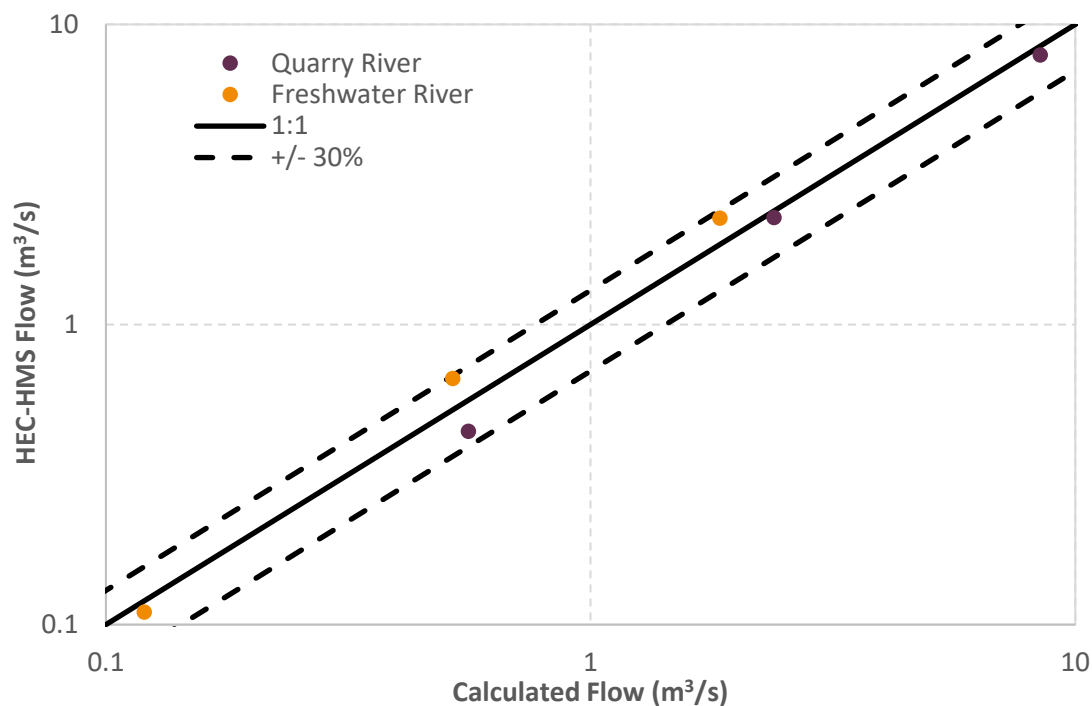
FIGURE 65: COMPARISON OF SIMULATED AND PRORATED PEAK FLOWS IN FERRYLAND

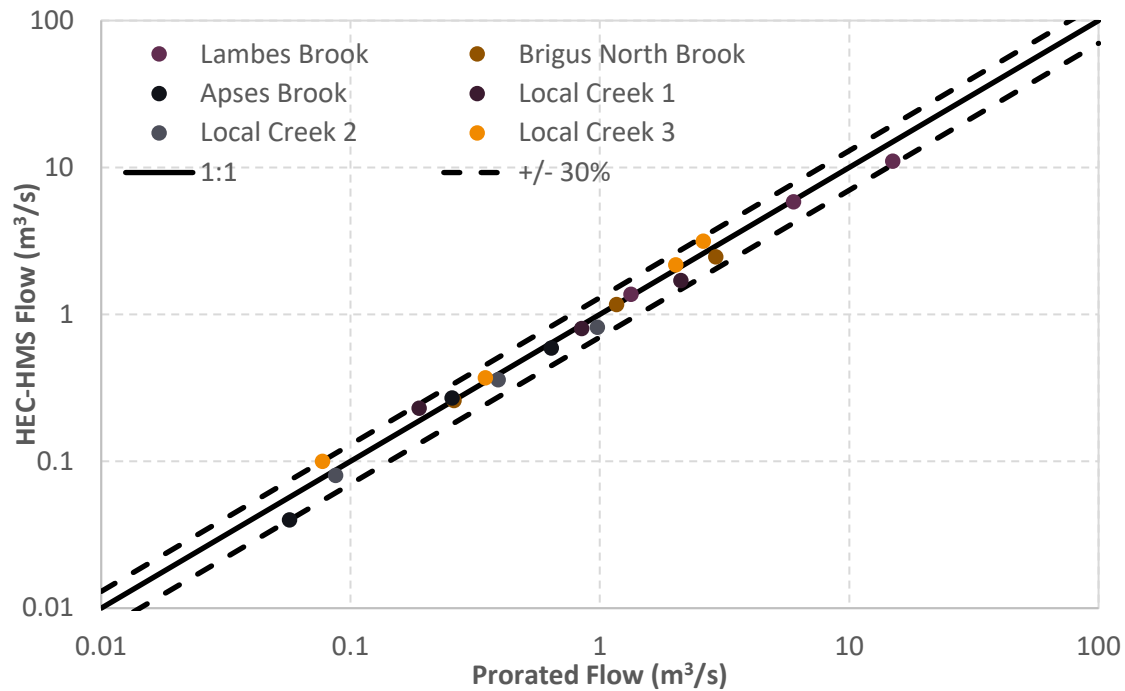
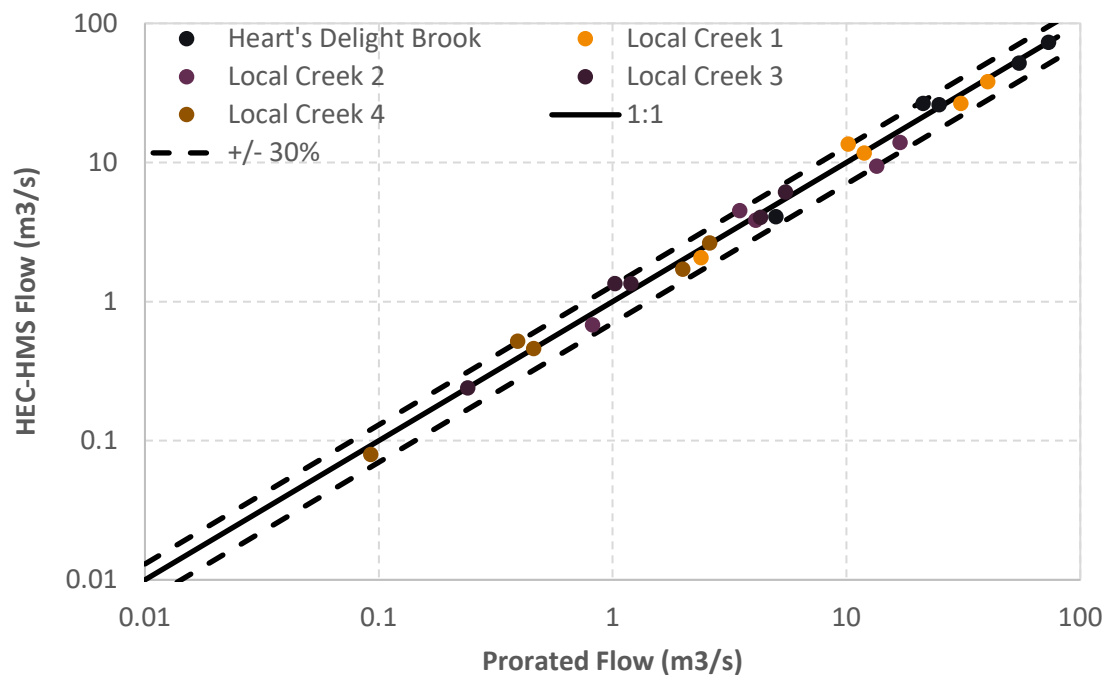
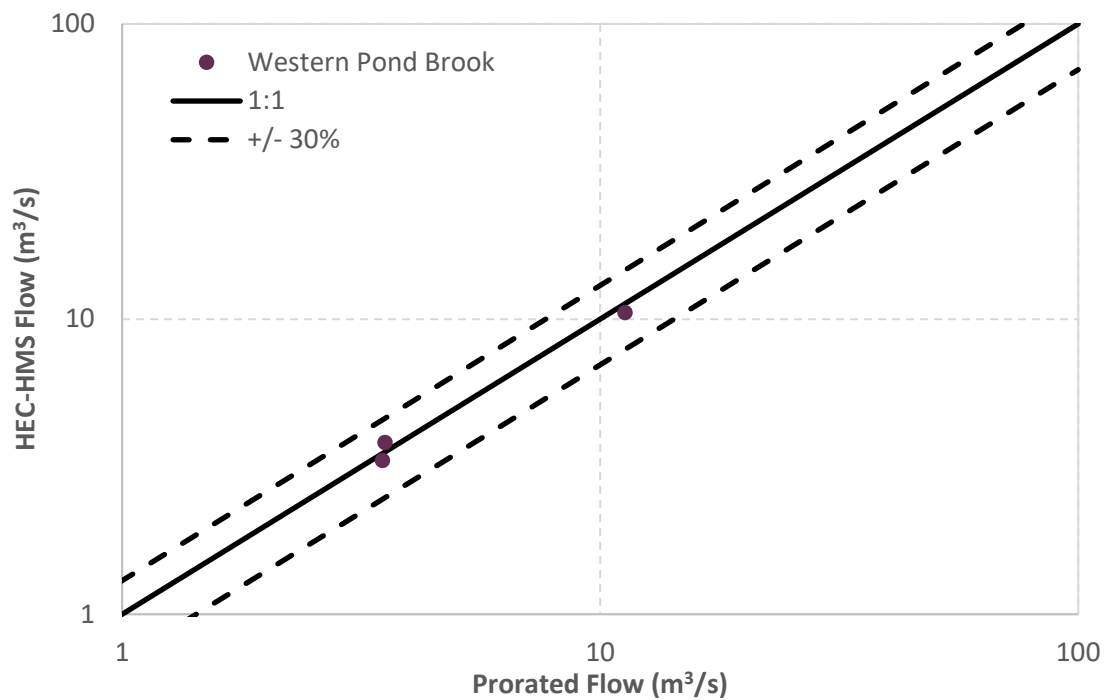
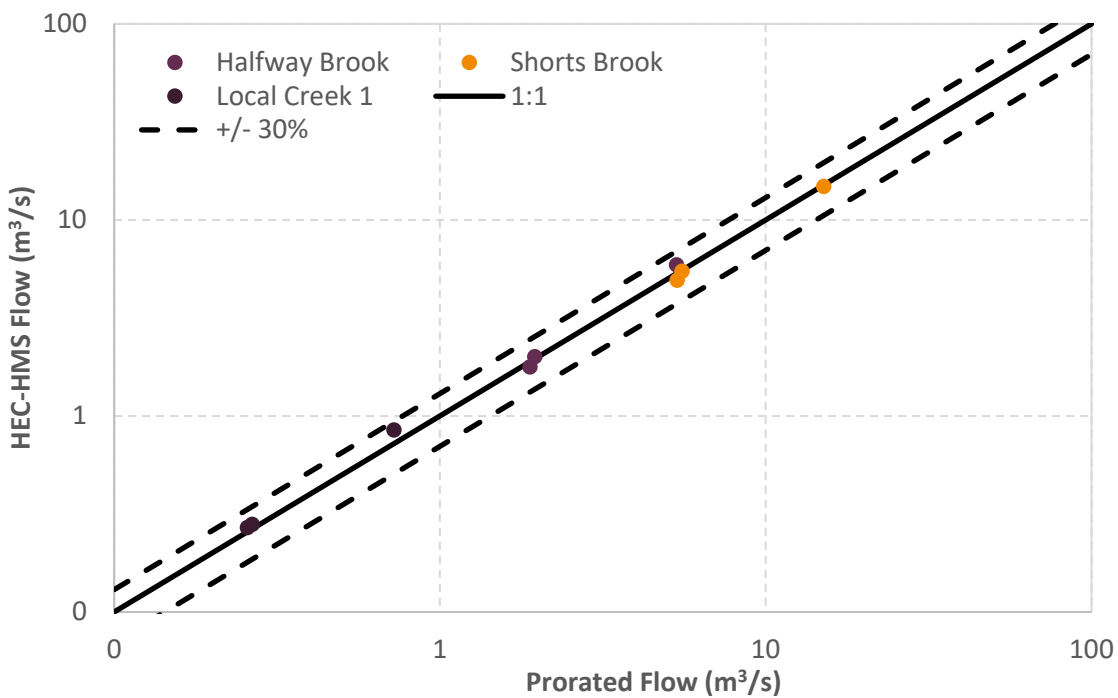
FIGURE 66: COMPARISON OF SIMULATED AND PRORATED PEAK FLOWS IN BRIGUS**FIGURE 67: COMPARISON OF SIMULATED AND PRORATED PEAK FLOWS IN HEART'S DELIGHT - ISLINGTON**

FIGURE 68: COMPARISON OF SIMULATED AND PRORATED PEAK FLOWS IN WINTERTON**FIGURE 69: COMPARISON OF SIMULATED AND PRORATED PEAK FLOWS IN HANT'S HARBOUR**

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%. Accordingly, 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.

6.5 Precipitation Analysis

6.5.1 EXISTING CONDITIONS IDF CURVES

As part of our 2021 Climate Change Flood Risk Mapping Study for Placentia, Carbonear, Salmon Cove, and Victoria (KGS Group, 2021), an update was completed for IDF curves at Argentia and St. John's for inclusion in the hydrologic modelling to define flow rates on the various rivers and creeks for that study. These stations were selected for updating as they are the closest stations to the study areas, although for this study, only the St. John's IDF curves are applicable. The status of the St. John's station, as well as the data available for that station, is summarized in Table 25.

TABLE 25: SUMMARY OF ECCC IDF CURVE STATIONS

Station Name	Station ID	Duration of Data in IDF Curve	Number of Years of Data	Status of Station
St. John's A	8403506	1949-1996	35	Inactive (as of 2012)

The IDF curve for St. John's A was 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 ($<0^{\circ}\text{C}$), 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).

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 70 and Figure 71.

FIGURE 70: UPDATED IDF CURVE FOR ST. JOHN'S A

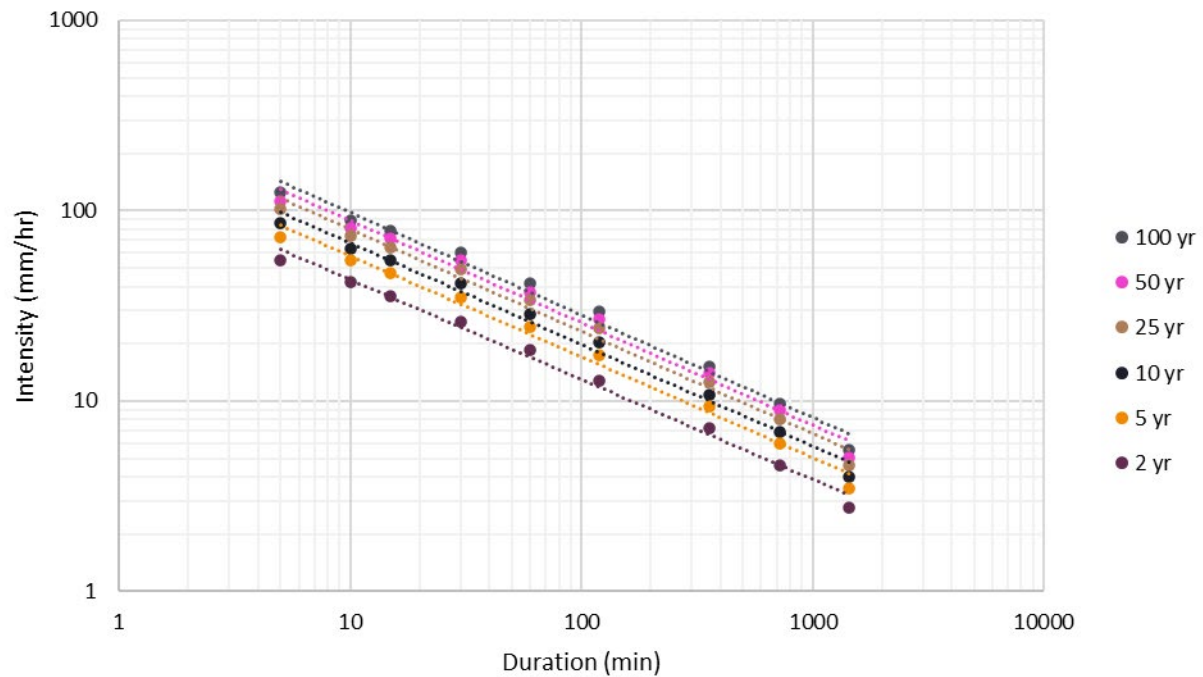
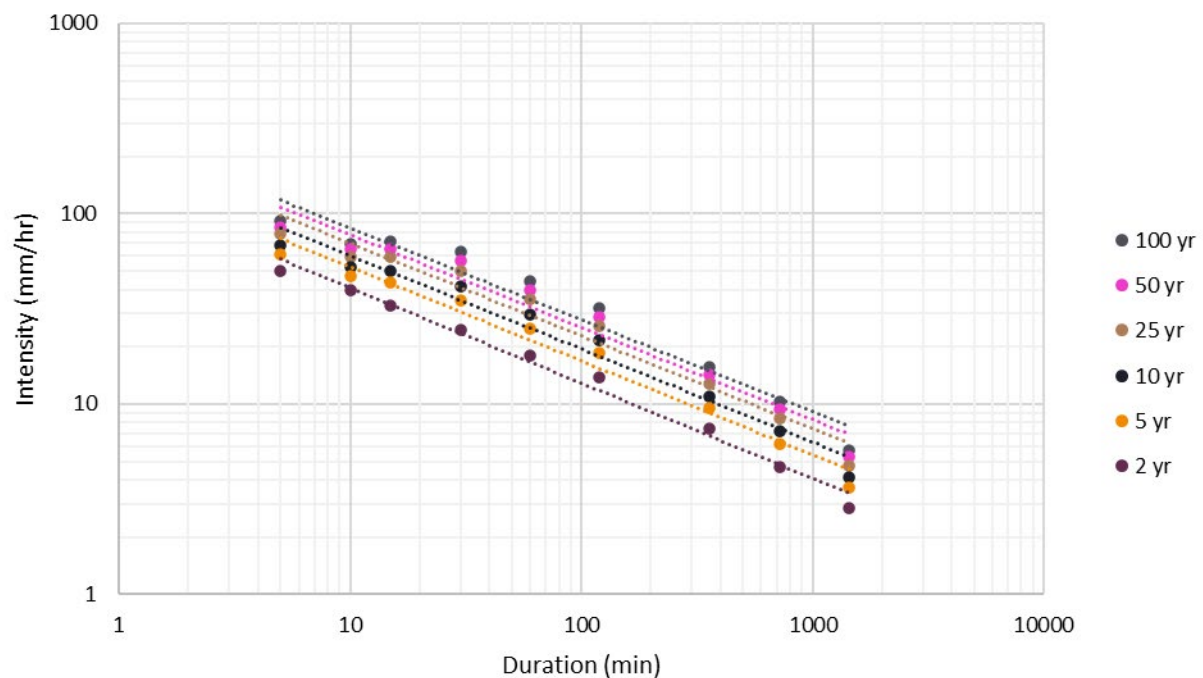


FIGURE 71: UPDATED IDF CURVE FOR ST. JOHN'S RUBY LINE



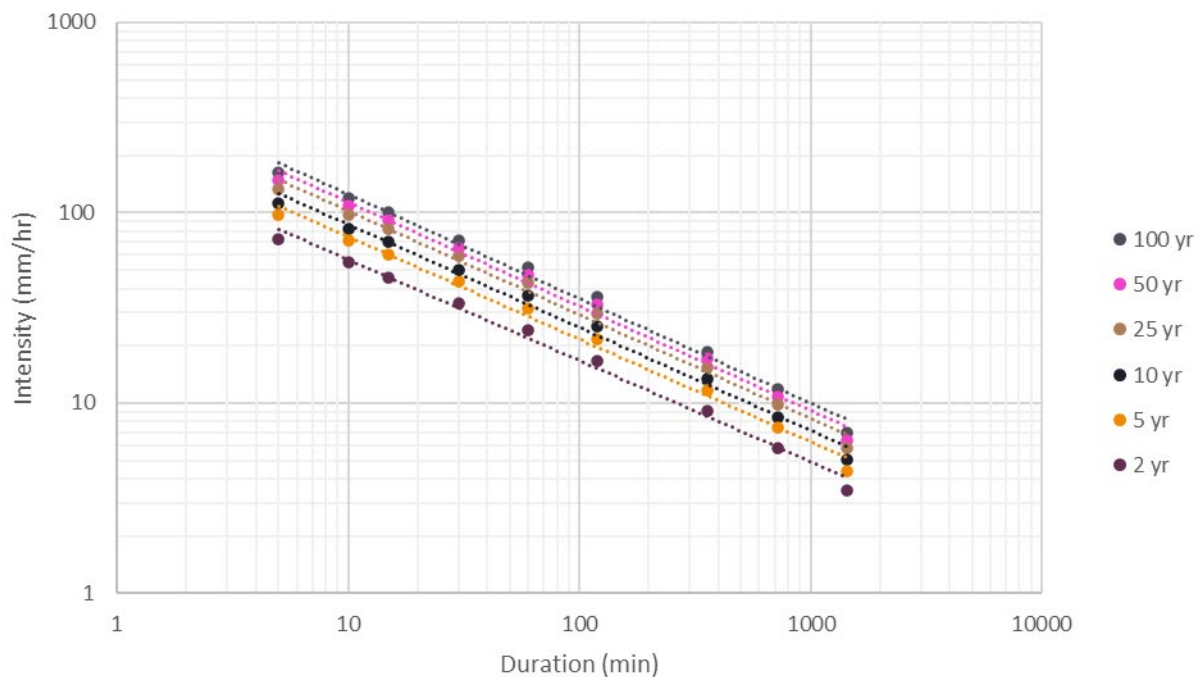
Rainfall hyetographs developed using the St. John's Ruby Line IDF curve were found to result in greater river flows, and as such the Ruby Line IDF curve was conservatively adopted for the subsequent development of rainfall hyetographs for inclusion in the hydrologic modelling.

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 F. The updated IDF curves for St. John's A is also included in a tabular format in Appendix G, for reference.

6.5.2 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 curve for St. John's is shown on Figure 72.

FIGURE 72: 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.

6.6 Definition and Routing of the 1:20 and 1:100 AEP Rainfall Events

Based on the precipitation analysis described in Section 6.5, synthetic hyetographs were developed representing the 20 and 100-year AEP design storms at the St. John's station. 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 study 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 study area are shown on Figure 73 to Figure 78.

FIGURE 73: 6-HOUR HYETOGRAPH (ALTERNATING BLOCK)

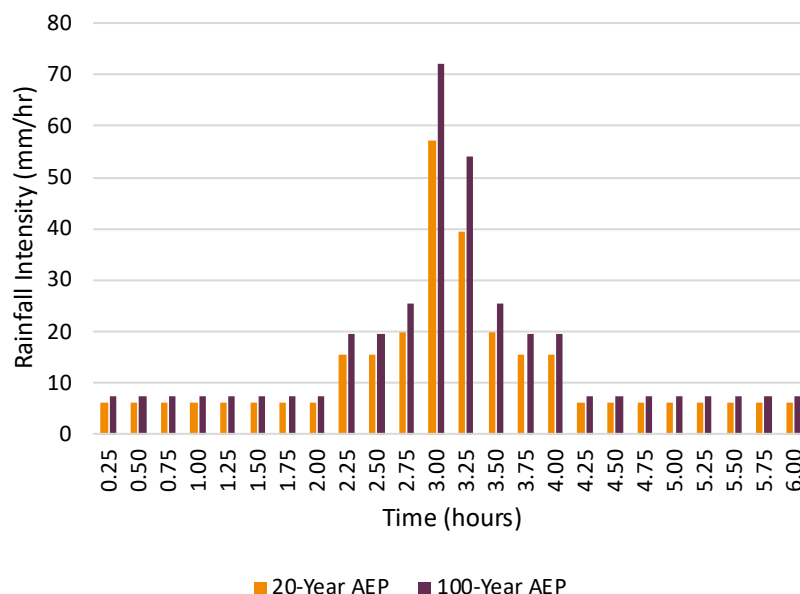


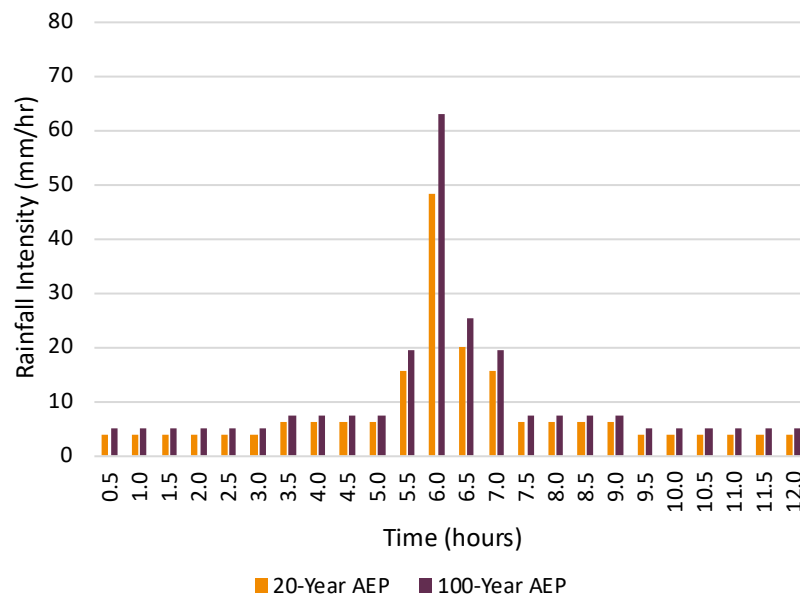
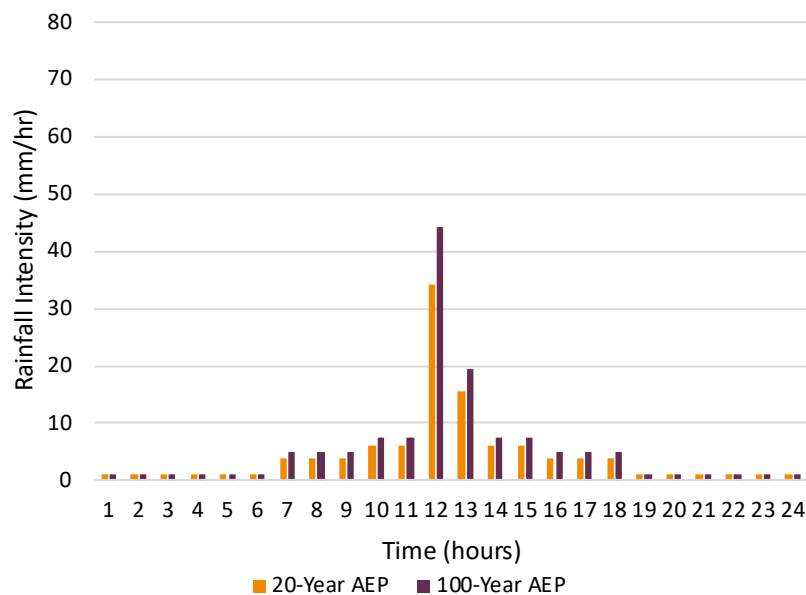
FIGURE 74: 12-HOUR HYETOGRAPH (ALTERNATING BLOCK)**FIGURE 75: 24-HOUR HYETOGRAPH (ALTERNATING BLOCK)**

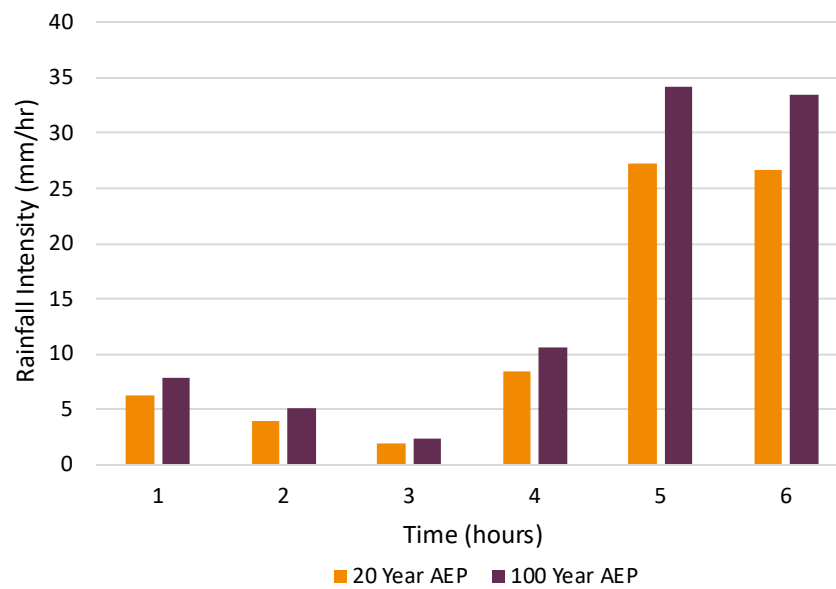
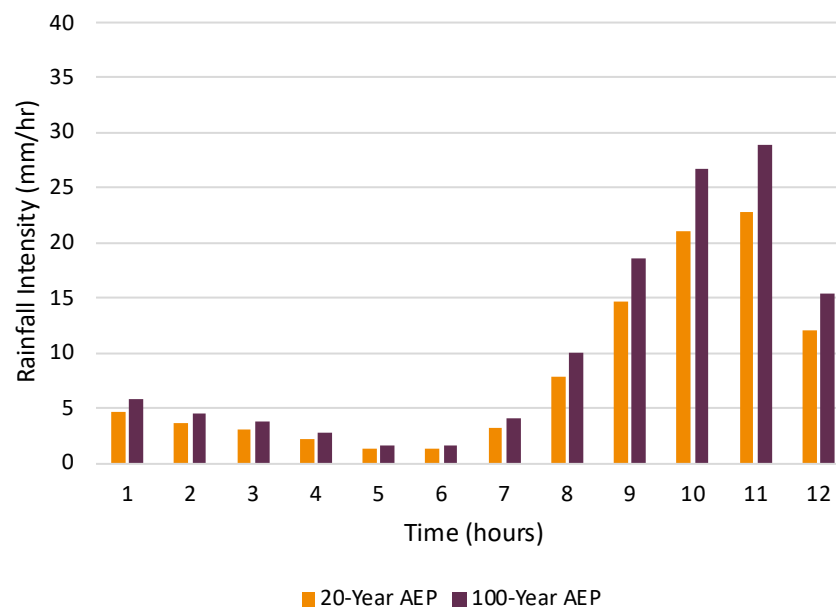
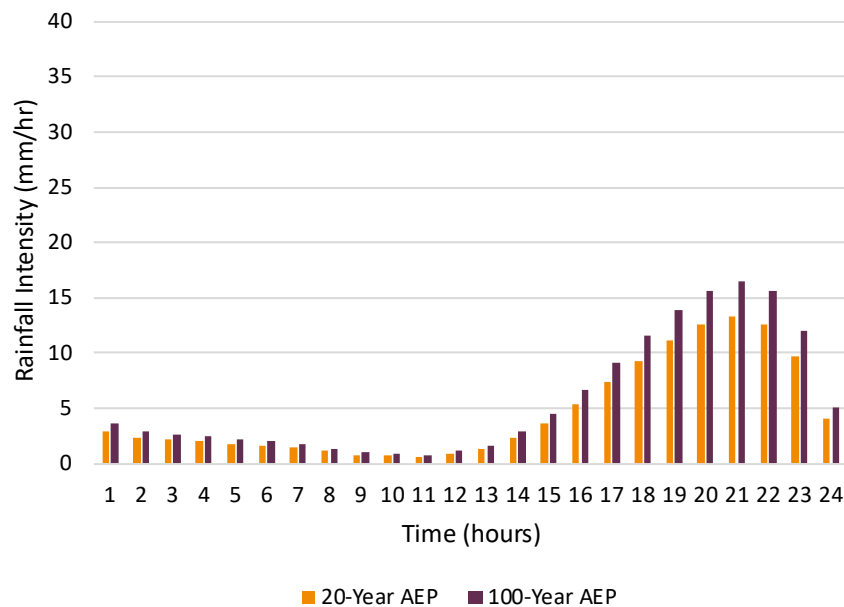
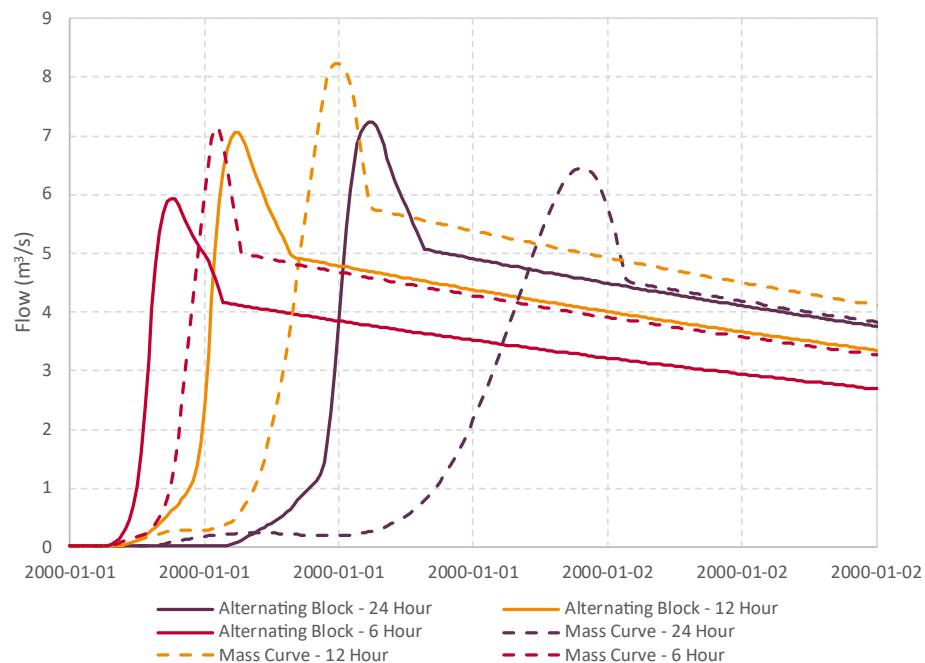
FIGURE 76: 6-HOUR HYETOGRAPH (MASS CURVE)**FIGURE 77: 12-HOUR HYETOGRAPH (MASS CURVE)**

FIGURE 78: 24-HOUR HYETOGRAPH (MASS CURVE)

The hyetographs were simulated using the Ferryland HEC-HMS model, and flows at the Freshwater River outlet were extracted for comparison. Comparisons of the resulting flows for the Alternating Block and Dimensionless Mass Curve methods are shown on Figure 79.

FIGURE 79: COMPARISON OF ALTERNATING BLOCK AND DIMENSIONLESS 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 12-hour and 24-hour Alternating Block hyetographs and 6-hour and 24-hour Mass Curve hyetographs resulted in similar flows on the Freshwater River. 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 Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour 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 study area are summarized in Table 26.

TABLE 26: SUMMARY OF HEC-HMS FLOWS

Town	Watershed	Subbasin	Drainage Area (km ²)	20-Year AEP Flow (m ³ /s)	AEP Flow (m ³ /s)
Ferryland	Freshwater River	Total	2.3	4.9	7.0
	Quarry River	Total	9.7	16.5	23.1
		Upstream North	5.8	9.4	13.0
		Upstream South	1.2	1.9	2.6
		Downstream	2.7	5.9	8.3
Brigus	Lambes Brook	Total	11.3	19.9	27.0
	Brigus North Brook	Total	2.2	4.2	5.7
	Apses Brook	Total	0.5	1.3	1.8
	Local Creek 1	Total	1.6	3.4	4.7
	Local Creek 2	Total	0.7	2.3	3.4
	Local Creek 3	Total	0.7	2.2	3.2
Heart's Delight - Islington	Heart's Delight Brook	Total	42.2	51.8	73.1
	Local Creek 1	Total	20.1	26.6	38.2
	Local Creek 2	Total	6.9	9.4	14.0
	Local Creek 3	Total	2.0	4.1	6.2
	Local Creek 4	Total	0.8	1.7	2.7
Winterton	Western Pond Brook	Total	12.9	22.6	29.2
		Upstream North	10.8	19.4	25.2
		Upstream South	1.2	2.6	3.3
		Downstream	1.0	0.9	1.1
Hant's Harbour	Halfway Brook	Total	20.1	34.0	43.9
	Halfway Brook	Upstream West	1.8	4.3	5.8
	Halfway Brook	Upstream East	14.0	21.7	27.8
	Halfway Brook	Downstream	4.3	8.9	11.7
	Shorts Brook	Total	7.1	14.4	19.0
	Shorts Brook	Upstream	3.6	7.4	9.7
	Shorts Brook	Downstream	1.5	3.6	4.8
	Shorts Brook	Southwest Brook	2.0	3.6	4.7
	Local Creek 1	Total	1.0	2.7	3.7

6.7 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. The Rational Method has a similar limitation insofar as that it is only appropriate for drainage basins smaller than 5 km². Accordingly, the proration of SSFA flows and use of RFFA equations for small basins, as well as use of the Rational Method for large (i.e. greater than 5 km²) within the study areas is inappropriate and prone to error. A comparison of the estimated flows based on the SSFA, RFFA, Rational Method, and HEC-HMS model for the rivers and creeks considered in the study areas are summarized in Table 27. Estimated flows where the application of a specific method is considered inappropriate are highlighted in yellow.

TABLE 27: COMPARISON OF FLOWS

Town	Watershed	Subbasin	Drainage Area (km ²)	20-Year AEP Flow (m ³ /s)					100-Year AEP Flow (m ³ /s)				
				SFFA	RFFA 1 Eq	RFFA 2 EQ	Method	HEC-HMS	SFFA	RFFA 1 Eq	RFFA 2 EQ	Method	HEC-HMS
Ferryland	Freshwater River	Total	2.3	4.0	4.9	5.6	5.1	4.9	5.7	6.3	6.8	6.5	7.0
	Quarry River	Total	9.7	13.0	15.9	15.2	10.3	16.5	18.3	21.0	20.6	12.8	23.1
		Upstream North	5.8	8.6	10.6	9.3	8.6	9.4	12.2	13.8	12.9	10.8	13.0
		Upstream South	1.2	2.4	2.9	3.4	2.6	1.9	3.4	3.7	4.1	3.3	2.6
		Downstream	2.7	4.6	5.6	6.4	6.3	5.9	6.5	7.2	7.8	8.0	8.3
Brigus	Lambes Brook	Total	11.3	15.5	18.0	17.7	11.2	19.9	23.6	23.9	23.7	14.0	27.0
	Brigus North Brook	Total	2.2	4.2	4.8	5.5	4.0	4.2	6.3	6.2	6.7	5.0	5.7
	Apses Brook	Total	0.5	1.2	1.4	1.5	1.3	1.3	1.9	1.8	1.8	1.6	1.8
	Local Creek 1	Total	1.6	3.2	3.7	3.7	3.1	3.4	4.9	4.7	4.7	3.9	4.7
	Local Creek 2	Total	0.7	1.7	2.0	2.4	2.1	2.3	2.6	2.5	2.8	2.7	3.4
	Local Creek 3	Total	0.7	1.6	1.8	1.9	2.0	2.2	2.4	2.3	2.4	2.6	3.2
Heart's Delight - Islington	Heart's Delight Brook	Total	42.2	45.0	52.2	44.9	36.4	51.8	68.3	71.1	65.6	45.1	73.1
	Local Creek 1	Total	20.1	24.8	28.8	25.2	19.6	26.6	37.7	38.6	36.0	24.4	38.2
	Local Creek 2	Total	6.9	10.5	12.2	10.7	9.4	9.4	16.0	16.0	14.9	11.8	14.0
	Local Creek 3	Total	2.0	3.9	4.5	5.2	4.3	4.1	5.9	5.8	6.3	5.5	6.2
	Local Creek 4	Total	0.8	1.8	2.1	2.5	2.0	1.7	2.7	2.6	2.9	2.6	2.7
Winterton	Western Pond Brook	Total	12.9	12.1	20.1	16.8	14.4	22.6	16.5	26.7	24.2	18.0	29.2
		Upstream North	10.8	10.5	17.4	14.0	13.3	19.4	14.2	23.0	20.5	16.6	25.2
		Upstream South	1.2	1.8	2.9	3.4	2.7	2.6	2.4	3.7	4.0	3.5	3.3
		Downstream	1.0	1.5	2.5	3.0	2.6	0.9	2.1	3.2	3.5	3.3	1.1
Hant's Harbour	Halfway Brook	Total	20.1	17.4	28.7	24.6	17.5	34.0	23.5	38.6	35.5	21.7	43.9
	Halfway Brook	Upstream West	1.8	2.5	4.1	4.7	3.2	4.3	3.4	5.3	5.7	4.1	5.8
	Halfway Brook	Upstream East	14.0	13.0	21.5	20.2	14.8	21.7	17.6	28.6	27.7	18.4	27.8
	Halfway Brook	Downstream	4.3	5.0	8.3	7.5	6.6	8.9	6.8	10.8	10.2	8.2	11.7
	Shorts Brook	Total	7.1	7.5	12.4	13.8	9.5	14.4	10.2	16.3	17.3	11.8	19.0
	Shorts Brook	Upstream	3.6	4.4	7.2	8.1	6.5	7.4	5.9	9.3	10.0	8.2	9.7
	Shorts Brook	Downstream	1.5	2.2	3.6	4.1	3.4	3.6	2.9	4.5	4.9	4.3	4.8
	Shorts Brook	Southwest Brook	2.0	2.7	4.5	5.1	3.1	3.6	3.7	5.7	6.2	3.9	4.7
	Local Creek 1	Total	1.0	1.5	2.5	2.9	2.7	2.7	2.0	3.1	3.4	3.5	3.7

In general, there is very good agreement between the SSFA, RFFA, Rational Method, and HEC-HMS estimates of the 20- and 100-year AEP flood flows throughout the study area, even considering flows defined by inappropriate methods. In general, the flows defined by the HEC-HMS model were found to be reasonable, if slightly conservative relative to the other methods, and could be consistently applied across all basins in the study area. Accordingly, the flood flows defined by the HEC-HMS model were adopted for subsequent analyses in this study. The final adopted flows for the study areas are summarized in Table 28.

TABLE 28: ADOPTED AEP FLOWS

Town	Watershed	Subbasin	Drainage Area (km ²)	20-Year AEP Flow (m ³ /s)	AEP Flow (m ³ /s)
Ferryland	Freshwater River	Total	2.3	4.9	7.0
	Quarry River	Total	9.7	16.5	23.1
		Upstream North	5.8	9.4	13.0
		Upstream South	1.2	1.9	2.6
		Downstream	2.7	5.9	8.3
Brigus	Lambes Brook	Total	11.3	19.9	27.0
	Brigus North Brook	Total	2.2	4.2	5.7
	Apses Brook	Total	0.5	1.3	1.8
	Local Creek 1	Total	1.6	3.4	4.7
	Local Creek 2	Total	0.7	2.3	3.4
	Local Creek 3	Total	0.7	2.2	3.2
Heart's Delight - Islington	Heart's Delight Brook	Total	42.2	51.8	73.1
	Local Creek 1	Total	20.1	26.6	38.2
	Local Creek 2	Total	6.9	9.4	14.0
	Local Creek 3	Total	2.0	4.1	6.2
	Local Creek 4	Total	0.8	1.7	2.7
Winterton	Western Pond Brook	Total	12.9	22.6	29.2
		Upstream North	10.8	19.4	25.2
		Upstream South	1.2	2.6	3.3
		Downstream	1.0	0.9	1.1
Hant's Harbour	Halfway Brook	Total	20.1	34.0	43.9
	Halfway Brook	Upstream West	1.8	4.3	5.8
	Halfway Brook	Upstream East	14.0	21.7	27.8
	Halfway Brook	Downstream	4.3	8.9	11.7
	Shorts Brook	Total	7.1	14.4	19.0
	Shorts Brook	Upstream	3.6	7.4	9.7
	Shorts Brook	Downstream	1.5	3.6	4.8
	Shorts Brook	Southwest Brook	2.0	3.6	4.7
	Local Creek 1	Total	1.0	2.7	3.7

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 Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour.

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 17% to 36% on the various rivers and creeks due to the projected climate change impacts, with differences in impacts due to climate change resulting from different physiographic characteristics and hydrologic responses to increased precipitation in each of the study watersheds.

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 al., 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 0.66 m in Ferryland, 0.63 m in Brigus, 0.63 m in Heart's Delight – Islington, 0.63 m in Hant's Harbour, and 0.63 m in Winterton relative to the ground elevation by the end of the century.

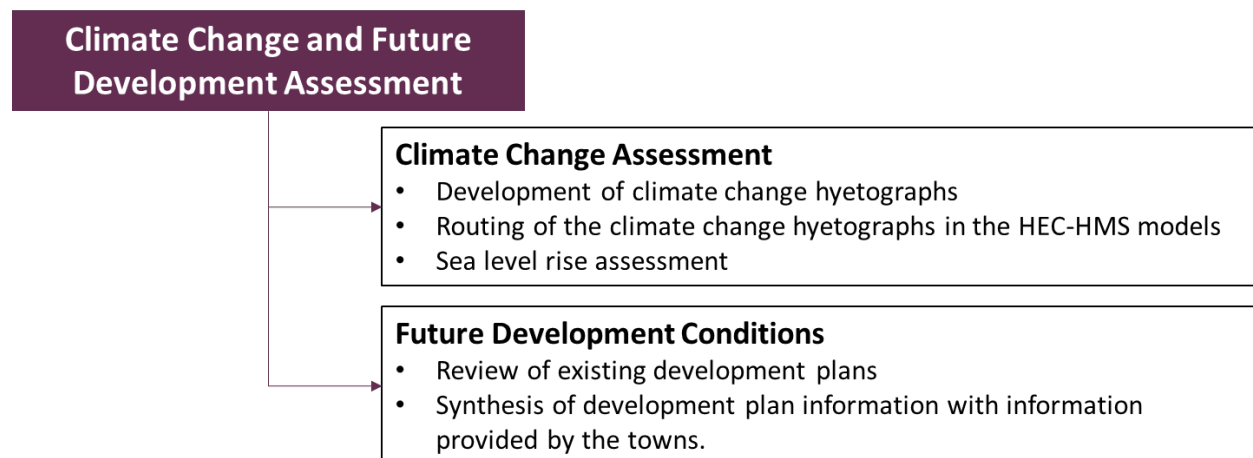
Ice processes, including the potential for ice jamming, are expected to be affected by climate change due to the projected rising temperatures. The current state of research regarding climate change impacts on ice jams suggests that, given the relatively rare occurrence of ice jamming in Heart's Delight – Islington, Winterton and Hant's Harbour, 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 Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour 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 (i.e. infill development and / or redevelopment) 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 80.

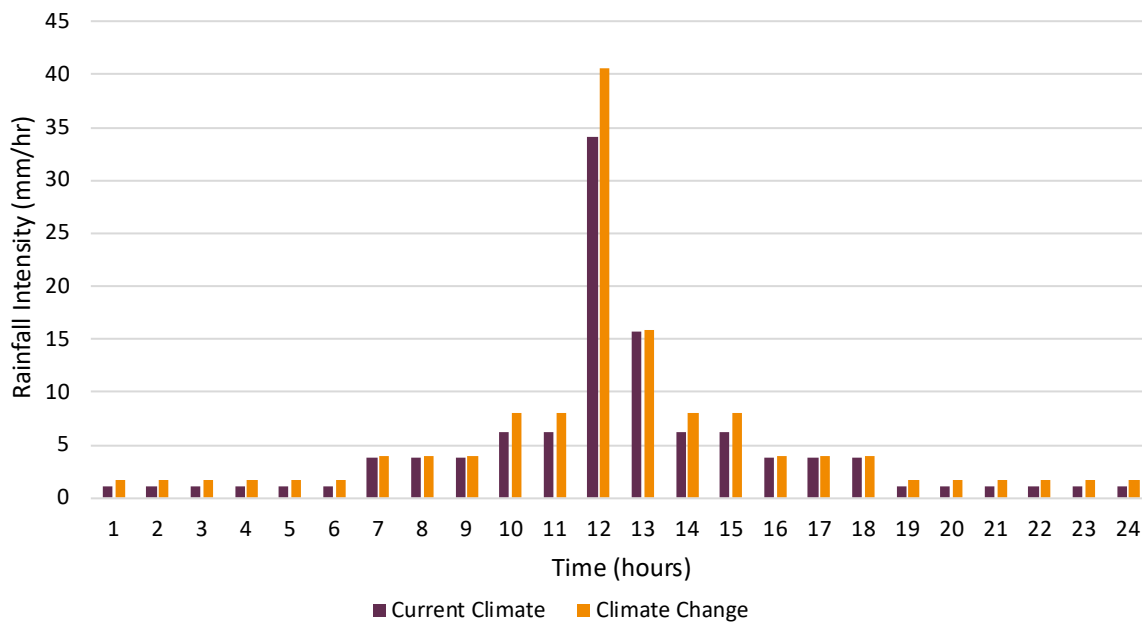
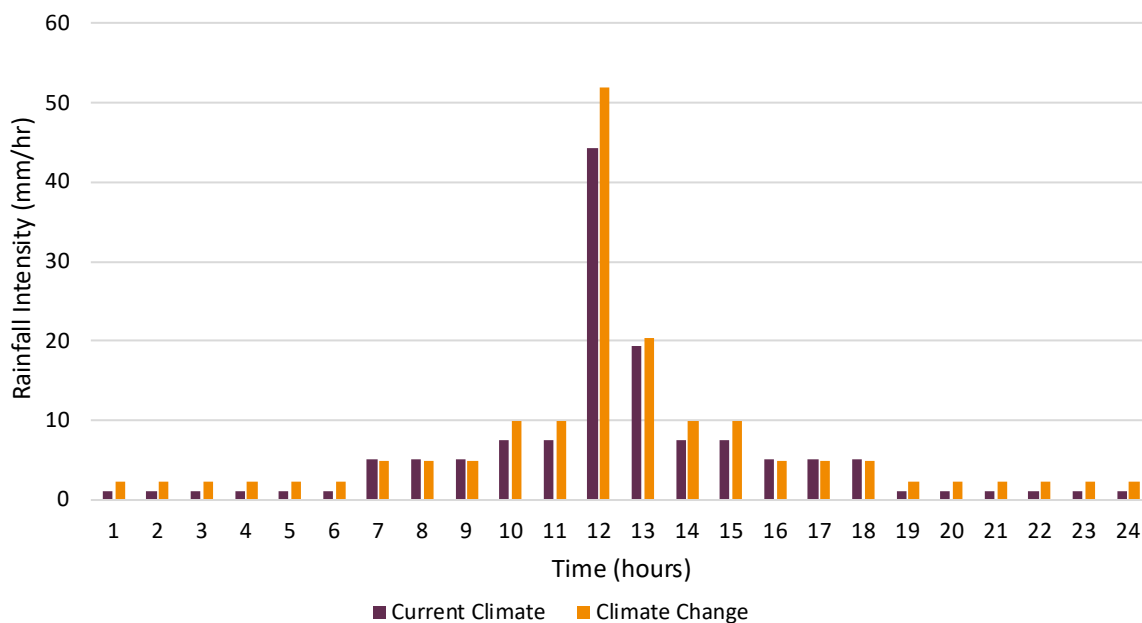
FIGURE 80: OVERVIEW OF CLIMATE CHANGE AND FUTURE DEVELOPMENT ASSESSMENT



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. Synthetic hyetographs were defined based for climate change conditions based on the climate change-affected IDF curves developed for St. John's, as described in Section 6.5.2, specifically considering the RCP 8.5 scenario projected to the 2071 – 2100 timeframe. A comparison of the 20-year AEP rainfall hyetographs for current climate and climate change conditions for the study area are shown on Figure 81. Similarly, a comparison of the current climate and climate change 100-year AEP hyetographs are shown on Figure 82.

FIGURE 81: COMPARISON OF CURRENT CLIMATE AND CLIMATE CHANGE 20-YEAR AEP HYETOGRAPHS**FIGURE 82: COMPARISON OF CURRENT CLIMATE AND CLIMATE CHANGE 100-YEAR AEP HYETOGRAPHS**

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 in Table 29.

TABLE 29: COMPARISON OF CURRENT CLIMATE AND CLIMATE CHANGE FLOWS

Town	Watershed	Subbasin	Current Climate Flow (m ³ /s)		Climate Change Flow (m ³ /s)	
			20-Year AEP Flow	100-Year AEP Flow	20-Year AEP Flow	100-Year AEP Flow
Ferryland	Freshwater River	Total	4.9	7.0	6.4	9.1
	Quarry River	Total	16.5	23.1	21.0	29.6
		Upstream North	9.4	13.0	12.0	16.6
		Upstream South	1.9	2.6	2.4	3.4
		Downstream	5.9	8.3	7.6	10.8
Brigus	Lambes Brook	Total	19.9	27.0	24.8	33.6
	Brigus North Brook	Total	4.2	5.7	5.2	7.0
	Apses Brook	Total	1.3	1.8	1.7	2.3
	Local Creek 1	Total	3.4	4.7	4.2	5.8
	Local Creek 2	Total	2.3	3.4	3.0	4.4
	Local Creek 3	Total	2.2	3.2	2.8	4.0
Heart's Delight - Islington	Heart's Delight Brook	Total	51.8	73.1	67.5	95.3
	Local Creek 1	Total	26.6	38.2	35.0	50.5
	Local Creek 2	Total	9.4	14.0	12.6	18.9
	Local Creek 3	Total	4.1	6.2	5.5	8.3
	Local Creek 4	Total	1.7	2.7	2.3	3.6
Winterton	Western Pond Brook	Total	22.6	29.2	27.3	35.3
		Upstream North	19.4	25.2	23.4	30.4
		Upstream South	2.6	3.3	3.0	3.9
		Downstream	0.9	1.1	1.0	1.3
Hant's Harbour	Halfway Brook	Total	34.0	43.9	41.2	53.5
	Halfway Brook	Upstream West	4.3	5.8	5.3	7.0
	Halfway Brook	Upstream East	21.7	27.8	26.1	33.7
	Halfway Brook	Downstream	8.9	11.7	10.9	14.4
	Shorts Brook	Total	14.4	19.0	17.5	23.1
	Shorts Brook	Upstream	7.4	9.7	9.0	11.8
	Shorts Brook	Downstream	3.6	4.8	4.4	5.8
	Shorts Brook	Southwest Brook	3.6	4.7	4.4	5.7
	Local Creek 1	Total	2.7	3.7	3.3	4.5

The relative impact that climate change is anticipated to have on the peak flows on the waterways considered in the study areas is summarized in Table 30. It should be noted that the variability in impacts to flows between communities can be attributed to different physiological conditions in the watersheds in those communities, as well as different hydrological responses to increased precipitation.

TABLE 30: RELATIVE IMPACT OF CLIMATE CHANGE ON RIVER FLOWS

Town	Watershed	Subbasin	20-Year AEP Flow	100-Year AEP Flow
Ferryland	Freshwater River	Total	29.3%	29.1%
	Quarry River	Total	27.4%	28.2%
		Upstream North	27.4%	28.1%
		Upstream South	27.8%	30.3%
		Downstream	29.2%	29.7%
Brigus	Lambes Brook	Total	24.5%	24.6%
	Brigus North Brook	Total	22.9%	22.6%
	Apses Brook	Total	27.5%	27.7%
	Local Creek 1	Total	24.9%	24.4%
	Local Creek 2	Total	30.6%	28.0%
	Local Creek 3	Total	29.5%	26.9%
Heart's Delight - Islington	Heart's Delight Brook	Total	30.2%	30.3%
	Local Creek 1	Total	31.7%	32.2%
	Local Creek 2	Total	33.5%	35.7%
	Local Creek 3	Total	35.1%	35.1%
	Local Creek 4	Total	35.6%	34.6%
Winterton	Western Pond Brook	Total	20.7%	20.6%
		Upstream North	20.3%	20.6%
		Upstream South	17.4%	18.0%
		Downstream	20.2%	19.5%
Hant's Harbour	Halfway Brook	Total	21.2%	21.9%
	Halfway Brook	Upstream West	21.4%	21.9%
	Halfway Brook	Upstream East	20.5%	21.3%
	Halfway Brook	Downstream	21.8%	22.3%
	Shorts Brook	Total	21.6%	22.0%
	Shorts Brook	Upstream	21.4%	21.9%
	Shorts Brook	Downstream	21.5%	21.8%
	Shorts Brook	Southwest Brook	21.6%	22.1%
	Local Creek 1	Total	24.9%	24.0%

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 International Panel of Climate Change (IPCC) Fifth Assessment Report (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, which includes 0.1 m to 0.11 m of sea level rise relative to the 1986 – 2005 condition, to the year 2100. The RCP 8.5 median relative sea level rise projections to the year 2100, including land subsidence and accounting for sea level rise that has already occurred since the baseline condition (i.e. 1986 – 2005) that were adopted for Trinity Bay (i.e. 0.63 m), Conception Bay (i.e. 0.63 m) and Ferryland (i.e. 0.66 m) are shown on Figure 83 to Figure 85.

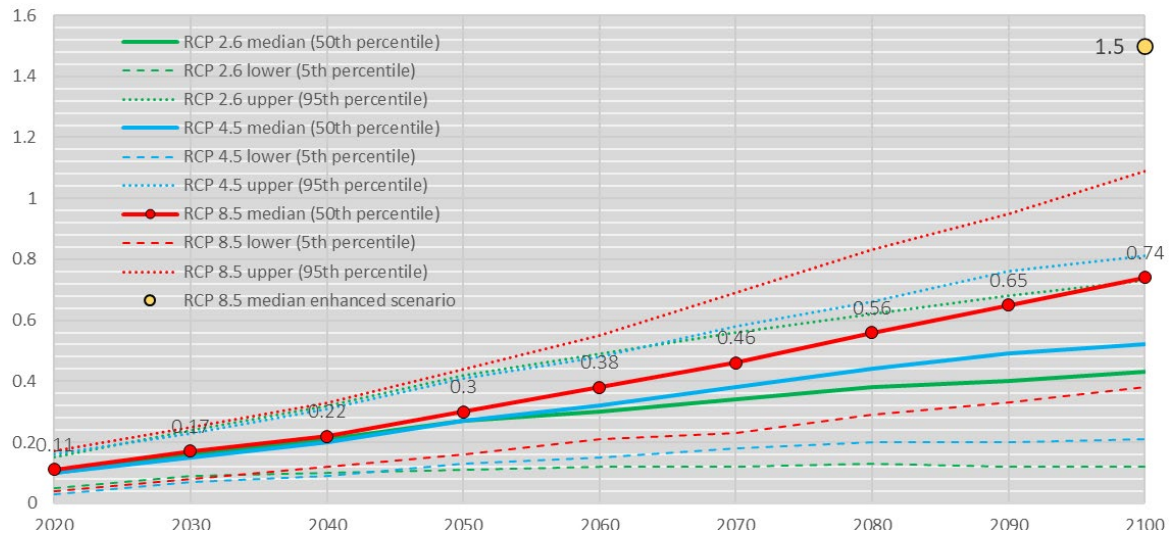
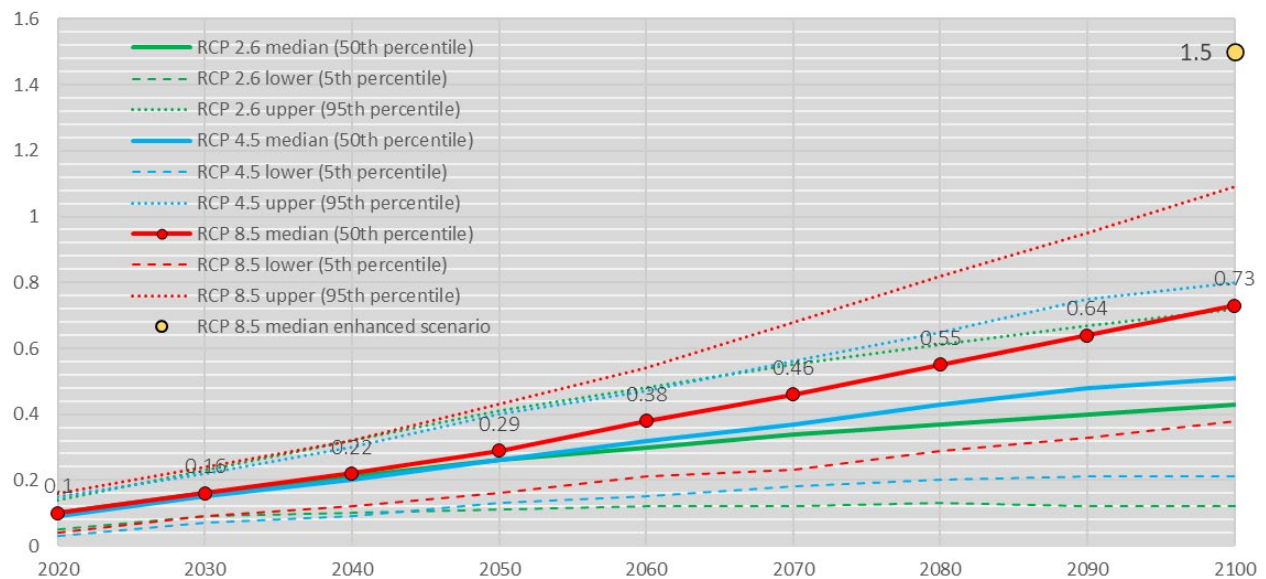
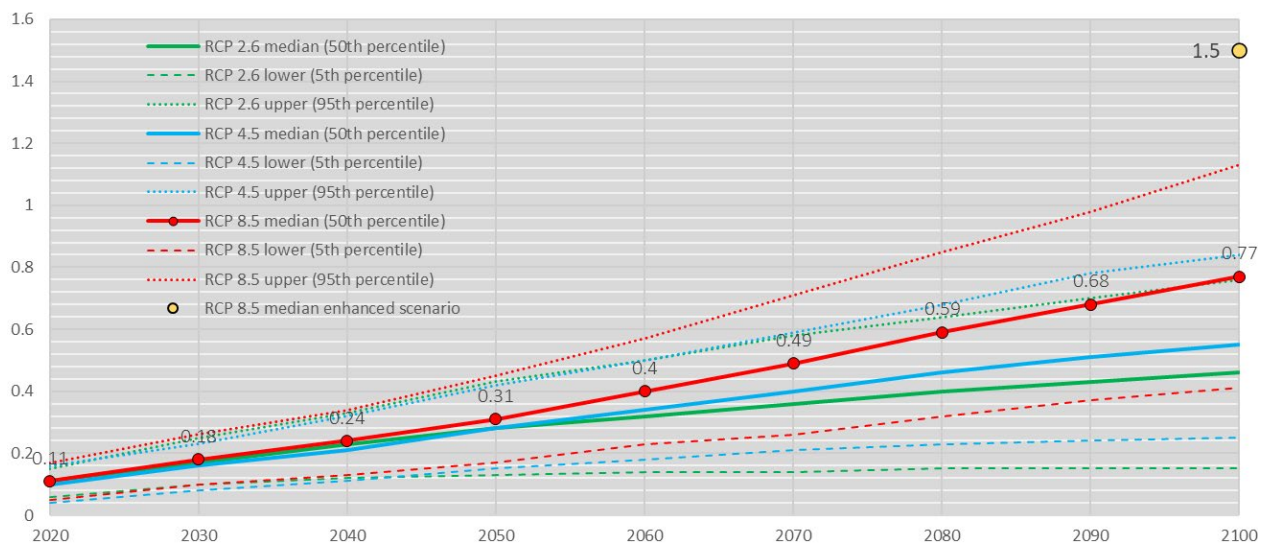
FIGURE 83: PROJECTED SEA LEVEL RISE FOR TRINITY BAY**FIGURE 84: PROJECTED SEA LEVEL RISE FOR CONCEPTION BAY**

FIGURE 85: PROJECTED SEA LEVEL RISE FOR FERRYLAND

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 STORM SURGE AND WAVES

To inform the projected changes to storm surge and wave climate at each of the communities of interest, a series of climate change analyses were completed as part of the development of the Atlas of Storm Surge and Wave climates along the coasts of Newfoundland and Labrador (DHI, 2024), as described further in Section 12.0 and as documented in Appendix O. Outputs at the most representative output point for each of the communities were extracted and analyzed.

Figure 86 to Figure 89 present the model output locations considered to obtain information on the projected changes for each community.

The projected changes were obtained for two horizons, specifically Mid-Century (i.e. 2041-2070) and Late-Century (i.e. 2071-2100), and for several statistics, specifically the 50th and 99th percentiles and Average Annual Maximum (AAM). The changes were calculated for the Water Level Residual (i.e. storm surge) and Significant Wave Height (i.e. Hm0). The projected changes are relative to the historical Baseline (i.e. 1985-2015) and consider the Shared Socioeconomic Pathway (SSP) 5-8.5 scenario for two Global Climate Models (GCM), specifically EC-Earth3 and ACCESS-CM2. For each parameter, the simulated changes from Baseline to Mid-/Late-Century are provided as absolute (i.e. Table 31) and relative percentages (i.e. Table 32) for each output point.

It should be noted that no bias correction was applied to the model results, so the absolute values in Table 31 should be interpreted with caution. These values are provided to indicate the order of magnitude of changes. Generally, using relative values is recommended. Further discussion on the application of these values is provided in Section 12.0.

FIGURE 86: REPRESENTATIVE CLIMATE CHANGE ATLAS OUTPUT POINT FOR FERRYLAND COMMUNITY

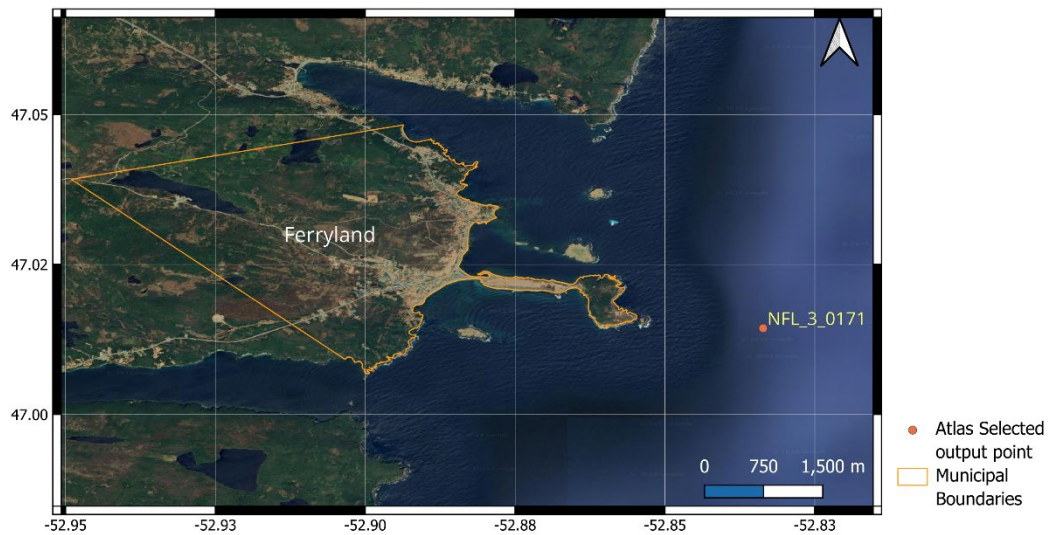


FIGURE 87: REPRESENTATIVE CLIMATE CHANGE ATLAS OUTPUT POINT FOR BRIGUS COMMUNITY

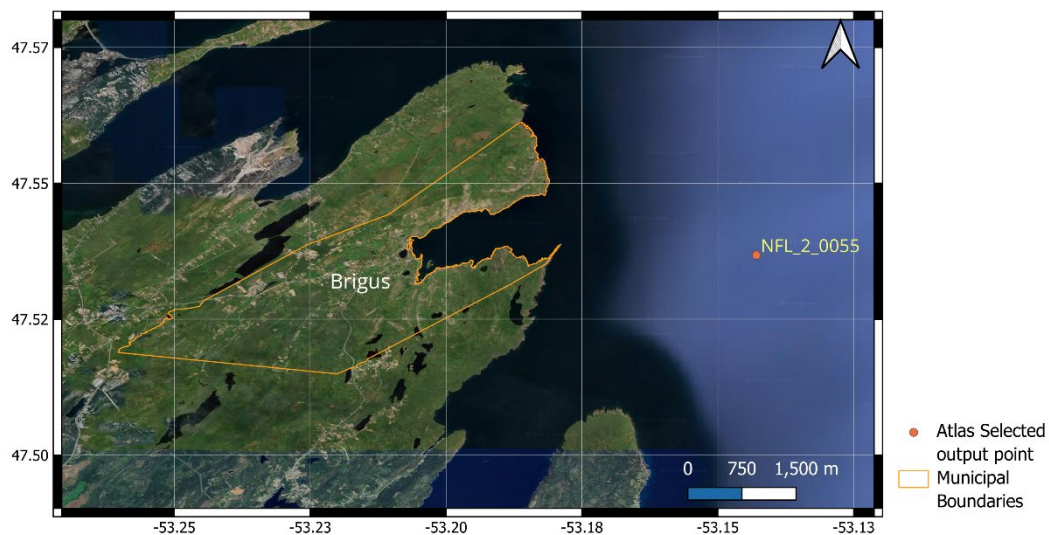


FIGURE 88: REPRESENTATIVE CLIMATE CHANGE ATLAS OUTPUT POINT FOR HANT'S HARBOUR AND WINTERTON COMMUNITIES

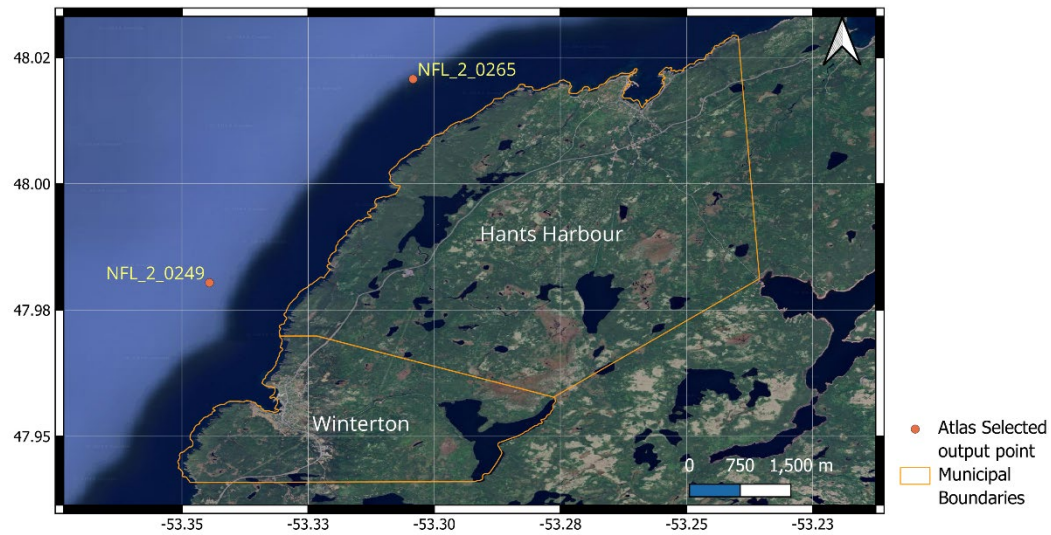


FIGURE 89: REPRESENTATIVE CLIMATE CHANGE ATLAS OUTPUT POINT FOR HEART'S DELIGHT – ISLINGTON COMMUNITY

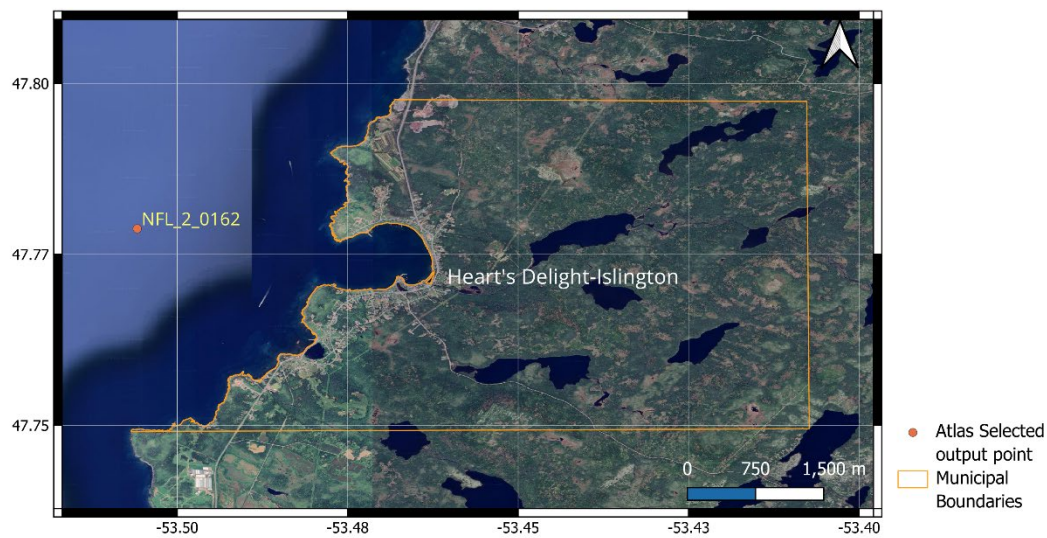


TABLE 31: ABSOLUTE PROJECTED CHANGE FOR STORM SURGE AND SIGNIFICANT WAVE HEIGHT STATISTICS FOR THE 5 COMMUNITIES OF INTEREST (BRIGUS, WINTERTON, HANT'S HARBOUR, HEART'S DELIGHT – ISLINGTON AND FERRYLAND)

Community	Climate model	Absolute Change, relative to Baseline (1985-2015) Storm surge [m]						Absolute change, relative to Baseline (1985-2015) Hm0 [m]					
		Mid-century (2041-2070)			Late century (2071-2100)			Mid-century (2041-2070)			Late century (2071-2100)		
		50 th %tile	99 th %tile	AAM	50 th %tile	99 th %tile	AAM	50 th %tile	99 th %tile	AAM	50 th %tile	99 th %tile	AAM
Brigus	EC-EARTH3	0.00	0.04	0.11	0.00	0.05	0.06	0.08	0.21	0.09	0.06	0.14	0.06
	ACCESS-CM2	0.00	0.02	0.02	0.00	0.01	0.01	-0.05	-0.05	-0.15	-0.12	0.01	-0.10
Winterton	EC-EARTH3	0.00	0.04	0.10	0.00	0.05	0.06	0.11	0.18	0.17	0.09	0.14	0.04
	ACCESS-CM2	0.00	0.02	0.03	0.00	0.02	0.01	0.03	0.03	-0.09	-0.04	0.01	-0.08
Hant's Harbour	EC-EARTH3	0.00	0.04	0.11	0.00	0.05	0.07	0.12	0.20	0.11	0.10	0.17	0.02
	ACCESS-CM2	0.00	0.02	0.04	0.00	0.02	0.02	0.03	0.03	-0.15	-0.06	0.02	-0.13
Heart's Delight-Islington	EC-EARTH3	0.00	0.04	0.10	0.00	0.05	0.06	0.06	0.03	0.12	0.04	-0.02	-0.01
	ACCESS-CM2	0.00	0.02	0.03	0.00	0.01	0.01	0.02	0.04	-0.05	-0.03	-0.01	-0.06
Ferryland	EC-EARTH3	0.00	0.05	0.13	0.00	0.05	0.06	-0.06	-0.09	0.12	-0.09	-0.14	0.27
	ACCESS-CM2	0.00	0.02	0.02	0.00	0.02	0.02	0.04	0.03	0.00	-0.02	-0.03	-0.12

TABLE 32: PERCENTAGE OF PROJECTED CHANGE FOR STORM SURGE AND SIGNIFICANT WAVE HEIGHT STATISTICS FOR THE 5 COMMUNITIES OF INTEREST (BRIGUS, WINTERTON, HANT'S HARBOUR, HEART'S DELIGHT – ISLINGTON AND FERRYLAND)

Community	Climate model	Percentage of change, relative to Baseline (1985-2015) Storm surge [%]						Percentage of change, relative to Baseline (1985-2015) Hm0 [%]					
		Mid-century (2041-2070)			Late century (2071-2100)			Mid-century (2041-2070)			Late century (2071-2100)		
		50 th %tile	99 th %tile	AAM	50 th %tile	99 th %tile	AAM	50 th %tile	99 th %tile	AAM	50 th %tile	99 th %tile	AAM
Brigus	EC-EARTH3	0%	14%	20%	0%	14%	11%	13%	9%	2%	10%	6%	2%
	ACCESS-CM2	0%	5%	5%	0%	4%	0%	-7%	-2%	-4%	-17%	0%	-3%
Winterton	EC-EARTH3	0%	14%	20%	0%	15%	13%	18%	9%	6%	15%	7%	1%
	ACCESS-CM2	0%	6%	7%	0%	5%	3%	4%	1%	-3%	-6%	1%	-2%
Hant's Harbour	EC-EARTH3	0%	14%	21%	0%	15%	13%	19%	8%	3%	15%	7%	0%
	ACCESS-CM2	0%	6%	7%	0%	5%	3%	4%	1%	-4%	-7%	1%	-3%
Heart's Delight-Islington	EC-EARTH3	0%	14%	20%	0%	15%	12%	14%	2%	5%	8%	-1%	0%
	ACCESS-CM2	0%	6%	7%	0%	5%	2%	3%	2%	-2%	-6%	0%	-2%
Ferryland	EC-EARTH3	0%	16%	21%	0%	13%	10%	-4%	-2%	2%	-6%	-3%	4%
	ACCESS-CM2	0%	5%	4%	0%	5%	4%	3%	1%	0%	-1%	-1%	-2%

The projected increased wave and surge conditions defined by the EC-Earth3 model relative to the ACCESS-CM2 model is primarily driven by a larger relative reduction in sea-ice cover compared to the ACCESS-CM2 model. In the historical period, the EC-Earth3 model simulates substantially more sea ice around the communities than the ACCESS-CM2 model, while by the late century both models indicate virtually ice-free conditions in the area. Consequently, the magnitude of change is larger in the EC-Earth3 model. This difference particularly influences the 50th-percentile (i.e. “average conditions”) statistics, which are more sensitive to the changes in ice cover. The larger relative decrease in wave conditions at Brigus projected by the ACCESS-CM2 model for the late century (i.e. -17%, -0.12 m) is consistent with the results within Conception Bay. This is also in line with the broader trend of decreasing wave conditions toward the southern regions of Newfoundland and the North Atlantic in general (e.g. Lemos et al., 2021) and is therefore not considered an anomaly.

It should be noted that expected changes of equal or less than 1% are not considered in the comments below. Additionally, all absolute changes less than 0.01 m are considered as “no change” and therefore are set to 0%. The following comments can be made on the simulated project changes:

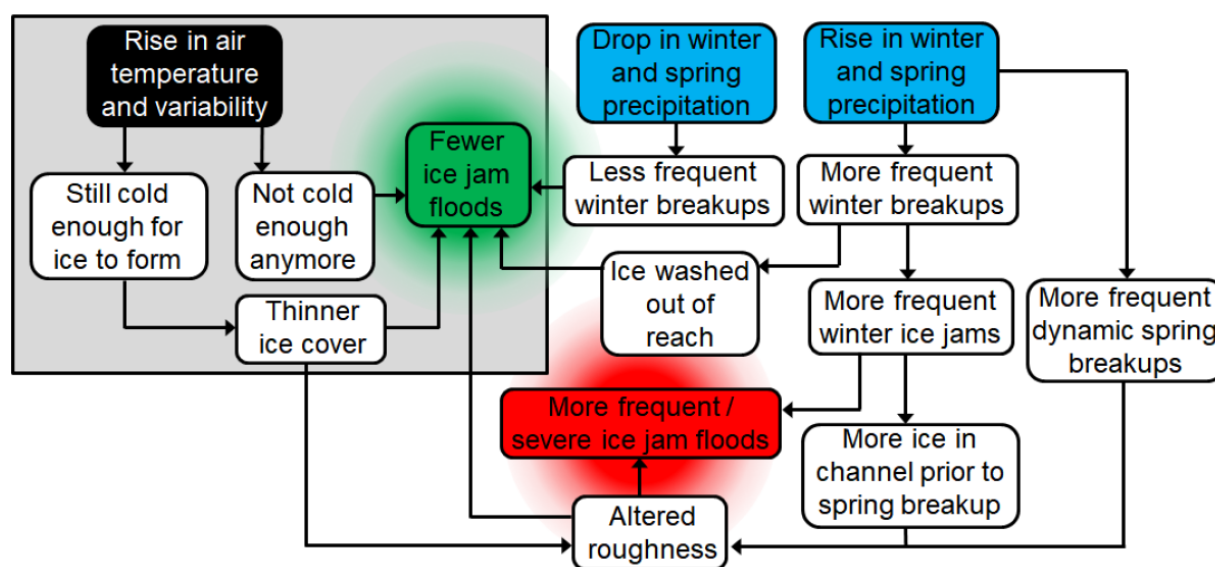
- Projected changes for Storm Surge:
 - No significant changes are expected for the 50th percentile for neither Mid-Century nor Late-Century.
 - Both projections agree that the 99th percentile of the storm surges are expected to increase for both Mid- and Late-Century. The percentage of increase varies from approximately 5% (i.e. 0.02 m) using ACCESS-CM2 to 15% (i.e. 0.05 m) using EC-Earth3.
 - Both projections agree that the AAM is expected to increase for both Mid- and Late-Century, but with higher increase for Mid-Century than Late-Century.
 - The percentage of increase for Mid-Century varies from approximately 5% (i.e. 0.02 m) using ACCESS-CM2 to 20% (i.e. 0.10 m) using EC-Earth3.
 - The percentage of increase for Late-Century varies from approximately 3% (i.e. 0.01 m) using ACCESS-CM2 to 10% (i.e. 0.06 m) using EC-Earth3.
- Projected changes for Significant Wave Height:
 - When using EC-Earth3, wave height statistics are expected to increase for both Mid-Century and Late-Century for all communities except Ferryland.
 - The expected increase is more pronounced for the 50th percentile (i.e. up to 19% or 0.12 m at Hant’s Harbour, Mid-Century), followed by 99th percentile (i.e. up to approximately 10% or 0.20 m at Brigus and Winterton, Mid-Century) and less pronounced for AAM (i.e. up to 6% or 0.17 m at Winterton, Mid-Century), and generally more pronounced for Mid-Century than Late-Century.
 - Ferryland presents a different behavior with an expected decrease in the order of 5% in 50th and 99th percentile and an increase in AAM of approximately 5% for both Mid- and Late-Century
 - The ACCESS-CM2 model indicates less pronounced changes than EC-Earth3. It can be noted that:
 - For the Late-Century a decrease is expected for all statistics and communities, with a more pronounced decrease of -17% (i.e. -0.12 m) at Brigus 50th percentile and a mild decrease of less than 10% for the other statistics/communities.
 - For the Mid-Century, ACCESS-CM2 indicates a small increase (less than 5% or 0.05 m) for 50th and 99th percentile for all communities except for Brigus, where a decrease of approximately

0.05 m is reported. The AAM for Mid-Century is reported with a decrease expectation for all communities. This is in line with global wave climate projections which indicate a reduction in wave heights in this area of North Atlantic (e.g. Lemos et al., 2021).

7.2.4 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 90.

FIGURE 90: 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 St. John's (i.e. the nearest location to the study areas) by the year 2100. Precipitation in St. John's, precipitation is projected to decrease slightly by 1% for winter conditions and increase by 13% for spring conditions.

In Hant's Harbour, Winterton, and Heart's Delight - Islington, 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 Ferryland, Brigus, and Heart's Delight – Islington to identify any proposed developments that could affect the hydrology of the rivers and creeks being considered as part of this study. Municipal plans were not available for Winterton and Hant's Harbour. These reviewed municipal plans included:

- The 2011 – 2021 Development Plan for Brigus,
- The 2011 – 2021 Municipal Plan for Ferryland, and
- The Town of Heart's Delight – Islington Municipal Plan (2015)

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 or redevelopment 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 hazard 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 Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour 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 flooding. 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 risks associated with flooding, a number of computer models were developed to assess the river and coastal 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 Hant's Harbour, Winterton, and Heart's Delight - Islington, 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 risk of flooding for these coastal communities.

A large, regional coastal model of the north Atlantic was developed to simulate historical storm surges on the ocean. Three smaller, more detailed models of Trinity Bay, Conception Bay, and the eastern coast of the Avalon Peninsula were also developed to take outputs from the larger model and use those outputs to better estimate the storm surge along the coastlines in Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour. 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.

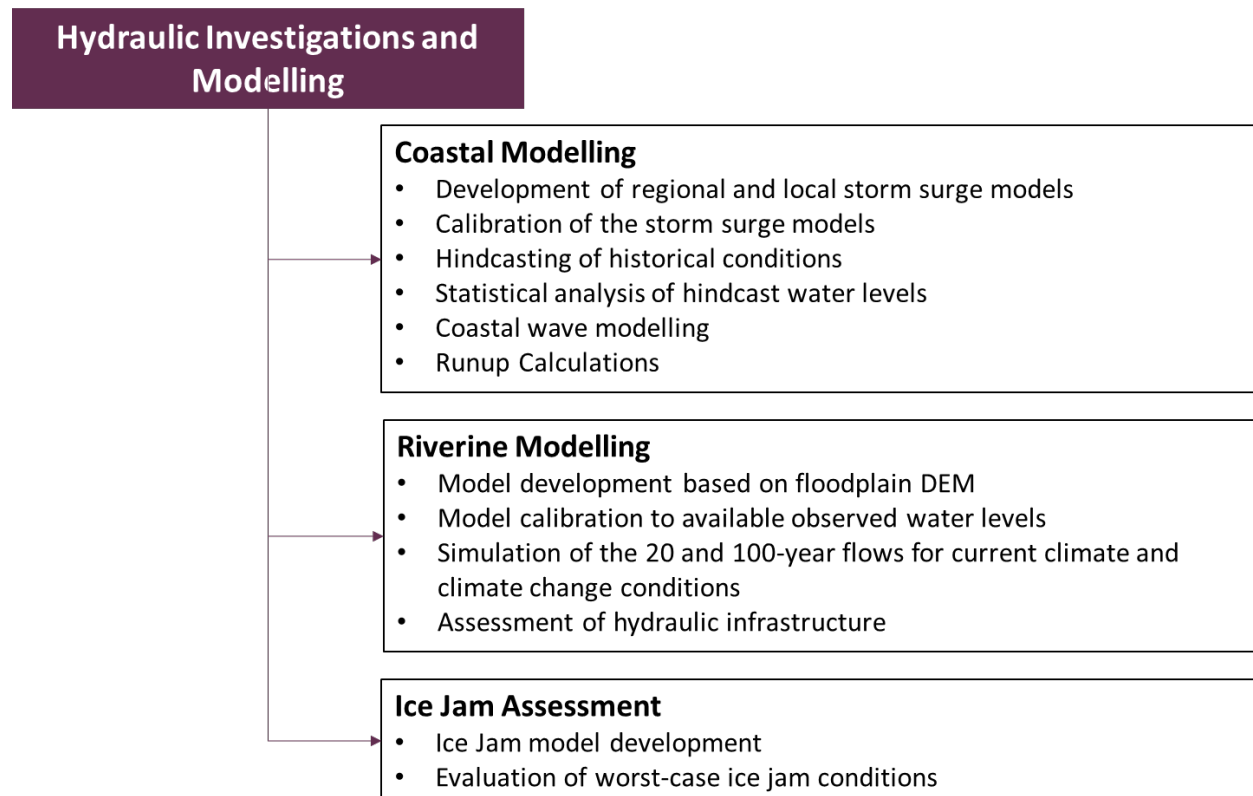
Numerous river hydraulic models were developed throughout the communities of Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour to define water levels caused by the 20 and 100-year AEP rainfall events. The models were adjusted to accurately reproduce recorded water levels, where they were available, and were found to be accurate.

Ice jam models were developed for Western Pond Brook (i.e. Winterton), Heart's Delight Brook (i.e. Heart's Delight – Islington), and Halfway Brook (Hant's Harbour) 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 hazard maps that show the extent of flooding, as well as flood risk 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 91.

FIGURE 91: 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 Ferryland, Brigus, Heart's Delight-Islington, Winterton and Hant's Harbour due to:

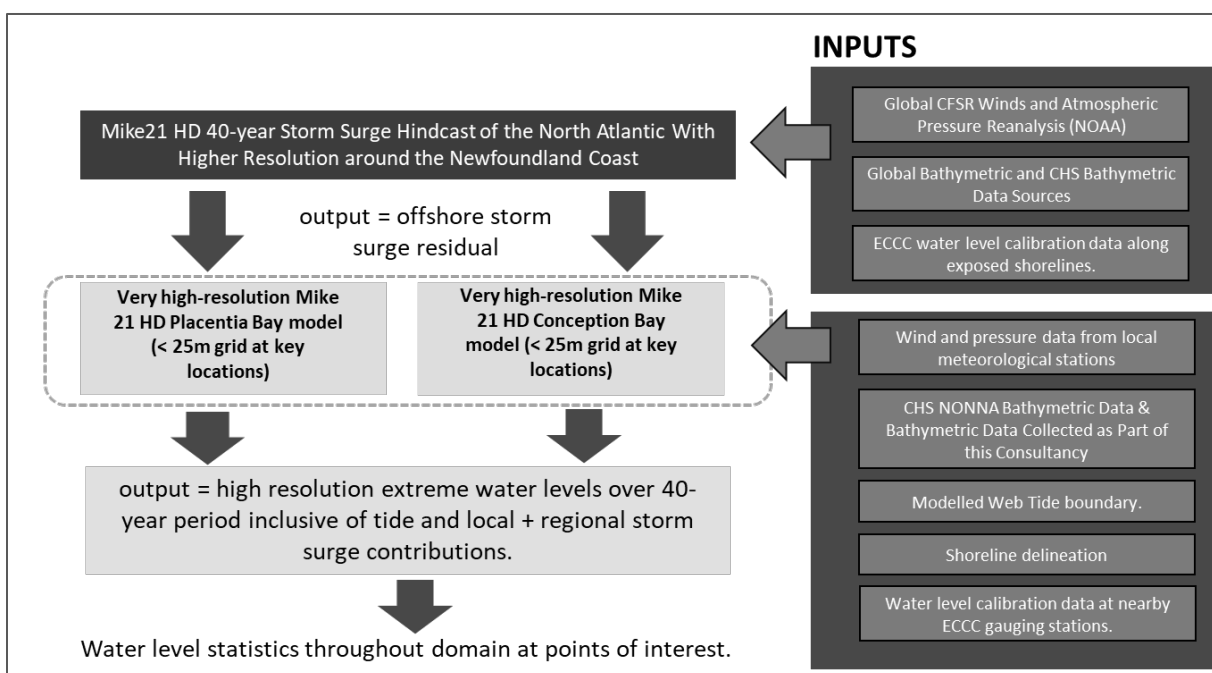
- A lack of nearby available data,

- 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 43-year storm surge hindcast for Trinity Bay, Conception Bay, and Ferryland, with sufficient resolution along the coastlines of the five communities of interest, is shown on Figure 92.

FIGURE 92: STORM SURGE MODELLING FRAMEWORK



A high-level summary of the key steps to determine water level statistics based on this modelling framework is provided below:

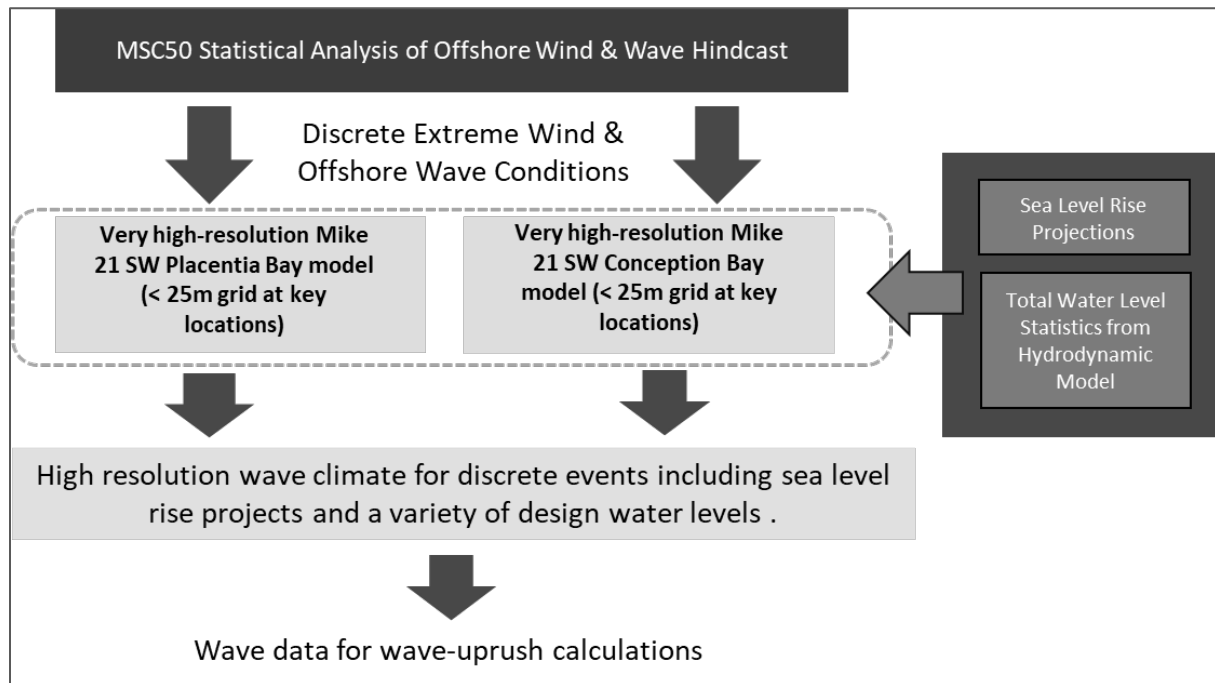
- **A regional storm surge model** was developed for the North-Atlantic, with higher resolution around the Province of Newfoundland. The regional MIKE21 Flexible Mesh (FM) Hydrodynamic (HD) model includes global spatially and temporally varying wind and pressure fields using the global Climate Forecast 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 Trinity Bay, Conception Bay and Ferryland** with a mesh resolution down to 25 m at the communities of interest were developed in the MIKE21 FM HD model environment.

Bathymetric data is sourced from the CHS NONNA bathymetric data repository and complemented with locally collected bathymetric and topographic data collected as part of this consultancy.

- **Boundary conditions for the local models** are derived from the regional north Atlantic HD storm surge model and combined with 42-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 43-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 1980-2022.
- **Model data can then be interpreted** using a combination of a peak-over-threshold (POT) analysis and an 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 selected discrete points in the various domains are interpolated for the development of flood and risk mapping products.

To calculate wave uprush along coastal reaches of the five communities, the industry standard MIKE21 FM Spectral Wave (SW) model is 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 uprush modelling is summarized in Figure 93.

FIGURE 93: WAVE MODELLING FRAMEWORK



Greater detail outlining the MIKE21 FM SW model development, input data, and calibration is provided in Section 8.2.6 and Section 8.2.7, and is broadly summarized by the following steps:

- **The MIKE21 FM SW modelling** was completed using the same computational grid and domain for Trinity Bay and Ferryland as for the MIKE21 FM HD models. For Conception Bay (covering Brigus) the wave model was slightly extended offshore to better capture extreme offshore wave conditions derived from MSC50.
- **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 uprush.
- **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 were assessed and an EVA analysis performed to derive the 1 to 100-year AEP wave conditions. To obtain the extreme water level scenarios, an EVA analysis was performed on the surge residual derived from the results of the MIKE21 FM HD storm surge high resolution models, in addition to sea level rise scenarios and tidal higher high-water levels, to simulate a range of discrete multidirectional extreme wave conditions at a high resolution along the five communities' shorelines.
- **Outputs from the wave model along the shoreline were used to perform 1D wave uprush calculations** along a selection of coastal profiles generated in GIS, extracted from the flood plain DEM.

8.2.2 AVAILABLE DATA

A variety of input and calibration data is required to develop the numerical models. This section presents a summary of the datasets that were used as input to the numerical modelling investigation of coastal processes.

Bathymetry Data & Shoreline Delineation

The regional North-Atlantic and local 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).
- CHS NONNA bathymetric data along the Newfoundland coastline.
- Locally collected bathymetric data collected as part of this project.

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.

Tides

The local MIKE21 FM HD models require a continuous tidal signal at the boundary, which is combined with the regional MIKE21 FM HD surge residual output. Tidal boundary conditions for the model were generated at 30 minutes intervals using the NRCan BIO Northwest Atlantic WebTide model, as described by Dupont, F. et. Al (2002).

Water levels in the model were simulated relative to CGVD2013, which was consistent with the vertical datum of the MIKE21 model. After referencing the model bathymetry to CGVD2013, the tidal conditions for each domain were also converted to be referenced to CGVD2013 as well. The difference between CGVD2013 and the mean sea level – around which the tides oscillate – was obtained using official information from NRCan and DFO for representative locations among the high-resolution domains and applied to the water level timeseries imposed to the boundaries. The conversion between Chart Datum (CD) and CGVD2013 for representative stations inside the modeling domain is presented in Table 33. The tidal conditions in Chart Datum (CD) and CGVD2013 at the representative stations are summarized in Table 34 to Table 36. This approach was taken to minimize potential differences between the vertical datums across large areas.

TABLE 33: CONVERSION BETWEEN CHART DATUM AND CGVD2013 FOR THREE REPRESENTATIVE STATIONS

Station	CD to CGVD2013
Heart's Content	1.2 m
Holyrood Bay	1 m
Lance Cove	1.1 m

**TABLE 34: TIDAL CONDITIONS AT HEART'S CONTENT STATION
(TRINITY BAY HIGH-RESOLUTION DOMAIN)**

Tide	Tide m (CD)	Tide m (CGVD2013)
Higher high water large tide (HHWLT)	1.35	0.15
Higher high water mean tide (HHWMT)	1.13	-0.07
Mean water level (MWL)	0.7	-0.50
Lower low water mean tide (LLWMT)	0.31	-0.89
Lower low water large tide (LLWLT)	0.04	-1.16

**TABLE 35: TIDAL CONDITIONS AT HOLYROOD BAY STATION
(CONCEPTION BAY HIGH-RESOLUTION DOMAIN)**

Tide	Tide m (CD)	Tide m (CGVD2013)
Higher high water large tide (HHWLT)	1.46	0.46
Higher high water mean tide (HHWMT)	1.17	0.17
Mean water level (MWL)	0.71	-0.29
Lower low water mean tide (LLWMT)	0.3	-0.70
Lower low water large tide (LLWLT)	0.01	-0.99

**TABLE 36: TIDAL CONDITIONS AT LANCE COVE STATION (FERRYLAND
HIGH-RESOLUTION DOMAIN)**

Tide	Tide m (CD)	Tide m (CGVD2013)
Higher high water large tide (HHWLT)	1.49	0.39
Higher high water mean tide (HHWMT)	1.21	0.11
Mean water level (MWL)	0.69	-0.41
Lower low water mean tide (LLWMT)	0.23	-0.87
Lower low water large tide (LLWLT)	-0.06	-1.16

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 CFSR hindcast model administered by the National Oceanic and Atmospheric Administration's (NOAA) 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 37, 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 37: 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 – 2022)	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 2022. 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 38. 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 38: SPECIFICATIONS OF CFSR PARAMETERS

Abbreviation	Unit	Description	Comment
WS₁₀ or U₁₀	m/s	Wind speed at height 10m MSL	Representative of 2-hour averages
WD₁₀ or D₁₀	°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 2022 at a 25 km resolution, where wind and pressure fields varied temporally at 4-hour intervals.

Measured Water Level Data

Measured coastal water level data throughout Newfoundland 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 St. John's (i.e. Station 905), Bonavista (i.e. Station 990), Holyrood (i.e. Station 925), Bell Island (i.e. Station 915), Long Pond (i.e. Station 920) and Long Cove (i.e. Station 962). Additionally, predicted tides timeseries were downloaded for Lance Cove (i.e. Station 893) and Hearts Content (i.e. Station 955). The location of these measurement stations is presented in Figure 94 and Table 39 summarizes key characteristics of these datasets.

FIGURE 94: LOCATIONS OF THE WATER LEVEL GAUGES

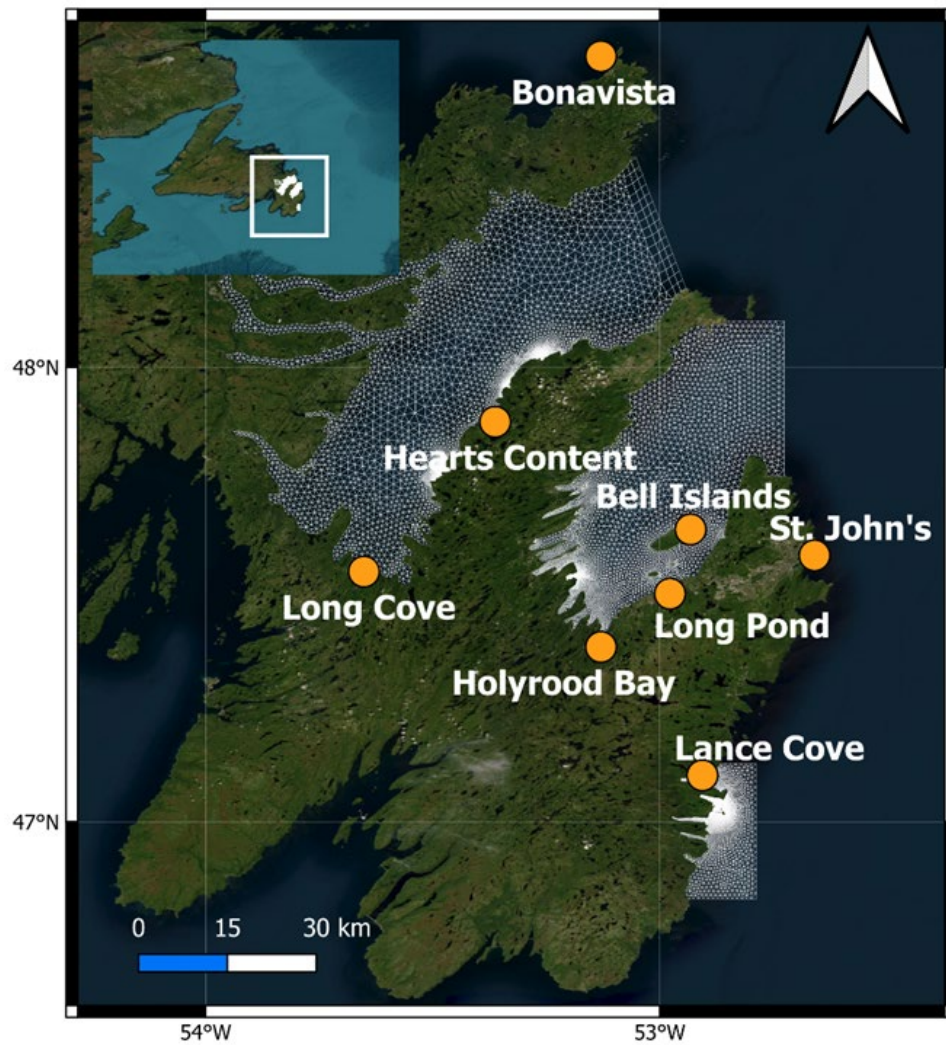


TABLE 39: KEY CHARACTERISTICS OF THE WATER LEVEL GAUGES

Station	Type	Domain	Lon/Lat	Time range
Bell Island - 915	Observed water level	Conception Bay	-52.916; 47.633	1987/09/16 - 1987/10/15
Holyrood Bay - 925	Observed water level	Conception Bay	-53.135; 47.4	2017/07/10 - 2018/04/30
Long Pond - 920	Observed water level	Conception Bay	-52.966; 47.516	1990/07/17 - 1990/11/14
Lance Cove - 893	Predicted Tides	Ferryland	-52.900; 47.083	-
Long Cove - 962	Observed water level	Trinity Bay	-53.667; 47.566	2005/10/04 - 2005/11/17
Hearts Content - 955	Predicted Tides	Trinity Bay	-53.367; 47.867	-
St. Johns - 905	Observed water level	Regional Surge Model	-52.716; 47.566	1973 - Today
Bona Vista - 990	Observed Water Level	Regional Surge Model	-53.115; 48.651	1983 - Today

MSC50 Hindcast data

Wave statistics driving the MIKE21 FM SW model were derived from the MSC50 Atlantic wave hindcast product from ECCC. This dataset covers the period January 1954 to December 2018 period, 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 local domains to derive spatially varying discrete wave conditions for use in the wave uprush analysis. Further details of the analysis of the MSC50 hindcast data is provided in Section 8.2.6.

8.2.3 COMPUTATIONAL MESH AND BATHYMETRY

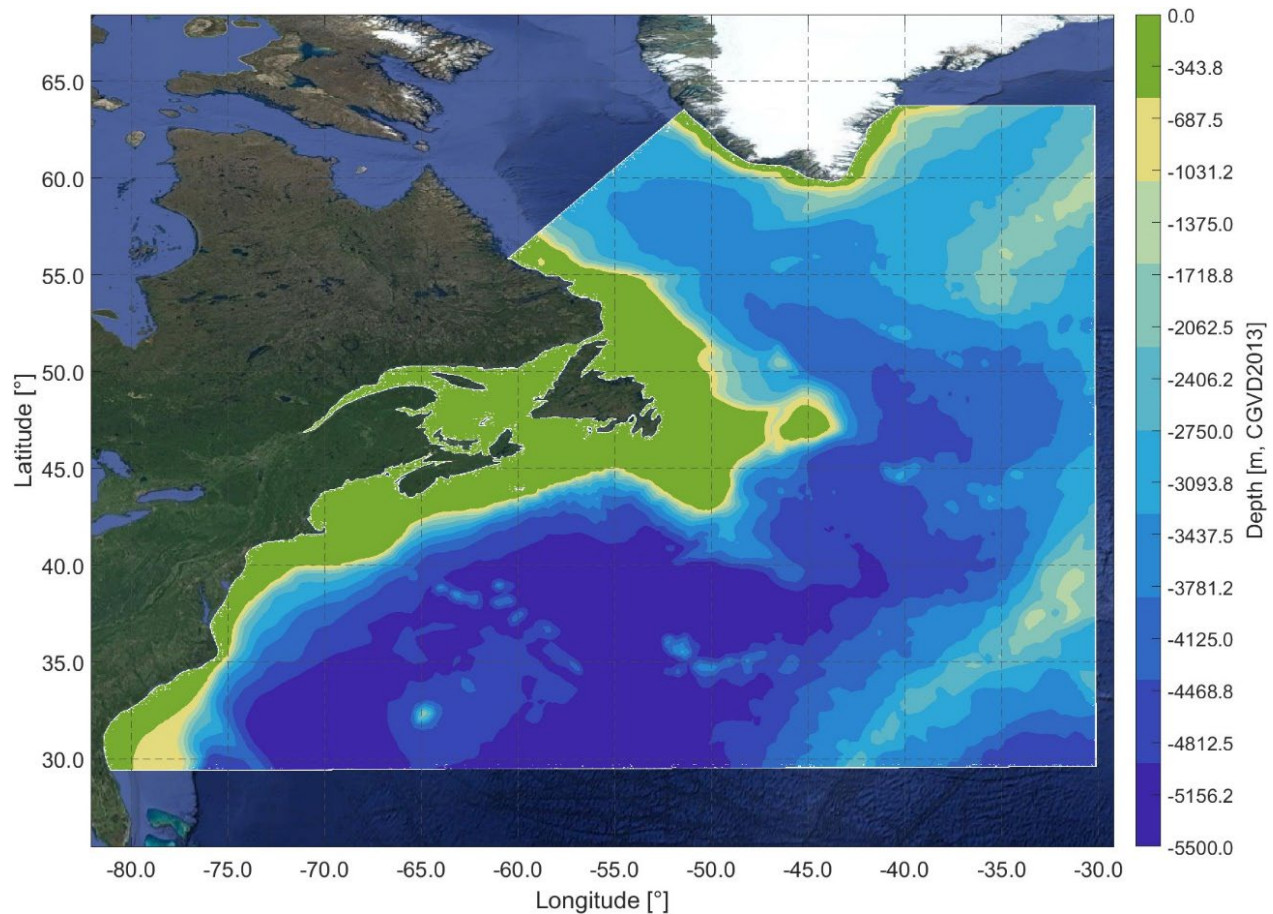
As outlined in Section 8.2.1, a regional storm surge model was developed to provide boundary conditions for the local high-resolution models focusing on the five communities of interest.

All hydrodynamic models (regional and local) were developed using MIKE21 FM HD, 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 was also integrated into the model to better represent the physical processes that affect the hydrodynamics of the region.

The North-Atlantic regional hydrodynamic model domain is shown on Figure 95. The model mesh was constructed with 81,764 triangular elements with increasing resolution from 40 km in the offshore

boundaries down to 10 km in the nearshore area of Newfoundland. 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 95: NORTH-ATLANTIC REGIONAL MODEL DOMAIN



Three high-resolution local models of Trinity Bay, Conception Bay and Ferryland, as shown in Figure 96 to Figure 100, are nested into the regional North-Atlantic model, further increasing resolution in the areas of interest down to 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.

Different and complementary sources of oceanographic bathymetric data domains - local surveys and NONNA dataset - have been merged and smoothly interpolated to compose the DEM for the three high resolution.

Since the different bathymetric sources as well as tidal water level timeseries are in different vertical datums (i.e. Chart Datum and MSL), conversions were performed so that all the MIKE21 FM models are tied to the CGVD2013 vertical datum.

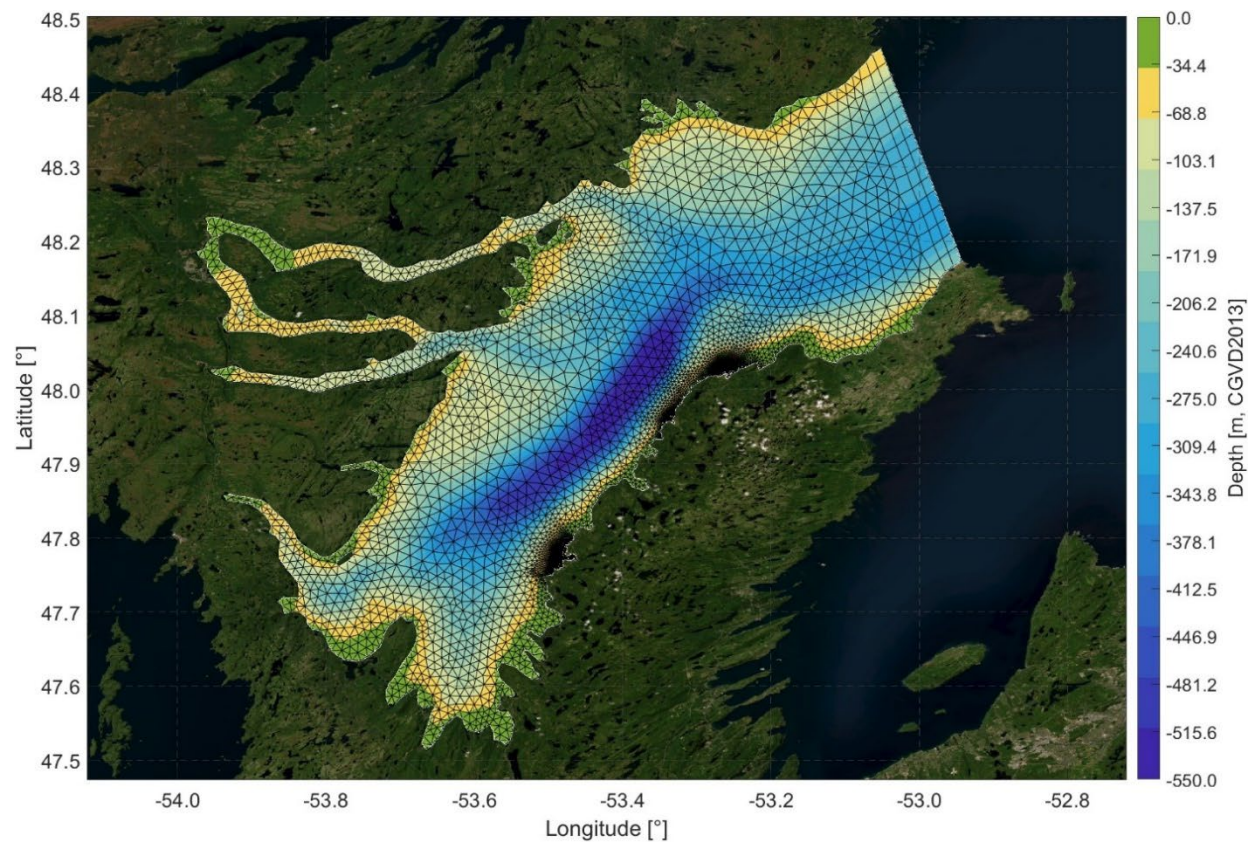
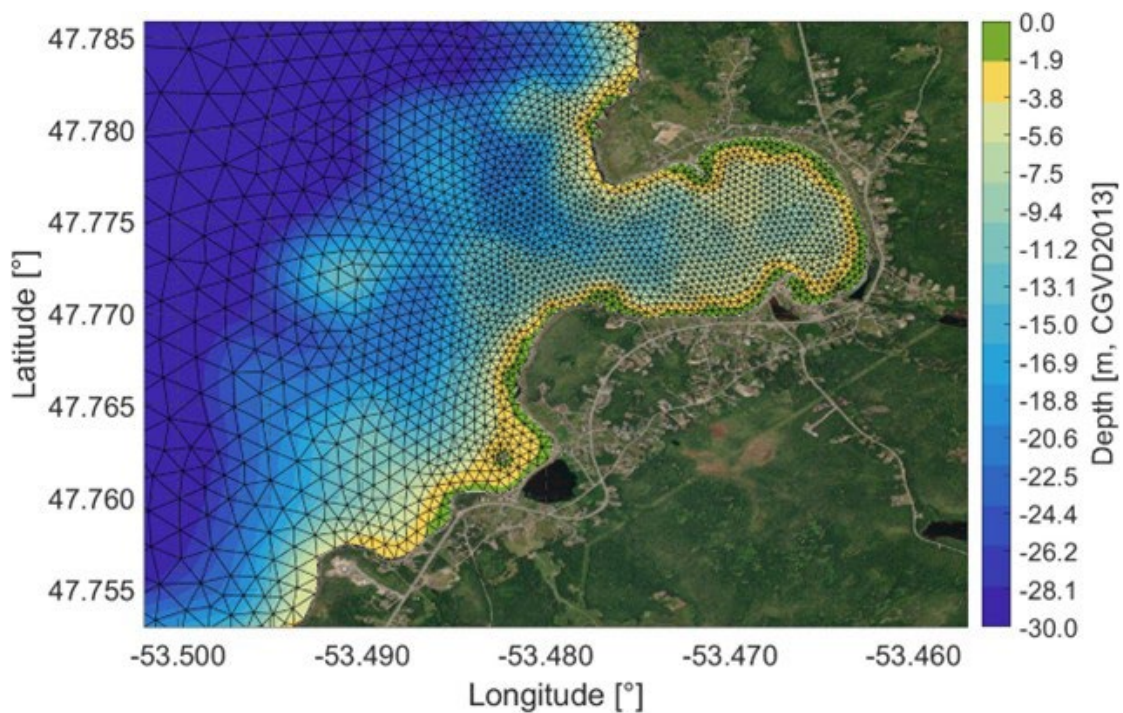
FIGURE 96: TRINITY BAY MODEL DOMAIN AND COMPUTATIONAL MESH**FIGURE 97: ZOOM ON HEART'S DELIGHT – ISLINGTON COMMUNITY**

FIGURE 98: ZOOM ON WINTERTON (UPPER) AND HANT'S HARBOUR (LOWER) COMMUNITIES

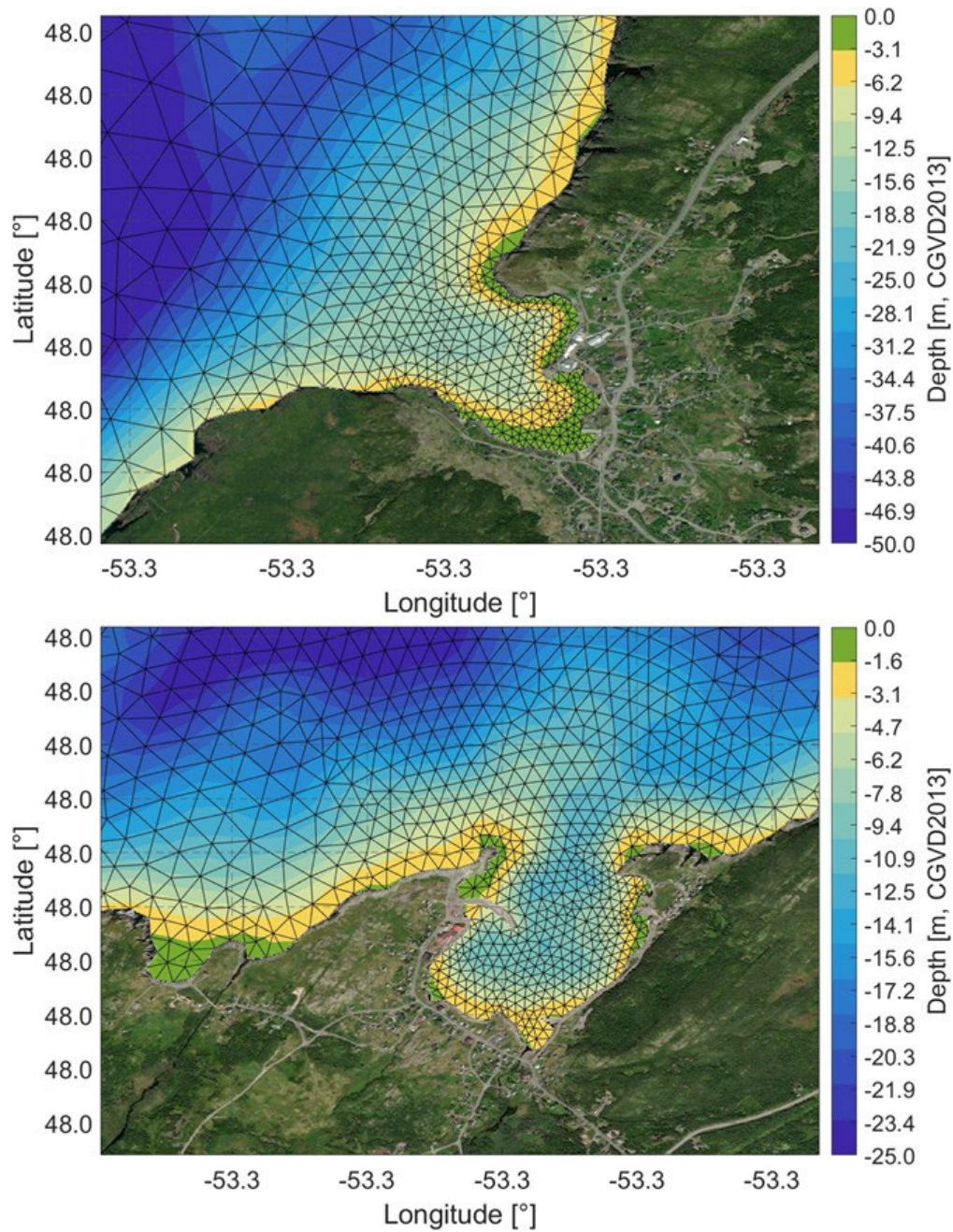


FIGURE 99: CONCEPTION BAY MODEL DOMAIN AND COMPUTATIONAL MESH (UPPER) AND ZOOM ON BRIGUS COMMUNITY (LOWER)

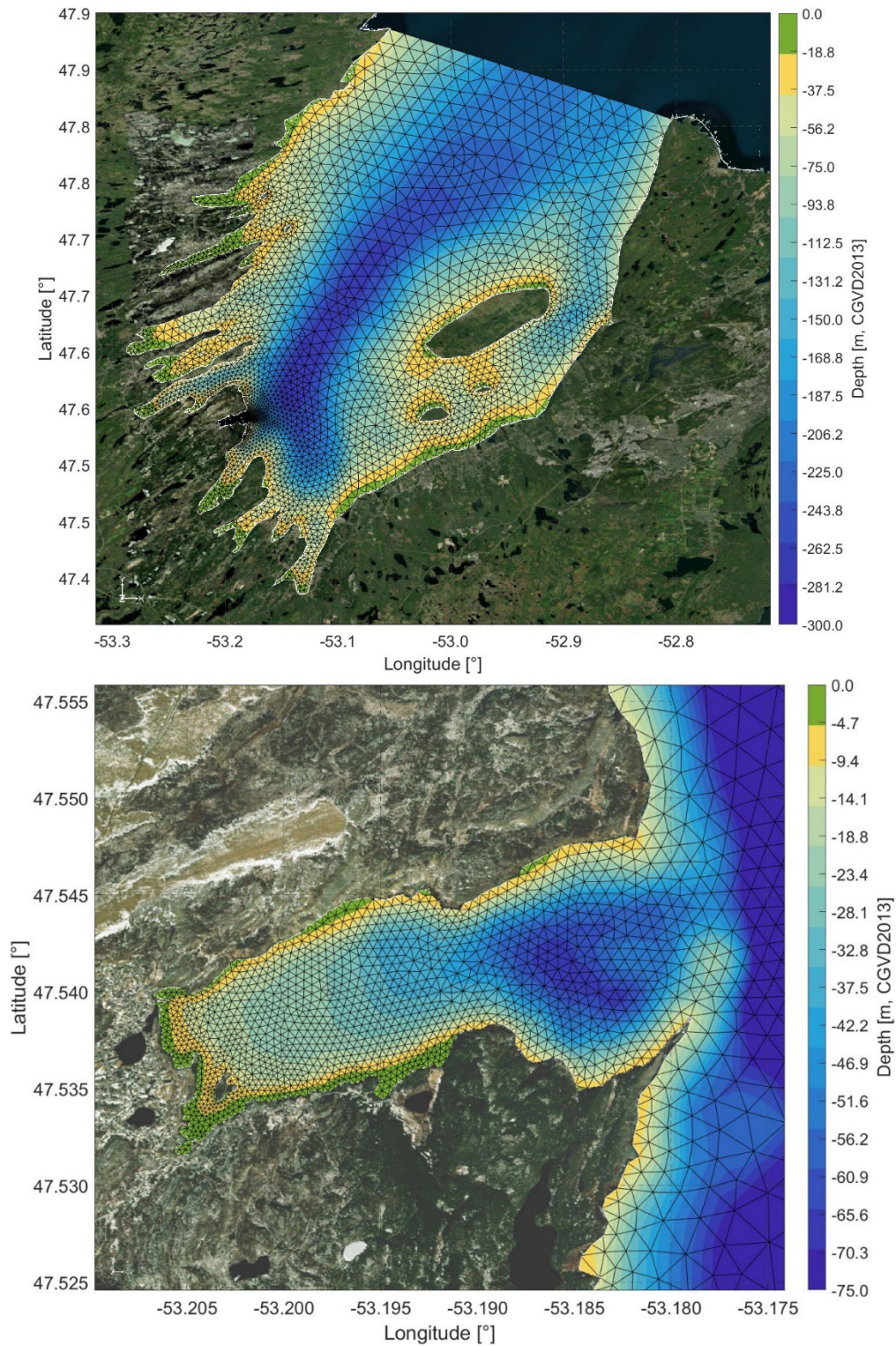
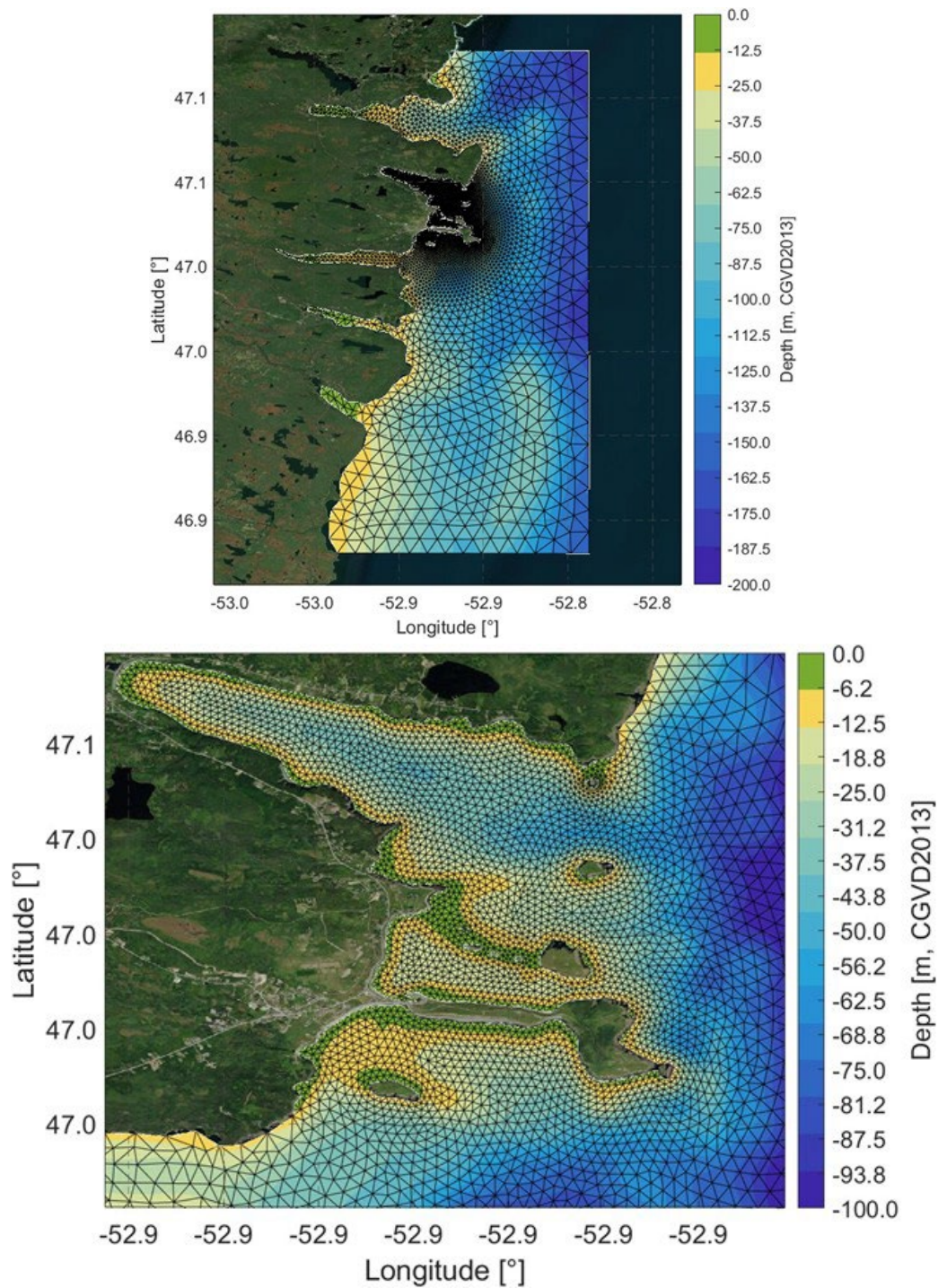


FIGURE 100: FERRYLAND MODEL DOMAIN AND COMPUTATIONAL MESH (UPPER) AND ZOOM ON THE COMMUNITY (LOWER)



8.2.4 HYDRODYNAMIC MODEL SETUP AND VALIDATION

Regional Storm Surge Model

The regional storm surge model was developed for the North-Atlantic Ocean, with higher resolution around the Province of Newfoundland. The regional MIKE21 Flexible Mesh (FM) Hydrodynamic (HD) model includes global spatially and temporally varying ice coverage, 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. A summary of the Regional Storm Surge model configuration is presented in Table 40.

TABLE 40: REGIONAL STORM SURGE MODEL CONFIGURATION

Setting	Regional Storm Surge Model (MIKE21 FM HD)
Mesh Resolution	40 km offshore ~ 10 km nearshore
Simulation Period	1980-01-01 – 2022-12-31 (43 years)
Output Time Step	1 hour
Density	Barotropic
Eddy Viscosity	Smagorinsky formulation with a constant value of 0.28
Bed Resistance	Manning number of 36 m ^{1/3} /s
Wind & Pressure Forcing	CFSR Atmospheric Reanalysis
Ice Coverage	CFSR Global Ice Coverage
Tide	No Tide
Bathymetry	GEBCO, NONNA Dataset and Digital Navigation Charts

Measured total water level data (i.e. surge and tide) is available at St John's for the entire hindcast period from 1980 to 2022 and at Bonavista from 2006 to 2022. The total water level signal at the two stations was analyzed over the entire hindcast period and the tidal component was extracted from the timeseries using a harmonic analysis to isolate and extract the storm surge residual. The extracted storm surge residual can then be compared to the simulated storm surge from the regional North-Atlantic hydrodynamic model.

Figure 101 and Figure 102 presents a comparison between the measured and simulated storm surge residual water levels and a good agreement is observed at both locations.

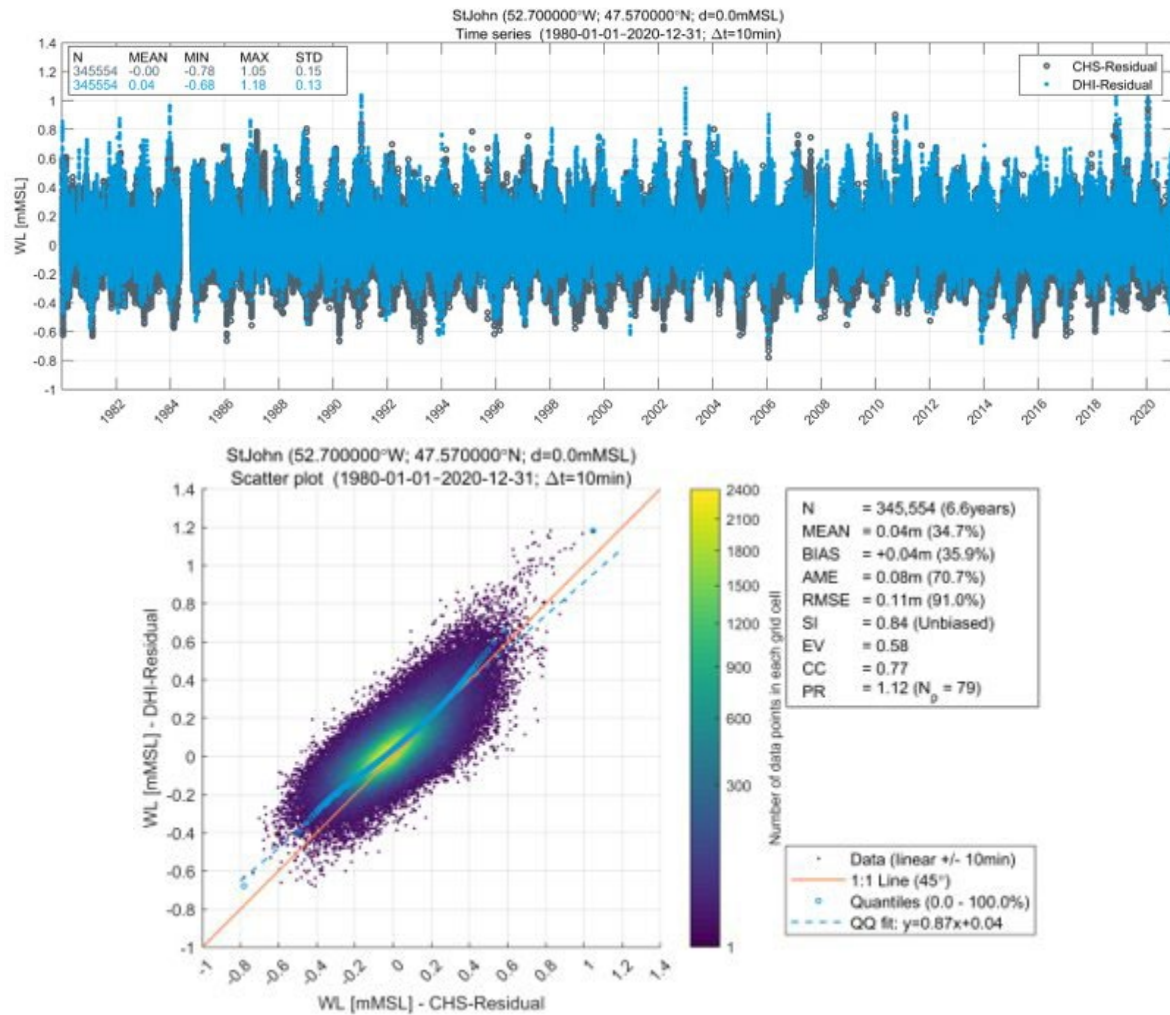
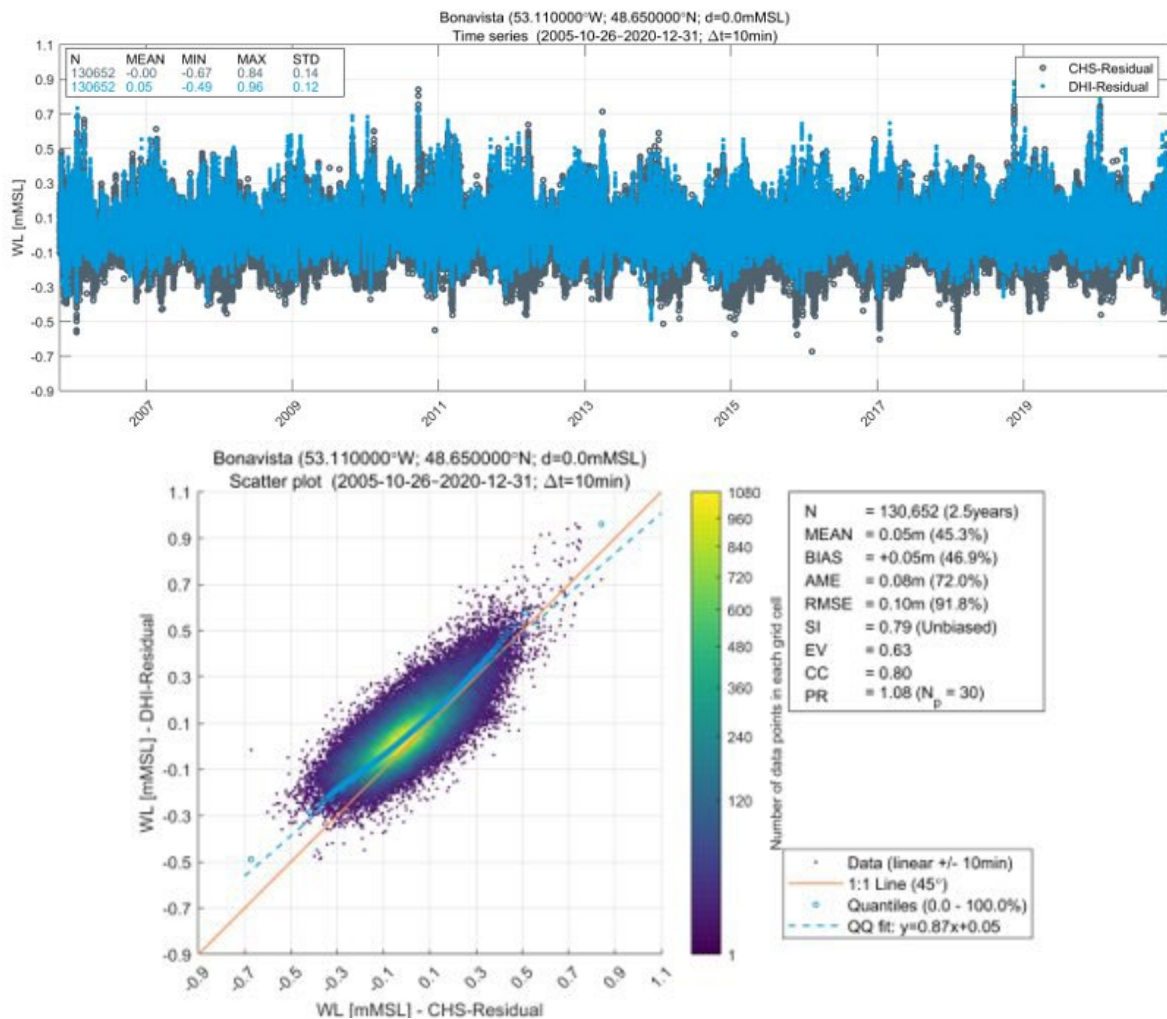
FIGURE 101: REGIONAL MODEL VALIDATION ST. JOHN'S – SURGE RESIDUAL

FIGURE 102: REGIONAL MODEL VALIDATION AT BONAVIDA – SURGE RESIDUAL

Local High-Resolution Hydrodynamic Models

The local high-resolution hydrodynamic models were developed for Trinity Bay, Conception Bay, and Ferryland, with mesh resolutions down to 25 m at the studied communities' nearshore areas. The bathymetry was sourced from the CHS NONNA dataset, supplemented with local bathymetric surveys collected as part of the project. Boundary conditions for the local domains were generated using outputs from the regional storm surge model, together with tidal forcing from the Bedford Institute of Oceanography's (BIO) WebTide model, resulting in total water level signals that combine both surge and tide. The models incorporate spatially and temporally varying wind and atmospheric pressure fields to represent local surge dynamics. Table 41 presents a summary of the local high-resolution HD models basic configuration.

TABLE 41: LOCAL HIGH-RESOLUTION HYDRODYNAMIC MODEL CONFIGURATION

Setting	Regional Storm Surge Model (MIKE21 FM HD)
Mesh Resolution	25 metres
Simulation Period	1980-01-01 – 2022-12-31 (43 years)
Output Time Step	10 minutes
Density	Barotropic
Eddy Viscosity	Smagorinsky formulation with a constant value of 0.28
Bed Resistance	Manning number of 36 m ^{1/3} /s
Wind & Pressure Forcing	CFSR Atmospheric Reanalysis
Ice Coverage	CFSR Global Ice Coverage
Boundary Conditions	Regional Storm Surge Model outputs combined with tidal signal from WebTide (BIO)
Bathymetry	NONNA Dataset, Digital Navigation Charts and local bathymetry surveys.

Figure 103 to Figure 112 present the performance of the local high-resolution models in comparison to the available measured water levels. At the stations where the observed water levels are available, the comparison is presented both for the total water level and for the storm surge residual water level (i.e. tidal signal is filtered out). These figures indicate a strong agreement between measurements and observations in all three domains, and the three local model calibrations can thus be considered satisfactory for long-term statistical analysis. Table 42 presents a summary of key comparison metrics for the available stations.

TABLE 42: LOCAL HIGH-RESOLUTION MODELS VALIDATION SUMMARY

Station	Bias (m)	RMSE (m)	CC
Long Cove (Total Water Level)	0.00	0.12	0.92
Long Cove (Residual)	0.00	0.12	0.61
Heart's Content (Predicted Tides)	0.00	0.07	0.96
Holyrood Bay (Total Water Level)	-0.01	0.11	0.94
Holyrood Bay (Residual)	0.00	0.09	0.69
Long Pond (Total Water Level)	0.00	0.07	0.97
Long Pond (Residual)	0.00	0.06	0.64
Bell Island (Total Water Level)	0.00	0.09	0.95
Bell Island (Residual)	0.00	0.08	0.59
Lance Cove (Predicted Tides)	0.00	0.07	0.97

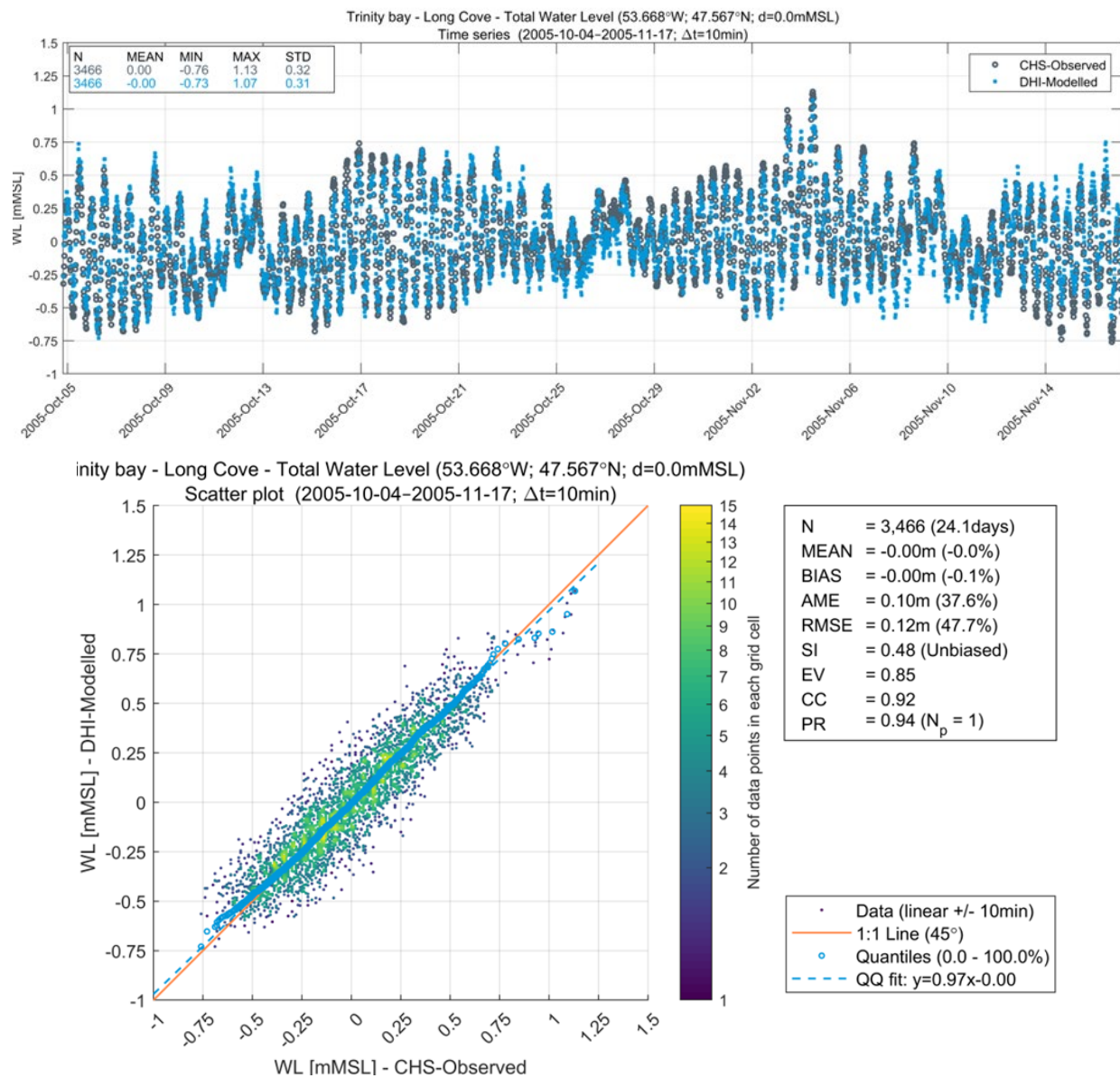
FIGURE 103: MODEL CALIBRATION AT LONG COVE (TRINITY BAY) – TOTAL WATER LEVEL

FIGURE 104: MODEL CALIBRATION AT LONG COVE (TRINITY BAY) – SURGE RESIDUAL

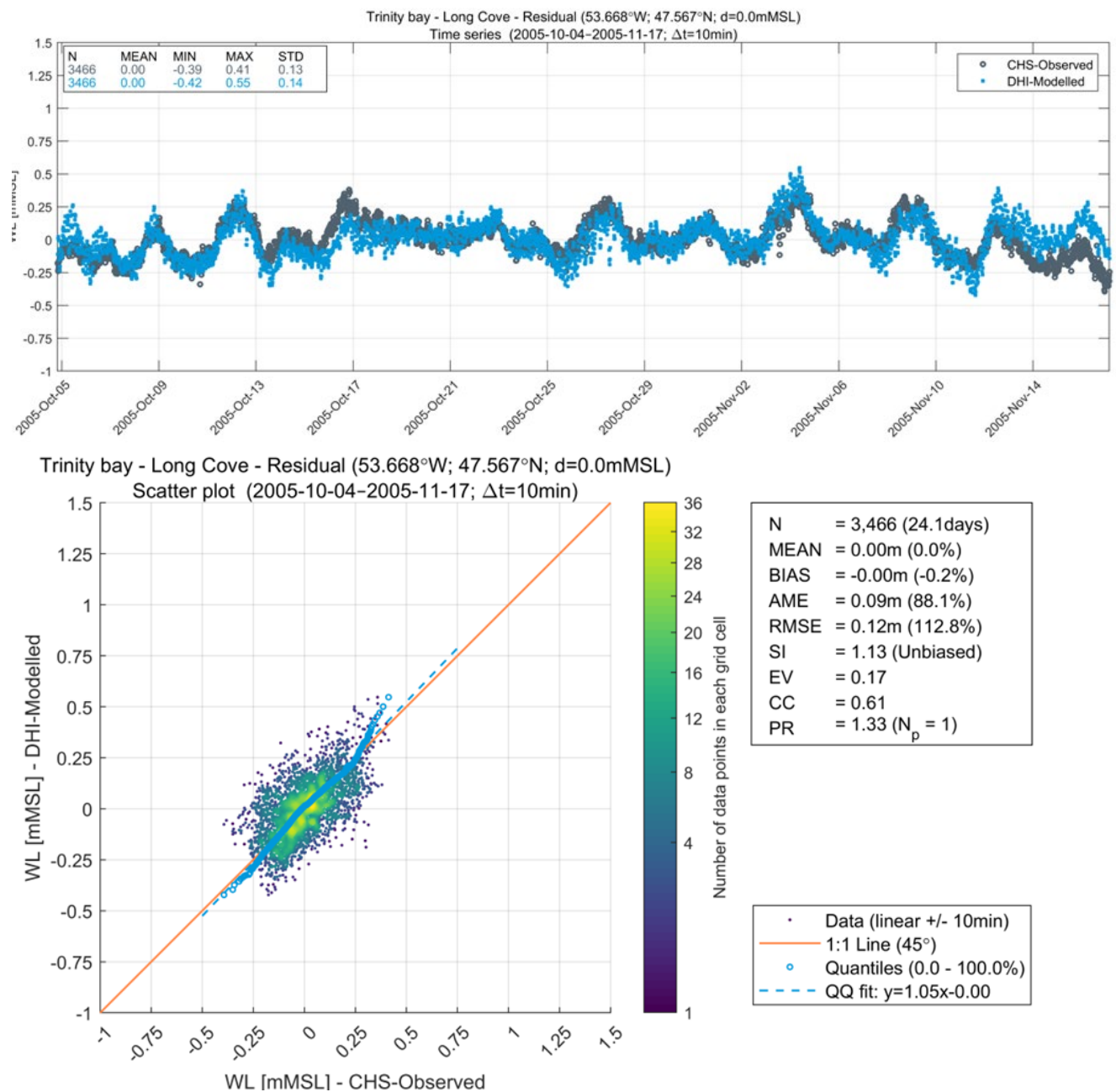


FIGURE 105: MODEL CALIBRATION AT HEART'S CONTENT (TRINITY BAY) – PREDICTED TIDES

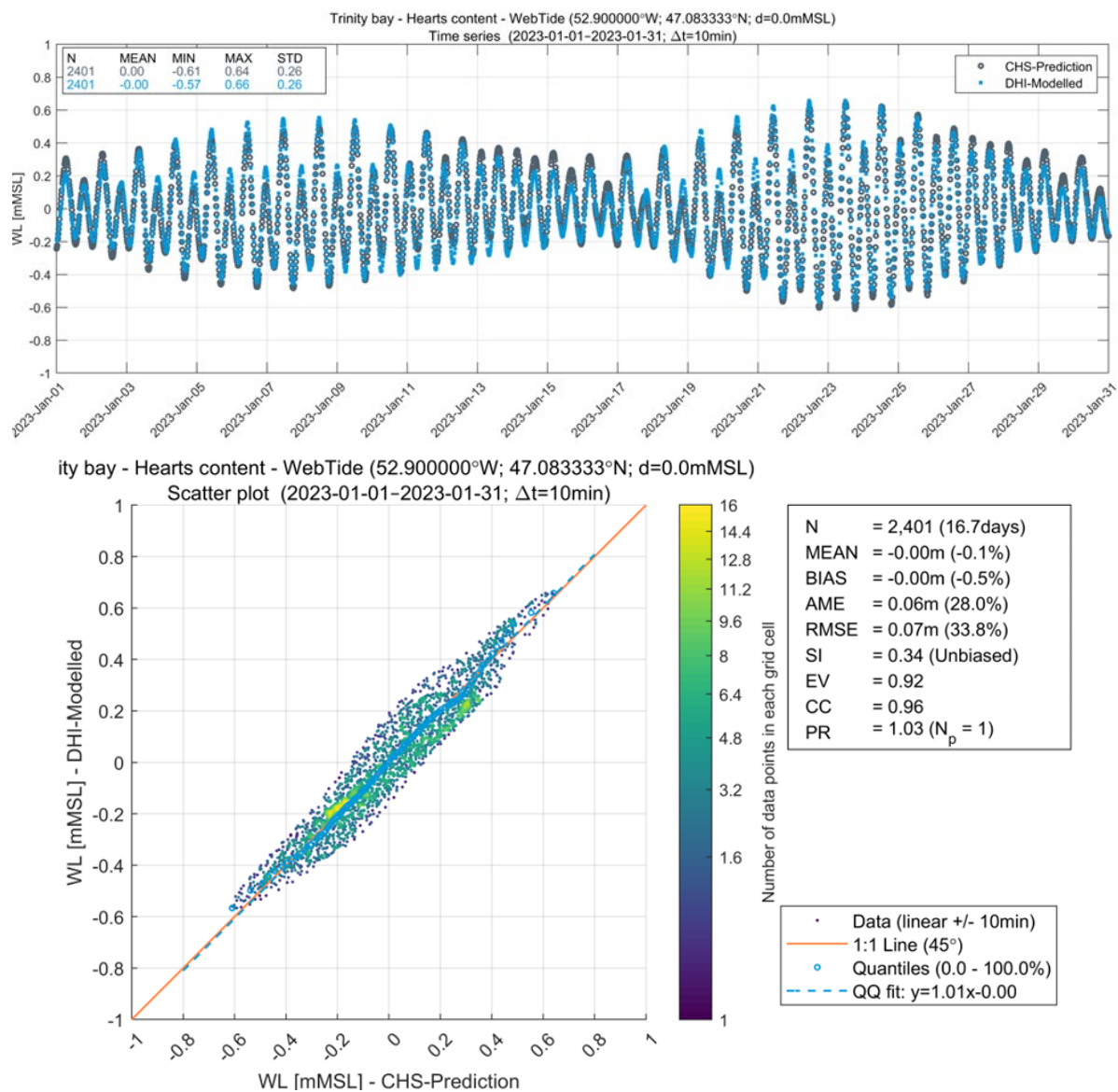


FIGURE 106: MODEL CALIBRATION AT HOLYROOD BAY (CONCEPTION BAY MODEL) – TOTAL WATER LEVEL

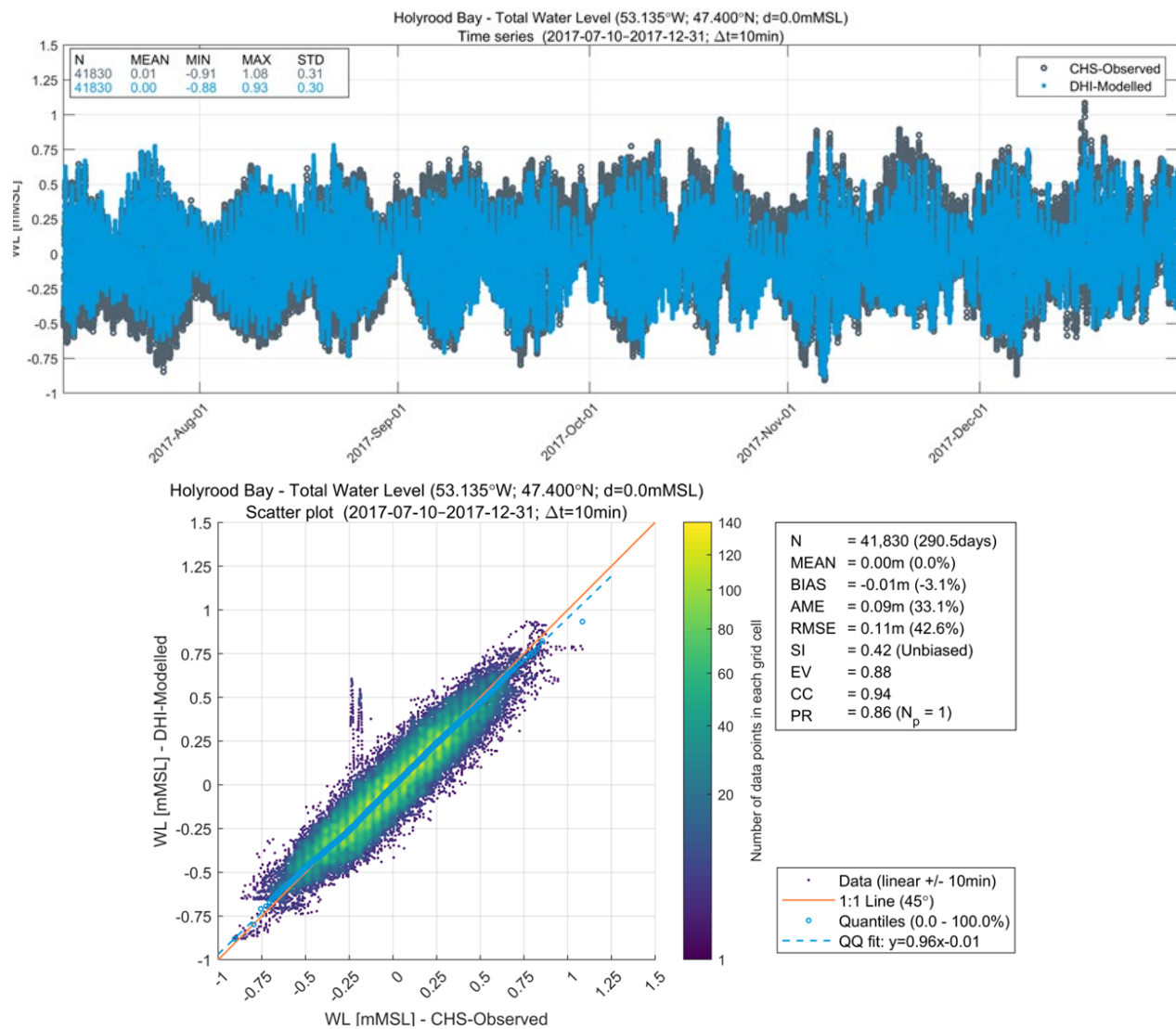


FIGURE 107: MODEL CALIBRATION AT HOLYROOD BAY (CONCEPTION BAY MODEL) – SURGE RESIDUAL

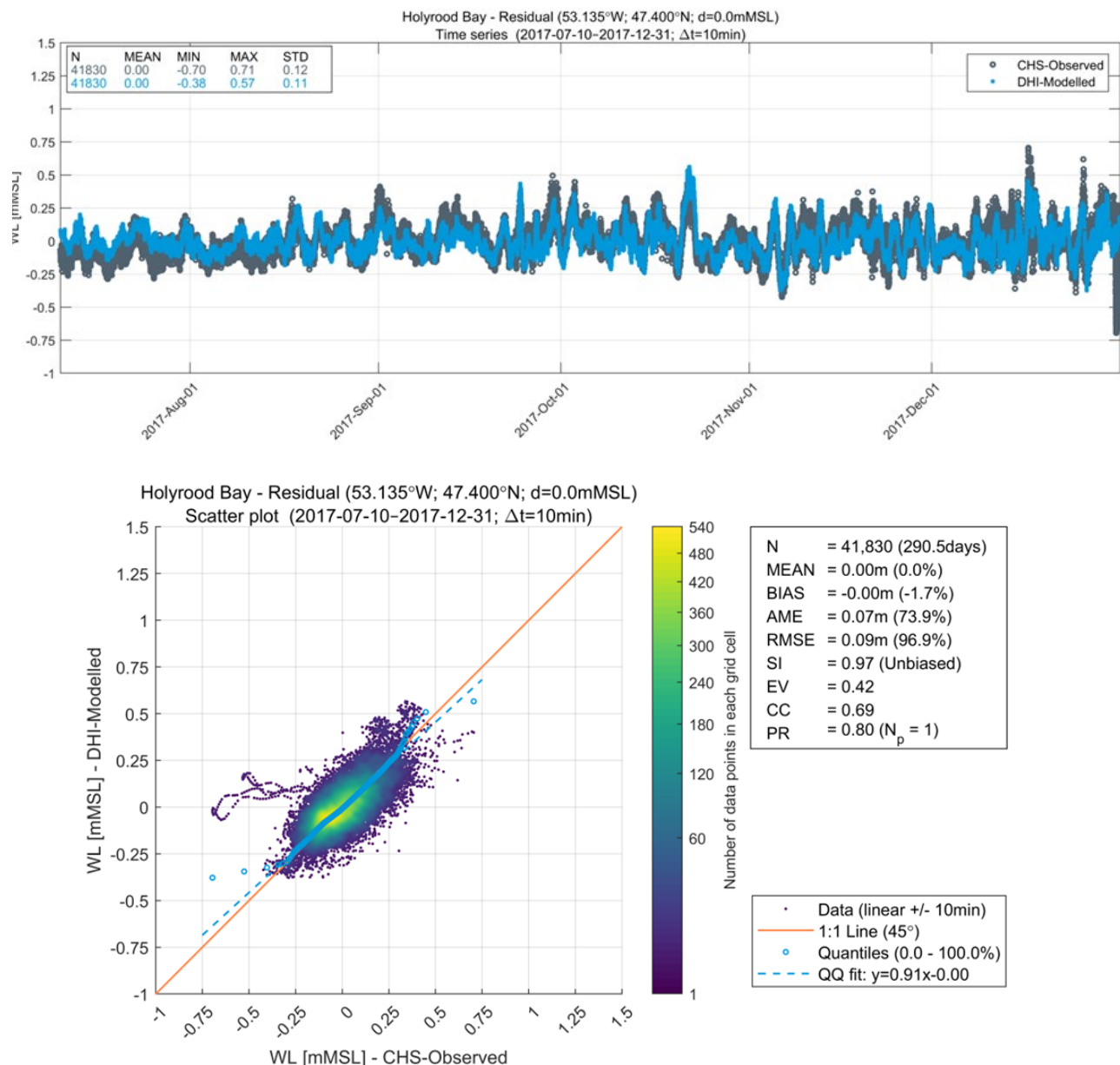


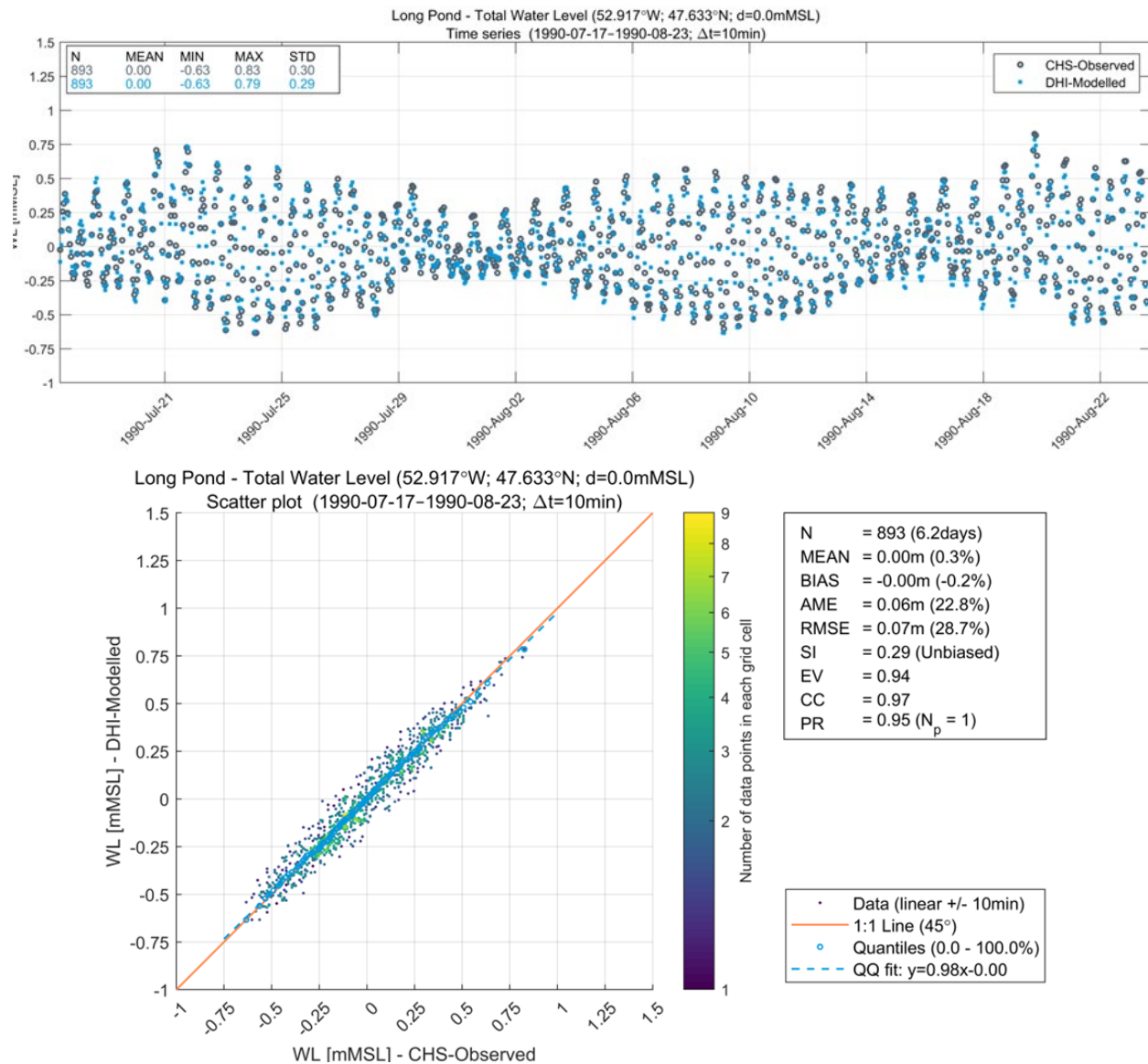
FIGURE 108: MODEL CALIBRATION AT LONG POND (CONCEPTION BAY MODEL) – TOTAL WATER LEVEL

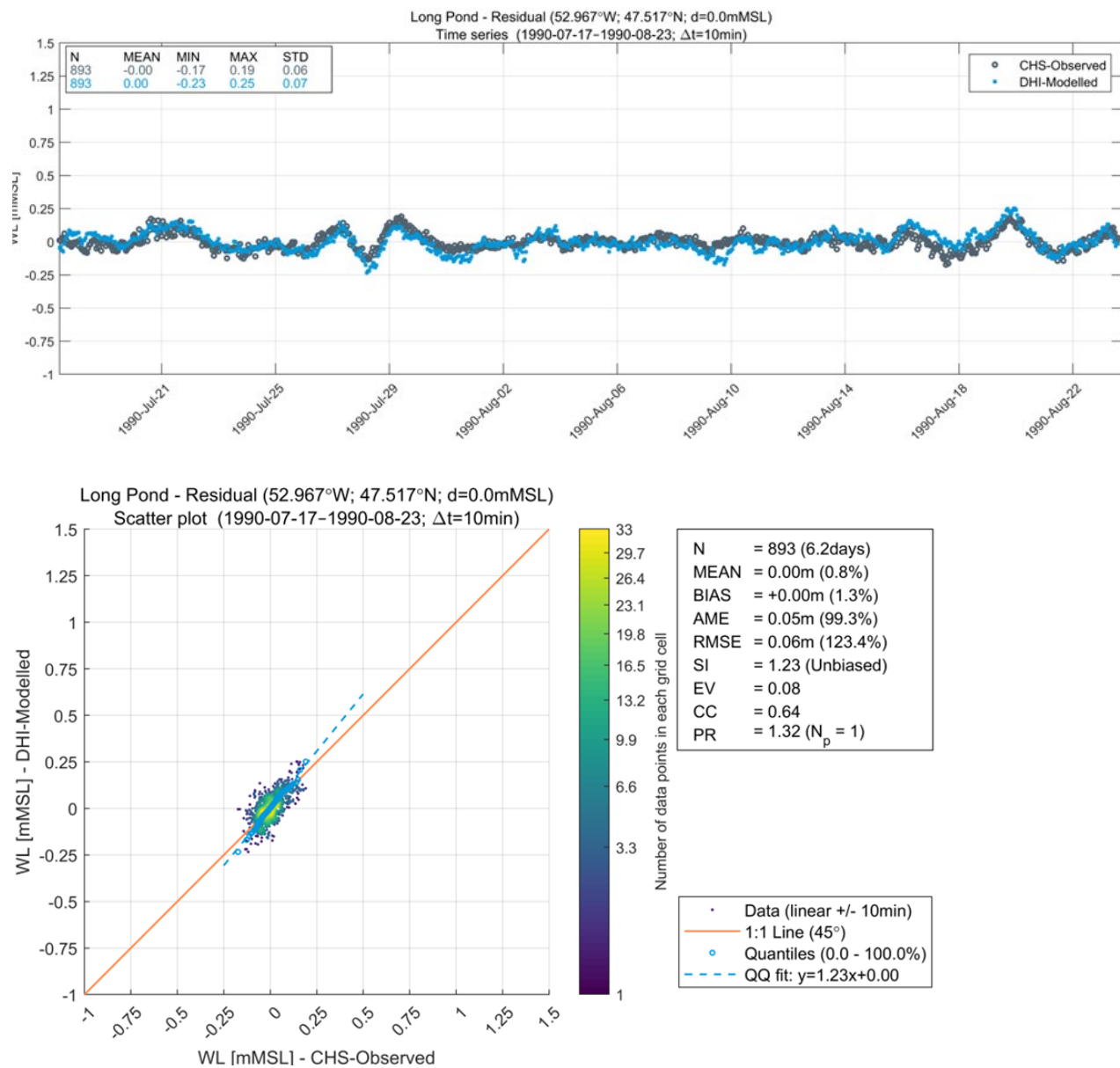
FIGURE 109: MODEL CALIBRATION AT LONG POND (CONCEPTION BAY MODEL) – SURGE RESIDUAL

FIGURE 110: MODEL CALIBRATION AT BELL ISLAND (CONCEPTION BAY MODEL) – TOTAL WATER LEVEL

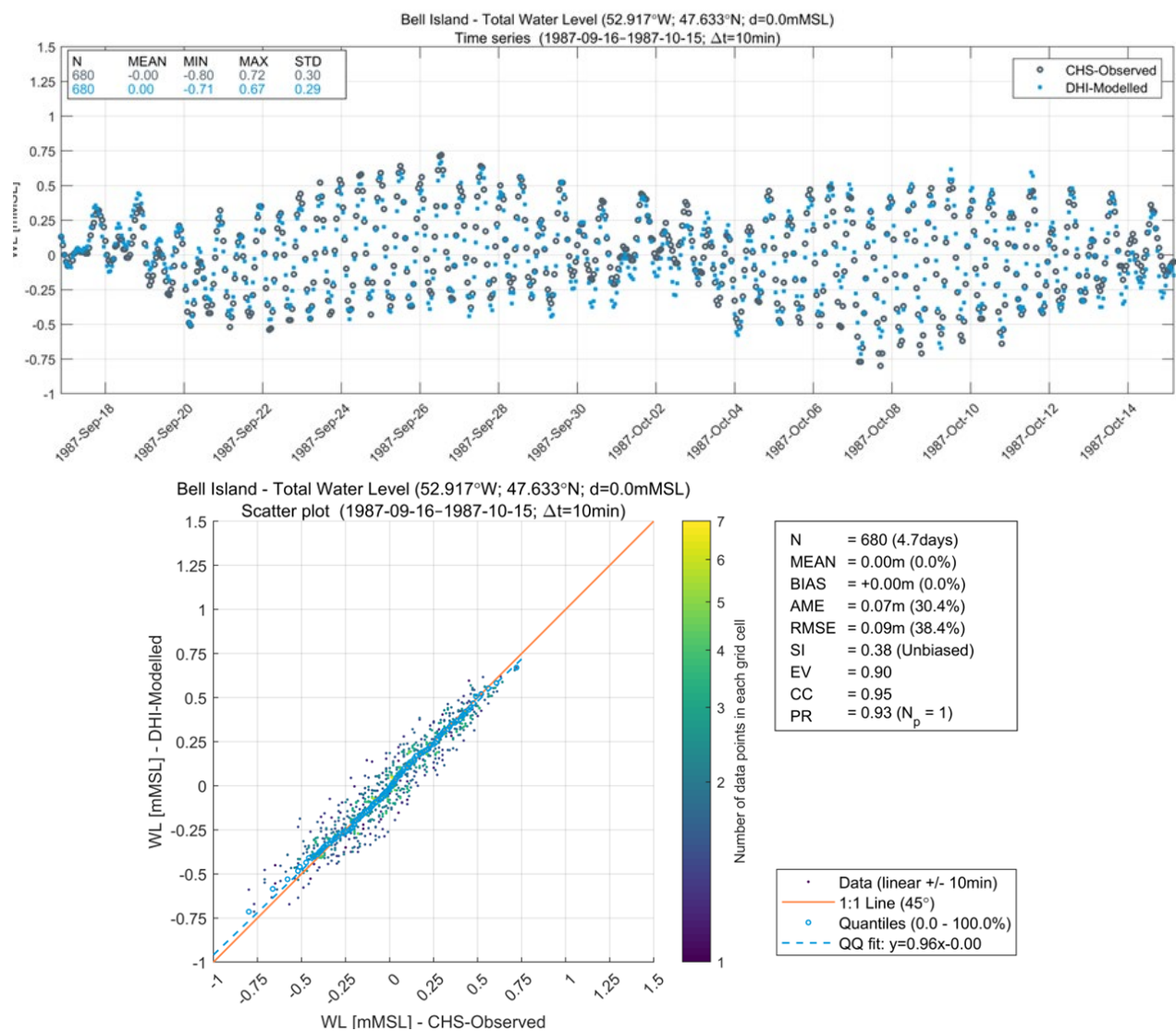


FIGURE 111: MODEL CALIBRATION AT BELL ISLAND (CONCEPTION BAY MODEL) – SURGE RESIDUAL

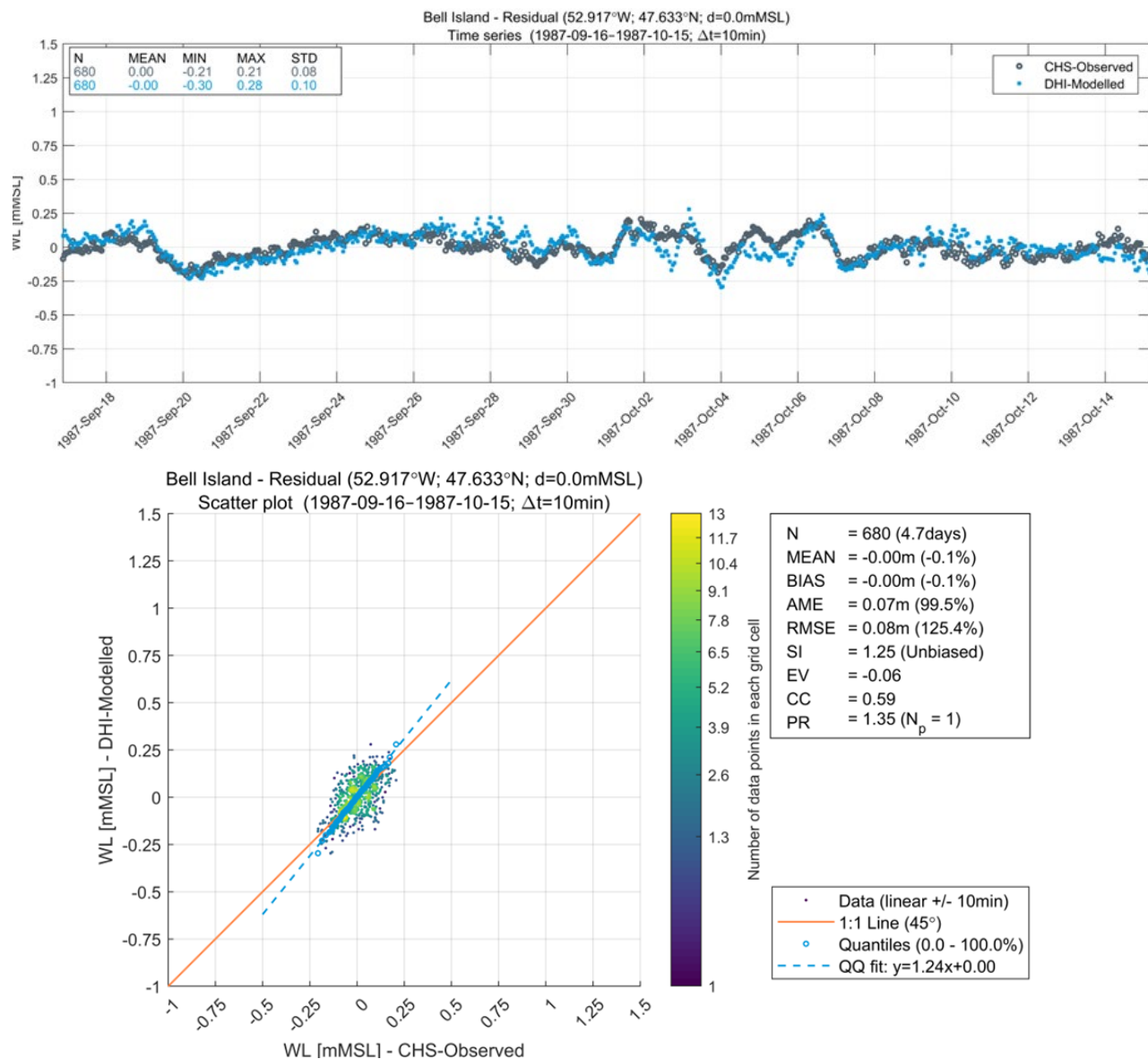
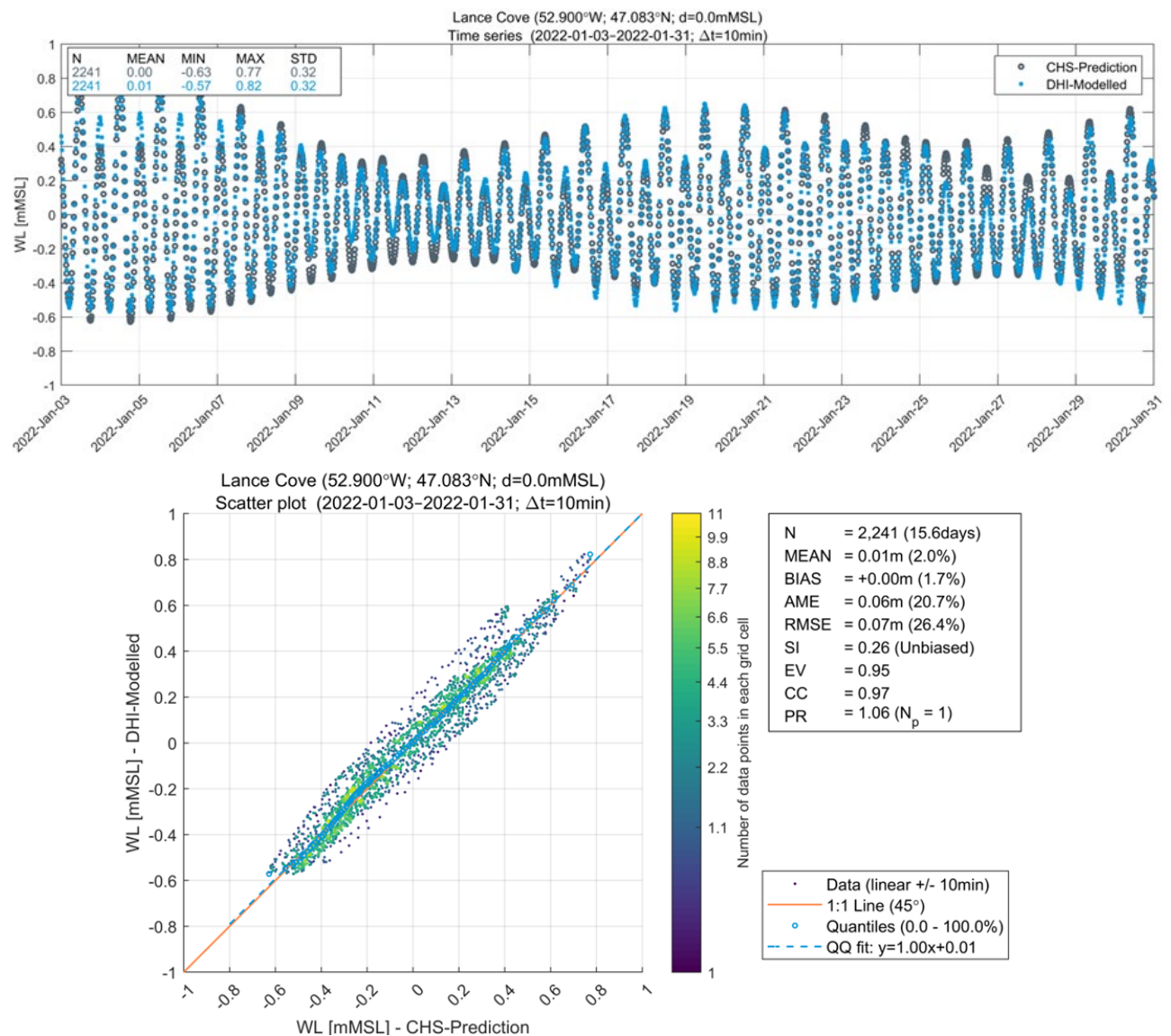


FIGURE 112: MODEL CALIBRATION AT LANCE COVE (FERRYLAND MODEL) – PREDICTED TIDES



8.2.5 DEFINITION OF THE 1:20 AND 1:100 COASTAL FLOOD LEVELS

Water levels are available at 10-minute intervals at every node in the hydrodynamic model domain from 1981 to 2022. To derive AEP storm surge flood levels, total water levels with a defined AEP are required throughout the flood mapping area of interest. Producing AEP statistics at each node in the model is neither practical nor feasible, given that the models have thousands of nodes and that total water level differences between neighboring nodes can often be negligible. Instead, a representative selection of up to 6 nodes have been chosen for analysis and interpretation for each community. The locations of the nodes selected for further analysis were defined at the toe of each transect used to calculate the wave uprush to best integrate the total water level AEP and the wave uprush results presented in Section 8.2.8.

At each data extraction point, timeseries of total water levels and depth-averaged velocities were extracted for integration into the flood hazard and flood risk maps. Subsequently, an EVA was performed for each timeseries by selecting storm peaks based on a POT method, the AEP for total water levels and depth averaged currents were defined by fitting representative statistical distributions to the data.

The EVA analysis at each point is included for reference in Appendix H.

Trinity Bay

Examples of the maximum simulated water level in 2010 near Hant's Harbour, Winterton and Heart's Delight-Islington are depicted in Figure 113 and Figure 114. These maps illustrate the spatial variability of the maximum water level along the coastlines. It should be noted that these maps are generated by computing the statistical maximum water level during 2010 in each of the computational cells and therefore do not necessarily represent a single point in time.

FIGURE 113: 2010 MAXIMUM TOTAL WATER LEVEL IN HANT'S HARBOUR (UPPER) AND WINTERTON (LOWER)

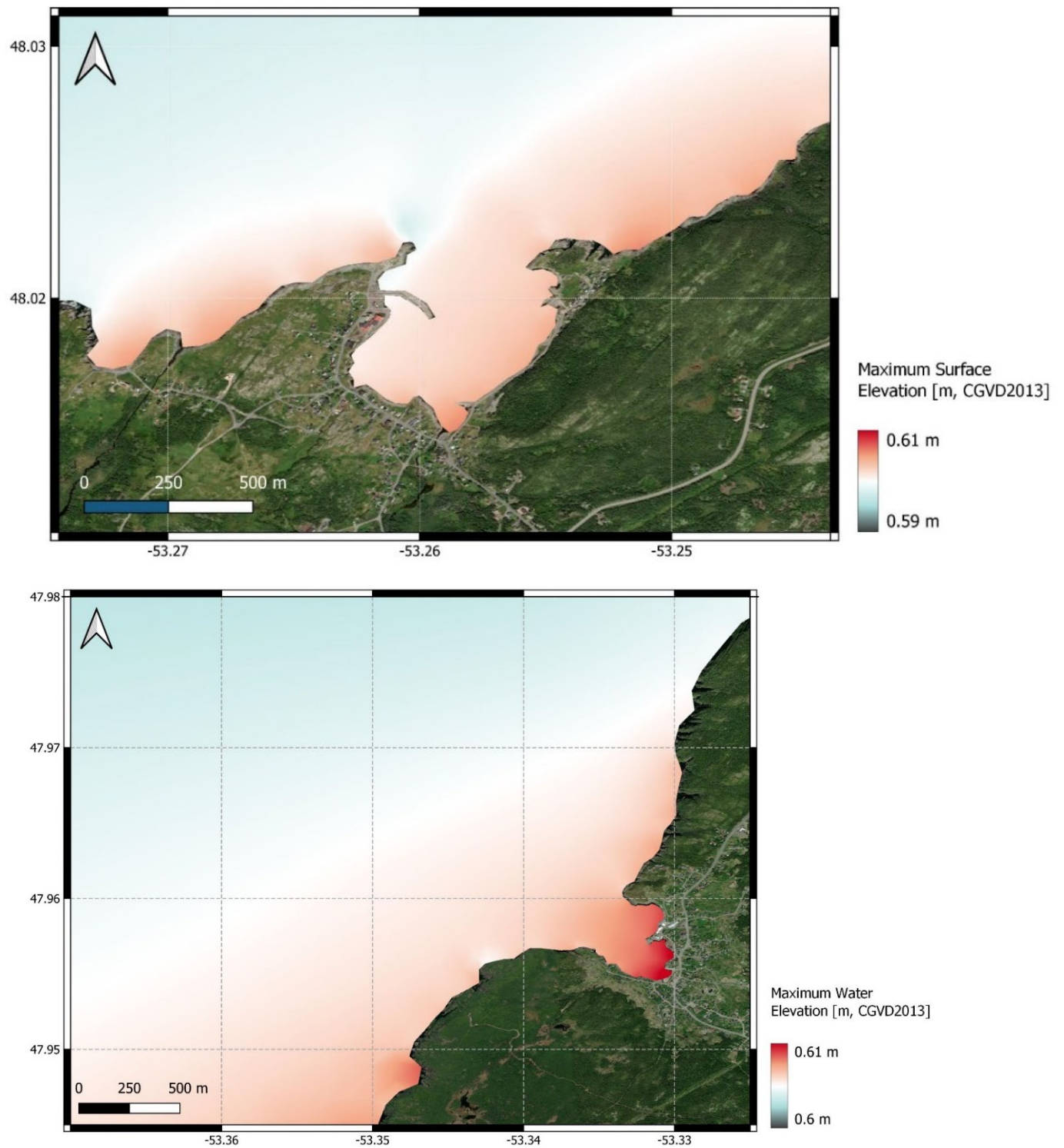
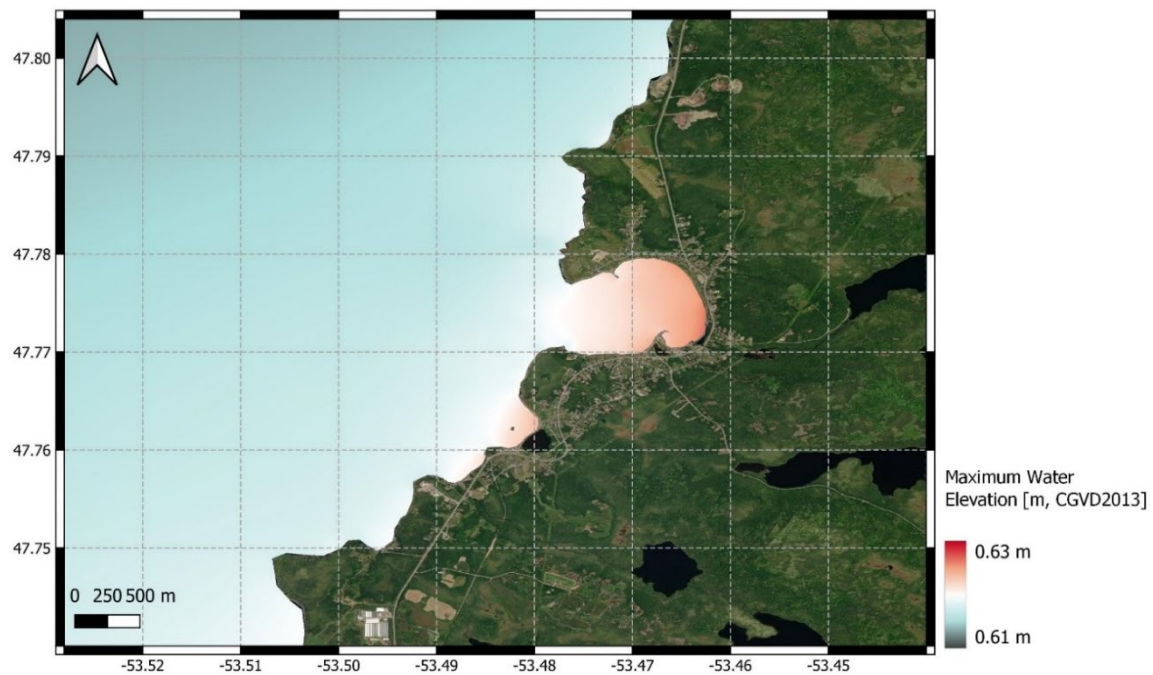


FIGURE 114: 2010 MAXIMUM TOTAL WATER LEVEL NEAR HEART'S DELIGHT – ISLINGTON



Locations where EVA analyses were completed for Hant's Harbour, Winterton and Heart's Delight-Islington are shown on Figure 115 to Figure 117. The resulting AEP water levels and depth-averaged velocities are summarized in the Hant's Harbour area in Table 43 to Table 45.

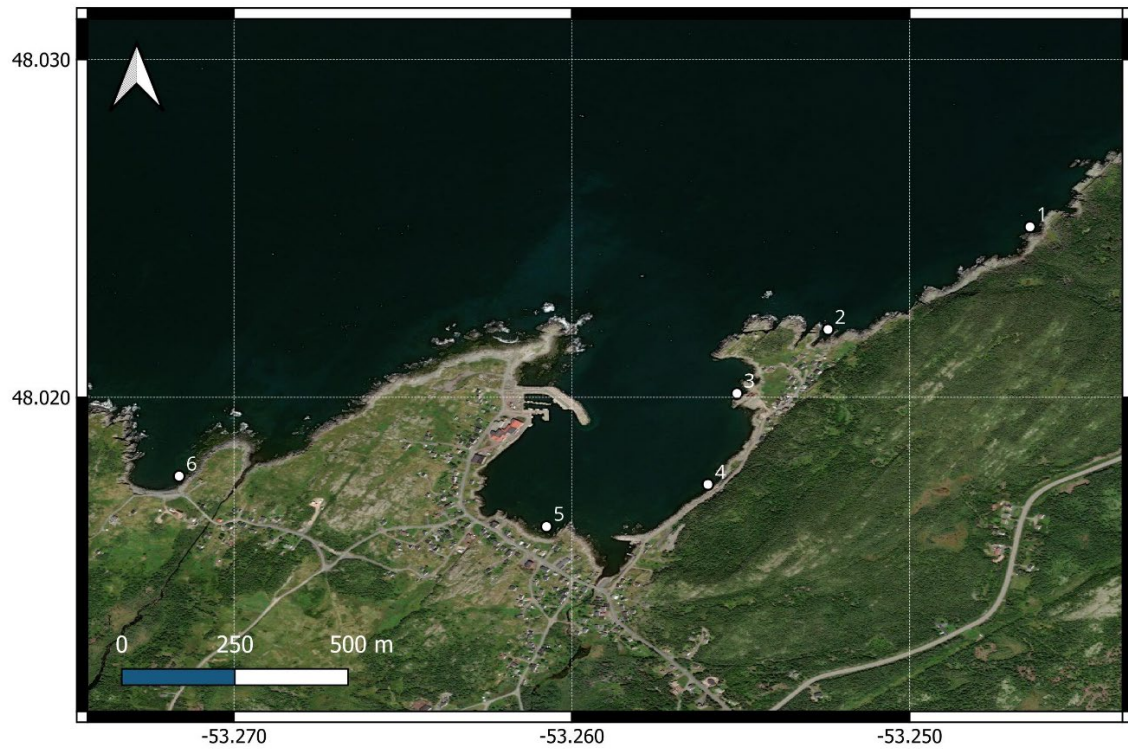
FIGURE 115: EVA LOCATIONS IN HANT'S HARBOUR

TABLE 43: AEP WATER LEVELS AND VELOCITIES IN HANT'S HARBOUR

		Total Water Levels (m, CGVD2013)						Depth-averaged Currents (m/s)					
		100%	20%	10%	5%	2%	1%	100%	20%	10%	5%	2%	1%
s01	Lower bnd.	0.55	0.65	0.69	0.73	0.77	0.80	0.31	0.35	0.36	0.37	0.38	0.39
	Central Est.	0.56	0.69	0.74	0.79	0.85	0.90	0.32	0.36	0.37	0.38	0.40	0.41
	Upper bnd.	0.58	0.72	0.78	0.84	0.92	0.98	0.32	0.36	0.38	0.39	0.42	0.43
s02	Lower bnd.	0.55	0.65	0.69	0.73	0.77	0.80	0.25	0.28	0.29	0.29	0.30	0.31
	Central Est.	0.56	0.69	0.74	0.79	0.85	0.90	0.26	0.29	0.30	0.31	0.32	0.33
	Upper bnd.	0.58	0.72	0.78	0.85	0.93	0.99	0.26	0.29	0.31	0.32	0.34	0.35
s03	Lower bnd.	0.55	0.65	0.69	0.72	0.76	0.80	0.18	0.21	0.22	.23	0.25	0.26
	Central Est.	0.56	0.69	0.74	0.79	0.85	0.90	0.18	0.22	0.24	0.26	0.28	0.30
	Upper bnd.	0.58	0.72	0.78	0.85	0.93	0.99	0.19	0.23	0.26	0.28	0.31	0.33
s04	Lower bnd.	0.55	0.66	0.69	0.73	0.77	0.81	0.17	0.19	0.20	0.20	0.21	0.22
	Central Est.	0.56	0.69	0.74	0.79	0.85	0.90	0.17	0.20	0.21	0.21	0.23	0.24
	Upper bnd.	0.58	0.72	0.79	0.85	0.93	0.99	0.18	0.20	0.21	0.22	0.24	0.25
s05	Lower bnd.	0.55	0.65	0.69	0.73	0.77	0.81	0.13	0.14	0.15	0.16	0.17	0.17
	Central Est.	0.56	0.69	0.74	0.79	0.85	0.90	0.13	0.15	0.16	0.18	0.19	0.20
	Upper bnd.	0.58	0.72	0.78	0.84	0.93	0.99	0.13	0.16	0.18	0.19	0.21	0.23
s06	Lower bnd.	0.55	0.66	0.70	0.73	0.78	0.80	0.09	0.10	0.10	0.11	0.11	0.11
	Central Est.	0.57	0.69	0.74	0.79	0.85	0.90	0.09	0.10	0.11	.11	0.12	0.12
	Upper bnd.	0.59	0.72	0.78	0.84	0.92	0.98	0.09	0.11	0.11	0.12	0.12	0.13

FIGURE 116: EVA LOCATIONS IN WINTERTON

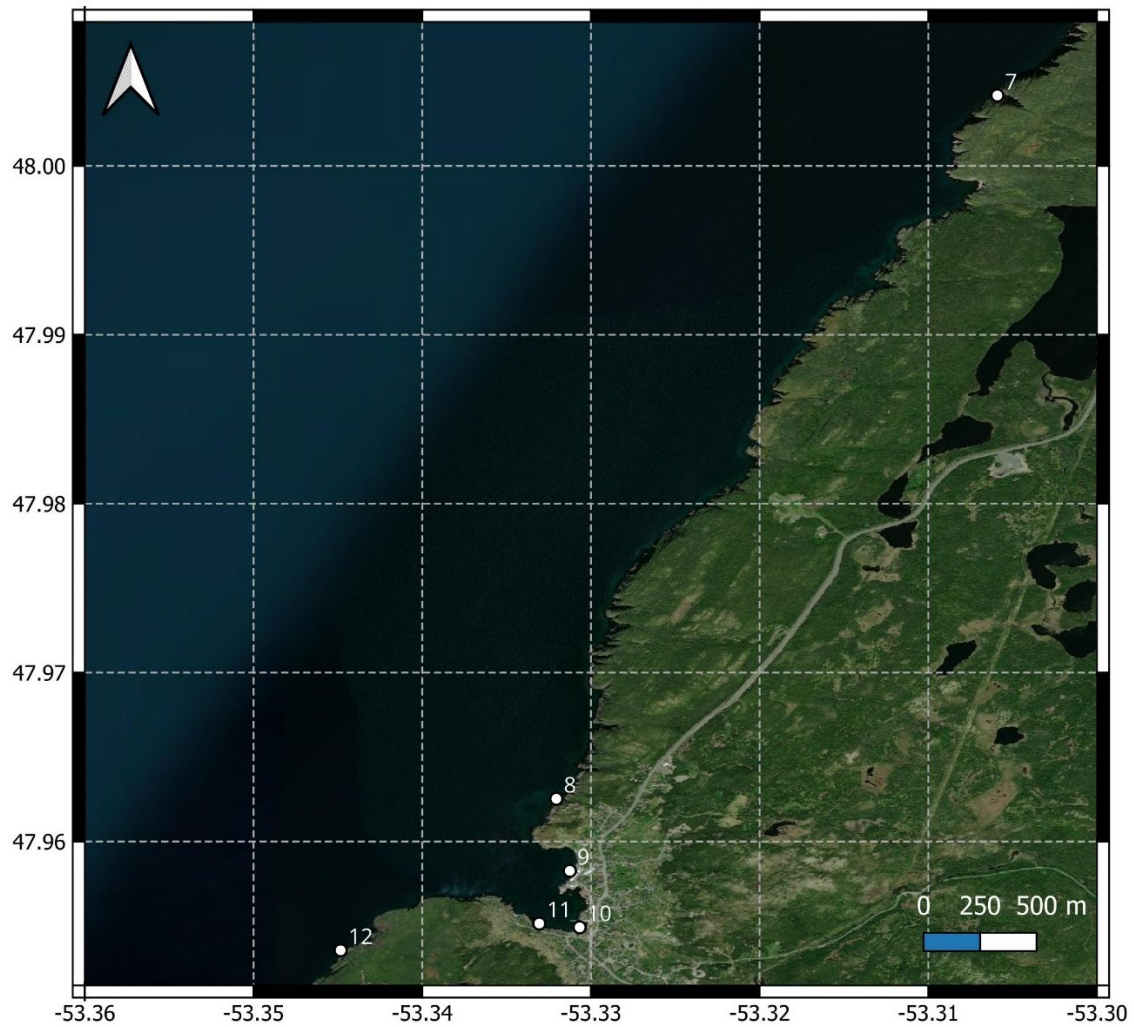


TABLE 44: AEP WATER LEVELS AND VELOCITIES IN WINTERTON

		Total Water Levels (m, CGVD2013)						Depth-averaged Currents (m/s)					
		100%	20%	10%	5%	2%	1%	100%	20%	10%	5%	2%	1%
s07	Lower bnd.	0.56	0.66	0.70	0.73	0.78	0.81	0.44	0.48	0.50	0.51	0.53	0.54
	Central Est.	0.57	0.70	0.75	0.80	0.86	0.90	0.45	0.49	0.51	0.53	0.55	0.57
	Upper bnd.	0.59	0.73	0.79	0.85	0.93	0.98	0.46	0.50	0.52	0.54	0.57	0.58
s08	Lower bnd.	0.56	0.67	0.71	0.74	0.78	0.82	0.34	0.38	0.39	0.40	0.42	0.43
	Central Est.	0.58	0.70	0.75	0.80	0.86	0.91	0.35	0.39	0.41	0.43	0.46	0.48
	Upper bnd.	0.60	0.74	0.80	0.86	0.94	1.00	0.35	0.41	0.43	0.46	0.49	0.51
s09	Lower bnd.	0.56	0.66	0.70	0.74	0.78	0.81	0.22	0.25	0.26	0.27	0.28	0.29
	Central Est.	0.58	0.70	0.75	0.80	0.87	0.91	0.22	0.26	0.27	0.28	0.30	0.32
	Upper bnd.	0.60	0.74	0.80	0.86	0.94	1.00	0.23	0.27	0.28	0.30	0.32	0.34
s10	Lower bnd.	0.57	0.67	0.71	0.74	0.79	0.82	0.10	0.12	0.13	0.13	0.14	0.14
	Central Est.	0.58	0.71	0.76	0.81	0.87	0.91	0.11	0.13	0.14	0.15	0.17	0.18
	Upper bnd.	0.60	0.74	0.80	0.86	0.94	0.99	0.11	0.14	0.15	0.17	0.19	0.21
s11	Lower bnd.	0.56	0.66	0.70	0.74	0.78	0.81	0.19	0.21	0.21	0.22	0.23	0.24
	Central Est.	0.58	0.71	0.76	0.80	0.87	0.91	0.19	0.21	0.22	0.23	0.24	0.25
	Upper bnd.	0.60	0.74	0.80	0.86	0.94	1.01	0.20	0.22	0.23	0.24	0.25	0.27
s12	Lower bnd.	0.56	0.66	0.70	0.74	0.78	0.82	0.39	0.42	0.44	0.45	0.47	0.48
	Central Est.	0.58	0.70	0.75	0.80	0.86	0.91	0.39	0.44	0.45	0.47	0.50	0.51
	Upper bnd.	0.60	0.74	0.80	0.86	0.93	0.99	0.40	0.45	0.47	0.49	0.52	0.55

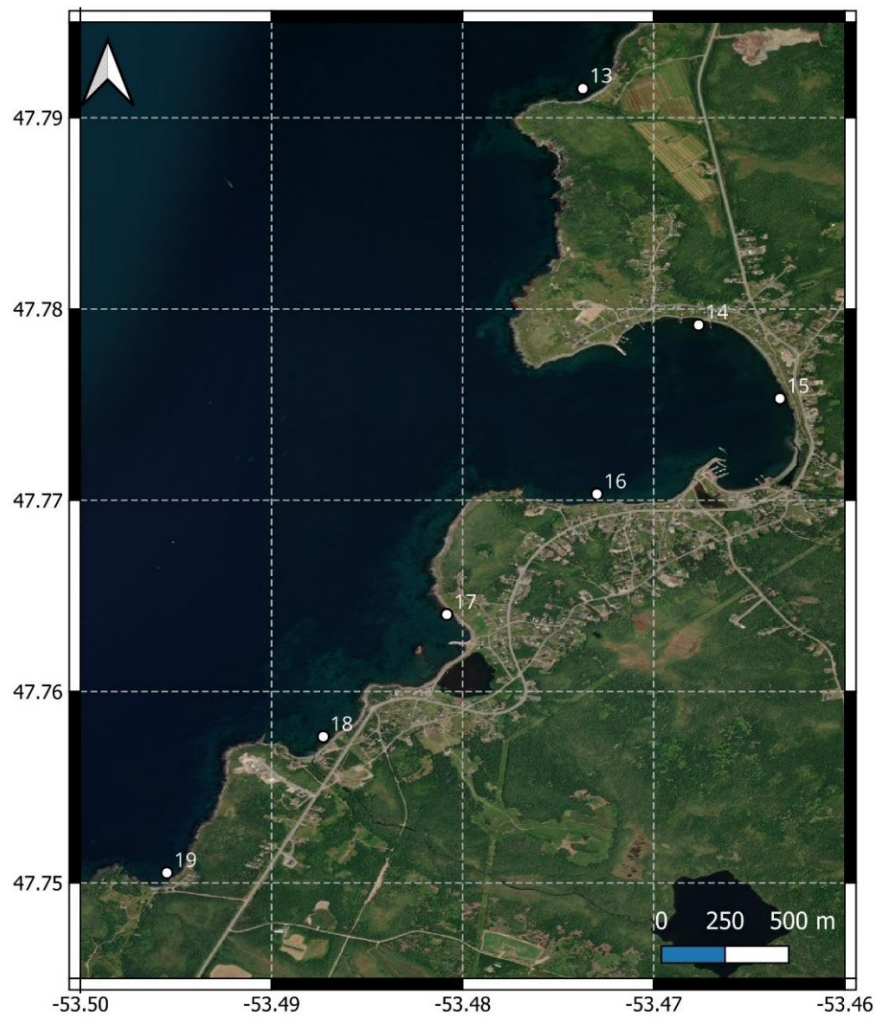
FIGURE 117: EVA LOCATIONS IN HEART'S DELIGHT – ISLINGTON

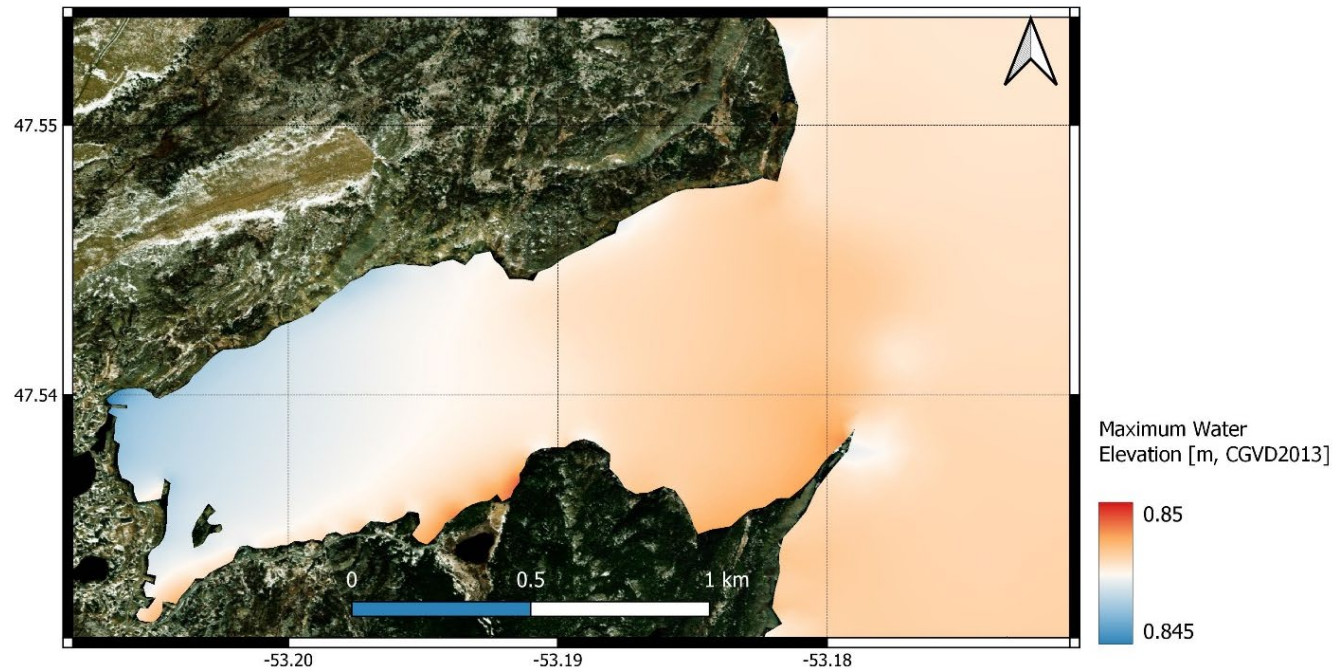
TABLE 45: AEP WATER LEVELS AND VELOCITIES IN HEART'S DELIGHT – ISLINGTON

		Total Water Levels (m, CGVD2013)						Depth-averaged Currents (m/s)					
		100%	20%	10%	5%	2%	1%	100%	20%	10%	5%	2%	1%
S13	Lower bnd.	0.58	0.69	0.73	0.76	0.81	0.84	0.13	0.15	0.15	0.16	0.16	0.17
	Central Est.	0.60	0.73	0.78	0.83	0.89	0.94	0.13	0.15	0.16	0.17	0.18	0.18
	Upper bnd.	0.62	0.76	0.82	0.88	0.96	1.02	0.14	0.16	0.17	0.17	0.18	0.19
S14	Lower bnd.	0.59	0.70	0.74	0.78	0.83	0.86	0.22	0.24	0.24	0.25	0.26	0.27
	Central Est.	0.61	0.73	0.79	0.84	0.90	0.95	0.22	0.24	0.25	0.26	0.27	0.28
	Upper bnd.	0.62	0.76	0.83	0.89	0.97	1.03	0.22	0.25	0.26	0.27	0.29	0.30
S15	Lower bnd.	0.59	0.70	0.74	0.78	0.82	0.86	0.21	0.24	0.25	0.26	0.27	0.28
	Central Est.	0.61	0.74	0.79	0.84	0.90	0.95	0.22	0.25	0.26	0.27	0.29	0.30
	Upper bnd.	0.63	0.77	0.83	0.89	0.97	1.03	0.22	0.25	0.27	0.29	0.32	0.33
S16	Lower bnd.	0.59	0.69	0.74	0.77	0.82	0.85	0.20	0.22	0.23	0.23	0.24	0.25
	Central Est.	0.61	0.74	0.79	0.84	0.90	0.95	0.20	0.23	0.23	0.24	0.25	0.26
	Upper bnd.	0.62	0.77	0.83	0.89	0.97	1.03	0.21	0.23	0.24	0.25	0.26	0.27
S17	Lower bnd.	0.59	0.70	0.74	0.77	0.82	0.85	0.20	0.22	0.22	0.23	0.24	0.24
	Central Est.	0.61	0.74	0.79	0.84	0.90	0.95	0.20	0.23	0.24	0.25	0.26	0.27
	Upper bnd.	0.62	0.77	0.83	0.89	0.97	1.02	0.20	0.23	0.25	0.26	0.28	0.29
S18	Lower bnd.	0.59	0.70	0.74	0.77	0.82	0.85	0.16	0.17	0.18	0.19	0.19	0.20
	Central Est.	0.61	0.74	0.79	0.84	0.90	0.95	0.16	0.18	0.19	0.20	0.21	0.22
	Upper bnd.	0.63	0.77	0.83	0.89	0.96	1.02	0.16	0.19	0.20	0.21	0.22	0.23
S19	Lower bnd.	0.59	0.70	0.74	0.77	0.82	0.85	0.14	0.15	0.16	0.16	0.17	0.18
	Central Est.	0.61	0.74	0.79	0.84	0.90	0.95	0.14	0.16	0.17	0.17	0.18	0.19
	Upper bnd.	0.63	0.77	0.84	0.89	0.98	1.03	0.14	0.16	0.17	0.18	0.20	0.20

Conception Bay

An Example of the maximum simulated water level in 2010 near Brigus is depicted in Figure 118. The water elevation gradients demonstrate the spatially varying total water level within the area of interest.

FIGURE 118: 2010 MAXIMUM TOTAL WATER LEVEL NEAR BRIGUS



Locations where EVA analyses and interpretation were completed for Brigus as shown on Figure 119. The resulting AEP water levels and depth-averaged velocities are summarized in Table 46.

For Brigus, only small variations between the selected points are observed in the computed extreme total water level (i.e. 0.02 to 0.03 m for the computed 100-year AEP) which illustrates a relative uniformity of the extreme water levels along Brigus shoreline. For current speed, larger differences were noted due to the complex shoreline morphology representation, which significantly influences the current speed and direction along the shoreline.

FIGURE 119: EVA LOCATIONS IN BRIGUS

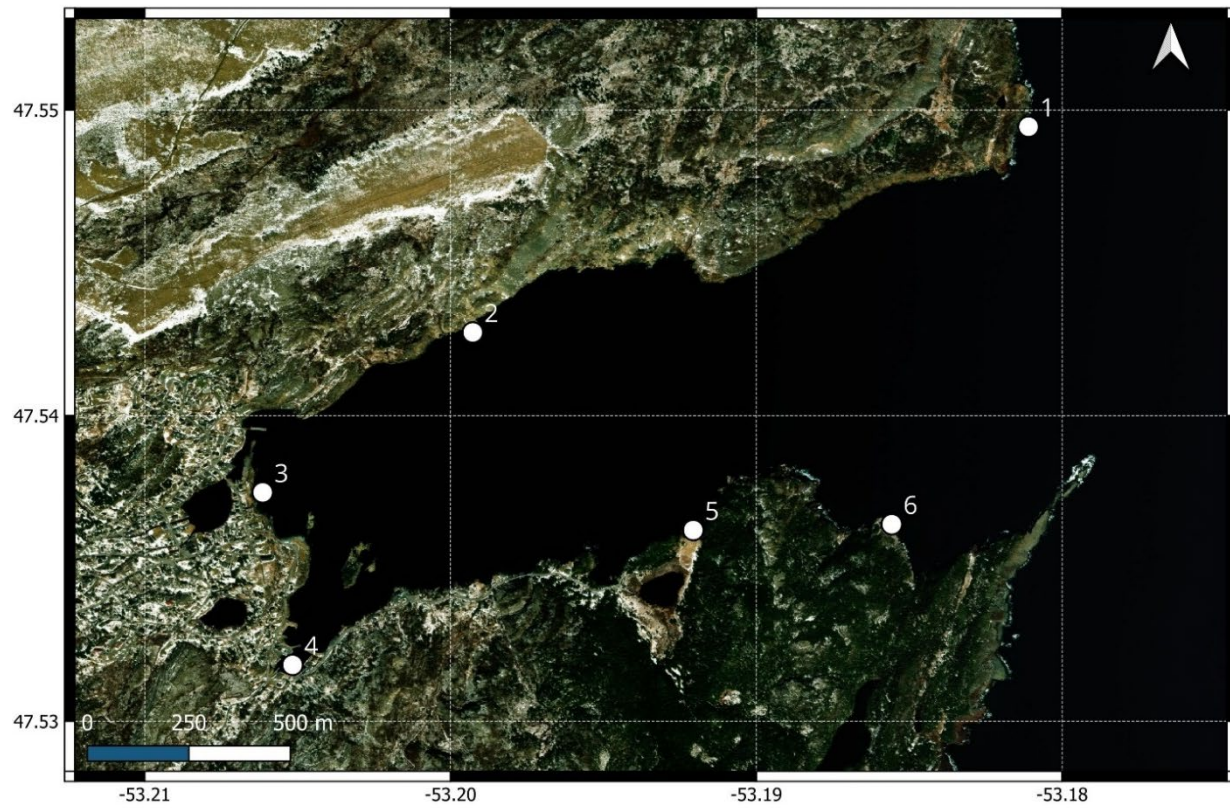
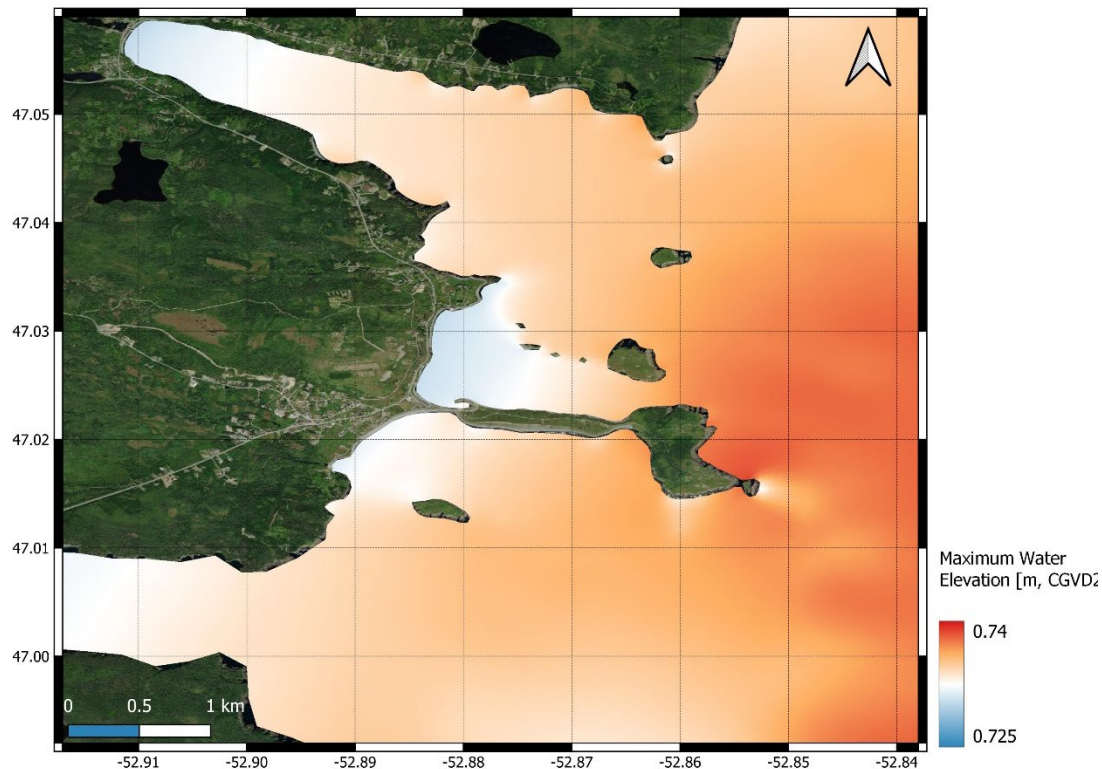


TABLE 46: AEP WATER LEVELS AND VELOCITIES IN BRIGUS

		Total Water Levels (m, CGVD2013)						Depth-averaged Currents (m/s)					
		100%	20%	10%	5%	2%	1%	100%	20%	10%	5%	2%	1%
S01	Lower bnd.	0.77	0.89	0.93	0.96	0.99	1.01	0.30	0.35	0.36	0.38	0.39	0.40
	Central Est.	0.78	0.93	1.00	1.07	1.16	1.23	0.31	0.36	0.38	0.40	0.42	0.44
	Upper bnd.	0.81	0.99	1.06	1.14	1.25	1.33	0.32	0.38	0.40	0.42	0.45	0.47
S02	Lower bnd.	0.77	0.89	0.93	0.96	0.99	1.01	0.23	0.25	0.26	0.27	0.28	0.29
	Central Est.	0.78	0.93	1.00	1.07	1.16	1.23	0.23	0.26	0.27	0.28	0.30	0.31
	Upper bnd.	0.80	0.99	1.06	1.14	1.26	1.34	0.23	0.27	0.28	0.30	0.32	0.33
S03	Lower bnd.	0.77	0.88	0.92	0.95	0.99	1.01	0.16	0.18	0.19	0.20	0.21	0.22
	Central Est.	0.78	0.93	1.00	1.07	1.16	1.23	0.17	0.19	0.20	0.21	0.23	0.24
	Upper bnd.	0.80	0.98	1.06	1.14	1.24	1.32	0.17	0.20	0.21	0.22	0.24	0.25
S04	Lower bnd.	0.77	0.89	0.92	0.96	0.99	1.01	0.05	0.06	0.06	0.06	0.06	0.07
	Central Est.	0.78	0.93	1.00	1.07	1.16	1.24	0.05	0.06	0.06	0.06	0.07	0.07
	Upper bnd.	0.81	0.98	1.06	1.15	1.26	1.34	0.05	0.06	0.06	0.07	0.07	0.07
S05	Lower bnd.	0.77	0.89	0.93	0.96	1.00	1.03	0.13	0.15	0.16	0.16	0.17	0.18
	Central Est.	0.78	0.93	1.00	1.07	1.16	1.24	0.14	0.16	0.17	0.18	0.19	0.20
	Upper bnd.	0.81	0.98	1.06	1.14	1.25	1.34	0.14	0.16	0.17	0.19	0.20	0.21
S06	Lower bnd.	0.77	0.89	0.93	0.96	0.99	1.02	0.12	0.13	0.14	0.14	0.15	0.15
	Central Est.	0.78	0.93	1.00	1.07	1.16	1.23	0.12	0.13	0.14	0.15	0.16	0.16
	Upper bnd.	0.80	0.98	1.06	1.14	1.25	1.33	0.12	0.14	0.15	0.15	0.16	0.17

Ferryland

Examples of the maximum simulated water level in 2010 near Ferryland is depicted in Figure 120. The water elevation gradients demonstrate the spatially varying total water level within the area of interest.

FIGURE 120: 2010 MAXIMUM TOTAL WATER LEVEL NEAR FERRYLAND

Output locations chosen for analysis and interpretation for Ferryland as shown on Figure 121. The resulting AEP water levels and depth-averaged velocities are summarized in Table 47.

Similar to Brigus, only small variations were noted between the computed extreme total water levels in Ferryland (i.e. 0.01 to 0.02 m for the 100-year AEP), which illustrates a relative uniformity of the extreme water levels along Ferryland shorelines. For current speed, larger differences were noted, since the complex shoreline morphology representation significantly affects the current speed and direction along the shoreline.

FIGURE 121: EVA LOCATIONS IN FERRYLAND

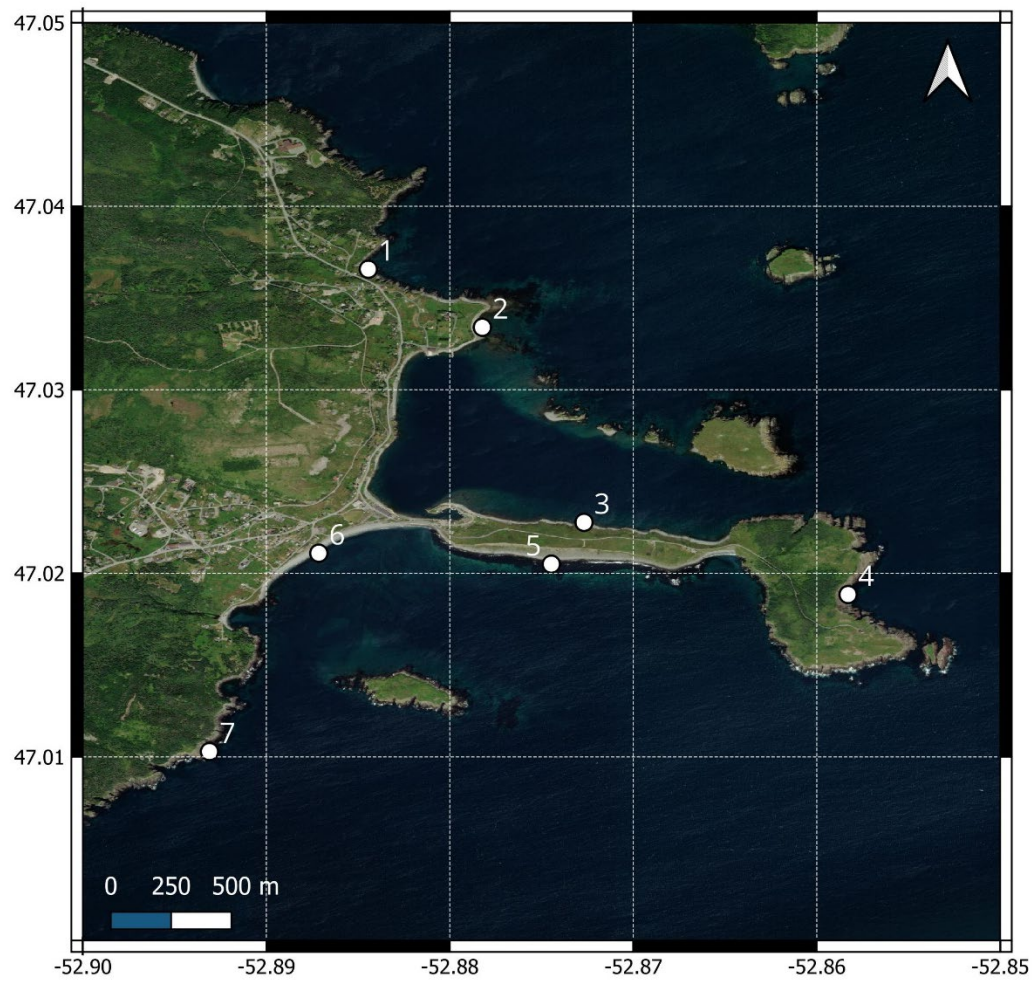


TABLE 47: AEP WATER LEVELS AND VELOCITIES IN FERRYLAND

		Total Water Levels (m, CGVD2013)						Depth-averaged Currents (m/s)					
		100%	20%	10%	5%	2%	1%	100%	20%	10%	5%	2%	1%
S01	Lower bnd.	0.76	0.90	0.96	1.01	1.06	1.10	0.12	0.14	0.14	0.15	0.15	0.16
	Central Est.	0.77	0.97	1.05	1.14	1.25	1.34	0.13	0.14	0.15	0.16	0.17	0.17
	Upper bnd.	0.81	1.02	1.13	1.24	1.39	1.50	0.13	0.15	0.16	0.17	0.18	0.19
S02	Lower bnd.	0.75	0.91	0.96	1.01	1.06	1.10	0.16	0.17	0.17	0.18	0.18	0.19
	Central Est.	0.77	0.97	1.05	1.14	1.25	1.33	0.16	0.17	0.18	0.18	0.19	0.20
	Upper bnd.	0.80	1.03	1.13	1.24	1.39	1.50	0.16	0.18	0.18	0.19	0.20	0.20
S03	Lower bnd.	0.75	0.91	0.96	1.01	1.07	1.10	0.19	0.21	0.22	0.22	0.23	0.23
	Central Est.	0.77	0.97	1.05	1.14	1.25	1.34	0.19	0.22	0.23	0.24	0.25	0.26
	Upper bnd.	0.81	1.04	1.14	1.25	1.41	1.54	0.20	0.23	0.24	0.25	0.27	0.28
S04	Lower bnd.	0.76	0.91	0.97	1.02	1.08	1.11	0.13	0.14	0.15	0.15	0.16	0.16
	Central Est.	0.78	0.97	1.06	1.15	1.26	1.35	0.13	0.15	0.15	0.16	0.16	0.17
	Upper bnd.	0.81	1.03	1.14	1.25	1.40	1.52	0.14	0.15	0.16	0.16	0.17	0.18
S05	Lower bnd.	0.75	0.90	0.96	1.01	1.07	1.10	0.31	0.34	0.35	0.36	0.38	0.39
	Central Est.	0.77	0.96	1.05	1.13	1.25	1.34	0.32	0.35	0.37	0.38	0.40	0.41
	Upper bnd.	0.80	1.02	1.13	1.24	1.39	1.51	0.32	0.36	0.38	0.39	0.41	0.42
S06	Lower bnd.	0.75	0.90	0.95	1.00	1.06	1.10	0.22	0.23	0.24	0.25	0.25	0.26
	Central Est.	0.77	0.96	1.04	1.13	1.24	1.33	0.22	0.24	0.25	0.26	0.27	0.28
	Upper bnd.	0.80	1.02	1.12	1.23	1.38	1.50	0.22	0.25	0.26	0.28	0.29	0.31
S07	Lower bnd.	0.75	0.90	0.95	1.00	1.06	1.10	0.29	0.33	0.34	0.36	0.37	0.38
	Central Est.	0.77	0.96	1.05	1.13	1.25	1.34	0.30	0.34	0.35	0.37	0.38	0.40
	Upper bnd.	0.81	1.02	1.13	1.24	1.39	1.51	0.31	0.35	0.36	0.37	0.39	0.40

8.2.6 OFFSHORE WAVE CONDITIONS

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).

Trinity Bay – MSC50 Data Point M6013845

The location of the MSC50 data point used to force the MIKE21 FM SW model for Trinity Bay area is depicted in Figure 122. A summary of the wave statistics for the significant wave height (i.e. H_s , m) and the peak wave period (i.e. T_p , seconds), is provided in a rose plot format in Figure 123. Prevailing offshore waves are from the northeast, which is consistent with prevailing offshore wave conditions along the northeastern shore of Newfoundland.

FIGURE 122: MSC50 M6013845 LOCATION RELATIVE TO MODEL GRID

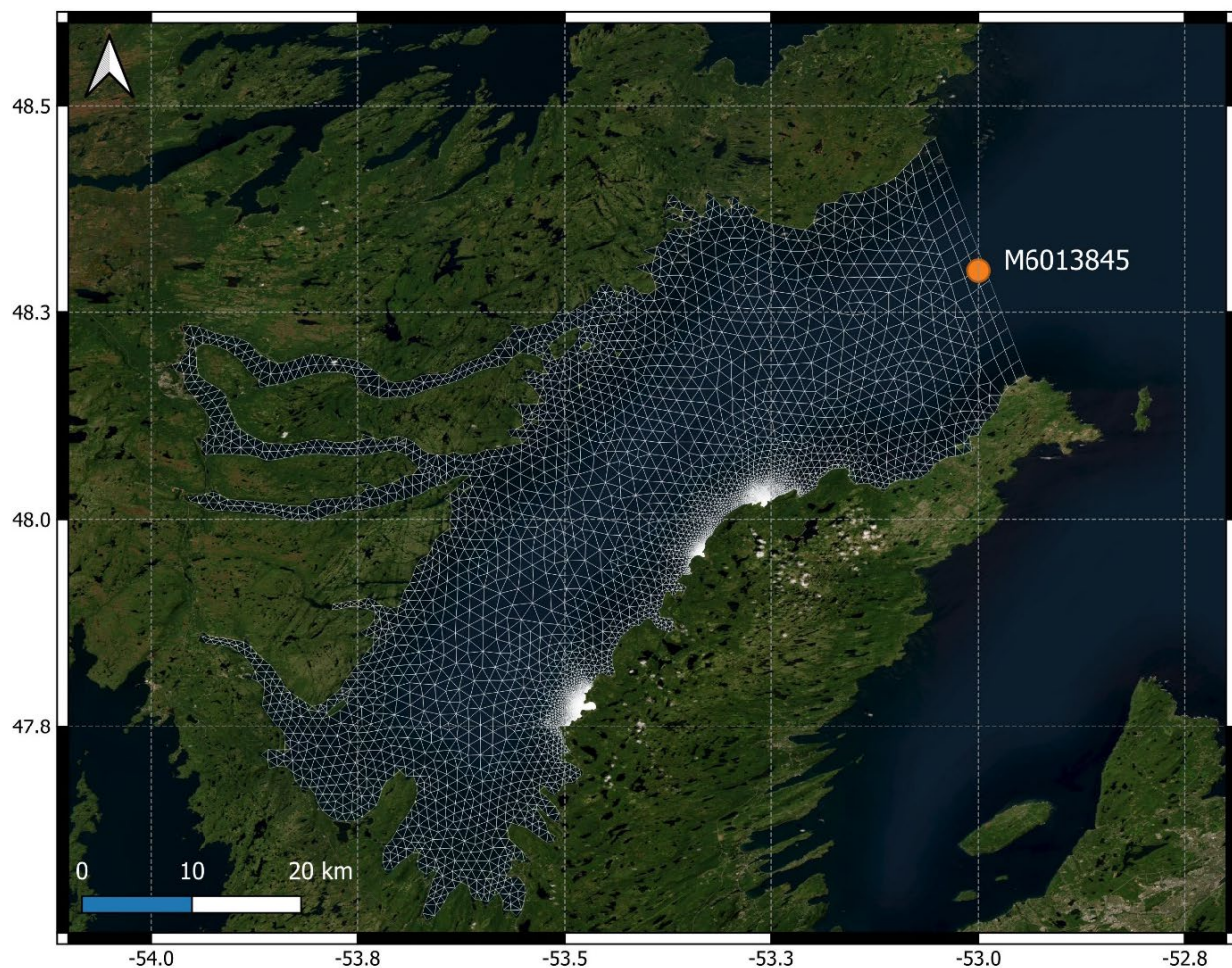
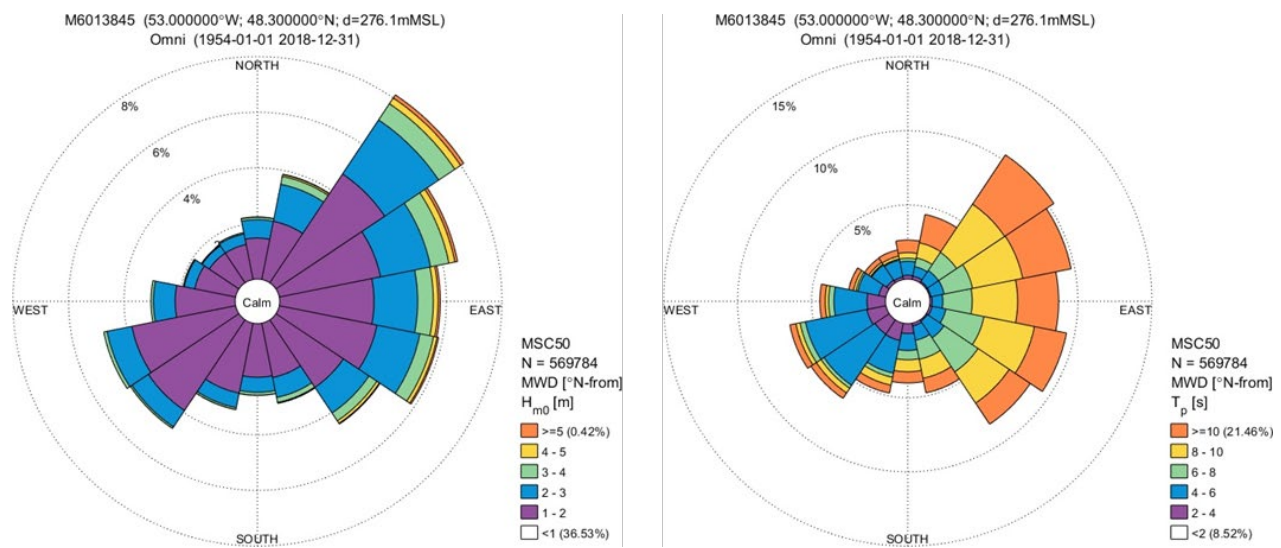


FIGURE 123: MSC50 M6013845 WAVE HEIGHT AND WAVE PERIOD

Monthly wave roses for Trinity Bay, provided in Appendix I, indicate that:

- Trinity Bay sea state is mainly composed by swell waves coming from northeast and east direction, but southwest wind waves of up to 3.5 m can be generated inside the bay area.
- The fall (i.e. September to November) and winter (i.e. December to March) months experience the highest energy waves, predominantly from NE, E and SE, and are typically associated with storm activity.
- Prevailing lower energy waves are from the southwest, generated from inside the Trinity Bay area.

Other wind and wave statistics, which are provided in Appendix I, for point M6013845 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 48 and Table 49.

TABLE 48: AEP SIGNIFICANT WAVE HEIGHT PER DIRECTION FOR MSC50 M6013845

Significant Wave Height (m) per Direction												
AEP	180°	210°	240°	270°	300°	330°	360°	30°	60°	90°	120°	150°
100%	3.57	3.33	3.26	3.10	2.88	2.92	3.28	4.39	4.75	4.54	4.59	4.05
10%	4.61	4.32	4.17	4.03	3.93	4.14	4.64	6.40	7.03	6.71	6.75	5.69
5%	4.92	4.62	4.44	4.30	4.24	4.51	5.05	7.01	7.72	7.36	7.40	6.19
2%	5.33	5.01	4.81	4.67	4.66	4.99	5.59	7.81	8.63	8.22	8.27	6.84
1%	5.64	5.31	5.08	4.95	4.97	5.36	6.00	8.42	9.31	8.87	8.92	7.33

TABLE 49: AEP WIND SPEED PER DIRECTION FOR MSC50 M6013845

Wind Speed (m/s) per Direction												
AEP	180°	210°	240°	270°	300°	330°	360°	30°	60°	90°	120°	150°
100%	18.79	18.76	19.94	20.53	20.36	19.54	17.90	16.48	15.99	16.01	18.34	19.11
10%	21.99	22.16	22.92	23.74	24.28	23.46	21.63	20.14	19.85	20.00	21.79	22.30
5%	22.92	23.11	23.67	24.57	25.31	24.51	22.64	21.13	20.88	21.09	22.70	23.19
2%	24.12	24.32	24.62	25.61	26.61	25.83	23.92	22.40	22.20	22.50	23.84	24.34
1%	25.03	25.22	25.30	26.36	27.55	26.79	24.86	23.33	23.16	23.53	24.67	25.19

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 125. A summary of the wave statistics for the significant wave height (i.e. H_s , m) and the peak wave period (i.e. T_p , seconds), is provided in a rose plot format in Figure 125. Prevailing offshore waves are from the southeast to northeast, which is consistent with prevailing offshore wave conditions along the northeastern shore of Newfoundland.

FIGURE 124: MSC50 M6013197 LOCATION RELATIVE TO MODEL GRID

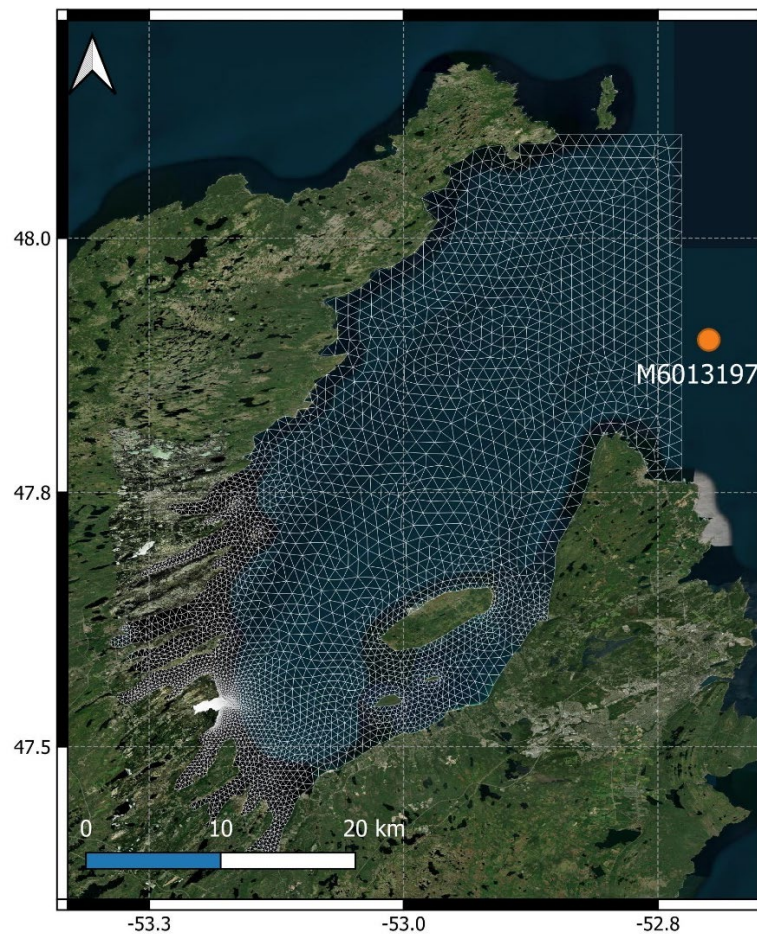
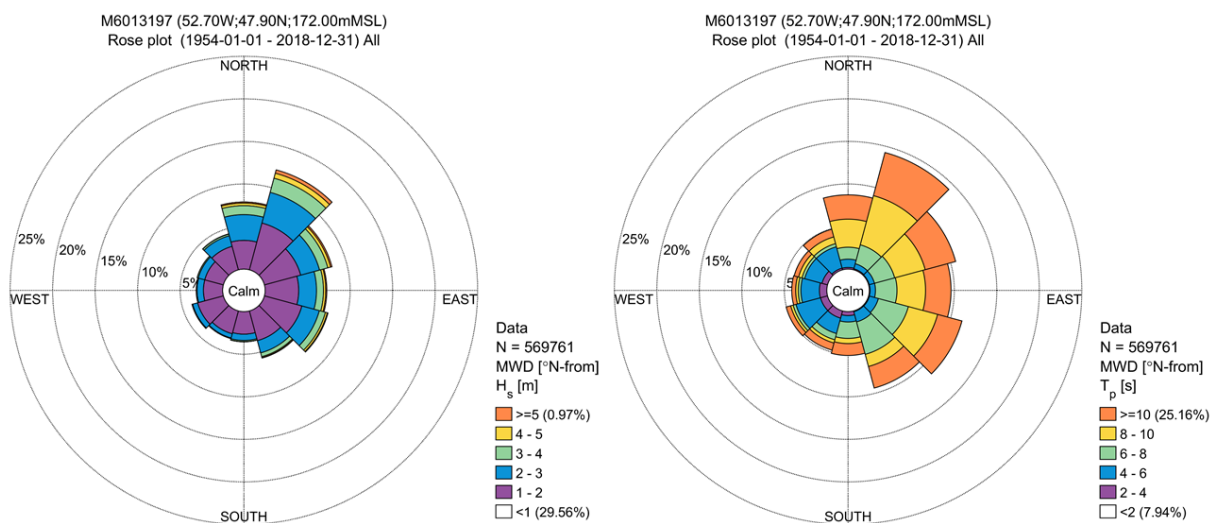


FIGURE 125: MSC50 M6013197 WAVE HEIGHT AND WAVE PERIOD



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

- Conception Bay is exposed mainly to waves coming from northeast to east.
- Prevailing lower energy waves occur during summer months (i.e. May to August) and are composed by wind waves from southwest generated inside the bay and by east and northeast waves coming from offshore.
- 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 east, and are typically associated with storm activity.

Offshore wave and wind statistics are provided in Appendix I for point M6013197. The timeseries data for the significant wave 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 50 and Table 51.

TABLE 50: 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%	3.74	3.44	3.33	3.24	3.30	3.57	5.08	6.00	5.18	5.01	5.12	4.67
10%	4.79	4.29	4.01	3.93	4.06	4.80	7.13	8.35	7.24	7.38	7.22	6.32
5%	5.09	4.53	4.19	4.12	4.26	5.16	7.72	9.01	7.85	8.09	7.82	6.79
2%	5.48	4.83	4.42	4.35	4.52	5.64	8.48	9.86	8.65	9.04	8.60	7.39
1%	5.76	5.06	4.59	4.52	4.71	6.00	9.05	10.49	9.25	9.76	9.18	7.83

TABLE 51: AEP WIND SPEED PER DIRECTION FOR MSC50 M6013197

Wind Speed (m/s) per Direction												
AEP	180°	210°	240°	270°	300°	330°	360°	30°	60°	90°	120°	150°
100%	19.01	19.15	20.54	21.11	20.50	19.63	18.09	16.91	16.38	16.38	18.51	19.11
10%	22.30	22.87	23.54	24.52	24.39	23.79	21.77	20.46	20.23	20.58	21.44	23.21
5%	23.27	23.90	24.27	25.37	25.41	24.93	22.75	21.44	21.28	21.76	22.17	24.55
2%	24.56	25.22	25.17	26.42	26.70	26.38	24.0	22.71	22.63	23.29	23.09	26.37
1%	25.52	26.20	25.81	27.18	27.65	27.45	24.91	23.65	23.63	24.42	23.76	27.79

Ferryland – MSC50 Data Point M6011567

The location of the MSC50 data point used to drive the MIKE21 FM SW model for Ferryland area is depicted in Figure 126. A summary of the wave statistics for the significant wave height and the peak wave period for Ferryland is provided in a rose plot format in Figure 127. Prevailing offshore waves are from the south to northeast, which is consistent with prevailing offshore wave conditions along the eastern shore of Newfoundland.

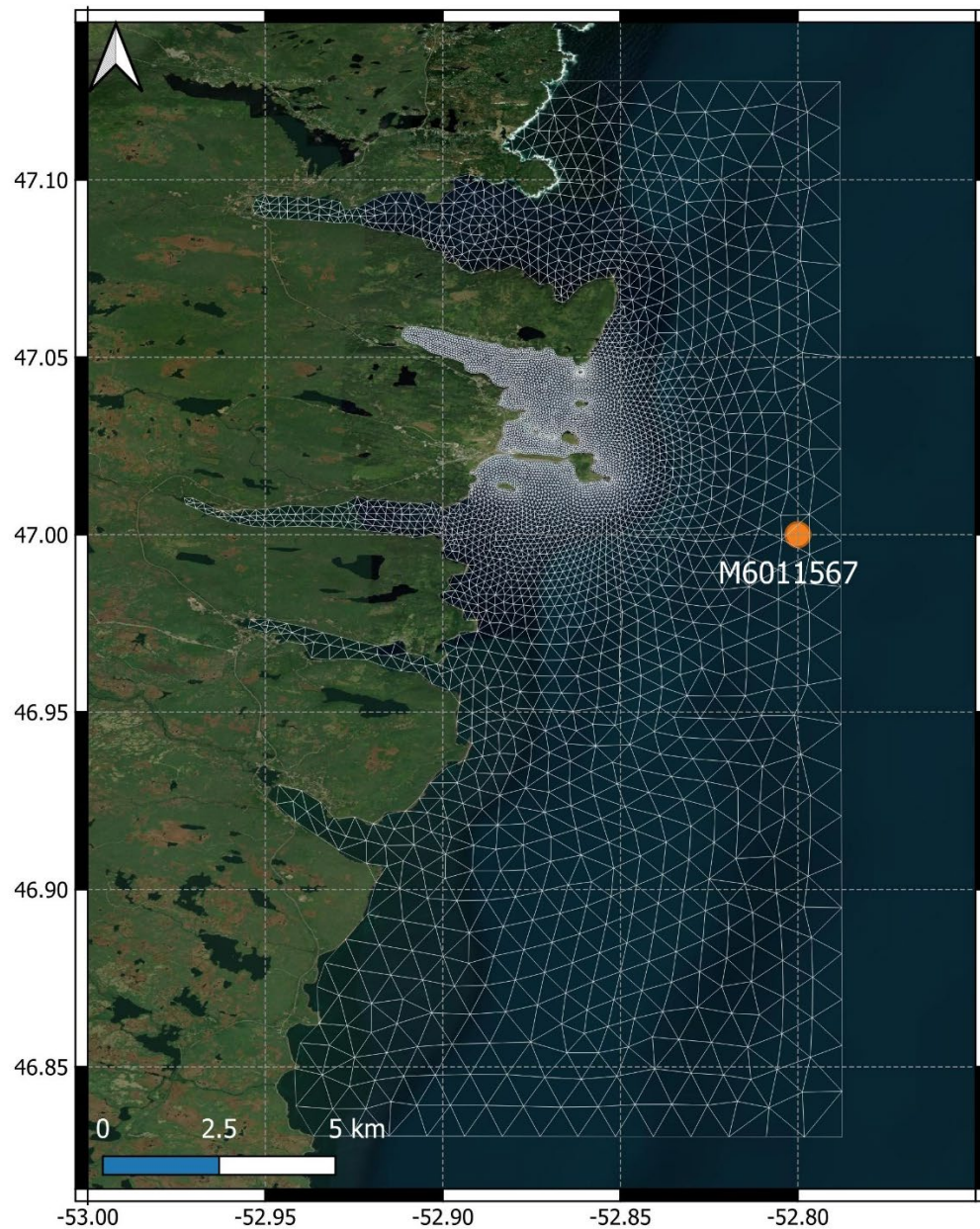
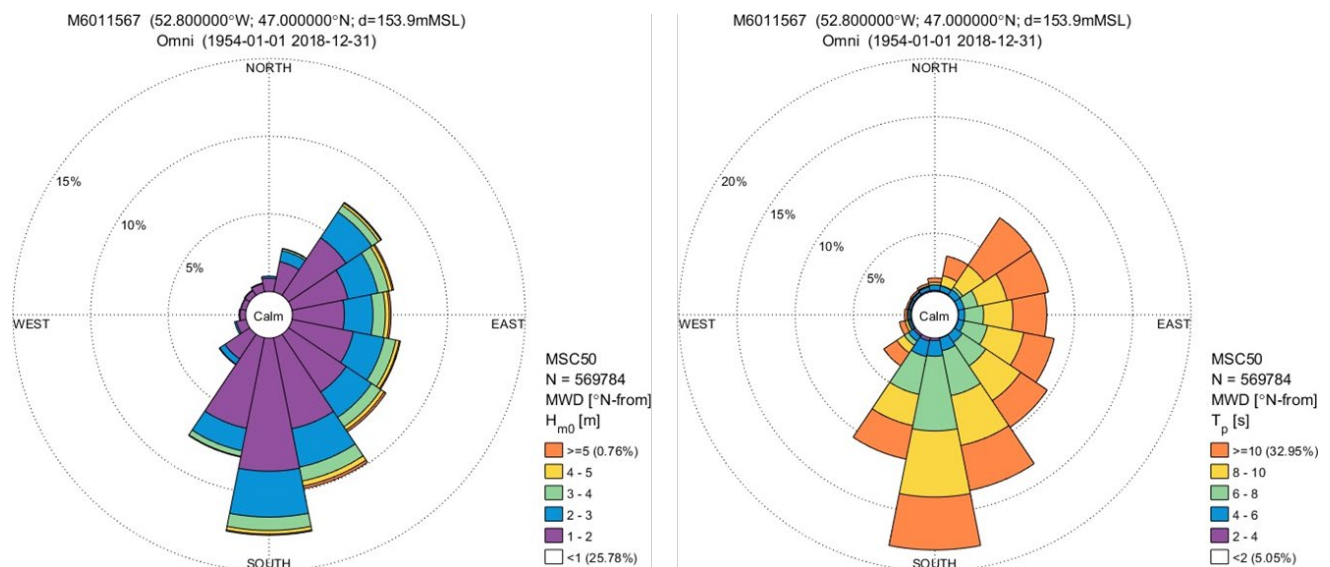
FIGURE 126: MSC50 M6011567 LOCATION RELATIVE TO MODEL GRID

FIGURE 127: MSC50 M6011567 WAVE HEIGHT AND WAVE PERIOD

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

- The more energetic northeast waves are more frequent from October to November, while the south and southeastern waves are more frequent from December to March.
- October to March months experience the highest energy waves, predominantly from south, southeast, east, and northeast, and are typically associated with storm activity.
- Ferryland community is exposed to a large range of wave directions.

Offshore wave and wind statistics are provided in Appendix I for point M6011567. The timeseries data for the significant wave 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 M6011567 are summarized in Table 52 and Table 53.

TABLE 52: AEP SIGNIFICANT WAVE HEIGHT PER DIRECTION FOR MSC50 M6011567

Significant Wave Height (m) per Direction												
AEP	180°	210°	240°	270°	300°	330°	360°	30°	60°	90°	120°	150°
100%	5.40	3.79	2.58	2.25	2.18	2.20	2.44	3.93	4.73	5.04	5.38	6.24
10%	6.92	4.81	3.20	2.90	2.90	2.96	3.27	5.51	6.87	7.24	7.66	8.16
5%	7.30	5.07	3.34	3.08	3.12	3.19	3.49	5.91	7.48	7.93	8.36	8.61
2%	7.76	5.39	3.52	3.31	3.41	3.50	3.77	6.42	8.28	8.85	9.31	9.15
1%	8.08	5.62	3.64	3.47	3.62	3.73	3.98	6.78	8.86	9.55	10.03	9.53

TABLE 53: AEP WIND SPEED PER DIRECTION FOR MSC50 M6011567

AEP	Wind Speed (m/s) per Direction											
	180°	210°	240°	270°	300°	330°	360°	30°	60°	90°	120°	150°
100%	19.37	19.63	21.20	21.54	20.42	19.43	17.87	17.71	17.63	17.38	18.78	19.56
10%	22.70	24.35	24.65	25.14	24.39	23.56	21.88	21.45	22.06	21.63	22.07	22.79
5%	23.58	25.71	25.43	25.98	25.36	24.54	22.89	22.31	23.20	22.72	22.80	23.57
2%	24.68	27.48	26.34	26.98	26.54	25.72	24.13	23.33	24.62	24.05	23.66	24.51
1%	25.46	28.79	26.96	27.67	27.37	26.55	25.01	24.04	25.63	25.00	24.25	25.16

8.2.7 COASTAL WAVE MODELLING

Spectral wave modelling, which is used to simulate 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 FM 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, and
- 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 extreme total water levels (i.e. 20-year AEP and 100-year AEP, presented for each community in Section 8.2.5) and extreme offshore wave conditions and sustained winds from the MSC50 hindcast presented in Section 8.2.6.

The spectral wave model has not been calibrated to locally observed wave conditions as these are not publicly available along the studied communities' shorelines. It is understood that the collection of wave data for the purposes of model calibration is outside of the present scope of work. DHI has reliably applied its models, using regionally tuned settings and parameters, to simulate extreme wave conditions, for regional flood hazard mapping purposes. It is therefore anticipated that the spectral wave model developed for this study will provide robust and reliable wave inputs for the purposes of this investigation. The basic model setup and parameters is presented in Table 54.

TABLE 54: COASTAL WAVE MODEL SETUP

Setting	Coastal Wave Model (MIKE21 FM SW)
Mesh resolution	~5 km at the offshore boundaries
Simulation period	Statistical Discrete Events - Multidirectional Extreme Conditions
Basic equations	Fully spectral quasi-stationary
Spectral discretisation	30 frequencies with logarithmic increment factor of 1.1 and fmin of 0.06 Hertz, 36 directions of 10°
Water level	Total Water Level Extreme Conditions (20-year AEP and 100-year AEP) combined with Sea Level Rise Scenarios.
Energy transfer	Quadruplet-wave interaction included
Wind forcing	Multidirectional Wind Speed Extreme Conditions (20-year AEP and 100-year AEP).
Air/water density ratio	Constant
Wave breaking	Included, Specified Gamma, $\gamma=0.8$, $\alpha=1$
Bottom friction	Homogeneous along the domain.
White capping	Modified WAM cycle 4. Cdis=1.33. Ddis=0.5.
Wave Boundary conditions	Multidirectional Wave Extreme Conditions (20-year AEP and 100-year AEP).

Summaries of the spectral wave simulations for Trinity Bay, Conception Bay and Ferryland are provided below.

Trinity Bay

Model outputs showing discrete extreme wave conditions in Heart's Delight-Islington, Winterton and Hant's Harbour are shown for an illustrative case (i.e. 100-year, 60° prevailing wind and offshore waves) in Figure 128 to Figure 131.

The model outputs illustrate the site-specific impacts of extreme wave events throughout the model domain.

FIGURE 128: 100-YEAR, 60° PREVAILING WINDS AND OFFSHORE WAVES AEP SIGNIFICANT WAVE HEIGHT AT TRINITY BAY

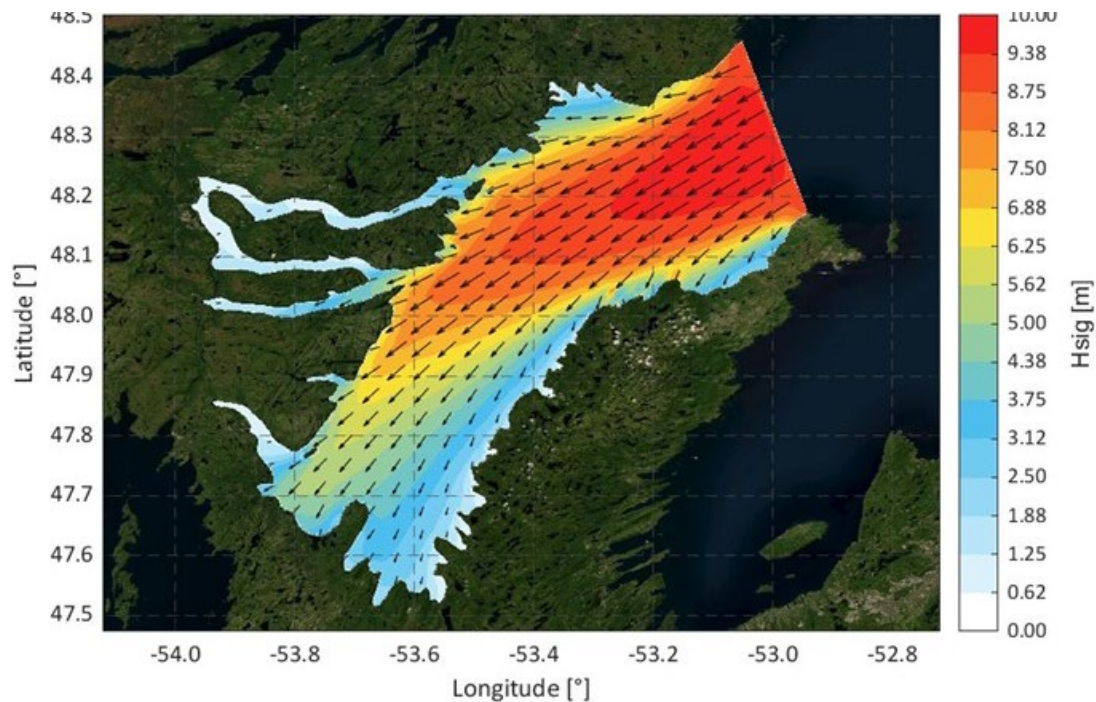


FIGURE 129: 100-YEAR 30° PREVAILING WINDS AND OFFSHORE WAVES AEP SIGNIFICANT WAVE HEIGHT NEAR HEART'S DELIGHT – ISLINGTON

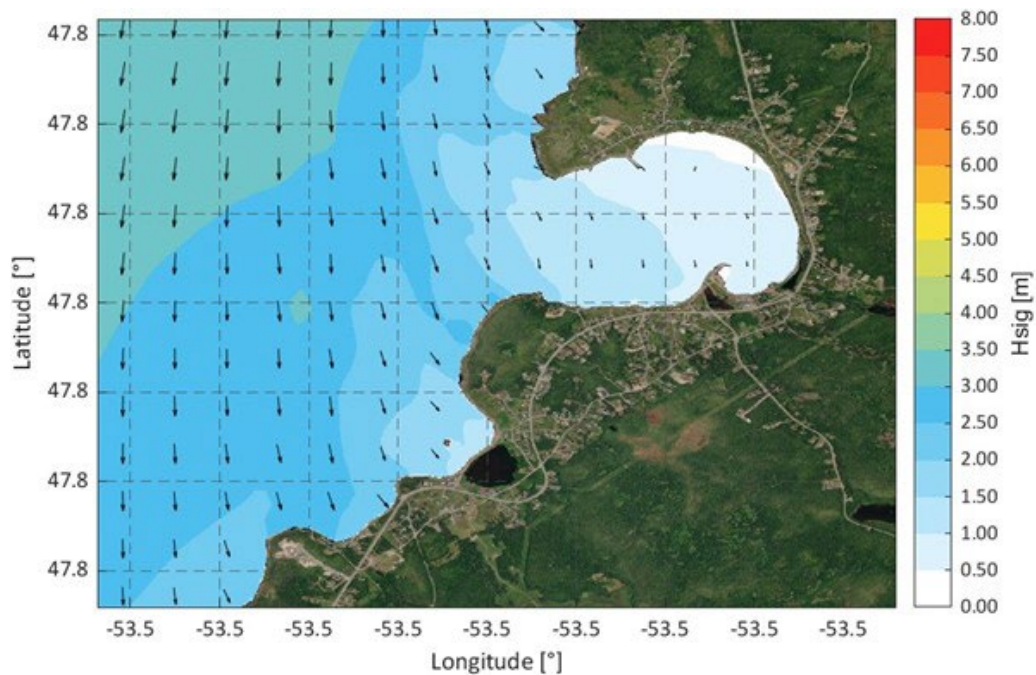


FIGURE 130: 100-YEAR 30° PREVAILING WINDS AND OFFSHORE WAVES SIGNIFICANT WAVE HEIGHT NEAR WINTERTON

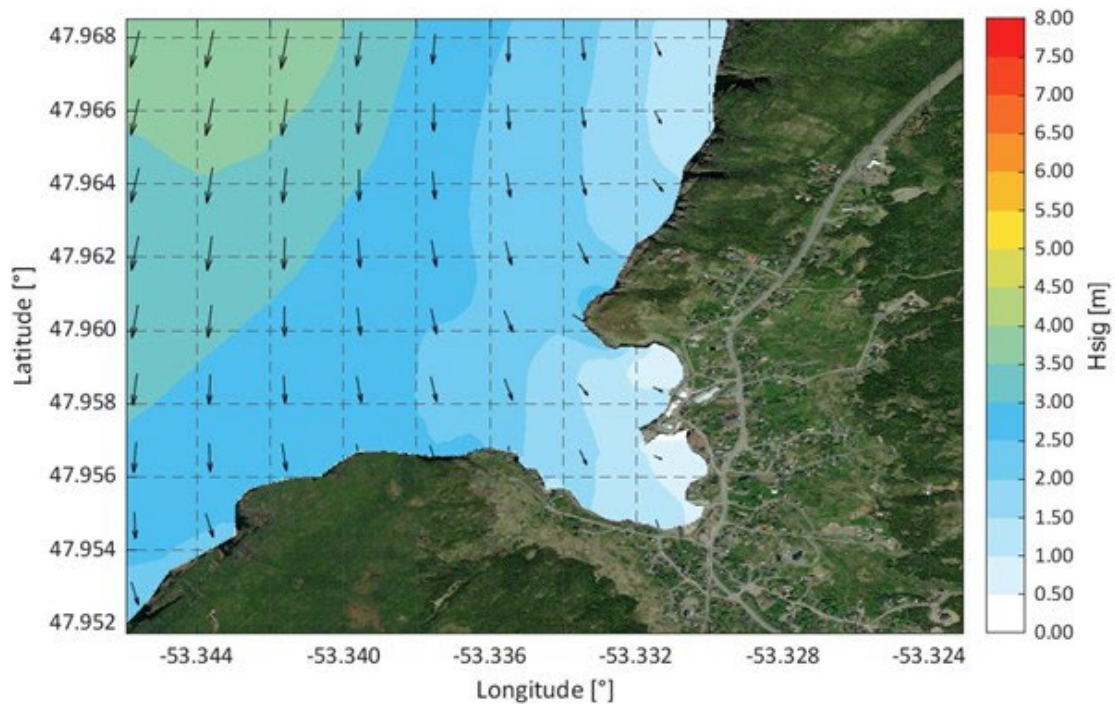
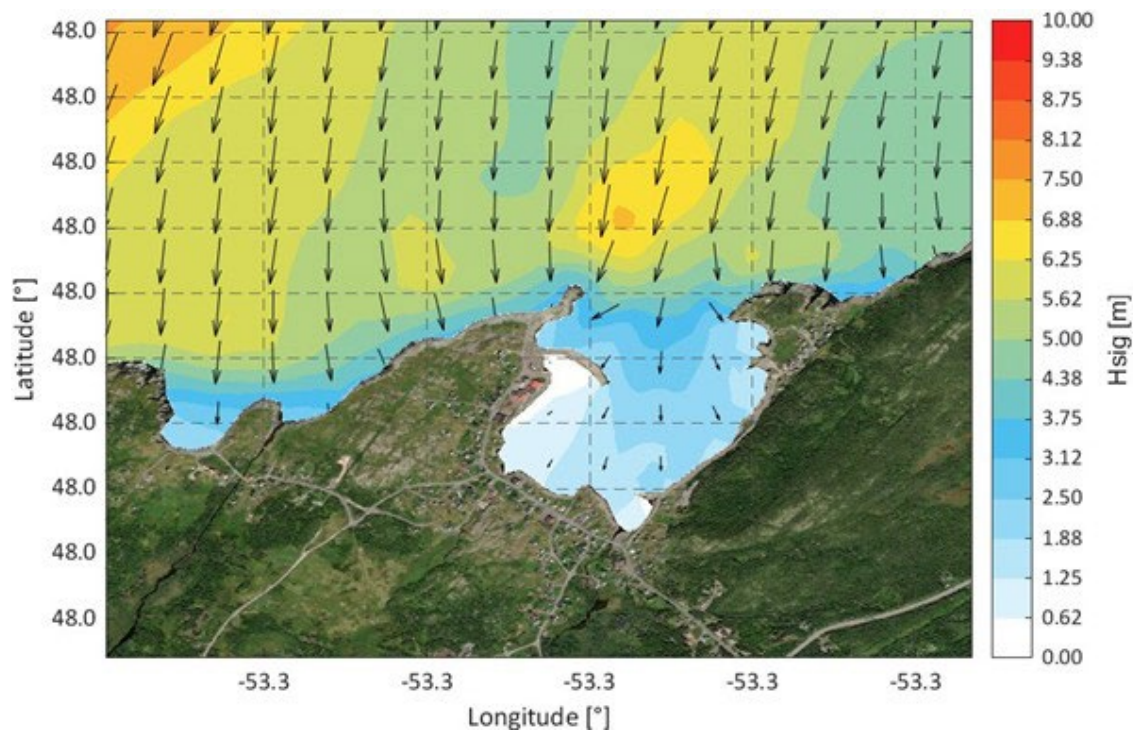


FIGURE 131: 100-YEAR 30° PREVAILING WINDS AND OFFSHORE WAVES SIGNIFICANT WAVE HEIGHT NEAR HANT'S HARBOUR



Conception Bay - Brigus

Model outputs showing discrete extreme wave conditions in Brigus are shown for an illustrative case (i.e. 100-year, 30° prevailing wind and offshore waves) in Figure 132 and Figure 133.

FIGURE 132: 100-YEAR, 30° PREVAILING WINDS AND OFFSHORE WAVES AEP SIGNIFICANT WAVE HEIGHT AT CONCEPTION BAY

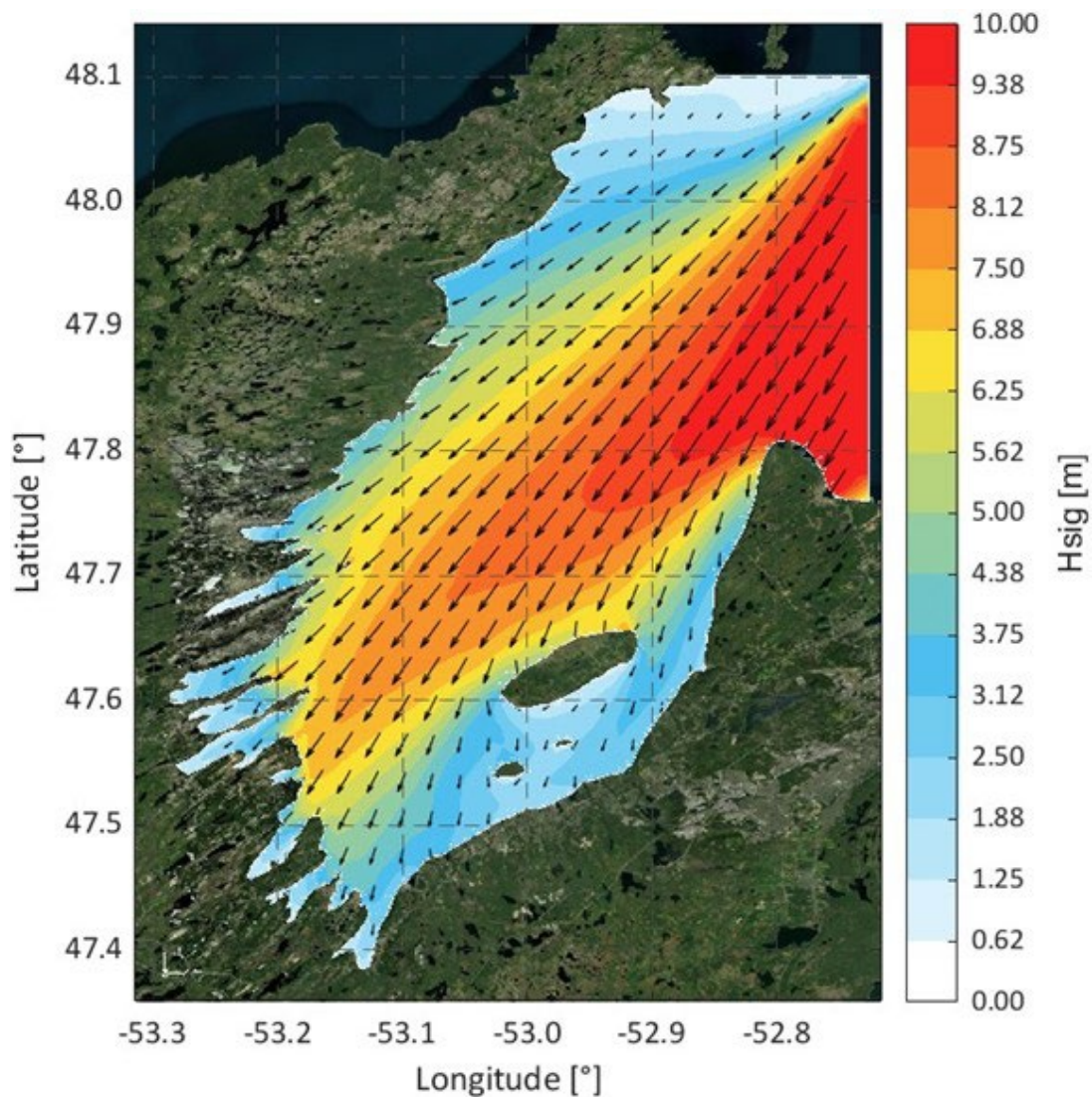
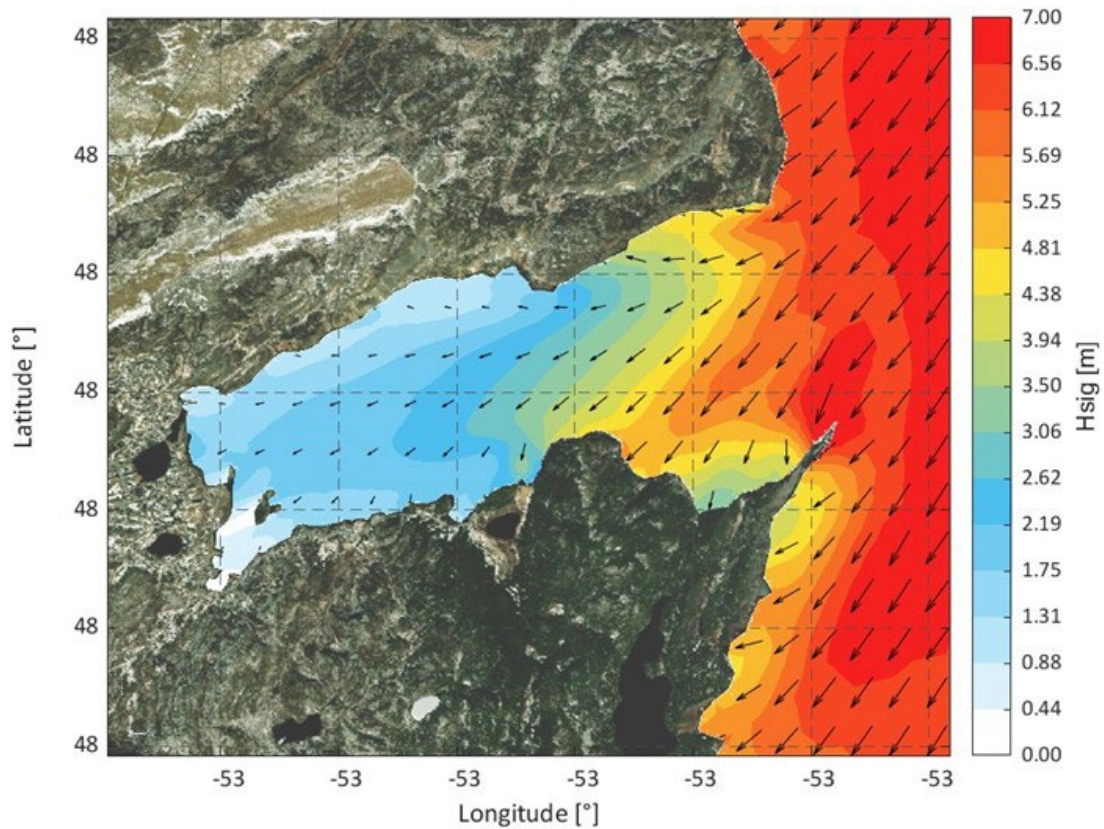


FIGURE 133: 100-YEAR, 30° PREVAILING WINDS AND OFFSHORE WAVES AEP SIGNIFICANT WAVE HEIGHT AT BRIGUS



Ferryland

Model outputs showing discrete extreme wave conditions in Ferryland are shown for an illustrative case (i.e. 100-year, 150° prevailing wind and offshore waves) in Figure 134 and Figure 135.

FIGURE 134: 100-YEAR, 150° PREVAILING WINDS AND OFFSHORE WAVES AEP SIGNIFICANT WAVE HEIGHT AT FERRYLAND

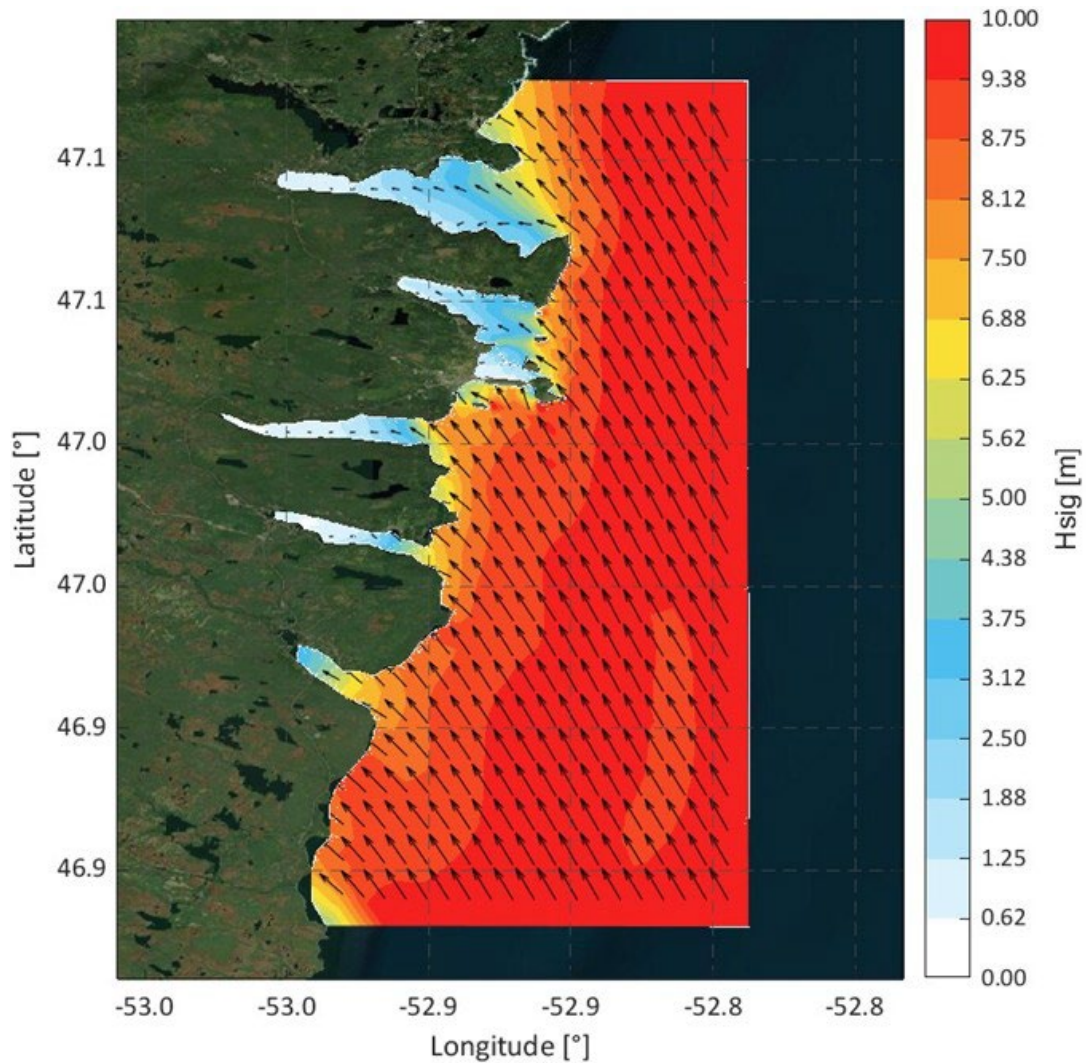
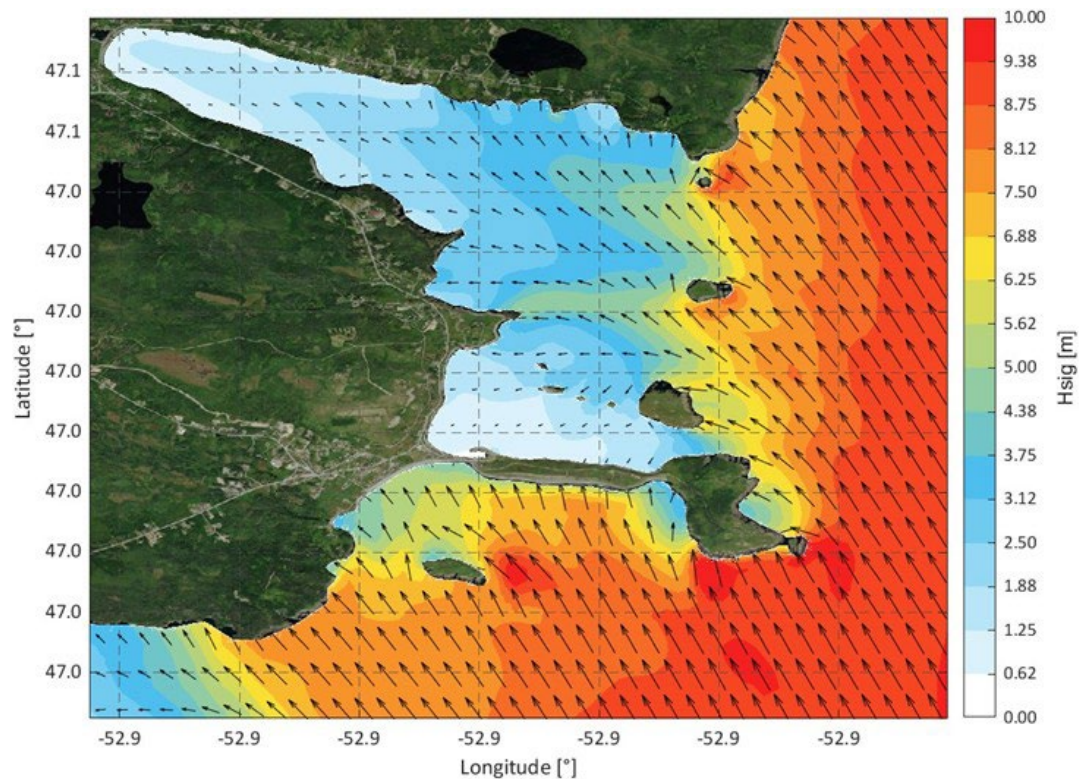


FIGURE 135: 100-YEAR, 150° PREVAILING WINDS AND OFFSHORE WAVES AEP SIGNIFICANT WAVE HEIGHT AT FERRYLAND



Wave model outputs for several additional directions and 20- and 100-year AEP events are included in Appendix J.

8.2.8 WAVE UPRUSH CALCULATION

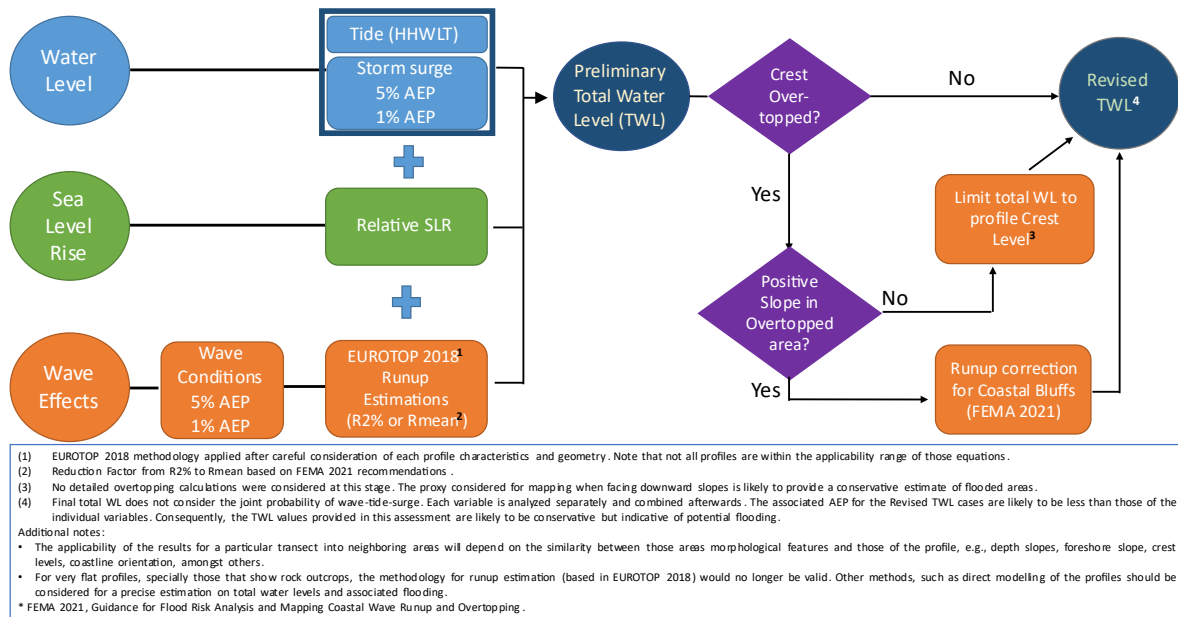
This assessment focused on the wave uprush calculation for specific profiles located along the shoreline of the five communities of interest. Wave uprush (i.e. wave runoff) is the maximum vertical extent that wave-driven water reaches as it moves up the shore above the static-water level. Note that the two terminologies (i.e. uprush or runoff) are used interchangeably in the report. The wave uprush was calculated considering the contributions of water levels from surge, tide and sea level rise, which are considered as part of the “static water level”, since their variation in time is in the scale of hours (i.e. surge and tide) to years.

The wave uprush calculation involved using results from the hydrodynamic and spectral wave models as well as sea level rise estimations at the different communities. The methodology applied here does not consider the probability of joint occurrence of the different phenomena contributing to the wave uprush total water level. The probability of occurrence of each parameter was considered independently, based on either projected future values, in the case of sea level rise, or individual return periods of each process. Once these contributions are combined, their joint probability of occurrence is lower than that the probability of each occurring individually.

Wave uprush was calculated at individual profiles which were selected to represent different areas of each community. Results from the spectral wave model were used as an input for empirical formulations to

compute wave uprush. Once a preliminary estimate for the wave uprush total water level at a profile was obtained, its value was compared with the main features of the profile and, if needed, corrections were applied to it. This revised wave uprush total water level (TWL) can be used as a proxy for flooding estimation in the communities. An overview of the applied methodology is provided in Figure 136.

FIGURE 136: FLOWCHART OF THE METHODOLOGY APPLIED FOR ESTIMATION OF WAVE UPRUSH



Cross-shore profiles were defined at locations of interest using a selection criterion which considered local topographic and bathymetric features as well as flood risk exposure and vulnerability of infrastructure assets. The profiles represent distinct regions within each community, where up to six profiles were initially assessed per community. In communities characterized by more complex geometries, additional profiles were introduced as necessary. The placement of each profile was determined by considering local attributes such as slope, coastline orientation, the nature of coastal features (e.g., beaches, man-made structures, cliffs), the number of affected houses, and other relevant factors.

Wave uprush levels at each of the profiles were calculated using empirical formulas, based on the EUROTOP 2018 methodology. These empirical formulas are mostly based on measurements conducted in wave flumes, where beaches and man-made structures are idealized and modelled at scale, and a range of wave conditions is simulated. The application of these empirical formulations requires extensive analysis and schematization of site-specific profiles in addition to careful consideration of the wave conditions, to keep calculations within the range of conditions for which the empirical formulas were derived.

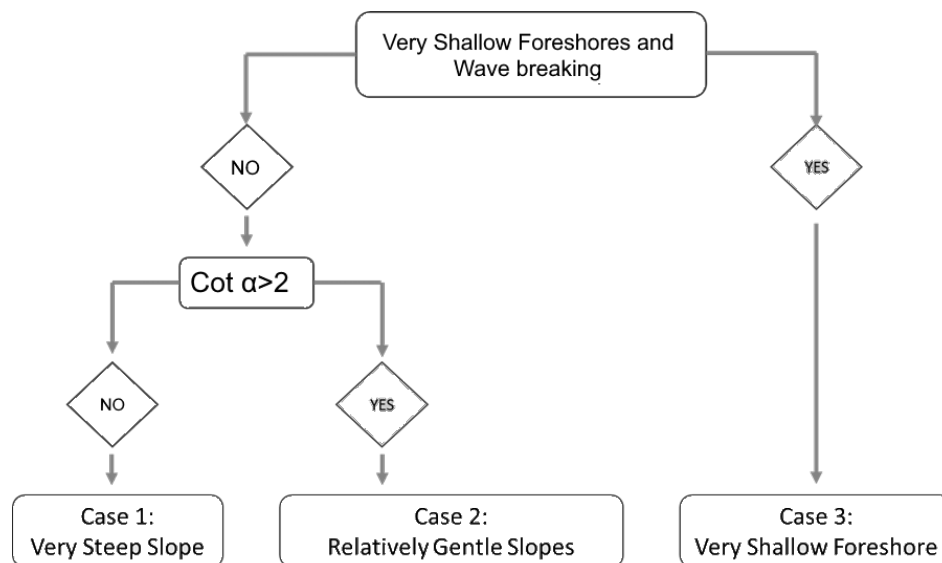
The coastline conditions found around Newfoundland consist mostly of bluffs, cliffs, steep rocky slopes, and artificial structures. While EUROTOP was originally developed to estimate wave run-up and overtopping on coastal defenses, it can also be applied to rocky formations by treating them as analogous to coastal

defenses. This approach is widely accepted as standard practice for run-up estimation (e.g. Murphy, et al. (2019)).

EUROTOP 2018 focuses on the calculation of the 2% wave run-up (R2%), which is the run-up value exceeded by 2% of the waves. This parameter was originally selected based on experiments in physical models in the Netherlands, with the idea that if only 2% of the wave runup reached the crest of a coastal defense, such as a dike or an embankment, this defense would need minimal protection measures. The value of R2% was then widely adopted as the wave runup estimation to be used for flood hazard studies, two examples being: (1) the Federal Hydrologic and Hydraulic Procedures for Flood Hazard Delineation (NRCAN, 2023) and (2) the Guidance for Flood Risk Analysis and Mapping (FEMA, 2021)

A key concept used in the EUROTOP 2018 methodology is the “toe of the structure” which corresponds to the location of the separation between the gently sloping sea bottom and the coastal structure or feature. EUROTOP 2018 requires wave conditions to be determined at the toe of the structure, prior to their use of the formulas for run-up. Other relevant concepts include the crest level, when present, which could be represented by the actual crest of the coastal structure or the location of the local road in the back of the beach or coastal area.

EUROTOP 2018 acknowledges the stochastic nature of the run-up measurements used to derive the empirical formulas by multiplying the different equations by coefficients “C”, which are assumed to be random variables with a mean equal to $\bar{X}$ and a standard deviation σ . Expressions where the coefficient corresponds to $C = \bar{X}$ are named “mean value approach” while those where the coefficient corresponds to $C = \bar{X} + \sigma$ are defined as “design and assessment approach”. In this study the second category has been considered. It should be noted that in both cases the formulations provide the R2%, the only difference being the degree of conservatism applied to the “mean” and the “design and assessment” approaches. The diagram shown in Figure 137 shows the decision process to be followed to decide which of the empirical formulas presented above should be used to determine Runup 2%.

FIGURE 137: DECISION DIAGRAM FOR WAVE RUNUP – MODIFIED FROM EUROTOP 2018

In the present study $R_{2\%}$ values are recommended for flood mapping, however, R_{mean} values were also derived and are provided in this document. To calculate R_{mean} , an equation provided in FEMA (2021) was used relating $R_{2\%}$ and R_{mean} , which assumes that wave runup elevations follow a Rayleigh distribution

The methodology described above apply to cases where the final wave uprush level remains below the crest of the structure. Special considerations arise when run-up extends beyond the crest of the primary line of defense and reaches a topographic plateau—defined as areas inland of the crest with a flat or gently rising slope—or when wave run-up exceeds the crest elevation of coastal barriers (such as seawalls) and the landward slope is negative, leading to ponding behind the structure. For each scenario, the main considerations for determining the final wave uprush total water level are outlined below:

- Scenario A: Run-up on a slope without overtopping.** For this scenario the obtained total water level does not require a correction as there is no overtopping. The obtained wave uprush level can be directly mapped for flooding finding the incursion of water as the point in the profile where this level would be reached.
- Scenario B: Run-up and overtopping on a slope followed by a plateau with a positive slope.** Because of overtopping, the final wave uprush total water level will be smaller than that obtained from the calculations of static plus runup water level contributions. For the present assessment, an approach outlined in FEMA 2021 based on French (1982), was applied. This approach considers that due to the positive slope of the plateau, it is possible to calculate the inland reach of water. To perform this calculation, a variable called “fictitious run-up” which is the difference between the wave uprush total water level, and the crest of the profile is used, in combination with the value of the plateau’s slope. The corrected wave uprush total water level can then be used for flood mapping purposes.

- Scenario C: Run-up and overtopping on a slope followed by a plateau with a negative slope.** As in Scenario 2, overtopping implies that the initially calculated wave uprush total water level will not be reached as water will start flowing to the back of the profile's crest. In this case, local 2D effects (e.g., lateral flows) in combination with the rate of overtopping become crucial to determine the potentially flooded areas. For these cases, the wave uprush level will be correlated to the crest level of the profile. This simplified approach is generally conservative and can be easily implemented to obtain wave uprush levels for mapping.

The selected representative transects for the five communities are shown on Figure 138 to Figure 142, while wave uprush heights for two annual AEPs are summarized in Table 55 to Table 59. For each community, cross-section and wave uprush calculation case (i.e. Rmean and R2% for current climate and climate change), the wave uprush scenario is shown in brackets to help the reader's interpretation. For example, for Ferryland XS-2, the wave uprush level exceeds the profile crest for all studied cases (i.e. overtopping occurs) and the plateau that follows the crest presents a negative slope (i.e. Scenario C), thus the wave uprush level is capped to the crest level of the profile.

FIGURE 138: WAVE UPRUSH CALCULATION LOCATIONS IN FERRYLAND

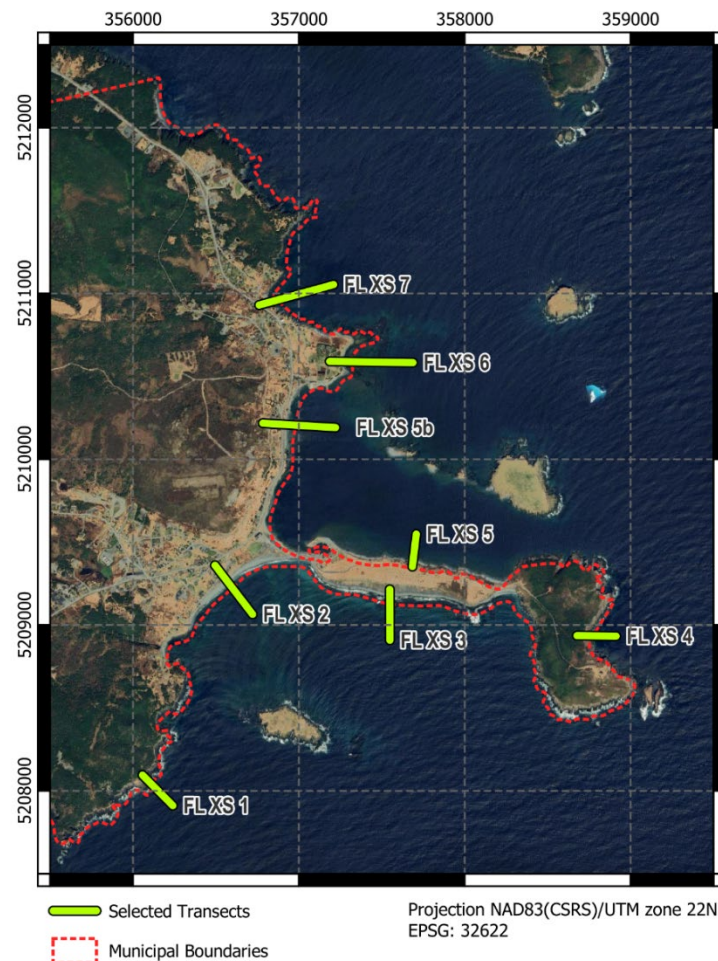


TABLE 55: AEP WAVE UPRUSH IN FERRYLAND

Profile	Current Climate				Climate Change			
	Rmean		R2%		Rmean		R2%	
	5% AEP Runup Level (m)	1% AEP Runup Level (m)	5% AEP Runup Level (m)	1% AEP Runup Level (m)	5% AEP Runup Level (m)	1% AEP Runup Level (m)	5% AEP Runup Level (m)	1% AEP Runup Level (m)
FL XS 1	4.6 [A]	5.3 [A]	5.4 [C]	5.4 [C]	5.4 [C]	5.4 [C]	5.4 [C]	5.4 [C]
FL XS 2	4.0 [C]	4.0 [C]	4.0 [C]	4.0 [C]	4.0 [C]	4.0 [C]	4.0 [C]	4.0 [C]
FL XS 3	4.4 [A]	5.0 [A]	7.6 [A]	8.7 [A]	5.8 [A]	6.5 [A]	10.0 [A]	11.0 [A]
FL XS 4	4.3 [A]	5.0 [A]	7.5 [A]	8.6 [A]	5.8 [A]	6.4 [A]	9.9 [A]	11.0 [A]
FL XS 5	4.4 [A]	5.1 [A]	7.6 [A]	8.7 [A]	5.8 [A]	6.5 [A]	10.0 [A]	11.1 [A]
FL XS 5b	3.0 [A]	3.7 [A]	4.7 [A]	5.8 [A]	4.6 [A]	5.3 [A]	7.2 [A]	8.4 [A]
FL XS 6	3.9 [A]	4.3 [C]	4.3 [C]	4.3 [C]	4.3 [C]	4.3 [C]	4.3 [C]	4.3 [C]
FL XS 7	4.5 [A]	5.2 [A]	7.7 [B]	8.5 [B]	6.0 [A]	6.7 [A]	9.6 [B]	10.5 [B]

FIGURE 139: WAVE UPRUSH CALCULATION LOCATIONS IN BRIGUS

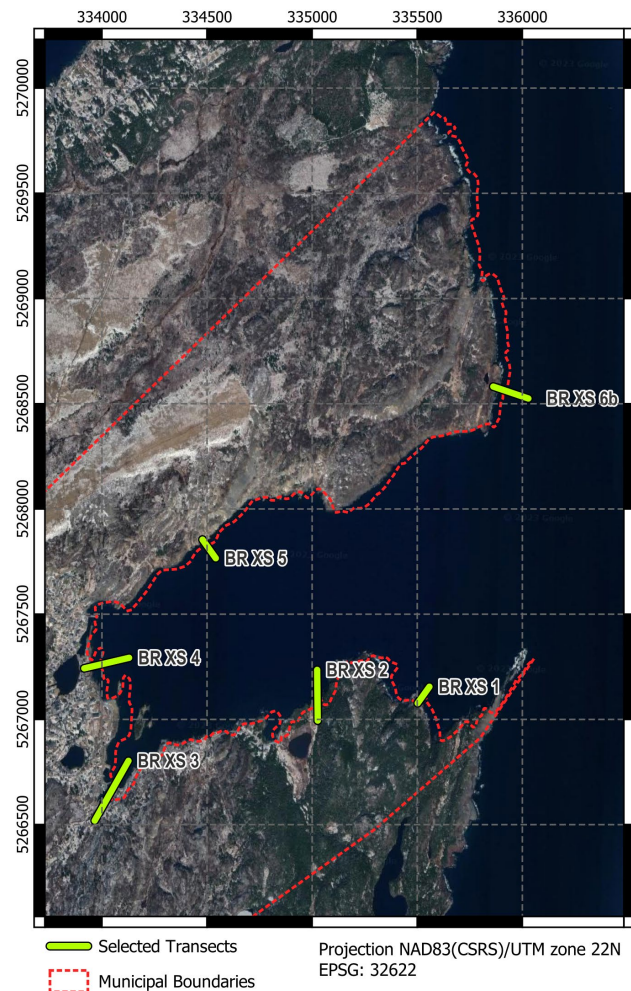


TABLE 56: AEP WAVE UPRUSH IN BRIGUS

Profile	Current Climate				Climate Change			
	Rmean		R2%		Rmean		R2%	
	5% AEP Runup Level (m)	1% AEP Runup Level (m)	5% AEP Runup Level (m)	1% AEP Runup Level (m)	5% AEP Runup Level (m)	1% AEP Runup Level (m)	5% AEP Runup Level (m)	1% AEP Runup Level (m)
BR XS 1	3.5 [A]	4.0 [A]	5.9 [A]	6.6 [A]	4.8 [A]	5.3 [A]	8.0 [A]	8.7 [A]
BR XS 2	4.2 [A]	4.6 [C]	4.6 [C]	4.6 [C]	4.6 [C]	4.6 [C]	4.6 [C]	4.6 [A]
BR XS 3	2.5 [A]	2.9 [A]	3.6 [A]	4.2 [A]	3.2 [A]	3.6 [A]	4.3 [A]	4.9 [A]
BR XS 4	3.5 [A]	3.8 [C]	3.8 [C]	3.8 [C]	3.8 [C]	3.8 [C]	3.8 [C]	3.8 [C]
BR XS 5	3.3 [A]	3.7 [A]	5.4 [A]	6.0 [A]	4.2 [A]	4.8 [A]	6.6 [A]	7.6 [A]
BR XS 6b	4.5 [A]	4.9 [A]	8.0 [A]	8.7 [A]	5.8 [A]	6.3 [A]	10.2 [A]	11.0 [A]

FIGURE 140: WAVE UPRUSH CALCULATION LOCATIONS IN HEART'S DELIGHT - ISLINGTON

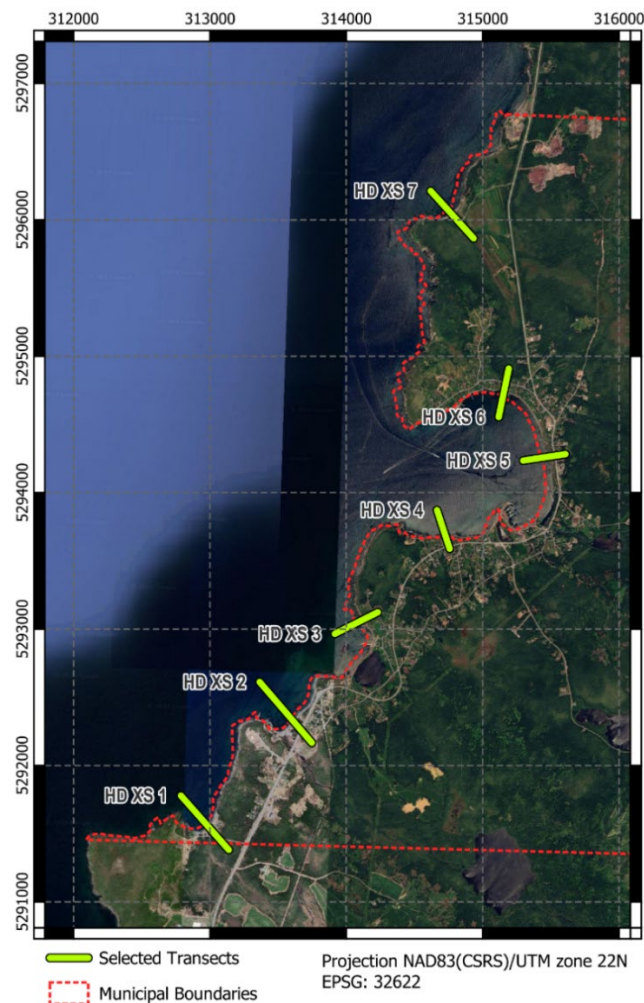


TABLE 57: AEP WAVE UPRUSH IN HEART'S DELIGHT – ISLINGTON

Profile	Current Climate				Climate Change			
	Rmean		R2%		Rmean		R2%	
	5% AEP Runup Level (m)	1% AEP Runup Level (m)	5% AEP Runup Level (m)	1% AEP Runup Level (m)	5% AEP Runup Level (m)	1% AEP Runup Level (m)	5% AEP Runup Level (m)	1% AEP Runup Level (m)
HD XS 1	2.7 [A]	3.3 [A]	4.2 [B]	5.0 [B]	3.9 [B]	4.3 [B]	5.8 [B]	6.6 [B]
HD XS 2	3.0 [A]	3.2 [B]	3.5 [B]	3.8 [B]	3.3 [B]	3.5 [B]	4.1 [B]	4.4 [B]
HD XS 3	2.9 [A]	3.5 [A]	4.8 [B]	5.1 [B]	4.1 [A]	4.6 [A]	5.4 [B]	5.7 [B]
HD XS 4	2.9 [A]	3.5 [A]	4.9 [A]	5.8 [A]	4.2 [A]	4.7 [A]	6.9 [A]	7.8 [A]
HD XS 5	2.8 [A]	3.3 [A]	4.5 [A]	5.3 [A]	4.0 [A]	4.5 [A]	6.4 [A]	6.5 [C]
HD XS 6	1.7 [C]	1.7 [C]	1.7 [C]	1.7 [C]	1.7 [C]	1.7 [C]	1.7 [C]	1.7 [C]
HD XS 7	3.1 [A]	3.7 [A]	4.6 [C]	4.6 [C]	4.5 [A]	4.6 [C]	4.6 [C]	4.6 [C]

FIGURE 141: WAVE UPRUSH CALCULATION LOCATIONS IN HANT'S HARBOUR

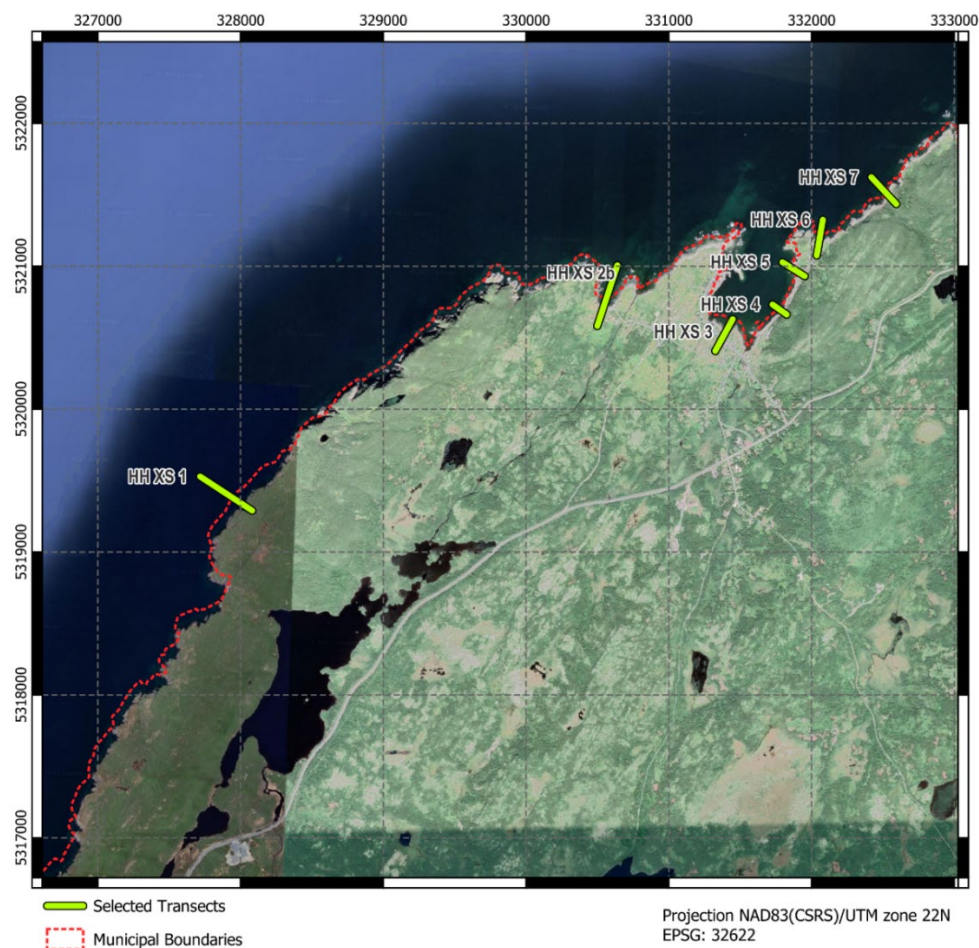


TABLE 58: AEP WAVE UPRUSH IN HANT'S HARBOUR

Profile	Current Climate				Climate Change			
	Rmean		R2%		Rmean		R2%	
	5% AEP Runup Level (m)	1% AEP Runup Level (m)	5% AEP Runup Level (m)	1% AEP Runup Level (m)	5% AEP Runup Level (m)	1% AEP Runup Level (m)	5% AEP Runup Level (m)	1% AEP Runup Level (m)
HH XS 1	3.3 [A]	3.9 [A]	5.7 [A]	6.7 [A]	4.7 [A]	5.3 [A]	7.9 [A]	9.0 [A]
HH XS 2b	3.2 [A]	3.8 [A]	4.4 [C]	4.4 [C]	4.4 [C]	4.4 [C]	4.4 [C]	4.4 [C]
HH XS 3	2.1 [A]	2.5 [A]	3.0 [A]	3.5 [A]	2.8 [A]	3.2 [A]	3.9 [A]	4.4 [A]
HH XS 4	3.9 [A]	4.8 [A]	6.6 [B]	7.8 [B]	4.5 [A]	5.3 [A]	7.0 [B]	8.2 [B]
HH XS 5	1.7 [A]	2.1 [A]	2.3 [A]	2.7 [A]	2.4 [A]	2.8 [A]	3.0 [A]	3.2 [C]
HH XS 6	3.2 [A]	3.3 [C]	3.3 [C]	3.3 [C]	3.3 [C]	3.3 [C]	3.3 [C]	3.3 [C]
HH XS 7	3.2 [A]	3.8 [A]	5.5 [A]	6.5 [A]	4.6 [A]	5.2 [A]	7.8 [A]	8.8 [A]

FIGURE 142: WAVE UPRUSH CALCULATION LOCATIONS IN WINTERTON

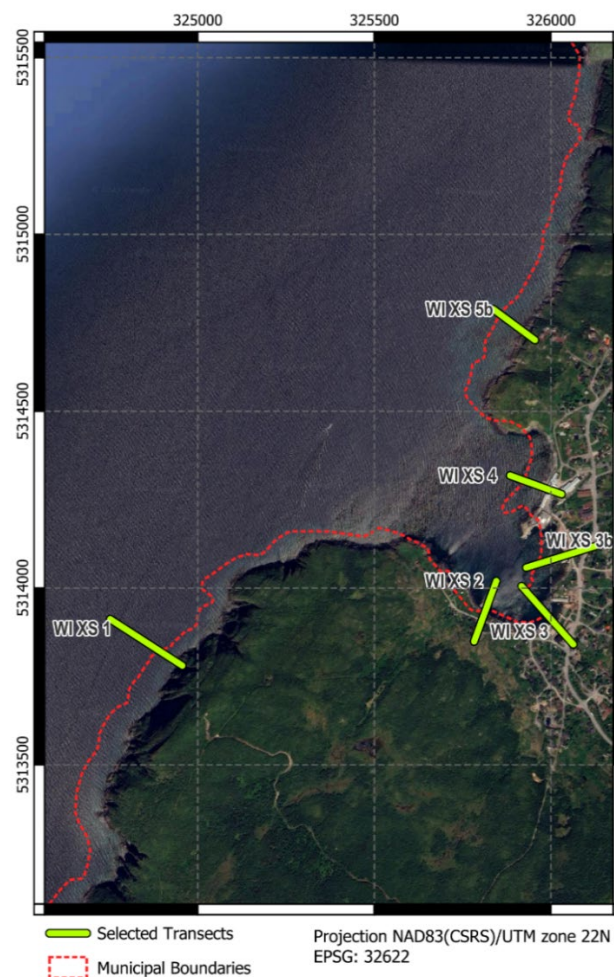


TABLE 59: AEP WAVE UPRUSH IN WINTERTON

Profile	Current Climate				Climate Change			
	Rmean		R2%		Rmean		R2%	
	5% AEP Runup Level (m)	1% AEP Runup Level (m)	5% AEP Runup Level (m)	1% AEP Runup Level (m)	5% AEP Runup Level (m)	1% AEP Runup Level (m)	5% AEP Runup Level (m)	1% AEP Runup Level (m)
WI XS 1	2.4 [A]	2.9 [A]	3.7 [A]	4.6 [A]	3.7 [A]	4.2 [A]	5.8 [A]	6.6 [A]
WI XS 2	2.7 [A]	3.3 [A]	4.5 [A]	5.3 [A]	4.0 [A]	4.5 [A]	6.4 [A]	7.3 [A]
WI XS 3	2.1 [A]	2.7 [A]	3.1 [A]	4.1 [A]	3.4 [A]	3.9 [A]	5.1 [A]	5.6 [B]
WI XS 3b	1.8 [C]	1.8 [C]	1.8 [C]	1.8 [C]	2.1 [A]	2.6 [A]	2.3 [A]	3.0 [A]
WI XS 4	2.8 [A]	3.2 [C]	2.8 [C]	2.8 [C]	3.2 [C]	3.2 [C]	2.8 [C]	2.8 [C]
WI XS 5b	3.1 [A]	3.7 [A]	5.2 [A]	6.2 [A]	4.5 [A]	5.1 [A]	7.5 [A]	8.6 [A]

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 6.3.

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 hazard mapping studies.

The models developed throughout Ferryland, Brigus, Heart's Delight – Islington, Winterton and Hant's Harbour were developed as 2D models to ensure the accurate representation of both channel and floodplain flows, as well as to accurately represent any potential for breakout flows. 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. Lakes within the model domains were represented in the models via the model mesh and flood plain DEMs, with outflow from the lakes controlled by the lake outlet geometry, such that any attenuation could be represented in the model calibration. However, attenuation was not considered in the AEP flood simulations, as those simulations were completed under steady state conditions, thus filling any potential lake storage, and ensuring that outflow from the lake matched the anticipated AEP flows for the given flood scenario.

The layouts of the hydraulic models for the various rivers and creeks considered in the study area are shown on Figure 143 to Figure 147.

FIGURE 143: FERRYLAND HEC-RAS MODEL DOMAIN

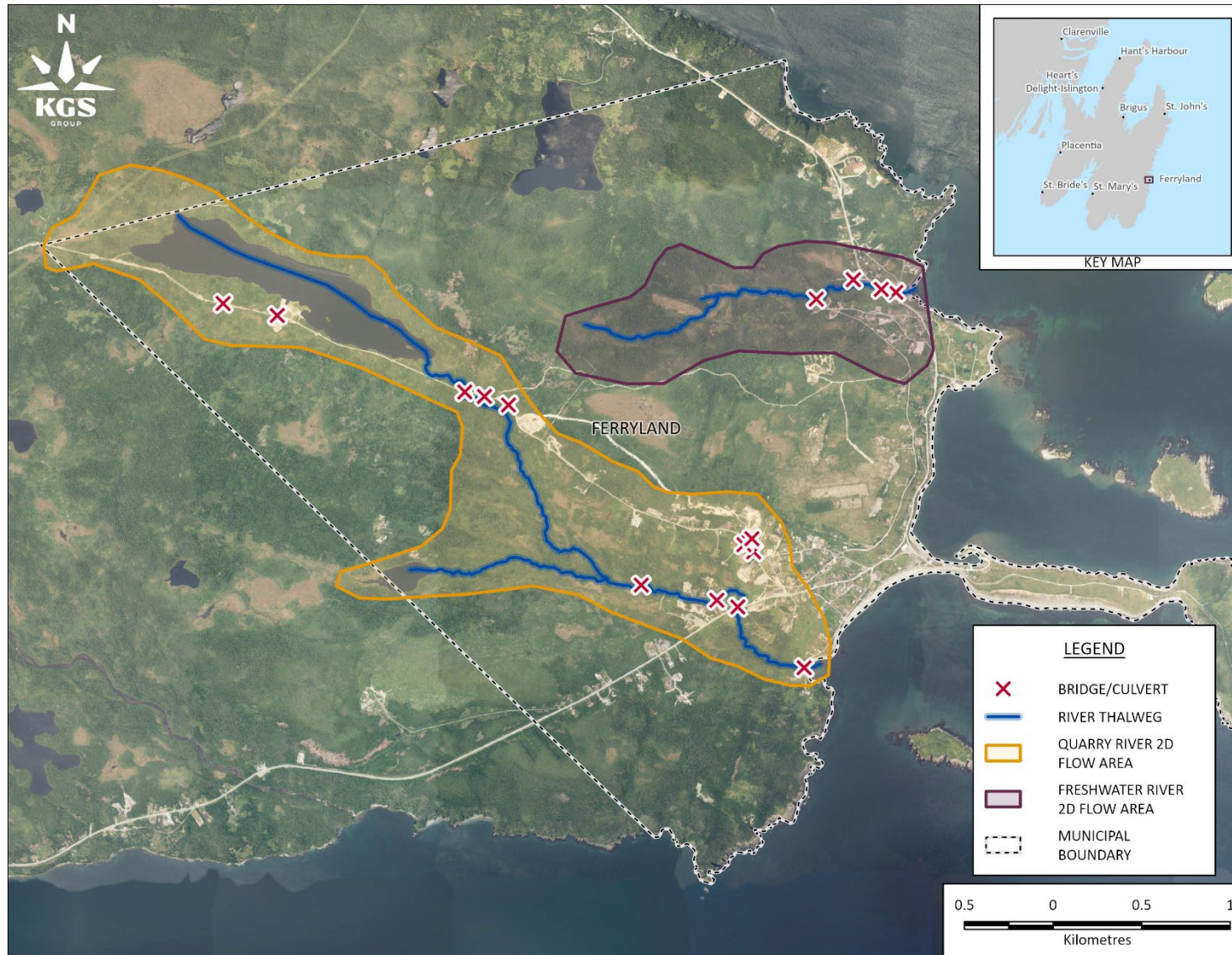


FIGURE 144: BRIGUS HEC-RAS MODEL DOMAIN

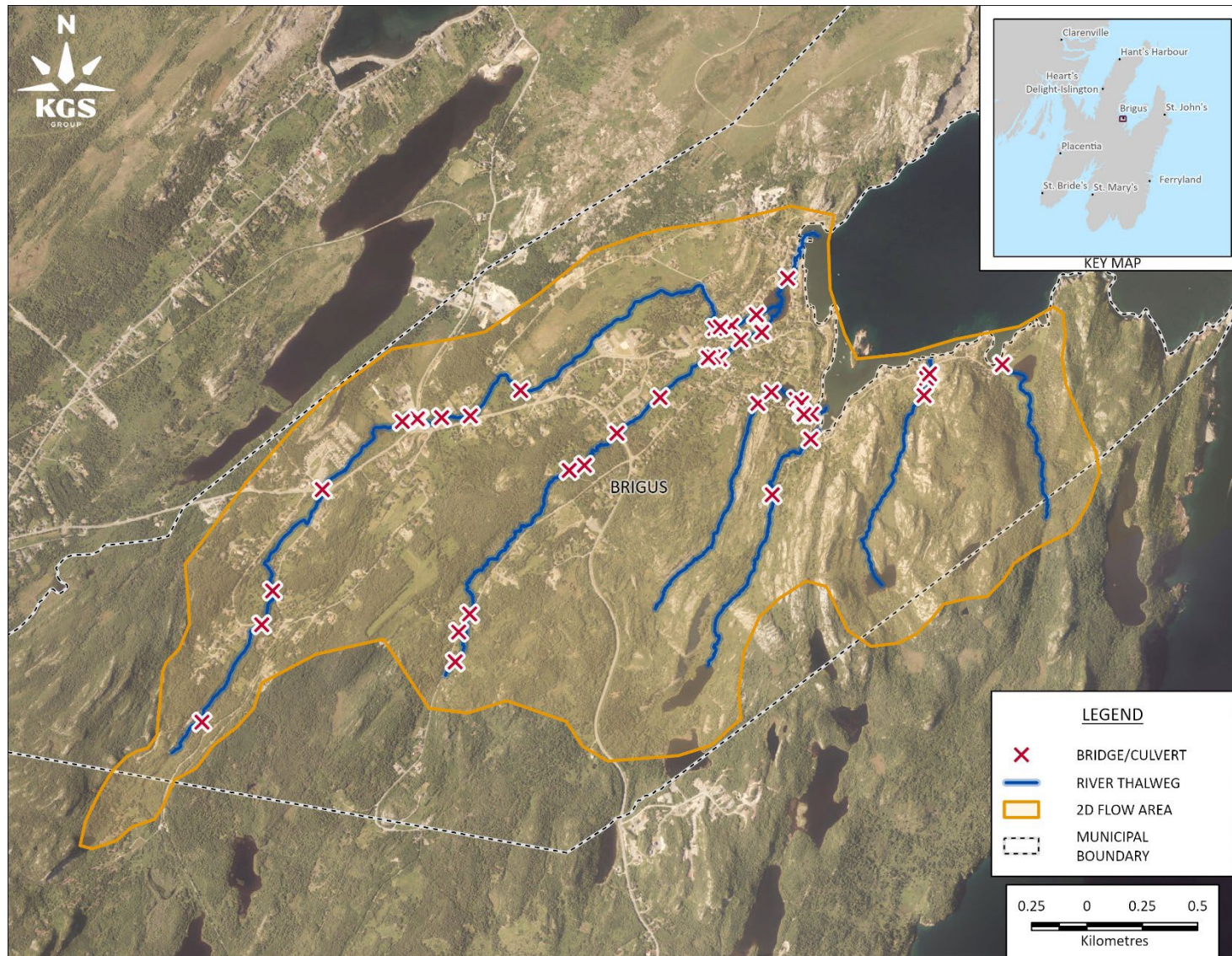


FIGURE 145: HEART'S DELIGHT - ISLINGTON HEC-RAS MODEL DOMAIN

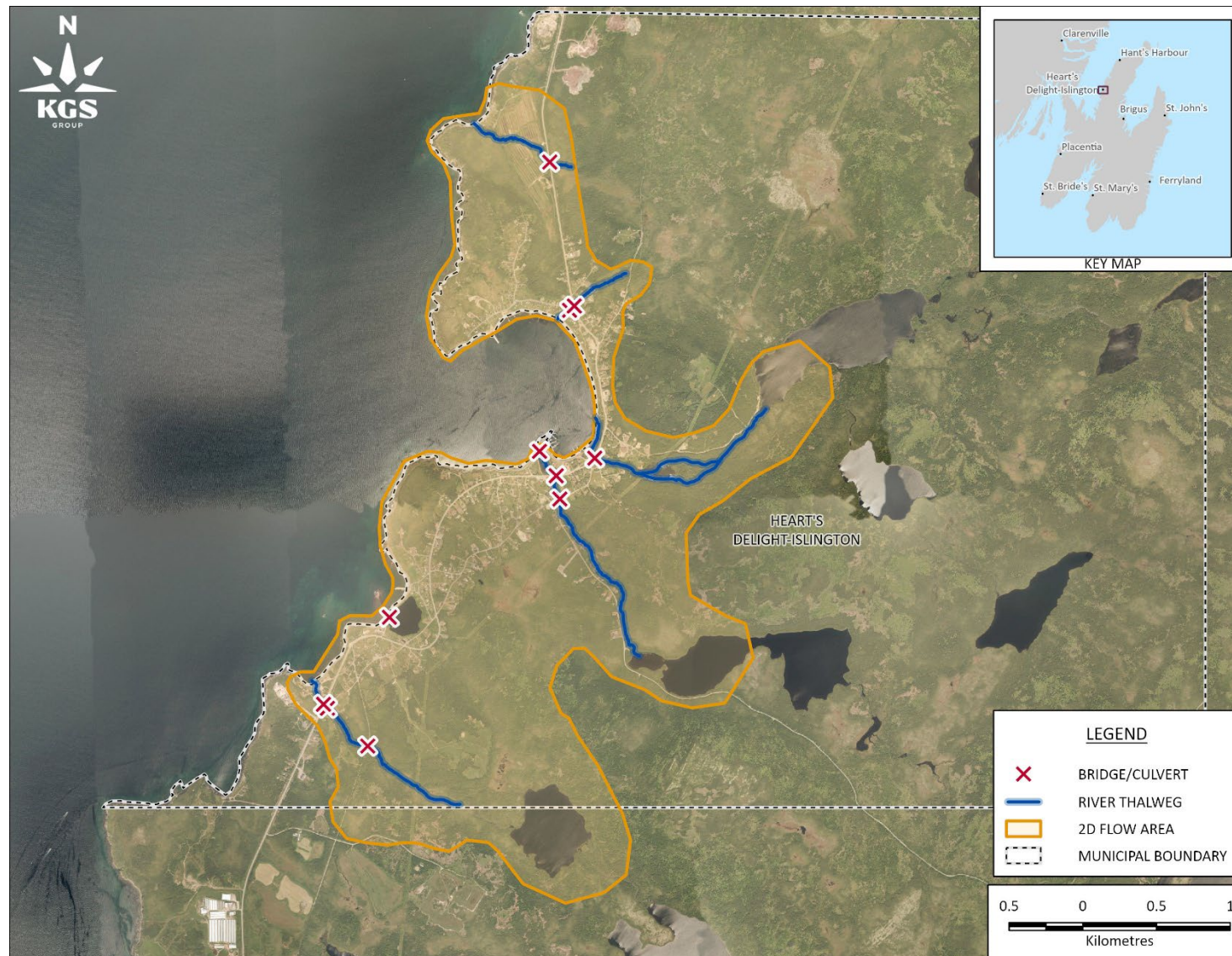


FIGURE 146: WINTERTON HEC-RAS MODEL DOMAIN

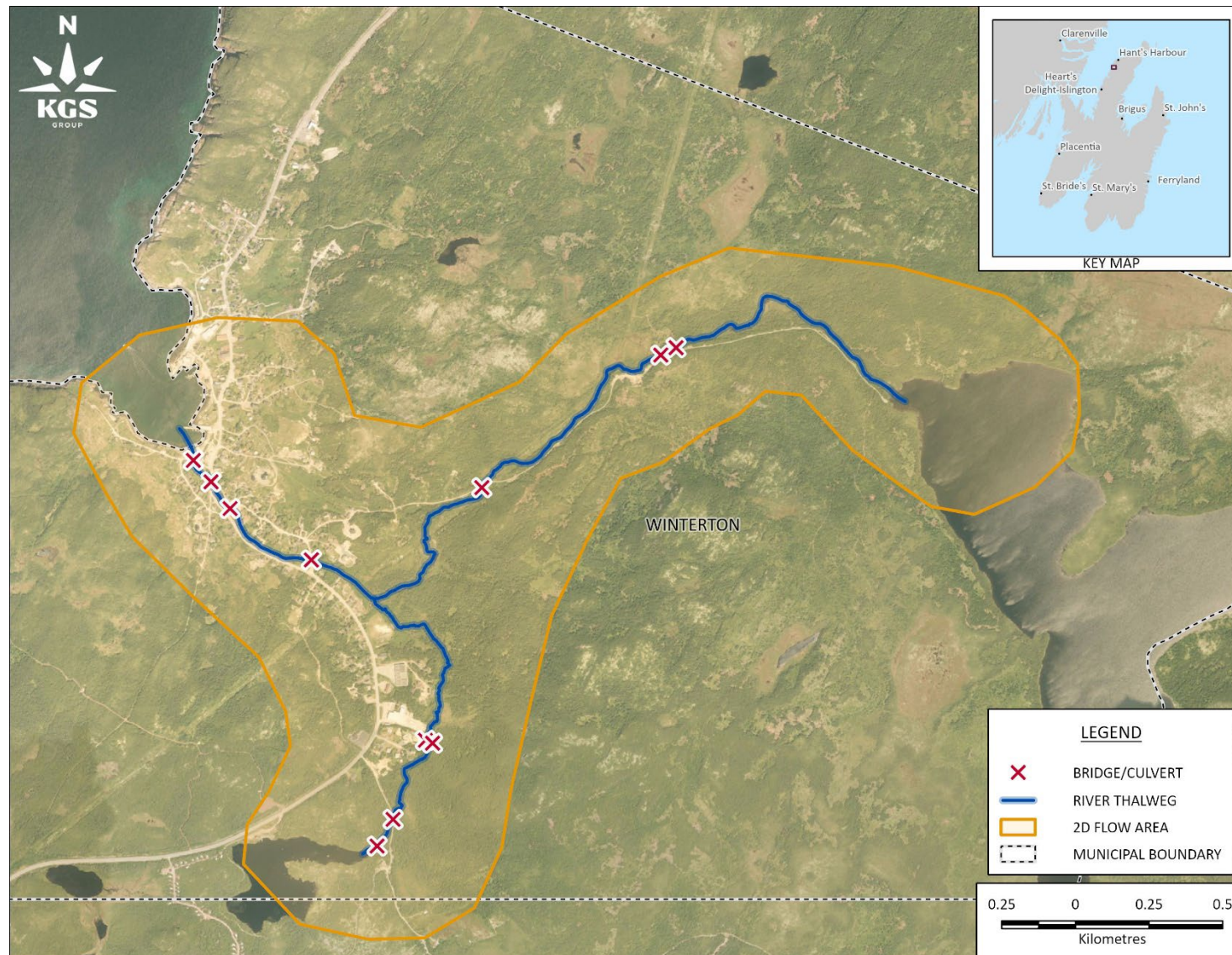
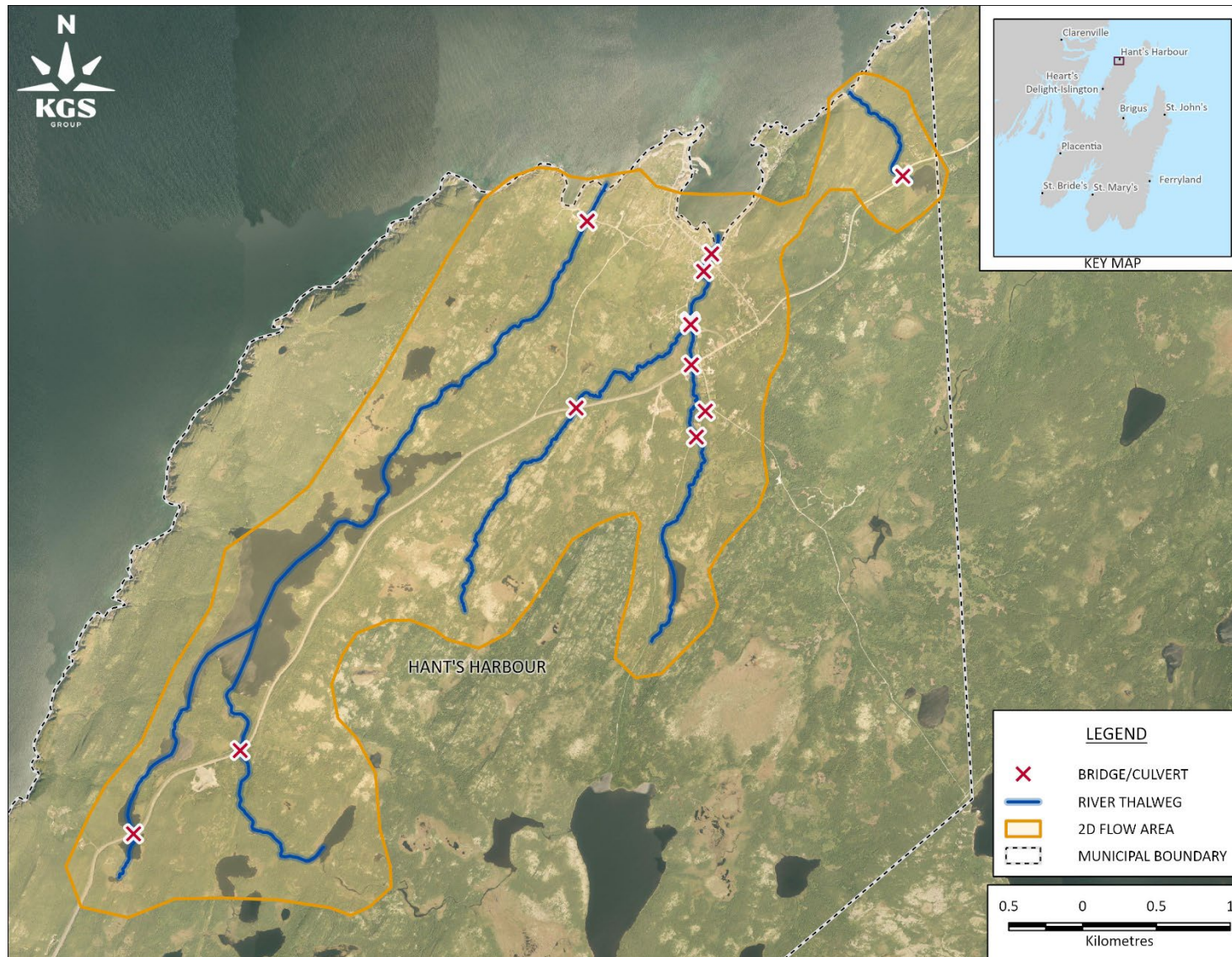


FIGURE 147: HANT'S HARBOUR HEC-RAS MODEL DOMAIN



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 4 m² along waterways, roadways, and in the immediate floodplain, to 100 m² in locations far away from the main flow areas that were not expected to be flooded.

Roughness coefficients were defined in the model based on the land use classification described in Section 5.3. 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 60.

TABLE 60: 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 models. The boundary conditions types included in the models are summarized in Table 61. Note that for flow boundary conditions that are not located at the upstream extent of a given waterway, the flow value for that boundary condition represents the local inflow at that location, rather than the total flow on the river at that location.

TABLE 61: HEC-RAS BOUNDARY CONDITIONS

Town	Localtion	Boundary Type
Ferryland	Freshwater River at U/S Model Boundary	Flow (m ³ /s)
	Freshwater River at D/S Model Boundary	Water Level (m)
	Quarry River North Branch U/S Model Boundary	Flow (m ³ /s)
	Quarry River South Branch U/S Model Boundary	Flow (m ³ /s)
	Quarry River Downstream of North and South Branch Confluence	Flow (m ³ /s)
	Quarry River at D/S Model Boundary	Water Level (m)
Brigus	Lambes Brook at U/S Model Boundary	Flow (m ³ /s)
	Brigus North Brook at U/S Model Boundary	Flow (m ³ /s)
	Lambes Brook at D/S Model Boundary	Water Level (m)
	Apses Brook at U/S Model Boundary	Flow (m ³ /s)
	Apses Brook at D/S Model Boundary	Water Level (m)
	Local Creek 1 at U/S Model Boundary	Flow (m ³ /s)
	Local Creek 1 at D/S Model Boundary	Water Level (m)
	Local Creek 2 at U/S Model Boundary	Flow (m ³ /s)
	Local Creek 2 at D/S Model Boundary	Water Level (m)
	Local Creek 3 at U/S Model Boundary	Flow (m ³ /s)
	Local Creek 3 at D/S Model Boundary	Water Level (m)
Heart's Delight - Islington	Heart's Delight Brook at U/S Model Boundary	Flow (m ³ /s)
	Heart's Delight Brook at D/S Model Boundary	Water Level (m)
	Local Creek 1 at U/S Model Boundary	Flow (m ³ /s)
	Local Creek 1 at D/S Model Boundary	Water Level (m)
	Local Creek 2 at U/S Model Boundary	Flow (m ³ /s)
	Local Creek 2 at D/S Model Boundary	Water Level (m)
	Local Creek 3 at U/S Model Boundary	Flow (m ³ /s)
	Local Creek 3 at D/S Model Boundary	Water Level (m)
	Local Creek 4 at U/S Model Boundary	Flow (m ³ /s)
	Local Creek 4 at D/S Model Boundary	Water Level (m)
Winterton	Western Pond Brook North Branch at U/S Model Boundary	Flow (m ³ /s)
	Western Pond Brook South Branch at U/S Model Boundary	Flow (m ³ /s)
	Western Pond Brook D/S of North and South Branch Confluence	Flow (m ³ /s)
	Western Pond Brook at D/S Model Boundary	Water Level (m)
Hant's Harbour	Halfway Brook West Branch at U/S Model Boundary	Flow (m ³ /s)
	Halfway Brook East Branch at U/S Model Boundary	Flow (m ³ /s)
	Halfway Brook D/S of East and West Branch Confluence	Flow (m ³ /s)
	Halfway Brook at D/S Model Boundary	Water Level (m)
	Short's Brook at U/S Model Boundary	Flow (m ³ /s)
	Southwest Brook at U/S Model Boundary	Flow (m ³ /s)
	Short's Brook D/S of Short's Brook at Southwest Brook Confluence	Flow (m ³ /s)
	Short's Brook at D/S Model Boundary	Water Level (m)
	Local Creek 1 at U/S Model Boundary	Flow (m ³ /s)
	Local Creek 1 at D/S Model Boundary	Water Level (m)

8.3.2 MODEL CALIBRATION

Hydraulic model calibration was completed on select rivers where water level loggers were deployed by KGS Group. Accordingly, the only rivers with data available for calibration were:

- Quarry River near Highway 10 (Ferryland),
- Lambes Brook near North St. (Brigus),
- Heart's Delight Brook near Highway 80 (Heart's Delight – Islington),
- Western Pond Brook near Highway 80 (Winterton), and
- Shorts Brook near Critch's Lane (Hant's Harbour).

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 Western Pond Brook and Shorts Brook, inflows were defined estimated by prorating recorded flows from WSC gauge 02ZL005 (i.e. Big Brook at Lead Cove) on the basis of drainage area. Similarly, flows on the Heart's Delight Brook and Lambes Brook were defined by prorating flows from WSC gauge 02ZL004 (i.e. Shearstown Brook at Shearstown) on the basis of drainage area, while flows on Quarry River were estimated by prorating flows from WSC gauge 02ZM009 (i.e. Seal Cove Brook near Cappahayden) on the basis of drainage area. Calibration events were selected in each hydraulic model to coincide with the highest water level conditions that were recorded by the water level loggers, which occurred on January 24, 2023 in Ferryland, Brigus, and Heart's Delight – Islington, and December 20, 2022 in Winterton and Hant's Harbour.

The final calibrated roughness coefficients for the waterways identified above are summarized in Table 62.

TABLE 62: CALIBRATED ROUGHNESS COEFFICIENTS

Community	Waterway	Initial Roughness Coefficient	Final Roughness Coefficient
Hant's Harbour	Shorts Brook	0.035	0.030
Winterton	Western Pond Brook	0.035	0.035
Heart's Delight - Islington	Heart's Delight Brook	0.035	0.050
Brigus	Lambes Brook	0.035	0.027
Ferryland	Quarry River	0.035	0.035

Based on the calibrated roughness coefficients, riverbed roughness values on ungauged waterways within the communities were set to be consistent with the calibrated waterway coefficients, with the exception of those in Heart's Delight – Islington. These values were reasonable estimates of the typical riverbed characteristics in those communities, and were consistent with industry standard values. In the community of Heart's Delight - Islington, the riverbed conditions on Heart's Delight Brook were characterised as a very rocky riverbed with several pools and riffles, which was inconsistent with other waterways in the community. Instead, a riverbed roughness coefficient of 0.04 was adopted for other waterways within Heart's Delight –

Islington, based on observations of riverbed conditions obtained during the field survey and flow monitoring programs.

The model representations of the recorded water levels are summarized on Figure 148 to Figure 152, although it should be noted that the timing of the simulated water levels in Ferryland were adjusted due to attenuation that occurs within the hydraulic model.

FIGURE 148: SHORT'S BROOK CALIBRATION NEAR CRITCH'S LANE (HANT'S HARBOUR)

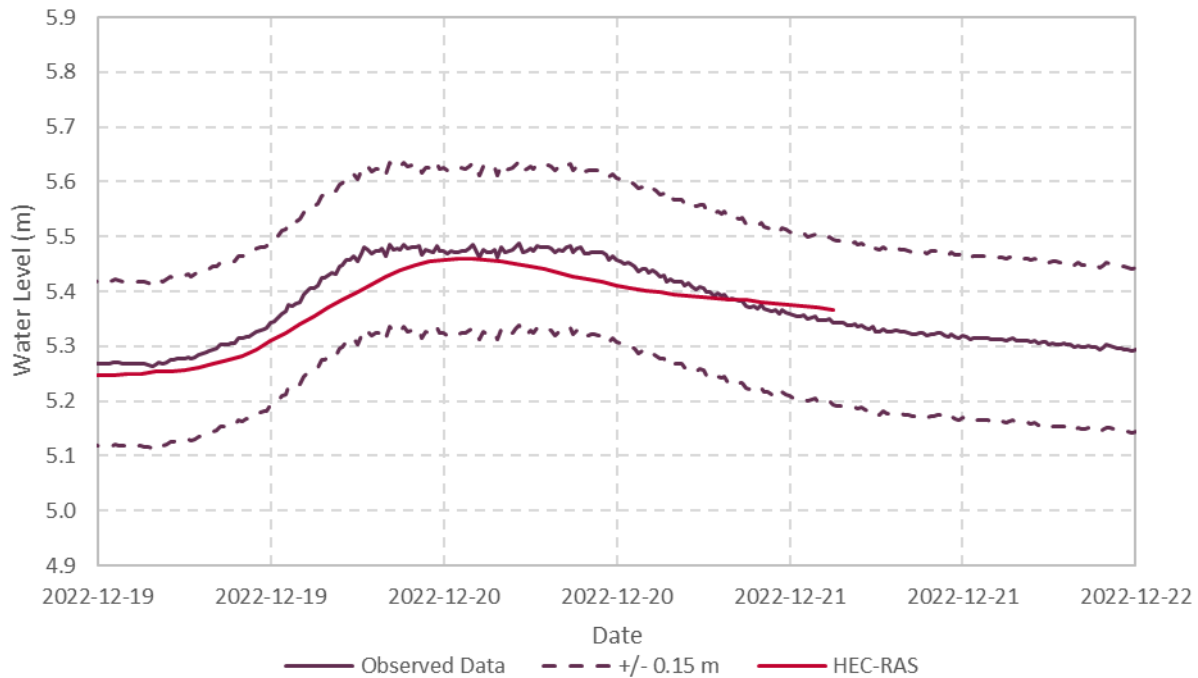
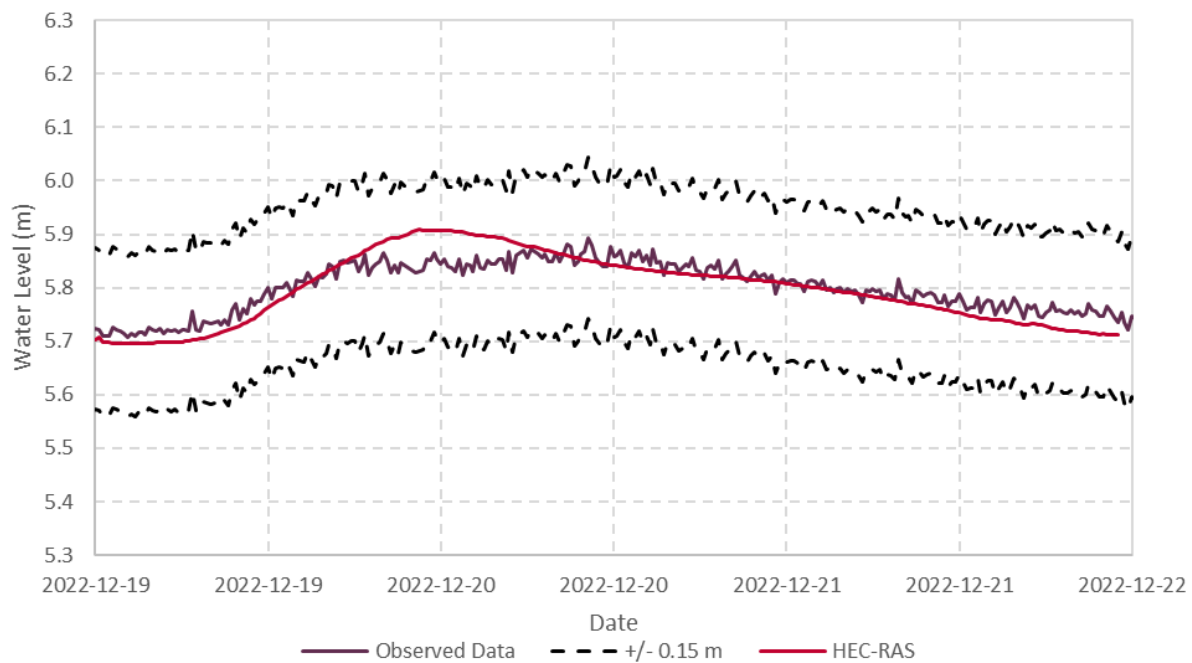
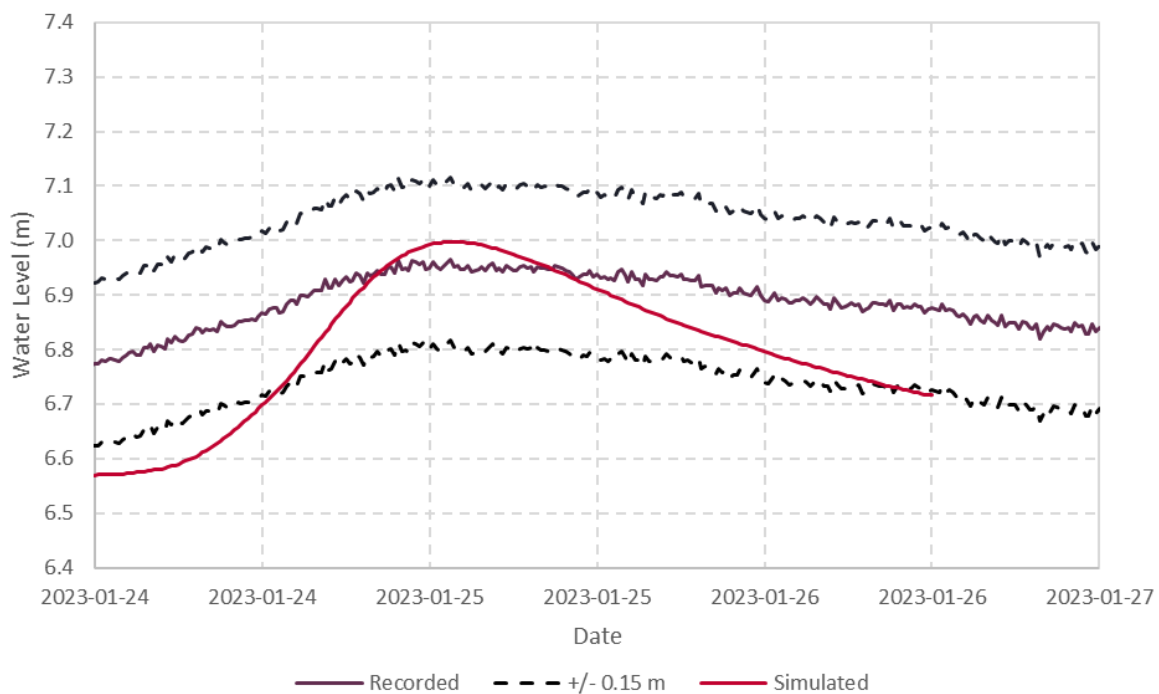
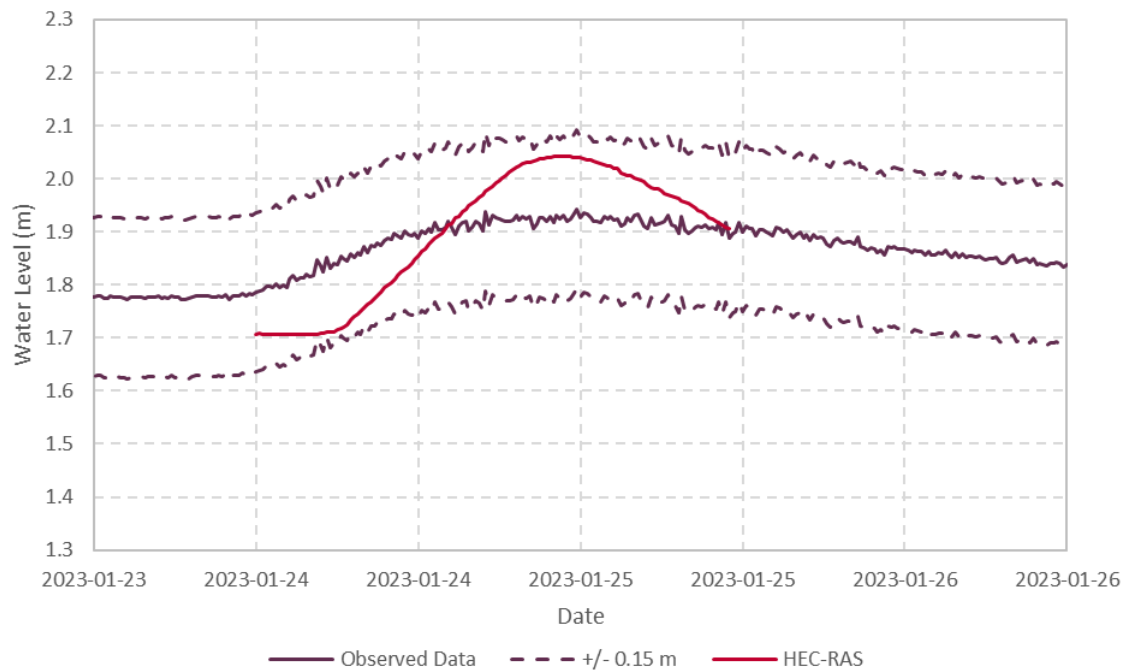
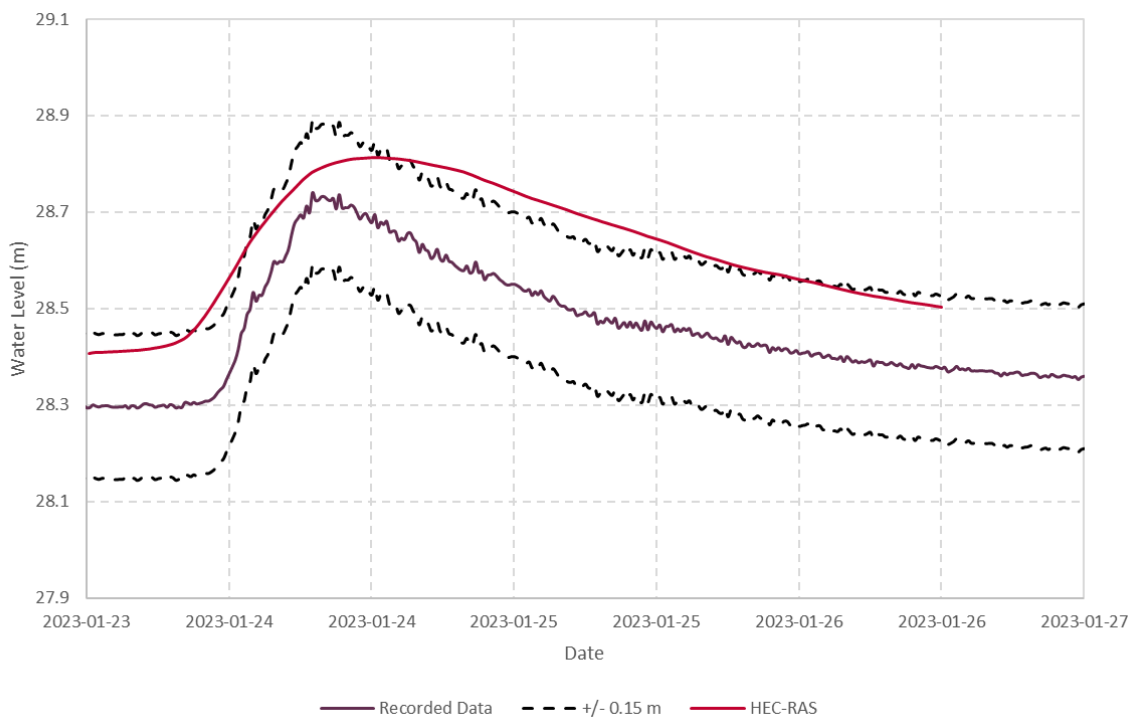


FIGURE 149: WESTERN POND BROOK CALIBRATION NEAR HIGHWAY 80 (WINTERTON)**FIGURE 150: HEART'S DELIGHT BROOK CALIBRATION NEAR HIGHWAY 80 (HEART'S DELIGHT - ISLINGTON)**

**FIGURE 151: LAMBES BROOK CALIBRATION NEAR NORTH ST.
(BRIGUS)****FIGURE 152: QUARRY BROOK CALIBRATION NEAR HIGHWAY 10
(FERRYLAND)**

The hydraulic models were found to generally be well calibrated, with the simulated peak water levels being well within 0.15 m of the observed peak water level, and were as such considered to be suitable for estimating the flood extents associated with the 1:20 and 1:100 AEP flood events.

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 1:20 and 1:100-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 was 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. The boundary conditions included in the HEC-RAS models are summarized in Table 63.

TABLE 63: 1:20 AND 1:100 AEP BOUNDARY CONDITIONS

Town	Localtion	Boundary Type	Current Climate		Climate Change Flow	
			20-Year AEP	100-Year AEP	20-Year AEP	100-Year AEP
Ferryland	Freshwater River at U/S Model Boundary	Flow (m ³ /s)	4.9	7.0	6.4	9.1
	Freshwater River at D/S Model Boundary	Water Level (m)	1.35	1.61	2.01	2.27
	Quarry River North Branch U/S Model Boundary	Flow (m ³ /s)	9.4	13.0	12.0	16.6
	Quarry River South Branch U/S Model Boundary	Flow (m ³ /s)	1.9	2.6	2.4	3.4
	Quarry River Downstream of North and South Branch Confluence	Flow (m ³ /s)	5.9	8.3	7.6	10.8
	Quarry River at D/S Model Boundary	Water Level (m)	1.35	1.62	2.01	2.28
Brigus	Lambes Brook at U/S Model Boundary	Flow (m ³ /s)	19.9	27.0	24.8	33.6
	Brigus North Brook at U/S Model Boundary	Flow (m ³ /s)	4.2	5.7	5.2	7.0
	Lambes Brook at D/S Model Boundary	Water Level (m)	1.24	1.42	1.87	2.05
	Apses Brook at U/S Model Boundary	Flow (m ³ /s)	1.3	1.8	1.7	2.3
	Apses Brook at D/S Model Boundary	Water Level (m)	1.25	1.44	1.88	2.07
	Local Creek 1 at U/S Model Boundary	Flow (m ³ /s)	3.4	4.7	4.2	5.8
	Local Creek 1 at D/S Model Boundary	Water Level (m)	1.25	1.44	1.88	2.07
	Local Creek 2 at U/S Model Boundary	Flow (m ³ /s)	2.3	3.4	3.0	4.4
	Local Creek 2 at D/S Model Boundary	Water Level (m)	1.24	1.44	1.87	2.07
	Local Creek 3 at U/S Model Boundary	Flow (m ³ /s)	2.2	3.2	2.8	4.0
	Local Creek 3 at D/S Model Boundary	Water Level (m)	1.24	1.44	1.87	2.07
Heart's Delight - Islington	Heart's Delight Brook at U/S Model Boundary	Flow (m ³ /s)	51.8	73.1	67.5	95.3
	Heart's Delight Brook at D/S Model Boundary	Water Level (m)	1.00	1.14	1.63	1.77
	Local Creek 1 at U/S Model Boundary	Flow (m ³ /s)	26.6	38.2	35.0	50.5
	Local Creek 1 at D/S Model Boundary	Water Level (m)	1.00	1.13	1.63	1.76
	Local Creek 2 at U/S Model Boundary	Flow (m ³ /s)	9.4	14.0	12.6	18.9
	Local Creek 2 at D/S Model Boundary	Water Level (m)	1.00	1.14	1.63	1.77
	Local Creek 3 at U/S Model Boundary	Flow (m ³ /s)	4.1	6.2	5.5	8.3
	Local Creek 3 at D/S Model Boundary	Water Level (m)	1.00	1.14	1.63	1.77
	Local Creek 4 at U/S Model Boundary	Flow (m ³ /s)	1.7	2.7	2.3	3.6
	Local Creek 4 at D/S Model Boundary	Water Level (m)	0.99	1.13	1.62	1.76
Winterton	Western Pond Brook North Branch at U/S Model Boundary	Flow (m ³ /s)	19.4	25.2	23.4	30.4
	Western Pond Brook South Branch at U/S Model Boundary	Flow (m ³ /s)	2.6	3.3	3.0	3.9
	Western Pond Brook D/S of North and South Branch Confluence	Flow (m ³ /s)	0.9	1.1	1.0	1.3
	Western Pond Brook at D/S Model Boundary	Water Level (m)	0.97	1.10	1.60	1.73
Hant's Harbour	Halfway Brook West Branch at U/S Model Boundary	Flow (m ³ /s)	4.3	5.8	5.3	7.0
	Halfway Brook East Branch at U/S Model Boundary	Flow (m ³ /s)	21.7	27.8	26.1	33.7
	Halfway Brook D/S of East and West Branch Confluence	Flow (m ³ /s)	8.9	11.7	10.9	14.4
	Halfway Brook at D/S Model Boundary	Water Level (m)	0.95	1.09	1.58	1.72
	Short's Brook at U/S Model Boundary	Flow (m ³ /s)	7.4	9.7	9.0	11.8
	Southwest Brook at U/S Model Boundary	Flow (m ³ /s)	3.6	4.7	4.4	5.7
	Short's Brook D/S of Short's Brook at Southwest Brook Confluence	Flow (m ³ /s)	3.6	4.8	4.4	5.8
	Short's Brook at D/S Model Boundary	Water Level (m)	0.96	1.10	1.59	1.73
	Local Creek 1 at U/S Model Boundary	Flow (m ³ /s)	2.7	3.7	3.3	4.5
	Local Creek 1 at D/S Model Boundary	Water Level (m)	0.95	1.09	1.58	1.72

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 64. Water levels that exceed the road crest elevation are shown in red, while entries of 'N/A' indicate that the inlet of the culvert was dry for the given flood scenario. Similarly, any culverts denoted with a crossing name of 'Est' were estimated from available imagery and LiDAR to maintain hydraulic connectivity during the passage of the AEP floods.

TABLE 64: HYDRAULIC STRUCTURE CAPACITY

Town	River	Crossing Name	UTM Easting (m)	UTM Northing (m)	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
Heart's Delight - Islington	Local Creek 1	HD_LC1_C01	268284.1	5290825.2	Dual 2.2 m High, 3.5 m Wide Pipe Arch Culvert	5.2	4.5	5.0	4.9	5.3
Heart's Delight – Islington	Local Creek 1	HD_LC1_B02	268307.8	5290798.7	5.9 m Single Span Bridge	4.7	5.0	5.2	5.2	5.4
Heart's Delight – Islington	Local Creek 1	HD_LC1_B03	268580.9	5290543.0	5.0 m Single Span Bridge	6.3	6.3	6.5	6.4	6.6
Heart's Delight – Islington	Local Creek 2	HD_LC2_C01	269746.5	5292540.4	Dual 1.65 m Dia. Culverts	1.9	1.7	2.1	2.1	2.3
Heart's Delight – Islington	Local Creek 2	HD_LC2_B02	269860.9	5292375.8	3.1 m Single Span Bridge	2.3	2.0	2.5	2.5	2.6
Heart's Delight – Islington	Local Creek 2	HD_LC2_C03	269884.6	5292217.4	Triple 0.75 m Dia. Culverts	3.6	3.1	3.2	3.2	3.3
Heart's Delight – Islington	Local Creek 2 Overflow	Est Church Road	269969.5	5292257.7	Triple 0.79 m Dia. Culverts	3.0	3.0	3.1	3.1	3.2
Heart's Delight – Islington	Heart's Delight Brook	HD_HDB_B01	270120.3	5292495.3	8.6 m Single Span Bridge	2.7	2.6	3.1	3.0	3.5
Heart's Delight – Islington	Local Creek 3	HD_LC3_C01	269950.6	5293494.3	Single 1.8 m Dia. Culverts / Single 1.2 m Dia. Culvert	3.3	2.7	3.0	3.0	3.1
Heart's Delight – Islington	Local Creek 3	HD_LC3_C02	269980.0	5293521.9	Single 1.8 m Dia. Culvert	4.6	3.9	4.4	4.3	4.7
Heart's Delight – Islington	Local Creek 3	HD_LC3_C03	270039.1	5293584.9	Single 1.3 m Dia. Culvert	6.2	6.4	6.6	6.6	6.7
Heart's Delight – Islington	Local Creek 4	HD_LC4_C01	269816.3	5294499.5	Single 1.05 m High, 1.7 m Wide Pipe Arch Culvert	13.5	12.7	13.1	12.9	13.3
Heart's Delight – Islington	Local Creek 4 Overflow	Est 1	269723.7	5294993.9	Single 0.9 m Dia. Culvert	13.2	N/A	N/A	11.7	12.1
Heart's Delight - Islington	Local Creek 4 Overflow	Est 2	269804.6	5295043.9	Single 0.9 m Dia. Culvert	10.7	N/A	N/A	N/A	N/A
Brigus	Local Creek 1	BR_LC1_C01	289299.3	5265819.1	Single 1.0 m High, 1.4 m Wide Culvert	1.4	1.7	1.8	1.9	2.1
Brigus	Local Creek 1	BR_LC1_C02	289129.3	5265568.0	Single 0.8 m Dia. Culvert / Single 0.65 m Dia. Culvert	16.3	16.5	16.6	16.6	16.6
Brigus	Local Creek 2	BR_LC2_C01	289843.7	5266125.8	Single 1.4 m Dia. Culvert	10.4	11.2	11.3	11.3	11.3
Brigus	Local Creek 2	BR_LC2_B02	289816.3	5266094.7	2.3 m Single Span Bridge	12.7	12.5	12.7	12.7	12.9
Brigus	Local Creek 2	BR_LC2_B03	289810.6	5266019.6	3.0 m Single Span Bridge	16.7	16.0	16.0	16.0	16.0
Brigus	Local Creek 3	BR_LC3_C01	290164.2	5266161.9	Single 0.9 m Dia. Culvert	1.2	1.4	1.5	1.9	2.1
Brigus	Brigus North Brook	BR_BNB_B01	289192.6	5266544.7	10.1 m Single Span Bridge	1.9	1.3	1.5	1.9	2.1
Brigus	Brigus North Brook	BR_BNB_B02	289076.3	5266303.2	3.2 m Single Span Bridge	1.0	1.4	1.6	1.9	2.1
Brigus	Brigus North Brook	BR_BNB_B03	288981.5	5266269.3	2.5 m Single Span Bridge	1.2	1.6	1.7	1.9	2.1
Brigus	Brigus North Brook	BR_BNB_C04	288857.8	5266194.3	Single 1.4 m High, 1.8 m Wide Culvert	3.3	3.4	3.6	3.4	3.7
Brigus	Brigus North Brook	BR_BNB_B05	288837.1	5266189.2	2.5 m Single Span Bridge	3.6	3.9	4.0	4.0	4.0
Brigus	Brigus North Brook	BR_BNB_B06	288618.3	5266011.2	1.8 m Single Span Bridge	9.0	9.3	9.3	9.3	9.4
Brigus	Brigus North Brook	BR_BNB_C07	288424.6	5265850.0	Single 1.3 m Dia. Culvert	24.4	22.4	23.9	23.3	24.5
Brigus	Brigus North Brook	BR_BNB_C08	288278.3	5265704.5	Single 1.3 m High, 1.6 m Wide Pipe Arch Culvert	32.1	32.1	32.2	32.2	32.2
Brigus	Brigus North Brook	BR_BNB_B09	288209.1	5265681.3	1.3 m Single Span Bridge	34.5	35.0	35.1	35.0	35.1
Brigus	Brigus North Brook	BR_BNB_C10	287755.5	5265029.6	Single 1.0 m Dia. Culvert	51.8	51.9	52.0	51.9	52.0
Brigus	Brigus North Brook	BR_BNB_C11	287695.7	5264817.4	Single 0.4 m Dia. Culvert	56.4	56.9	57.0	57.0	57.0
Brigus	Brigus North Brook	BR_BNB_C12	287710.8	5264950.8	Single 0.5 m Dia. Culvert	54.1	54.3	54.4	54.3	54.4
Brigus	Brigus North Brook Overflow	BR_BNB_OF_C01	288887.4	5266184.2	Single 0.4 m Dia. Culvert	3.1	2.8	3.1	3.2	3.2
Brigus	Apses Brook	BR_AB_C01	289302.6	5265936.4	Single 0.7 m High, 1.0 m Wide Culvert	2.2	1.8	2.0	2.0	2.2

Town	River	Crossing Name	UTM Easting (m)	UTM Northing (m)	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
Brigus	Apses Brook	BR_AB_C02	289267.9	5265933.9	Single 0.9 m Dia. Culvert	4.4	4.4	4.5	4.4	4.6
Brigus	Apses Brook	BR_AB_C03	289258.8	5265943.6	Single 0.9 m Dia. Culvert	4.5	4.7	4.8	4.8	4.8
Brigus	Apses Brook	BR_AB_B04	289257.3	5265985.8	1.4 m Single Span Bridge	4.5	4.7	4.8	4.8	4.8
Brigus	Apses Brook	BR_AB_C05	289233.2	5266001.9	Single 1.15 m High, 1.7 m Wide Culvert	7.2	6.8	7.0	6.9	7.2
Brigus	Apses Brook	BR_AB_C06	289088.8	5266006.8	Single 0.7 m Dia. Culvert	9.3	9.3	9.3	9.3	9.4
Brigus	Lambes Brook	BR_LB_B01	289052.7	5266384.0	3.8 m Single Span Bridge	1.1	1.4	1.5	1.9	2.1
Brigus	Lambes Brook	BR_LB_B02	288941.6	5266336.0	4.6 m Single Span Bridge	1.8	2.1	2.2	2.1	2.2
Brigus	Lambes Brook	BR_LB_C03	288892.6	5266329.9	Single 2.3 m Dia Culvert	2.5	2.5	2.6	2.5	2.6
Brigus	Lambes Brook	BR_LB_C04	288862.1	5266322.0	Single 1.4 m High, 4.3 m Wide Box Culvert	3.2	3.4	3.5	3.5	3.6
Brigus	Lambes Brook	BR_LB_B05	287989.2	5266043.0	5.4 m Single Span Bridge	14.6	14.8	14.9	14.9	15.0
Brigus	Lambes Brook	BR_LB_B06	287761.7	5265926.4	5.1 m Single Span Bridge	16.6	17.2	17.3	17.2	17.3
Brigus	Lambes Brook	BR_LB_B07	287631.7	5265919.3	3.7 m Single Span Bridge	17.8	18.3	18.4	18.4	18.5
Brigus	Lambes Brook	BR_LB_B08	287533.9	5265914.3	4.7 m Single Span Bridge	19.8	19.1	19.2	19.2	19.4
Brigus	Lambes Brook	BR_LB_C09	287523.3	5265916.4	Dual 1.4 m High, 2.1 m Wide Culverts / Single 1.2 m Dia. Culvert	19.3	19.7	19.9	19.9	20.0
Brigus	Lambes Brook	BR_LB_B10	287454.1	5265903.9	4.3 m Single Span Bridge	18.7	19.8	19.9	19.9	20.0
Brigus	Lambes Brook	BR_LB_C11	287096.2	5265594.3	Dual 2.1 m Dia. Culvert	19.6	19.3	20.0	20.0	20.1
Brigus	Lambes Brook	BR_LB_B12	286868.5	5265138.1	4.5 m Single Span Bridge	26.8	26.8	27.0	26.9	27.1
Brigus	Lambes Brook	BR_LB_C13	286823.3	5264985.2	Single 1.6 m Dia Culvert / Single 1.5 m Dia. Culvert / Single 1.0 m Dia. Culvert	31.3	31.5	31.6	31.6	31.7
Brigus	Lambes Brook	BR_LB_B15	286546.8	5264544.8	3.2 m Single Span Bridge	37.5	38.0	38.1	38.1	38.1
Ferryland	Freshwater River	FL_FWR_C01	313492.8	5210815.1	Single 1.4 m Dia. Culvert	7.6	7.7	7.8	7.8	7.9
Ferryland	Freshwater River	FL_FWR_C02	313413.8	5210832.1	Single 2.0 m Dia. Culvert / Single 1.2 m Dia. Culvert	13.1	12.6	12.9	12.8	13.2
Ferryland	Freshwater River	FL_FWR_C03	313048.1	5210778.2	Single 1.1 m Dia. Culvert	33.9	34.0	34.1	34.1	34.2
Ferryland	Freshwater River Overflow	FL_FWR_OF_C01	313257.4	5210886.5	Single 0.6 m Dia. Culvert	19.9	N/A	N/A	N/A	N/A
Ferryland	Quarry River	FL_QR_C01	312979.1	5208697.5	Single 1.5 m High, 3.4 m Wide Culvert	3.1	3.0	3.2	3.2	3.4
Ferryland	Quarry River	FL_QR_B02	312604.6	5209040.6	5.9 m Single Span Bridge	30.4	29.5	29.9	29.8	30.3
Ferryland	Quarry River	FL_QR_B03	312486.5	5209078.4	7.3 m Single Span Bridge	30.8	30.3	30.4	30.4	30.5
Ferryland	Quarry River	FL_QR_B04	312059.9	5209164.1	5.7 m Single Span Bridge	34.8	35.2	35.3	35.3	35.4
Ferryland	Quarry River	FL_QR_B05	311063.8	5210254.6	3.0 m Single Span Bridge	76.2	75.0	75.4	75.3	75.7
Hant's Harbour	Local Creek 1	HH_LC1_C01	286754.2	5320067.5	Single 0.8 m Dia. Culvert	50.1	50.3	50.4	50.4	50.4
Hant's Harbour	Short's Brook	HH_SHB_B01	285454.7	5319525.2	6.3 m Single Span Bridge	2.3	1.3	1.4	1.6	1.8
Hant's Harbour	Short's Brook	HH_SHB_C02	285401.2	5319408.8	Dual 1.8 m Dia. Culverts	3.8	4.1	4.3	4.2	4.3
Hant's Harbour	Short's Brook	HH_SHB_C03	285307.9	5319064.2	Single 1.4 m Dia. Culvert	6.6	6.7	6.7	6.7	6.8
Hant's Harbour	Short's Brook	HH_SHB_C04	285317.6	5318773.6	Single 1.4 m High, 3.5 m Wide Arch Culvert	16.1	15.5	15.8	15.7	16.0
Hant's Harbour	Short's Brook	HH_SHB_C05	285351.5	5318284.5	Single 1.2 m Dia. Culvert	30.3	30.5	30.5	30.5	30.6
Hant's Harbour	Short's Brook Overflow	Est Trinity Rd. S	285230.5	5318722.4	Single 0.8 m Dia. Culvert	16.0	16.0	16.0	16.0	16.1
Hant's Harbour	Short's Brook Overflow	HH_SHB_OF_C01	285412.1	5318460.6	Single 0.6 m Dia. Culvert	26.8	26.3	26.3	26.3	26.3

Town	River	Crossing Name	UTM Easting (m)	UTM Northing (m)	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
Hant's Harbour	Southwest Brook	HH_SWB_C01	284537.8	5318482.8	Single 2.0 m Dia. Culvert	25.1	23.9	24.2	24.1	24.3
Hant's Harbour	Southwest Brook Overflow	Est 1	284742.9	5318519.1	Single 0.6 m Dia. Culvert	22.2	21.6	21.6	21.6	22.0
Hant's Harbour	Southwest Brook Overflow	Est 2	284825.9	5318546.8	Single 1.2 m Dia. Culvert	20.8	17.4	17.4	17.4	17.7
Hant's Harbour	Halfway Brook	HH_HWB_B01	284613.9	5319750.9	4.3 m Single Span Bridge	3.4	3.5	3.7	3.6	3.8
Hant's Harbour	Halfway Brook	HH_HWB_C02	282260.5	5316162.6	Single 2.4 m Dia. Culvert / Single 1.95 m Dia. Culvert / Single 1.3 m High, 1.1 m Wide Culvert	42.5	42.0	42.1	42.1	42.2
Hant's Harbour	Halfway Brook Local Creek 1	HH_HWB_LC1_C01	281542.6	5315597.7		43.1	43.1	43.2	43.1	43.2
Winterton	Western Pond Brook	WI_WPB_B01	280096.0	5312870.8	4.3 m Single Span Bridge	2.3	1.9	2.4	2.3	2.6
Winterton	Western Pond Brook	WI_WPB_B02	280153.7	5312800.0	7.0 m Single Span Bridge	7.8	8.1	8.4	8.3	8.5
Winterton	Western Pond Brook	WI_WPB_B03	280218.7	5312708.9	4.5 m Single Span Bridge	14.1	13.8	14.1	14.0	14.3
Winterton	Western Pond Brook	WI_WPB_B04	280493.9	5312534.7	6.4 m Single Span Bridge	20.4	20.3	20.6	20.5	20.7
Winterton	Western Pond Brook	WI_WPB_C05	281075.8	5312776.8	Dual 1.2 m Dia. Culverts	41.1	41.1	41.2	41.2	41.2
Winterton	Western Pond Brook	WI_WPB_B06	281682.4	5313227.7	6.2 m Single Span Bridge	68.1	68.6	68.7	68.7	68.8
Winterton	Western Pond Brook	WI_WPB_S07	281734.8	5313252.3	Single 0.6 m Dia. Culvert	53.1	70.4	70.5	70.5	70.5
Winterton	Western Pond Brook Tributary	WI_WPB_LC_C01	280883.9	5311918.5	Single 0.6 m Dia. Culvert	53.1	53.3	53.4	53.4	53.4
Winterton	Western Pond Brook Tributary	WI_WPB_LC_B02	280909.9	5311908.3	1.5 m Single Span Bridge	54.2	54.3	54.3	54.3	54.3
Winterton	Western Pond Brook Tributary	WI_WPB_LC_C03	280774.5	5311644.0	Dual 0.6 m Dia. Culvert	64.9	65.2	65.2	65.2	65.2
Winterton	Western Pond Brook Tributary	WI_WPB_LC_B04	280719.8	5311558.6	4.9 m Four Span Bridge	67.4	67.6	67.6	67.6	67.7
Winterton	Western Pond Brook Tributary Overflow	Est 1	280670.9	5311862.0	0.3 m Dia. Culvert	60.2	60.0	60.0	60.0	60.0
Winterton	Western Pond Brook Tributary Overflow	Est 2	280660.6	5311882.0	0.3 m Dia. Culvert	58.9	N/A	N/A	N/A	N/A
Winterton	Western Pond Brook Tributary Overflow	Est 3	280671.5	5311895.1	0.3 m Dia. Culvert	58.4	N/A	N/A	N/A	N/A
Winterton	Western Pond Brook Tributary Overflow	Est 4	280717.4	5311934.9	0.3 m Dia. Culvert	55.7	55.6	55.6	55.6	55.6
Winterton	Western Pond Brook Tributary Overflow	Est 5	280731.1	5311982.7	0.3 m Dia. Culvert	52.1	51.9	51.9	51.9	52.0
Winterton	Western Pond Brook Tributary Overflow	Est 6	280730.7	5312039.4	0.3 m Dia. Culvert	48.0	47.9	47.9	47.9	47.9
Winterton	Western Pond Brook Tributary Overflow	Est 7	280716.4	5312005.6	0.3 m Dia. Culvert	50.1	N/A	N/A	N/A	N/A
Winterton	Western Pond Brook Tributary Overflow	Est 8	280714.8	5312036.7	0.3 m Dia. Culvert	47.8	N/A	N/A	N/A	N/A
Winterton	Western Pond Brook Tributary Overflow	Est 9	280713.1	5312053.5	0.3 m Dia. Culvert	46.7	N/A	N/A	N/A	N/A

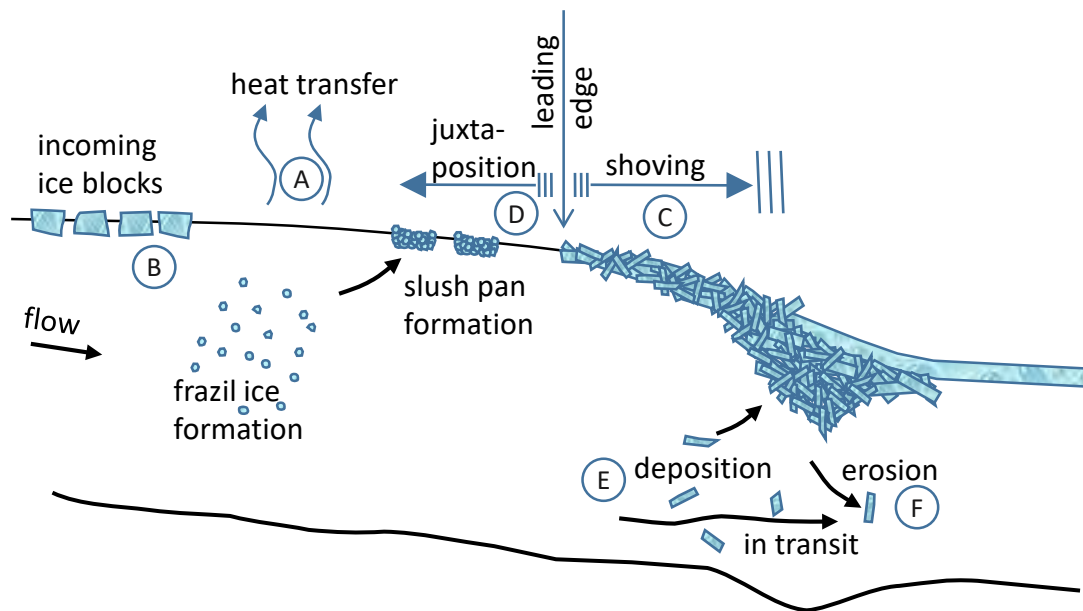
Town	River	Crossing Name	UTM Easting (m)	UTM Northing (m)	Structure Configuration	Top of Road Elevation (m)	Current Climate Water Level (m)		Climate Change Water Level (m)	
							20-Year AEP	100-Year AEP	20-Year AEP	100-Year AEP
Winterton	Western Pond Brook Tributary Overflow	Est 10	280707.9	5312097.5	0.3 m Dia. Culvert	43.1	N/A	N/A	N/A	N/A
Winterton	Western Pond Brook Tributary Overflow	Est 11	280724.9	5312107.3	0.3 m Dia. Culvert	42.2	42.1	42.1	42.1	42.1
Winterton	Western Pond Brook Tributary Overflow	Est 12	280706.3	5312133.7	0.3 m Dia. Culvert	40.5	N/A	N/A	N/A	N/A
Winterton	Western Pond Brook Tributary Overflow	Est 13	280704.5	5312160.0	0.3 m Dia. Culvert	38.5	N/A	N/A	N/A	N/A
Winterton	Western Pond Brook Tributary Overflow	Est 14	280721.8	5312151.4	0.3 m Dia. Culvert	39.8	39.5	39.5	39.5	39.6
Winterton	Western Pond Brook Tributary Overflow	Est 15	280718.3	5312180.2	0.3 m Dia. Culvert	38.1	37.9	37.9	37.9	37.9
Winterton	Western Pond Brook Tributary Overflow	Est 16	280698.8	5312200.2	0.3 m Dia. Culvert	36.3	N/A	N/A	N/A	N/A
Winterton	Western Pond Brook Tributary Overflow	Est 17	280714.8	5312203.1	0.3 m Dia. Culvert	36.9	N/A	N/A	N/A	N/A
Winterton	Western Pond Brook Tributary Overflow	Est 18	280683.7	5312247.2	0.3 m Dia. Culvert	31.9	N/A	N/A	N/A	N/A
Winterton	Western Pond Brook Tributary Overflow	Est 19	280672.6	5312271.0	0.3 m Dia. Culvert	30.4	N/A	N/A	N/A	N/A
Winterton	Western Pond Brook Tributary Overflow	Est 20	280660.1	5312295.4	0.3 m Dia. Culvert	29.4	N/A	N/A	N/A	N/A
Winterton	Western Pond Brook Tributary Overflow	Est 21	280654.9	5312305.8	0.3 m Dia. Culvert	28.8	N/A	N/A	N/A	N/A
Winterton	Western Pond Brook Tributary Overflow	Est 22	280644.7	5312323.7	0.3 m Dia. Culvert	28.2	N/A	N/A	N/A	N/A
Winterton	Western Pond Brook Tributary Overflow	Est 24	280629.2	5312347.9	0.3 m Dia. Culvert	27.4	N/A	N/A	N/A	N/A
Winterton	Western Pond Brook Tributary Overflow	Est 25	280611.3	5312371.0	0.3 m Dia. Culvert	26.8	N/A	N/A	N/A	N/A
Winterton	Western Pond Brook Tributary Overflow	Est 26	280593.6	5312391.1	0.3 m Dia. Culvert	26.1	N/A	N/A	N/A	N/A
Winterton	Western Pond Brook Tributary Overflow	Est 27	280567.4	5312417.3	0.3 m Dia. Culvert	24.6	N/A	N/A	N/A	N/A
Winterton	Western Pond Brook Tributary Overflow	Est 28	280551.4	5312431.0	0.3 m Dia. Culvert	24.1	N/A	N/A	N/A	N/A
Winterton	Western Pond Brook Tributary Overflow	Est 29	280539.4	5312441.2	0.3 m Dia. Culvert	23.5	N/A	N/A	N/A	N/A
Winterton	Western Pond Brook Tributary Overflow	Est 30	280517.5	5312457.0	0.3 m Dia. Culvert	22.3	N/A	N/A	N/A	N/A
Winterton	Western Pond Brook Tributary Overflow	Est 31	280507.8	5312478.0	0.3 m Dia. Culvert	21.6	N/A	N/A	N/A	N/A

Town	River	Crossing Name	UTM Easting (m)	UTM Northing (m)	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
Winterton	Western Pond Brook Tributary Overflow	Est 32	280505.4	5312502.9	0.3 m Dia. Culvert	20.2	20.5	20.6	20.5	20.7
Winterton	Western Pond Brook Overflow	Est 33	280369.7	5312869.1	0.3 m Dia. Culvert	16.5	N/A	N/A	N/A	N/A
Winterton	Western Pond Brook Overflow	Est 34	280364.9	5312883.9	0.3 m Dia. Culvert	16.0	N/A	N/A	N/A	N/A
Winterton	Western Pond Brook Overflow	Est 35	280274.7	5312974.7	0.3 m Dia. Culvert	4.7	N/A	N/A	N/A	N/A
Winterton	Western Pond Brook Overflow	Est 36	280188.1	5312986.9	0.3 m Dia. Culvert	2.6	1.5	1.5	1.6	1.7

8.4 Assessment of Potential Impacts due to River Ice

To evaluate the potential for ice jam flooding and the water levels associated with ice jamming, RIVICE models were developed for Halfway Brook (Hant's Harbour), Heart's Delight Brook (Heart's Delight – Islington), and Western Pond Brook (Winterton). Ice jam models were not developed for Brigus or Ferryland, as ice jamming was not identified as an issue in those communities. The key river ice processes simulated in RIVICE that are relevant to this study are shown on Figure 153.

FIGURE 153: 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 153, 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 153, 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 153 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:

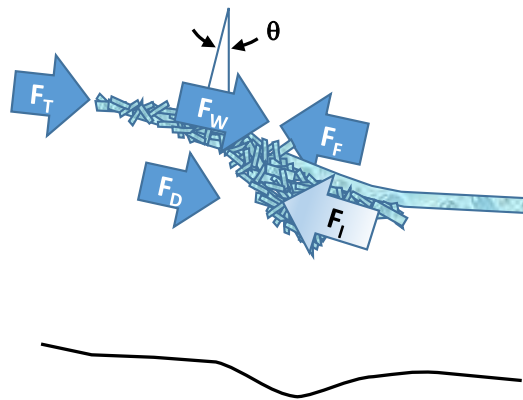
$$F_T + F_W + F_D > F_I + F_F \quad (\text{Eq. 5})$$

The second process is the progression of the ice cover upstream through juxtapositioning of the ice cover, represented as 'D' in Figure 153, 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 154 and summarized in Table 65.

FIGURE 154: FORCES APPLIED TO AN ICE-JAM COVER



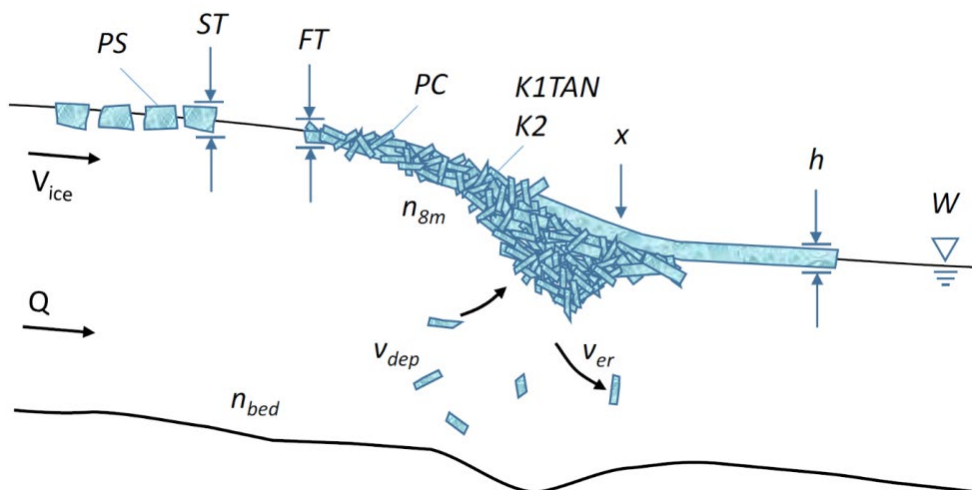
Source: Sheikholeslami et al. (2017)

TABLE 65: 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 153. 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 153.

These processes are represented using parameters specific to the processes in RIVICE, as shown on Figure 155 and summarized in Table 66.

FIGURE 155: PARAMETERS USED TO DESCRIBE THE ICE PROCESSES IN RIVICE

Source: Sheikholeslami et al. (2017)

TABLE 66: PARAMETERS USED TO DESCRIBE THE ICE PROCESSES IN RIVICE

Variable	Description
PS	Porosity of Incoming Ice Pans
ST	Thickness of Incoming Ice Pans
V_{ice}	Volume of Incoming Ice
PC	Ice Jam Front Porosity
FT	Ice Jam Front Thickness
h	Downstream Ice Cover Thickness
V_{dep}	Maximum Velocity for Ice Deposition
V_{er}	Minimum Velocity for Ice Erosion
n_{gm}	Ice Cover Underside Roughness Coefficient
n_{bed}	Riverbed Roughness Coefficient
$K1TAN$	Ice Strength Parameter
$K2$	Ice Strength Parameter
Q	River Flow
W	Downstream 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:

$$length = \frac{V_{ice}}{width \times ice\ thickness \times ice\ porosity} \quad (Eq. 7)$$

Coefficients for the roughness of the riverbed (i.e. n_{bed}) and the ice-cover's underside (i.e. n_{gm}) 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 67. Note that for different rivers, the acceptable range of parameters would be different.

TABLE 67: 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

8.4.1 RIVICE MODEL DEVELOPMENT

RIVICE models of the Halfway Brook (Hant's Harbour), Heart's Delight Brook (Heart's Delight – Islington), and Western Pond Brook (Winterton) 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 156 to Figure 158.

FIGURE 156: RIVICE MODEL IN HEART'S DELIGHT – ISLINGTON



FIGURE 157: RIVICE MODEL IN HANT'S HARBOUR

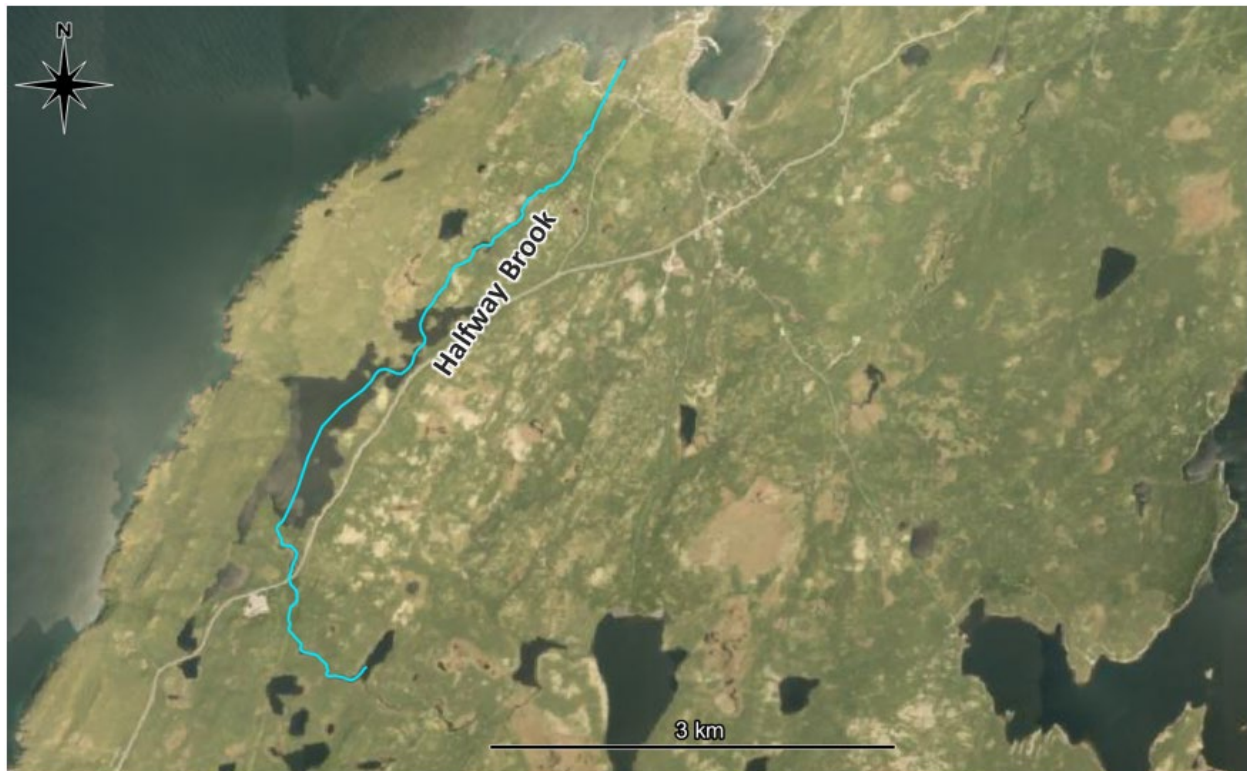
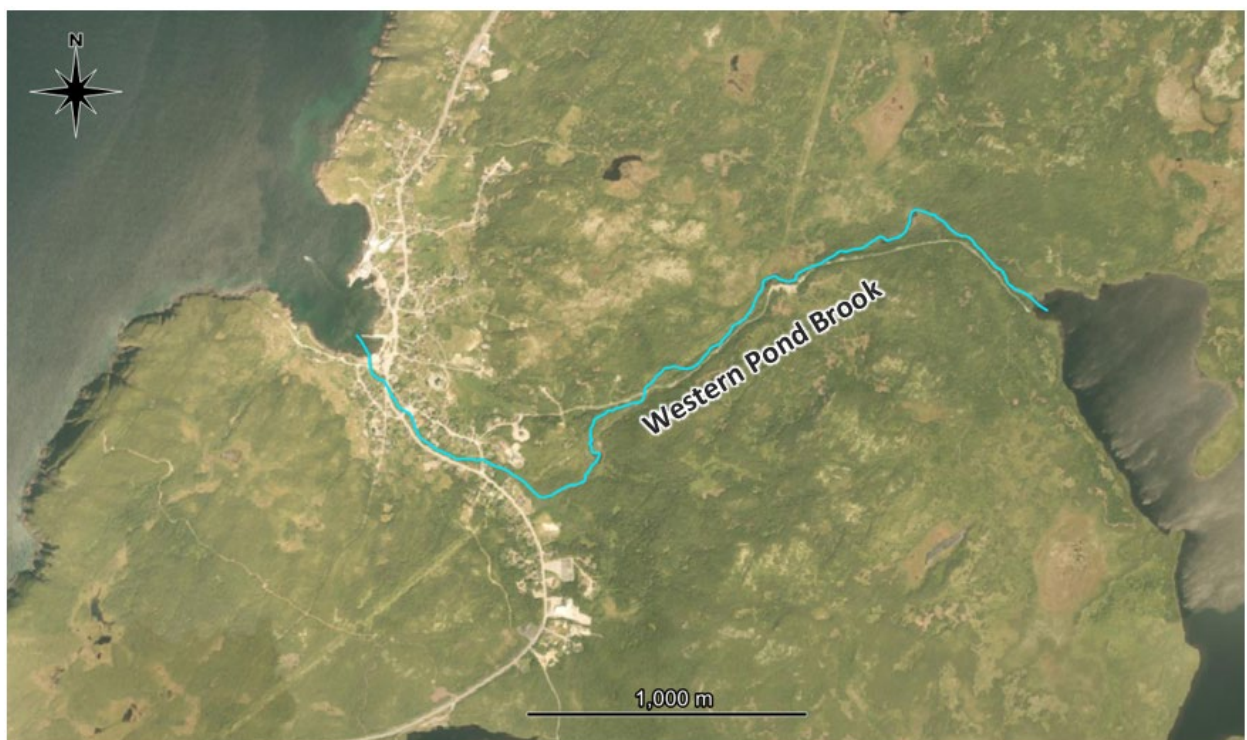


FIGURE 158: RIVICE MODEL IN WINTERTON



8.4.2 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 simulated in a simplified 1D version of the HEC-RAS models developed for the Western Pond Brook, Heart's Delight Brook, and Halfway Brook. Channel bed roughness coefficients were used in the 1D model that were consistent with the calibrated 2D model. Historical ice jam information, such as high water marks, were not available to calibrate the river ice processes in the RIVICE models. Instead, standard ranges for the various parameters were adopted in the Monte Carlo framework.

The 100-year AEP ice affected flows on Western Pond Brook, Heart's Delight Brook, and Halfway Brook were estimated by completing a frequency analysis of the annual peak ice-affected flow rates from WSC gauges 02ZL005 (i.e. Big Brook at Lead Cove) and 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 locations of the 02ZL004 and 02ZL005 gauges relative to Western Pond Brook, Heart's Delight Brook, and Halfway Brook are shown on Figure 56 and Figure 57. 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 100-year AEP ice-affected flows of 13.3 m³/s for WSC gauge 02ZL004 and 3.4 m³/s for WSC gauge 02ZL005. These flow was then prorated to Western Pond Brook, Heart's Delight Brook, and Halfway Brook on the basis of drainage area. The resulting estimated 100-year AEP ice-affected flows are summarized in Table 68.

TABLE 68: ICE-AFFECTED 100-YEAR AEP FLOWS

River	Drainage Area (km ²)	100-Year AEP Flow (m ³ /s)
Halfway Brook	20.1	6.4
Heart's Delight Brook	42.2	18.2
Western Pond Brook	12.9	4.5

Comparisons of the calibrated RIVICE water levels to the HEC-RAS levels models are shown on Figure 159 to Figure 161. It should be noted that for Halfway Brook and Heart's Delight Brook, it was necessary to adopt higher downstream boundary condition water levels to maintain numerical stability of the RIVICE models, and as such there is poor agreement between the RIVICE and HEC-RAS models in those locations.

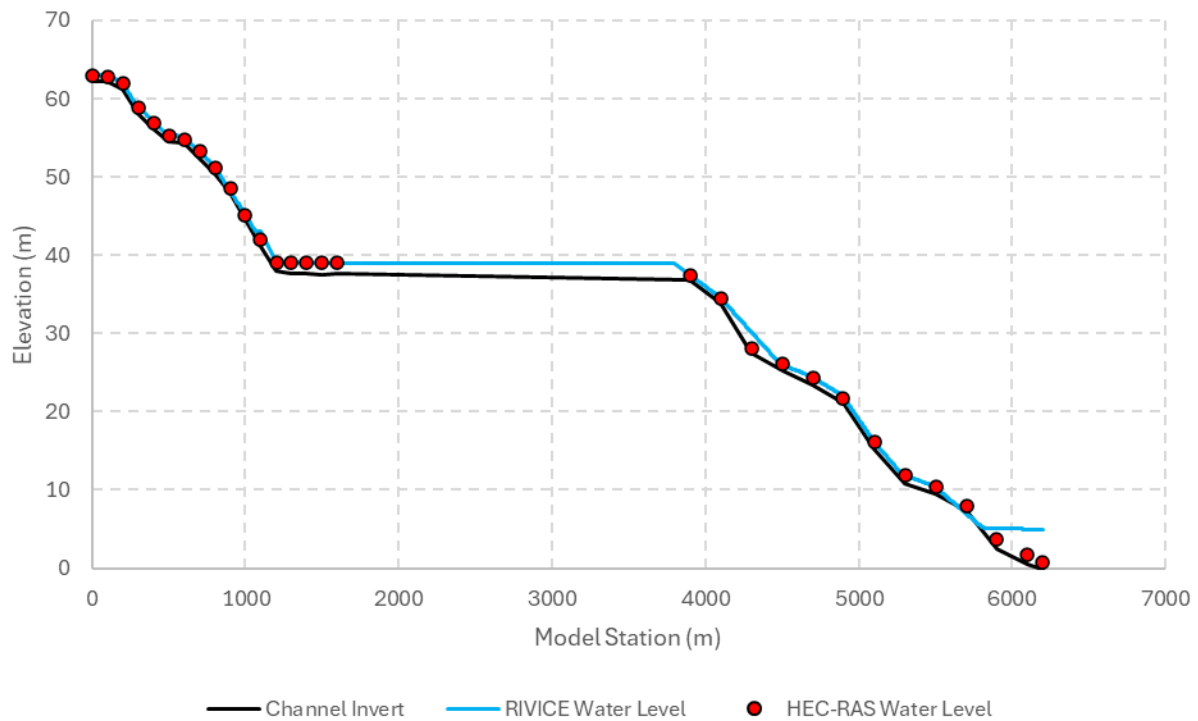
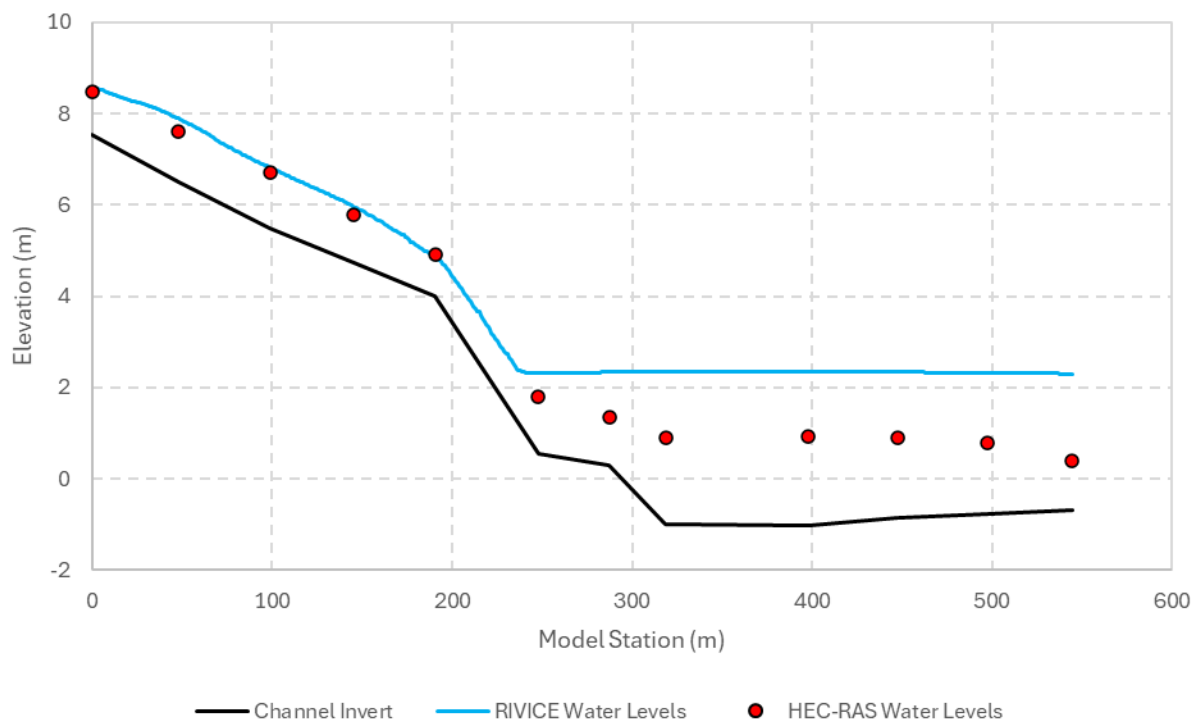
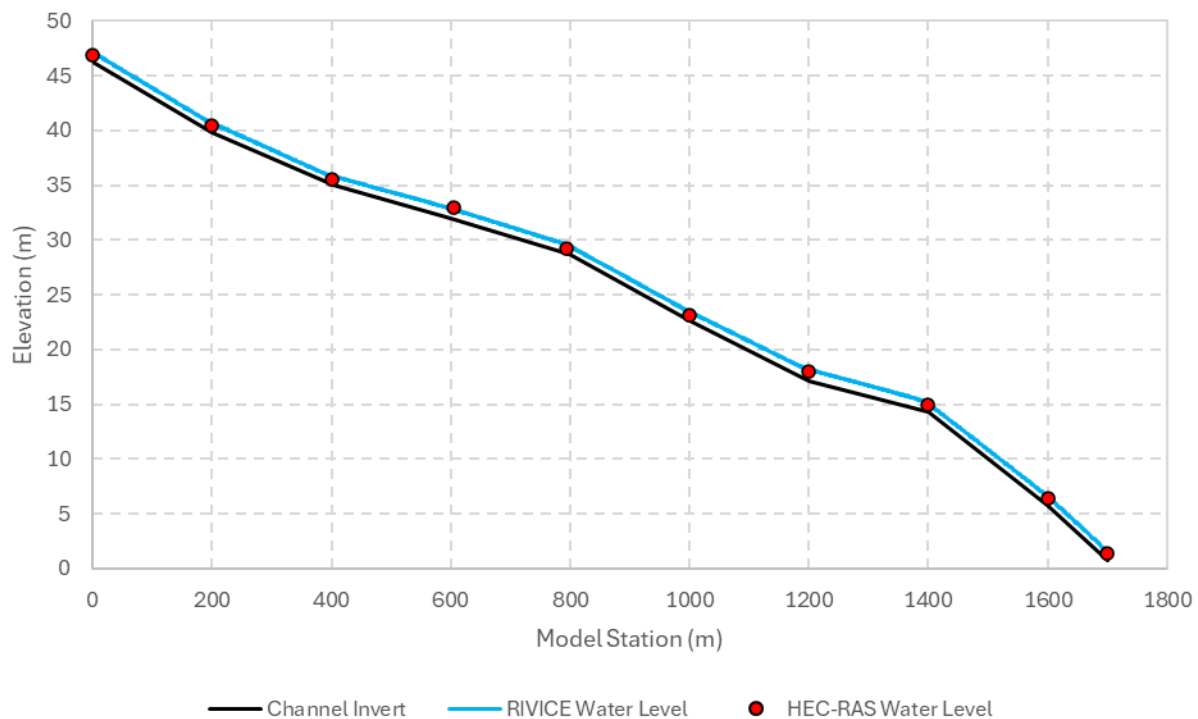
FIGURE 159: HALFWAY BROOK RIVICE CALIBRATION**FIGURE 160: HEART'S DELIGHT BROOK RIVICE CALIBRATION**

FIGURE 161: WESTERN POND BROOK RIVICE CALIBRATION

The simulated open water profiles defined by the RIVICE models were found to be in good agreement with those defined by the simplified HEC-RAS models on Halfway Brook, Heart's Delight Brook, and Western Pond Brook.

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 69, with the open water roughness coefficients shown for reference.

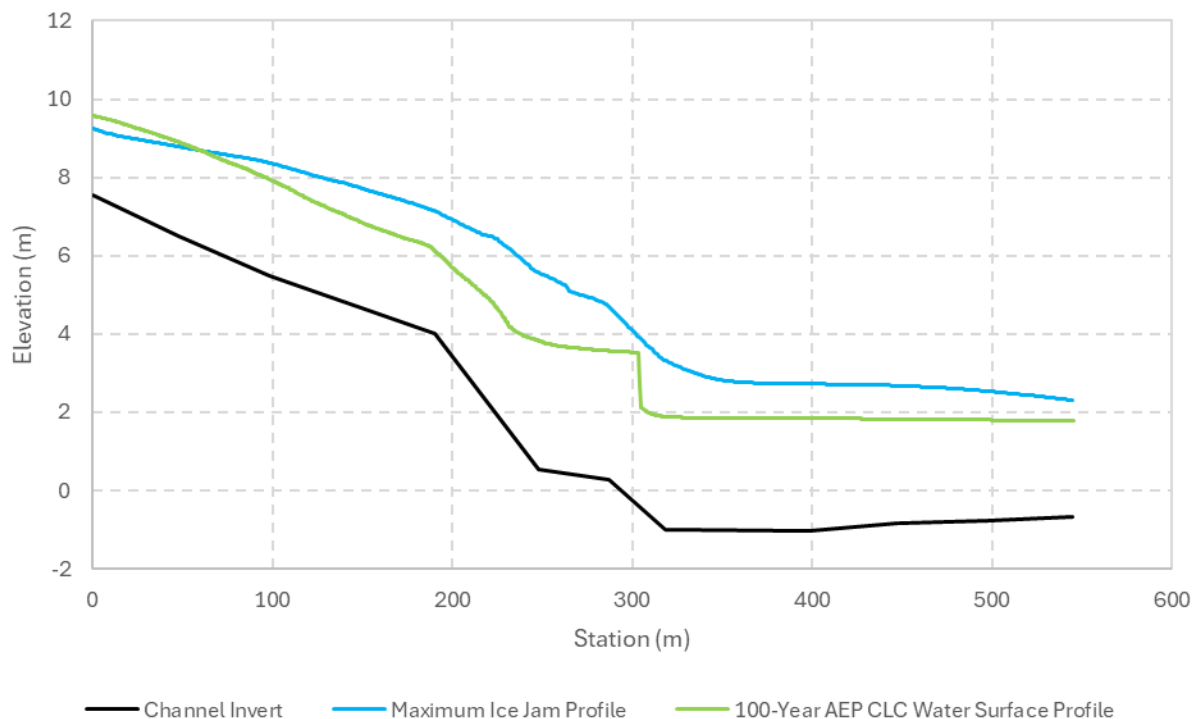
TABLE 69: CALIBRATED RIVICE ROUGHNESS COEFFICIENTS

River Reach	Open Water Roughness Coefficient	RIVICE Roughness Coefficient
Halfway Brook	0.030	0.090
Heart's Delight Brook	0.050	0.060
Western Pond Brook	0.035	0.090

8.4.3 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. However, it should be noted that despite numerous attempts, the RIVICE models for Halfway Brook and Western Pond Brook were unable to generate a stable ice jam profile along the reaches of the river, as those rivers are both too steep and narrow to allow for an ice jam to form in the RIVICE models. While this does not suggest that ice jams cannot form on those rivers, it does suggest that the severity of those ice jams would be limited by the steepness and narrowness of the rivers, as well as the relatively limited volume of ice available to form a jam during breakup events. The potential for ice jam floods on those rivers should be investigated further as part of future flood mapping efforts, provided that river ice jam modelling tools that are better suited to narrow, steep rivers become available.

On Heart's Delight Brook, the estimation of the maximum ice jam elevations required adjusting the downstream boundary condition to maintain numerical stability. The resulting adopted level was well above the 100-year storm surge level under climate change conditions, and as such is considered to be unrealistic, in particular considering the concurrent occurrence with the 100-year AEP ice jam flow. Comparisons of the maximum estimated ice jam elevations are shown on Figure 162, with the corresponding 100-year AEP climate change open water elevations, for reference.

FIGURE 162: HEART'S DELIGHT BROOK MAXIMUM ICE JAM ELEVATIONS

On Heart's Delight Brook, the ice jam water levels were considerably higher than the 100-year AEP open water levels under climate change conditions. However, given the very high downstream boundary condition, as well as the very high roughness coefficient adopted for the channel, both of which were required to maintain numerical stability, as well as the assumption that a sufficient high volume of ice would be available to allow for the ice jam to develop fully throughout the model domain, the ice jam levels are considered to be unrealistically conservative. Accordingly, the ice jam levels were not integrated into the flood hazard maps, and instead, the flood hazard 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 were completed to evaluate the sensitivity of the models 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.

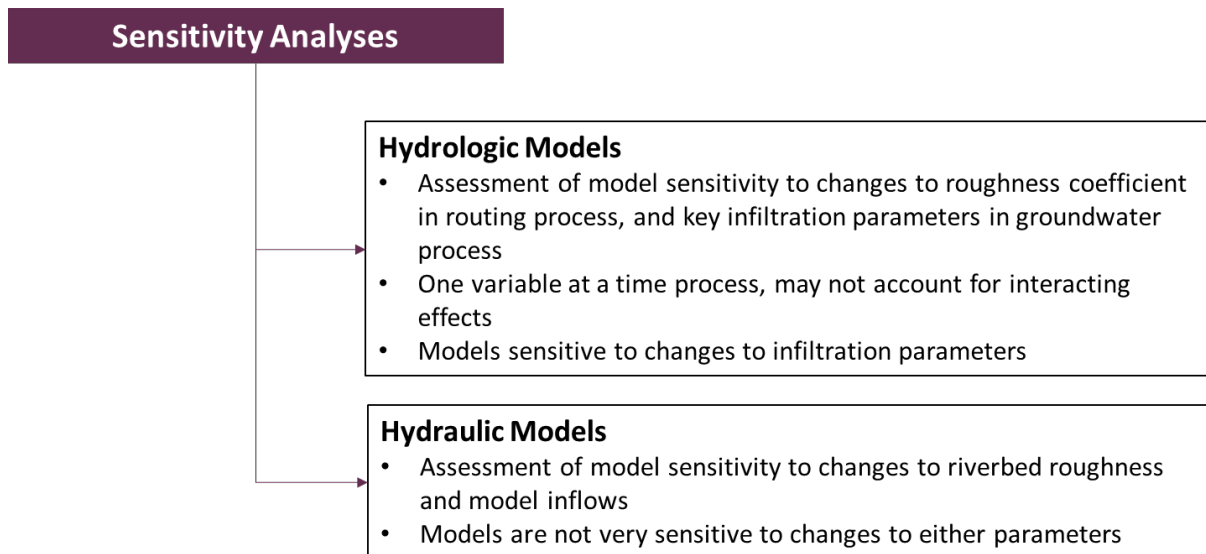
For the hydrological model, the sensitivity test checked how sensitive the model was to the parameters that represent channel roughness included in the hydrologic routing function of the model, as well as the parameters that represent how much rainfall gets absorbed by the ground during rain and melt 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 the river considered in the sensitivity tests. 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 163.

FIGURE 163: 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 hydrologic models for the watersheds in Ferryland, Brigus, Hant's Harbour, Winterton, and Heart's Delight-Islington are summarized in Table 70.

TABLE 70: HEC-HMS MODEL SENSITIVITY

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%
Ferryland	Quarry River Outlet	-32.2%	-22.9%	-12.3%	14.2%	30.6%	48.9%	0.3%	0.2%	0.1%	-0.1%	-0.2%	-0.3%
	Freshwater River Outlet	-33.1%	-23.9%	-13.0%	15.9%	35.5%	59.4%	0.4%	0.2%	0.1%	-0.1%	-0.3%	-0.4%
Brigus	Lambes Brook Outlet	-39.2%	-28.9%	-15.9%	19.1%	20.4%	20.4%	---	---	---	---	---	---
	Local Creek 3 Outlet	-40.4%	-29.3%	-16.1%	19.4%	41.0%	47.3%	---	---	---	---	---	---
	Local Creek 2 Outlet	-42.6%	-30.7%	-16.7%	20.0%	43.4%	61.7%	---	---	---	---	---	---
	Local Creek 1 Outlet	-42.0%	-30.1%	-16.2%	18.8%	38.3%	39.4%	---	---	---	---	---	---
	Brigus North Brook Outlet	-43.3%	-31.7%	-17.8%	14.2%	14.2%	14.2%	---	---	---	---	---	---
	Apses Brook Outlet	-49.1%	-36.7%	-20.5%	25.2%	39.9%	39.9%	---	---	---	---	---	---
Winterton	Western Pond Brook Outlet	-59.2%	-42.1%	-22.1%	9.9%	9.9%	9.9%	0.1%	0.0%	0.0%	0.0%	0.0%	-0.1%
Hant's Harbour	Halfway Brook Outlet	-40.8%	-28.6%	-14.9%	11.1%	12.5%	12.5%	-0.9%	-0.9%	-0.9%	0.0%	0.0%	0.0%
	Shorts Brook Outlet	-48.3%	-34.2%	-18.5%	17.2%	18.4%	18.4%	0.1%	0.1%	0.0%	-0.1%	-0.1%	-0.1%
	Local Creek 1 Outlet	-49.5%	-35.3%	-19.4%	19.2%	27.6%	27.6%	-0.1%	-0.1%	-0.1%	-0.1%	-0.1%	-0.1%
Heart's Delight - Islington	Heart's Delight Brook Outlet	-36.0%	-25.7%	-13.8%	16.1%	35.0%	56.1%	---	---	---	---	---	---
	Local Creek 1 Outlet	-33.6%	-23.8%	-12.6%	14.5%	31.1%	50.3%	---	---	---	---	---	---
	Local Creek 2 Outlet	-31.1%	-22.0%	-11.7%	13.4%	28.9%	46.9%	---	---	---	---	---	---
	Local Creek 3 Outlet	-31.1%	-21.9%	-11.6%	13.2%	28.5%	46.1%	---	---	---	---	---	---
	Local Creek 4 Outlet	-30.3%	-21.3%	-11.3%	12.8%	27.5%	44.3%	---	---	---	---	---	---

The sensitivity analysis showed that the 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 59.2%, although more typically on the order of 30% to 40%. An increase of 30% to the SCS curve number results in increases to flow rates of up to 61.7% in Brigus, although more typically in the 40% to 50% range. Accordingly, the model is considered to be sensitive to changes to the SCS curve number. 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 on the Avalon Peninsula. This could include reinstatement of WSC gauges that have been taken out of service to improve the geospatial coverage of gauges throughout the Avalon Peninsula (e.g. WSC gauges 02ZL003, 02ZM004, 02ZM003, etc.), or installation of new hydrometric stations on small watersheds, particularly along the coast of Trinity Bay (e.g. Heart's Delight Brook, Western Pond Brook, etc.).

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. Given the computational cost associated with simulating the sensitivity simulations throughout all communities, as well as the range in physiographic and hydraulic conditions throughout Brigus, the HEC-RAS model for Brigus served as the basis for the sensitivity analyses, and was assumed to be reasonably representative of the HEC-RAS model sensitivities in other communities.

The results of the sensitivity analysis for the Brigus HEC-RAS model are summarized in Table 71. 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 71, while the model sensitivity to changes to Manning's roughness coefficient and flow on each river as a percentage change to the depth of flow is provided in Table 72. Water level changes at each of the water level extraction locations are included in Appendix K.

TABLE 71: BRIGUS HEC-RAS MODEL SENSITIVITY (WATER LEVEL CHANGE)

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%
Lambes Brook	Minimum Change	-0.25	-0.17	-0.08	0.00	0.00	0.00	-0.26	-0.16	-0.08	0.00	0.00	0.00
	Average Change	-0.12	-0.09	-0.04	0.03	0.06	0.09	-0.15	-0.09	-0.04	0.04	0.08	0.11
	Maximum Change	0.00	0.00	0.00	0.07	0.13	0.19	0.00	0.00	0.00	0.07	0.13	0.26
Brigus North Brook	Minimum Change	-0.78	-0.13	-0.09	0.00	0.00	0.00	-1.70	-1.17	-0.67	0.00	0.00	0.00
	Average Change	-0.09	-0.05	-0.03	0.02	0.05	0.07	-0.14	-0.09	-0.05	0.04	0.07	0.10
	Maximum Change	0.00	0.00	0.00	0.06	0.10	0.14	0.00	0.00	0.00	0.43	0.55	0.62
Apses Brook	Minimum Change	-0.14	-0.10	-0.04	0.00	0.00	0.00	-0.18	-0.14	-0.07	0.00	0.00	0.00
	Average Change	-0.05	-0.03	-0.02	0.01	0.03	0.04	-0.06	-0.05	-0.02	0.02	0.04	0.05
	Maximum Change	0.00	0.00	0.00	0.04	0.08	0.11	0.00	0.00	0.00	0.07	0.14	0.17
Local Creek 1	Minimum Change	-0.28	-0.08	-0.04	0.00	0.00	0.00	-0.13	-0.08	-0.05	0.00	0.00	0.00
	Average Change	-0.07	-0.05	-0.02	0.02	0.04	0.06	-0.08	-0.05	-0.03	0.02	0.04	0.06
	Maximum Change	0.00	0.00	0.00	0.04	0.08	0.11	0.00	0.00	0.00	0.04	0.08	0.11
Local Creek 2	Minimum Change	-0.10	-0.05	-0.05	0.00	0.00	0.00	-0.18	-0.13	-0.05	0.00	0.00	0.00
	Average Change	-0.04	-0.02	-0.01	0.01	0.02	0.03	-0.04	-0.03	-0.01	0.01	0.03	0.04
	Maximum Change	0.00	0.00	0.00	0.02	0.04	0.06	0.00	0.00	0.00	0.05	0.11	0.15
Local Creek 3	Minimum Change	-0.14	-0.07	-0.03	0.00	0.00	0.00	-0.11	-0.05	-0.03	0.00	0.00	0.00
	Average Change	-0.04	-0.03	-0.01	0.01	0.03	0.04	-0.05	-0.03	-0.02	0.02	0.03	0.05
	Maximum Change	0.00	0.00	0.00	0.03	0.05	0.07	0.00	0.00	0.00	0.03	0.05	0.08

TABLE 72: BRIGUS HEC-RAS MODEL SENSITIVITY (PERCENT CHANGE IN DEPTH)

River	Change	Water Depth Difference (%)						Water Depth Difference (%)					
		n - 30%	n - 20%	n - 10%	n + 10%	n + 20%	n + 30%	Q - 30%	Q - 20%	Q - 10%	Q + 10%	Q + 20%	Q + 30%
Lambes Brook	Minimum Change	-28.1%	-17.9%	-8.5%	0.0%	0.0%	0.0%	-19.8%	-12.3%	-5.9%	0.0%	0.0%	0.0%
	Average Change	-7.4%	-4.7%	-2.2%	2.1%	4.0%	5.8%	-8.7%	-5.4%	-2.5%	2.3%	4.5%	6.6%
	Maximum Change	0.0%	0.0%	0.0%	8.0%	15.5%	21.3%	0.0%	0.0%	0.0%	5.2%	10.0%	14.4%
Brigus North Brook	Minimum Change	-38.8%	-15.1%	-16.4%	0.0%	0.0%	0.0%	-81.3%	-73.8%	-58.0%	0.0%	0.0%	0.0%
	Average Change	-9.6%	-6.0%	-2.9%	2.6%	5.1%	7.5%	-11.7%	-7.4%	-4.1%	4.1%	6.9%	9.7%
	Maximum Change	0.0%	0.0%	0.0%	8.8%	13.2%	19.2%	0.0%	0.0%	0.0%	94.6%	124.8%	148.2%
Apses Brook	Minimum Change	-29.1%	-19.6%	-9.5%	0.0%	0.0%	0.0%	-31.8%	-14.2%	0.0%	0.0%	0.0%	-31.8%
	Average Change	-10.7%	-6.9%	-3.3%	3.3%	6.3%	9.2%	-8.8%	-4.2%	3.9%	7.6%	9.4%	-8.8%
	Maximum Change	0.0%	0.0%	0.0%	9.5%	17.6%	25.1%	0.0%	0.0%	21.8%	26.0%	25.4%	0.0%
Local Creek 1	Minimum Change	-32.8%	-25.1%	-10.9%	0.0%	0.0%	0.0%	-22.4%	-15.1%	-14.2%	0.0%	0.0%	0.0%
	Average Change	-11.7%	-7.5%	-3.6%	3.4%	6.6%	9.7%	-11.6%	-7.2%	-3.9%	3.7%	6.4%	9.8%
	Maximum Change	0.0%	0.0%	0.0%	7.8%	13.5%	19.7%	0.0%	0.0%	0.0%	10.9%	13.1%	19.5%
Local Creek 2	Minimum Change	-24.1%	-16.2%	-7.6%	0.0%	0.0%	0.0%	-24.1%	-16.5%	-6.5%	0.0%	0.0%	0.0%
	Average Change	-8.3%	-5.4%	-2.5%	2.3%	4.8%	6.9%	-9.3%	-6.3%	-2.5%	2.4%	5.7%	8.1%
	Maximum Change	0.0%	0.0%	0.0%	6.9%	14.4%	21.0%	0.0%	0.0%	0.0%	6.5%	14.8%	21.6%
Local Creek 3	Minimum Change	-55.8%	-20.9%	-13.4%	0.0%	0.0%	0.0%	-41.0%	-18.0%	-11.8%	0.0%	0.0%	0.0%
	Average Change	-9.6%	-6.2%	-3.3%	3.0%	6.1%	8.9%	-12.2%	-7.1%	-3.5%	3.4%	6.7%	11.0%
	Maximum Change	0.0%	0.0%	0.0%	7.0%	13.9%	20.1%	0.0%	0.0%	0.0%	9.5%	14.9%	23.4%

The HEC-RAS sensitivity analyses showed that the model 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, and average water level changes throughout all rivers ranging from -0.12 m to 0.09 m associated with changes to roughness of +/-30%, and average changes of -0.15 to 0.11 m for changes to flow of +/-30%. The relatively limited model sensitivity to changes in roughness coefficients and flow is largely attributed to the steep nature of the rivers and creeks considered in the study area. 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. For Local Creek 2, the substantial minimum and maximum changes are in areas where there were numerical instabilities in the sensitivity simulations, and should be ignored.

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 +/- 0.1 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 HAZARD MAPPING

10.1 Overview

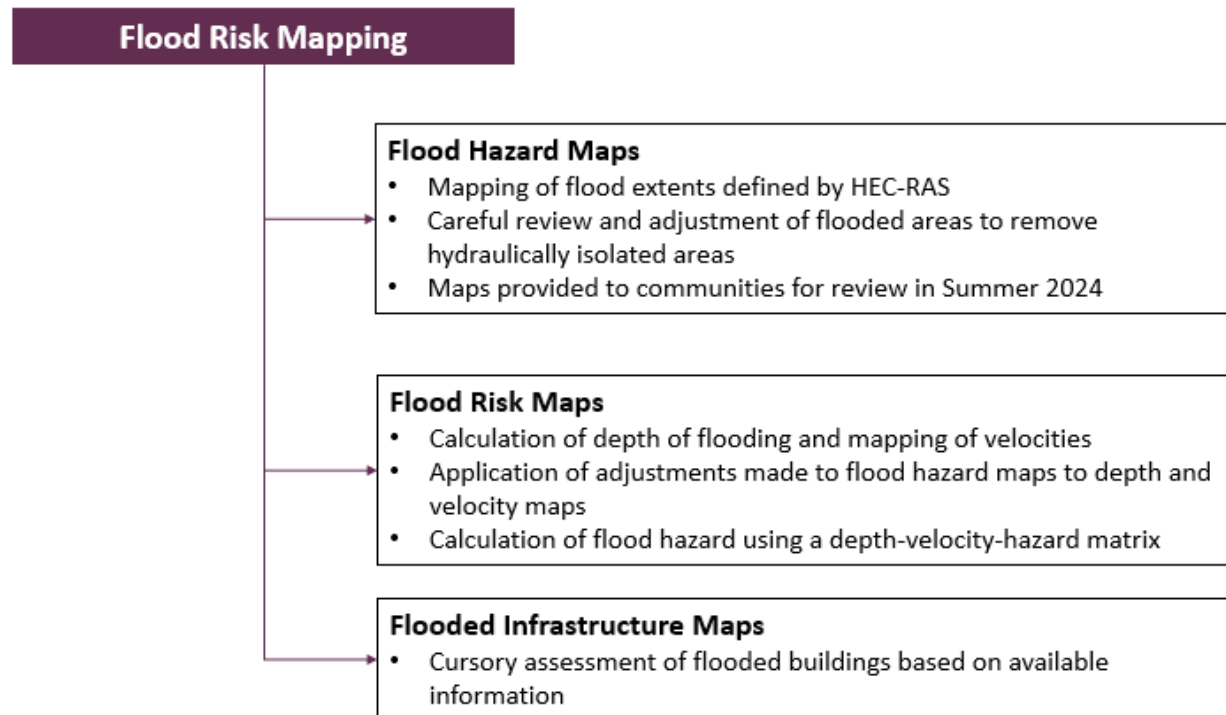
Once water levels on the various rivers and creeks were estimated for the 20 and 100-year AEP floods under the current climate and climate change conditions, the modelled water levels, flooding depths and flow velocities were used in combination with the ground elevation model to develop the flood hazard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

The flood hazard 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 hazard 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 hazard maps. The flow velocity maps were defined based on the modelled river and flood plain velocities from the hydraulic models. Finally, flood risk maps were defined that consider both the depth of flooding and flow velocities to define different levels of flood risk, 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 hazard mapping tasks is shown on Figure 164.

FIGURE 164: OVERVIEW OF FLOOD RISK MAPPING



10.2 Flood Hazard 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 model represented the maximum flooded area associated with each AEP condition were output directly by the software. The RAS Mapper extension overlays the simulated water levels on top of the bare earth DEM, as described in Section 4.4, to define the flooded areas within the model domain. 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 hazard maps were provided to the Towns of Ferryland, Brigus, Heart's Delight-Islington, Winterton, and Hant's Harbour, 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. Each set of flood hazard maps showed both the 20-year and 100-year flood zones, and consisted of 18 map sheets in Ferryland, 17 map sheets in Brigus, 26 map sheets in Hant's Harbour, 10 map sheets in Winterton, and 19 maps sheets in Heart's Delight-Islington showing the flood zones in developed areas. These maps are included in Appendix L. Maps showing the comparison between the historical flood hazard with the flood hazard defined as part of this study for the 20 and 100-year AEP

floods are included in Appendix M. It should be noted that the historical 20 year AEP flood extents defined for Ferryland show considerable additional flooding relative to those defined as part of this study. This can be attributed to different methodological approaches to define storm surge. Specifically, the storm surge heights estimated in the historical study were defined leveraging a frequency analysis of storm surge heights at St. John's Harbour and applied to Ferryland, while those defined as part of this study were based on hindcasting of historical surges, and frequency analyses at select locations of the model outputs in the study areas.

The total flooded area in each community for each flood condition and flood mechanism is summarized in Table 73. For the storm surge and riverine flood mechanism, the flooded area represents the total inland flooded area due to combined storm surge and riverine flooding conditions. For the wave runoff flood mechanism, the flooded area represents the total inland flooded area resulting strictly from wave runoff conditions, as described in Section 8.2.8. These flooded areas do not include areas beyond the present-day coastal shorelines, as those would not change under future conditions.

TABLE 73: COMPARISON OF FLOODED AREAS

Flood Mechanism	Community	Flooded Area (ha)			
		Current Climate		Climate Change	
		20-Year AEP	100-Year AEP	20-Year AEP	100-Year AEP
Storm Surge / Riverine	Ferryland	78.3	85.2	89.6	96.1
	Brigus	65.2	72.4	72.3	79.2
	Hant's Harbour	176.1	186.0	186.3	196.7
	Winterton	133.9	137.4	137.3	140.8
	Heart's Delight-Islington	157.4	167.6	167.8	178.3
Wave Runup	Ferryland	42.2	45.2	47.7	49.6
	Brigus	14.1	14.7	15.4	16.5
	Hant's Harbour	26.8	29.6	32.8	35.6
	Winterton	5.3	5.9	7.3	8.3
	Heart's Delight-Islington	19.0	21.2	23.7	26.1

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 Risk Maps

In addition to the flood hazard maps showing the total inundated area, digital mapping data were developed for the depth of flooding, velocity, and flood risk 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 hazard 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 similarly output directly from RASMapper.

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 risk where caution should be exercised, yellow representing a moderate risk that may be dangerous for some (i.e. children, the elderly and the infirm), orange represents a significant risk that is a danger for most, including the general public, and red represents an extreme risk that is considered to be a danger for all, including emergency services. The classification scheme is shown on Figure 165. It should be noted that for wave run-up flood risk, all areas within the wave run-up flood hazard areas were deemed to be of severe risk due to the highly dynamic nature of the flooding.

FIGURE 165: FLOOD RISK CLASSIFICATION

Velocity (m/s)	Depth (m)											
	0.05	0.10	0.20	0.30	0.40	0.50	0.60	0.80	1.00	1.50	2.00	2.50
0.00	Green	Green	Green	Yellow	Yellow	Yellow	Orange	Orange	Orange	Orange	Red	Red
0.10	Green	Green	Green	Yellow	Yellow	Orange	Orange	Orange	Orange	Orange	Red	Red
0.25	Green	Green	Green	Yellow	Orange	Orange	Orange	Orange	Orange	Red	Red	Red
0.50	Green	Green	Green	Orange	Orange	Orange	Orange	Orange	Orange	Red	Red	Red
1.00	Green	Green	Yellow	Orange	Orange	Orange	Orange	Red	Red	Red	Red	Red
1.50	Green	Green	Yellow	Orange	Orange	Orange	Red	Red	Red	Red	Red	Red
2.00	Green	Yellow	Yellow	Orange	Orange	Red	Red	Red	Red	Red	Red	Red
2.50	Green	Yellow	Yellow	Orange	Red	Red	Red	Red	Red	Red	Red	Red
3.00	Green	Yellow	Yellow	Red	Red	Red	Red	Red	Red	Red	Red	Red
3.50	Green	Yellow	Orange	Red	Red	Red	Red	Red	Red	Red	Red	Red
4.00	Green	Yellow	Orange	Red	Red	Red	Red	Red	Red	Red	Red	Red
4.50	Yellow	Yellow	Orange	Red	Red	Red	Red	Red	Red	Red	Red	Red
5.00	Yellow	Yellow	Orange	Red	Red	Red	Red	Red	Red	Red	Red	Red

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

The depth of flooding, velocity, and flood risk 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 risk for the 20 and 100-year AEP floods for current climate and climate change conditions are included in Appendix N.

10.4 Flooded Infrastructure

KGS Group completed a cursory assessment of buildings affected by the 20 and 100-year AEP floods in Ferryland, Brigus, Heart's Delight-Islington, Winterton and Hant's Harbour. Building footprints from the Government of Canada's Automatically Extracted Buildings database (NRCan, 2025) were compared to the 20 and 100-year AEP flood extents to identify any buildings (e.g. residences, commercial buildings, sheds, fishing stages, etc.) affected by those 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 74. It should be noted that the substantial number of flooded buildings identified in Brigus is due to extensive flooding in the densely populated area near the coast.

TABLE 74: SUMMARY OF FLOODED BUILDINGS

Flood Mechanism	Town	Number of Flooded Buildings			
		Current Climate		Climate Change	
		20-Year AEP	100-Year AEP	20-Year AEP	100-Year AEP
Storm Surge / Riverine	Ferryland	6	14	21	30
	Brigus	192	219	230	254
	Heart's Delight – Islington	19	29	38	47
	Winterton	21	27	28	47
	Hant's Harbour	10	16	19	32
Wave Runup	Ferryland	37	41	45	47
	Brigus	13	15	15	19
	Heart's Delight – Islington	27	30	32	40
	Winterton	17	18	30	34
	Hant's Harbour	44	59	65	78

11.0 DEVELOPMENT OF A FLOOD FORECASTING STRATEGY

11.1 Overview

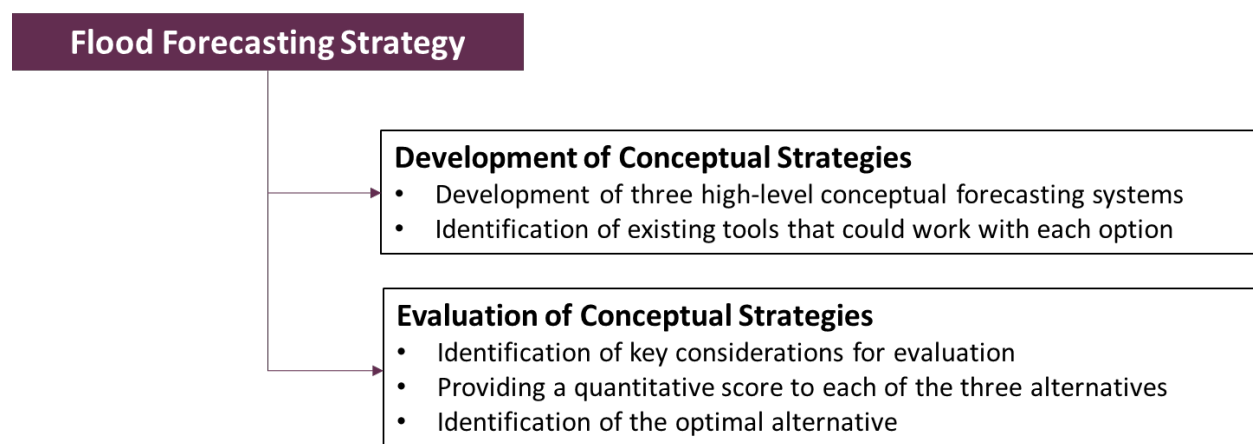
To support any future development and implementation of a flood forecasting service in Ferryland, Brigus, Heart's Delight-Islington, Winterton and Hant's Harbour, a series of high-level conceptual flood forecasting strategies were developed and evaluated. The conceptual flood forecasting strategies included:

- **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 hazard 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 166.

FIGURE 166: OVERVIEW OF THE FLOOD FORECASTING STRATEGY TASKS



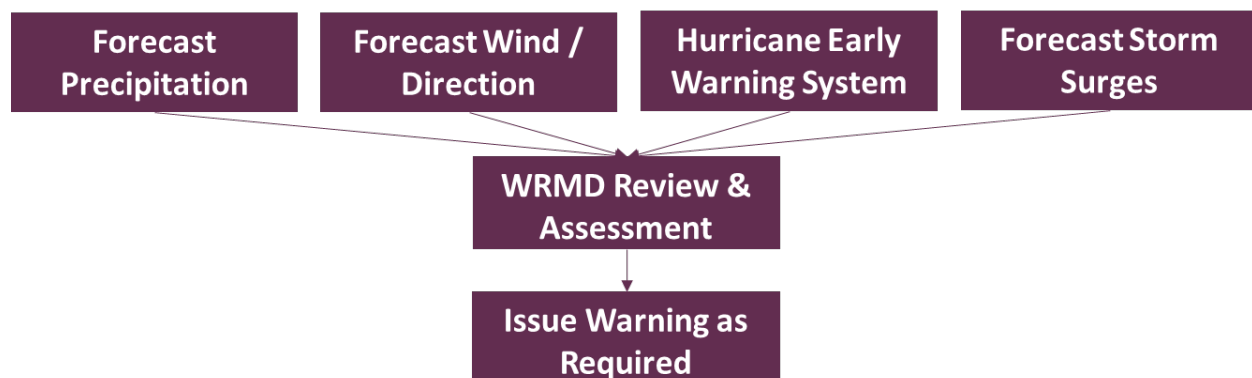
11.2 Development of Conceptual Strategies

Three high-level conceptual flood forecasting strategies were developed for the communities of Ferryland, Brigus, Heart's Delight-Islington, Winterton and Hant's Harbour, 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 hazard 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 167.

FIGURE 167: 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 flooding in Ferryland, Brigus, Heart's Delight-Islington, Winterton and Hant's Harbour is often a result of storm surges, wave runup, 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. Similarly, forecast warnings from ECCC regarding high wind could similarly provide early warning for wave events. Additional tools that could be monitored by government personnel include:

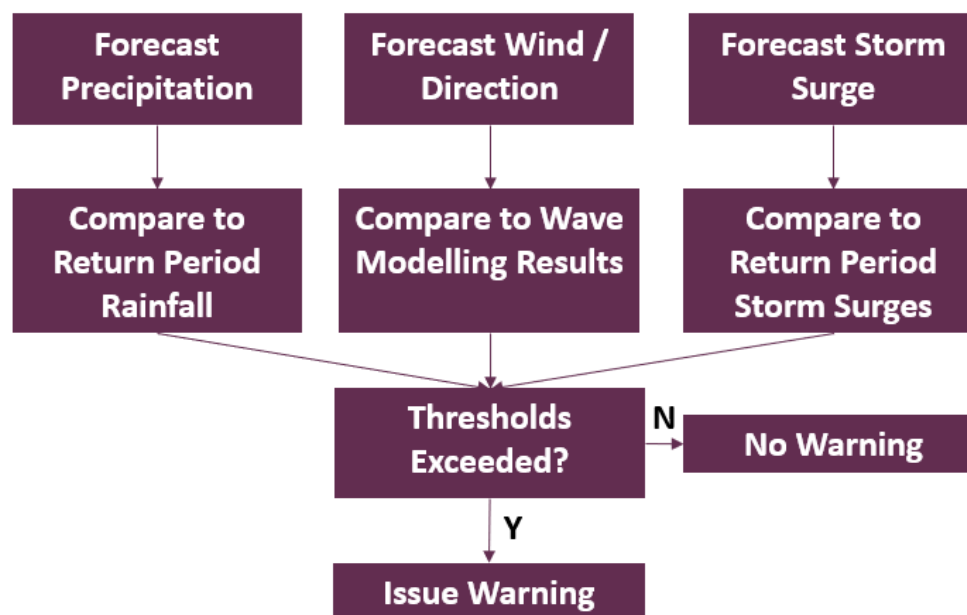
- ECCC forecast storm surge data, including from the Global Deterministic Storm Surge Prediction System and the Regional Ensemble Storm Surge Prediction System.
- ECCC forecast meteorological data, including the Global Deterministic Prediction System and Numerical Weather Prediction data.

- 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 168.

FIGURE 168: FORECASTING STRATEGY OPTION 2

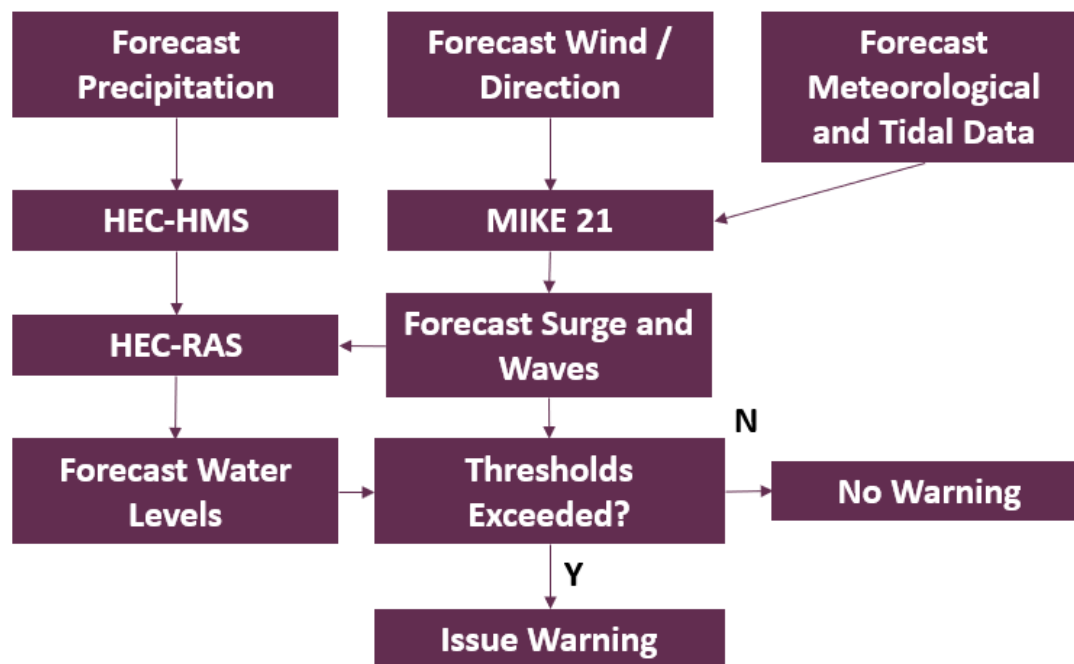


11.2.3 FORECASTING STRATEGY OPTION 3

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 169.

FIGURE 169: 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 Ferryland, Brigus, Heart's Delight-Islington, Winterton and Hant's Harbour are largely driven by storm surge, wave runup, and large rainfall that is typically associated with post-tropical depressions, which are relatively well forecast. It was noted in Ferryland that high wind events can cause flooding due to wave runup, regardless of tidal and / or storm surge levels.

The resulting evaluation of the three conceptual options is shown schematically on Figure 170, with green representing higher ranking, yellow representing moderate ranking, and red representing the lowest ranking.

FIGURE 170: QUALITATIVE EVALUATION OF FLOOD FORECASTING STRATEGIES

	Option 1	Option 2	Option 3
Development Cost	●	●	●
Maintenance Cost	●	●	●
Operational Effort	●	●	●
Computational Cost	●	●	●
Forecast Level of Detail	●	●	●

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, who concurred that Option 1 was most suitable.

12.0 REGIONAL ASSESSMENT OF STORM SURGE AND WAVES

To inform coastal floodplain mapping efforts throughout the province, and to provide a consistent basis for the modelling and interpretation of coastal processes and hazards related to flooding, an Atlas of Storm Surge and Wave climates along the coasts of Newfoundland and Labrador has been established for WRMD (DHI, 2024) as part of this project, and is included in Appendix O for reference. Since this work was completed as part of this study, the technical aspects of the scope of work associated with the development of the Atlas are summarized below, and documented in detail in Appendix O. The intent of this Atlas is to provide a Provincial dataset that is forward looking and provides insight into how coastal conditions will change throughout the province, over time, as the climate continues to change. Results from the development of the Atlas were used to define climate change impacts in Ferryland, Brigus, Heart's Delight – Islington, Winterton, and Hant's Harbour. Prior to the establishment of this dataset, a series of interviews were conducted with climate change experts from ECCC, National Research Council of Canada (NRC), NRCan, and other institutes to refine the methodology applied for the development of the Atlas.

A set of advanced numerical models were specifically developed for this initiative which cover the entire province's coastline with spatial resolutions as fine as 1.5 km. The models were developed to simulate both the past (hindcast), and the future (climate change scenarios), to see how present-day coastal baselines may shift under various climate scenarios. In particular, the loss of nearshore sea ice in Labrador, and rising sea levels throughout the province, are anticipated to have profound impacts in the coastal nearshore of Newfoundland & Labrador, including in communities such as Ferryland, Brigus, Heart's Delight-Islington, Winterton and Hant's Harbour.

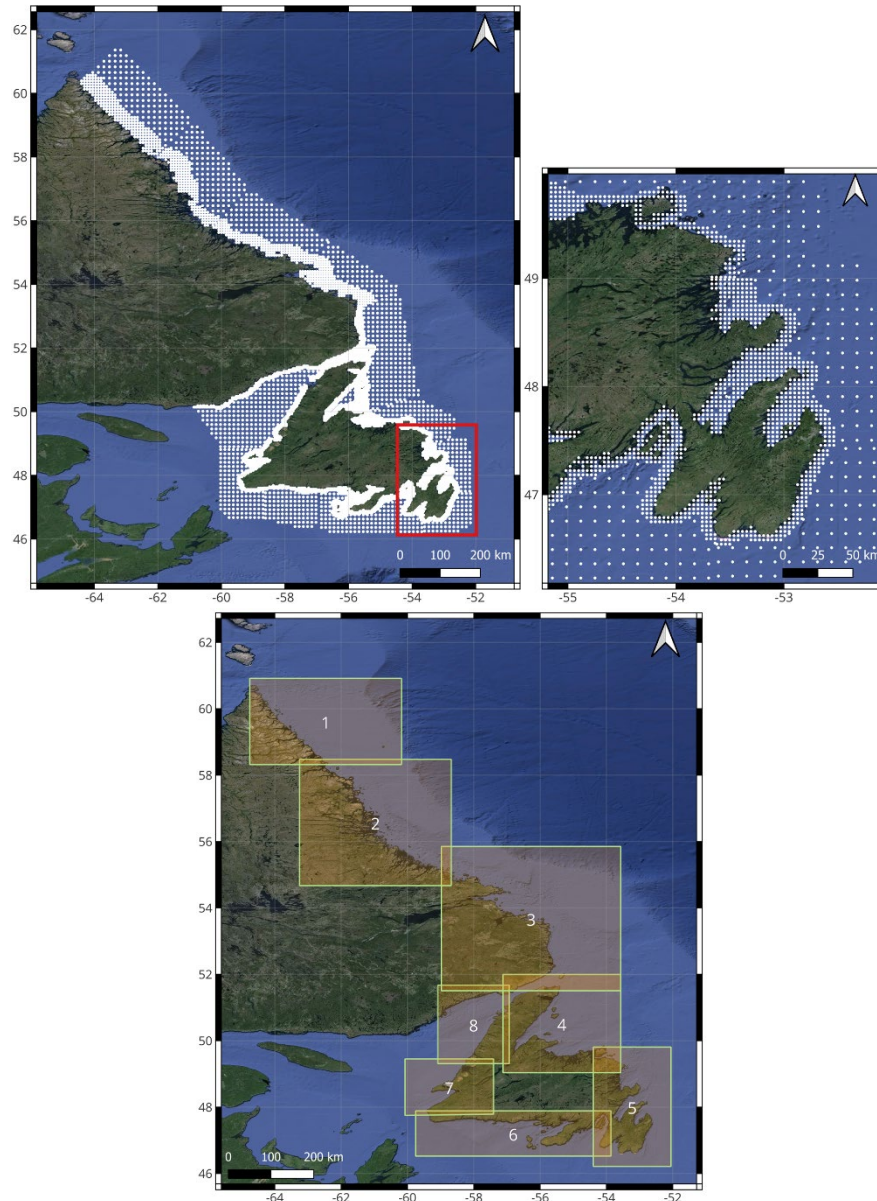
The Atlas provides a range of digital datasets, including time series, extreme value tables, GeoJSON and raster maps, which can be made available digitally upon request from the WRMD. The data package is split into hindcast (i.e. a historical period covering 1980-2022) and the climate change projections (i.e. a historical baseline from 1984-2014 and future projection from 2015-2100). The models used to generate the data have been extensively validated against measurements at various points around the province, demonstrating their reliability and accuracy.

The climate change projections of storm surge and wave climates rely on the downscaling of two Global GCMs considering the SSP5-8.5 scenario. The selected models are the EC-Earth3 and ACCESS-CM2 from the Coupled Model Intercomparison Project (Phase 6) (CMIP6). These models were chosen as they constituted the sole CMIP6 global wave climate projections accessible at the time of the project. Details on model performance with respect to wave conditions are provided in Meucci et al (2023). At present the Atlas contains results from two GCMs and should be considered as a first step towards developing a more comprehensive and robust climate projection product, with a larger ensemble of models and scenarios.

Detailed technical documentation of the Atlas can be found in DHI (2024) and in Appendix O. The Atlas' technical document describes the data that is provided within the Atlas, including a description of the methodology and the models used to generate the datasets, the limitations and typical use cases for the

dataset, and guidance on how this information can be used to inform coastal floodplain mapping. Figure 171 provides an overview of the extraction points and coverage of the 2D tiles composing the Atlas.

FIGURE 171: OUTPUT LOCATIONS FOR THE METOCEAN PARAMETERS ALONG THE COASTS OF NEWFOUNDLAND AND LABRADOR (UPPER) AND OVERVIEW OF RASTER MAPS TILES FOR STORM SURGE STATISTICS COVERING THE ENTIRE PROVINCE



The various climate change projections (i.e. models) considered in the Atlas must be considered together as an ensemble, or multiple lines of evidence, as they represent possible futures rather than definitive outcomes. It is important not to prioritize one projection over another for subsequent analysis. Instead, these

projections provide high-level guidance on the potential evolution of the climate and help outline a plausible range of future scenarios.

In some cases, the downscaled GCMs indicate contradicting trends (e.g., increases versus decreases) across various communities, time horizons, and statistics. When this occurs, it is not feasible to draw firm conclusions about future climate trends. However, these discrepancies offer relevant insight into the inherent uncertainties in climate projections, which are critical for high-level assessments.

The projections described in the Atlas complement the detailed assessments, such as those presented in Section 8.2.8, which rely on extreme values derived from long-term hindcasts. However, it is important to emphasize that metrics such as the 50th, 99th percentile, and AAM values from the climate change projections models should not be directly applied to AEPs derived from historical hindcast datasets. The two approaches—climate projections and hindcasts—serve distinct purposes and require careful integration for meaningful use in coastal flood assessments.

The results described in the Atlas are intended for strategic and preliminary decision-making rather than direct application in engineering design. For site-specific or community-level projects, studies using detailed models are necessary to appropriately capture the complexities of climate change impacts and associated uncertainties at the location of interest. Incorporating these uncertainties into future applications will improve the robustness of the outcomes, ensuring that the designs or policies remain adaptive to a range of future conditions. Recommendations for applying such climate change projections are detailed in the Atlas technical documentation.

13.0 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 watersheds within Hant's Harbour and Winterton would experience similar hydrologic responses to rainfall as the Big Brook watershed. Similarly, the watersheds within Brigus and Heart's Delight – Islington would experience similar hydrologic responses to the Shearstown Brook watershed and the watersheds in Ferryland would experience similar hydrologic responses as the Seal Cove Brook watershed.
- Evapotranspiration, surface storage, and canopy storage were assumed to have a negligible impact on short (i.e. 24-hour or less) rainfall events.
- The 20 and 100-year AEP rainfall events based off on the IDF curve at St. John's would be representative throughout the various watersheds considered in the study.

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 and discussions with representatives from the towns. While near-term development plans are either not anticipated, limited, or planned for areas outside of the watersheds considered in this study area, any future development plans have assumed that those 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 in Ferryland, Brigus, Hant's Harbour, Winterton, and Heart's Delight – Islington were assumed based on nearby surveyed cross sections.
- 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 Heart's Delight Brook to accumulate to the upstream boundaries of those models.
- The downstream boundary water level on Heart's Delight Brook set to an elevation required to maintain numerical stability.

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 Hazard Mapping

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

14.0 CONCLUSIONS

The following conclusions can be made from the Climate Change Flood Risk Mapping Study for Ferryland, Brigus, Hant's Harbour, Winterton, and Heart's Delight – Islington

- 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 Ferryland, Brigus, Hant's Harbour, Winterton, and Heart's Delight – Islington. 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 17% to 35% under climate change conditions. Sea levels are anticipated to rise by 0.63 m in Trinity Bay and Conception Bay, and 0.66 m in Ferryland.
- Riverine hydraulic models were developed for the various rivers and creeks assessed as part of this study. Where available, models were calibrated to water levels recorded by 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 Halfway Brook (Hant's Harbour), Heart's Delight Brook (Heart's Delight – Islington), and Western Pond Brook (Winterton) 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 RIVICE models were unable to establish an ice jam on Halfway Brook and Western Pond Brook, and the Heart's Delight Brook, the simulated ice jam elevations 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 Trinity Bay, Conception Bay, and in the vicinity of Ferryland. The regional coastal model was calibrated and validated to available historical tidal gauge data, and used as inputs to the Trinity Bay, Conception Bay, and Ferryland area 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 Ferryland, Brigus, Hant's Harbour, Winterton, and Heart's Delight – Islington 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 20 and 100-year AEP wave uprush heights throughout the study areas.

- Flood hazard maps were developed for current climate and climate change conditions in wave uprush. The mapping deliverables included 18 map sheets in Ferryland, 17 map sheets in Brigus, 26 map sheets in Hant's Harbour, 10 map sheets in Winterton, and 19 map sheets in Heart's Delight-Islington, as well as digital data showing the depth of flooding, flow velocities, and flood risk in each of the communities.
- The regional-scale storm surge and wave model was used to establish near-shore AEP storm surge level and wave heights along the entire coast of Newfoundland and Labrador. The resulting report documenting the analysis provides technical documentation of the model development and calibration, as well as guidance for the use of the resulting AEP storm surge levels and wave heights.
- Several buildings are affected by flooding in Ferryland, Brigus, Hant's Harbour, Winterton, and Heart's Delight – Islington under current climate conditions.
 - In Ferryland, there are 6 and 14 buildings that are flooded by storm surge / riverine flooding, and 13 and 41 buildings that are flooded by wave runup for the 20 and 100-year AEP floods under current climate conditions. Under climate change conditions, the number of flooded buildings increase to 21 and 30 buildings that are flooded by storm surge / riverine flooding, and 45 and 47 buildings that are flooded by wave runup for the 20 and 100-year AEP floods.
 - In Brigus, there are 192 and 219 buildings that are flooded by storm surge / riverine flooding, and 13 and 15 buildings that are flooded by wave runup for the 20 and 100-year AEP floods under current climate conditions. Under climate change conditions, the number of flooded buildings increase to 230 and 254 buildings that are flooded by storm surge / riverine flooding, and 15 and 19 buildings that are flooded by wave runup for the 20 and 100-year AEP floods.
 - In Heart's Delight - Islington, there are 19 and 29 buildings that are flooded by storm surge / riverine flooding, and 27 and 30 buildings that are flooded by wave runup for the 20 and 100-year AEP floods under current climate conditions. Under climate change conditions, the number of flooded buildings increase to 38 and 47 buildings that are flooded by storm surge / riverine flooding, and 32 and 40 buildings that are flooded by wave runup for the 20 and 100-year AEP floods.
 - In Winterton, there are 21 and 27 buildings that are flooded by storm surge / riverine flooding, and 17 and 18 buildings that are flooded by wave runup for the 20 and 100-year AEP floods under current climate conditions. Under climate change conditions, the number of flooded buildings increase to 28 and 47 buildings that are flooded by storm surge / riverine flooding, and 30 and 34 buildings that are flooded by wave runup for the 20 and 100-year AEP floods.
 - In Hant's Harbour, there are 10 and 16 buildings that are flooded by storm surge / riverine flooding, and 44 and 59 buildings that are flooded by wave runup for the 20 and 100-year AEP floods under current climate conditions. Under climate change conditions, the number of flooded buildings increase to 19 and 32 buildings that are flooded by storm surge / riverine flooding, and 65 and 78 buildings that are flooded by wave runup for the 20 and 100-year AEP floods.
- Three high-level conceptual flood forecasting strategies were developed for the communities of Ferryland, Brigus, Hant's Harbour, Winterton, and Heart's Delight – Islington, 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.

15.0 RECOMMENDATIONS

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

- The community of Ferryland has noted that coastal erosion is a pressing concern for at select locations within the community. A study should be completed to understand the nature of the coastal erosion and to develop erosion mitigation measures to reduce or prevent ongoing erosion.
- The communities of Ferryland, Brigus, Hant's Harbour, Winterton, and Heart's Delight – Islington should adopt development policies to ensure that any future developments do not result in net increases in flow on the rivers and creeks near those proposed developments.
- Limited meteorological data is available in Ferryland, Brigus, Hant's Harbour, Winterton, and Heart's Delight – Islington. A meteorological station should be installed in Hant's Harbour, Winterton, or Heart's Delight – Islington to enhance the understanding of the hydrology in the area.
- Throughout the study area, there is limited information available regarding the hydrology of small creeks, as there are no WSC gauges installed on any of the waterways considered in the study. This gap in information could be addressed by the reinstatement of WSC gauges that have been taken out of service on the Avalon Peninsula (e.g. WSC gauges 02ZL003, 02ZM004, 02ZM003, etc.), or the installation of new hydrometric stations on small watersheds, particularly along the coast of Trinity Bay (e.g. Heart's Delight Brook, Western Pond Brook, etc.).
- The potential for ice jam floods on Western Pond Brook (Winterton), Heart's Delight Brook (Heart's Delight – Islington), and Halfway Brook (Hant's Harbour) should be investigated further as part of future flood mapping efforts, provided that river ice jam modelling tools that are better suited to narrow, steep rivers become available.
- Representatives from the Town of Ferryland noted that offshore earthquakes could trigger tsunamis, as occurred in 1929, and result in coastal flooding. A study should be completed to evaluate flood potential associated with tsunamis.
- The collection of topo-bathy LiDAR should be considered for future flood hazard mapping studies, as it represents an efficient means of collecting bathymetric data in shallow water.

16.0 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. Conestoga-Rovers & Associates (2015). *Intensity-Duration-Frequency Curve Update for Newfoundland and Labrador*. Mount Pearl, NFLD: Conestoga-Rovers & Associates.
5. 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.
6. EurOtop (2018). *Manual on Wave Overtopping of Sea Defences and Related Structures – An Overtopping Manual Largely Based on European Research, but for Worldwide Application*.
7. FEMA, "Guidance for Flood Risk Analysis and Mapping, Coastal Wave Runup and Overtopping," 2021.
8. 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.
9. French, J. 1982. Memorandum on Special Computation Procedure Developed for Wave Runup Analysis for Casco Bay. FIS - Maine, 9700-153. Camp Dresser & McKee
10. 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*.
11. KGS Group (2021). Climate Change Flood Mapping Study for Placentia, Carbonear, Salmon Cove and Victoria – Final Report. *KGS Group: Winnipeg, MB, Canada*.
12. Lemos, Menendez, Semedo, Miranda, Hemer, (2021). On the decreases in North Atlantic significant wave heights from climate projections. *Climate Dynamics*, 57(9-10), 2301-2324.
13. A. Meucci., I. R. Young, M. Hemer, C. Trenham and I. G. Watterson, "140 years of global ocean wind-wave climate derived from CMIP6 ACCESS-CM2 and EC-Earth3 GCMs: Global trends, regional changes, and future projections" *Journal of Climate*, pp. 36(6): 1605-1631, 2023.
14. E. Murphy, J. Boisvert, R. McLean, V. Pilechi, J. Cousineau, L. Sushama and Z. Liang, "Wave Run-up Contributions to Coastal Flood Hazards in New Brunswick," in CSCE Annual Conference, Laval, 2019.

15. Natural Resources Canada (2025). *Automatically Extracted Buildings*. Retrieved from <https://open.canada.ca/data/en/dataset/7a5cda52-c7df-427f-9ced-26f19a8a64d6>
16. Natural Resources Canada, "Federal Hydrologic and Hydraulic Procedures for Flood Hazard Delineation Version 2.0," Natural Resources Canada, 2023.
17. Robin, C., Craymer, M., Ferland, R., James, T. S., Lapelle, E., Piraszewski, M., and Zhao, Y. NAD83V70VG: A New National Crustal Velocity Model for Canada. *Geomatics Canada: Ottawa, ON, Canada*.
18. 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
19. 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.
20. Town of Heart's Delight – Islington (2015). Heart's Delight – Islington Municipal Plan 2015. *Town of Heart's Delight - Islington: Heart's Delight – Islington, NL, Canada*.
21. 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.
22. 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.
23. 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>.
24. USACE (2021). *HEC-RAS User's Manual*. Washington, D.C.: U.S. Army Corps of Engineers. Retrieved from <https://www.hec.usace.army.mil/confluence/rasdocs/rasum/latest>.

APPENDIX A

Summary of Background Information

APPENDIX B

Historical Flood Event Inventory

APPENDIX C

Survey Processing Reports

APPENDIX D

Culvert and Bridge Crossing Details

APPENDIX E

RFFA Statistical Screening Results

APPENDIX F

Annual Maximum Precipitation Data

APPENDIX G

IDF Curve Data

APPENDIX H

EVA Analysis Results

APPENDIX I

Monthly Wave Rose Data

APPENDIX J

Wave Model Outputs

APPENDIX K

HEC-RAS Sensitivity Analysis Results

APPENDIX L

Flood Hazard Maps

APPENDIX M

Comparison of Historical and Updated Flood Hazard
Maps

APPENDIX N

Flood Depth, Velocity, and Risk Overview Maps

APPENDIX O

Newfoundland and Labrador Atlas of Storm Surge
and Wave Climates



Experience in Action