

# **Climate Change Flood Risk Mapping Study and the Development of a Flood Forecasting Service: Humber River Communities**

## **Volume 1: Flood Risk Mapping Development**

**Government of Newfoundland and Labrador  
4th Floor, West Block, Confederation Bldg.  
PO Box 8700, St. John's, NL, Canada, A1B 4J6**

December 17, 2021





# **Climate Change Flood Risk Mapping Study and the Development of a Flood Forecasting Service: Humber River Communities**

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## **Final Project Report – Volume 1: Flood Risk Mapping Development**

**Project # TPB188156**

### **Prepared for:**

Water Rights, Investigations, and Modelling Section  
Water Resources Management Division  
Department of Environment and Climate Change  
Government of Newfoundland and Labrador  
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**17-Dec-2021**

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**GOVERNMENT OF  
NEWFOUNDLAND AND LABRADOR**

**CLIMATE CHANGE FLOOD RISK MAPPING STUDY and the  
DEVELOPMENT OF A FLOOD FORECASTING SERVICE  
HUMBER RIVER COMMUNITIES**

**PROJECT REPORT**

**VOLUME 1: FLOOD RISK MAPPING DEVELOPMENT**

Submitted to:



Water Rights, Investigations, and Modelling Section  
Water Resources Management Division  
Department of Environment and Climate Change  
Government of Newfoundland and Labrador

Submitted by:

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December 17, 2021

TPB188156 R00

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December 17, 2021

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To: Department of Environment and Climate Change  
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Attn: Mr. Mohammad Khayer, M.Eng., P.Eng.  
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Water Rights, Investigations, and Modelling Section  
Water Resources Management Division (WRMD)

Dear Sir:

Re: Climate Change Flood Risk Mapping Study and the Development of a Flood Forecasting Service:  
Humber River Communities - Final Project Report

Wood Environment & Infrastructure Solutions, a Division of Wood Canada Limited, is pleased to provide the final project report for the above noted project.

We trust this submission meets with your requirements. We would be happy to discuss any aspect of the submission with you.

Yours truly,

Wood Environment & Infrastructure Solutions,  
a Division of Wood Canada Limited

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<b>Amir Ali Khan, Ph.D, P.Eng</b>	Manager
<b>Mohammad Khayer, M.Eng., P.Eng.</b>	Senior Engineer
<b>Rob Holloway</b>	Senior Environmental Scientist
<b>Shabnam Mostofi, Ph.D., EIT</b>	Environmental Engineer
<b>Neil Stapleton</b>	Environmental Scientist

Wood also acknowledges the efforts and contributions of the following staff from the Corporate Services and Projects group in the Office of the Chief Information Officer participating in the implementation of the Humber River Flood Forecasting Service:

<b>Adele Costello</b>	Delivery Manager
<b>Jackie Osmond, B. Eng</b>	Project Manager

To complete this study, Wood led a diverse and highly experienced Project Team, with members from different companies supporting key project elements, including:

- Wood – Wood Environment & Infrastructure Solutions, a division of Wood Canada Limited was responsible for the overall management of the project and was responsible all aspects of the study, including mainly, the development of the hydrologic and hydraulic models used for development of flood risk mapping and the flood forecasting system.
- Mosaic 3D (Geniarp Group) - Mosaic 3D completed the aerial LiDAR and ortho-photo survey for the project.
- Dr. Karl-Erich Lindenschmidt – Dr. Lindenschmidt (Associate Professor at the School of Environment and Sustainability, at the University of Saskatchewan.) worked closely with Wood to assess ice jam flood events.
- 4DM Inc. – 4DM was responsible for the development of the software framework (i.e. HydrologiX) that enabled the development of the Humber River Flood Forecasting System. 4DM was specifically responsible for the model runners, hydro-meteorological and gauge data retrieval and processing, web user interface design and the internal workings of the forecasting application.
- SEM Ltd / Yates and Wood Ltd– Sikumiut Environmental Management (SEM) Limited and Yates and Wood Limited were responsible for various topographic and bathymetric survey services supporting study objectives.

## **EXECUTIVE SUMMARY**

The report, *Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation* (Warren and Lemmen, 2014), has advanced a number of considerations with regard to projected precipitation under the influences of climate change, namely:

- Increases in precipitation are projected for the majority of the country and for all seasons;
- More frequent heavy precipitation events are projected, with an associated increased risk of flooding;
- Rare extreme precipitation events are currently projected to become about twice as frequent by mid-century over most of Canada;
- Increases in winter streamflow are projected for many regions in southern Canada; and
- Widespread decreases in the duration of snow cover are projected across the Northern Hemisphere.

The more recent Canada's Changing Climate Report (Bush and Lemmen, 2019) maintains these themes, through the report's key messages about precipitation, namely:

- There is medium confidence that annual mean precipitation has increased, on average, in Canada, with larger percentage increases in northern Canada.
- Annual and winter precipitation is projected to increase everywhere in Canada over the 21st century, with larger percentage changes in northern Canada. Total summer precipitation is projected to decrease over southern Canada under a high emission scenario towards the end of the 21st century.
- For Canada as a whole, observational evidence of changes in extreme precipitation amounts, accumulated over periods of a day or less, is lacking. However, in the future, daily extreme precipitation is projected to increase with high confidence.

As global climate changes and increases in human population and development continue in the coming decades, sustainable management of water resources will be critical. One potential result of the interplay of these global influences is an increase in flooding. Floods have the potential to cause significant personal injury, damages to property and loss of life. To assist with planning in and around potential flood zones and to minimize damages associated with flooding, information on the projected spatial extent and expected frequency of floods is critical. The factors that affect flooding must also be evaluated periodically, particularly when those factors are subject to on-going change. Changes in climate and land use through development can have significant impacts on flood risk and both have been changing at an increasing rate. The nature of these changes and their associated impacts on flood risk need to be evaluated on a periodic basis.

Wood Environment & Infrastructure Solutions, a division of Wood Canada Limited was retained by the Province of Newfoundland and Labrador, Department of Environment and Climate Change, Water Resources Management Division in October 2018 to develop flood risk mapping for an area within the Humber River Watershed focusing on the reach extending, generally, from the community of Steady Brook to the community of Reidville.

This Climate Change Flood Risk Mapping study was funded under the federal National Disaster Mitigation Program (NDMP) and by the province of Newfoundland and Labrador.

This flood risk mapping project has employed acceptable industry standard techniques and available historic/recorded data and new data developed through this project. The technical guidelines developed under the Canada-Newfoundland Flood Damage Reduction Program (Hydrologic and Hydraulic Procedures for Flood Plain Delineation, Environment Canada, 1976); the new Federal Flood Mapping Guidelines Series; and the study Terms of Reference which includes the province's Technical Document for Flood Risk Mapping Studies have all provided the basis for the guiding principles for all components of the study. This basis was then supplemented with additional information available in the manuals for software applied in the study and industry standard approaches.

As defined in the Request for Proposal (RFP), WRMD has directed that this study focus on development of flood risk information for several communities within the study area of the Humber River, as follows:

- a) Estimate water levels, flows and flood risk maps indicating flood plains associated with the 1 in 20-year and 1 in 100-year Annual Exceedance Probability (AEP), using hydrological and hydraulic modelling, for scenarios including current and future climate and current and future development conditions.
- b) Estimate flood inundation limits, flood velocity, and develop flood hazard maps associated with the 1 in 20-year and 1 in 100-year AEP for current climate and current development scenario.
- c) Evaluate and implement a flood forecasting service for the study area using the hydrologic and hydraulic models implemented in this study.
- d) Provide a hydraulic capacity assessment of all existing and modelled hydraulic structures.

The following RFP requirements have guided this study:

- The current climate condition was defined by the latest Intensity-Duration-Frequency (IDF) data as available from *Final Report - Intensity-Duration-Frequency Curve Update for Newfoundland and Labrador* (CRA, 2015) and Environment and Climate Change Canada.
- Climate change influences regarding precipitation and sea level were estimated using information from the following sources:
  - ▶ Information regarding projected precipitation increases was defined using information documented in the report (CRA, 2015) noted above.
  - ▶ *Projected Impacts of Climate Change for the Province of Newfoundland & Labrador: 2018 Update*, (Finnis and Daraio, 2018).
  - ▶ Projections for climate change influenced sea level rise were defined by the projections documented in *Past and Future Sea-Level Change in Newfoundland and Labrador: Guidelines for Policy and Planning* (Batterson and Liverman, 2010).
- The current development condition was defined by a study specific land cover/land use analysis completed in compliance with the requirements as defined in the RFP.

- The fully developed watershed condition was defined based on consultation with local communities and their associated future land use plans.

A review of known flood events identified forty-six (46) flood events in the existing inventory for the period 1944 to 2013 events having occurred in the Humber River study area. Based on the review of readily available materials, five (5) additional flood events were added to the inventory.

Flood risk and hydrotechnical studies were previously completed in the area for Steady Brook in 1984 and Deer Lake in 1987, on behalf of the Government of Newfoundland and Labrador.

The field program for this study included collection of high-resolution LiDAR DTM of the Humber River watershed which was completed in Spring 2019 and collection of bathymetric data for the main Humber River and select tributaries over the study period. Further, a field survey for the hydraulic structures in the study area was conducted which included nine (9) hydraulic structures (i.e. bridges, culverts, etc.). Additionally, the field program included Real Time Kinematic survey of a number of streamflow recording stations to establish the conversion from the local datum used for recording of water levels to the Canadian Geodetic Vertical Datum of 2013.

The Humber River watershed is influenced by three reservoirs, namely Hinds Lake, Grand Lake and Deer Lake. Hinds Lake and Grand Lake are both regulated by hydroelectric developments, while Deer Lake is an unregulated, natural reservoir.

The 1 in 20-year and 1 in 100-year Annual Exceedance Probability (AEP) streamflows were estimated for the Humber River and tributaries using both statistical and deterministic methodologies. The deterministic hydrological modelling completed for this study was based on the software HEC-HMS developed by the US Army Corp of Engineers (USACE). Comparative assessment of the flow estimates over the range of methodologies concluded that the deterministic model results provided a good and supportable estimate of streamflow for these watersheds. The methods used in the current study led to comparable flood flow estimates which provide confidence in the results.

It is understood that any hydrologic model is sensitive to a variety of input parameters including rainfall and Soil Conservation Service Curve Numbers (SCS-CN). These parameters were developed based upon the best available soil information from Agriculture Canada and land cover data as determined through this study; the latter reflecting conditions in 2017.

A hydraulic model based on the USACE program HEC-RAS was developed for reaches of the Humber River and tributaries including eighteen (18) watercourses defined using ninety-six (96) separate reaches and covering a linear distance of approximately 178 km (with almost 1,500 cross-sections). The model was developed based on field surveyed bathymetric data and LiDAR survey conducted in 2018 and 2019. The new hydraulic model also includes sixteen (16) bridges and seventy-nine (79) culverts. Coding of structures was supported by topographic field survey, visual inspection, available drawings and measurement. It should be noted that the open water flood assessment is based on summertime 1 in 20-year AEP and 1 in 100-year AEP floods.

Ice Jam assessments were completed for the Town of Deer Lake and the Town of Steady Brook, as a component of this study. The Town of Deer Lake assessment focused on the January 2018 event and

concluded that the January 2018 event was the result of a unique set of snow cover, wind, frazil ice, temperature and other conditions that produced a most extreme case, approximating a 1 in 500-year event.

As well, the Town of Steady Brook assessment provided a high-level overview to determine if patterns are present between the ice, hydraulic and meteorological regimes of the brook, its basin and surrounding region. It was concluded that the reasons for flooding in the Town of Steady Brook are multifaceted: potential ice conditions in winter, snowmelt and rain-on-snow events in spring and high precipitation and flows accompanied by high antecedent moisture conditions in the autumn. It was also concluded that the currently available Steady Brook streamflow gauge record does not cover a sufficient time period to allow for the determination of patterns between the ice, hydraulic and meteorological regimes of the watercourse.

Since all hydraulic model input parameters were selected based on reliable background information, it is expected that the uncertainty associated with model output is minimal. As such, it is recommended that the hydraulic model be used as the basis by which to simulate the required flood scenarios.

An evaluation of the potential impacts of climate change on flood risk was completed. Estimates of flood plains for the 2080 period were computed and delineated. It was concluded from this assessment that climate change has the potential to increase flood risk in the Humber River watershed.

It should be noted that there is a great deal of uncertainty with all climate models, statistical downscaling and projection of rainfall to point locations. The quantification of rainfall and, subsequently, flood plain estimates should not be interpreted as an accurate portrayal of possible future events. These estimates provide a good indication of upward and downward trends and general sense of the magnitude of the potential change but should not be considered absolute.

Key recommendations stemming from the assessments completed for this study are outlined, as follows:

1. A series of recommendations specific to the continued development of the Flood Events Inventory are detailed with the objective of increasing usability and integrity of the database.
2. It is recommended that the municipalities located within the study area adopt the flood lines developed by the current study for its municipal plan and development regulations.
3. It is recommended that the municipalities located within the study area and their partners make use of the up-to-date LiDAR topographic data and orthophotography which was collected for this study for relevant municipal initiatives.
4. It is recommended that the municipalities located within the study area engage in a program to measure water levels at designated watercourse crossing structures during flood events. This will expand the database of information which could be used to support both hydrologic and hydraulic modelling in the future.
5. It is recommended that a program focused on unregulated streamflow data collection be developed for Humber River and its associated tributaries. Additional recording stations at strategic locations (e.g., outflow from each of the unregulated tributary areas) would provide a foundation of data that would enhance the hydrologic model calibration and validation processes.

6. It is noted that gauging station 02YL012, located on the Steady Brook, may be influenced by the main Humber River when water levels are high. It is recommended that this situation be investigated in greater detail.
7. It is recommended that WRMD engage in a program to collect and develop stage-storage-discharge curves and operational data including rules curves, gate(s) settings and reservoir water levels for all dams in the Province. Significant resources were utilized with the current project to first determine the ownership of the data (i.e. the contact person within the dam owner organization) and also to deal with delays that resulted from the time that was found to be necessary to obtain the information, once the most appropriate contact was established. If this information was already available through WRMD at the outset of the project, the development of the hydrologic model would have been more efficient.
8. It is recommended that the application of HEC-GeoHMS, HEC-HMS, HEC-GeoRAS and HEC-RAS be continued in future watershed and flood studies as their use both simplifies the development of deterministic models, as well as provides for the generation of a significant warehouse of information that can be used for other ancillary purposes beyond hydrologic assessments.
9. The Deer Lake Reach 2 watercourse between cross-sections 1043.76 and 1292.89 experiences a spill to the west. This area, generally to the west of the TransCanada Highway and south-west of The Viking Trail/ Old Bonne Bay Road, lies on a side slope with the down slope transitioning to the main Humber River to the west. Given the general topography in the area, flood waters would spill down slope directly to the main Humber River and not follow the Deer Lake Reach 2 watercourse which generally flows to the north. While the HEC-RAS 1D modelling approach applied for this project is considered appropriate for flood mapping purposes, the design of any mitigation strategies (e.g. enhanced and/or additional conveyance for spill waters) may benefit from the application of a HEC-RAS 2D modelling approach.
10. It is recommended that two-dimensional (2D) hydraulic analysis be considered for the confluence of the Humber River with Steady Brook to characterize flooding mechanisms in this area in greater detail.
11. It is recommended that a program focused on field-based collection of ice thickness/accumulation data should be implemented in areas when ice jamming occurs. A database of ice thickness/accumulation data would enhance and provide additional confidence the ice modelling process and results.
12. It is recommended, for future study beyond the present work scope, that the continuous HEC-HMS model developed for the flood forecasting component of this study be augmented to model the Steady Brook watershed discretely and in greater detail. Using this tool, in conjunction with the available long-term meteorological record, the available streamflow time series may be extended providing a longer dataset upon which to base the ice jamming assessment and its associated conclusions.
13. It is recommended that the municipalities located within the study area consider stream and/or structure rehabilitation in the areas where water levels exceed the river banks during the 1 in 100-year AEP flood and spill over land. This will confine extreme flood flows to the river channel and avoid the risk of overland flooding.
14. It is recommended that meteorological conditions in the Humber River study area be monitored towards determination of increasing trends in rainfall and generally extreme weather.

15. It is recommended that climate change be integrated into municipal planning in those areas where increasing flood risk is relevant such as infrastructure and emergency planning.
16. It is recommended that this study should be revisited in approximately ten (10) years, after which time additional detail may be available from rainfall and streamflow gauges in the basin.
17. It is recommended that LiDAR topographic survey and orthophoto databases continue to be used for future flood risk mapping studies as they provide an accurate means of collecting high quality topography information over large areas.

## Table of Contents

<b>1.0</b>	<b>Introduction.....</b>	<b>1</b>
1.1	Study Area.....	3
1.2	Work Scope.....	6
1.3	Reporting Structure.....	8
<b>2.0</b>	<b>Background Review and Data Acquisition.....</b>	<b>11</b>
2.1	Data Acquisition.....	12
2.2	Data Analysis.....	16
2.2.1	1984 Hydrotechnical Study of the Steady Brook Area.....	16
2.2.2	1987 Hydrotechnical Study of the Deer Lake Area.....	25
2.2.3	Review of Existing Humber River Flood Forecasting Systems.....	36
2.3	Historical Flooding Inventory.....	41
2.3.1	Flood Events Review.....	41
2.3.2	Flood Inventory Database Review.....	47
2.3.3	Flood Inventory Database Analytics.....	49
2.3.4	Flood Inventory Database Recommendations.....	50
2.4	Consultation with the Municipalities.....	51
<b>3.0</b>	<b>Field Program.....</b>	<b>53</b>
3.1	Overview.....	54
3.2	Methodology.....	54
3.3	Field Survey Required for Hydraulic Model Cross-Sections.....	57
3.3.1	Field Survey – Lower Humber River.....	57
3.3.2	Field Survey - Steady Brook.....	57
3.3.3	Field Survey - South Brook, Pasadena.....	61
3.3.4	Field Survey - Upper Humber River.....	62
3.3.5	Field Survey – Nichols Brook.....	62
3.3.6	Field Survey - Deer Lake.....	65
3.3.7	Field Survey Summary.....	65
3.4	Stream Crossing Structures (Bridge) Survey.....	65
3.5	Study Specific Water Level and Flow Monitoring.....	66
<b>4.0</b>	<b>LiDAR and Aerial Photography.....</b>	<b>67</b>
4.1	Overview.....	68
4.2	Planning and Preparation.....	68
4.2.1	Establish Survey Limits.....	68
4.2.2	Plan Flight Lines.....	69
4.2.3	Establish GPS Base Stations.....	70
4.3	Data Acquisition.....	70
4.4	Data Processing.....	73
4.4.1	LiDAR Processing.....	73
4.4.2	Orthophoto Processing.....	73
4.4.3	Datum for Deliverables Production.....	74
4.5	Quality Assurance and Control.....	74
4.6	Deliverables.....	74

4.7	Problems Encountered, Solutions Found .....	75
<b>5.0</b>	<b>Remote Sensing .....</b>	<b>77</b>
5.1	Overview .....	78
5.2	Methodology .....	78
5.3	Data .....	78
5.4	Pre-processing of Sentinel-2 Imagery .....	81
5.4.1	Atmospheric Correction .....	81
5.4.2	Converting Multi-temporal Images to a Single Image .....	82
5.4.3	Mosaicking, Clipping, and Stacking .....	82
5.5	Preparation of the Training Data .....	82
5.6	Object-based Classification .....	85
5.7	Reclassification of Urban Areas .....	85
5.8	Accuracy Assessment .....	94
5.9	Remote Sensing Summary and Conclusions .....	94
<b>6.0</b>	<b>Hydrologic Investigations and Modelling .....</b>	<b>97</b>
6.1	Overview .....	97
6.2	Statistical Analysis .....	98
6.2.1	Review of Data .....	98
6.2.2	Single Station Frequency Analysis .....	100
6.2.3	Survey of Streamflow Gauging Stations .....	102
6.2.4	Regional Flood Frequency Analysis .....	102
6.3	Deterministic Analysis .....	103
6.3.1	Model Setup .....	103
6.3.2	Rainfall Hyetograph Development .....	126
6.3.3	Model Calibration and Validation .....	126
6.3.4	Comparison of HEC-HMS Results with Previous Studies .....	128
6.3.5	Comparison of Results with Measured Flows at Gauges .....	130
6.3.6	Comparison of Results with Regional Flood Frequency Equations .....	131
6.3.7	Future Development Scenario HEC-HMS Model Development .....	133
6.3.8	HEC-HMS Modelled Scenarios .....	133
6.4	Conclusions and Recommendations .....	134
<b>7.0</b>	<b>Hydraulic Investigations and Modelling .....</b>	<b>135</b>
7.1	Overview .....	135
7.2	Hydraulic Model Development .....	136
7.2.1	HEC-RAS .....	136
7.2.2	Cross Sections .....	137
7.2.3	Hydraulic Structures .....	139
7.2.4	Lateral Structures .....	140
7.2.5	Energy Loss Coefficients .....	140
7.2.6	Starting Water Surface Elevations .....	142
7.3	Model Calibration and Verification .....	147
7.3.1	Station 02YL001 - Upper Humber River near Reidville .....	147
7.3.2	Station 02YL003 - Humber River at Humber Village Bridge .....	148
7.3.3	Station 02YL012 - Steady Brook above Confluence to Humber River .....	149

7.4	Simulation of the 1 in 20-year and 1 in 100-year AEP Flood Events.....	150
7.4.1	Capacity of the Stream Crossing Structures.....	150
7.5	Ice Jam Assessments.....	159
7.5.1	Deer Lake – January 2018.....	159
7.5.2	Steady Brook.....	172
7.6	Summary, Conclusions and Recommendations.....	186
7.6.1	Summary.....	186
7.6.2	Conclusions and Recommendations.....	187
<b>8.0</b>	<b>Sensitivity Analysis and Climate Change .....</b>	<b>189</b>
8.1	Sensitivity Analysis.....	190
8.1.1	Sensitivity to Hydrologic Model Inputs.....	190
8.1.2	Sensitivity of Hydraulic Model Inputs.....	193
8.1.3	Sensitivity Analysis Conclusions.....	198
8.1.4	Sensitivity Analysis Recommendations.....	199
8.2	Climate Change Influences on Flood Risk.....	199
8.2.1	Hydrologic Modelling.....	200
8.2.2	Hydraulic Modelling.....	201
8.2.3	Projected Sea Level Rise.....	201
8.3	Conclusions and Recommendations.....	202
8.3.1	Conclusions.....	202
8.3.2	Recommendations.....	202
<b>9.0</b>	<b>Flood Risk Mapping Preparation .....</b>	<b>203</b>
9.1	Preparation of Flood Risk Mapping.....	204
9.1.1	Comparison of Current Climate/Current Development to Historical Maps.....	206
9.2	Flood Depth Mapping Development.....	213
9.3	Flow Velocity Mapping Development.....	214
9.4	Flood Hazard Mapping Preparation.....	214
9.5	Verification of Draft Flood Delineations.....	216
9.5.1	Field Verification.....	216
9.5.2	Community Review of Draft Flood Maps.....	216
9.6	Assessment of Stream Crossing Capacity.....	229
<b>10.0</b>	<b>Map to Map Workflow.....</b>	<b>231</b>
<b>11.0</b>	<b>Flood Forecasting Service .....</b>	<b>233</b>
11.1	Overview.....	233
<b>12.0</b>	<b>Summary and Recommendations.....</b>	<b>235</b>
12.1	Summary.....	235
12.2	Recommendations.....	237
<b>13.0</b>	<b>References.....</b>	<b>241</b>



## List of Appendices

- Appendix A: Flood Inventory Summaries
- Appendix B: Community Engagement Summarizes
- Appendix C: SEM Field Survey Report
- Appendix D: Field Survey Bathymetry Data
- Appendix E: Natural Resources Canada correspondence regarding conversion of chart datum to CGVD-2013
- Appendix F: 1 in 20-year and 1 in 100-year AEP Flood Risk Mapping  
Current Climate and Current Development Conditions
- Appendix G: 1 in 20-year and 1 in 100-year AEP Flood Risk Mapping  
Current Climate and Fully Developed Watershed Conditions
- Appendix H: 1 in 20-year and 1 in 100-year AEP Flood Risk Mapping  
Climate Change and Current Development Conditions
- Appendix I: 1 in 20-year and 1 in 100-year AEP Flood Risk Mapping  
Climate Change and Fully Developed Watershed Conditions
- Appendix J: Change of flood plains associated with the historical 1 in 20-year and 1 in 100-year AEP and the new  
1 in 20-year and 1 in 100-year AEP for current climate and current development conditions
- Appendix K: Change of flood plains associated with the 1 in 20-year and 1 in 100-year AEP for current climate  
and current development conditions and the 1 in 20-year and 1 in 100-year AEP for climate change  
and current development conditions
- Appendix L: Flood inundation, flood velocity, and flood hazard maps associated with the 1 in 20-year and 1 in  
100-year AEP for current climate and current development conditions
- Appendix M: HEC-HMS Reports
- Appendix N: HEC-RAS Reports
- Appendix O: HEC-RAS Sensitivity Analysis Tables
- Appendix P: Photos of locations in the Town of Steady Brook – June 2020 flooded conditions and August 2020  
“no flood” conditions
- Appendix Q: LiDAR and Aerial Surveys Report
- Appendix R: Identification of Watercourses within Municipal Boundaries to be included in the  
Inundation Mapping Area and Stream Network (IMA&SN)

## List of Figures

Figure 1-1:	Humber River Study Area – Regional Context.....	3
Figure 1-2:	Humber River Watershed and Study Extent – Local Context .....	4
Figure 1-3:	Humber River Study Extent with Local Communities.....	5
Figure 1-4:	Project Reporting Structure.....	9
Figure 2-1:	Background Review and Data Acquisition Summary .....	11
Figure 2-2:	1984 SSARR Model Humber River Watershed Discretization .....	19
Figure 2-3:	1984 SSARR Humber River Schematic.....	21
Figure 2-4:	Grand Lake and Hinds Lake Rule Curves .....	22
Figure 2-5:	1984 Steady Brook Hydrotechnical Study – Deer Lake Rating Curves .....	23
Figure 2-6:	Deer Lake Bathymetry.....	24
Figure 2-7:	Steady Brook Cross Sections - 1984 Steady Brook Flood Study.....	26
Figure 2-8:	Humber River Cross Sections - 1984 Steady Brook Flood Study.....	27
Figure 2-9:	1984 Steady Brook Flood Inundation Mapping.....	28
Figure 2-10:	1984 Steady Brook Inundation Mapping - Downstream of Deer Lake .....	29
Figure 2-11:	1987 Flood Study Cross Sections on Deer Lake and Upper Humber.....	31
Figure 2-12:	1987 Inundation Mapping (Overall Study Area) .....	32
Figure 2-13:	1987 Flood Inundation Mapping - Deer Lake.....	33
Figure 2-14:	1987 Flood Inundation Mapping - South Brook - Pasadena .....	34
Figure 2-15:	1987 Flood Inundation Mapping - near Governors Point.....	35
Figure 2-16:	May 9, 2018 Snow Extent Product for the Upper and Lower Humber River Watersheds .....	37
Figure 2-17:	Examples of Data from Station NLENCL0007 - Upper Humber River above Black Brook.....	39
Figure 2-18:	Examples of Data from Station NLENCL0007 - Upper Humber River above Black Brook.....	40
Figure 2-19:	Historical Flood Prone Areas (as of 1984) .....	45
Figure 3-1:	Field Program Summary .....	53
Figure 3-2:	Bathymetric profiling conducted using a rigid inflatable boat.....	55
Figure 3-3:	River Surveyor M9 Sample Bathymetric Profile.....	56
Figure 3-4:	Lower Humber River Transects Map 1 (Steady Brook shown as inset).....	59
Figure 3-5:	Lower Humber River Transects Map 2 (South Brook shown as inset) .....	60
Figure 3-6:	Snow and ice on Steady Brook in November, 2018 (Photo 1).....	61
Figure 3-7:	Snow and ice on Steady Brook in November, 2018 (Photo 2).....	62
Figure 3-8:	Upper Humber River Transects (Junction Brook shown as inset).....	63
Figure 4-1:	LiDAR and Aerial Photography Summary.....	67
Figure 4-2:	LiDAR Project Boundary Limits.....	69
Figure 4-3:	LiDAR Flight Path.....	71
Figure 4-4:	Aerial Photography Flight Path .....	72
Figure 5-1:	Remote Sensing Summary.....	77
Figure 5-2:	Sentinel-2 Imagery.....	80
Figure 5-3:	True Colour Composite of the Pre-Processed, Mosaicked, and Clipped Sentinel-2 Imagery over the Study Area.....	83
Figure 5-4:	Example A - Comparison of the Segmented Image versus the Original Image.....	86
Figure 5-5:	Example B - Comparison of the Segmented Image versus the Original Image .....	87
Figure 5-6:	Example C - Comparison of the Segmented Image versus the Original Image.....	88
Figure 5-7:	Classified Image over the Study Area Before Dividing the Urban Class .....	89
Figure 5-8:	Final Classification of the Study Area.....	90
Figure 5-9:	Example A - Zoomed areas of the original versus the classified image.....	91
Figure 5-10:	Example B - Zoomed areas of the original versus the classified image.....	92

Figure 5-11: Example C - Zoomed areas of the original versus the classified image.....	93
Figure 6-1: Hydrologic Investigations and Modelling Task Flow and Project Linkages.....	98
Figure 6-2: Humber River HEC-HMS Subcatchment Discretization.....	105
Figure 6-3: Humber River HEC-HMS Model - Soil Types Map.....	108
Figure 6-4: Humber River HEC-HMS Model – Land Classification Map.....	109
Figure 6-5; Humber River HEC-HMS Model – Comparison of Existing and Future Development Conditions.....	110
Figure 6-6: Humber River HEC-HMS Model – Curve Number Grid Map.....	111
Figure 6-7: Deer Lake Stage-Discharge Curve based on data from Stations 02YL003 (Flow) and 02YL007 (Stage) over the period 1987 to 2018.....	119
Figure 6-8: Deer Lake Stage-Discharge Curve based on data from Stations 02YL003 (Flow) and 02YL007 (Stage) for the months of June and July 1987 to 2018.....	121
Figure 6-9: Deer Lake Stage-Discharge Curve based on data from Stations 02YL003 (Flow) and 02YL007 (Stage) for the months of August and September 1987 to 2018.....	122
Figure 6-10: Rainfall Stations and Gage Weight Polygons.....	123
Figure 6-11: Comparison between Frequency Analysis Peak Flows and Calibrated HEC-HMS Peak Flows.....	127
Figure 7-1: Hydraulic Investigations and Modelling Task Flow and Project Linkages.....	136
Figure 7-2: Relation between tidal surfaces, charting datums and physical features.....	145
Figure 7-3: 40-year return level of extreme storm surges.....	146
Figure 7-4: Ice was flowing down the Humber River near the Nicholsville Bridge.....	159
Figure 7-5: Air temperatures recorded at Deer Lake in January and February 2018.....	160
Figure 7-6: Total Rain and Snow-on-Ground for January 2018 at Deer Lake Airport.....	161
Figure 7-7: Generalised extreme value (GEV) distribution with 95% confidence band of maximum daily-averaged flows recorded in the months of January between 1930 and 2020 (except 1934 – 1937) at the gauge “Upper Humber River near Reidville”.....	161
Figure 7-8: Water level elevations recorded at the Deer Lake gauge near generating station for the first three months of 2018.....	162
Figure 7-9: Extreme value I (Gumbel) distribution of maximum daily mean water level elevations recorded at the Deer Lake gauge near the generating station in all months of January between 1987 and 2018.....	162
Figure 7-10: Sentinel-1 radar image of Deer Lake and the upper Humber River on January 10, 2018.....	163
Figure 7-11: Wind roses for January 7 to 9, 2019 (left panel) and January 14 & 15, 2018 (right panel).....	164
Figure 7-12: Water level elevations recorded at the Grand Lake gauge east of Grand Lake Brook for the January, February and March 2018.....	164
Figure 7-13: Radarsat-2 ultra-fine wide image of northeast end of Deer Lake acquired January 17, 2018.....	165
Figure 7-14: Spillway on Grand Lake Main Dam.....	166
Figure 7-15: "Turbulent waters constantly churning out of the Deer Lake Power plant ...".....	167
Figure 7-16: Open-water calibration with varying Manning’s roughness coefficients $n$ along the modelled reach of the upper Humber River.....	167
Figure 7-17: Sentinel-1A image of the upper Humber River acquired on January 19, 2018.....	168
Figure 7-18: Flow and stage hydrographs recorded at the Humber River gauge near Reidville.....	169
Figure 7-19: Ice-cover simulation of the January 2018 event.....	169
Figure 7-20: Depiction of parameters and boundary conditions used for the sensitivity analysis of the upper Humber River ice model.....	171
Figure 7-21: Sensitivities of parameters and boundary conditions on the backwater profile of a fully extended ice cover along the upper Humber River.....	171
Figure 7-22: Ensemble of 1,000 Backwater Profiles.....	172
Figure 7-23: Selected locations of surveyed reach of Steady Brook.....	175
Figure 7-24: Surveyed section of the Steady Brook and Steady Brook Falls.....	176
Figure 7-25: Steady Brook Falls in September 2018 (left panel) and January 2018 (right panel).....	177
Figure 7-26: Meteorological data recorded at Corner Brook in January 1976.....	178

Figure 7-27: Meteorological data recorded at Corner Brook in January 1977 .....	178
Figure 7-28: Small ice jam on the Twillick Brook in the Upper Salmon Area of south-central Newfoundland .....	179
Figure 7-29: Cumulative degree days of freezing (CDDF) .....	179
Figure 7-30: Ice cover growth curves in riffles (top panel) and pools (bottom panel) on the Rimouski River (width ~ 50 m) .....	180
Figure 7-31: Frequency distributions of Maximum Water Level and Daily Mean Discharge for Stations 02YL007 and 02YL003.....	181
Figure 7-32: Flows recorded at Steady Brook above its confluence to the lower Humber River (gauge: 02YL012).....	182
Figure 7-33: Area of Steady Brook flooded during the spring 2020 event.....	182
Figure 7-34: Ortho-photograph ( <i>top panel</i> ) and DEM ( <i>bottom panel</i> ) of the lower Humber River/Steady Brook confluence.....	183
Figure 7-35: Air temperature and precipitation normals for 1981 to 2010 at Corner Brook.....	184
Figure 7-36: Flows recorded in the South Brook at Pasadena (gauge: 02YL004) used here as a proxy for the magnitude of flows in the Steady Brook .....	185
Figure 7-37: Maximum daily mean discharges of the Humber River recorded at the Humber Village Bridge (gauge: 02YL003) in November for the years 1982 to 2019 (n = 38).....	185
Figure 7-38: Meteorological data recorded at Corner Brook in Nov. 2013 .....	186
Figure 8-1: Sensitivity Analysis and Climate Change Summary .....	189
Figure 9-1: Flood Risk Mapping Preparation Summary .....	203
Figure 9-2: Flood Map Extent Overview – Map 1 of 4.....	207
Figure 9-3: Flood Map Extent Overview – Map 2 of 4.....	208
Figure 9-4: Flood Map Extent Overview – Map 3 of 4.....	209
Figure 9-5: Flood Map Extent Overview – Map 4 of 4.....	210
Figure 9-6: Example Floodplain Map - Current Climate and Current Development Condition .....	211
Figure 9-7: Example Floodplain Map – Climate Change and Fully Developed Condition.....	212
Figure 9-8: Steady Brook Flood Photos from June and August 2020.....	219
Figure 9-9: Town of Steady Brook Photos from June and August 2020 for select Properties.....	220
Figure 9-10: Graphical representation of Single Station Frequency Analysis for Steady Brook above Confluence with Humber River (02YL012).....	223
Figure 9-11: Sensitivity Assessment of Flood Delineations associated with the June 2020 Flood .....	224
Figure 9-12: Section Location Comparison Cumming-Cockburn (1984) to Current Study.....	225
Figure 9-13: Section Comparison - Cumming-Cockburn (1984) to Current Study.....	226
Figure 9-14: Steady Brook – Current to 1984 Flood Delineation Comparison .....	228

## List of Tables

Table 2-1:	Rainfall Stations with IDF Data relevant to the Study Area.....	12
Table 2-2:	Streamflow, Water level and Climate Data Stations Relevant to the Study Area .....	13
Table 2-3:	Watercourse Crossing Structures Relevant to the Study Area.....	15
Table 3-1	Summary of Surveyed Cross Sections by Watercourse Section.....	65
Table 5-1:	The Characteristics of Sentinel-2A and Sentinel-2B Satellite Bands.....	79
Table 5-2:	The Characteristics of Sentinel-2A and Sentinel-2B Images Downloaded from the Sentinel Science Hub .....	81
Table 5-3:	The Classes Requested by the Client and Equivalent Classes in the Produced Map.....	85
Table 5-4:	Final Classified Map Accuracy Assessment.....	94
Table 5-5:	Area of Each Land Class in the Study Area .....	95
Table 6-1:	Study Relevant Hydrometric Stations .....	99
Table 6-2:	2014 RFFA Frequency Flows.....	101
Table 6-3:	Peak Flows for the Period 2013 to 2019 .....	101
Table 6-4:	Updated Single Station Frequency Flows.....	101
Table 6-5:	Comparison of 2014 and 2020 Single Station Frequency Flows.....	102
Table 6-6:	Single Station Frequency Flows for Other Stations.....	102
Table 6-7:	Selected Modelling Methods and Parameter Requirements .....	104
Table 6-8:	Curve Numbers for Typical Land Uses.....	107
Table 6-9:	Main Dam at Grand Lake Stage-Storage-Discharge Relationships .....	115
Table 6-10:	Hinds Lake Stage-Storage-Discharge Relationship .....	116
Table 6-11:	Annual Maximum Daily Discharge for Station 02YK006.....	117
Table 6-12:	Deer Lake Stage-Storage-Discharge Relationship as defined in the SSARR Model.....	118
Table 6-13:	Current Climate and Climate Change IDF data – Daniels Harbour .....	124
Table 6-14:	Current Climate and Climate Change IDF data – Deer Lake.....	125
Table 6-15:	Current Climate and Climate Change IDF data – Stephenville .....	125
Table 6-16:	Humber River HEC-HMS Model Calibration.....	127
Table 6-17:	Comparison of Computed Flows - Previous Studies with 2020 Results.....	128
Table 6-18:	Maximum Instantaneous Flow and Rainfall Comparison .....	130
Table 6-19:	Chronology of Regional Flood Frequency Analysis Updates for Newfoundland and Labrador.....	131
Table 6-20:	North-West Region of Newfoundland - One Parameter Equations.....	131
Table 6-21:	Comparison of Computed Flows – Regional Flood Frequency Analysis.....	132
Table 6-22:	Summary of Key HEC-HMS Model Parameters across the Existing Development Scenario Base and Calibrated and Future Development Scenario Models .....	133
Table 7-1:	HEC-RAS Watercourse Naming and Associated Reaches .....	138
Table 7-2:	Minimum/Maximum Channel Elevations by HEC-RAS Watercourse.....	139
Table 7-3:	Deer Lake Reach 2 – Comparison of Computed Water Levels with / without Lateral Weir.....	141
Table 7-4:	Tidal Elevations.....	144
Table 7-5:	Observed and Simulated Water Surface Elevation at Station 02YL001 (Upper Humber River near Reedville - Humber River Reach 025 Cross Section 2428.85).....	148
Table 7-6:	Observed and Simulated Water Surface Elevation at Station 02YL003 (Humber River at Humber Village Bridge - Humber River Reach 006 Cross Section 6748.05).....	148
Table 7-7:	Observed and Simulated Water Surface Elevation at Station 02YL012 (Steady Brook above Confluence to Humber River - Steady Brook Reach 1 Cross Section 563.18).....	149
Table 7-8:	Watercourse Crossings – Structure Overtopping Summary – Humber River and Tributaries .....	150
Table 7-9:	Watercourse Crossings - Overtopping Summary – Humber River and Tributaries – 1 in 20-year AEP Flood .....	151

Table 7-10:	Watercourse Crossings - Overtopping Summary – Humber River and Tributaries – 1 in 100-year AEP Floods .....	155
Table 7-11:	Steady Brook Ice Assessment – Floods Summary .....	173
Table 8-1:	HEC-HMS Sensitivity Analysis - SCS Curve Number – Range of Values .....	191
Table 8-2:	HEC-HMS Sensitivity Analysis - SCS Curve Number - Results .....	192
Table 8-3:	HEC-HMS Sensitivity Analysis – Manning’s Roughness – Range of Values .....	192
Table 8-4:	HEC-HMS Sensitivity Analysis - Manning’s Roughness Coefficient - Results .....	193
Table 8-5:	HEC-RAS Sensitivity Analysis - Manning’s Roughness Coefficient - Results .....	194
Table 8-6:	HEC-RAS Sensitivity Analysis - Manning’s Roughness Coefficient – Change in Critical Depth Occurrence .....	195
Table 8-7:	HEC-RAS Sensitivity Analysis - Peak Discharge.....	196
Table 8-8:	HEC-RAS Sensitivity Analysis – Peak Discharge – Change in Critical Depth Occurrence.....	196
Table 8-9:	Streamflow Summary for Existing and Future Conditions.....	201
Table 8-10:	Comparison of Existing and Future Computed Water Surface Elevations .....	201
Table 9-1:	Flood Mapping Deliverables Summary .....	204
Table 9-2:	Summary of Flooded Area .....	213
Table 9-3:	Flood Hazard Ratings.....	214
Table 9-4:	Flood Hazard Matrix.....	216
Table 9-5:	Community Flood Mapping .....	217
Table 9-6:	Comparison of 1984 and Current Study Flow Data .....	221
Table 9-7:	Estimation of Steady Brook AEP Peak Flows using various Regional Flood Frequency Equations .....	222
Table 9-8:	Summary of Single Station Frequency Analysis for Steady Brook above Confluence with Humber River (02YL012).....	222
Table 9-9:	Summary of Community Engagement Supporting Review of Draft Floodplain Mapping.....	229

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## 1.0 Introduction

Synopsis: In Canada, flooding costs the Canadian economy more than any other natural hazard. Flood risk mapping identifies the boundaries of a potential flood event to support informed decisions and investments to reduce the impacts of flooding on communities. Furthermore, climate change increases risks to infrastructure and communities as weather patterns shift causing more extreme weather conditions that vary regionally. To reduce the onset of flood damage, land use planning and development of emergency management plans are effective methods to identify and prepare for flood hazards in the future. The impact on current climate and development conditions were conducted using annual exceedance probabilities to understand the extent of impacts within the Upper and Lower Humber River study areas and communities including Reidville, Deer Lake, Pasadena, Humber Village, Little Rapids, Steady Brook and Corner Brook. This study focuses on the development of flood risk information for these communities through data acquisition and analyses, field programs, LiDAR and aerial photography collection, remote sensing, hydrology and hydraulic investigations and modelling, climate change and sensitivity analyses, flood risk mapping preparation, mapping workflow and developing, testing and commissioning flood forecasting services.

Infrastructure, whether built, human or natural, is critical to people and economies. The purpose of infrastructure is to protect the life, health, property and social welfare of all of its beneficiaries from the weather elements, to host economic activities and to sustain aesthetic and cultural values. When infrastructure fails under extreme weather conditions and can no longer provide services to communities, the result is often a disaster. As the climate changes, it is likely that risks for infrastructure failure will increase as weather patterns shift and extreme weather conditions become more variable and regionally more intense. Since infrastructure underpins so many economic activities of societies, these impacts will be significant and will require adaptation measures. Adaptation planning enables government and industry to understand the impacts, risks and opportunities posed by a changing climate and provide a basis for preparation of strategic roadmaps towards long-term resiliency.

As the global climate changes, and increases in human population, development and green energy demand continue in the coming decades, understanding and sustainable management of water resources will be critical. One potential result of the interplay of these global changes is an increase in flooding. To assist with planning in and around potential flood zones and to minimize damages associated with flooding, information on the projected spatial extent and expected frequency of floods is critical. The factors that affect flooding must also be evaluated periodically, particularly when those factors are subject to on-going change. Changes in climate and development can have significant impacts on flood risk and both have been changing at an increasing rate. The nature of these changes and their associated impacts on flood risk need to be evaluated on a periodic basis.

Under the Canadian constitution, flood plain management is subject to the jurisdiction of the provinces, as they are primarily responsible for water resources and land use matters. The objective of the Federal

government is to reduce major disruptions to regional economies and to reduce disaster assistance payments. Traditionally, this had been achieved by building structural measures to control flooding. In the 1950s, 1960s, 1970s, and to a lesser extent in the 1980s, the Federal government allocated millions of dollars, in conjunction with the provinces, to build dams and dykes. Extensive flood damages across Canada in the early 1970s clearly demonstrated that a new approach to reducing flood damages was needed. These flood events were the catalyst for the Federal government to initiate the national Flood Damage Reduction Program (FDRP) in 1975 under the Canada Water Act. The FDRP was carried out under cost shared Federal-Provincial agreements.

The Federal minimum criterion for defining a flood risk area is the 1 in 100-year annual exceedance probability (AEP) flood (i.e. a flood that has one chance in one hundred of being equalled or exceeded in any given year). However, the Federal government adopts provincial criteria if they are more stringent. For example, in British Columbia the 200-year flood is used, in Saskatchewan the 500-year flood is used, and in parts of Ontario a "Regional Storm" (based on Hurricane Hazel or the Timmins Storm) or highest observed flood is used.

Newfoundland and Labrador joined the FDRP in 1981 signing General and Mapping Agreements and two years later a Studies Agreement. Since signing these agreements, the Province has delineated over 30 areas and flood risk information maps have been produced for the benefit of Federal, Provincial and Municipal governments, private companies and the general public. These maps illustrate the area flooded under the 1 in 20-year and 1 in 100-year AEP floods. The 1 in 20-year AEP flood was used to designate the floodway and the 1 in 100-year AEP flood to designate the flood fringe. The FDRP ended in 1999 with the final study in Newfoundland and Labrador being completed in 1996.

The Department of Environment and Climate Change, Water Resources Management Division (WRMD) first incorporated climate change projections into flood risk mapping in 2008/2009, when the flood risk maps for Stephenville and Cold Brook were updated. The Stephenville/Cold Brook study was the first in Canada to delineate climate change-based Regulatory flood risk mapping but only included the worst-case climate change scenario.

Wood Environment & Infrastructure Solutions, a division of Wood Canada Limited (Wood) was retained by WRMD in October 2018 to develop flood risk mapping for an area within the Humber River Watershed focusing on the reach extending, generally, from the community of Steady Brook to the community of Reidville.

This Climate Change Flood Risk Mapping study is funded under the federal National Disaster Mitigation Program (NDMP) and by the province of Newfoundland and Labrador.

This flood risk mapping project employed acceptable industry standard techniques and available historic/recorded data and new data developed through this project. The technical guidelines developed under the Canada-Newfoundland Flood Damage Reduction Program (Hydrologic and Hydraulic Procedures for Flood Plain Delineation, Environment Canada, 1976); the new Federal Flood Mapping Guidelines Series (Public Safety Canada, 2019); and the study Terms of Reference which includes the Technical Document for Flood Risk Mapping Studies (provided as Appendix B in the RFP) have all provided the basis for the guiding

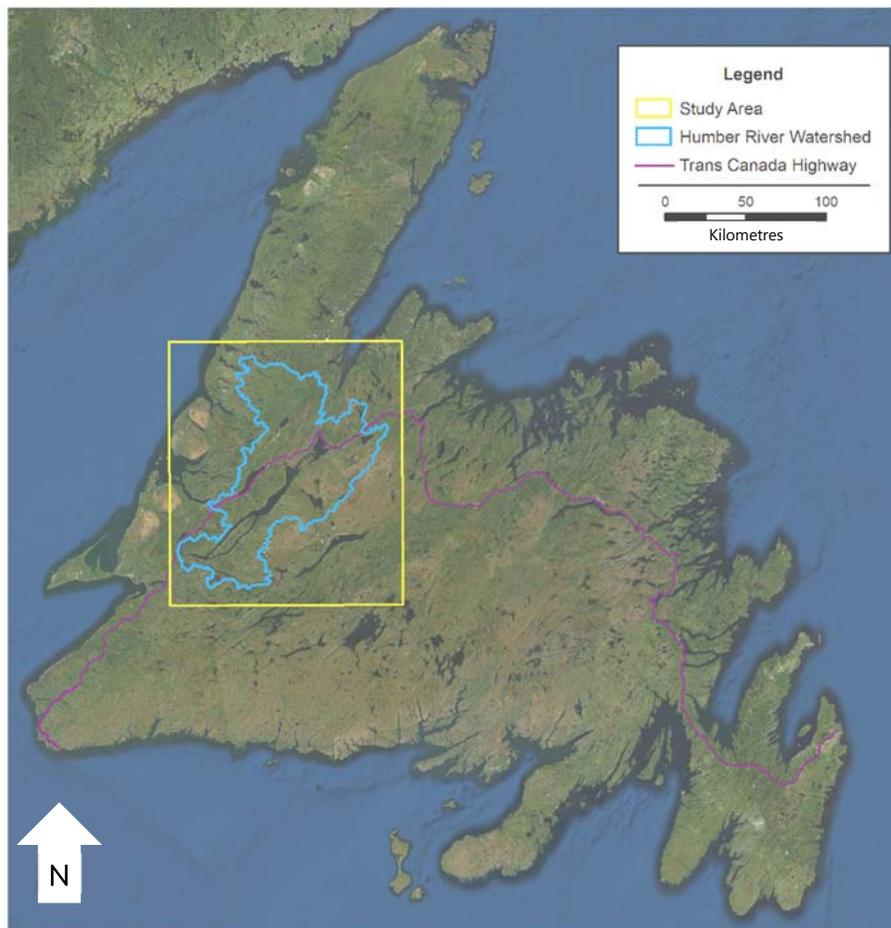
principles for all components of the study. This basis was then supplemented with additional information available in the manuals for software applied in the study and industry standard approaches.

This report summarizes the technical analyses and other efforts and work on this project.

## 1.1 Study Area

The study area, located on the western side of the island of Newfoundland, includes several communities situated alongside the Humber River, Deer Lake, and the streams and tributaries at their confluence (ref. Figure 1-1 and Figure 1-2). Floodplains were developed for the area bounded by the Upper Humber River (near Reidville) and the mouth of the Humber River in the Bay of Islands. The study area includes both sides of the Humber River, Deer Lake, and Steady Brook (with no gaps) and the communities of Reidville, Deer Lake, Pasadena, Little Rapids, Steady Brook and Corner Brook (ref. Figure 1-3).

The Humber River basin encompasses an area of approximately 7,860 km<sup>2</sup>, making it the second largest watershed on the island. The headwaters of the basin drain portions of the eastern slopes of the Long-Range Mountains before discharging into the Gulf of St. Lawrence, near Corner Brook. Historically, the basin has been divided into the Upper Humber and the Lower Humber, based on location and elevation.



**Figure 1-1: Humber River Study Area – Regional Context**

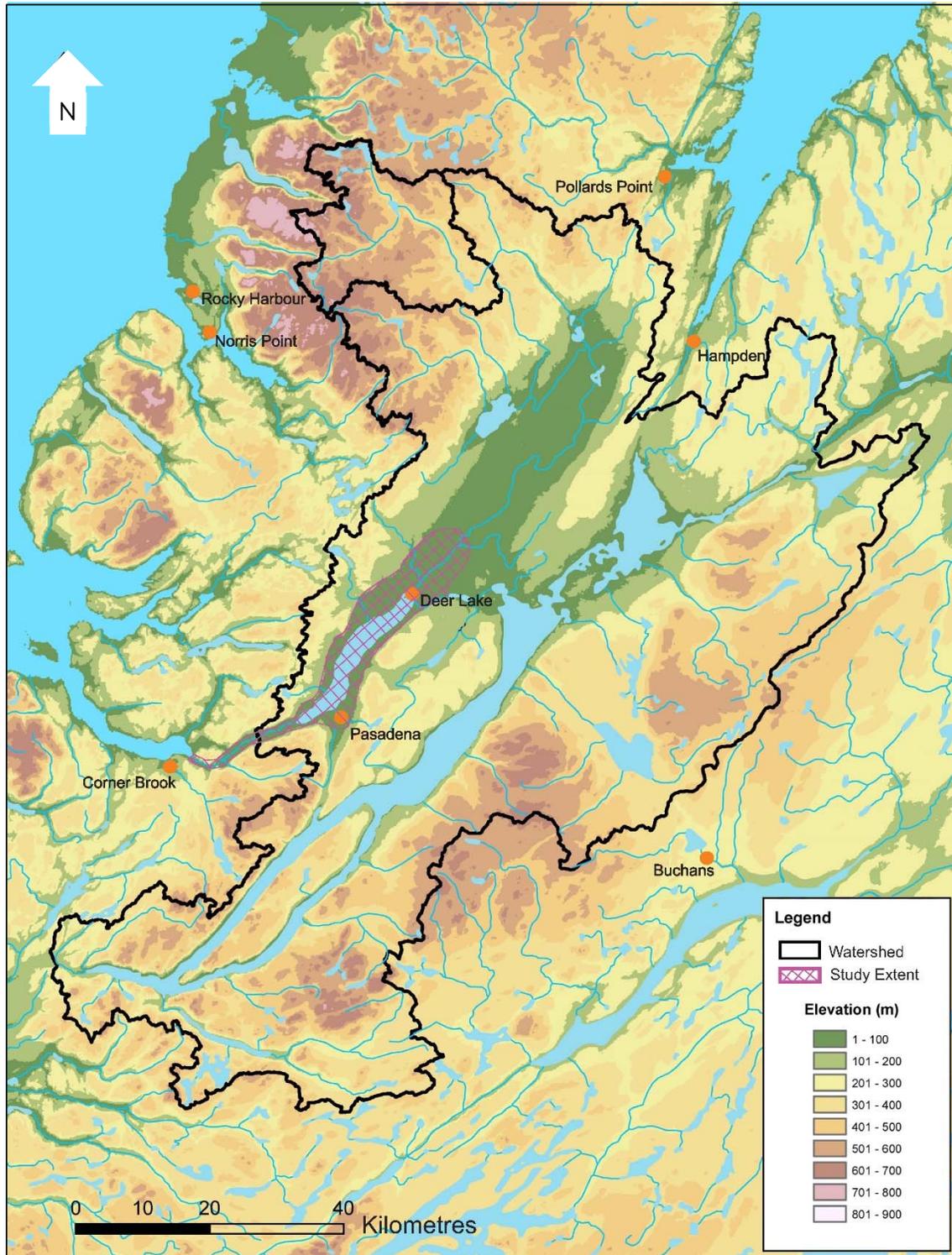
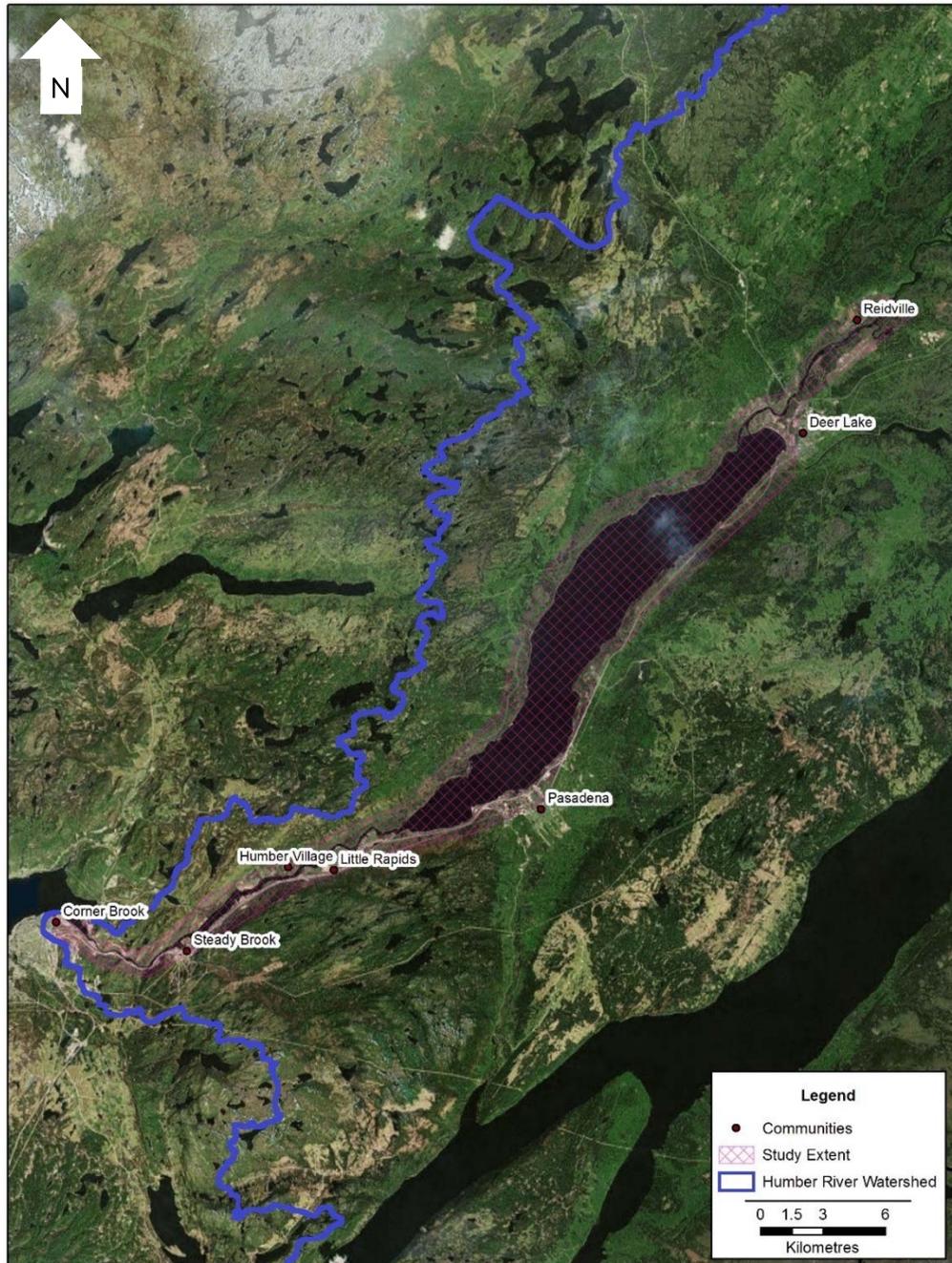


Figure 1-2: Humber River Watershed and Study Extent – Local Context



**Figure 1-3: Humber River Study Extent with Local Communities**

(RFP imagery georeferenced in ESRI ArcGIS)

The Upper Humber River originates in Gros Morne National Park and flows in a southerly direction. The average slope of the river profile is very steep for the first nine (9) kilometres (km) from Pilgrim Pond. It then slopes moderately for the next 36 km, to the outlet of Silver Mountain Pond. Approximately five (5) km further downstream the river merges with the Black Brook, a tributary that runs from the north. From the outlet of Silver Mountain Pond, the river runs at a steep gradient for approximately 13 km, before entering an area known as Birchy Flats, near the mouth of Taylors Brook. Immediately downstream of Birchy Lake the Upper Humber River merges with the Adies River on the right bank. With a drainage area of about 625 km<sup>2</sup>, the Adies River is the largest tributary of the Upper Humber River. From the confluence, the Upper Humber River gradient is very gentle for the next 50 km, to Deer Lake near Reidville. When measured from the Water Survey of Canada hydrometric station near Reidville (station number 02YL001), the Upper Humber River has a length of approximately 130 km and a total drainage area of about 2,100 km<sup>2</sup>. Elevations in the Upper Humber River basin are in the range of 600 – 800 m and there is snow cover, typically, from October to April. The Upper Humber River is unregulated and stream flows are strongly influenced by snowmelt.

The Lower Humber River has a drainage area of over 5,000 km<sup>2</sup> and an average elevation of 100 m. There are three main reservoirs in the Lower Humber River watershed, namely: Grand Lake, Hinds Lake and Deer Lake. Downstream from Deer Lake, the watercourse flows approximately twelve (12) km in a southwesterly direction past Humber Village towards Corner Brook and its outlet at Humber Arm.

The study area includes mapping of Humber River tributaries and Steady Brook, up to the road that leads to Marblewood Village. The Steady Brook watershed is relatively small, draining an area of 81.4 km<sup>2</sup>.

Flood plain mapping for named and unnamed tributaries is defined within the municipal boundaries of the communities located within the study area.

## 1.2 Work Scope

As defined in the Request for Proposal (RFP), WRMD has directed that this study focus on development of flood risk information for several communities within the study area of the Humber River, as follows:

- a) Provide estimates of the water levels, flows and flood risk maps indicating flood plains associated with the:
  - ▶ 1 in 20-year and 1 in 100-year Annual Exceedance Probability (AEP) for current climate and current development conditions;
  - ▶ 1 in 20-year and 1 in 100-year AEP for current climate and a fully developed watershed condition;
  - ▶ 1 in 20-year and 1 in 100-year AEP for climate change and current development conditions; and
  - ▶ 1 in 20-year and 1 in 100-year AEP for climate change and a fully developed watershed condition.
- b) Provide flood risk maps indicating the change of flood plains associated with the historical 1 in 20-year and 1 in 100-year AEP and the new 1 in 20-year and 1 in 100-year AEP for current climate and current development conditions.

- c) Provide flood risk maps indicating the change of flood plains associated with the 1 in 20-year and 1 in 100-year AEP for current climate and current development conditions and the 1 in 20-year and 1 in 100-year AEP for climate change and current development conditions.
- d) Provide flood inundation, flood velocity, and flood hazard maps associated with the 1 in 20-year and 1 in 100-year AEP for current climate and current development conditions.
- e) Provide the linked hydro fabric, namely the datasets and models used in the development of the flood risk maps.
- f) Evaluate and implement a flood forecasting service for the study area using the hydrologic and hydraulic models implemented in this study and including river ice modeling if necessary. The flood forecasting service must factor in all meteorological, hydrological, and hydraulic factors that trigger flooding.
- g) Provide a hydraulic capacity assessment (based on modelling results and field surveys) of all existing hydraulic structures for the:
  - ▶ the 1 in 20-year and 1 in 100-year AEP for current climate and current development conditions
  - ▶ the 1 in 20-year and 1 in 100-year AEP for climate change climate and current development conditions.

Additionally, the following RFP requirements guided this study:

- The current climate condition was defined by the latest Intensity-Duration-Frequency (IDF) data as available from:
  - ▶ *Final Report - Intensity-Duration-Frequency Curve Update for Newfoundland and Labrador*, prepared for the Office of Climate Change and Energy Efficiency, Government of Newfoundland and Labrador by Conestoga-Rovers & Associates (Mount Pearl, NL), April 14, 2015.  
Report available via URL [http://www.exec.gov.nl.ca/exec/occ/publications/idf\\_curve\\_2015.pdf](http://www.exec.gov.nl.ca/exec/occ/publications/idf_curve_2015.pdf)
  - ▶ Environment and Climate Change Canada  
Where the most recent data in the IDF curve is more than 5 years old, update of the IDF curve with the most recent weather data available was completed.
- The climate change condition was defined to include both climate change influenced increases in precipitation and sea level using information from the following sources:
  - ▶ Information regarding projected precipitation increases was defined using information documented in the report (CRA, 2015) noted above.
  - ▶ *Projected Impacts of Climate Change for the Province of Newfoundland & Labrador: 2018 Update*, prepared by Dr. Joel Finnis (Department of Geography) and Dr. Joseph Daraio (Faculty of Engineering), Memorial University of Newfoundland, March 29, 2018.  
Report available via URL [https://www.exec.gov.nl.ca/exec/occ/publications/Final\\_Report\\_2018.pdf](https://www.exec.gov.nl.ca/exec/occ/publications/Final_Report_2018.pdf)  
The 2018 Update report (Finnis and Daraio, 2018) supersedes information presented in the associated 2015 report (Finnis, 2013).

- ▶ Projections for climate change influenced sea level rise were defined by the projections documented in:

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

Report available via URL

[http://www.nr.gov.nl.ca/mines&en/geosurvey/publications/CR2010/2010\\_Batterson-Liverman.pdf](http://www.nr.gov.nl.ca/mines&en/geosurvey/publications/CR2010/2010_Batterson-Liverman.pdf)

- The current development condition was defined by a study specific land cover/land use analysis completed in compliance with the requirements as defined in the RFP.
- The fully developed watershed condition was defined in consideration of anticipated future developments in the study watershed based on consultation with the following communities:
  - ▶ Town of Deer Lake
  - ▶ Town of Pasadena
  - ▶ Town of Reidville
  - ▶ Town of Steady Brook
  - ▶ and other smaller communities in the floodplain where data regarding future land use conditions is available.

### 1.3 Reporting Structure

The project reporting structure, internal project task linkages and reader direction to specific reporting sections were visualized in Figure 1-4. As indicated in Figure 1-4, the project reporting comprises two (2) volumes (under separate covers), namely:

- Volume 1: Flood Risk Mapping Development (*this report*)
- Volume 2: Flood Forecasting System Development

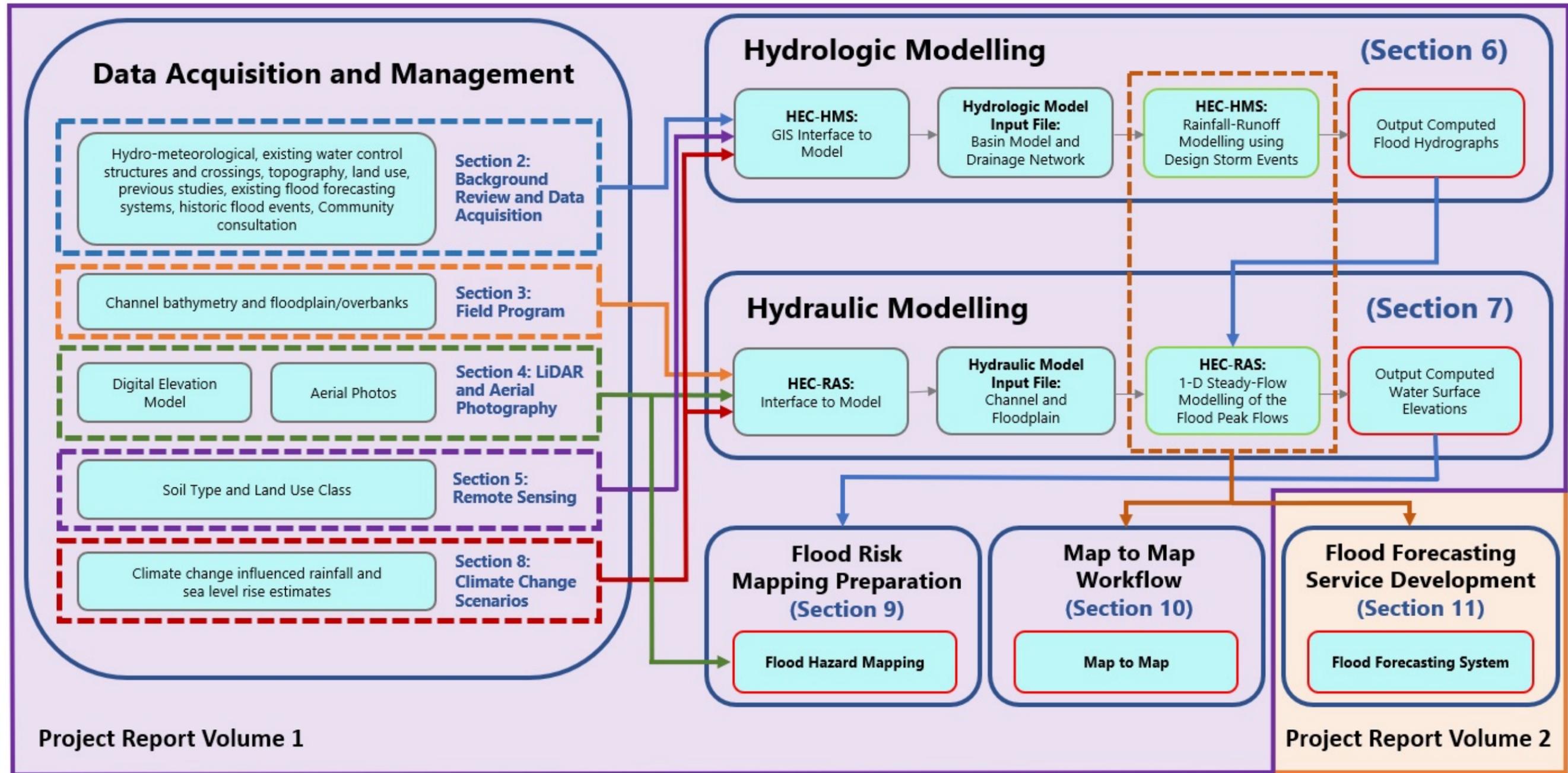


Figure 1-4: Project Reporting Structure

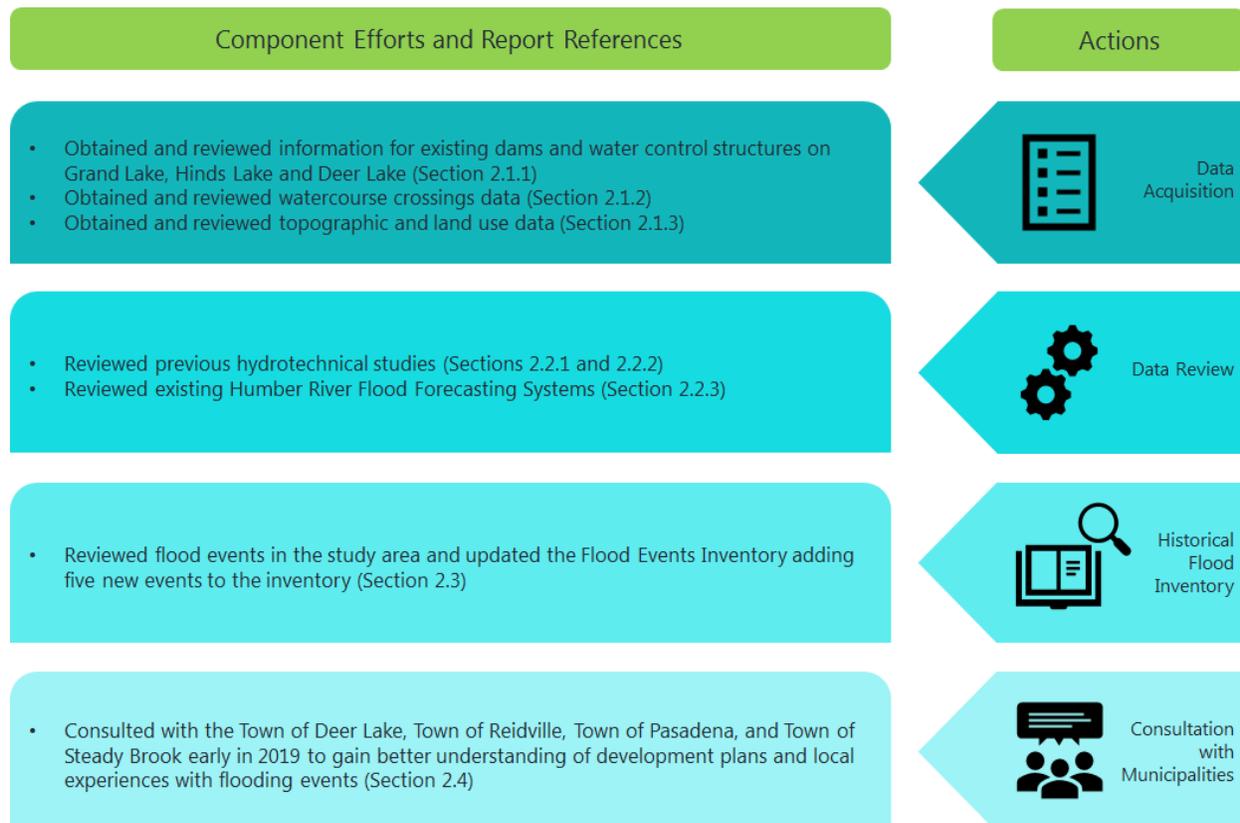
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## 2.0 Background Review and Data Acquisition

Synopsis: Information relevant to the development of new flood plain mapping for the Humber River study area was obtained and reviewed following the guidance provided by the “Technical Document for Flood Risk Mapping Studies”. This included hydro-meteorological datasets (e.g. rainfall, snow, temperature, stream flow, tides, etc.), information regarding the existing dams and water control structures/lakes at Grand Lake, Hinds Lake and Deer Lake, watercourse crossing (e.g. bridges and culverts), topographic and land use datasets and previously completed hydrotechnical studies (specifically the 1984 Hydrotechnical Study of the Steady Brook Area and the 1987 Hydrotechnical Study of the Deer Lake Area). As well, a review of the existing Humber River flood forecasting systems was completed and the existing Flood Events Inventory augmented to include five (5) new flood events that have occurred in the study area in recent memory. Study area municipalities were engaged in 2019 to gain a better understanding of community development plans and experiences with past flooding events to support this project’s broader efforts to develop up-to-date floodplain maps.

**Figure 2-1: Background Review and Data Acquisition Summary**



## 2.1 Data Acquisition

The "Technical Document for Flood Risk Mapping Studies" contained in Appendix B of the RFP provides an extensive list of potentially relevant information and data sources. In conjunction with WRMD, Wood used this list to guide the project data acquisition strategy for the following hydro-meteorological information:

- Precipitation and Intensity-Duration-Frequency (IDF) relationships for those stations identified in Table 2-1. Precipitation data used for this study was sourced from "Projected impacts of Climate Change for the Province of Newfoundland & Labrador: 2018 Update" (Finnis and Daraio, 2018)

**Table 2-1: Rainfall Stations with IDF Data relevant to the Study Area**

Station	Number	Period of Record	# of Years of Record
Daniels Harbour	8401400	1969 - 1995	26
Deer Lake Airport	8401501	1966 - 2002	36
Stephenville	8403820	1967 - 2017	55
Corner Brook	8401298	2004 - 2009	6

- Snow Course and accumulation data such as that illustrated in Figure 2-16.
- Temperature as available from climate stations noted in Table 2-2.
- Streamflow, water levels and rating curves for the hydrometric stations as noted in Table 2-3.
  - A Real Time Kinematic (RTK) survey of the gauging stations 02YL001, 02YL003, 02YL004, and 02YL012 was completed to establish the conversion from the local datum used for recording of water levels and a geodetic datum. The geodetic datum selected is the Canadian Geodetic Vertical Datum of 2013 (CGVD-2013). Summary information for these surveys is provided in Appendix C. The surveys determined the following elevation adjustments of +8.627 m, +0.429 m, +13.128 m, and +1.077 m for stations 02YL001, 02YL003, 02YL004, and 02YL012, respectively to convert from the local datum water level readings to CGVD-2013 based water level readings.
- Tidal Water Levels were sourced from the Fisheries and Oceans Canada station at Corner Brook. It is noted that published tides data in Canada is referenced to Chart Datum (Fisheries and Oceans Canada, n.d.). However, to support aspects of this project it was necessary to convert the tidal data from Chart Datum to the CGVD-2013. Wood requested the conversion factor from Natural Resources Canada (NRCan). NRCan provided the conversion factor as -1.609 m. (see Appendix E for a detailed methodology etc.).

**Table 2-2: Streamflow, Water level and Climate Data Stations Relevant to the Study Area**

Station	Name	Notes	Latitude / Longitude	Data Available	Drainage Area	Period of Record	Regulation Type
02YK002	Lewaseechjeech Brook at Little Grand Lake	Lewaseechjeech is an inflow to Grand Lake	48.62 / -57.93	Stage, Flow	470	1952 - 2020	Natural
02YK005	Sheffield Brook near TransCanada Highway	One of the inflows to Grand Lake	49.34 / -56.67	Stage, Flow	391	1972 - 2020	Natural
02YK008	Boot Brook at TransCanada Highway		49.27 / -57.10	Stage, Flow	20.4	1985 - 2020	Natural
02YK010	Grand Lake east of Grand Lake Brook	Grand Lake is regulated by a dam which flows into the Humber River at Deer Lake	48.67 / -58.08	Stage, Climate	n/a	1988 - 2020	Regulated
02YL001	Upper Humber River Near Reidville	45 km upstream of Humber Village Bridge	49.24 / -57.36	Stage, Flow	2110	1928 - 2020	Natural
02YL003	Humber River at Humber Village Bridge	Humber Village Bridge	48.98 / -57.76	Stage, Flow	7860	1982 - 2020	Regulated
02YL004	South Brook at Pasadena	Inflow into Deer Lake	49.01 / -57.61	Stage, Flow	58.5	1983 - 2020	Natural
02YL007	Deer Lake Near Generating Station	33 km upstream of Humber Village Bridge	49.17 / -57.44	Stage	n/a	1987 - 2020	Regulated
02YL008	Upper Humber River above Black Brook	74 km upstream of Humber Village Bridge	49.62 / -57.29	Stage, Flow	471	1988 - 2020	Natural
02YL009	Corner Brook Lake at Lake Outlet		48.85 / -56.15	Stage	n/a	1989 - 2020	Regulated
02YL012	Steady Brook above Confluence to Humber River	6.5 km downstream from Humber Village Bridge	48.95 / -57.83	Stage, Flow	77.2	2015 - 2020	Natural
02YM004	Indian Brook diversion Above Birchy Lake	A portion of the discharge from Indian Brook is diverted to Birchy Lake via a man-made canal	49.47 / -56.62	Stage, Flow, Climate	238	1989 - 2020	Natural
NLEN CL0003	Humber River at Humber Village Bridge (Weather)	Humber Village Bridge	48.98 / -57.76	Climate	n/a	n/a	n/a
NLEN CL0005	Sandy Lake near Birchy Narrows (Camp 55)	Snow and climate monitoring used to measure runoff to Sandy lake which flows into Grand Lake)	49.27 / -56.85	Snow, Climate	n/a	n/a	n/a
NLEN CL0007	Upper Humber River above Black Brook	Snow and climate monitoring station	49.62 / -57.29	Climate	n/a	n/a	n/a
NLEN HM0004	Humber River at Nicholville Bridge	37 km upstream of Humber Village Bridge	49.19 / -57.44	Stage	n/a	n/a	n/a
ADIES Climate	Adies Lake	No longer recording data	49.41 / -57.27	n/a	n/a	n/a	n/a
HINDS Climate	Hinds Lake	No longer recording data	49.08 / -57.18	n/a	n/a	n/a	n/a

### 2.1.1.1 Existing Dams and Water Control Structures

As already noted, there are three main reservoirs in the Lower Humber River watershed, namely: Grand, Hinds and Deer Lakes.

- Grand Lake reservoir outflow was originally conveyed into the Upper Humber River system through Junction Brook. A system of water control structures (owned/operated by the Deer Lake Power Company/Kruger), were built in the period from 1923-1924 to re-direct runoff from Grand Lake for the purposes of hydroelectric generation. The hydroelectric generating station infrastructure includes the Main Dam, the Power Canal (which includes the Intake Control Dam, the Long Bank Dam, the Deep Bank Dam and the West Bank Dyke) and the Forebay Dam (Golder, 2017a). The Main Dam is located across a deep valley and is approximately 280 m long. The Grand Lake reservoir has a surface area of approximately 497 km<sup>2</sup> and the hydroelectric development operates under a rated net head of 74 m (CLPPL, 2016).
- Hinds Lake is located on the eastern shore of Grand Lake. The Hinds Lake hydroelectric development (owned and operated by Newfoundland Power) began operations in 1980, operates under an average net head of 214 m and generates 75 MW under a rated flow of 40 m<sup>3</sup>/s (NLHYDRO, 2018).
- Deer Lake is an unregulated, natural reservoir with significant residential development adjacent to the shoreline. It is expected that under high flow conditions, the Grand Lake reservoir will provide attenuation to inflow flood peaks. Historical water levels in Deer Lake, measured since 1987 at gauging station 02YL007 (*Deer Lake near Generating Station*), indicate water levels in Deer Lake typically peak in May. In May and June, when levels are strongly influenced by spring flood, daily levels in Deer Lake have exceeded the average monthly level by more than 1.5 m in some years. The southeast shore of Deer Lake (near the communities of South Brook, Pasadena and Governor's Point) is quite flat, rising at an average slope of 0.040 m/m. Historical flooding along Deer Lake has been attributed to the combination of high waves and lake levels acting on the shoreline communities (Cumming Cockburn, 1987). Previous work completed by Wood for the Humber River basin indicates there is strong correlation between inflows from the Upper Humber River and Deer Lake water levels.

In conjunction with WRMD, Wood consulted with Deer Lake Power (Kruger) and Nalcor (Newfoundland Hydro) with respect to access to relevant information for the hydroelectric systems and structures. Relevant data was also made available from the Dam Safety Program within the Department of Environment and Climate Change. The data which was made available includes:

- Main Dam at Grand Lake Inundation Study (Acres, 1999)
- Hinds Lake information sourced from an inventory binder of NL Hydro dams
- Cummings Cockburn (1984) Deer Lake rating curve (ref. Figure 2-4)
- Cummings Cockburn (1984) Deer Lake bathymetry map (ref. Figure 2-6)
- Humber River watershed Streamflow Synthesis and Reservoir Regulation (SSARR) model.

This data was integrated, where possible, to develop Stage-Storage-Discharge relationships for each of these storage features to support development of the study hydrologic models.

### 2.1.1.2 Watercourse Crossings Data

The watercourse crossing structures identified in Table 2-3 are located within the study area and are of relevance to the development of the study hydraulic models. Information for these structures was requested from the asset owners. For those structures where no data was available, the structure was field surveyed as a component of the field data collection program.

**Table 2-3: Watercourse Crossing Structures Relevant to the Study Area**

Structure #	Structure Name/ Location	Structure Type	Watercourse
Lower Humber River			
TW-4-129	The North Shore Highway Bridge that crosses the Lower Humber River down near the River's End Motel	Bridge	Lower Humber River
LHR-001	Tamarack Street bridge that leads to Humber Village	Bridge	Lower Humber River
LHR-002	Bridge that crosses the Lower Humber, at the outlet of Deer Lake, that leads to Humber Valley Resort	Bridge	Lower Humber River
Town of Steady Brook			
SB-001	Bridge that crosses Steady Brook on the way to Marblewood Village	Bridge	Steady Brook
TW-TCH-124	TCH bridge – North Bound	Bridge	Steady Brook
TW-TCH-124	TCH bridge – South Bound	Bridge	Steady Brook
TW-4-163	Marble Drive bridge that crosses Steady Brook near the confluence with the Lower Humber River	Bridge	Steady Brook
Pasadena			
TW-TCH-162	TCH bridge – North Bound	Bridge	South Brook
TW-TCH-163	TCH bridge – South Bound	Bridge	South Brook
Deer Lake			
TW-4-050	Nicholsville Road Bridge	Bridge	Upper Humber River
TW-4-085	Viking Trail Bridge	Bridge	Upper Humber River
Upper Humber River			
TW-4-175	Bridge on Route 422/Cormack Road that crosses the River near Sir Richard Squires Memorial Provincial Park	Bridge	Upper Humber River
Notes:			
1. The structures noted above with a number preceded by TW indicates the asset is managed by the Department of Transportation and Infrastructures.			

### 2.1.1.3 Topographic and Land Use Data

Topographic maps, aerial/satellite photographs, soil maps and reports, municipal planning maps, etc. were acquired through the course of the study to support various project efforts. These datasets are referenced throughout this project report.

## 2.2 Data Analysis

### 2.2.1 1984 Hydrotechnical Study of the Steady Brook Area

A *Hydrotechnical Study of the Steady Brook Area* was completed in 1984 under the Canada-Newfoundland FDRP (Cummings Cockburn, 1984). As part of the 1984 study, the watercourses of relevance to the Steady Brook area were characterized into five (5) main reaches:

1. *Humber River from its outlet at Humber Arm to its confluence with Steady Brook*: this reach is characterised by a narrow flood-plain with a well-defined valley. Overbank areas were heavily vegetated with heavy timber stands, brush and debris to the north with more open areas on the south side of the river (e.g. an area cleared for the Trans-Canada Highway). A developed area thinned for rural/residential land use was found to the east of the Ballam Bridge, upstream of Corner Brook City Limits. The channel of the river was found to be relatively flat (average slope of 0.0025 m/m), with virtually no channel vegetation.
2. *Humber River upstream of its confluence with Steady Brook to Humber Village*: this reach is characterised by overbank areas consisting of trees and brush as well as residential areas. Typical floodplain widths were found to be in the range of 250 – 400 m. The floodplain was approximately 150 m wide near the Humber Village Bridge. The channel slope along this reach was non-uniform (average slope less than 0.001 m/m) and was comprised mostly of sand, cobbles and boulders.
3. *Humber River from Humber Village to the Deer Lake outlet*: moderately wide flood plain, being 150 – 200 m wide along most of the reach downstream of Rapid Pond. Floodplain broadens to a width of more than 1 km near Governors Point (outlet of Deer Lake). Slope of the channel reach is relatively flat (average of 0.0005 m/m). Areas of channel rapids and pools are common.
4. *Steady Brook from its confluence with the Humber River upstream from the railway trestle*: Residential development extensive in the eastern overbank (community of Steady Brook). Channel is relatively straight and gently sloped (average slope of 0.005 m/m).
5. *Steady Brook above the railway trestle to the water supply pump house*: relatively straight and steep, with an average slope of 0.021 m/m. The floodplain along that reach was found to differ substantially from other areas, being a mixture of barren rock and densely vegetated areas. The floodplain upstream of the Trans-Canada Highway is steep (average slope of 0.031 m/m).

#### 2.2.1.1 1984 Hydrological Model

The hydrological analyses completed for the 1984 study used a continuous simulation model (accounting for antecedent conditions) to estimate flood peaks. A SSARR model was developed by discretizing the Humber River watershed into 11 sub-watersheds and three reservoirs and lakes (ref. Figure 2-2 and Figure 2-3). It was evident from a review of the hydro-meteorological characteristics of the Humber River that flooding was often the result of spring snowmelt and rain on snow conditions. The SSARR model afforded the opportunity to model flood conditions resulting from spring snowmelt and rain on snow conditions (via the temperature index snowmelt option and snow-band option).

Reservoir rule curves (ref. Figure 2-4) served as rough estimates for reservoir levels. At the highest target elevations specified on the rule curves, the potential storage of Grand Lake and Hinds Lake was  $1.72 \times 10^9 \text{ m}^3$  and  $2.68 \times 10^8 \text{ m}^3$ , respectively. The effects of the reservoir for reducing peak discharges downstream from Deer Lake were assumed to be small, given inflows from the Upper Humber River (Cummings Cockburn, 1984). Flow downstream of Grand Lake, simulated using the SSARR model, were found to be highly erratic in magnitude and not representative of discharge when compared to historical records. As a result, extensive hydrometric records for the outlet of Grand Lake and the Upper Humber River were used to simulate a long-term hydrometric record near the study reach.

The natural reservoir of Deer Lake (operating under free flow conditions) was modelled using a Stage-Storage-Discharge relationship derived by utilizing a rating curve for the outlet (developed by the Bowater Power Company) and a storage relationship (ref. Figure 2-5) derived from existing bathymetry and 1:50,000 topographic mapping. Bathymetric information used in the previous Deer Lake flood study (Cummings Cockburn, 1987) were derived from an unpublished lake depth map supplied by Environment Canada based on soundings conducted in July-August 1955 (ref. Figure 2-6).

Peak discharges exceeding  $700 \text{ m}^3/\text{s}$  downstream of Deer Lake were simulated to within an average of 5% of recorded values in 1982 and 1983.

A 39-year sequence of peak flows was simulated using long-term measured discharge sequences at upstream locations combined with flow simulated by the SSARR model from ungauged watersheds using available long-term meteorological input data. Annual maximum flows were extracted from the simulated model to undertake a flood frequency analysis. The 1 in 20-year and 1 in 100-year AEP peak flow estimates along the study area were found to be:

- Outlet of Deer Lake: 1 in 20-year AEP =  $948 \text{ m}^3/\text{s}$  and 1 in 100-year AEP =  $1,180 \text{ m}^3/\text{s}$
- Just downstream of Steady Brook: 1 in 20-year AEP =  $957 \text{ m}^3/\text{s}$  and 1 in 100-year AEP =  $1,180 \text{ m}^3/\text{s}$ .

These SSARR model peak flow estimates were compared to estimates obtained by Regional Flood Frequency Analysis (RFFA), frequency analysis of Deer Lake water levels and application of the SSARR model as a single event model. The model was also used to estimate flows associated with 1 in 100-year, 10-day snowmelt plus rainfall events.

The Steady Brook watershed was considered too small to be represented directly in the SSARR model. No streamflow measurements were available for Steady Brook and peak flow estimates for the reach were obtained using RFFA equations. The 1 in 20-year and 1 in 100-year AEP peak flows at the outlet of Steady Brook were estimated as  $105 \text{ m}^3/\text{s}$  and  $134 \text{ m}^3/\text{s}$ , respectively. A HYMO<sup>1</sup> hydrologic model was used as a means of obtaining a secondary peak flow estimate.

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<sup>1</sup> Williams, J. R., and Hann, R. W., Jr., 1973, HYMO: Problem-oriented computer language for hydrologic modelling. User Manual. USDA-ARS, ARS-S-9, 76 pgs.

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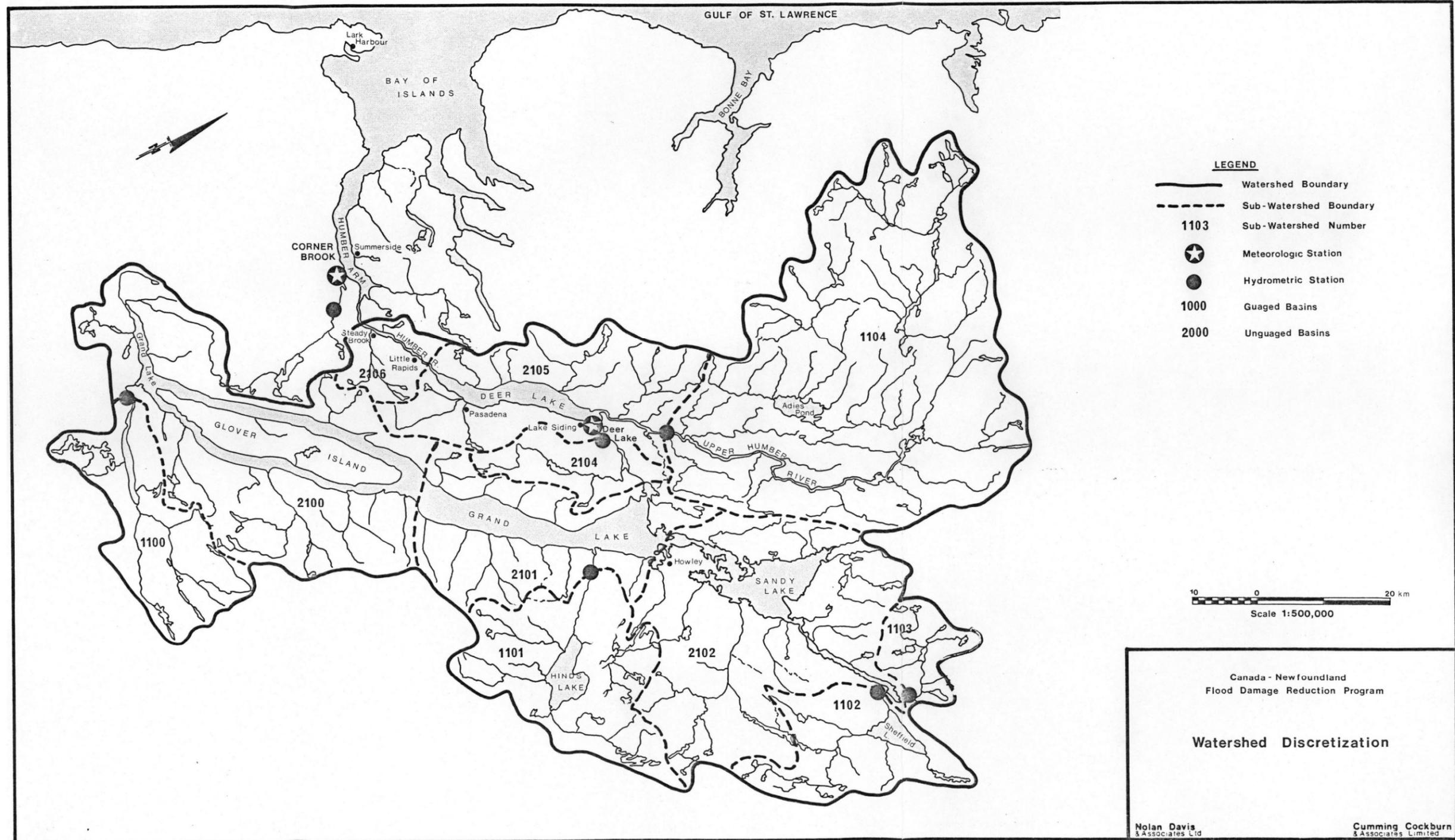
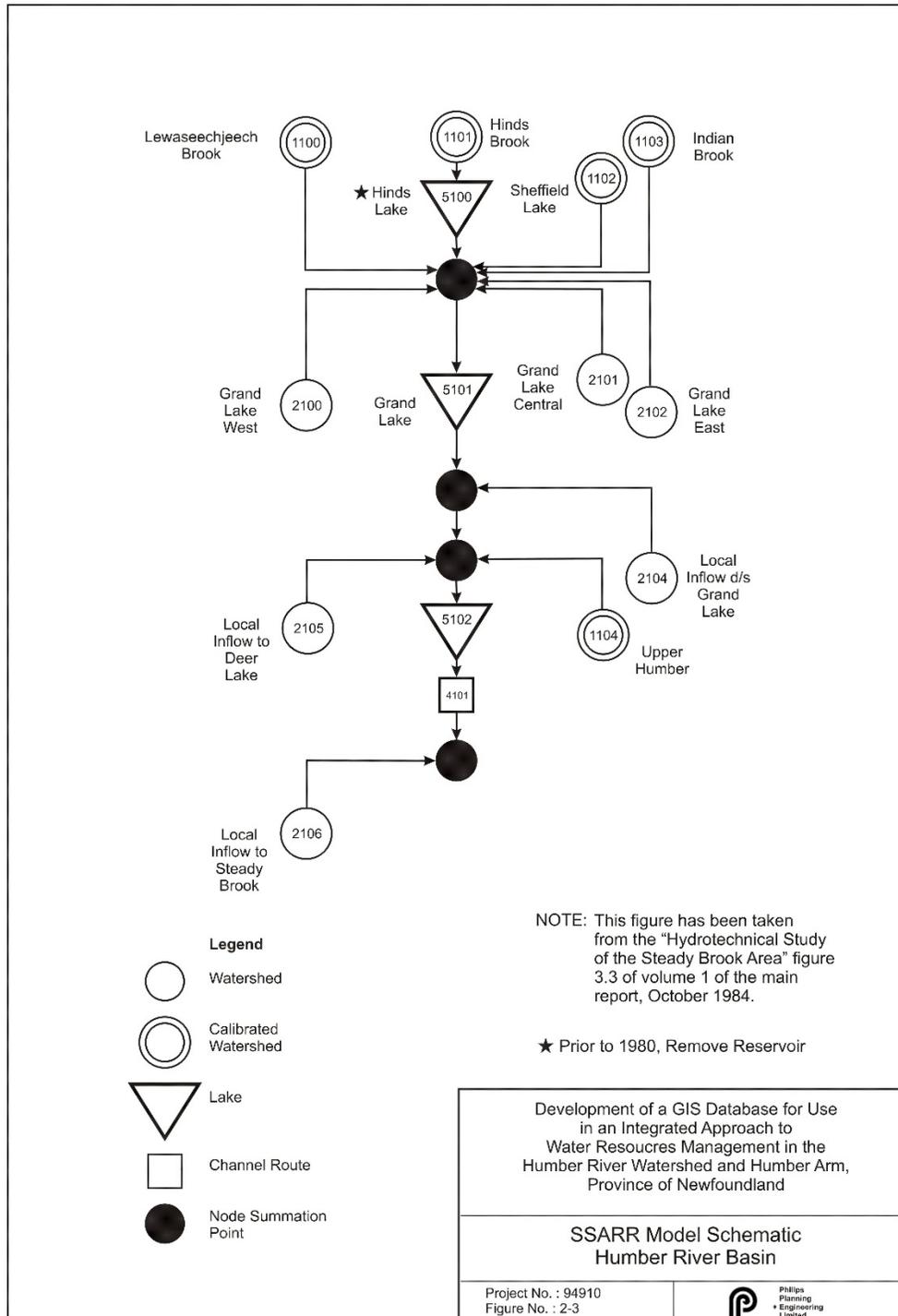


Figure 2-2: 1984 SSARR Model Humber River Watershed Discretization  
(Source: Figure 3.2 from Cummings Cockburn, 1984)

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**Figure 2-3: 1984 SSARR Humber River Schematic**

(Source: reconstructed from Figure 2-3 from Philips, 1996)

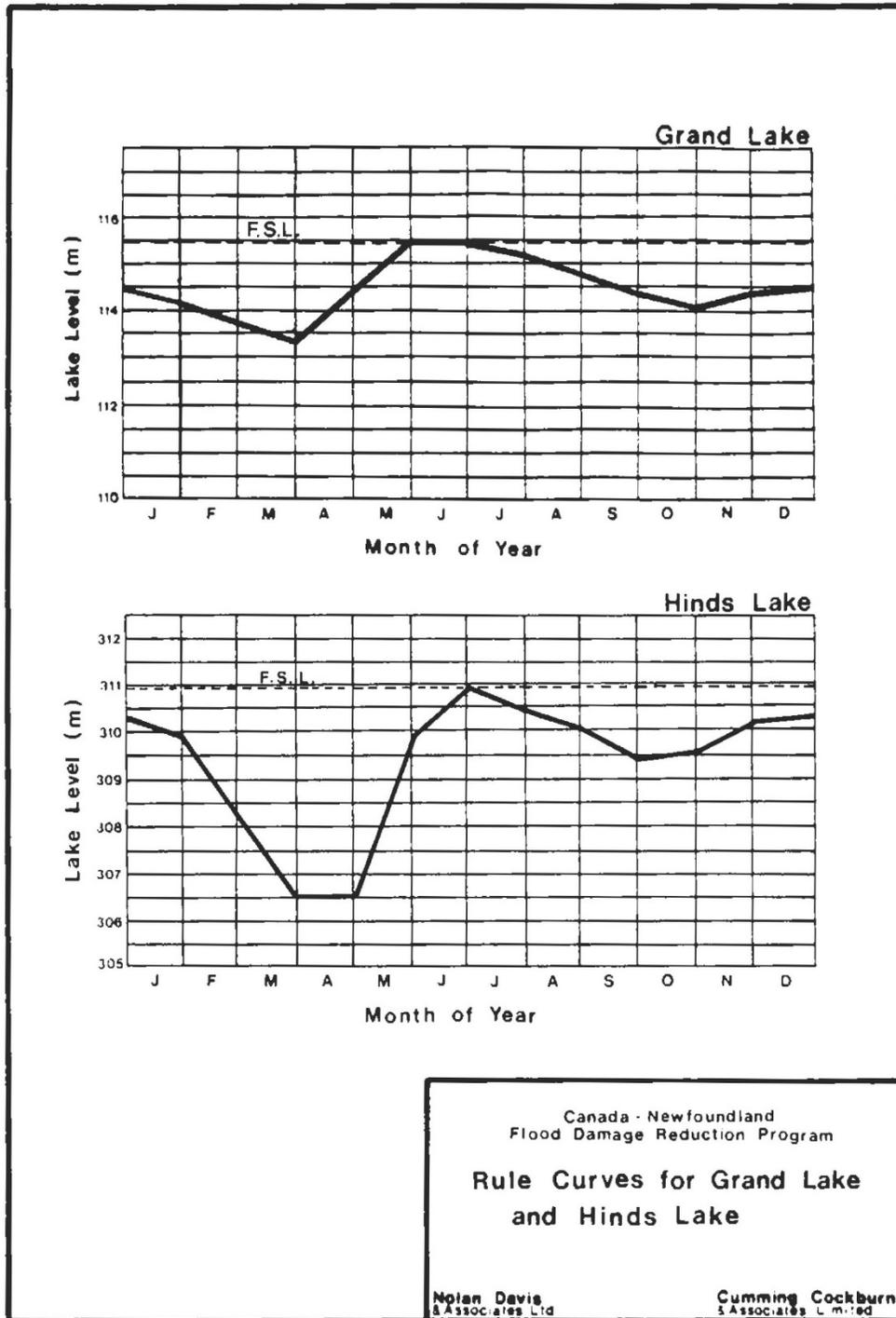


Figure 2-4: Grand Lake and Hinds Lake Rule Curves

(Source: Figure 2.5 from Cummings Cockburn, 1984)

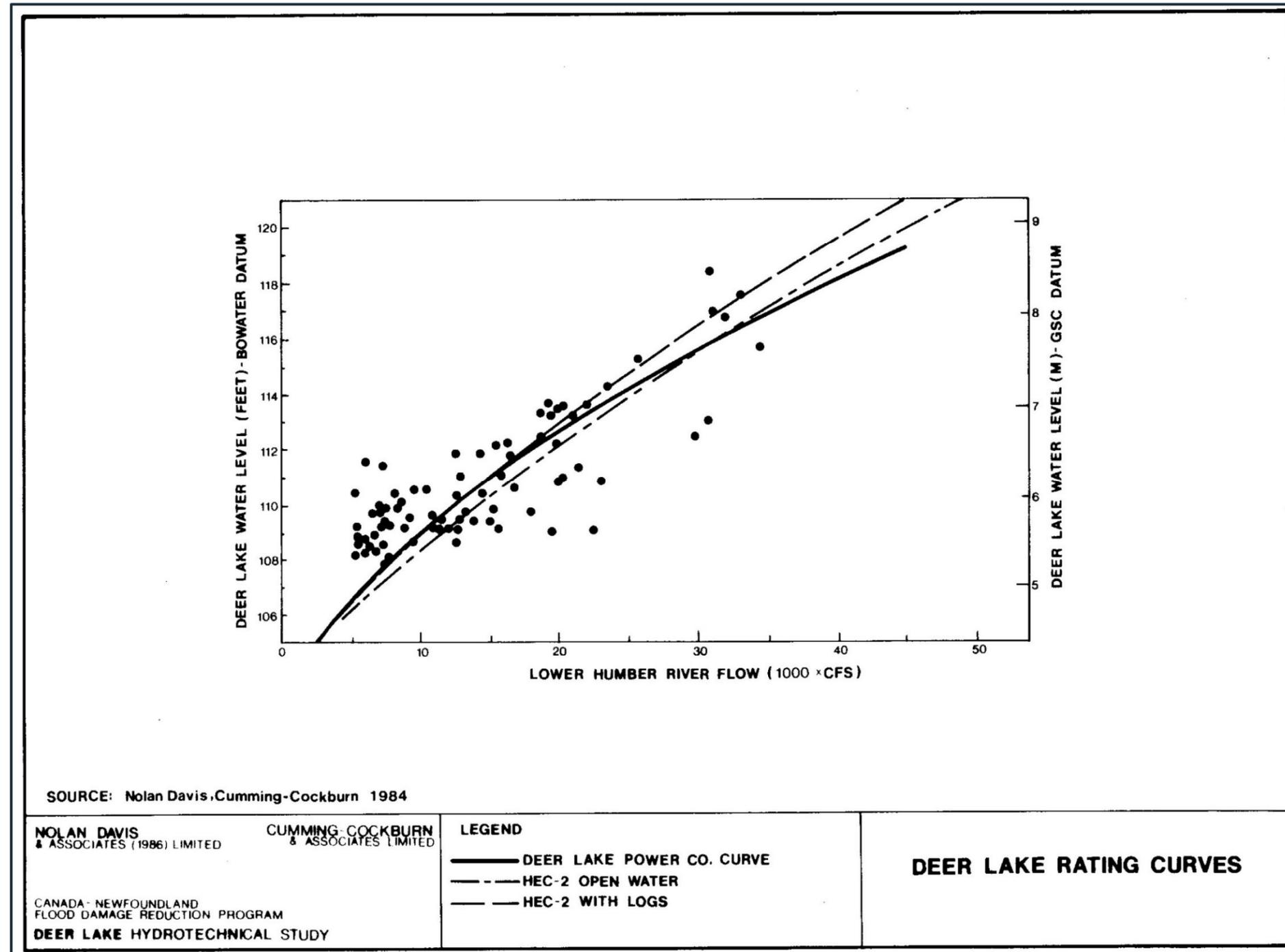
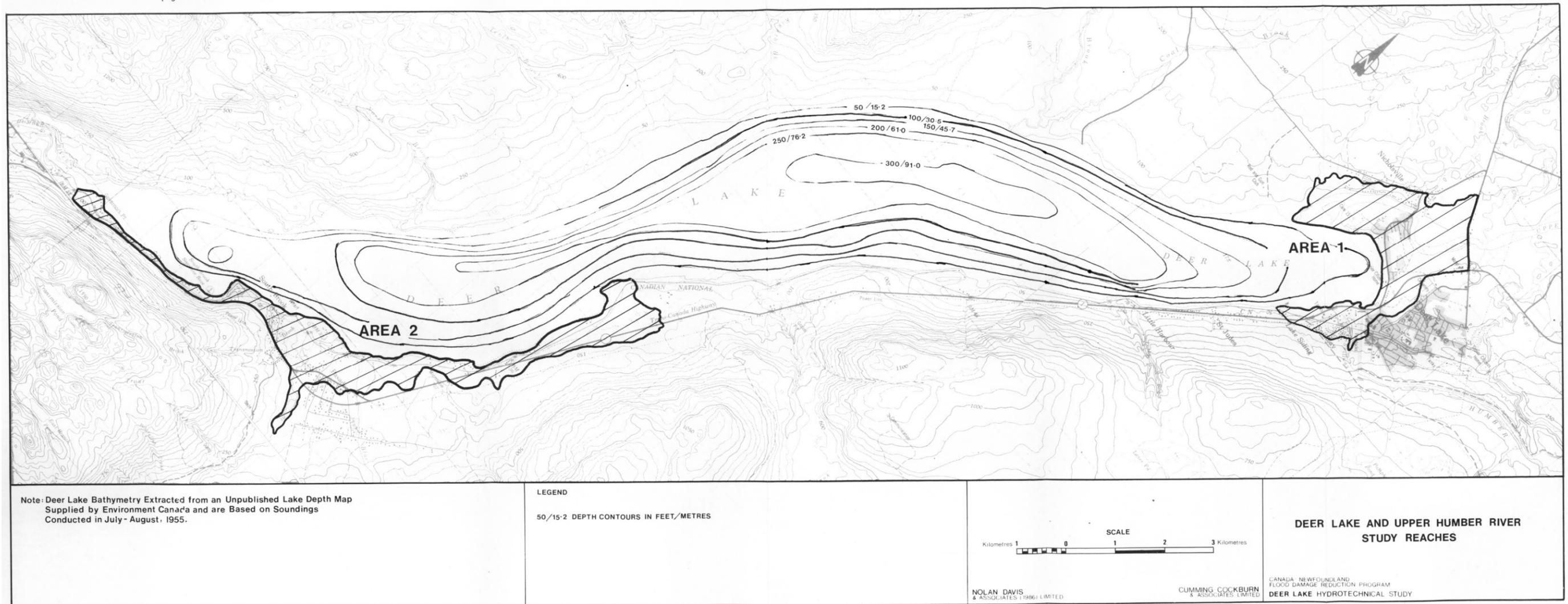


Figure 2-5: 1984 Steady Brook Hydrotechnical Study – Deer Lake Rating Curves

(Source: Figure 3.4 from Cummings Cockburn, 1987)



**Figure 2-6: Deer Lake Bathymetry**  
(Source: Figure 1.2 from Cummings Cockburn, 1987)

### 2.2.1.2 1984 Hydraulic Model

The study area for the 1984 hydraulic floodplain modelling extended from the outlet of Deer Lake to just downstream of the confluence of Steady Brook with the Humber River. A hydraulic assessment of the study area was completed using HEC-2. Discharge data used in the analysis was estimated using a deterministic model for the Humber River and regional techniques for Steady Brook.

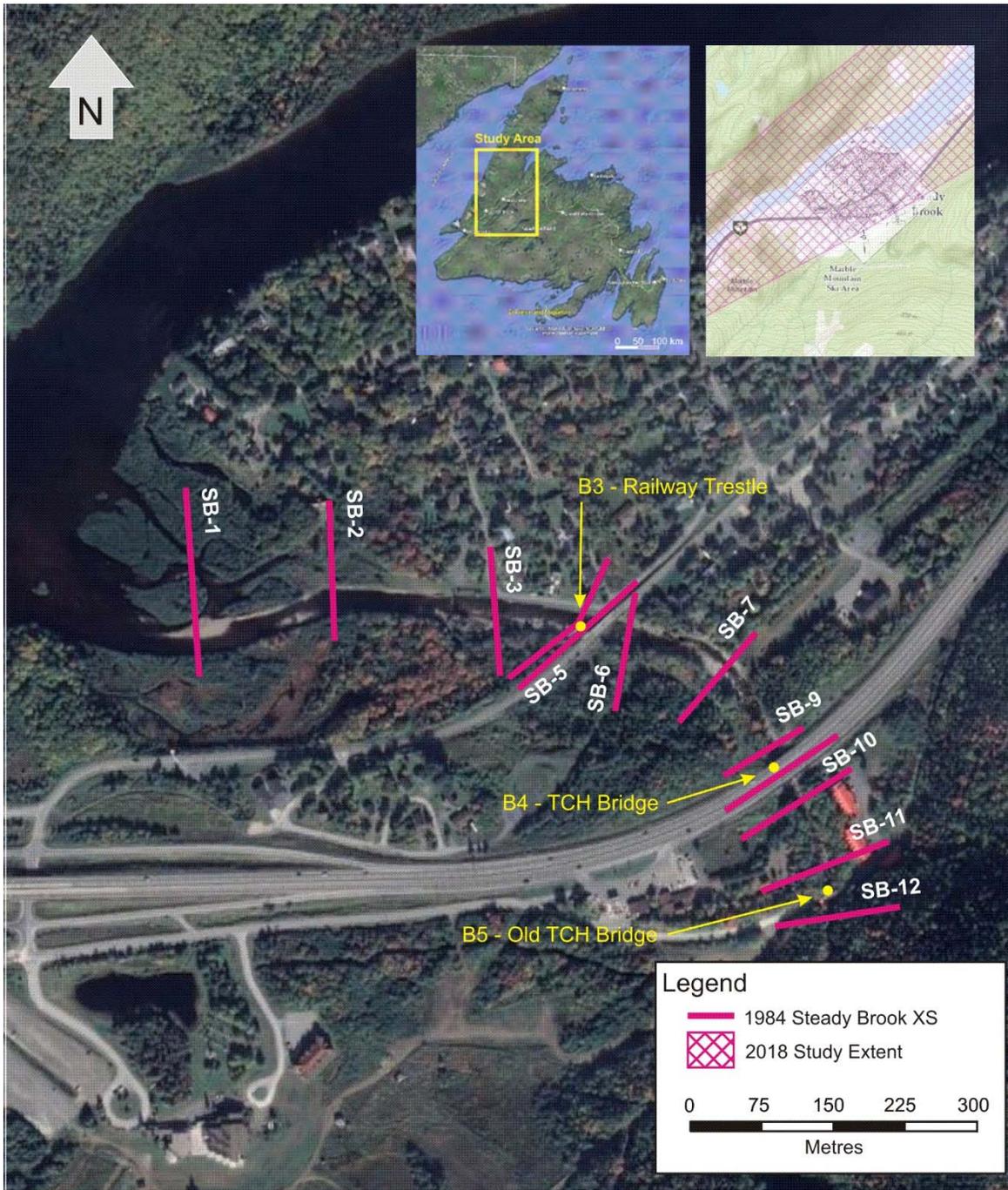
Cross-sections were surveyed along the study reaches to support model development. Figure 2-7 illustrates the cross-sections along Steady Brook and highlights the location of three bridges (the railway trestle, the Trans-Canada Highway Bridge and the old Trans-Canada Highway Bridge). Figure 2-8 illustrates the cross-sections along the Lower Humber, downstream of the Deer Lake Outlet. Further details on the physical surveys and field program can be found in Volume 2 of 1984 report (Cummings Cockburn, 1984).

The 1984 Steady Brook study indicated tidal influence was not a significant factor with respect to water levels along the study area of the Humber River (the water surface profile below Ballam Bridge was the only area subject to significant tidal influence). The 1984 study also indicated there was a moderate to high potential for severe ice jam formation and growth at multiple locations. The selection of ice jam locations and degrees of ice/debris cover were based on discussion with residents. When modelled, ice-related water levels during the 1 in 20-year AEP event in parts of Steady Brook were increased by 0.6 m when compared to those associated with free flow conditions. Due to the steepness of the stream, the increase in water level was found to be localized, extending approximately 100 – 150 m upstream of the jam location. Flooding of Steady Brook caused by ice jams was found to be independent of flooding of the Humber River.

The results of the hydraulic modelling were used to develop inundation maps for the study area. The available report does not contain background information on the process used to delineate the flood lines. Flood maps (georeferenced images) for Steady Brook and the Humber River downstream of Deer Lake are illustrated in Figure 2-9 and Figure 2-10, respectively.

### 2.2.2 1987 Hydrotechnical Study of the Deer Lake Area

The 1987 Hydrotechnical Study of the Deer Lake Area (Cummings Cockburn, 1987) built upon work completed in the 1984 Hydrotechnical Study of the Steady Brook Area (Cummings Cockburn, 1984). The study area focused on the southern and northern portion of the eastern shore of Deer Lake to a point approximately three (3) km upstream of the confluence of the Upper Humber River with Deer Lake (including the community of Nicholsville). Historical flooding in this area was known to be the result of high lake levels combined with wind and wave setup and ice jam events.



**Figure 2-7: Steady Brook Cross Sections - 1984 Steady Brook Flood Study**  
(Image source: Google Earth Pro™)

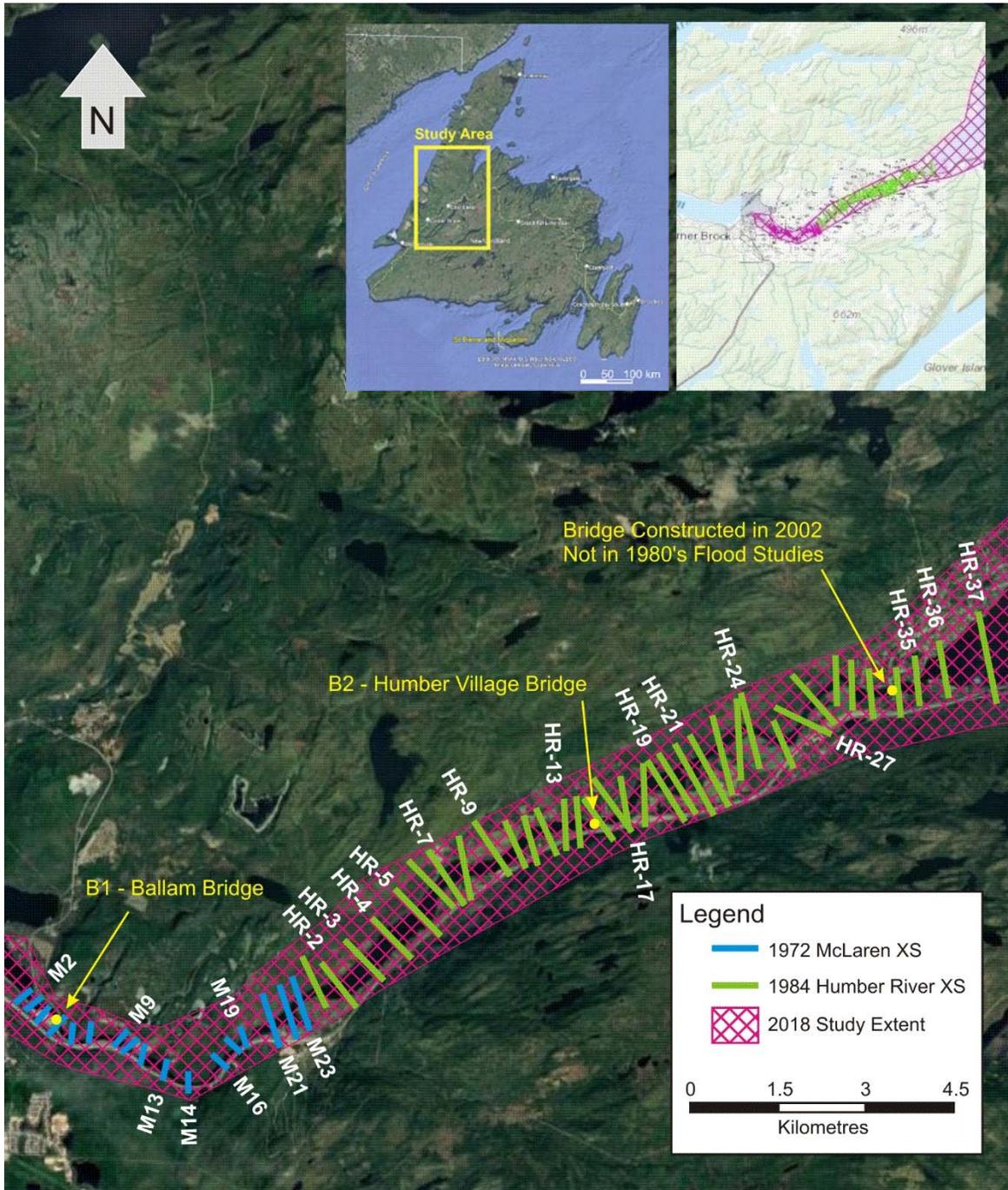


Figure 2-8: Humber River Cross Sections - 1984 Steady Brook Flood Study

(Image source: Google Earth Pro™)

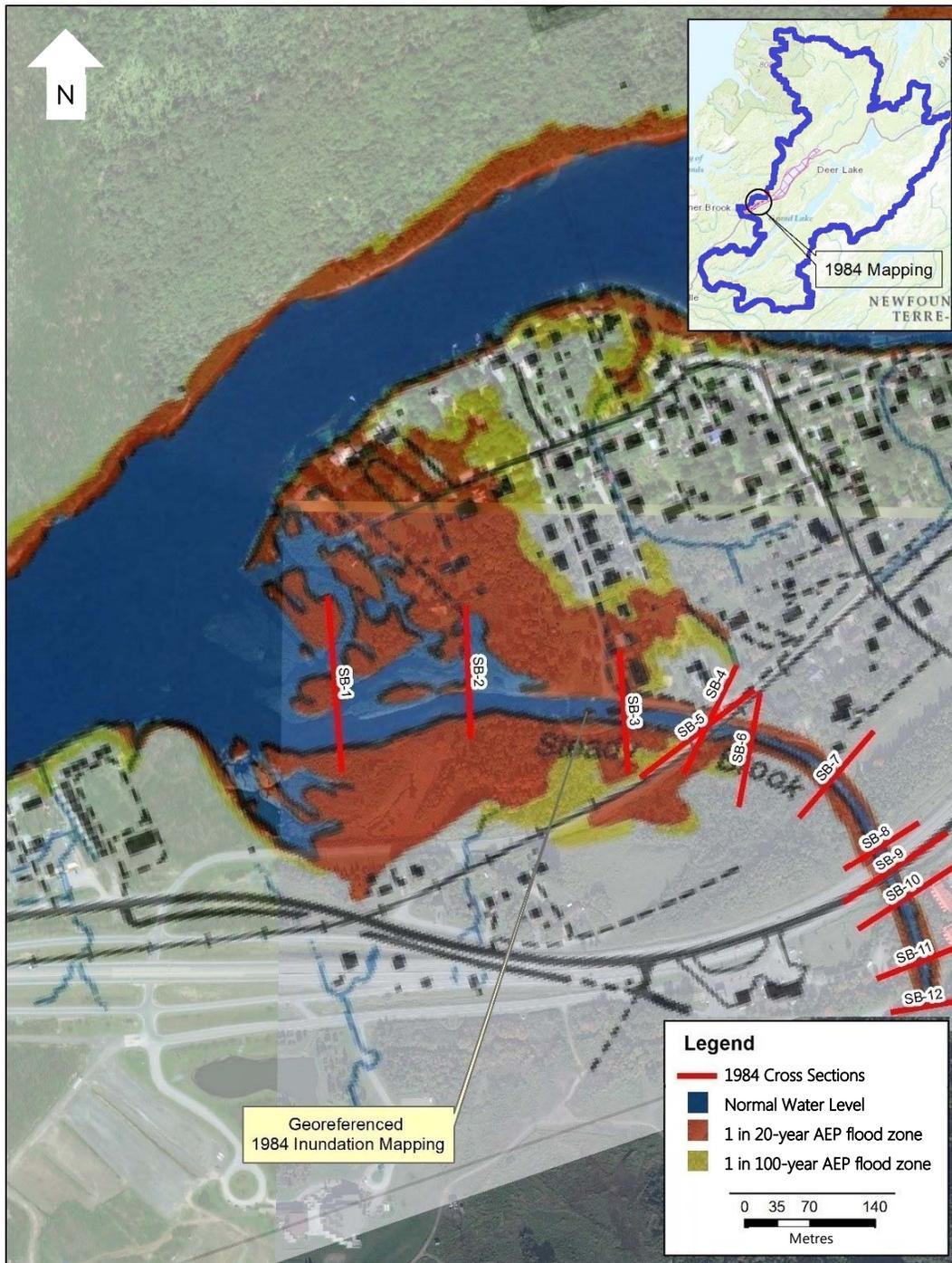
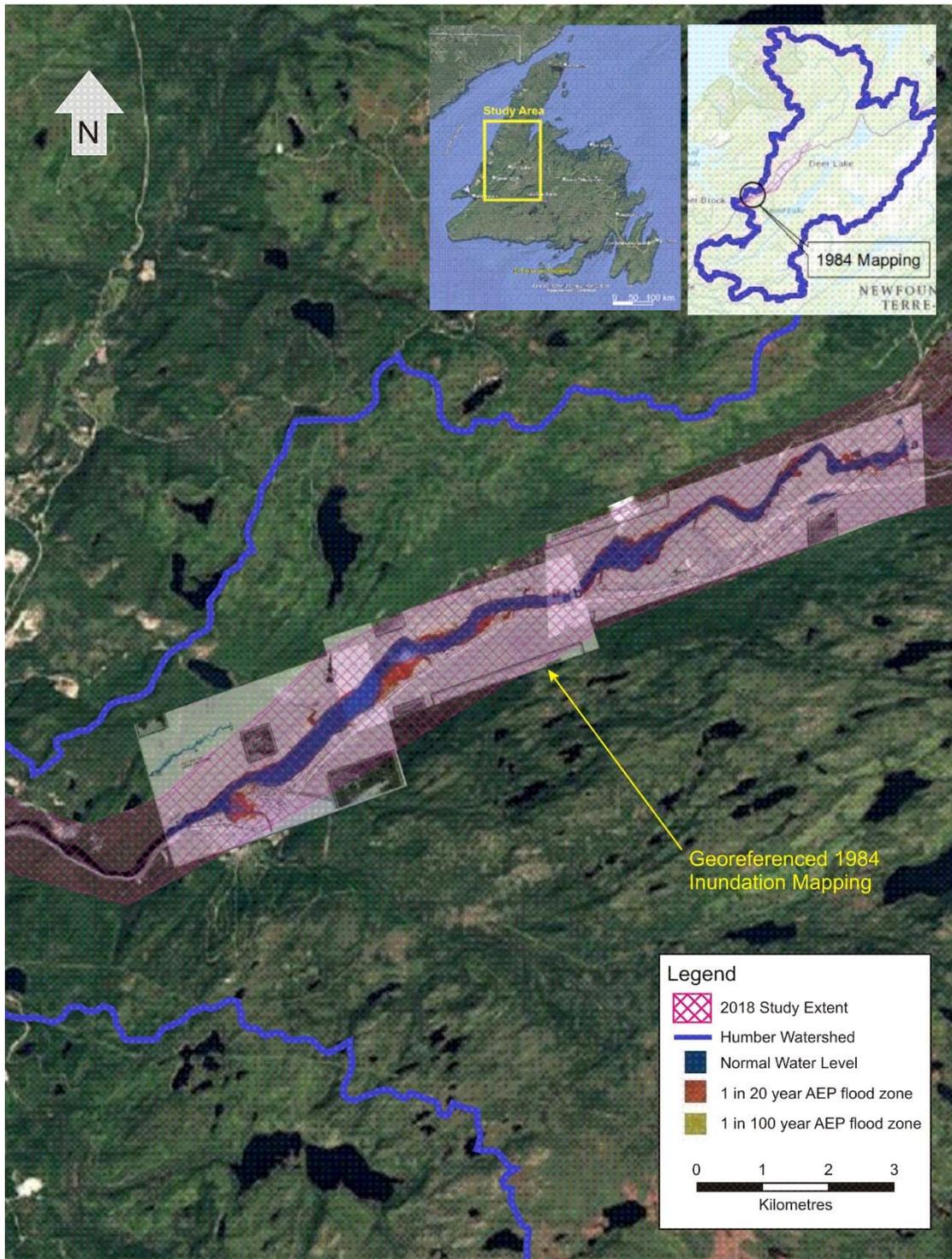


Figure 2-9: 1984 Steady Brook Flood Inundation Mapping



**Figure 2-10: 1984 Steady Brook Inundation Mapping - Downstream of Deer Lake**

(Image source: Google Earth Pro™)

### 2.2.2.1 1987 Hydrologic Model

The watershed discretization adopted for the 1987 study was the same as that used for the 1984 Steady Brook study (i.e. Humber watershed represented by eleven [11] sub-watersheds and three [3] reservoirs and lakes). The stage-discharge rating curve for Deer Lake was used to convert the 1 in 2-year, 1 in 20-year and 1 in 100-year AEP water levels to peak discharge estimates with a corresponding recurrence interval. The SSARR model was used to establish 1 in 20-year and 1 in 100-year AEP peak flow estimates for the Upper Humber River at the outlet to Deer Lake 1,160 m<sup>3</sup>/s and 1,370 m<sup>3</sup>/s, respectively. Peak static levels in Deer Lake were estimated by combining daily mean hydrometric data at the outlet of Grand Lake and the Upper Humber River via the SSARR model. The 1 in 20-year AEP static water level for Deer Lake was 7.98 m and the 1 in 100-year AEP water level was 8.58 m.

### 2.2.2.2 1987 Hydraulic Model

1 in 20-year and 1 in 100-year AEP water levels for Deer Lake of 8.21 m and 8.84 m, respectively, were established using the calibrated SSARR model with the addition of wind and wave setup on the flood elevation. The determination of 1 in 20-year and 1 in 100-year AEP water levels in the Nicholville area (Upper Humber River) were determined using a HEC-2 backwater model. The model consisted of two reaches: 1) the Upper Humber River from its outlet at Deer Lake upstream to the Nicholville Bridge and 2) Nicholville Bridge to the upstream study limit (3.3 km upstream of Deer Lake). The model was supported by nine (9) surveyed cross-sections along the study reach (ref. Figure 2-11) and eleven (11) shore profiles along Deer Lake (i.e. necessary for nearshore bathymetry data required in the wind and wave setup calculations). The Nicholville Bridge was also surveyed as it was identified as being a potential flow constriction and ice formation location (i.e. a 3.5 m thick ice jam, equivalent to the diameter of a solid ice flow overturning at the location, was simulated). Crest gauge data retrieved from the Nicholville Bridge supported HEC-2 model calibration.

Flood risk maps for the study area (geo-referenced images) were developed using 2,500 scale topographic mapping data and are illustrated in Figure 2-12 (overall), Figure 2-13 (Deer Lake), Figure 2-14 (South Brook) and Figure 2-15 (near Governors Point). Nicholville was found to be at risk of flooding from peak flows in the Upper Humber River. Ice jams along the Upper Humber River (i.e. Nicholville Bridge) contribute to the flood risk in this small community. Backwater influence from Deer Lake was also found to be a significant factor with respect to water levels in the Upper Humber River. The northeastern overbank areas of Deer Lake (in the Town of Deer Lake) had a moderate to low risk of flood damage and areas that had been developed near South Brook and Governors Point were also found susceptible to flooding.

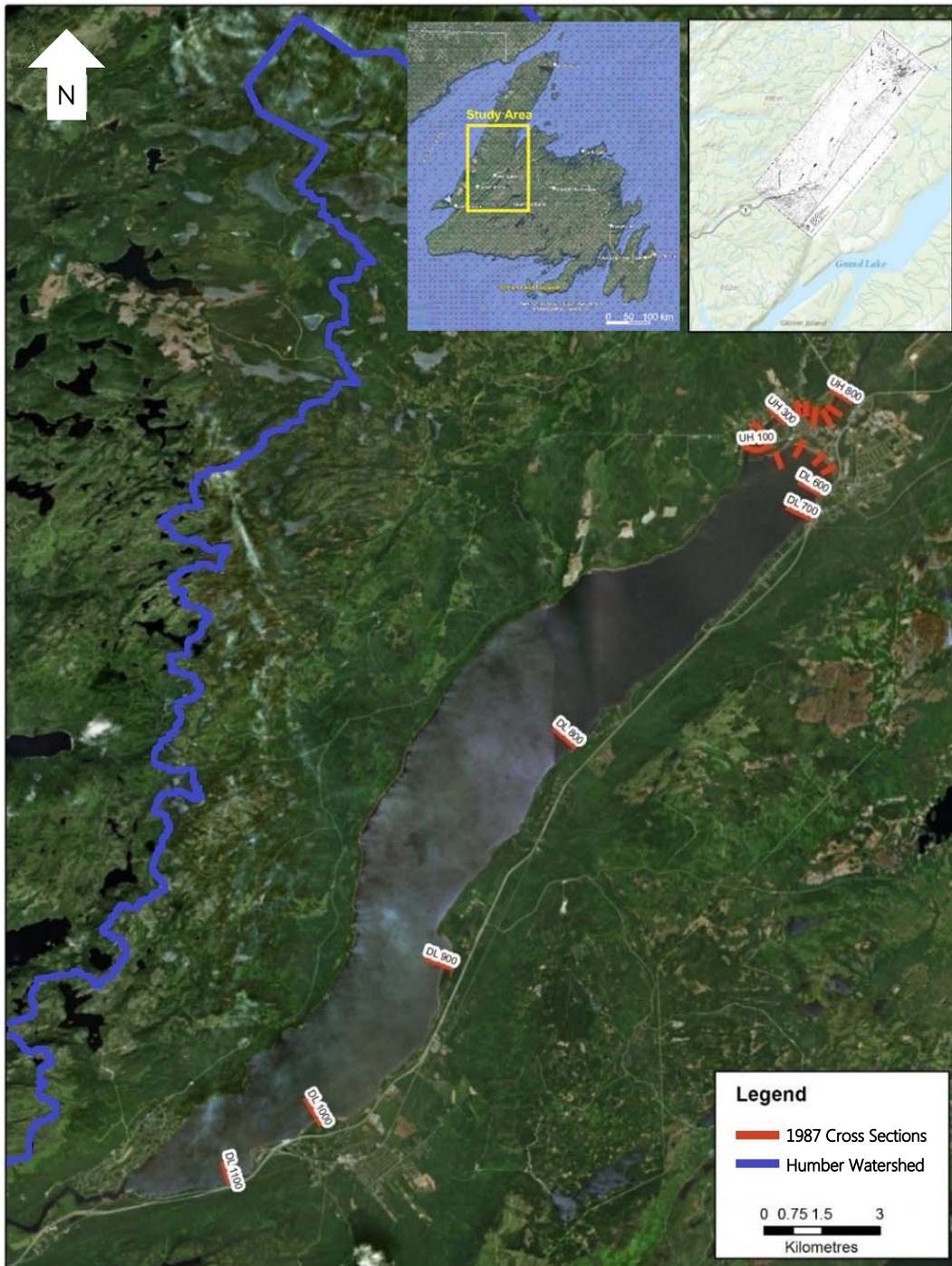


Figure 2-11: 1987 Flood Study Cross Sections on Deer Lake and Upper Humber

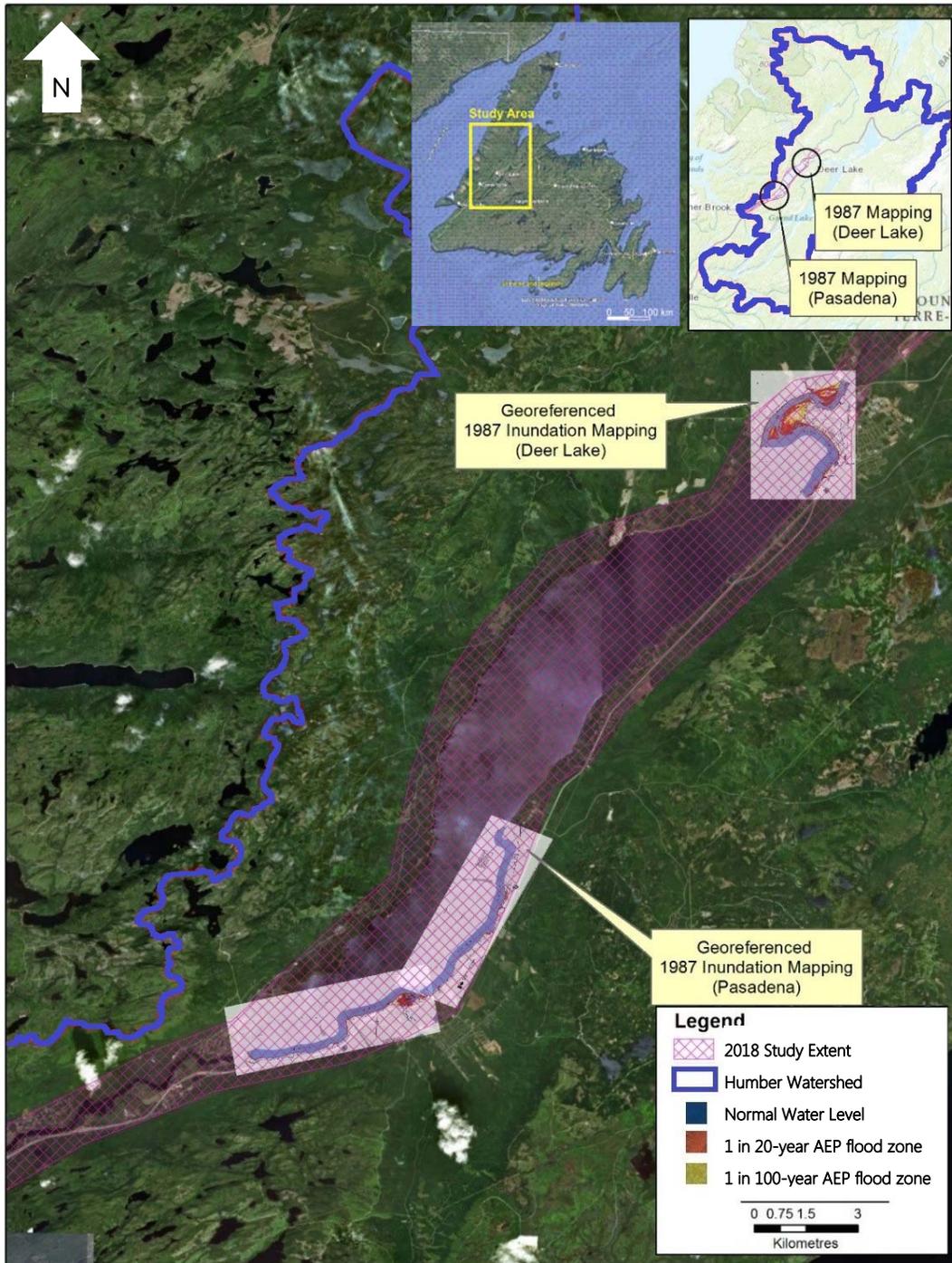


Figure 2-12: 1987 Inundation Mapping (Overall Study Area)

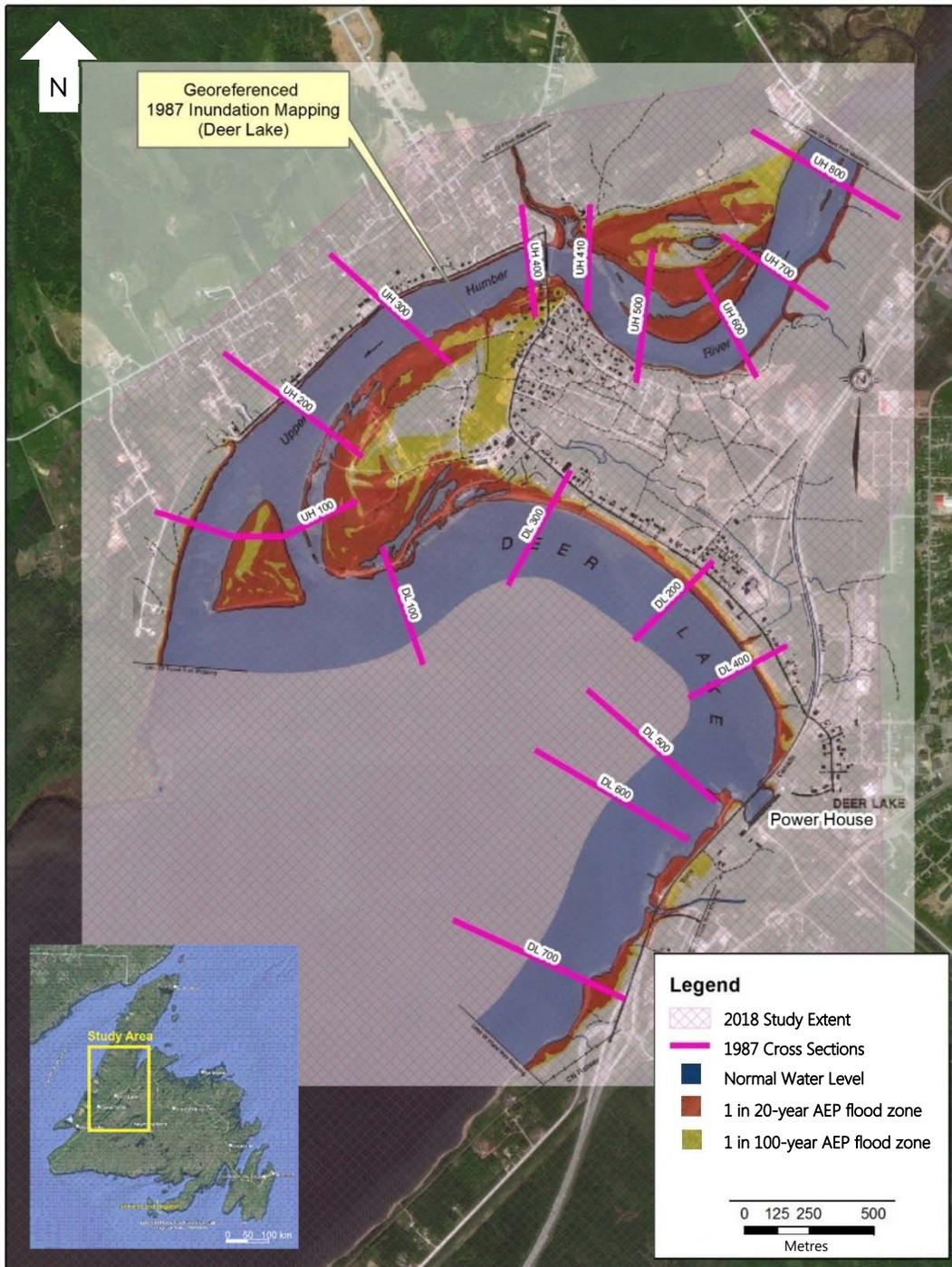


Figure 2-13: 1987 Flood Inundation Mapping - Deer Lake

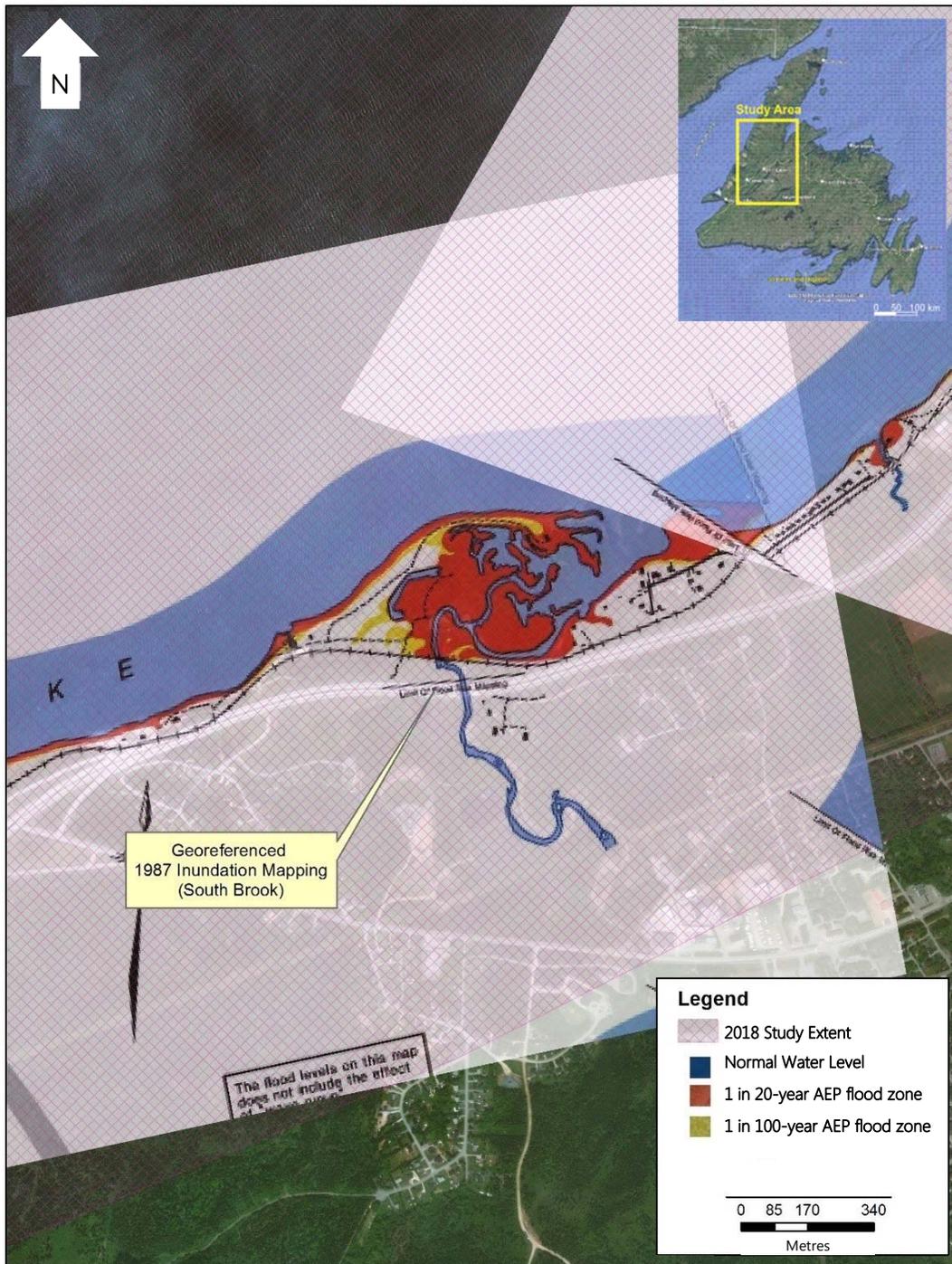


Figure 2-14: 1987 Flood Inundation Mapping - South Brook - Pasadena



Figure 2-15: 1987 Flood Inundation Mapping - near Governors Point

### 2.2.3 Review of Existing Humber River Flood Forecasting Systems

The Water Resources Management Division is mandated by the Government of Newfoundland and Labrador to provide flood forecasting services for the Humber River since 1995. While a variety of flood forecasting models have been developed over the years, two flood forecasting models are currently in operation during the spring-runoff period, namely a dynamic regression model (DR) and a neural network (NN) model.

The DR Model was introduced in 1996. This linear time series model predicts flow using lagged flows and precipitation as input to dynamic (linear) regression models developed at flow gauging stations along the Humber River. This modelling approach provides three-day flow forecasts but does not account for snowmelt that occurs in the Upper Humber River Watershed (Picco, 1997).

The NN Model was introduced in 2010 and was derived from the fields of artificial intelligence. The NN model, as described in *Flood Forecasting on the Humber River Using an Artificial Neural Network Approach* (Cai, 2010), uses lagged air temperature, precipitation, cumulative degree-days and flow data to provide one-day flow forecasts.

Both the DR and NN models divide the Humber River Watershed into three reaches coincident with the following hydrometric gauges:

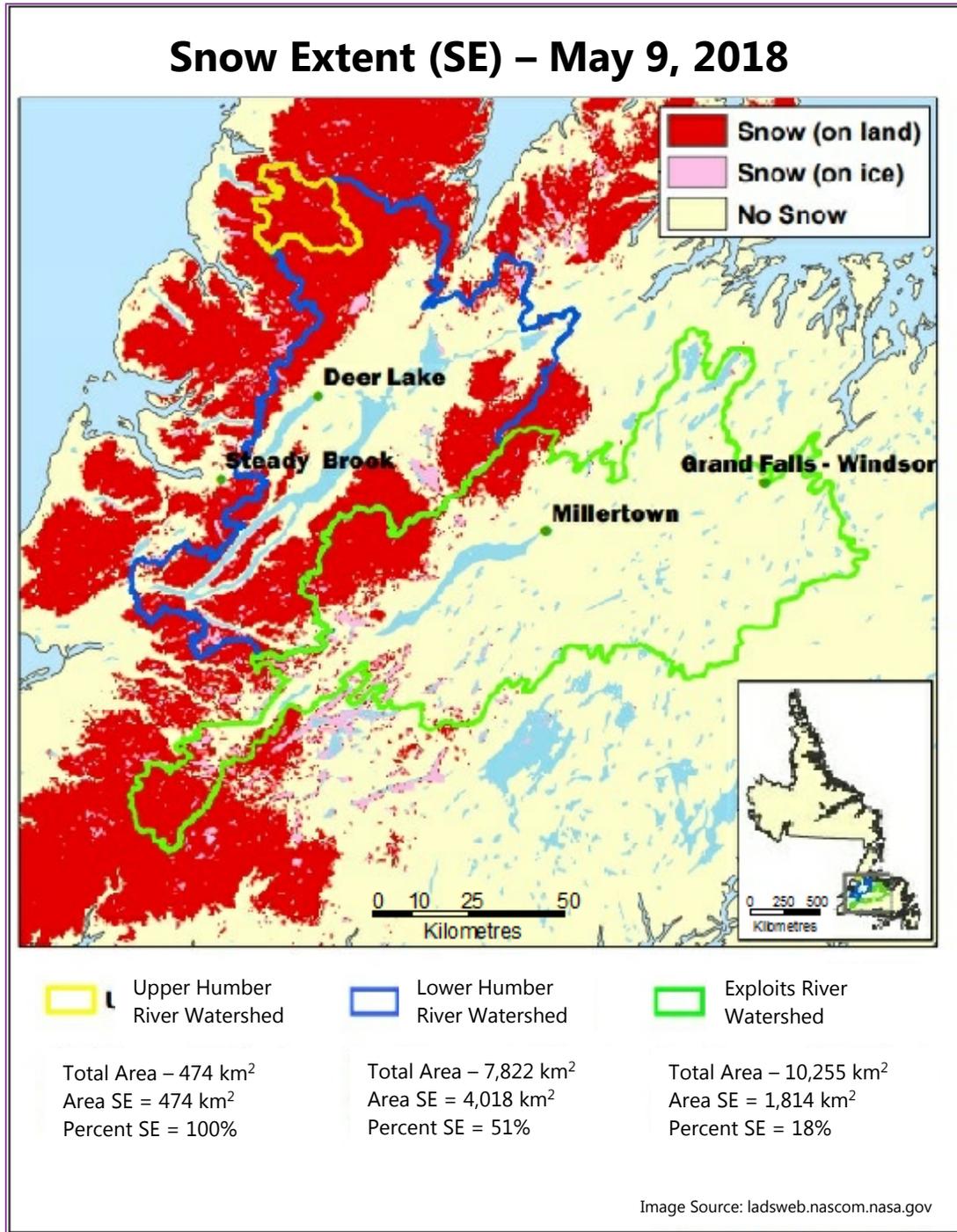
- Upper Humber above Black Brook (02YL008 – 74 km upstream from Humber Village Bridge),
- Upper Humber Near Reidville (02YL001 – 45 km upstream from Humber Village Bridge), and
- Humber River at Humber Village Bridge (02YL003).

In 2010, research efforts were also directed at incorporating remotely sensed snow cover data into daily flow modelling for the Upper Humber River (Tom, 2010). WRMD has since actively monitored snow cover (SE) and snow water equivalent (SWE) in the Humber River Watershed through a combination of satellite-based snow products, annual in-field snow survey and two real-time snow monitoring stations. These real-time snow monitoring stations are located at:

- Sandy Lake near Birchy Narrows (Camp 55), installed in 2010, and
- Upper Humber River above Black Brook, station # NLENCL0007, installed in 2015.

An example of the snow product developed for the Upper and Lower Humber Watersheds is illustrated as Figure 2-16.

Examples of data available from the real-time monitoring station on the Upper Humber River above Black Brook is presented as Figures 2-17 and 2-18.



**Figure 2-16: May 9, 2018 Snow Extent Product for the Upper and Lower Humber River Watersheds**

(Source: MAE, 2018)

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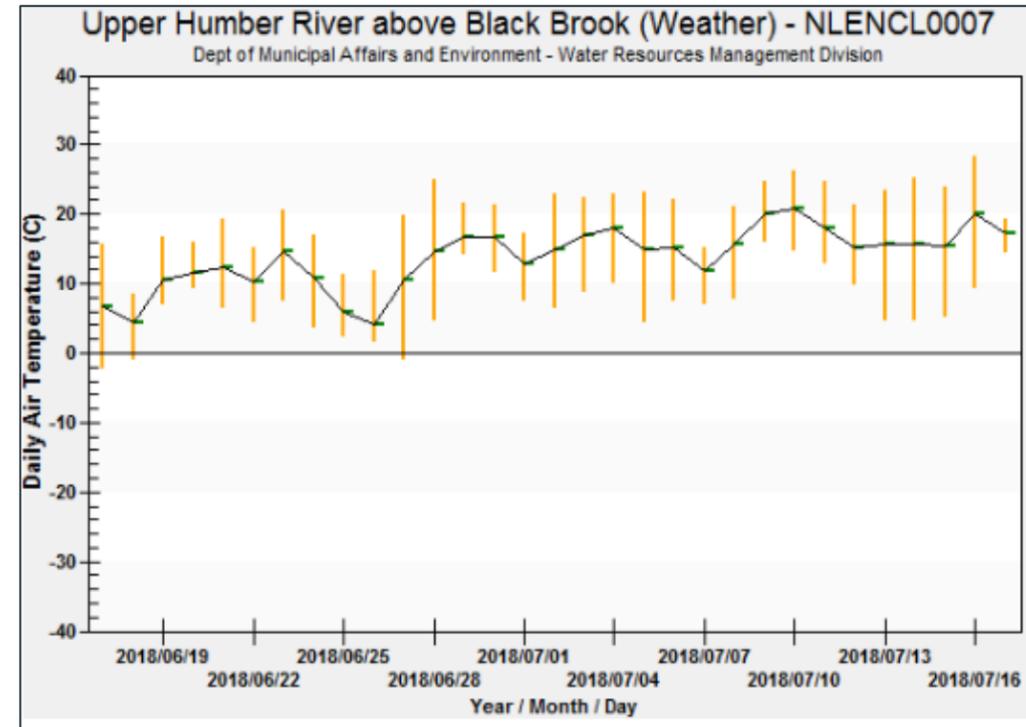
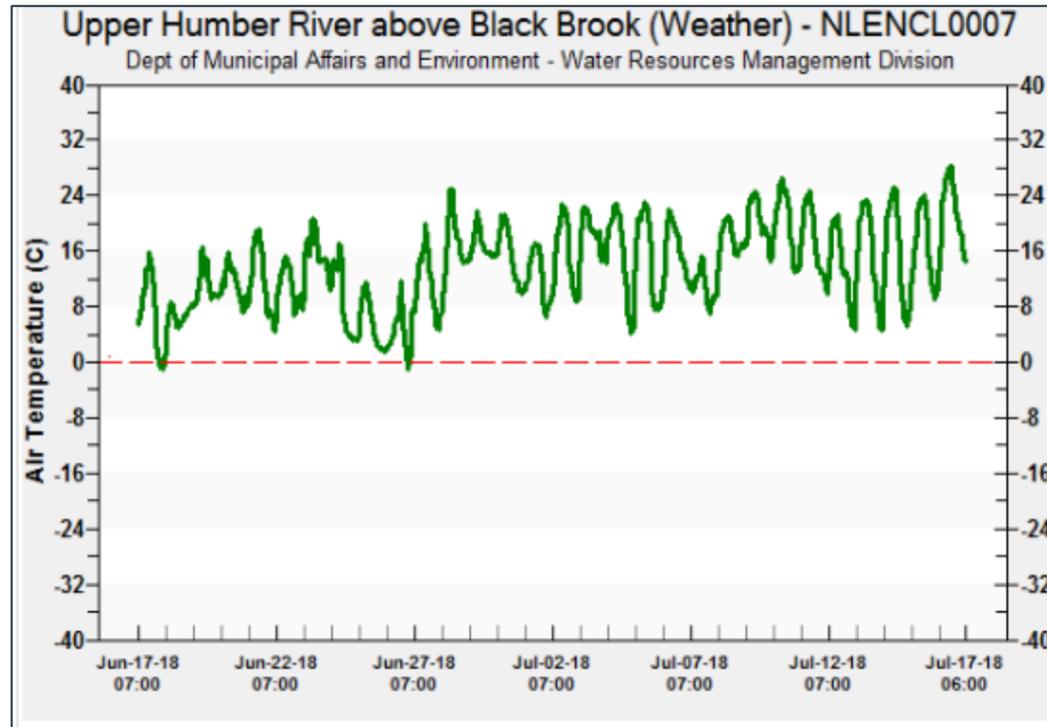
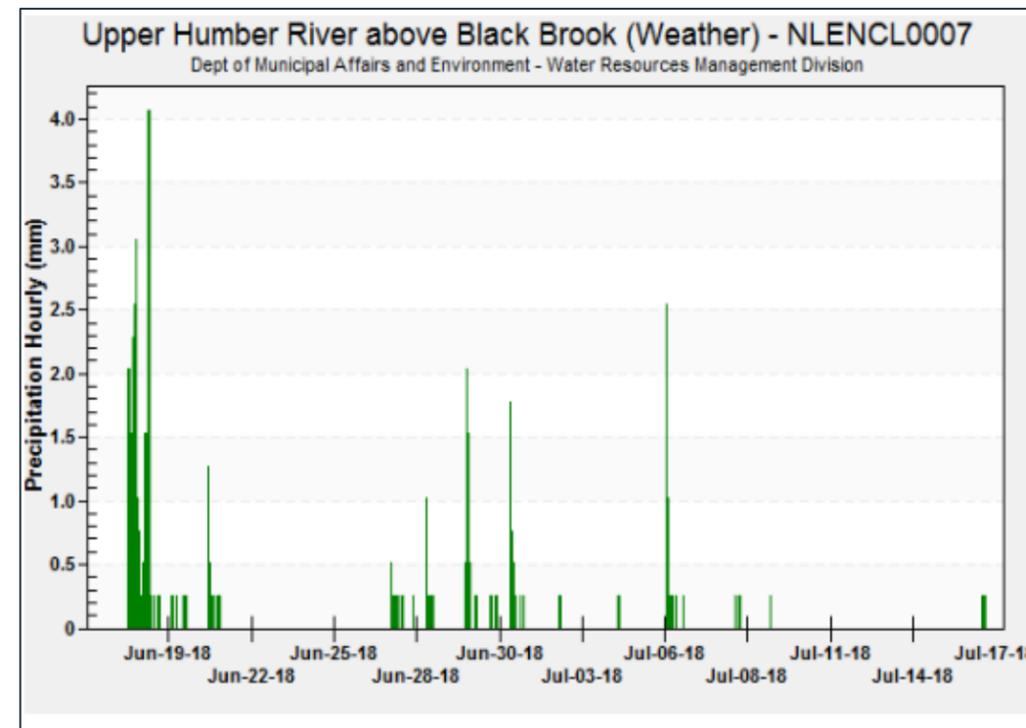
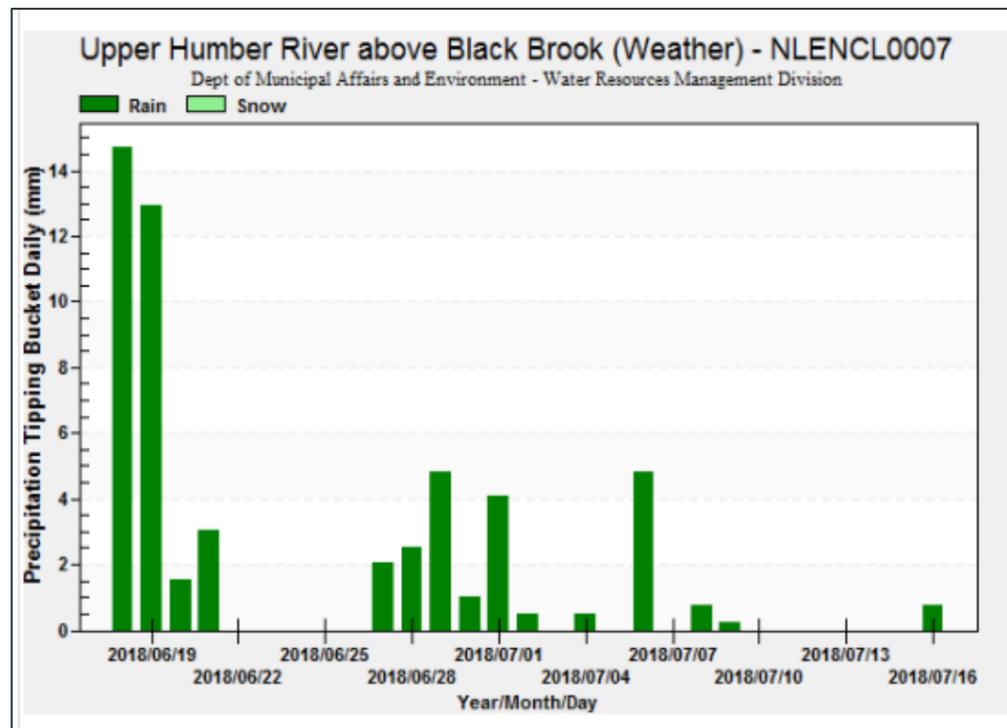
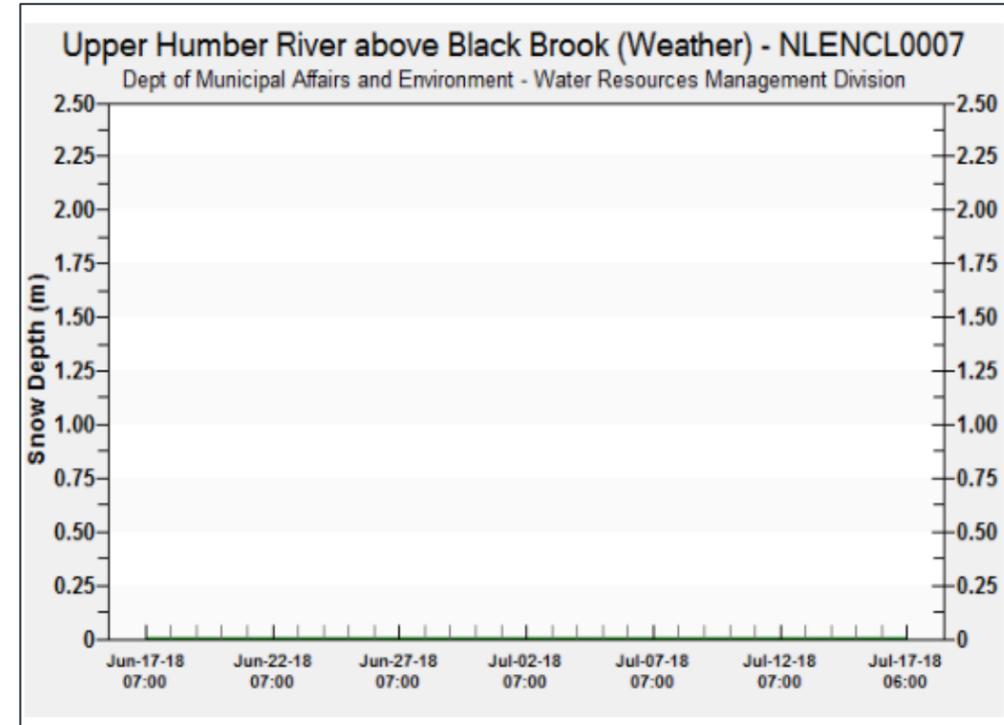
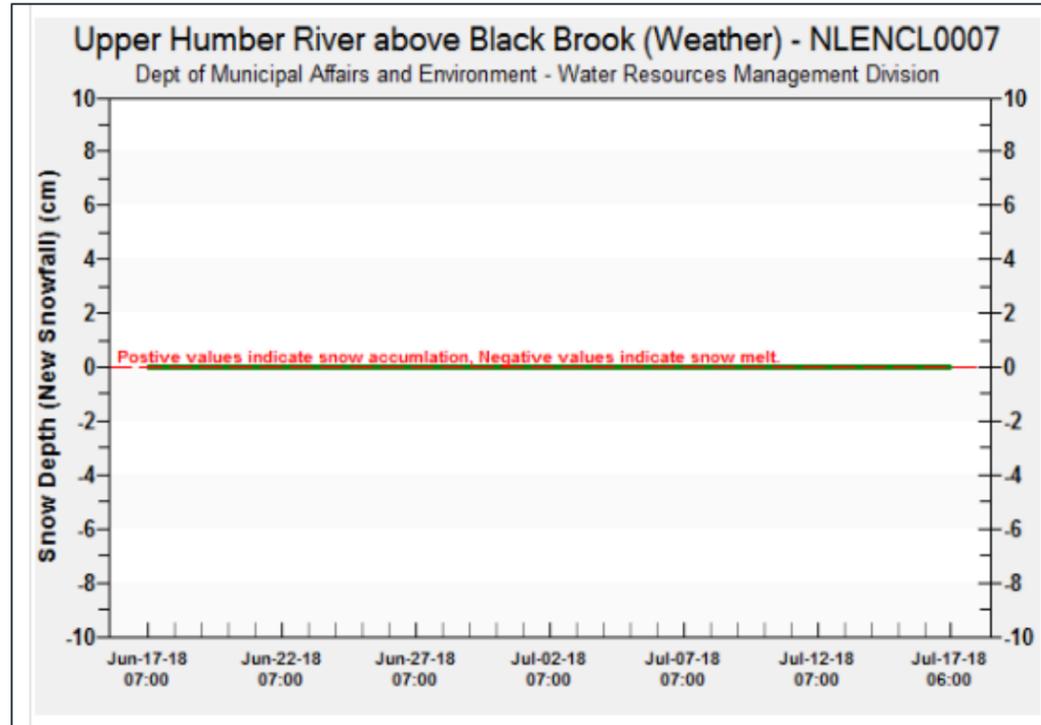
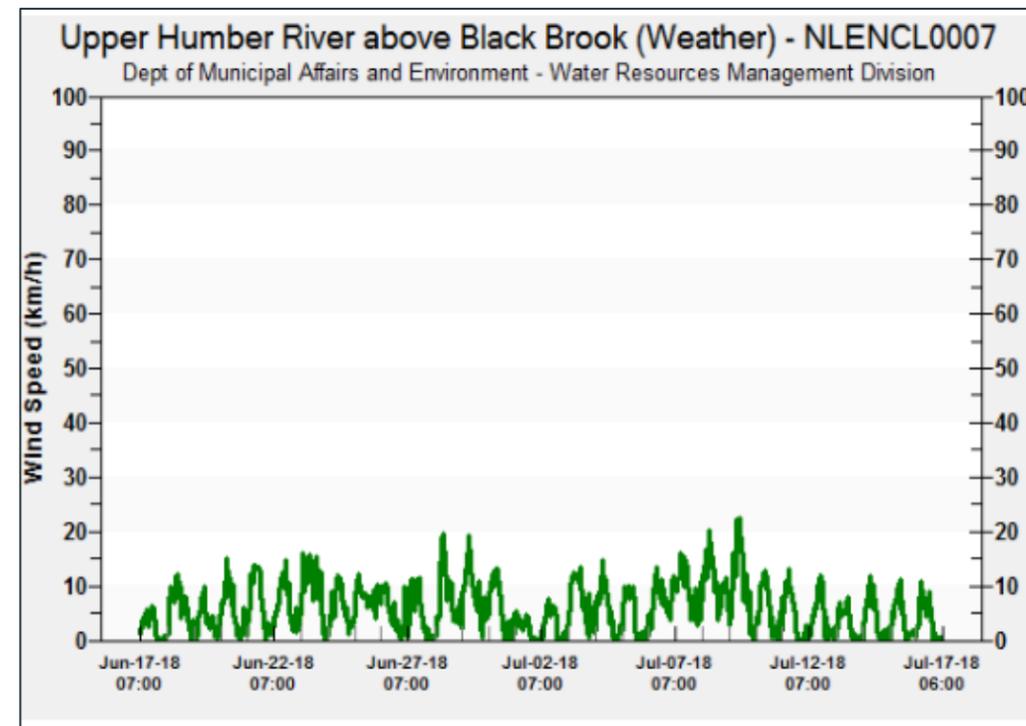
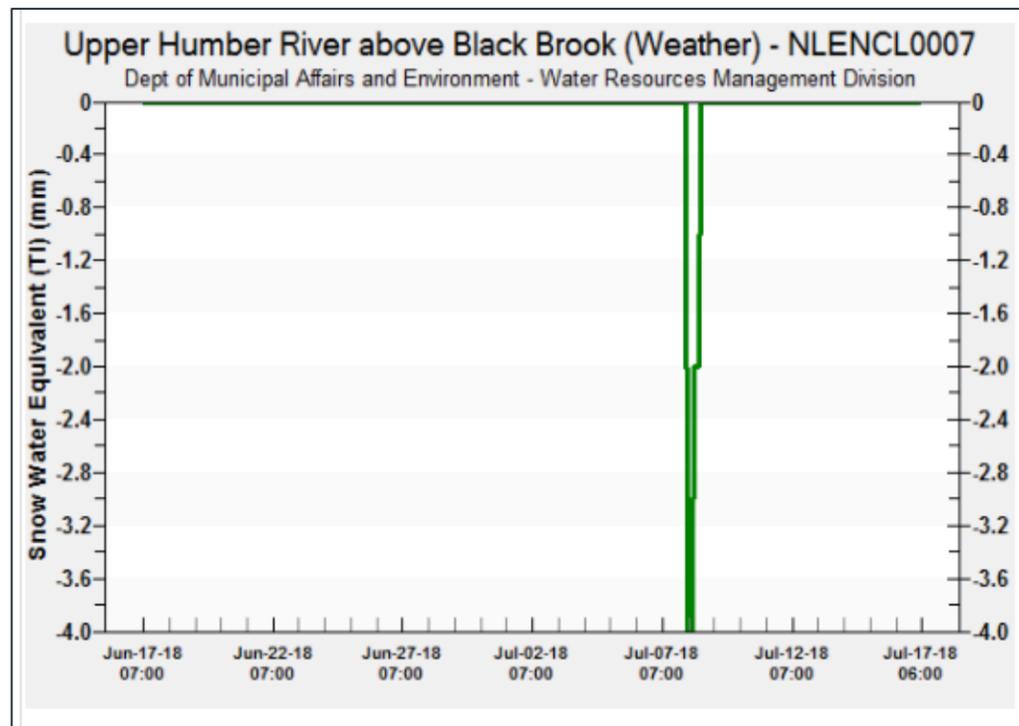


Figure 2-17: Examples of Data from Station NLENCL0007 - Upper Humber River above Black Brook





**Figure 2-18: Examples of Data from Station NLENCL0007 - Upper Humber River above Black Brook**



## 2.3 Historical Flooding Inventory

The 2012 Flood Event Inventory (1950-2011) for Newfoundland and Labrador, represented the starting point for compilation of flooding experiences in the Project area. This database was augmented by consulting local and other sources as outlined in the report sections that follow. As well, the identified flood records were added to the Flood Events Inventory Excel<sup>®</sup> spreadsheet, provided by WRMD to this project.

### 2.3.1 Flood Events Review

#### **Shawmont Newfoundland Ltd. (1969) - A Report on High Flows on the Humber**

A report prepared by Shawmont Newfoundland Ltd. (Shawmont, 1969) discussed the causes and effects of high levels and flows on the Humber River in May of 1969. The report concluded that if the hydroelectric plant had not been built, the flooding (past, present and future) would be, or would have been, at least as severe and probably more severe than with the development of the storage system (applied to Deer Lake and the reach of the Humber River between Deer Lake as far downstream as Steady Brook). With respect to high flows in 1969 (e.g. Deer Lake was reported to have risen 1.4 metres between May 21-24th, and Steady Brook rose 4 m above normal), it was concluded that the hydroelectric development has had a beneficial effect on the water levels and flows, hence decreasing flood risk, downstream from Deer Lake.

#### **MacLaren (1972) - Study of Steady Brook Flooding**

Long-term residents of Steady Brook believed significant flooding in recent years (up to 1972) was the result of the construction of the Trans-Canada Highway (TCH) on the southern shore of the Humber River (i.e. partial infilling of the channel caused a backwater effect resulting in increased flooding in Steady Brook). MacLaren (1972) report indicated the infilling had no significant impact on flood levels along the Humber River.

#### **Department of Environment (1982) – Report on May 1981 Flooding of Steady Brook**

The Department of Environment (DAE-WRD, 1982) report briefly reviewed the recurring flooding problems experienced by residents of the Humber Valley and the reservoir operational requirements of the Bowater Power Company (now Kruger Inc.). The study concluded the Steady Brook area is prone to flooding without any contribution from the Main Dam spillway (Humber River channel capacity is only about 708 m<sup>3</sup>/s). For relatively large floods, the regulatory effects of the reservoir were deemed to be insignificant.

#### **Environment Canada (1980) – Flooding Events in Newfoundland and Labrador (Historical Perspective)**

The Environment Canada (1980) historical perspective of flooding in the province confirmed a high potential for future flood losses within the community of Steady Brook.

#### **Cumming-Cockburn Ltd. (1984) – Hydrotechnical Study of the Steady Brook Area**

The 1984 Steady Brook Area Flood Study (Cumming-Cockburn Ltd., 1984) reviewed documentation on historical floods for the period of 1944 to 1984. A summary of historical flooding was provided in Table 2.1 of the report and further detailed in Appendix A of the report. At the time of writing of the 1984 study, it

was evident that the majority of damage producing flood events had been the result of rain on snowmelt conditions. It was also evident that flood damages occur as a result of heavy rains in the summer or fall. Historically flood prone areas were identified on Figure 2.1 of the Cumming-Cockburn Ltd. (1984) report (included in this document as Figure 2-19).

The earliest record of flooding along the Humber River suggested flood damages were predominantly in the vicinity of Corner Brook. The areas of South Brook, Bell's Brook, and Governor's Point (at the outlet of Deer Lake) were also historically sensitive to flooding.

Post-1970, the Steady Brook area was also subjected to severe flooding (the increased frequency of damage was indicative of additional development of floodplain lands). It was also noted that ice and debris jamming along Steady Brook increased the flood risk in the area. Long term residents also indicated the accumulation of logs and debris (particularly upstream of old log boom piers) in the Humber River increased flood levels in the vicinity of Steady Brook.

The Cumming-Cockburn Ltd. (1984) report documented peak flow estimates for the Humber River immediately downstream from Steady Brook of 1,180 m<sup>3</sup>/s for the 1 in 100-year AEP flood. A moderate to low flood risk was identified for the area of Governor's Point.

It was determined that one of most beneficial non-structural measures to reduce flood losses in the area would be to modify the operational procedures of the Grand Lake Dam to improve its effectiveness in attenuating flood peaks.

### **Cumming-Cockburn Ltd. (1987) – Hydrotechnical Study of the Deer Lake Area**

This report concluded that excessive rainfall during spring months, leading to rapid snowmelt and high peak flows was the predominant cause of flooding in the Humber River watershed.

Peak flow estimates for the Upper Humber River at the outlet of Deer Lake were found to be 1,370 m<sup>3</sup>/s for the 1 in 100-year AEP flood. The 1 in 100-year design lake elevation for Deer Lake was determined to be 8.84 m (resulting from the output of a calibrated SSARR model and the addition of wind/wave setup for the flood elevations). It was determined that the effects of wave set-up on Deer Lake static design water levels would increase the design estimate by approximately 0.3 m for the 1 in 100-year event. The effect of run-up on design lake level estimates increased the 1 in 100-year design estimate by 0.6 m.

The main flood hazard areas identified in the Cumming-Cockburn Ltd. (1987) study include:

- Nicholsville: classified as having a flood risk due to peak flows in the Upper Humber River. Peak flows and ice jams along the Upper Humber River would contribute to flood risk upstream of Nicholsville Bridge. Based on the Cumming-Cockburn Ltd. (1987) study, upstream of the Nicholsville Bridge, the velocity and Froude numbers were found to average 1.15 m/s and 0.12 respectively (indicating a higher potential for ice jam formation and ice growth throughout this reach of the Upper Humber River). The simulation of an ice jam (3.5 m thick) upstream of the bridge resulted in an increase in water surface elevation of 0.91 m from free flow conditions. Flooding was anticipated to be fairly shallow as a result of open water flow events. Flooding in the area would result from sheet overland flow spilling into the overbank areas to the south of the bridge.

- North-eastern Overbank Areas of Deer Lake (within the Town of Deer Lake): low risk of flood damage.
- South Brook and Governors Point: susceptible to shallow flooding as a result of wave setup events.
- Access routes along the eastern shore of Deer Lake and Upper Humber River: high flood risk.

### **Post-1987 Flood Events**

The 2012 Flood Inventory Update documents eight (8) flood events that occurred after the completion of the Cumming-Cockburn Ltd. (1987) hydrotechnical study (ref. Appendix A). Beyond 2014, the most significant flooding events of relevance to the study area occurred on:

- January 12 to 14, 2018: rainfall, snowmelt and ice jams caused significant damage in Deer Lake and Reidville.
- February 3, 2018: Five residents of the Maple Place area of Pasadena were evacuated from their homes Saturday morning due to dangerously high-water levels that resulted from an ice dam in South Brook, which extended from the mouth of the brook at Deer Lake back to beyond Maple Place.

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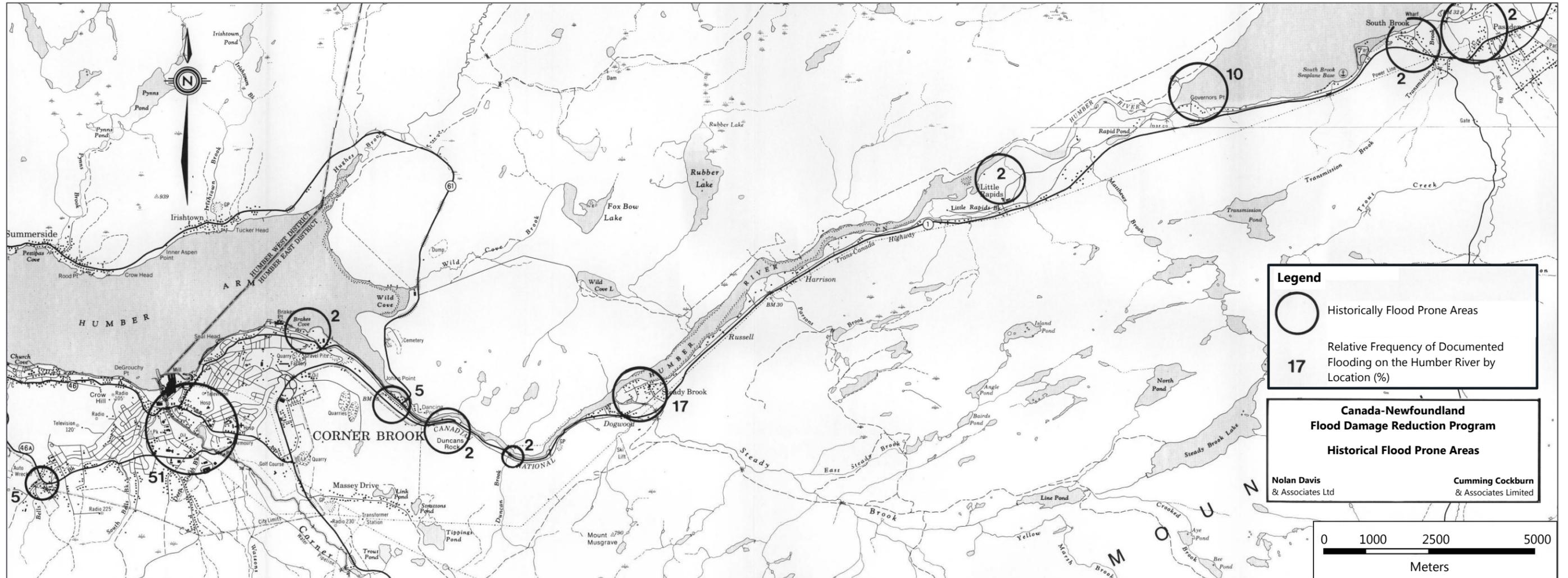


Figure 2-19: Historical Flood Prone Areas (as of 1984)

(Source: Figure 2.1 from Cumming Cockburn, 1984)

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### 2.3.2 Flood Inventory Database Review

As noted previously, the 2012 Flood Event Inventory (1950-2011) for Newfoundland and Labrador, prepared by AMEC Environment & Infrastructure (now Wood) (AMEC, 2012a), was used as a source of information to identify flood risk in the Humber Valley area. This database has also, since its original development, been updated periodically by WRMD.

A review of the available information identified forty-six (46) flood events in the existing inventory for the period 1944 to 2013 events having occurred in the Humber River study area. Based on the review of the materials described previously, five (5) additional flood events were added to the inventory, namely:

#### **February 2-3, 1973**

Mild temperatures, rain, melting snow and ice jams caused minor washouts on several gravel roads throughout Corner Brook. This event is defined as flood #783.

Three other flood events are defined in the inventory on this date (#81, 82 and 83) associated with a single storm event #62. These three floods are associated with the Stephenville area, and the Rushoon and Burin Peninsula areas. It is surmised that the flood event which occurred in Corner Brook on this date is also associated with storm #62.

The source of the information for this event is the 1984 Hydrotechnical Study of the Steady Brook Area (ref. Table 2.1 from the 1984 report).

#### **November 18, 1977**

A power outage resulted in the emergency spillway being activated resulting in heavy spilling of water and inundation of TCH at Spillway Brook closing the highway for a period of time. This event is defined as flood #784.

No other flood events are presently defined in the inventory for this date. Although the catalyst for this flood event was not meteorological, a new Storm (#351) was defined and the nature of the event noted in the text description.

The source of the information for this event is the 1984 Hydrotechnical Study of the Steady Brook Area (ref. Table 2.1 from the 1984 report).

#### **August 5, 2007**

Parts of Deer Lake experienced flooding on this date as a result of 31 mm of rain falling in 20 minutes. Deer Lake Mayor Darrel Kelly described the conditions in his community as a flash flood.<sup>2</sup> This event is defined as flood #785.

As no other flood or storm events are presently defined in the inventory for this date, this storm event was defined as #352.

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<sup>2</sup> Source: <https://web.archive.org/web/20070816234553/https://www.cbc.ca/canada/newfoundland-labrador/story/2007/08/06/deerlake-flood.html#skip300x250>

### **January 12-14, 2018**

The catalyst for the flood event was an ice jam that formed between Reidville and Deer Lake. On January 12 temperatures rose to 11°C and the area also experienced 12.6 mm of rain. On January 13 there was a high temperature of 12.7°C and another 29.6 mm of rain fell. The depth of snow on ground was reduced from 68 cm on January 11 to 8 cm on January 14.<sup>3</sup>

At the mouth of the Upper Humber River, where it empties into Deer Lake, there is an island that separates the flow into two channels. Ice and debris collected on the eastern side of the island causing rafting of ice and the already high water to begin backing up into the river. Waters rose high enough to flood parts of the old road along the river in Reidville and high water backed up enough to flood much of the Reidville Walking Trail.

Multiple roads were closed, and a state of emergency was declared in Deer Lake. Significant erosion of river banks along Pine Tree Drive and Riverbank Road in Deer Lake was experienced and this issue was still not resolved as of January 2019. The TCH experienced significant damages near little Rapids.

In Deer Lake, large sections of the riverbank sloughed into the water when the Humber River filled with rain and chunks of snow, pushing land with it.

It is noted that this event was already defined in the inventory as Flood #780 associated with Storm #349. Additional attribute information was included with this database entry based on research completed for this project.

### **February 3, 2018**

Five residents of the Maple Place area of Pasadena were evacuated from their homes Saturday morning due to dangerously high-water levels. The catalyst for the flood event was an ice jam.<sup>4</sup>

The road, which only has a few houses on it, is near a brook that courses through the middle of town. The brook flooded after Friday's heavy rains and mild temperatures and overflowed onto the road, rendering it impassable by regular traffic. An ice jam in a bend in the river forced the brook to redirect its flow towards Maple Place.

Several hundred metres of ice damming occurred on South Brook, which extended from the mouth of the brook at Deer Lake back to beyond Maple Place. Flooding was known to have previously occurred in this area.

It is noted that this event was already defined in the inventory as Flood #782 associated with Storm #350. Additional attribute information is included with this database entry based on research completed for this project.

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<sup>3</sup> Source: <https://www.saltwire.com/news/local/update-corner-brook-humber-arm-south-declare-state-of-emergency-amid-flooding-road-washouts-in-western-nl-177008/>

<sup>4</sup> Source: <https://www.cbc.ca/news/canada/newfoundland-labrador/flooding-pasadena-evacuation-5-1.4518381>

### 2.3.3 Flood Inventory Database Analytics

The original database developed for the 2012 Flood Event Inventory project had 650 flood events defined. Since that time, WRMD has added additional information and the defined flood events now number 782.

The 2012 Flood Event Inventory presented a number of summary analytics of information housed in the Inventory. These included:

- Total Flood Damages Estimate by Season, Decade, Year, and Season
- Storm Occurrence by Season, Month, Year and Region
- Flood Occurrence by 'Types of Events', Season in Specific Communities, Community and Type of Event



**Photo 2-1 February 3, 2018 Flood Event - Pine Tree Drive area of Deer Lake**

(Source: Western Star, 2018)

### 2.3.4 Flood Inventory Database Recommendations

The following recommendations were offered to assist the Government of Newfoundland and Labrador, as a component of the 2012 Flood Event Inventory project, in support of its future planning and adaptive capacity and resiliency building efforts. A review of these recommendations is presented below.

- It is recommended that WRMD endeavor to include flood events which occurred earlier than 1950 in the Inventory with the next Flood Events Inventory update. Many flood events pre-dating 1950 are documented in the source data collections used for this update effort. Having these events included may assist in better defining/understanding the long-term cyclical nature of storm events in the Province.
  - The Province has acted on this recommended since the initial development of the Inventory and has added 98 flood events for the period 1900 to 1950.
- It is recommended that some consideration be given to splitting the 'Types of Event' field into primary and secondary (and perhaps even tertiary) causal factors. This would allow for consolidation of entries within a more concise listing of primary/secondary causes and perhaps better understanding of the nature of flood events; although it is unclear how difficult such a classification effort would be and whether sufficient data sources are available.
  - *This recommendation has, to date, not been adopted.*
- It is recommended that WRMD consider the addition of a data field to identify the watershed within which the community is located. This can be completed by an overlay analysis.
  - *This recommendation has, to date, not been adopted.*
- It is recommended that WRMD consider evolving the Flood Events Inventory software platform from Microsoft Excel<sup>®</sup> to a database platform such as Microsoft Access<sup>®</sup>. This would facilitate capture of additional flood related information from multiple sources, better data entry and management, in addition, to the ability for more efficient linking to other databases (such as the Local Government Profiles database) and GIS. Microsoft Access<sup>®</sup> can be used as part of a relational database management system, whereas Microsoft Excel<sup>®</sup> cannot. Microsoft Access<sup>®</sup> enables data management advantages such as easier importing of data into a GIS environment.
  - *This recommendation has, to date, not been adopted.*
  - It is further noted that manipulation of the data in the Excel-based inventory (i.e. merging of fields) has introduced a significant limitation into the use of the inventory, as the merged fields preclude use of the database directly as a whole. Use of the information must now be prefaced by creating a copy of the data of interest in a new spread sheet and the remnants (if any) of the merged fields cleaned. It is surmised the merged fields were implemented as a means of representing the one to many relationships (e.g. storm events to flood events, flood events to references, etc.). This action of merging fields, and the limitation it has fostered, reinforces the need to move the flood inventory to another more suitable database platform.

- It is recommended that WRMD develop a process whereby the information relevant to the Flood Events Inventory is gathered in a timely fashion after a flood or storm event.
  - It is understood that any WRMD managed hydrotechnical project includes scope for update of the flood inventory. This is considered a reasonable accommodation for this recommendation.

## 2.4 Consultation with the Municipalities

As a required component of this study, Wood consulted with every formal community in the study area. Initial meetings were held to apprise the communities of this project and to request their input regarding flooding issues in their communities and, as well, to gain an understanding of their future development plans. The communication with each of these communities is summarized in Appendix B and a brief summary of each initial meeting is provided in this section of the report.

Outreach to the communities was also facilitated in 2020 for review of draft flood plain mapping. This engagement is described in detail in Section 9 of this report.

### **Town of Deer Lake – Meeting date January 28, 2019**

Wood representatives met with the Town Manager and Superintendent – Public Works.

It was noted that:

- Deer Lake has a history of damage from flooding and that historically flooding has generally been attributed to Deer Lake Power opening their flood gates.
- The last time Kruger/Deer Lake Power opened the flood gates from the Main Dam at Junction Brook was in May 2013. This was the first time that they opened the flood gates in 15-20-years. Prior to that, the gates were opened often. Reduced spillage from the Main Dam was attributed to changes in power distribution from Deer Lake Power. In the past power generated was used only to power Corner Brook Pulp and Paper. Electricity flow to the grid was integrated in the last 10-20-years, resulting in less spillage.
- The Town of Deer Lake noted its interest in being part of the flood risk study process and provided input on historically impacted locations, as well as, a copy of their draft official plan, as the Town is waiting for government input to have it finalized.

### **Town of Reidville – Meeting date January 28, 2019**

Wood representatives met with the Town Clerk.

It was noted that:

- Significant flooding has not occurred in Reidville prior to 2018. The Town Clerk indicated that ice damming was not experienced before that year (2018). The Town Clerk's historical knowledge of the area is extensive, with grandparents having settled in Reidville.
- There are three locations within the Town that are susceptible to flooding, including the Tranquil Waters Subdivision, Meadow Brook Subdivision and Riverview Subdivision.

- The town plan was completed in 2009 and will be updated within the next couple of years, likely with the results of this flood study included. The town plan presently includes an environmental protection area that includes the flood risk areas.

**Town of Pasadena – January 28, 2019**

Wood representatives met with the Town Operations Manager.

It was noted that:

- Flooding consistently occurs in the Town at three key locations, namely:
  - Homes on Maple Place
  - Park Road Subdivision floods every year
  - West Haven Lodge likely floods (retirement home)

**Town of Steady Brook – January 30, 2019**

Wood representatives met with the Town Engineer.

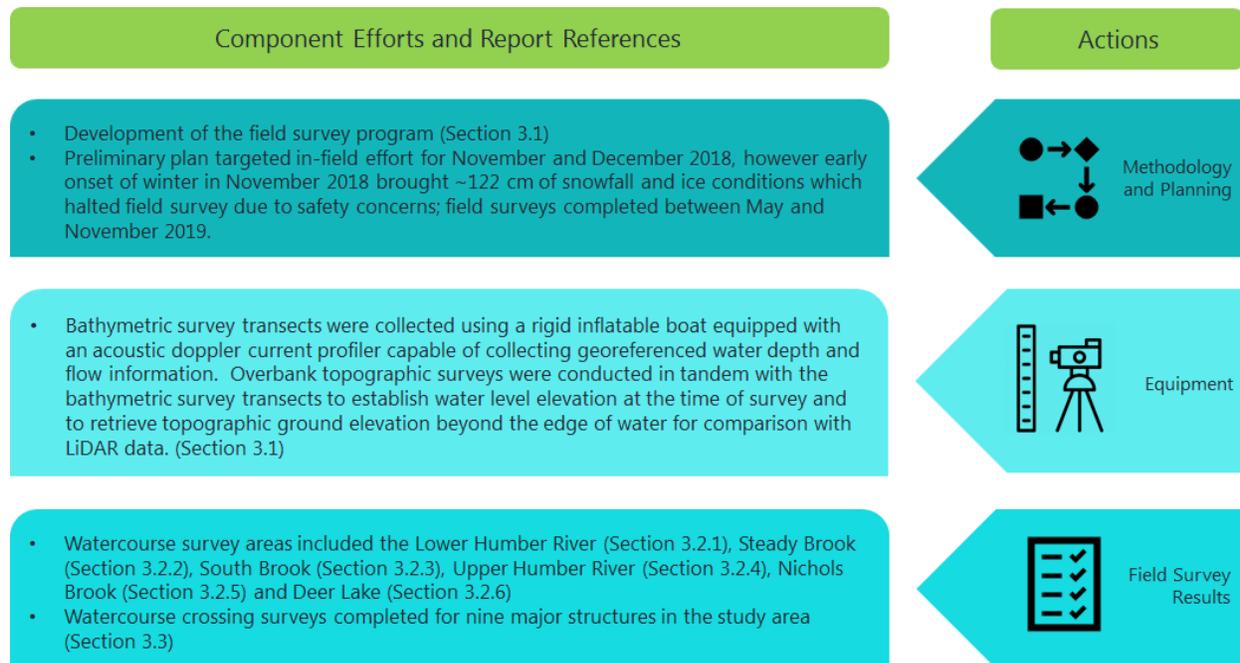
It was noted that:

- In 2018, flooding reached as high as the bottom of Steady Brook Bridge and halfway up the retaining wall. The retaining wall is 8-10 feet high and was built 30-40 years ago.
- During potential flooding, the town watches levels on the stream behind the sewage settling ponds near Marble Mountain.
- Another known flooding issue is associated with the property at 241 Marble Drive.

### 3.0 Field Program

Synopsis: The objective of the field survey program was to collect data required for establishing the hydrological and hydraulic models to be used in the flood risk mapping study and the flood forecasting system. The field survey areas included the Upper Humber River and tributaries deemed to be of hydraulic significance including Deer Lake; South Brook; Steady Brook; Nichols Brook and Lower Humber River and its outlet channel. The completion of the survey was delayed until 2019 due to early onset of winter conditions in late 2018. The field topographic survey program for this study consisted of nine crossing structures to support hydraulic modelling; and watercourse cross-sections required for establishing the hydraulic geometry below the water level and within the main channel of the river. The data obtained from these surveys, in combination with LiDAR survey data, are required for development of the hydraulic model.

**Figure 3-1: Field Program Summary**



### 3.1 Overview

The objective of the field survey program was to collect data required to establish the hydrological and hydraulic models used in the flood risk mapping study and the flood forecasting system. The methodology and data collected from the field survey program is documented in the following report chapters. The field survey included the following streams and waterbodies within the study area as defined in the RFP:

- Upper Humber River and tributaries deemed to be of hydraulic significance;
- Deer Lake;
- South Brook;
- Steady Brook; and
- Lower Humber River and its outlet channel.

### 3.2 Methodology

In general, the field survey program consisted of the following activities:

- Development of the Inundation Mapping Area and Stream Network (IMA&SN);
- Development of the field survey program; and
- Field surveys for the Upper Humber River, Deer Lake, Steady Brook, and the Lower Humber River and its outlet channel.
- Based on discussions with the Technical Committee in December of 2018, bathymetric profiling of South Brook (Pasadena) and Nichols Brook (Nicholsville) were also deemed necessary and such data were collected in 2019.

It is noted that no survey of Grand Lake, or the hydroelectric structures operated by Kruger, was conducted as a component of this field program as the data made available from Kruger, as well as other background information was deemed sufficient to support model development.

To develop the field survey program and for subsequent hydrological and hydraulic modelling, it was necessary to define the IMA&SN. The perennial stream network was evaluated using NTS 1:50,000 topographic maps and the National Hydro Network (NHN Edition 1.1).

Flood maps produced in previous studies (i.e., Cumming-Cockburn, 1984 and Cumming-Cockburn, 1987) were georeferenced in ESRI ArcMap (ref. Figures 2-12 to 2-14) to serve as an initial point of reference for establishing transects along the Humber River and in Steady Brook.

Given the size of the study area, the field program was limited to the area within the study extent depicted in the RFP (ref. Figure 1-3), except for the Upper Humber River, which for the purposes of RIVICE modelling required bathymetric upstream of the study extent. The field topographic survey program for this study consisted of the following components:

- Stream crossing structures: to support hydraulic modelling of the study area;
- Stream cross-sections: required to establish the hydraulic geometry below the water level and within the main channel of the river. These surveys, in combination with LiDAR survey data, are required for hydraulic model development.

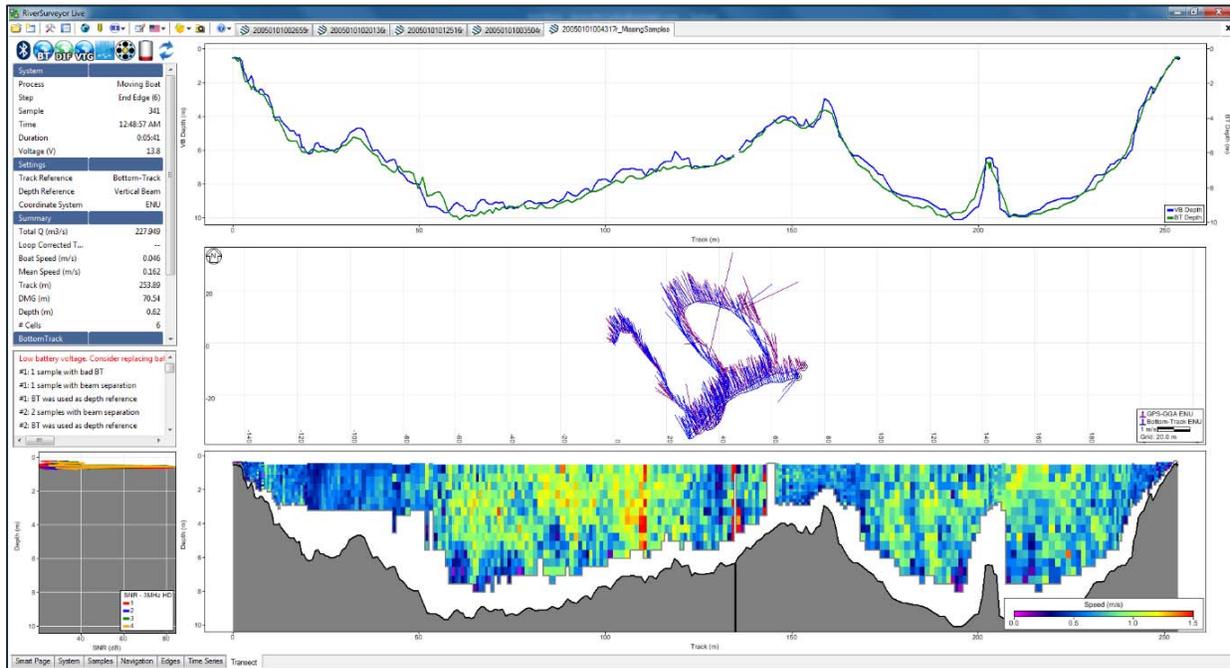
Bathymetric survey transects were collected using a rigid inflatable boat (ref. Figure 3-2) equipped with an acoustic doppler current profiler (ADCP; Sontek RiverSurveyor M9) capable of collecting georeferenced water depth and flow information (ref. Figure 3-3). Overbank topographic surveys were conducted in tandem with the bathymetric survey transects to establish water level elevation at the time of survey and to retrieve topographic ground elevation beyond the edge of water for comparison with LiDAR data.



**Figure 3-2: Bathymetric profiling conducted using a rigid inflatable boat**

The preliminary field survey plan, established in October 2018, defined a network of transects (cross-sections) and hydraulic structures of significance (e.g. bridges) on the Upper Humber River, Deer Lake, the Lower Humber River and Steady Brook. Wood’s hydraulic modelling team established the final transect locations in November 2018.

Field survey forms were prepared prior to the field survey for each river transect (cross-section) and for all noted hydraulic structures. These survey forms were designed to capture data of relevance for modelling purposes (e.g. transect location, water surface elevation at the time of survey, observations of the substrate material, etc.). All completed field survey forms are provided in Appendix D. Photographs of the left overbank, right overbank, upstream and downstream were collected and reviewed for each transect.



**Figure 3-3: River Surveyor M9 Sample Bathymetric Profile**

The input data for modelling a stream crossing structure in HEC-RAS consists of the structure geometry data for the structure itself, as well as four cross-sections. Two of the cross sections are located upstream and two downstream of the structure. These cross-sections are positioned to effectively define the flow contraction and expansion caused by the stream crossing structure. Each hydraulic structure survey consists of one survey form for the structure itself, and a survey form for each of the four associated cross sections. The survey forms for the cross sections are identified as either “A” (most downstream of the structure), “B” (located just downstream of the structure), “C” (located just upstream of the structure), or “D” (located most upstream of the structure).

Field surveys were initially scheduled for completion in November and December of 2018. Field personnel were cognizant that conditions encountered in the field might prompt a revision to the proposed field survey plan (e.g. additional surveying to pick up specific features not initially observed using the available mapping). The community of Deer Lake experienced its snowiest November since 1933, receiving approximately 122 cm of snowfall. Temperatures in November were lower than normal and significant ice cover formed earlier than usual on Steady Brook, along the shore of Deer Lake and in the Upper Humber. Consequently, the field program was suspended in early December 2018 and resumed in 2019 when weather conditions permitted. The remaining field surveys were completed in May and November 2019.

### 3.3 Field Survey Required for Hydraulic Model Cross-Sections

While field surveys of the Lower Humber River and its outlet were conducted as part of previous flood studies (Cumming-Cockburn, 1984), new stream surveys were completed as part of this project's scope due to possible sedimentation and erosion processes and the resulting changes in cross-sectional properties that would have occurred since the time of the original surveys.

#### 3.3.1 Field Survey – Lower Humber River

This survey included the stream cross sections not associated with the stream crossing structures. A preliminary set of cross-sections was established using transects surveyed on the Humber River and Steady Brook as part of historical flood mapping (Cumming-Cockburn, 1984; Cumming-Cockburn, 1987) and with consideration for the profiles for any other streams located within the IMA&SN.

To support effective hydraulic modelling of the floodplain in HEC-RAS, survey cross-sections were planned perpendicular to anticipated flow lines. Adequate points were surveyed to capture the geometry detail of the cross section and the underwater portion of the channel. Where practical, cross-sections surveyed extended a minimum of 5 m from the tops of the banks to ensure adequate overlap with the LiDAR data.

Transects completed using the ADCP on the Lower Humber River are illustrated in Figure 3-4 and Figure 3-5. The completed survey forms are included in Appendix D.

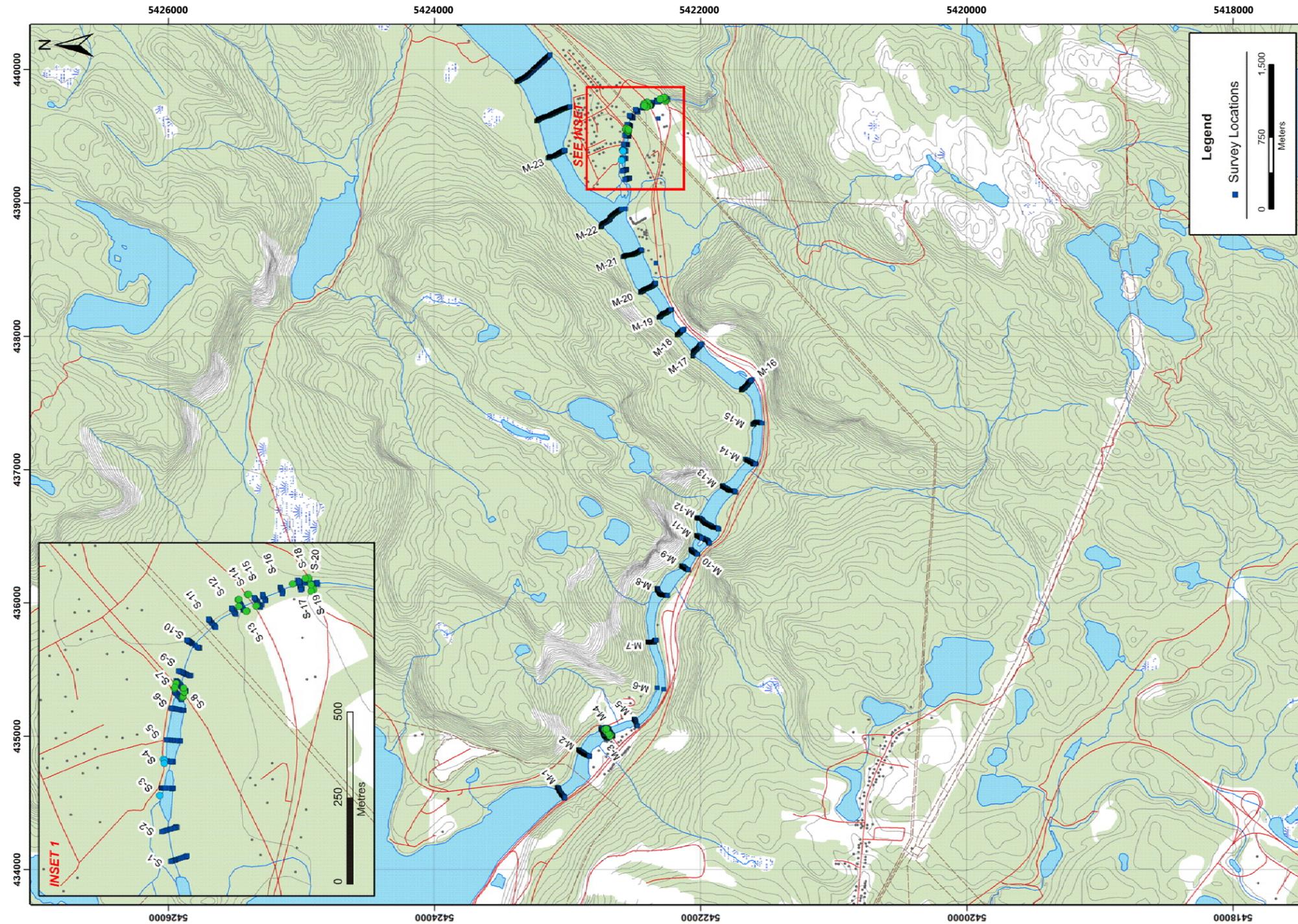
#### 3.3.2 Field Survey - Steady Brook

While field surveys of the Steady Brook channel were conducted in the past as part of the 1984 flood study investigations (Cumming-Cockburn, 1984; Figure 2-9), stream surveys were required as part of the current project scope due to likely sedimentation and erosion processes and the resulting changes in cross-sectional properties that have undoubtedly occurred since the time of the original surveys.

Field staff originally intended to complete the field survey for Steady Brook (20 transects and three (3) structures, namely Marble Drive bridge, Trans-Canada Highway Bridge, and the bridge leading to the Marblewood Village resort) in the fall of 2018. Though originally planned for 2018, a site visit to Steady Brook in November 2018 indicated access to the river was extremely limited due to the early arrival of snow and ice (ref. Figure 3-6 and Figure 3-7) and surveying of the river at that time was considered to be unsafe.

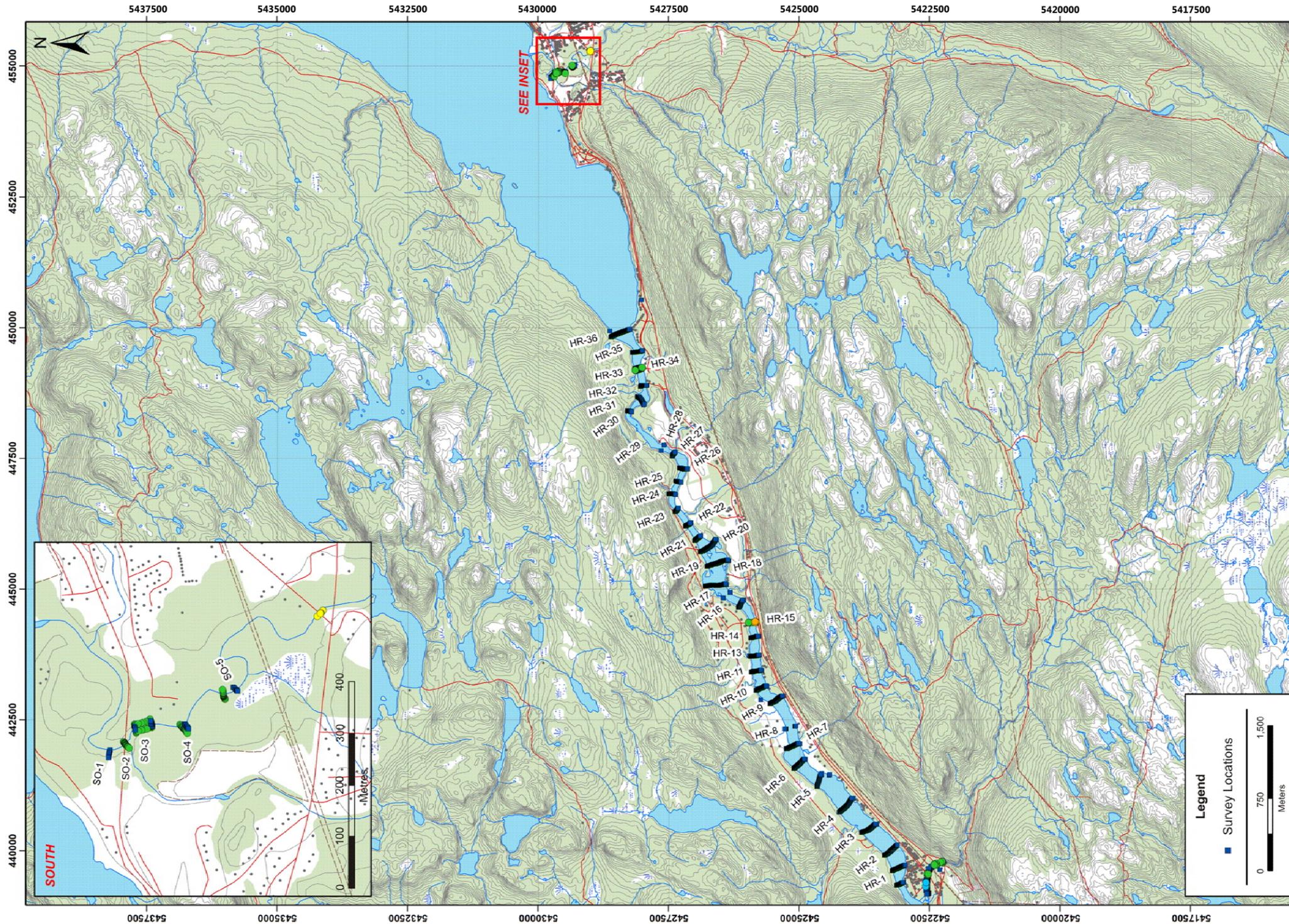
Field staff returned to Steady Brook in July 2019 to complete the field survey. Given the relatively shallow water depths in Steady Brook, bathymetric profiling was collected using real time kinematic (RTK) survey equipment (i.e. this data was not collected using the boat mounted ADCP system). The completed survey forms for the cross sections and Field survey forms for the structures are provided in Appendix D.

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<p><b>Client:</b> Government of Newfoundland and Labrador Department of Municipal Affairs and Environment Water Resources Management Division</p>		<p><b>Project:</b> Humber River - Flood Risk Mapping Project</p>	
<p><b>Notes:</b> 1. This map is intended to show relative locations in support of this report. 2. All locations, dimensions, and orientations are approximate. 3. All coordinates are UTM NAD83, Zone 21.</p>		<p><b>Date:</b> November 2019</p>	<p><b>Title:</b> Stream Crossings - Lower Region 1</p>
<p><b>wood.</b></p>		<p><b>Drawn by:</b> J. Abbott</p>	<p><b>Project No.:</b> TPB188156</p>
		<p><b>Approved by:</b> T. Praamsma</p>	<p><b>Scale:</b> As Shown</p>
			<p><b>Figure No.:</b> 2</p>

**Figure 3-4: Lower Humber River  
Transects Map 1 (Steady Brook shown  
as inset)**



Client: Government of Newfoundland and Labrador Department of Municipal Affairs and Environment Water Resources Management Division  <b>wood.</b>	Date: March 2019	Project: Humber River - Flood Risk Mapping Project
	Drawn by: J. Abbott	Title: Stream Crossings - Lower Region 2
	Approved by: T. Praamsma	Scale: As Shown
Notes: 1. This map is intended to show relative locations in support of this report. 2. All locations, dimensions, and orientations are approximate. 3. All coordinates are UTM NAD83, Zone 21.		Project No.: TPB188156 Figure No.: 3

**Figure 3-5: Lower Humber River  
Transects Map 2 (South Brook shown  
as inset)**

### 3.3.3 Field Survey - South Brook, Pasadena

Bathymetric transects for South Brook in Pasadena were not initially considered necessary for inclusion in the survey plan. Previous flood risk mapping shown in Cumming-Cockburn (1987) for South Brook is illustrated in Figure 2-14. No survey transects of South Brook appear to have been previously obtained to support the 1987 flood study, where South Brook was found susceptible to flooding resulting from wave setup events in Deer Lake.

Recent flood events, which appear to be unrelated to wave setup in Deer Lake have occurred in South Brook. As an example, in February 2018 five residents of the Maple Place area of Pasadena were evacuated from their homes due to dangerously high-water levels that resulted from an ice jam in South Brook, which extended from the mouth of South Brook at Deer Lake to beyond Maple Place (CBC News, 2018a).

Based on discussions with the Technical Committee in December of 2018, bathymetric profiling of South Brook (Pasadena) was deemed necessary for inclusion in this study and was conducted in November 2019. Given the relatively shallow water depths in South Brook, bathymetric profiling was collected using RTK survey equipment (i.e. this data was not collected using the boat mounted ADCP system)

The completed survey forms for the cross sections and selected photographs for the South Brook surveyed stream cross sections are included in Appendix D.



**Figure 3-6: Snow and ice on Steady Brook in November, 2018 (Photo 1)**

(Source: Wood, 2019)



**Figure 3-7: Snow and ice on Steady Brook in November, 2018 (Photo 2)**

(Source: Wood, 2019)

### 3.3.4 Field Survey - Upper Humber River

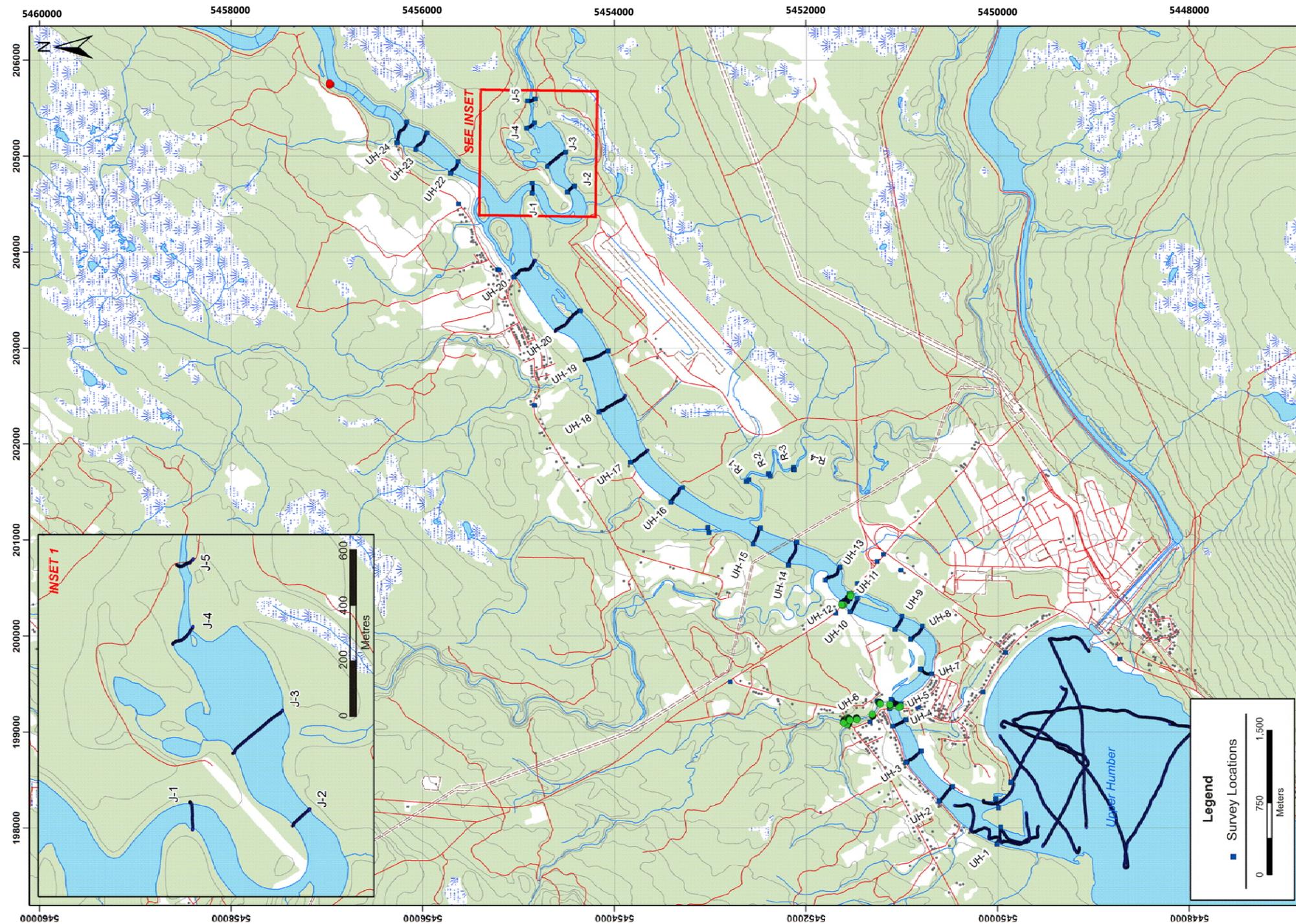
While field surveys of the Upper Humber River and its confluence with Deer Lake were conducted as part of previous flood studies (Cumming-Cockburn, 1987) (ref. Figure 2-13) new stream surveys were required in 2019 due to sedimentation and erosion of the river banks that would have occurred during historical flooding events.

The field survey for the Upper Humber River could not be conducted as originally planned in the 2018 field season as this portion of the river was inaccessible due to snow and ice. Field staff returned to the Upper Humber in June of 2019 to complete their field survey.

Transects completed on the Upper Humber River in May and June of 2019 using the ADCP are illustrated in Figure 3-8. The completed survey forms are included in Appendix D.

### 3.3.5 Field Survey – Nichols Brook

Previous flood studies did not include any bathymetric profiling of Nichols Brook (Cumming-Cockburn, 1987). The Nichols Brook field survey was conducted in November 2019. The completed survey forms for the cross sections and selected photographs for the surveyed stream cross sections are included in Appendix D.



Client: Government of Newfoundland and Labrador Department of Municipal Affairs and Environment Water Resources Management Division	Date: November 2019	Project: Humber River - Flood Risk Mapping Project	
		Drawn by: J. Abbott	Title: Stream Crossings - Upper Region
	Approved by: T. Praamsma	Scale: As Shown	Project No.: TPB188156
			Figure No.: 1

Notes:  
1. This map is intended to show relative locations in support of this report.  
2. All locations, dimensions, and orientations are approximate.  
3. All coordinates are UTM NAD83, Zone 21.

**Figure 3-8: Upper Humber River  
Transects (Junction Brook shown as  
inset)**

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### 3.3.6 Field Survey - Deer Lake

The field survey of Deer Lake was conducted in the in May and June of 2019. Bathymetric data was collected in Deer Lake, near the confluence with the Upper Humber River and the reservoir outlet and near Pasadena.

### 3.3.7 Field Survey Summary

Table 3-1 provides a summary of how many cross sections were surveyed on each branch/river, as outlined in this report section.

**Table 3-1 Summary of Surveyed Cross Sections by Watercourse Section**

Station Number	Sections Surveyed
Lower Humber River	61
Steady Brook	20
South Brook, Pasadena	5
Upper Humber River	22 <i>plus bathymetry survey at the confluence of Humber River and Deer Lake</i>
Junction Brook	5
Nichols Brook	6
Unnamed Creek near Deer Lake Airport	4

## 3.4 Stream Crossing Structures (Bridge) Survey

Bridge as-built drawings were obtained for the following hydraulic structures:

- Lower Humber River – North Shore Highway Bridge/Ballam Bridge (Newfoundland and Labrador Department of Transportation and Infrastructures (TW) Asset 4-129)
- Pasadena – TCH Bridges over South Brook (TW Assets TCH-162 and TCH-163)
- Steady Brook – TCH Bridges over Steady Brook (TW Assets TCH-124 and TCH-064)
- Upper Humber River – Bridge on Route 422/Cormack Road at Little Falls (TW Asset 4-175)
- Upper Humber River – Nicholville Bridge (TW Asset 4-050)
- Upper Humber River – Viking Trail Bridge (TW Asset 4-085)

The following bridges were RTK surveyed by SEM Ltd. in November 2019:

- Lower Humber River – Bridge to Humber Valley Resort
- Lower Humber River – North Shore Highway Bridge/Ballam Bridge (TW Asset 4-129)
- Lower Humber River – Tamarack Street Bridge (Not a TW Asset)
- Pasadena – TCH Bridges over South Brook (TW Assets TCH-162 and TCH-163)
- Steady Brook – Marble Drive Bridge (Not a TW Asset)

- Steady Brook – Bright to Marblewood Village (Not a TW Asset)
- Steady Brook – TCH Bridges over Steady Brook (TW Assets TCH-124 and TCH-064)
- Upper Humber River – Nicholsville Bridge (TW Asset 4-050)
- Upper Humber River – Viking Trail Bridge (TW Asset 4-085)

RTK GPS data were collected of the water level, road and top of deck by SEM Ltd. The underside of each bridge was collected with a measuring tape. Bridge field survey data collected by SEM Ltd. is provided in Appendix C.

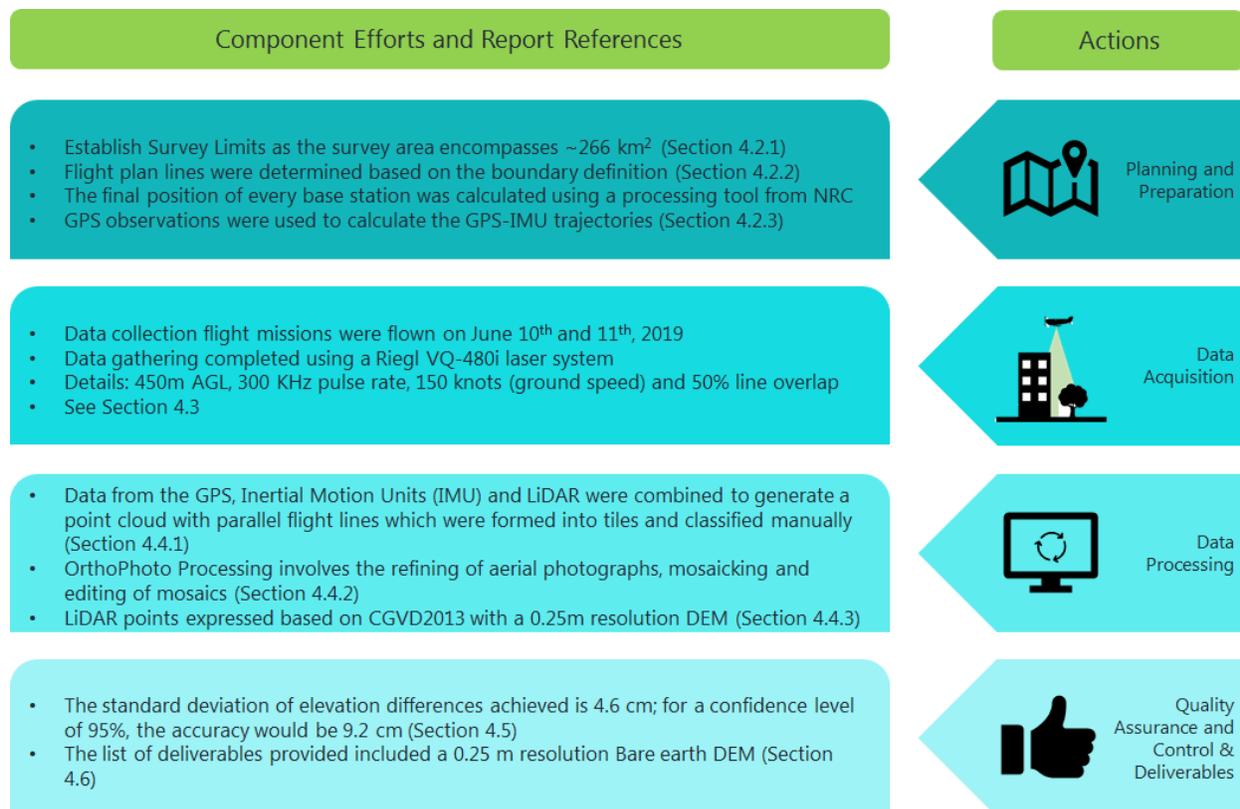
### 3.5 Study Specific Water Level and Flow Monitoring

As outlined in the RFP, additional water level and flow monitoring was considered for this study. Comprehensive reviews of the available gauging network were completed at the time of proposal preparation and project initiation. The consistent conclusion from these reviews was that implementation of additional water level and/or flow monitoring stations, specific to this project, was not necessary, and would not lead to improved modelling outcomes, given the current availability of streamflow records from existing gauging stations in the study area.

## 4.0 LiDAR and Aerial Photography

Synopsis: LiDAR (Light Detection and Ranging) allows capture of highly detailed topographic data, which provides highly detailed and accurate data on surface elevations. LiDAR data is used to update computer models required to support the development of floodplain mapping including hydrologic and hydraulic models. The extent of flooding is then delineated using the LiDAR data. The LiDAR data, in conjunction with modern software and analytic tools such as Global Positioning Systems (GPS) and Inertial Motion Units, is used to develop a Digital Elevation Model (DEM) of study area which assists in providing a more accurate prediction and understanding of areas at risk of flood. Aerial photography, collected coincidentally with LiDAR, provides a more broadly recognizable base of information upon which to illustrate the flood extents.

**Figure 4-1: LiDAR and Aerial Photography Summary**



## 4.1 Overview

Wood contracted with Mosaic 3D, with head office in Gatineau, Québec, to complete an aerial LiDAR and photo survey in the Deer Lake, Newfoundland area in support of the Humber River project. The survey area, approximately 266 km<sup>2</sup>, represents a portion of the overall study area. The purpose of the survey was the production of a calibrated and classified LiDAR point cloud (.LAS files), a Digital Elevation Model (DEM) and ortho-photography.

Post-processed spatially organized LiDAR data is known as point cloud data. The initial point clouds are collections of 3D elevation points, which include x, y, and z, along with additional attributes such as GPS time stamps. The specific surface features that the laser encounters when data are collected are classified after the initial LiDAR point cloud is post-processed. Elevations for the ground, buildings, forest canopy, highway overpasses, and anything else that the laser beam encounters during the survey constitutes point cloud data.<sup>5</sup>

A digital elevation model (DEM) is a bare-earth raster grid referenced to a vertical datum. When non-ground points, such as bridges, are filtered out, the result is a smooth digital elevation model. The built (power lines, buildings, and towers) and natural (trees and other types of vegetation) are not included in a DEM. Elevation points in a DEM are not regularly spaced.<sup>6</sup>

A Digital Terrain Model (DTM) is a data set composed of regularly spaced points and can also include natural features such as break lines. DTM points are regularly spaced and characterize the shape of the bare-earth terrain.<sup>6</sup>

The summary provided in this section was abstracted from the full *LiDAR and Photo Aerial Surveys over Deer Lake, Newfoundland* report prepared by Mosaic 3D which is provided in Appendix Q.

## 4.2 Planning and Preparation

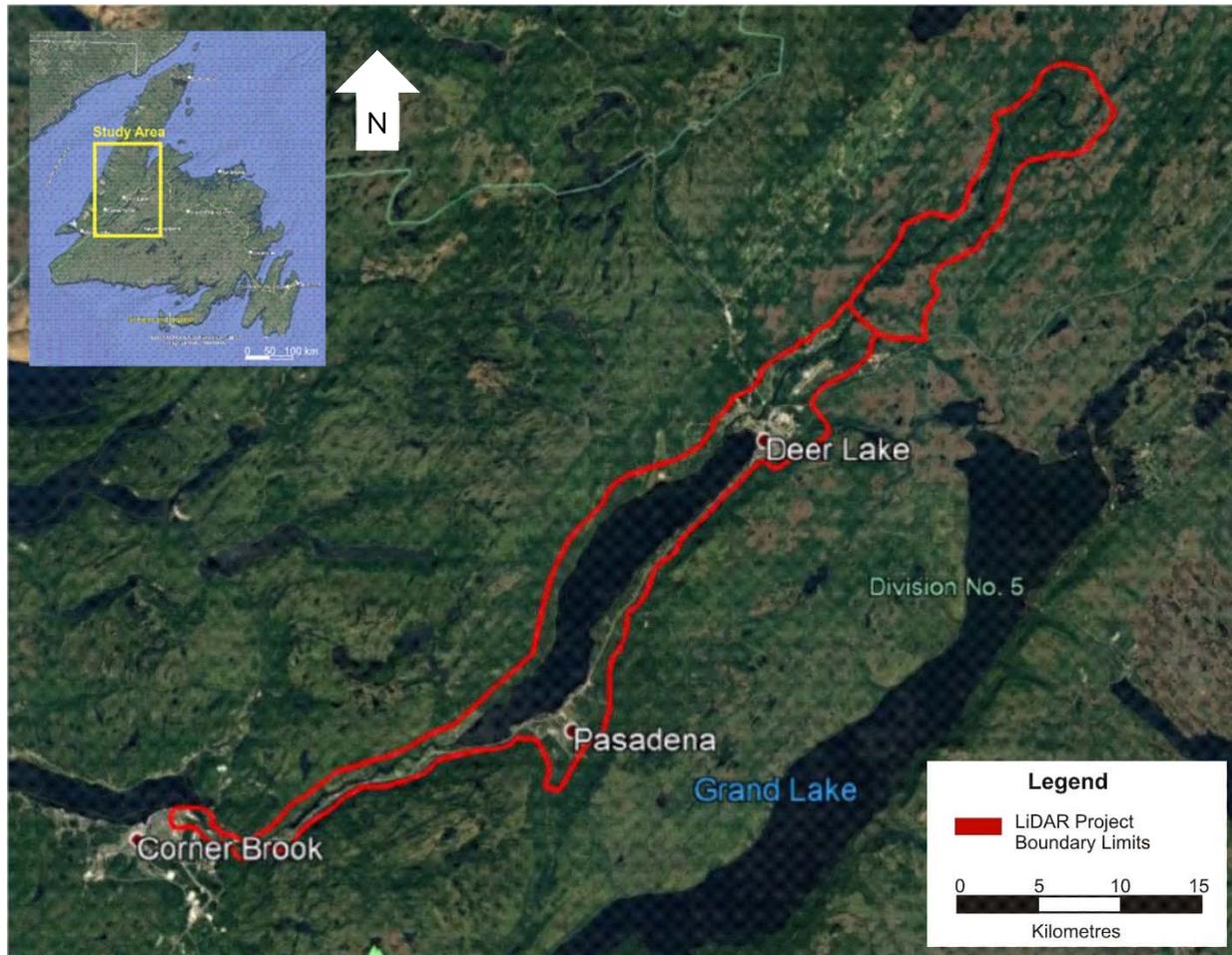
### 4.2.1 Establish Survey Limits

As previously noted, the project area encompasses approximately 266 km<sup>2</sup> located on the west coast of the island of Newfoundland. A boundary defining the area requiring survey was developed by Wood (ref. Figure 4-2).

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<sup>5</sup> Source: <https://desktop.arcgis.com/en/arcmap/10.3/manage-data/las-dataset/what-is-lidar-data-.htm>

<sup>6</sup> Source: <https://gisgeography.com/dem-dsm-dtm-differences/>



**Figure 4-2: LiDAR Project Boundary Limits**

#### 4.2.2 Plan Flight Lines

Based on the boundary definition, a flight plan was produced for the LiDAR and photo acquisition (ref. Figure 4-3 and Figure 4-4). Flight lines were determined taking into consideration the different parameters needed to comply with the specifications provided with the RFP (ref. Figure 4-3 and Figure 4-4).

Flight lines were planned and flown at the altitude of 450 m above ground level (AGL), with 50% side overlaps. As requested for this survey, the maximum swath was established at  $\pm 25^\circ$  ( $25^\circ$  from Nadir<sup>7</sup> for a total of  $50^\circ$ ). The flight speed was maintained at 150 Knots to obtain a point cloud density of 6 pts/m<sup>2</sup>.

<sup>7</sup> Images taken by a camera pointing to the *nadir* direction. Pointing to the *nadir* means that the camera axis (in the direction of the lens) is perpendicular to the ground / object (source: <https://support.pix4d.com/hc/en-us/articles/202559859-Vertical-vs-oblique-imagery>)

### 4.2.3 Establish GPS Base Stations

For every flight session, 1 or 2 GPS receivers were installed near the flight area, recording GPS observations every second. New base positions were established every day and located as close as reasonably possible to the daily flight lines. The final position of every base station was calculated using an on-line post processing tool from Natural Resources Canada (CSRS-PPP)<sup>8</sup>. Those GPS observations were used to calculate the GPS-IMU (Inertial Measurement Unit) trajectories during the flights and as reference stations to adjust the LiDAR during data acquisition.

## 4.3 Data Acquisition

The airborne system was installed in a plane; a Navajo, identification C-GOVX. LiDAR data acquisition was completed using a Riegl VQ-480i laser system with a data rate of 150 000 measurements per second. This LiDAR sensor was combined with an Inertial Motion unit (IMU), namely the Northrop Grumman Litef IMU- $\mu$ IMU-IC.

The aerial photos were taken using a 50 Megapixel (Mpx) Canon EOS 5DsR. Collection of both LiDAR and aerial photos were completed during the same flights.

As planned in the project preparation, all flights were done with the following parameters:

- Altitude: 450 m AGL
- Speed: 150 knots (ground speed)
- Pulse Rate: 300 KHz
- Line overlap: 50%

Data collection flight missions were flown on June 10 and 11, 2019.

It was originally scheduled to complete the LiDAR and orthophoto data collection in the fall of 2018 as an initial task of the project. It was acknowledged by all parties at the project initiation meeting in December 2018 that the LiDAR data collection program could not be engaged, as planned in the fall of 2018, given poor weather conditions and the early onset of winter conditions. Field conditions had also precluded LiDAR data collection efforts for other similar projects in Newfoundland.

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<sup>8</sup> Reference: <https://www.nrcan.gc.ca/maps-tools-publications/tools/geodetic-reference-systems-tools/tools-applications/10925#ppp>

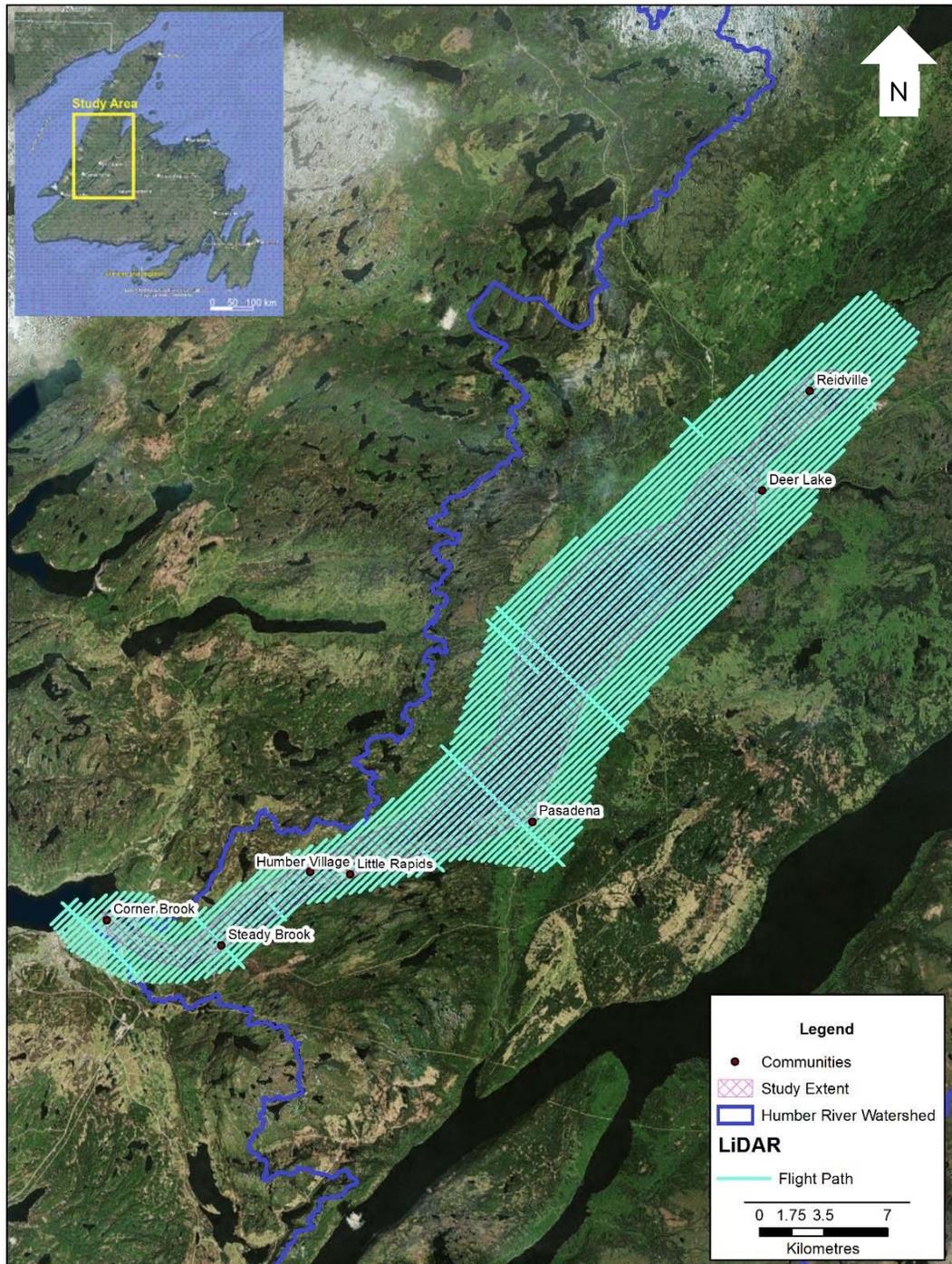


Figure 4-3: LiDAR Flight Path

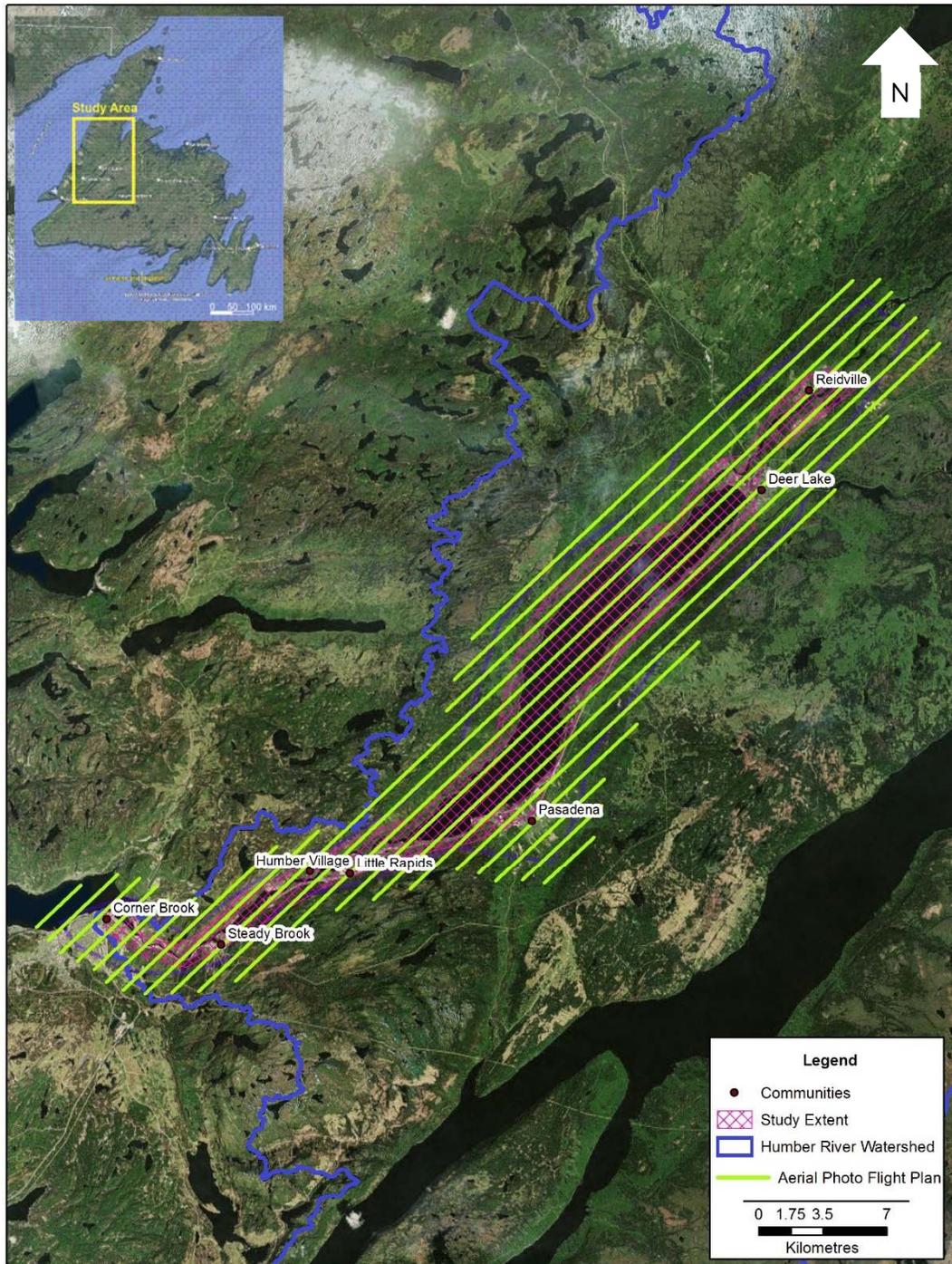


Figure 4-4: Aerial Photography Flight Path

## 4.4 Data Processing

### 4.4.1 LiDAR Processing

As the first data processing operation, data from the GPS system, IMU and the LiDAR sensor are combined to generate a point cloud. As a component of this processing, the flight lines are calibrated to have a block of lines that match perfectly together. This allows the creation of the final point cloud including all the lines.

Once the point cloud was generated, the project boundary was then segmented in the form of tiles. The purpose of this operation is to divide the total amount of LiDAR points into smaller and easier to manage files.

Following the creation of these tiles, the points were classified. The automatic classification (macro) distinguishes the points representing a ground surface (ground points) from other points (vegetation, buildings, etc.). This classification process is completed manually. All points were separated using the following classification categories: ground, man-made structures and vegetation.

### 4.4.2 Orthophoto Processing

Mosaic 3D's orthophoto processing software requires a 0.5 m DEM before processing the orthophoto data, which was developed using the LiDAR survey information. The orthophoto production process is divided into four steps, namely;

- refinement of the interior orientation parameter file,
- orthophoto production,
- mosaic production, and
- manual editing of mosaics.

The first step is refinement of the interior orientation parameter file. This step adds precision to the project, the camera calibration file, the interior parameter file and the Ground Control Point file (GCP file).

The second step is production of the orthophotos. This step produces orthophotos with precise orientations and uses the DEM, the interior parameters file and the raw picture file.

The third step is mosaic creation. This step produces a union of all the orthophotos using specific algorithm seam lines. During this step, it is possible to apply a color balance process. The color balancing completes a local, global and overall project analysis and then, applies a balance to the tones, colors, brightness, contrast, hue, etc. This step uses the orthophotos and the specific parameter files of the project.

The fourth step in the process is to validate and apply corrections, if needed, to the mosaics. This includes validation of the seam lines to ensure assignment to the correct locations and that no visual errors were created. The validation process also includes the adjustments of color balance. Any identified color balance discrepancies were manually edited using a photo editing software.

### 4.4.3 Datum for Deliverables Production

All LiDAR data for this project reference the NAD83-CSRS<sup>9</sup> coordinate system and are projected using the Modified 3° Transverse Mercator mapping projection (MTM-3). The model of the geoid height was based on the CGVD-2013 to reduce the ellipsoidal elevations to mean sea level.

The elevation of the LiDAR points is expressed relative to the CGVD-2013. No major error was observed when processing the LiDAR data to the point cloud.

## 4.5 Quality Assurance and Control

Quality control is provided in separate steps for a LiDAR collection project and identifies whether there are systematic errors affecting the LiDAR points. For example, an error of yaw, roll or pitch of the inertial system (of the plane/helicopter?) would be automatically identified as there would be a gap between the points of adjacent lines of the LiDAR data.

As well, quality control is performed using profiles and topographic points by superimposing the LiDAR points over the points obtained by conducting a GPS ground truthing survey. The differences between the two surveys provides the vertical and horizontal accuracy of the LiDAR points.

The GPS ground truthing survey was conducted by Yates & Woods Ltd, a local surveyor from Corner Brook, NL. This ground survey identified 790 ground control points over flat and hard surfaces such as centerline of roads, street cross sections and roof corners. The standard deviation of elevation differences between the LiDAR points and the ground truthing survey points is 4.6 cm (1 sigma, 68% of cases). For a confidence level of 95%, the accuracy would be 9.2 cm (2 sigma). The control report of the LiDAR compared with the ground survey, along with the statistical analysis, is provided in Appendix D.

## 4.6 Deliverables

Deliverables were provided in the following formats:

- Classified ground points cloud in LAS<sup>10</sup> tiles
- Classified ground, man-made structures and vegetation points cloud in LAS tiles
- 0.25 m resolution Bare earth DEM,
- Survey report

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<sup>9</sup> North American Datum 1983 - Canadian Spatial Reference System

<sup>10</sup> The LAS (LASer) format is a file format designed for the interchange and archiving of LiDAR point cloud data. It is an open, binary format specified by the American Society for Photogrammetry and Remote Sensing (ASPRS). The format is widely used and regarded as an industry standard for LiDAR data. (Source: <https://www.loc.gov/preservation/digital/formats/fdd/fdd000418.shtml>)

#### 4.7 Problems Encountered, Solutions Found

As previously noted, the LiDAR survey field data collection was completed in June 2019. All acquisition, LiDAR data processing and classification was performed without any problems.

The GPS surveyed ground truthing points (controls) were collected by Yates & Woods Ltd, our local surveyor sub-contractor. Those controls points helped to establish the vertical accuracy of the LiDAR points and facilitated the horizontal calibration/adjustment of the LiDAR point cloud.

As a component of its independent QA/QC process, Wood completed an independent review of the LiDAR point cloud using existing geodetic monuments available within the survey area. Several differences in elevations between the monuments published vertical values and the provided DEM altitude at the same location were identified.

Yates & Woods Ltd. was further engaged to complete a secondary survey of geodetic monuments in the survey area. Through detailed review of these additional survey data and LiDAR processing, it was established that GPS ground truthing points (controls) collected by Yates and Woods Ltd. were initially provided to Mosaic 3D in Canadian Geodetic Vertical Datum 1928 (CGVD-1928) instead of the required CGVD-2013 vertical geoid. As such, the LiDAR point cloud was initially provided to Wood in CGVD-1928.

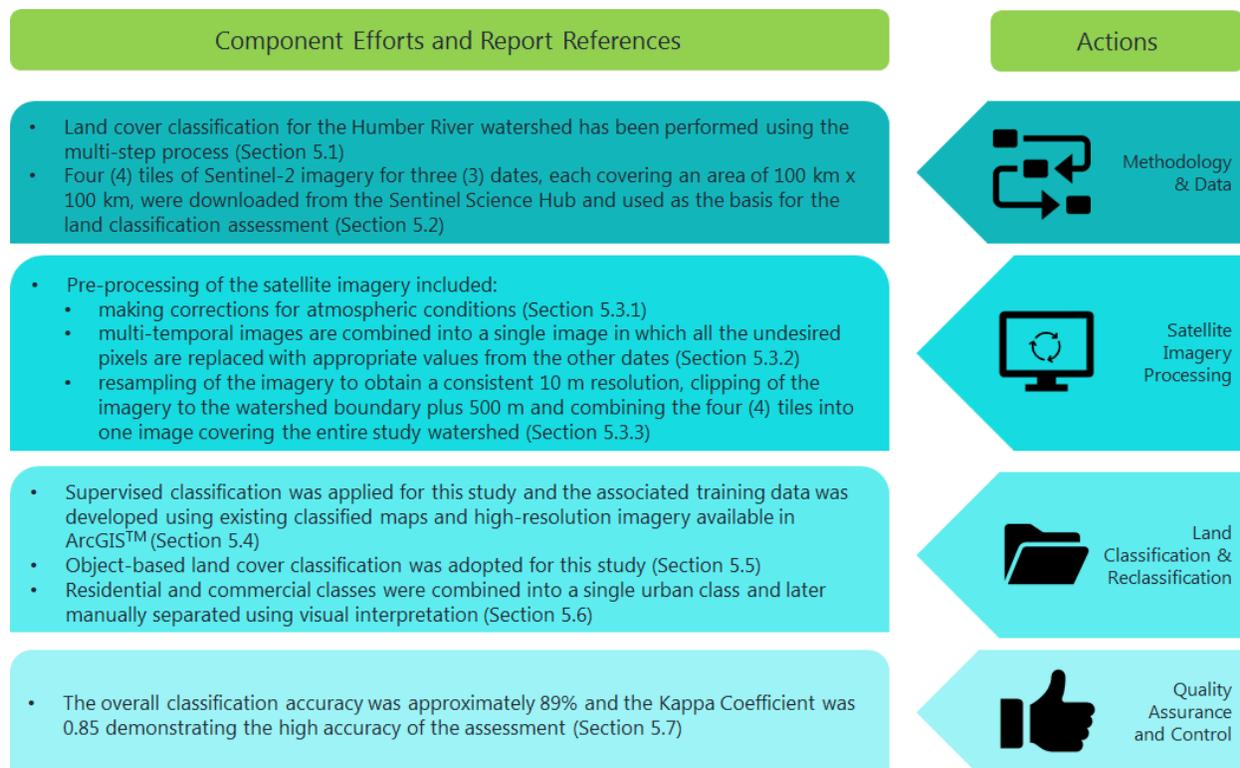
A vertical adjustment of the LiDAR point cloud and DEM was completed by Mosaic 3D to convert the data to CGVD-2013. Following this final vertical adjustment, the LiDAR survey was found to align well with geodetic monument elevations in CGVD-2013 and the attainment of the specifications for this contract was confirmed.

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## 5.0 Remote Sensing

Synopsis: Remote sensing was used to gather land cover classification information for the Humber River watershed to support hydrologic and hydraulic models development. Land classification was completed using a multi-step process of downloading satellite imagery, imagery pre-processing, preparing/training data, object-based classification and an accuracy assessment. The study area is primarily comprised of forest and wetlands while about 1% of the overall study area is commercial and residential. Remote sensing is focused on the delineation of soil types and land cover to support estimation of the Soil Conservation Services (SCS) Curve Number (CN) which is an input parameter for hydrological modelling reflecting the runoff potential for a drainage area.

**Figure 5-1: Remote Sensing Summary**



## 5.1 Overview

A land cover classification study of the Humber River watershed was conducted to support modeling of hydrologic and hydraulic responses from development and to assess flood vulnerability. Land cover classes (forest, wetland, deforested, barren, open, commercial and residential) were mapped using Sentinel-2 data.<sup>11</sup> The data was used as an input to hydrologic models described in Section 6.0. This report section documents the imagery and data sources, the imagery classification methods, and results.

## 5.2 Methodology

Land cover classification for the Humber River watershed was performed using the multi-step process illustrated in Figure 5-1. The general steps included:

- (1) downloading satellite imagery,
- (2) image preprocessing,
- (3) preparing training data,
- (4) object-based classification, and
- (5) assessing accuracy.

Free multi-temporal Sentinel-2 imagery was used and pre-processed using the Sentinel Application Platform (SNAP) software developed by the European Space Agency (ESA). The segmentation, classification, and accuracy assessment parts were then conducted in the ArcGIS™ software. Further description of the land cover classification methodology is included within the Results section (ref. Section 5.4).

## 5.3 Data

Sentinel-2 imagery was chosen to complete the land classification, as it provides good spatial resolution (10 m) for most of the land use classes specified in the RFP and works well for large areas, such as the Humber River watershed (approximately 8,000 km<sup>2</sup>). The spatial resolution of Sentinel-2 imagery does not support division of an urban land cover class into residential and commercial classes, per the RFP. Given that the urbanized area is a very small portion of the total watershed (approximately 10 km<sup>2</sup>, or less than 1% of the total watershed area), it was easily classified manually after the main classification (refer to Section 5.4 for further detail of the implemented manual classification technique).

The Sentinel-2 constellation mission, consisting of Sentinel-2A and Sentinel-2B satellites, provides a temporal frequency of up to two (2) to three (3) days in the mid-latitudes (ESA, 2019a). This satellite contains 13 spectral bands, the characteristics of which are summarized in Table 5-1 (ESA, 2019b).

The bands in the visible domain (i.e. the blue (2), green (3), and red (4) bands) are very useful for discriminating between visually distinguishable classes, as these bands are in the range to which the human eye is sensitive. The Red Edge bands (i.e. bands between the Red and Near Infrared [NIR] ranges in the

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<sup>11</sup> It should be noted that because multi-temporal imagery was used in this study, there was no cloud, snow, or ice in the synthesized Sentinel-2 imagery, and therefore there was no "unclassified" class in the final land cover map.

electromagnetic spectrum) are sensitive to the biophysical and biochemical characteristics, the chlorophyll content, and the water deficit of vegetation, and are therefore effective for accurate mapping of the classes which contain vegetation, especially wetlands. The NIR bands (bands 8 and 8A) are important for vegetation studies, estimating biomass content, vegetation health monitoring, and detecting water. These are predominant factors for differentiating several classes present in the study area, like forest, deforested, and wetland classes, as well as water bodies. Shortwave Infrared (SWIR) bands (i.e. bands 11 and 12) are sensitive to moisture content in soil and vegetation and are therefore applicable in wetland mapping. In this study, bands 1, 9, and 10 were not used as these bands do not support land cover classification (ref. Table 5-1).

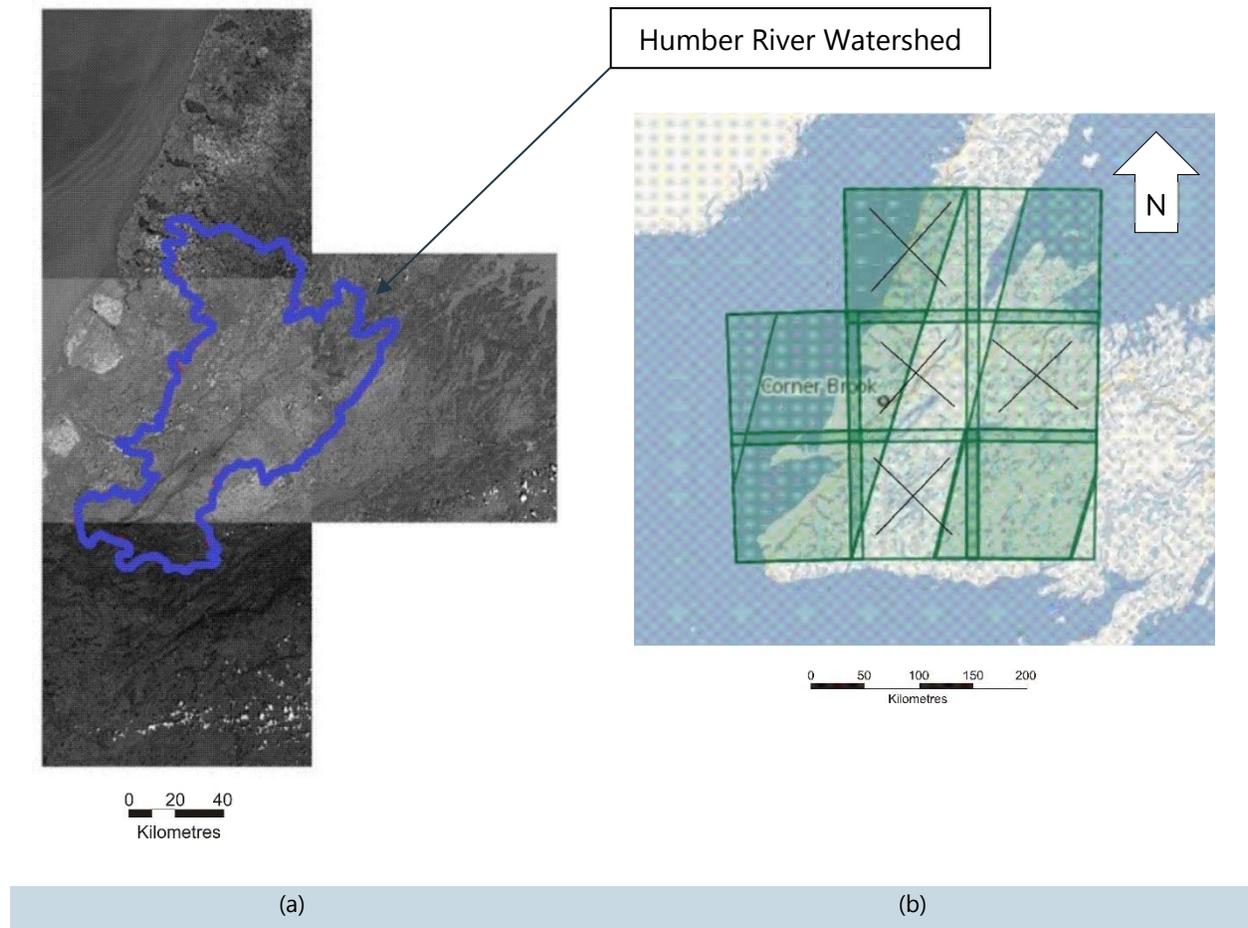
Satellite images were downloaded from the Sentinel Science Hub (Sinergise, 2019). Images acquired in 2017 were selected for the land cover classification as some of the pre-processing features were only available for the 2017 images, and the area did not change considerably between 2017 and 2018.

Several acquisitions of the Sentinel-2 imagery were used for the land cover classification. A single acquisition was not enough for the purposes of this study, as the study area is very large and, therefore, a single image completely free of cloud, shadow, snow, and other undesired representations could not be acquired. Consequently, several acquisitions were needed to compensate for the missing areas. This process is discussed in more detail in Section 5.4. Moreover, using several acquisitions in land cover classification was deemed to be helpful, because multi-temporal classification (i.e. including several dates of the same scene for the classification purposes) has proven beneficial compared to single-date imagery in several studies, especially when dynamic environments such as the wetlands in the Humber River watershed are to be classified (Mahdavi et al., 2017; Amani et al., 2017a; Amani et al., 2018).

**Table 5-1: The Characteristics of Sentinel-2A and Sentinel-2B Satellite Bands**  
 (Source: ESA, 2019b)

Band Number	Band Name	Spatial Resolution (m)
1	Coastal	60
2	Blue	10
3	Green	10
4	Red	10
5	Red Edge	20
6	Red Edge	20
7	Red Edge	20
8	NIR	10
8A	Narrow NIR	20
9	Water Vapour	60
10	SWIR-Cirrus	60
11	SWIR	20
12	SWIR	20

Four tiles of Sentinel-2 imagery were used to cover the entire study area (ref. Figure 5-2) and three acquisitions were downloaded for each tile (i.e. 12 Sentinel-2 images were used for the study area). Acquisition dates were selected such that there was minimal cloud cover in the images (i.e. during May to October 2017). Acquisition dates, tile numbers and the processing level of each tile of Sentinel-2 imagery are summarized in Table 5-2.



**Figure 5-2: Sentinel-2 Imagery**

(a) The four tiles of the Sentinel-2 imagery with the study area shown in red, (b) the four tiles (identified using a “x”) shown on a map of Western Newfoundland as accessed from the Sentinel Science Hub

(Source: Sinergise, 2019)

**Table 5-2: The Characteristics of Sentinel-2A and Sentinel-2B Images Downloaded from the Sentinel Science Hub**

(Source: ESA, 2019b)

Acquisition Date	Tile Number Field	Processing Level
2017/06/27	21UVP	2A
2017/07/17		
2017/09/15		
2017/06/27	21UVQ	
2017/07/17		
2017/09/15		
2017/06/27	21UVR	
2017/07/17		
2017/09/15		
2017/06/27	21UWQ	
2017/07/17		
2017/09/15		

## 5.4 Pre-processing of Sentinel-2 Imagery

The Sentinel Application Platform (SNAP) software was applied to pre-process the Sentinel-2 imagery. This software is open source and developed by the European Space Agency (ESA, 2018).

The downloaded Sentinel-2 imagery was already processed by the data provider (ESA) to Level 1C (L1C). L1C products have already been projected onto a cartographic geometry using a DEM, and the pixel values represent the top of atmosphere reflectance (ESA, 2019c).

### 5.4.1 Atmospheric Correction

L1C products have not been atmospherically corrected and if the study area is relatively small, the atmospheric effect can be assumed consistent throughout the image. For larger areas, like the current study area, however, this effect should be corrected. As such, the next processing step after downloading the Sentinel-2 imagery is atmospheric correction (i.e. converting the top of atmosphere reflectance to surface reflectance). Undesired classes (e.g. clouds, shadows, and no data areas) were identified and masked using the Sen2cor plug-in (ESA, 2019d). Sen2cor performs atmospheric, terrain, and cirrus corrections of Sentinel-2 L1C data and processes these data to Level 2A (L2A). Moreover, this processor provides the user with a classification for several classes including cloud and shadow and creates probabilities for cloud and snow presence (ESA, 2019d).

### 5.4.2 Converting Multi-temporal Images to a Single Image

After all the Sentinel-2 tiles were processed to L2A and the undesired pixels determined, multi-temporal images were combined into a single image in which all the undesired pixels were replaced with appropriate values from the other dates. Sen2three (ESA, 2019e) was applied to perform this task. Sen2three takes a time sequence of Sentinel-2 imagery over the same area as the input and processes those images to a single Level 3 (L3) image in which the undesired pixels of the input images are supplanted with more appropriate values following in time (ESA, 2019e). After processing the multi-temporal scenes to L3 images, three (3) images in a tile were downsampled to one (1) image. Through these steps, the 12 initial images were converted to four (4) high quality, cloud- and shadow-free images covering the entire study area.

### 5.4.3 Mosaicking, Clipping, and Stacking

Each band of Sentinel-2 imagery used in this study has either a resolution of 10 m or 20 m (ref. Table 5-1). Therefore, all existing bands were resampled to a 10 m resolution to facilitate subsequent processing. This task was conducted in SNAP for all L3 images.

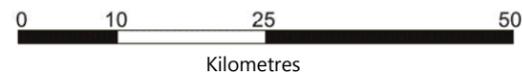
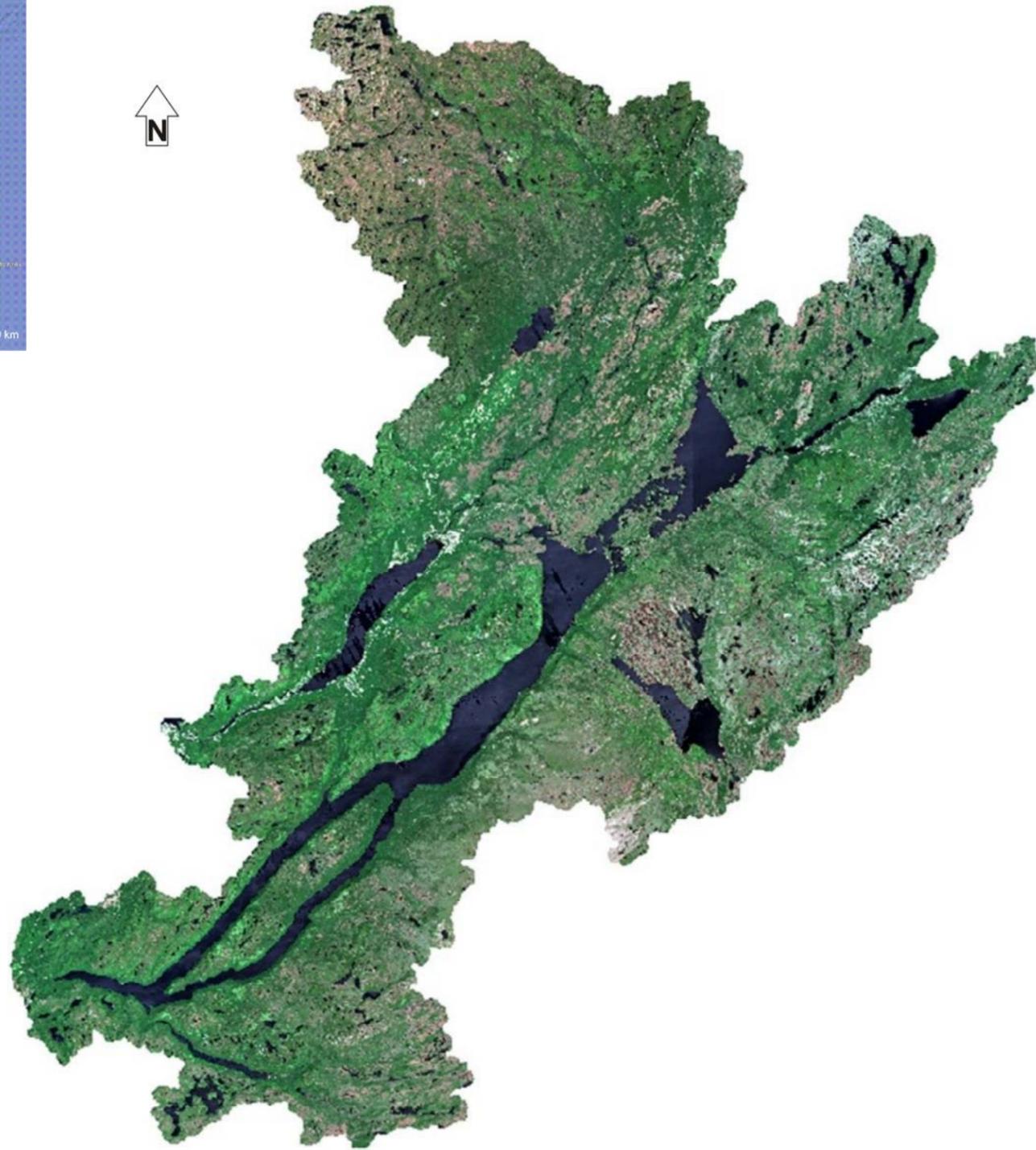
The boundary of the study area was buffered by 500 m in ArcMap™ to ensure all areas of interest were included in the classified map. Next, the four tiles of Sentinel-2 imagery were mosaicked, and each layer of the image was clipped separately using the buffered shapefile. Finally, all the layers were stacked together using the ArcMap™ software. After this step, the Sentinel-2 imagery was ready to be used in the classification algorithm. Figure 5-3 illustrates the output of the above pre-processing steps.

## 5.5 Preparation of the Training Data

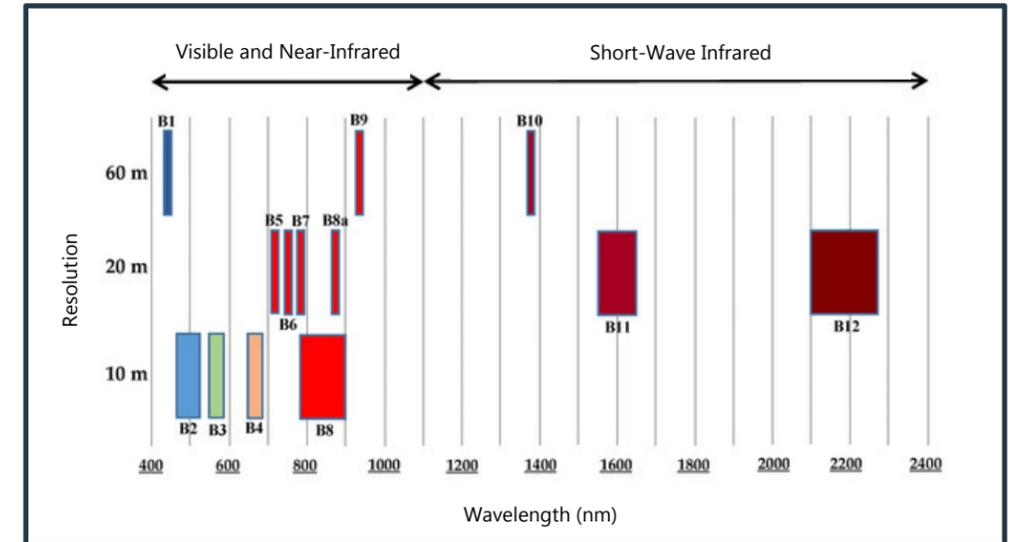
Generally, image classification algorithms are divided into two categories: supervised and unsupervised. Unsupervised classifications are based on the software analysis which divides the study area into classes designated by the user. Conversely, supervised classification requires field samples for each land cover class.

Supervised classification was used in this study, for which training data for each of the classes were required. The classes included in the final map are included in Table 5-3. One of the classes (Swamps/ wetlands/ waterbodies) was divided into two classes, including wetlands (bog, fen, marsh, swamp) and water (deep water and shallow water) (ref. Table 5-3). As residential and commercial classes were combined into an urban class, to be later divided into the residential and commercial classes manually (refer to Section 5.9 for further detail). It should be noted that because multi-temporal imagery was used, there was no cloud, snow, or ice in the synthesized Sentinel-2 imagery, and therefore there is no “unclassified” class in the final map, which is one of the advantages of multi-temporal classification methods.

Training polygons for wetlands and some of the forest and open polygons were obtained using existing classified maps for Deer Lake (Mahdavi et al. 2017; Amani et al. 2017a). For the other classes, the analyst selected the training polygons using high resolution imagery available in ArcGIS™ base maps. The base maps from which the training data were selected were also compared to the Sentinel-2 imagery to ensure no changes occurred between the time that the base maps and Sentinel-2 images were produced.



**Figure 5-3: True Colour Composite of the Pre-Processed, Mosaicked, and Clipped Sentinel-2 Imagery over the Study Area**



Source: <https://www.mdpi.com/2072-4292/9/6/584/htm>

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**Table 5-3: The Classes Requested by the Client and Equivalent Classes in the Produced Map**

Class requested by the client	Equivalent class in the final map	Description of the class
Forest	Forest	Forested areas
Residential	Urban	All buildings, parking lots, roads, etc.
Commercial		
Deforested Areas	Deforested	Areas with open green fields in forested zones
Barren Land	Barren	Areas covered by soil
Fields / pastures / open spaces	Open	Agricultural fields and pastures
Swamps/wetlands/waterbodies	Wetlands	Bogs, Fens, Marshes, Swamps
	Water	All water bodies (lakes, ponds, and rivers)
Unclassified	Not applicable	Cloud, Snow, Shadow, and Ice are masked in the final image

## 5.6 Object-based Classification

Object-based classification has a much better performance relative to pixel-based classification (Amani et al. 2017b; Mahdavi et al. 2017). Moreover, object-based classification enables the ingestion of spatial properties of the objects into the classification, in addition to the spectral properties.

Segmentation of the object-based image classification was performed using the Mean Shift segmentation algorithm available in the spatial analyst toolbox in ArcMap™. Figures 5-4, 5-5 and 5-6 illustrate examples of the segmented image versus the original image for several regions within the study area.

The training data and the Sentinel-2 stack were put into the Random Forest (RF) classifier to conduct the classification. The RF classifier has been shown to be very useful in wetland studies (Amani et al. 2017b) and, therefore, it was selected for the object-based land cover classification in this study. Figure 5-7 illustrates the result of the classification.

## 5.7 Reclassification of Urban Areas

The land cover classes developed using the RF classifier were further refined in ArcGIS™. Urban areas in the image were investigated to ensure they were classified accurately, as follows. After the classification was refined, there were two possible methods that could be used to divide the urban area into residential and commercial classes. One method identifies the differentiation based on the area of various segments, such that big segments would be assigned to the commercial class while smaller segments would be assigned to the residential class. A second method is based on visual investigation of the urban areas in the image and then differentiating between residential and commercial based on the visual analysis. The second method was adopted in this work. Figure 5-8 shows the final classified image after the refinement and division of the urban class into residential and commercial classes. Figures 5-9, 5-10 and 5-11 illustrate several zoomed areas of the classified versus the original image to present the accuracy of the classified map.

Original Image



Segmented  
Image

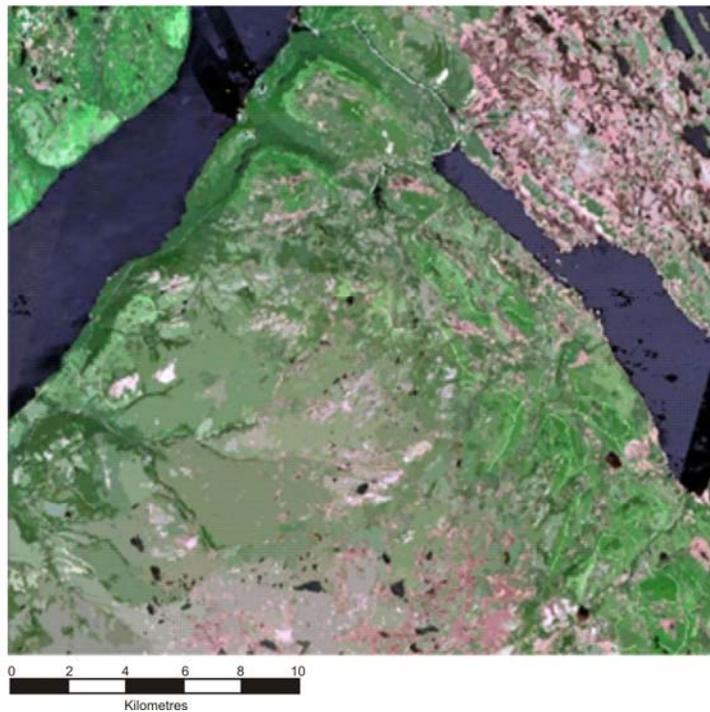


Figure 5-4: Example A - Comparison of the Segmented Image versus the Original Image

Original Image

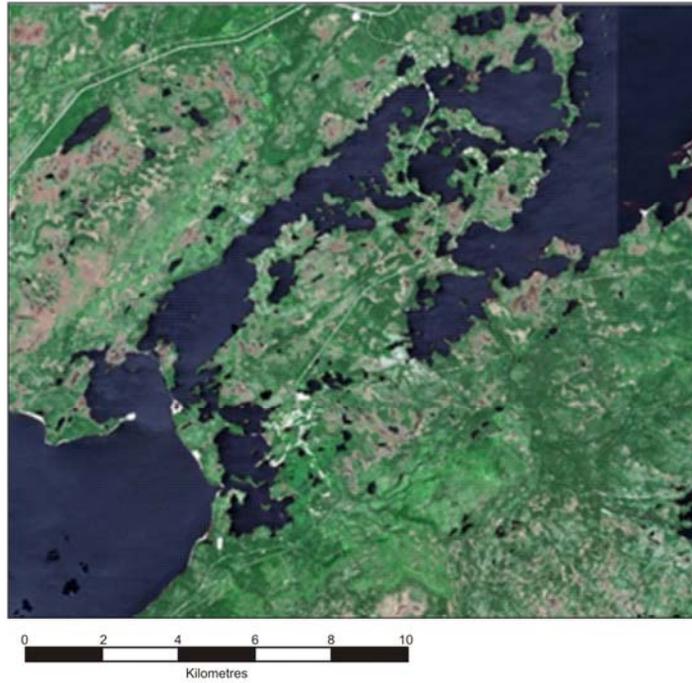


Segmented  
Image



Figure 5-5: Example B - Comparison of the Segmented Image versus the Original Image

Original Image



Segmented  
Image



Figure 5-6: Example C - Comparison of the Segmented Image versus the Original Image

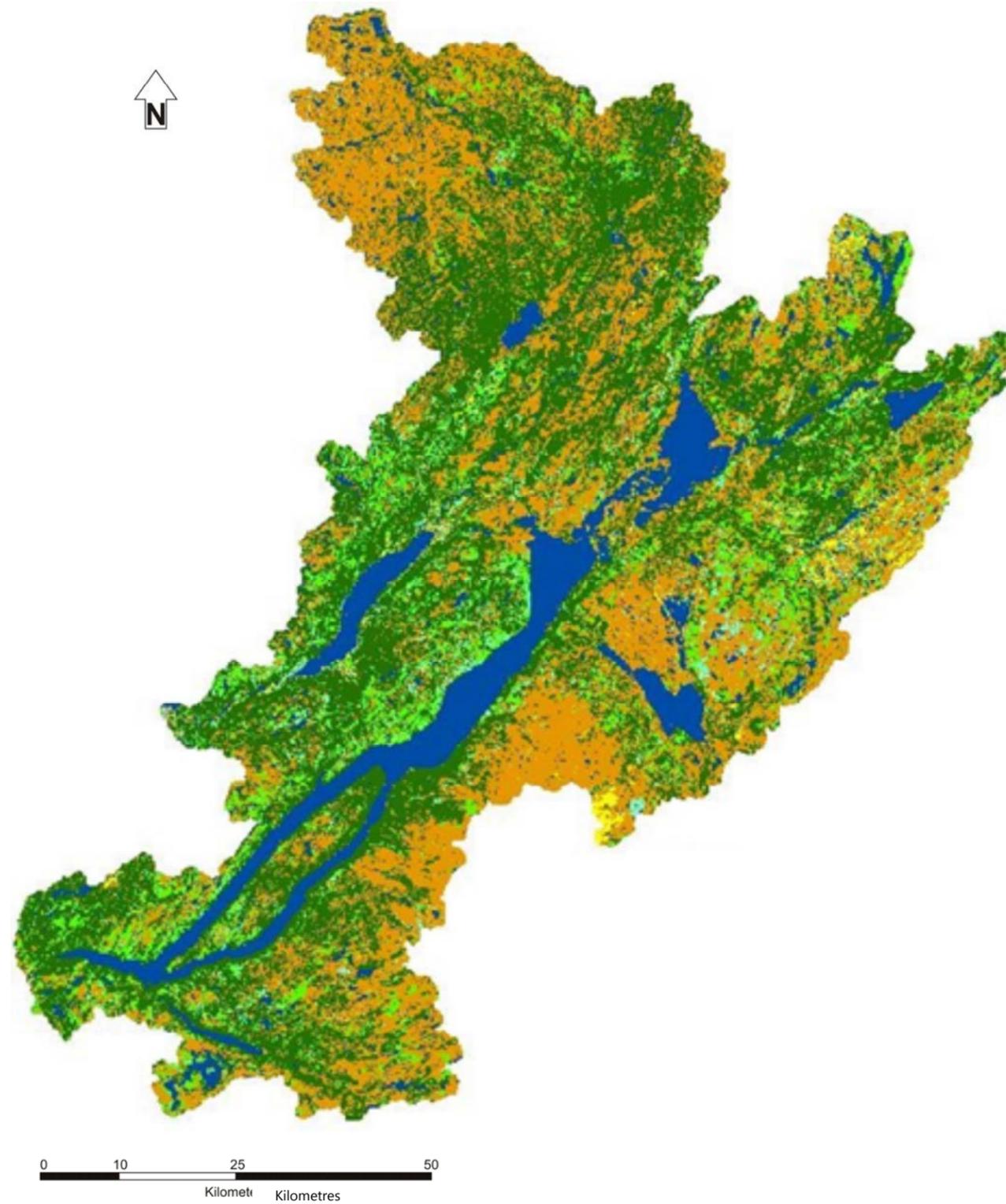
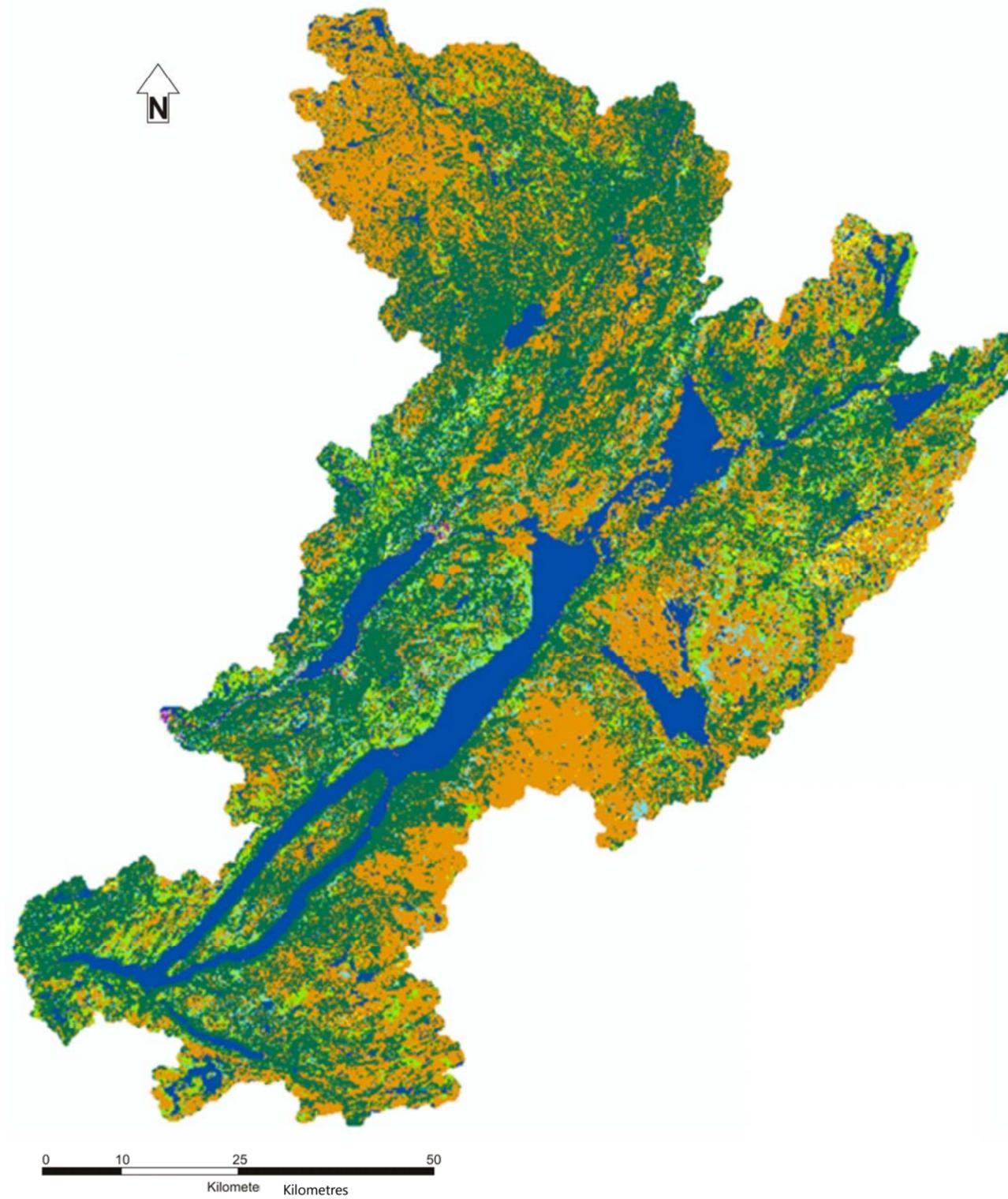


Figure 5-7: Classified Image over the Study Area Before Dividing the Urban Class

- Barren
- Deforested
- Forest
- Open
- Urban
- Water
- Wetland

Figure 5-8: Final Classification of the Study Area



- Barren
- Deforested
- Forest
- Open
- Urban (Residential & Commercial)
- Water
- Wetland

Original Image



Classified Image

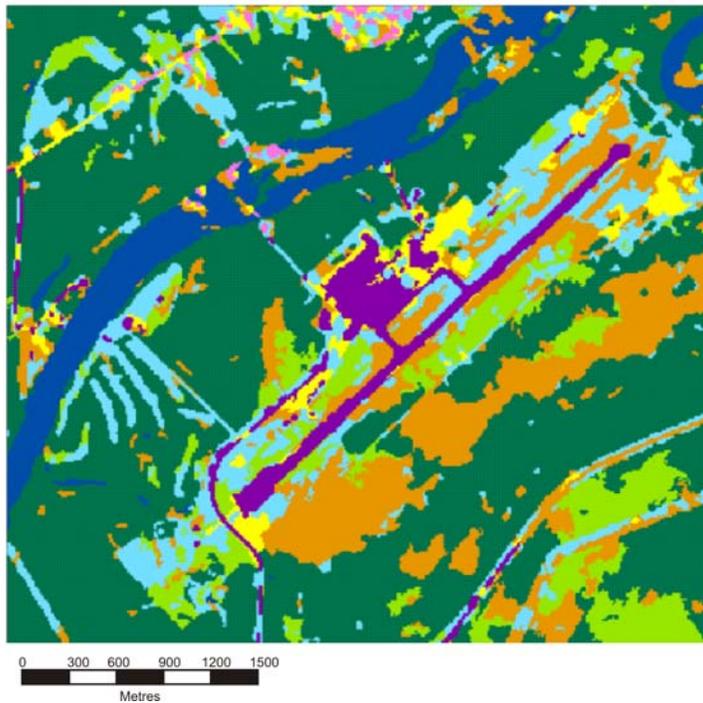


Figure 5-9: Example A - Zoomed areas of the original versus the classified image

Original Image



Classified Image

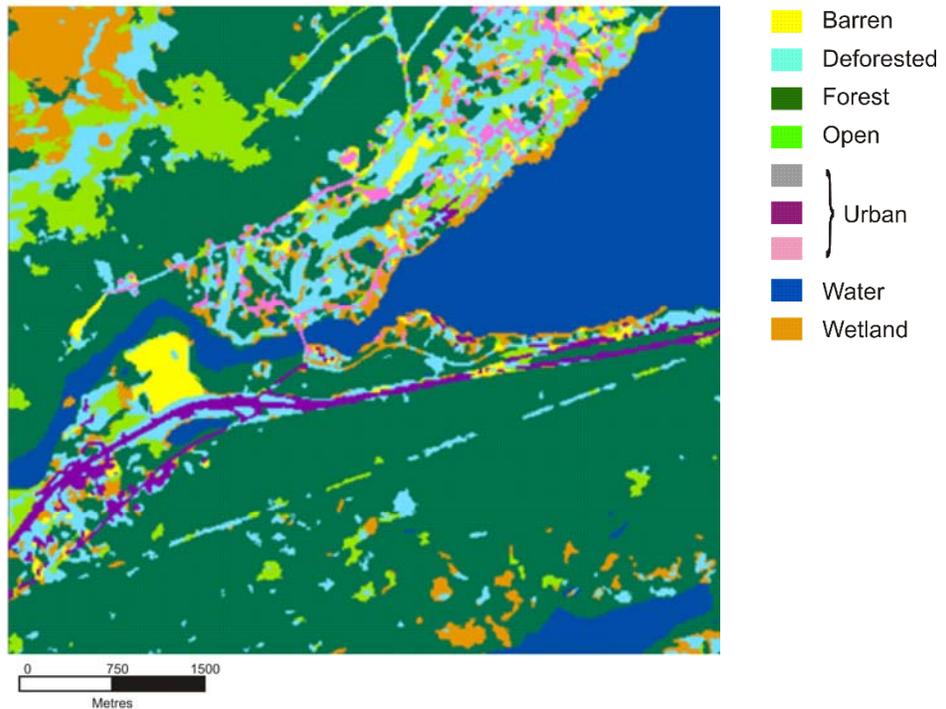
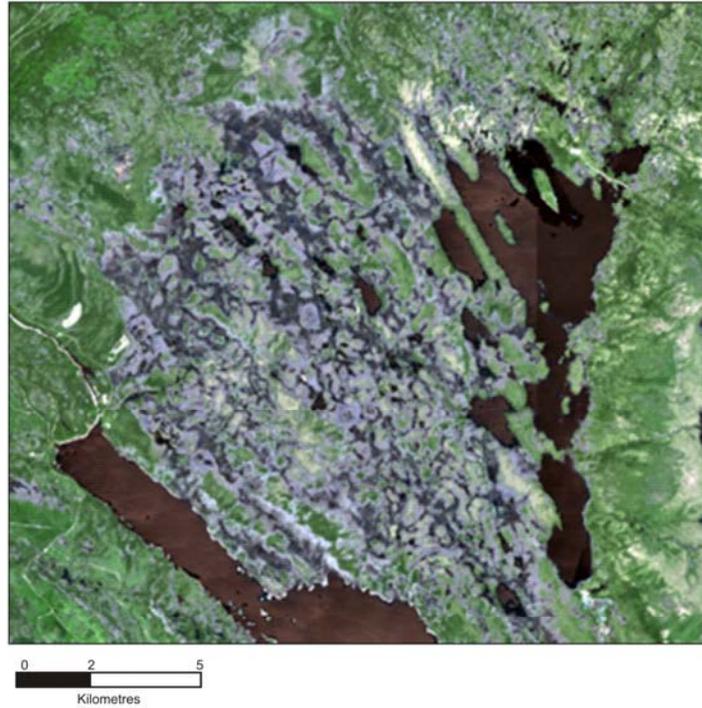


Figure 5-10: Example B - Zoomed areas of the original versus the classified image

Original Image



Classified Image

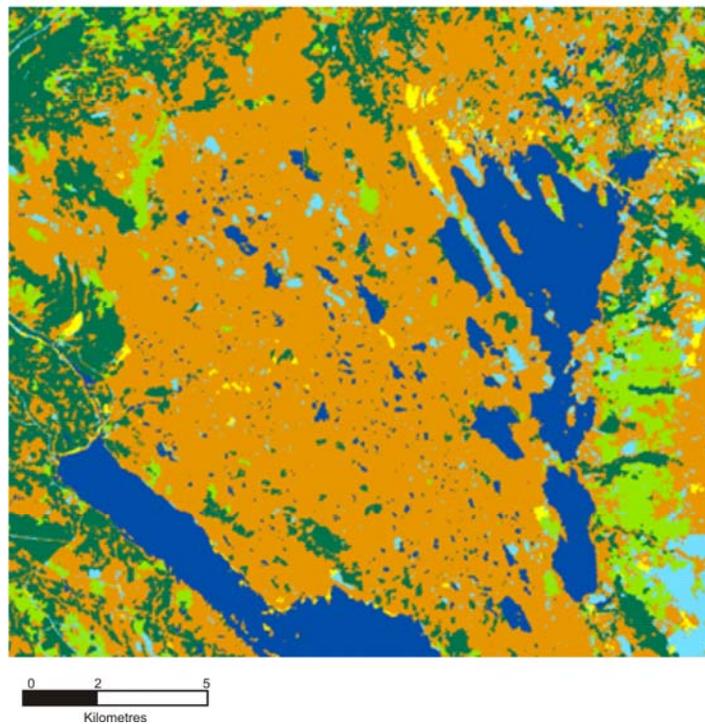


Figure 5-11: Example C - Zoomed areas of the original versus the classified image

## 5.8 Accuracy Assessment

An accuracy assessment was completed by randomly generating 376 points on the image for each class in proportion to the class area. The label of each point was determined using the classified image illustrated in Figure 5-8 while the ground-truth field of all points, showing the field observation of each point, was determined based on a visual analysis using high-resolution aerial photos existing in ArcGIS™. Finally, the overall and per-class producer and user accuracies were obtained (ref. Table 5-4).

The producer accuracy shows how much of the areas which were initially classified class A, are accurately classified as class A, while user accuracy shows how much of the areas classified as class A are actually class A. Producer accuracy has a relationship with omission error that indicates how much of a class has been omitted in the classification process. On the other hand, user accuracy has a relationship with commission error, which shows how much of the mapped class belongs to the other classes. The Kappa coefficient is a value between 0 and 1 that establishes the degree of agreement between the classified image and the ground truth data<sup>12</sup>. As is clear from the information presented in Table 5-4, the overall classification accuracy and the Kappa Coefficient were approximately 89% and 0.85, respectively, which shows the high performance of the method used in this study.

**Table 5-4: Final Classified Map Accuracy Assessment**

Class	Producer Accuracy (%)	User Accuracy (%)
Forest	94	90
Wetland	83	91
Deforested	67	71
Water	98	100
Barren	89	80
Open	92	82
Commercial	80	80
Residential	80	80
Overall Accuracy	89	
Kappa Coefficient	0.85	

## 5.9 Remote Sensing Summary and Conclusions

Sentinel-2 imagery was downloaded and pre-processed to perform an object-based classification of the Humber River watershed. Areal summary statistics for the established land cover classes are provided in Table 5-5. As shown, the largest portion of the study area consists of forests and wetlands, while commercial and residential areas represent less than 1% of the overall study area.

<sup>12</sup> If Kappa coefficient equals to 0, there is no agreement between the classified image and the reference image. If Kappa coefficient equals to 1, then the classified image and the ground truth image are totally identical. So, the higher the kappa coefficient, the more accurate the classification is. (Source: <http://www.50northspatial.org/classification-accuracy-assessment-confusion-matrix-method/>)

Based on the accuracy attained for this remote sensing assessment, the results are sufficient for to support hydrologic model development for the Humber River project.

**Table 5-5: Area of Each Land Class in the Study Area**

<b>Class</b>	<b>Area (km<sup>2</sup>)</b>	<b>Area (%)</b>
Forest	3486	41.53
Wetland	2813	33.50
Deforested	328	3.91
Water	1013	12.06
Barren	76	0.90
Open	669	7.97
Commercial	7	0.09
Residential	3	0.04
<i>Total</i>	8395	100.00

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## 6.0 Hydrologic Investigations and Modelling

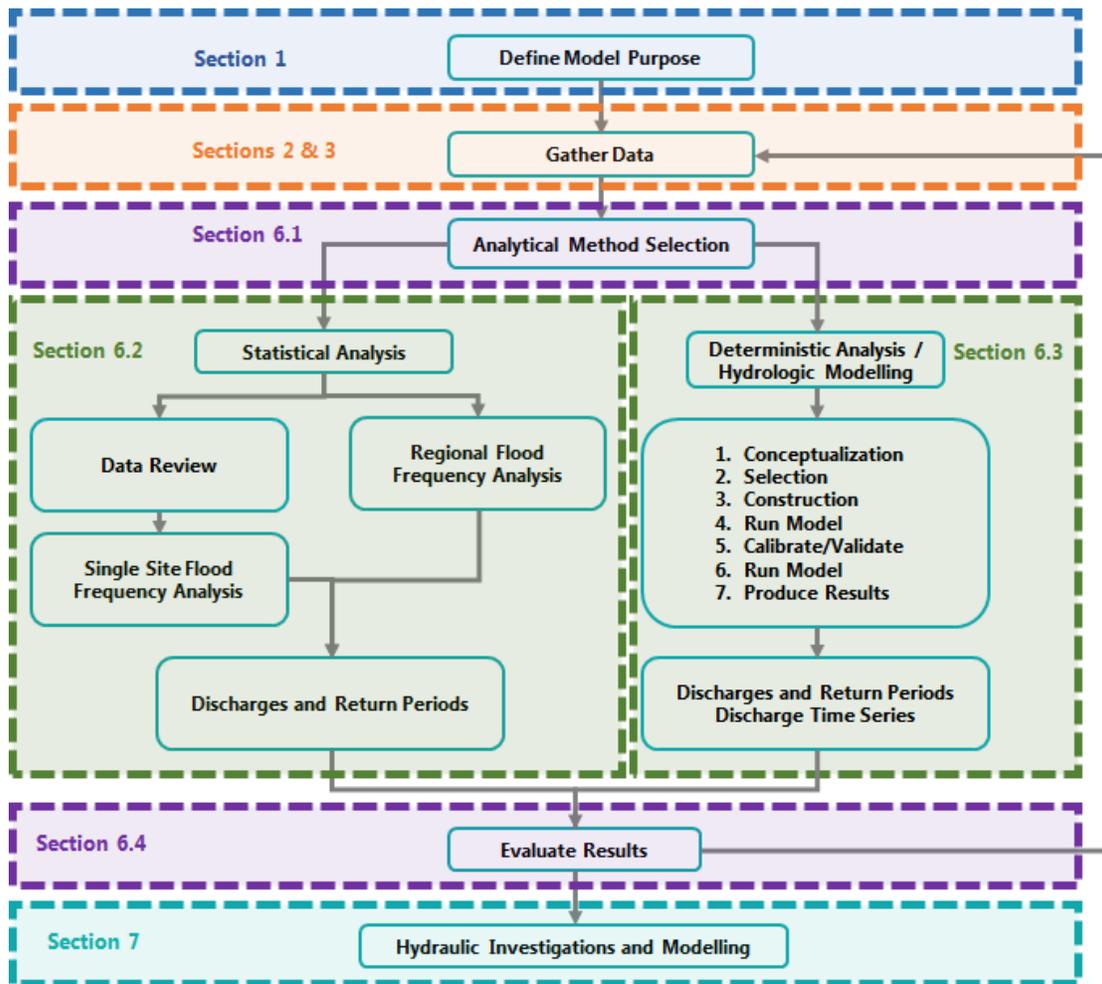
Synopsis: This study component has focused on the estimation of 1 in 20-year and 1 in 100-year Annual Exceedance Probability (AEP) flows, for both existing climate and projected future climate conditions, for locations within the Humber River Watershed. Land use scenarios which were modelled include both existing and projected future watershed development conditions. Estimates of the required AEP flows were computed using both statistical methods (single station frequency analysis and Regional Flood Frequency Analysis) and deterministic modelling (hydrologic simulation modelling). Given the uncertainty inherent in flood estimation, comparing results from alternative techniques enables an estimate to be adopted with greater confidence in its reliability and accuracy. In the case of this study, statistical estimates of flows were made by utilizing historical flow records from local hydrometric gauges. These statistical estimates have then been used as the basis for calibration of the deterministic hydrologic model HEC-HMS developed by the United States Army Corps of Engineers (USACE). The estimates of the required AEP flows from this task represent input to the Hydraulic Investigations and Modelling task (ref. Section 7).

### 6.1 Overview

The general objective of this task is to develop a hydrologic model of the Humber River watershed to support estimation of the 1 in 20-year and 1 in 100-year AEP flows for both existing climate and projected future climate conditions. Land use scenarios to be modelled include both existing watershed and projected future watershed development conditions. These flows were simulated in the hydraulic model to estimate flood levels across the study area.

Estimates of the 1 in 20-year and 1 in 100-year AEP flows were computed using both statistical methods and deterministic modelling. Given the uncertainty inherent in flood estimation, comparing results from alternative techniques enables an estimate to be adopted with greater confidence in its reliability and accuracy. In the case of this study, statistical estimates of flows were made by utilizing historical flow records from local hydrometric gauges. These statistical estimates were then used as the basis by which the deterministic hydrologic model HEC-HMS was calibrated.

The following sections of this report detail this approach. Figure 6-1 provides a visual flow chart for the components of the development of the hydrological modelling for the project, and relevant report sections, as well as linkages to other aspects of the project.



**Figure 6-1: Hydrologic Investigations and Modelling Task Flow and Project Linkages**  
(Please note that this flow chart was adapted from the federal flood mapping guidelines)

## 6.2 Statistical Analysis

### 6.2.1 Review of Data

The hydrometric stations (ref. Table 6-1) within the Humber River Watershed study area were reviewed in conjunction with the *Regional Flood Frequency Analysis for Newfoundland and Labrador - 2014 Update* (RFFA) (AMEC [now Wood], 2014) to identify possible sources of data to support calibration and validation of the hydrological and hydraulic models developed through this project.

Of the nineteen (19) stations located within the study area:

- eleven (11) stations continued to collect data for the period since the 2014 RFFA study was completed
- one (1) station, namely 02YK010 - Grand Lake East of Grand Lake Brook, records only water level information and is located outside of the hydraulic modelling area

- Three (3) stations, namely 02YK010 - Grand Lake East of Grand Lake Brook; 02YL007 - Deer Lake near Generating Station; and 02YL003 - Humber River at Humber Village Bridge record regulated flows
- Five (5) stations, as listed below contributed to the 2014 RFFA:
  - 02YM004 - Indian Brook Diversion above Birchy Lake
  - 02YL008 - Upper Humber River above Black Brook
  - 02YK008 - Boot Brook at Trans-Canada Highway
  - 02YL004 - South Brook at Pasadena
  - 02YL001 - Upper Humber River near Reidville

It is also noted that one additional station was installed after the completion of the 2014 RFFA study, namely station 02YL012 - Steady Brook above confluence to Humber River.

**Table 6-1: Study Relevant Hydrometric Stations**

Station Number	Station Name	Drainage Area (km <sup>2</sup> )	Regulated? <sup>1</sup>	Data Type <sup>2</sup>	Status	Period of Record	
						Span	# of Years
02YK001	Humber River at Grand Lake Outlet	5020	Y	F	Discontinued	1898 - 2010	113
02YK002	Lewaseechjeech Brook at Little Grand Lake	470	N	F & L	Active	1956 - 2020	65
02YK003	Sheffield River at Sheffield Lake	362	N	F	Discontinued	1955 - 1966	12
02YK004	Hinds Brook near Grand Lake	529	N	F	Discontinued	1956 - 1979	24
02YK005	Sheffield Brook near TransCanada Highway	391	N	F & L	Active	1972 - 2020	49
02YK006	Hinds Brook at Hinds Brook Power House	651	Y	F	Discontinued	1981 - 2010	30
02YK007	Glide Brook below Glide Lake	112	N	F	Discontinued	1984 - 1997	14
02YK008	Boot Brook at Trans-Canada Highway	20.4	N	F & L	Active	1985 - 2020	36
02YK009	Grand Lake at Main Dam	n/a	Y	L	Discontinued	1988 - 1990	3
02YK010	Grand Lake East of Grand Lake Brook	n/a	Y	L	Active	1988 - 2020	33
02YL001	Upper Humber River near Reidville	2110	N	F & L	Active	1929 - 2020	92
02YL003	Humber River at Humber Village Bridge	7860	Y	F & L	Active	1982 - 2020	39
02YL004	South Brook at Pasadena	58.5	N	F & L	Active	1983 - 2020	38
02YL006	Deer Lake near Pasadena	n/a	Y	L	Discontinued	1987 - 1990	4
02YL007	Deer Lake near Generating Station	n/a	Y	L	Active	1987 - 2020	34
02YL008	Upper Humber River above Black Brook	471	N	F & L	Active	1988 - 2020	33
02YL012	Steady Brook Above confluence to Humber River	77.2	N	F & L	Active	2015 - 2020	6
02YM002	Indian Brook Diversion to Birchy Lake	n/a	N	F	Discontinued	1963 - 1978	16
02YM004	Indian Brook Diversion above Birchy Lake	238	N	F & L	Active	1989 - 2020	32

Notes:

1. Streamflow is regulated by storing water in reservoirs and controlling the release. Regulation may be seasonal, annual, or long-term depending on the length of the period of accumulation and release.
2. F = Flow, L = Level/Stage

In review of the data available for these stations:

- 02YL012 only has one years' worth of data available - peak flow is 71.7 m<sup>3</sup>/s for 2016
- 02YL007, 02YK009, 02YL009 and 02YK010 has water level data only
- 02YK001 has no peak flow data, but has monthly mean discharges from 1926 to 2010 which can potentially be used in lieu of peak flow data
- 02YK007, 02YK003, 02YK004, 02YM002 and 02YJ003 have older data
- 02YL010 has level data only which is much older, and consists of two data points only (1995/1996)

### 6.2.2 Single Station Frequency Analysis

Single station frequency analysis has been conducted using the U.S. Army Corps of Engineers statistical software package, HEC-SSP, to estimate flows for individual streamflow gauges.

The U.S. Army Corps of Engineers, Hydrologic Engineering Center's (HEC) Statistical Software Package (HEC-SSP) v2.2 (USACE, 2019) was utilized to estimate frequency flows for relevant stations. HEC-SSP facilitates statistical analyses of hydrologic data, and can perform flood flow frequency analysis, generalized frequency analysis on not only flow data but other hydrologic data as well, volume frequency analysis on high or low flows, duration analysis, coincident frequency analysis, curve combination analysis, balanced hydrograph analysis, distribution fitting analysis, and mixed population analysis.

The theoretical probability distributions generally considered for single site frequency analysis are the Log-Normal (LN) and Three Parameter Log-Normal (3PLN) distributions; the Gumbel (EV-1) and Generalized Extreme Value (GEV). While all of these distributions have been historically recognized as possible flood frequency distributions in Newfoundland, streamflow estimates produced using these distributions typically lie within a narrow band. Further, the 3PLN distribution was selected for the single site frequency analysis completed for this study after careful consideration and statistical analysis of results. This approach is also consistent with similar analyses completed for the *Regional Flood Frequency Analysis for Newfoundland And Labrador - 2014 Update* (AMEC [now Wood], 2014).

Table 6-2 summarizes the single station frequency analyses results from the 2014 RFFA for the noted stations. The additional peak flow data was obtained from the Water Survey of Canada for those station which had supported the 2014 RFFA (ref. Table 6-3).

It is generally accepted that ten (10) or more years of data are required to perform a frequency analysis for the determination of recurrence intervals (USGS, n.d.). However, as would be expected, the confidence in the results improves as more years of historical data are made available to the analysis.

The resultant updated frequency flows are summarized in Table 6-4 and the comparison to the 2014 computed frequency flows is summarized in Table 6-5. As noted in Table 6-5, the updated frequency flows are generally comparable to the 2014 frequency flows. The exception to this is for station 02YL004 (South Brook at Pasadena) where a more significant increase (i.e. 38%) is noted for the 1 in 100-year event. It is surmised that the 2016 instantaneous peak flow of 71.7 m<sup>3</sup>/s, which is the fourth highest recorded instantaneous peak flow over the period of record, influenced the upward trend on results from the updated single station frequency for this station.

**Table 6-2: 2014 RFFA Frequency Flows**

Station #	Name	Flow by Return Period (m <sup>3</sup> /s)						
		Q2	Q5	Q10	Q20	Q50	Q100	Q200
02YK008	Boot Brook at Trans-Canada Highway	9.2	13.7	16.9	20.1	24.4	27.7	31.2
02YL001	Upper Humber River near Reidville	577.1	699.7	773.8	840.9	923.4	982.9	1040.6
02YL004	South Brook at Pasadena	41.6	60.3	73.3	86.0	103.1	116.3	129.8
02YL008	Upper Humber River above Black Brook	241.2	297.3	331.6	362.9	401.7	429.9	457.4
02YM004	Indian Brook Diversion above Birchy Lake	38.2	44.2	47.8	50.9	54.7	57.4	59.9

**Table 6-3: Peak Flows for the Period 2013 to 2019**

Station #	Name	Maximum Instantaneous Peak Flow by Year (m <sup>3</sup> /s)							
		2013	2014	2015	2016	2017	2018	2019	2020
02YK008	Boot Brook at Trans-Canada Highway	8.17	10.6	6.6	11.7	7.71	26.5	11.8	n/a
02YL001	Upper Humber River near Reidville	822	594	503	433	44	n/a	668	786
02YL004	South Brook at Pasadena	46.6	24.2	29	71.7	20.1	58.5	26.4	n/a
02YL008	Upper Humber River above Black Brook	316	n/a	304	174	142	366	137	n/a
02YM004	Indian Brook Diversion above Birchy Lake	44.1	43.7	40	30.4	31.9	n/a	35.8	n/a

Please note that the data in red text was available at the time of report writing but not available at the time of analysis.

**Table 6-4: Updated Single Station Frequency Flows**

Station Number	Description	Flow by AEP (m <sup>3</sup> /s)								
		2-Year			1 in 20-year			1 in 100-year		
		Lower Limit	Mean	Upper Limit	Lower Limit	Mean	Upper Limit	Lower Limit	Mean	Upper Limit
<b>Stations which had supported the 2014 RFFA</b>										
02YK008	Boot Brook At Trans-Canada Highway	8.0	9.1	10.4	16.7	20.0	25.7	22.6	28.5	39.8
02YL001	Upper Humber River Near Reidville	544.3	571.8	600.4	810.5	868.6	947.6	963.2	1,052.9	1,181.6
02YL004	South Brook At Pasadena	31.3	35.8	40.6	75.9	91.4	118.7	122.6	160.0	236.5
02YL008	Upper Humber River Above Black Brook	224.6	243.8	264.7	329.8	366.6	426.4	379.8	432.3	524.1
02YM004	Indian Brook Diversion Above Birchy Lake	36.6	38.7	40.9	45.8	49.0	53.9	48.9	52.9	59.2
<b>Other Stations</b>										
02YK002	Lewaseechjeech Brook At Little Grand Lake	99.8	106.6	113.8	159.5	174.7	196.6	194.8	218.9	255.8
02YK005	Sheffield Brook Near TransCanada Highway	60.1	65.6	71.6	97.5	109.3	127	115	131.7	158.4
02YL003	Humber River At Humber Village Bridge	617.6	645.7	674.8	796.8	845.8	917.7	884.4	953.7	1,061.8

**Table 6-5: Comparison of 2014 and 2020 Single Station Frequency Flows**

Station #	Name	Flow by AEP (m <sup>3</sup> /s)						% Change 2020 to 2014		
		2014			2020			Q2	Q20	Q100
		Q2	Q20	Q100	Q2	Q20	Q100			
02YK008	Boot Brook at Trans-Canada Highway	9.2	20.1	27.7	9.1	20.0	28.5	-1%	0%	3%
02YL001	Upper Humber River near Reidville	577.1	840.9	982.9	571.8	868.6	1,052.9	-1%	3%	7%
02YL004	South Brook at Pasadena	41.6	86.0	116.3	35.8	91.4	160	-14%	6%	38%
02YL008	Upper Humber River above Black Brook	241.2	362.9	429.9	243.8	366.6	432.3	1%	1%	1%
02YM004	Indian Brook Diversion above Birchy Lake	38.2	50.9	57.4	38.7	49.0	52.9	1%	-4%	-8%

### 6.2.3 Survey of Streamflow Gauging Stations

As noted previously, field survey of gauging stations 02YL001, 02YL003, 02YL004, and 02YL012 was completed to establish geodetic datums referencing CGVD-2013. The data collected at these stations currently references an assumed datum. Summary information for these surveys is provided in Appendix C. The surveys determined the elevation adjustments detailed in Table 6-6. Table 6-6 also details the association of the station location to the corresponding HEC-RAS cross-section included with the hydraulic model (ref. Section 7).

**Table 6-6: Single Station Frequency Flows for Other Stations**

Station #	Elevation Adjustment from Assumed Datum to CGVD-2013 (m)	HEC-RAS Section Key
02YL001	8.627	Humber River-Reach 1-2128.85
02YL003	0.429	Humber River-Reach 5-6748.05
02YL004	13.128	South Brook-Reach 1-2735.06
02YL012	1.077	Steady Brook-Reach 1-701.06

Notes:

- Please note that the HEC-RAS Section Key comprises the River name, Reach name and cross-section number as defined in the dataset.

### 6.2.4 Regional Flood Frequency Analysis

The approach documented in the *Regional Flood Frequency Analysis for Newfoundland and Labrador - 2014 Update* (RFFA) (AMEC, 2014) was reviewed for application to this project to support the calibration and validation effort. Given the availability of numerous streamflow gauging station data in the study area, application of the RFFA was not considered necessary for quantification of flows along the main Humber River.

However, the RFFA equations were used to assist in better understanding the flow regime for the Steady Brook watershed (ref. Section 9.3.2).

## 6.3 Deterministic Analysis

### 6.3.1 Model Setup

The 1 in 20-year and 1 in 100-year AEP flow estimates were simulated using a deterministic numerical model. There are several numerical models available for the analysis of the rainfall-runoff response of a watershed. The United States Army Corps of Engineers HEC-HMS (USACE, 2018) model was selected as it is a non-proprietary model which has been extensively used and tested. The numerical model includes a selection of methods to simulate watershed, channel and water control structure behaviour to predict flow, stage and timing. The advantages of a numerical model include the following:

- Synthesis and routing of hydrographs (quantifying basin response, flood volume and flow over time)
- Flow simulation distributed over several sub-watersheds and tributaries
- Simulation of reservoir routing
- Accounting for spatial variations in soil type and land cover, and
- Accounting for peak flow attenuation in channel and floodplain.

An advantage of this model is the HEC-GeoHMS (USACE, 2013) link which permits much of the model setup to occur within a GIS environment. This functionality was implemented for the current study and simplified the model development process. The following sections describe the model inputs, calibration and verification of the model and the resulting flood flow estimates.

The HEC-HMS model for the Humber River Watershed, including all elements defined in the IMA&SN, was developed using version 4.4 of the software, and additional supporting software, namely the USACE HEC-GeoHMS v10.1 operating in conjunction with ESRI ArcGIS 10.4. The HEC-GeoHMS extension has supported processing of the DEM, delineation of watersheds and sub-watersheds/drainage areas, determining watershed characteristics and parameters, and creating the HEC-HMS dataset.

#### 6.3.1.1 Model Elements

The elements of the HEC-HMS model prepared for the current study were developed using the HEC-GeoHMS tool which allows processing of the watershed in ESRI ArcGIS 9.3/10.0 and development of the model for import into HEC-HMS.

A DEM raster network with a resolution of 19 m x 19 m, based on the Canada digital elevation data (CDED) was used for model set up and to support parameterization. Terrain pre-processing was applied to prepare the DEM for model set-up. HEC-GeoHMS recommended steps were followed and sub-basins were delineated. The 0.25 m x 0.25 m high-resolution DEM developed for this project (ref. Section 4) was resampled to a resolution of 1 m x 1 m to refine the HEC-HMS model basin delineation for the Deer Lake area. The DEM was used to determine flow direction, flow accumulation (i.e. number of upstream grid cells), stream definition and basin delineation. Additional flow nodes at certain locations were added by further discretizing the delineated sub-basins. The sub-basin characteristics including river length, river slope, basin slope, longest flow path, basin centroid, basin centroid elevation, and centroidal flow path, were abstracted from the model DEM.

Figure 6-2 depicts the Humber River HEC-HMS model sub-basins. A total number of 274 sub-basins were delineated for Humber River Watershed HEC-HMS model.

The Muskingum-Cunge routing method was selected for simulation of routing in river reaches in the study area. Several model requirements including river length, river slope, basin slope, longest flow path, basin centroid, basin centroid elevation and centroidal flow path were determined using HEC-GeoHMS. Channel shape, length, slope and roughness coefficients for the channel and overbanks were developed from survey cross sections along the reach in conjunction with the DEM for areas without survey.

The loss and transform method, selected to convert rainfall to runoff, was the Soil Conservation Service<sup>13</sup> (SCS) method which requires several input parameters including Curve Number, initial abstraction and lag time for each sub-basin. The approach of addressing imperviousness through CN values is consistent with previous studies in the same area (i.e. Corner Brook and Petrie's Brook).

The parameters required as input are presented in Table 6-7. Parameter derivation equations and methods are described in Section 6.3.1.2.

**Table 6-7: Selected Modelling Methods and Parameter Requirements**

Component	Process	HEC-HMS Modelling Method	Parameters
Sub-Basin	Loss	SCS Curve Number Loss Method	Initial Abstraction, Curve Number, Percent Impervious
	Transform	SCS Unit Hydrograph	Basin Lag
Routing	Routing	Muskingum-Cunge	Channel Shape, Channel Length, Channel Slope, Roughness Coefficients

### 6.3.1.2 Sub-basin Inputs

SCS Curve Number (CN) is an index of the basin's runoff generation potential and is a function of soil type and land use. National Resource Conservation Service (NRCS), known formerly as the US Soil Conservation Service (SCS), has tabulated Curve Numbers based on soil type and land use. Four major hydrologic soil groups are defined which are briefly described as:

- Soil Group A: Well to excessively drained (high infiltration rates)
- Soil Group B: Moderately well to well drained (moderate infiltration rates)
- Soil Group C: Imperfectly drained (low infiltration rates)
- Soil Group D: Poorly to very poorly drained (very low infiltration rates)

Soil information for the study area was sourced from the Canadian Soil Information Service (CanSIS) of Agriculture Canada and Newfoundland and Labrador Geological Survey. The Humber River watershed is defined in the *Reconnaissance Soil Surveys of Stephenville – Port-Aux-Basques 1991* Report No. 12 (I2 B) and *Soils of the Red Indian Lake – Burgeo Area 1988* Report No. 9 (I2 A) [Agriculture Canada].

<sup>13</sup> The Soil Conservation Service is now known as the Natural Resources Conservation Service (NRCS)

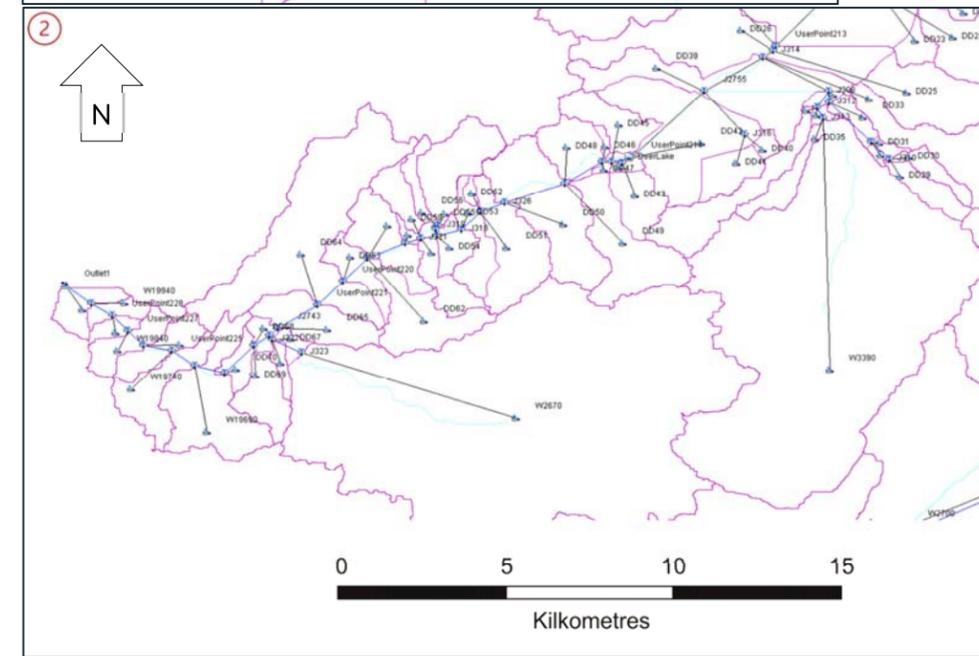
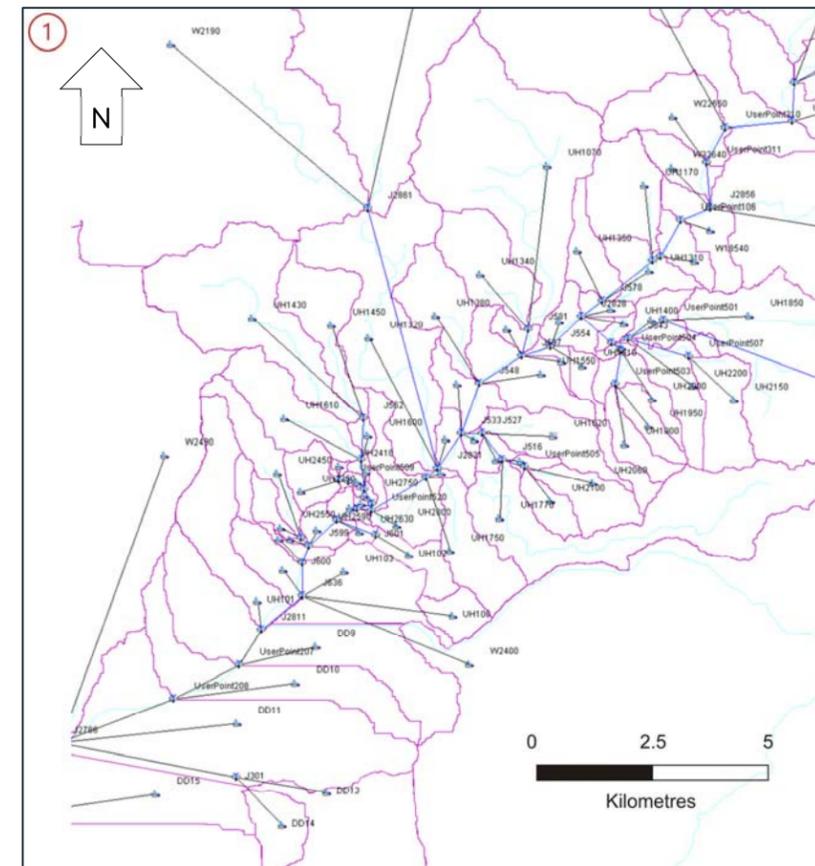
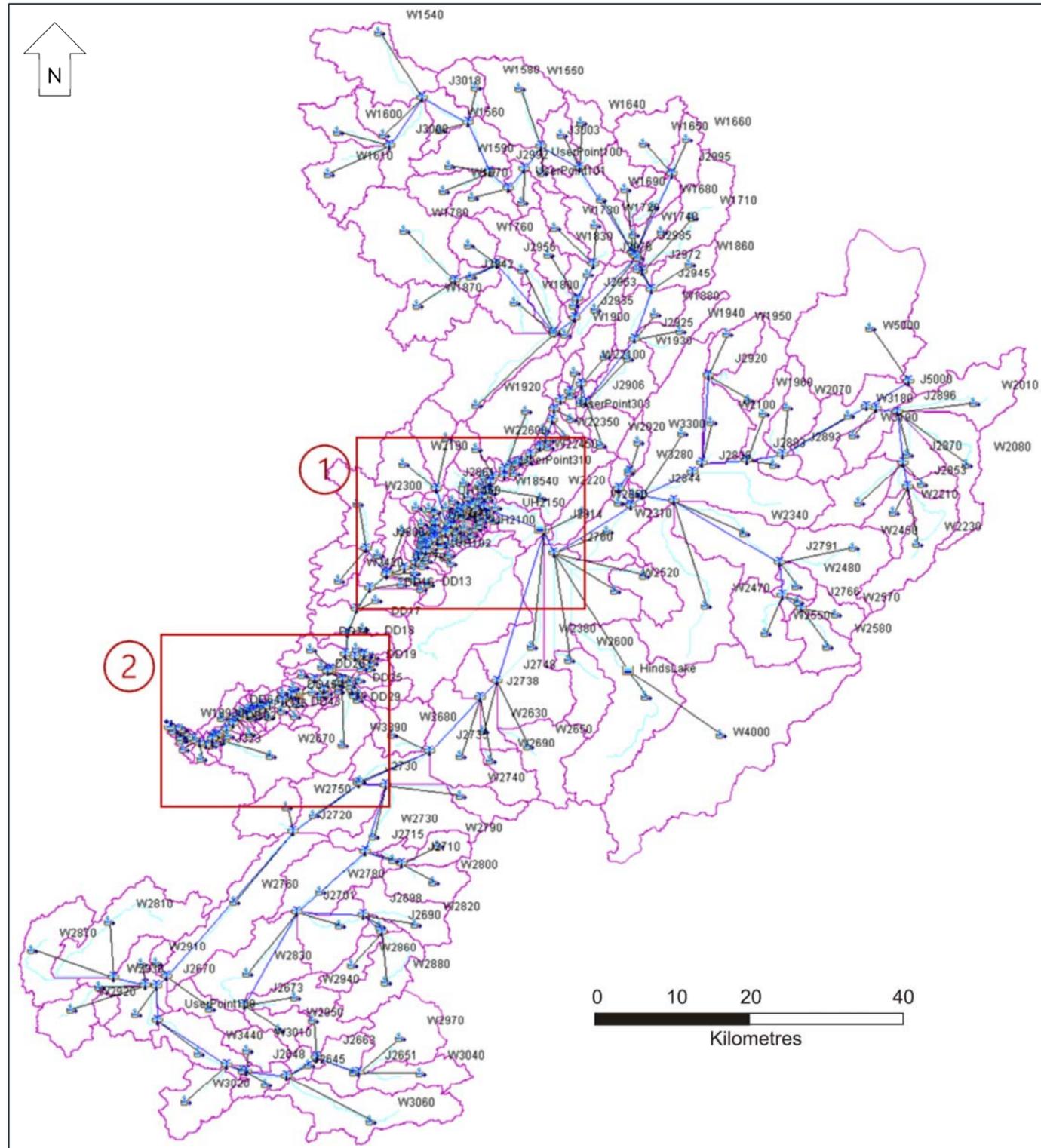


Figure 6-2: Humber River HEC-HMS  
Subcatchment Discretization

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The soil survey report, along with a corresponding GIS soil layer, were sourced from Agriculture Canada and used in the CN determination process. Hydrologic soil groups for different soil classes were determined based on soil class descriptions in Agriculture Canada (1988) and Agriculture Canada (1991). Humber River soil mapping, as well as SCS hydrological soil group classifications, are presented in Figure 6-3. The soil associations focused on the “Dominant Soil Association”, which indicates the soil series which is dominant within the GIS database spatial polygon occupying over 50% of the polygon by area.

Land use classification was completed using remote sensing data (ref. Section 5) as input and eight (8) land use classes were identified for the Humber River watershed areas, as outlined in Table 5-5, using a resolution of 10 m x 10 m. The figure illustrates that most of the watershed is of natural land cover, with the development mainly along Deer Lake. Based on the background information, the future watershed development would be expected to occur within the Deer Lake area. Land use class coverage for each HEC-HMS model subcatchment is provided in Appendix M. Figure 6-4 illustrates the land cover across the Humber River study area. Comparison of the current development condition and the future development condition is presented in Figure 6-5. Under the future development condition, the increases in residential and commercial land use would increase the impervious coverage and subsequently increase the runoff levels.

Having both land cover and soil information in GIS form permitted efficient estimation of Curve Number values across the watershed for the hydrologic model. Table 6-8 presents Curve Numbers for some typical land covers and soil group based on values recommended in the current NRCS handbook for various hydrologic soil-cover complexes. Figure 6-6 illustrates the Curve Number grid across the Humber River study area.

**Table 6-8: Curve Numbers for Typical Land Uses**

Land Use	Soil Type			
	A	B	C	D
Forest	30	55	70	78
Developed	99	99	99	99
Fields/Pastures	39	61	74	80
Wetlands	46	66	78	83
Water	100	100	10	100
Barren/Soil	76	85	89	91
Open Space	49	69	79	84
Deforested	49	69	79	84

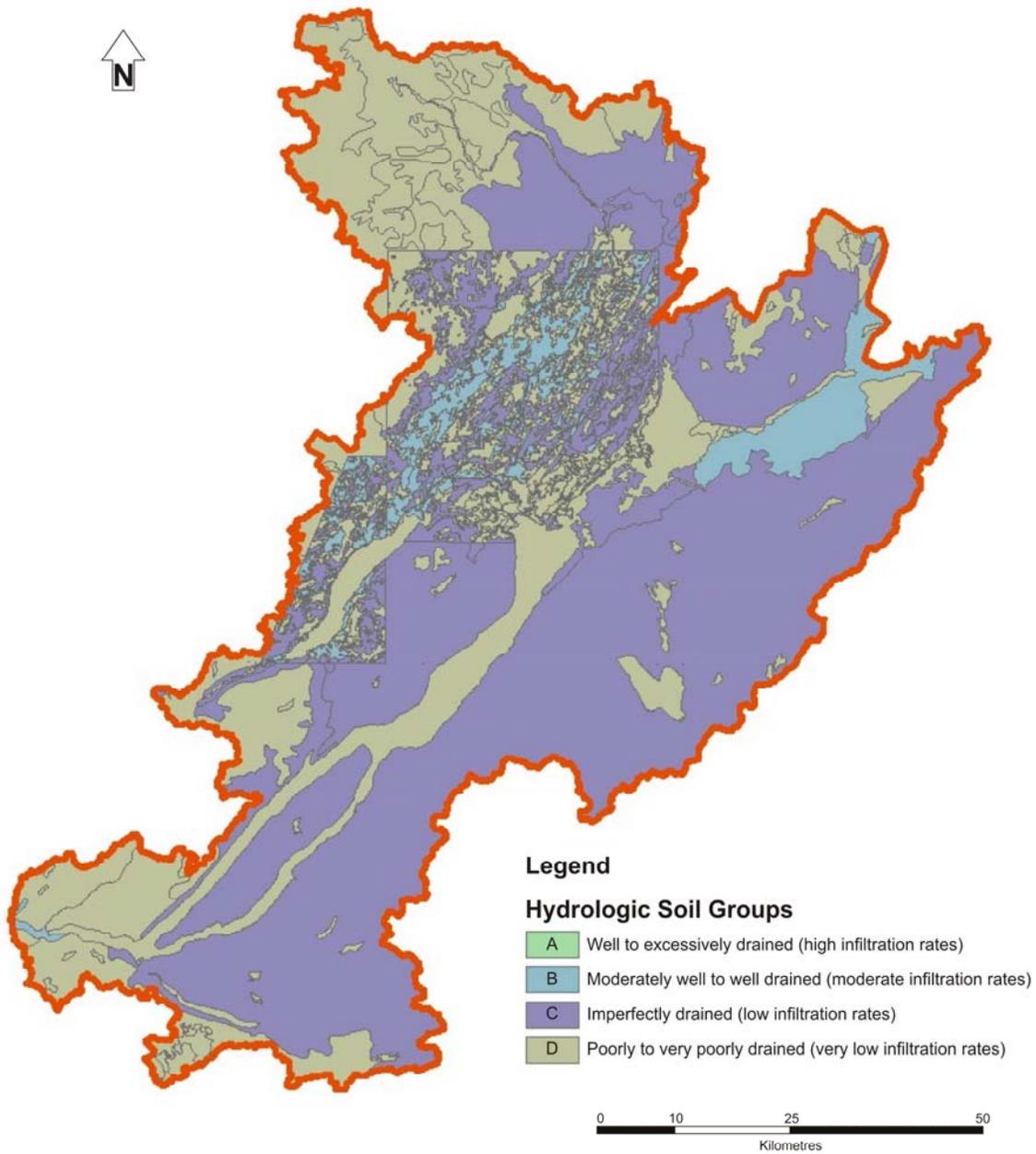


Figure 6-3: Humber River HEC-HMS Model - Soil Types Map

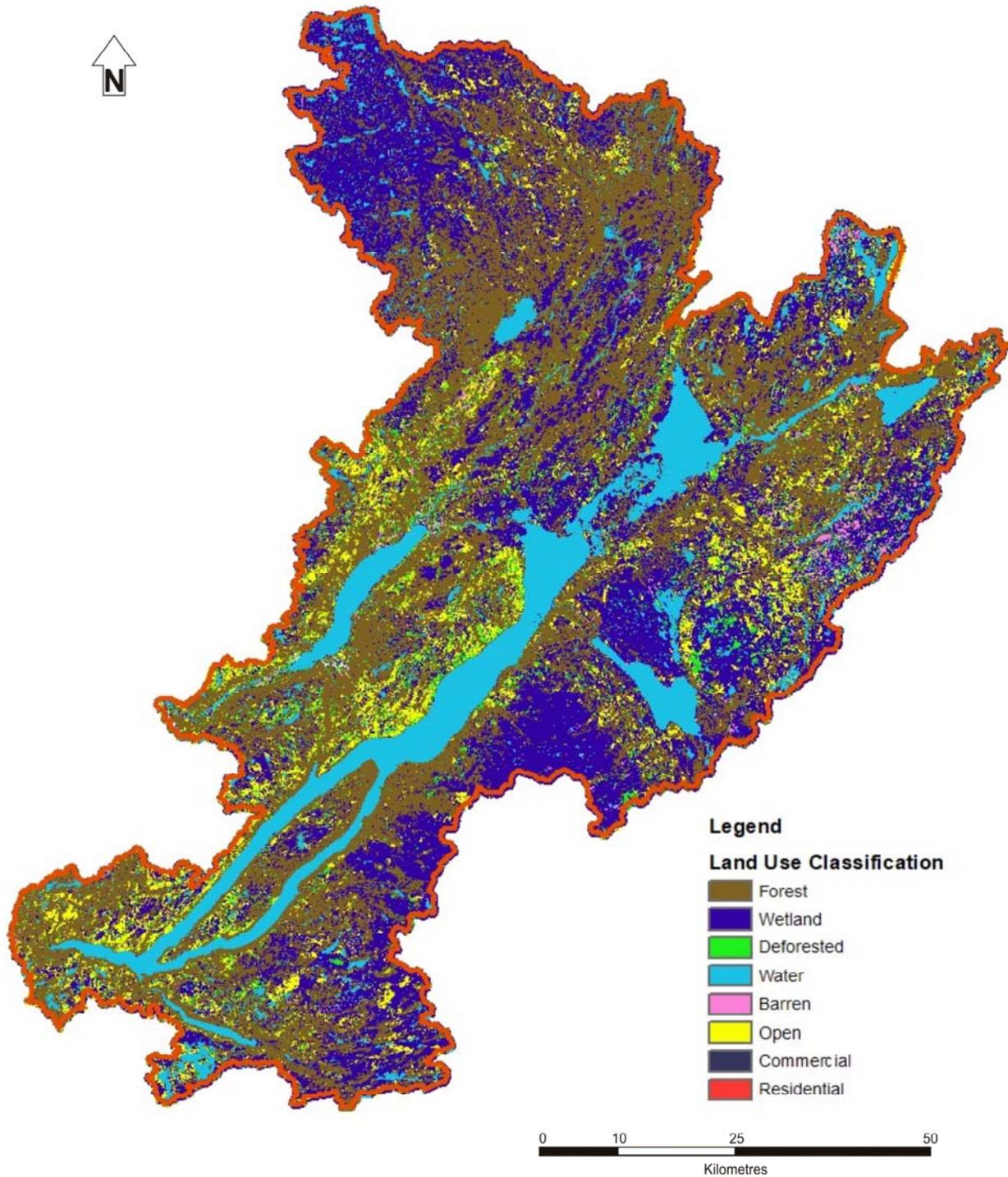
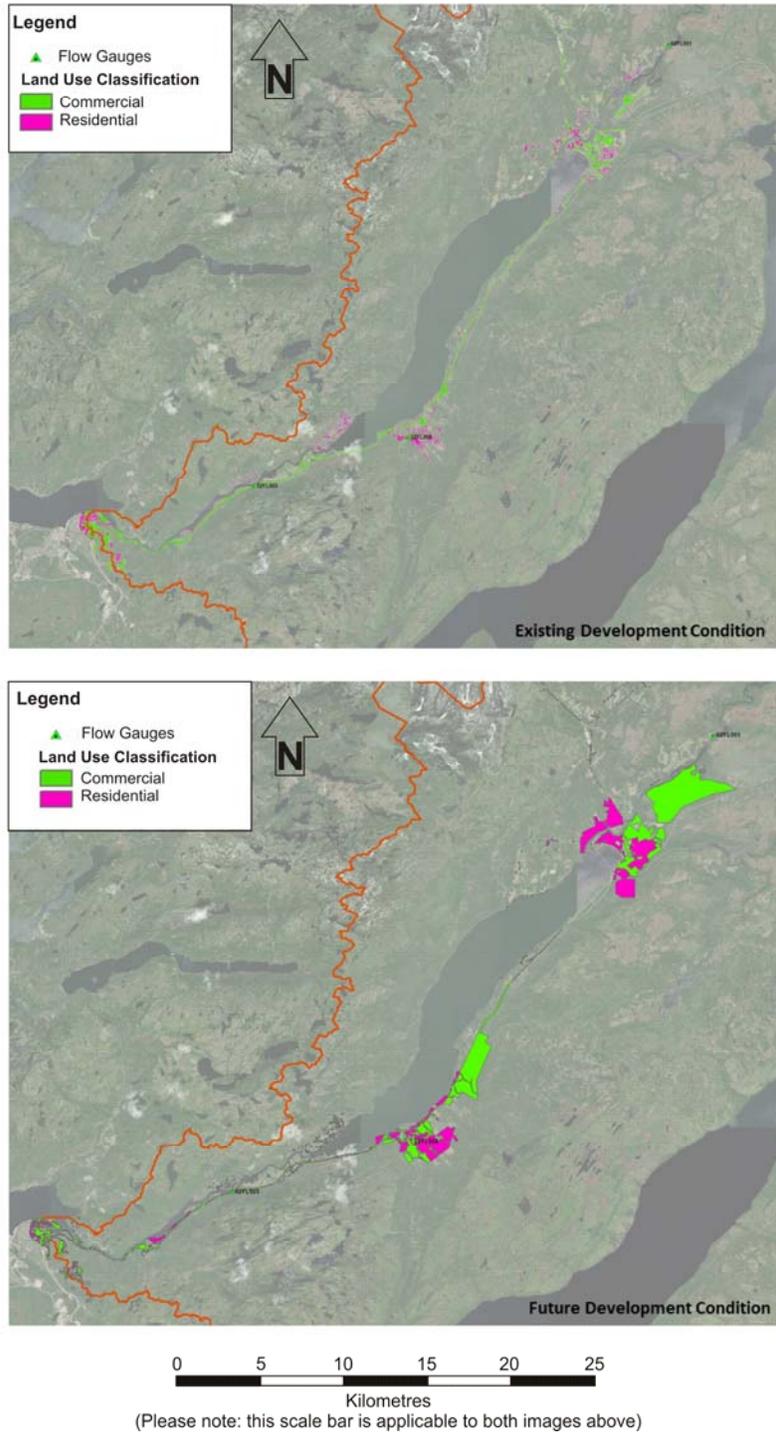


Figure 6-4: Humber River HEC-HMS Model – Land Classification Map



**Figure 6-5; Humber River HEC-HMS Model –  
Comparison of Existing and Future Development Conditions**

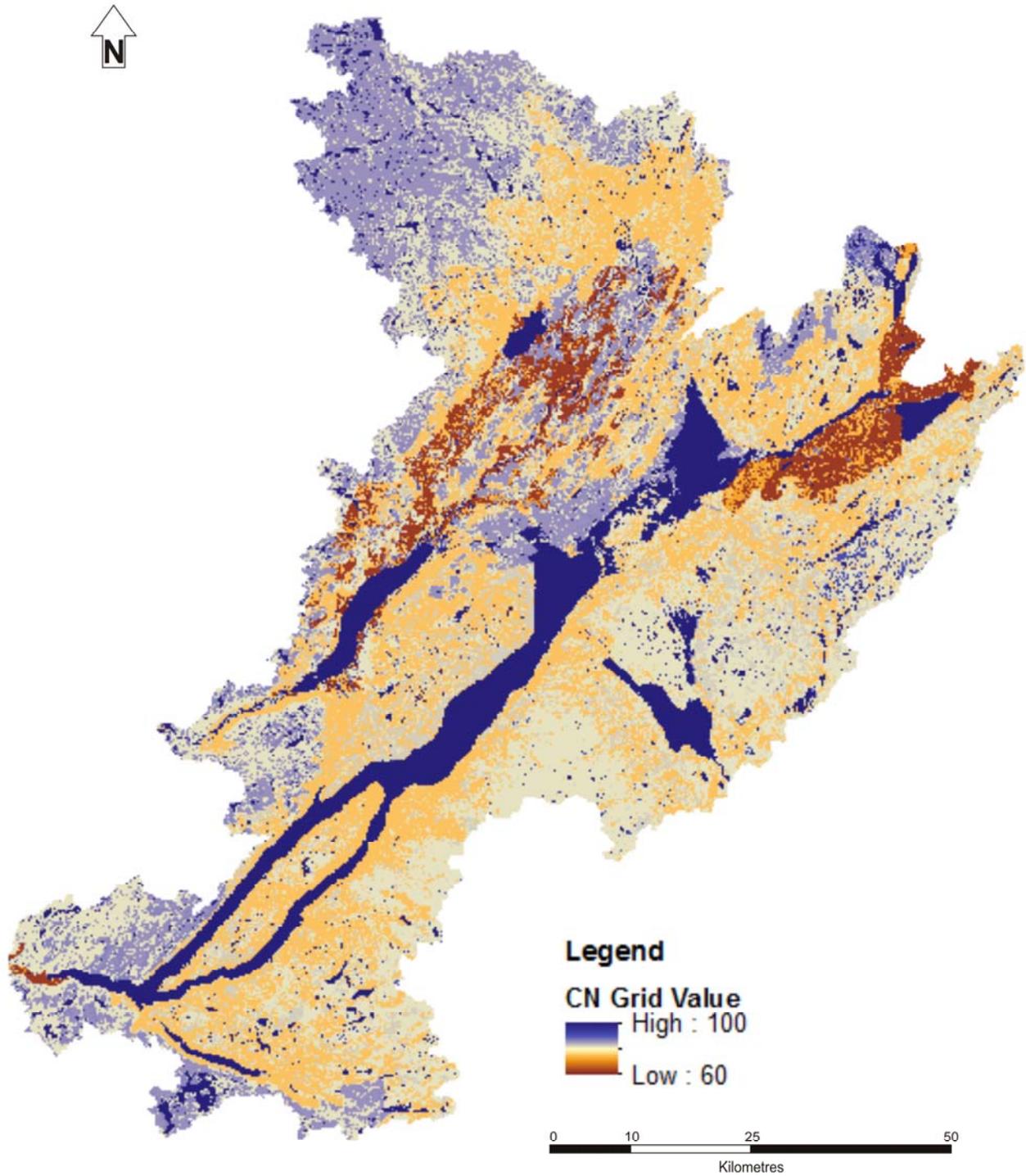


Figure 6-6: Humber River HEC-HMS Model – Curve Number Grid Map

The empirical CN values are subject to variability resulting from rainfall intensity and duration, total rainfall, soil moisture conditions, cover density, stage of growth and temperature; these causes of variability are collectively called the Antecedent Runoff Condition (ARC). ARC III was used for this analysis representing pre-wetted conditions per *Technical Document for Flood Risk Mapping Studies* (provided as Appendix B in the RFP).

Potential Storage or Potential Maximum Retention (S) is a measure of the ability of the watershed / catchment to abstract and retain precipitation. This value is calculated using the following equation:

$$S = \frac{(25400 - 254 * CN)}{CN} \quad (SI)$$

where CN = SCS curve number

Initial Abstraction (Ia) is a parameter that accounts for all losses prior to runoff and consists mainly of interception, infiltration, evaporation, and surface depression storage. In theory all rainfall minus Initial Abstraction will generate the runoff from a specified catchment. Initial Abstraction is utilized in the SCS method using the following equation:

$$Ia = 0.2 * S$$

Initial Abstraction is commonly equal to 20% of the storage potential.

Time of Concentration ( $t_c$ ) represents the time required for runoff to travel from the hydraulically most distant point in the watershed to the outlet. The hydraulically most distant point is the point with the longest travel time to the watershed outlet, and not necessarily the point with the longest flow distance to the outlet. This value is computed using the following equation:

$$t_c = t_{\text{sheet}} + t_{\text{shallow}} + t_{\text{channel}}$$

where

- $t_{\text{sheet}}$  is the sum of travel time in sheet flow segments over the watershed land surface
- $t_{\text{shallow}}$  is the sum of travel time in shallow flow segments, down streets, in gutters, or in shallow rills and rivulets
- $t_{\text{channel}}$  is the sum of travel time in channel segments

The travel time in sheet flow segments over the watershed land surface ( $t_{\text{sheet}}$ ) is computed as follows:

$$t_{\text{sheet}} = \frac{0.007 * (N*L)^{0.8}}{(P_2)^{0.5} * S^{0.4}} \quad (\text{hours})$$

where

- N = an overland-flow roughness coefficient
- L = flow length, in feet
- $P_2$  = 2-year, 24-hour rainfall depth, in inches
- S = slope of hydraulic grade line, (land slope ft/ft)

The time of travel in shallow flow segments, down streets, in gutters, or in shallow rills and rivulets ( $t_{\text{shallow}}$ ) is computed as follows:

$$t_{\text{shallow}} = \frac{L}{V} \quad (\text{hours})$$

where  $L$  = flow length, in feet

$V$  = average velocity estimated as follows:

- $16.1345(S)^{0.5}$  for unpaved surfaces
- $20.3282(S)^{0.5}$  for paved surfaces

The travel time in channel segments ( $t_{\text{channel}}$ ) is computed as follows:

$$t_{\text{channel}} = \frac{L}{V} \quad (\text{hours})$$

where  $L$  = channel length, in feet

$V$  = average velocity estimated by Manning's equation

Time of Concentration ( $t_c$ ) was estimated using functionality available in the HEC-GeoHMS tool per the NRCS TR-55 methodology described in the HEC-GeoHMS User's Manual.

Basin lag time ( $t_{\text{lag}}$ ), required for use of the SCS unit hydrograph transform method, was determined using the NRCS TR-55 methodology supported in the Hec-GeoHMS extension. The equation used for calculation of the basin lag parameter is:

$$t_{\text{lag}} = 0.6 * t_c \quad (\text{where } t_c = \text{time of concentration})$$

The required information for the TR-55 method includes the 2-year 24-hour rainfall amount and GIS derived slopes and flow distances (ref. computation of time of concentration).

### 6.3.1.3 Reservoir Data

As noted in Section 2, there are three main reservoirs in the Lower Humber River watershed, namely: Grand, Hinds and Deer Lakes. In conjunction with WRMD, Wood consulted with Deer Lake Power (Kruger) and Nalcor (Newfoundland Hydro) with respect to access to relevant information for the hydroelectric systems and structures to support this study. Relevant data was also made available from the Dam Safety Program within the Department of Environment and Climate Change. The data made available to this study included:

- Main Dam at Grand Lake Inundation Study (Acres International, 1999);
- Hinds Lake information sourced from an inventory binder of NL Hydro dams;
- Cummings Cockburn (1984) Deer Lake rating curve (ref. Figure 2-4);
- Cummings Cockburn (1984) Deer Lake bathymetry map (ref. Figure 2-6);
- Dam Breach Study and Stability Analysis of Deer Lake Structures (Draft) (Golder, 2017b);
- Humber River Watershed Streamflow Synthesis and Reservoir Regulation (SSARR) hydrologic model;

and

- Development of a GIS Database for Use in an Integrated Approach to Water Resources Management in the Humber River Watershed and Humber Arm, (Philips, 1996).

This data was integrated, where possible, to develop Stage-Storage-Discharge relationships for each of these storage features to support development of the study HEC-HMS models.

### Grand Lake

The purpose of the Main Dam at Grand Lake is to raise water levels on Newfoundland's largest lake causing the water to be conveyed through an 11 km long canal to the Hydro Electric Station at Deer Lake. The power station officially opened in 1925. The main dam is 225.6 m wide and 23.3 m tall. Eighteen (18), 4.7 m wide steel gates span the length of the dam and are opened by one of two gantry cranes located on top of the dam. When opened, the dam can spill 1840 m<sup>3</sup>/s into the Junction Brook Spillway<sup>14</sup>. The crest elevation of the main dam is 89.3 m. Grand Lake covers an area of approximately 550 km<sup>2</sup> at an elevation of about 85 m<sup>15</sup>. The spillway is 98.8 m long with crest elevation of 84.6 m. The reservoir full supply level is 87.7 m. The average annual power flow is 145 m<sup>3</sup>/s.

Two sources of stage-storage-discharge information are available for the Main Dam at Grand Lake, namely the SSARR model and the 1999 Acres International report (ref. Table 6-9). As can be noted from a review of the two stage-storage-discharge relationships, there does not seem to be any specific alignment, particularly regarding discharge. A further review of the stage-storage relationships, whereby the differences between elevations associated with common storage volumes were quantified, indicates a near constant +1.6 m difference (comparing the SSARR values to the Acres, 1999 values). This suggests the two datasets reference different datums.

The Acres (1999) report notes that Deer Lake Power information regarding the dam was maintained using an assumed vertical datum. The assumed datum information was converted to geodetic datum using a -27.87 m offset factor. However, the specifications of the geodetic datum are not detailed. As such, it was assumed that the Acres (1999) geodetic datum references CGVD-1928.

Unfortunately, no relationship between the discharge values defined in the SSARR model and those defined in Acres (1999) could be ascertained. Further, no information is presented in either source that details how the discharge values were quantified.

It was concluded from this review that the Acres (1999) stage-storage-discharge relationship is the most relevant to support the hydrologic modelling effort for this study given it is of a more recent vintage.

The Grand Lake starting water surface elevation was included in the hydrologic modelling as the full supply elevation 87.7 m.

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<sup>14</sup> Source: <https://www.hiddennewfoundland.ca/main-dam>

<sup>15</sup> Source: <https://www.thecanadianencyclopedia.ca/en/article/grand-lake>

**Table 6-9: Main Dam at Grand Lake Stage-Storage-Discharge Relationships**

As defined in the SSARR Model			As defined in Acres, 1999; Golder 2017b		
Elevation (m)	Discharge (m <sup>3</sup> /s)	Storage (m <sup>3</sup> )	Elevation (m)	Discharge (m <sup>3</sup> /s)	Storage (m <sup>3</sup> )
82.88	0	0	84.60	0	0
83.18	140	140,180,000	84.49		<i>57,471,866</i>
83.49	140	280,820,000	85.49		464,999,642
83.79	140	421,910,000	85.52	120.4	<i>479,084,511</i>
84.10	140	563,450,000	86.43	354.0	<i>906,325,554</i>
84.40	195	705,450,000	86.49		934,495,293
84.71	195	847,910,000	87.34	707.9	<i>1,341,211,337</i>
85.01	195	990,870,000	87.65	849.5	<i>1,489,543,070</i>
85.32	195	1,134,560,000	87.82		1,570,886,279
85.62	195	1,279,140,000	87.95	1019.4	<i>1,634,066,101</i>
85.92	195	1,424,600,000	88.87	1256.0	<i>2,081,184,839</i>
86.23	195	1,570,940,000	89.04		2,163,804,606
86.53	195	1,718,460,000	90.09	1531.0	2,677,778,801
86.84	400	1,863,250,000			
87.10	400	2,026,940,000			
87.95	650	2,400,000,000			

**Notes:**

1. Data for Acres, 1999 abstracted from Tables 2.1 and 2.2.
2. Acres, 1999 storage estimates based on conversion of surface areas to volumes using the equation for the volume of the frustum of a right circular cone.
3. Acres, 1999 storage estimates in *red italics* were estimated based on linear interpolation from the documented values.

### Hinds Lake

The Hinds Lake project consists of a total of four (4) dams, eight (8) cut-off dykes, one (1) power canal, two (2) spillways and two (2) diversion canals. The available documentation indicates that power generation from the facility is based on a rated flow of 40 m<sup>3</sup>/s.

The main dam has a crest elevation of 314.0 m and a live storage capacity of 252 million m<sup>3</sup> at the full supply level elevation of 310.9 m. Live storage capacity begins at water elevation 306.0 m (i.e. the minimum pool elevation). The inflow design flood for the dam is a Probable Maximum Flood (PMF) having a peak flow of 1,218 m<sup>3</sup>/s.

The main dam spillway is a reinforced concrete structure located in a deep rock cut channel at the south abutment dam. The spillway is used convey excess water from the reservoir in flood situations. The spillway discharges water through two (2) vertical lift gates and a flat slab base. The gates are remotely controlled and have dimension 9.150 m wide x 8.99 m high. The spillway is 21.3 m wide with vertical sides and has a design capacity of 909 m<sup>3</sup>/s at maximum flood level of 311.8 m. The spillway invert elevation was estimated

as 301.9 m (based on the full supply level of 310.9 less the gate height of 8.99 m). The main spillway is designed for a discharge capacity of 909 m<sup>3</sup>/s at elevation 311.8 m.

The Humber River SSARR model was used as the basis for definition of the stage-storage relationship for Hinds Lake reservoir (ref. Table 6-10). The stage-storage values from the SSARR model generally align well with the same data from other sources. However, the SSARR model does not define a discharge rating curve for Hinds Lake. As such, it was assumed that the discharge is a constant 40 m<sup>3</sup>/s under all condition except during flood conditions. As noted previously, during flood operations the spillway gates are opened such that 909 m<sup>3</sup>/s is discharged at an elevation of 311.8 m. The SSARR model provide a storage estimate at elevation 313.94 m (essentially the crest elevation of the dam), but the other available information provided no indication of discharge capability at this water elevation in the reservoir. Using a broad-crested weir equation and the parameters noted previously for the main dam spillway, the discharge capacity was estimated at approximately 1,225 m<sup>3</sup>/s at water level 313.94 m.

**Table 6-10: Hinds Lake Stage-Storage-Discharge Relationship**

Elevation (m)	Storage (m <sup>3</sup> )	Discharge (m <sup>3</sup> /s)
306.00	0	40
307.02	50,600,000	40
308.02	102,210,000	40
309.02	153,840,000	40
310.02	205,450,000	40
310.91	251,920,000	40
311.80	297,900,396	909
313.94	408,460,000	1,225

A review of daily flows at station 02YK006 (Hinds Brook at Hinds Brook Power House) (ref. Table 6-11) confirms that annual daily maximum flows, for the period of record, are generally in the 40 m<sup>3</sup>/s range. Only three exceptions to this are noted over the thirty (30) year period of record, namely 1982, 1994 and 1999.

The 1982 event is most notable given the documented flow, however no comparative indication of a flood event is documented further downstream in the river system, based on online searches and review of the flood inventory. Deer Lake daily weather data for April/May 1982 does indicate very warm temperatures and about 40 mm of rainfall in late April. This suggests the possibility of a significant snowmelt event along with rain on snow which is surmised to have prompted the high flows as recorded at station 02YK006.

A review of circumstances for the 1994 and 1999 events also concluded with no reference to any major flooding further downstream in the Humber River system. Notwithstanding, based on this review the assumption of constant discharge of 40 m<sup>3</sup>/s when not in flood conditions is considered reasonable.

The Hinds Lake starting water surface elevation was included in the hydrologic modelling as the full supply elevation of 310.9 m.

**Table 6-11: Annual Maximum Daily Discharge for Station 02YK006**

Year	Month-Day	Flow (m <sup>3</sup> /s)	Year	Month-Day	Flow (m <sup>3</sup> /s)
1981	05-13	46.5	1996	03-06	39.0
1982	05-02	234.0	1997	03-17	36.8
1983	02-24	39.0	1998	09-10	40.6
1984	05-30	40.3	1999	05-06	76.4
1985	05-23	40.5	2000	02-19	37.0
1986	02-16	36.8	2001	02-23	38.7
1987	12-28	38.9	2002	01-31	37.7
1988	04-08	38.5	2003	05-11	38.3
1989	02-18	38.8	2004	01-12	35.2
1990	01-09	42.1	2005	06-14	35.2
1991	02-04	39.2	2006	12-31	35.6
1992	05-26	38.2	2007	01-16	35.8
1993	06-03	39.0	2008	09-24	35.4
1994	07-26	71.1	2009	01-17	36.3
1995	06-09	38.5	2010	12-31	38.0

### Deer Lake

The background information available to support development of a stage-storage-discharge relationship for Deer Lake is as follows:

- the Humber River SSARR hydrologic model (ref. Table 6-12);
- 1955 Deer Lake bathymetry mapping (ref. Figure 2-6); and the
- 1984 Steady Brook Hydrotechnical Study – Deer Lake Rating Curves (ref. Figure 2-5);
- River bathymetry survey for reaches of the Humber River completed for this study (ref. Section 3).

The Deer Lake stage-discharge rating curve from the 1984 Steady Brook Hydrotechnical Study (ref. Figure 2-5) was investigated using recorded daily flow from station 02YL003 (Humber River at Humber Village Bridge [discharge]) and recorded water level data from station 02YL007 (Deer Lake near Generating Station [stage]) over the period 1987 to 2018. As illustrated in Figure 6-7, a general core trend can be seen with some outlier data both higher and lower than the core trend.

The outlier data was further investigated to determine if any specific phenomenon could be associated with the deviations from the observed core trend. The graphical data was reviewed for the period June through September (ref. Figures 6-8 and 6-9), as it was expected that ice influences in these months would be limited, for low outlier data as identified by flow value. These flow values were then identified in the database. It is noted that outlier data is limited and is identified, seemingly, randomly in the data series. However, one cluster of outlier data was identified to occur in 1994 with multiple occurrences in each of the interrogated months. No clear explanation could be determined.

**Table 6-12: Deer Lake Stage-Storage-Discharge Relationship as defined in the SSARR Model**

Elevation (m)	Discharge (m <sup>3</sup> /s)	Storage (m <sup>3</sup> )
4.385	74	9,000,000
4.685	110	31,510,000
4.985	159	54,020,000
5.285	212	81,290,000
5.585	286	99,040,000
5.885	354	121,930,000
6.185	430	144,050,000
6.485	513	162,570,000
6.785	600	189,070,000
7.085	691	203,210,000
7.385	736	234,080,000
7.685	906	243,860,000
8.085	1,014	279,110,000
8.385	1,133	284,500,000
8.685	1,246	324,120,000

Notes:  
1. It is assumed that the SSARR elevation data references CGVD-1928

A similar review of high outlier data was also completed (ref. Figures 6-8 and 6-9). This review resulted in a similar conclusion, although the high outlier data was found to occur most frequently in 1993 and 1997. Again, no clear explanation could be determined.

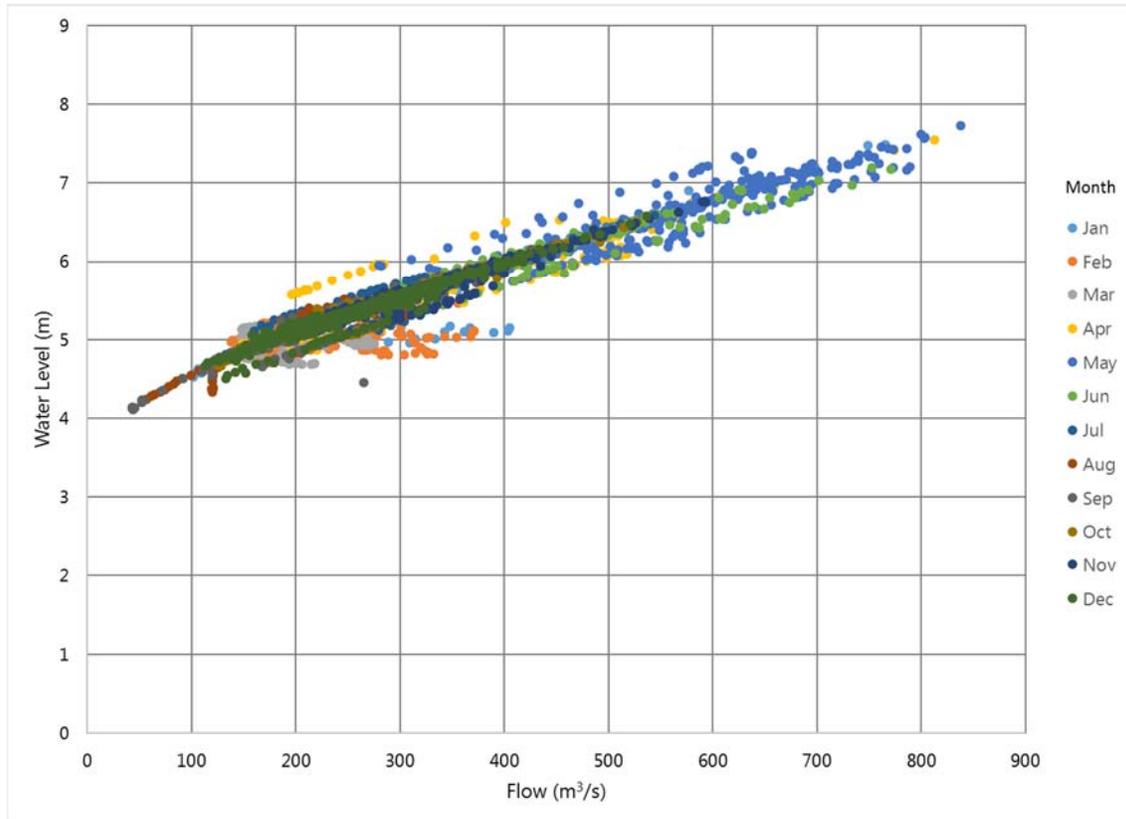
Based on this review two representations of the Deer Lake stage-discharge relationship were estimated based on the recorded data. The first using all of the station data and the second with the years 1993, 1994 and 1997 removed. The resultant trend lines are defined as follows:

All Data	Stage = 0.0042 * Flow + 4.2540	having an	$R^2 = 0.9586$	<i>Equation 6-1</i>
Years 1993, 1994 and 1997 removed	Stage = 0.0041 * Flow + 4.2625	having an	$R^2 = 0.8771$	<i>Equation 6-2</i>

These relationships were then used as a check of water levels documented in Table 6-12. This check identified deviations of computed values from those documented in Table 6-12 of +0.12 m and -0.06 for equations 6-1 and 6-2, respectively. Similarly, maximum deviations were computed as 0.80 m and -0.12 m, respectively.

It should also be considered that the 1987 to 2018 recorded streamflow data does not exceed 7.72 m and 838.0 m<sup>3</sup>/s. As such, it can be assumed that values in excess of these thresholds from Table 6-12 were estimated. If values above these thresholds are removed from consideration, deviations, as noted above, are reduced to -0.03 m and -0.04 m, for equations 6-1 and 6-2, respectively.

This cross-comparison of information supports a conclusion that the stage-discharge relationship as documented in Table 6-12 is reasonable.



**Figure 6-7: Deer Lake Stage-Discharge Curve based on data from Stations 02YL003 (Flow) and 02YL007 (Stage) over the period 1987 to 2018**

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Figure 6-8: Deer Lake Stage-Discharge Curve based on data from Stations 02YL003 (Flow) and 02YL007 (Stage) for the months of June and July 1987 to 2018

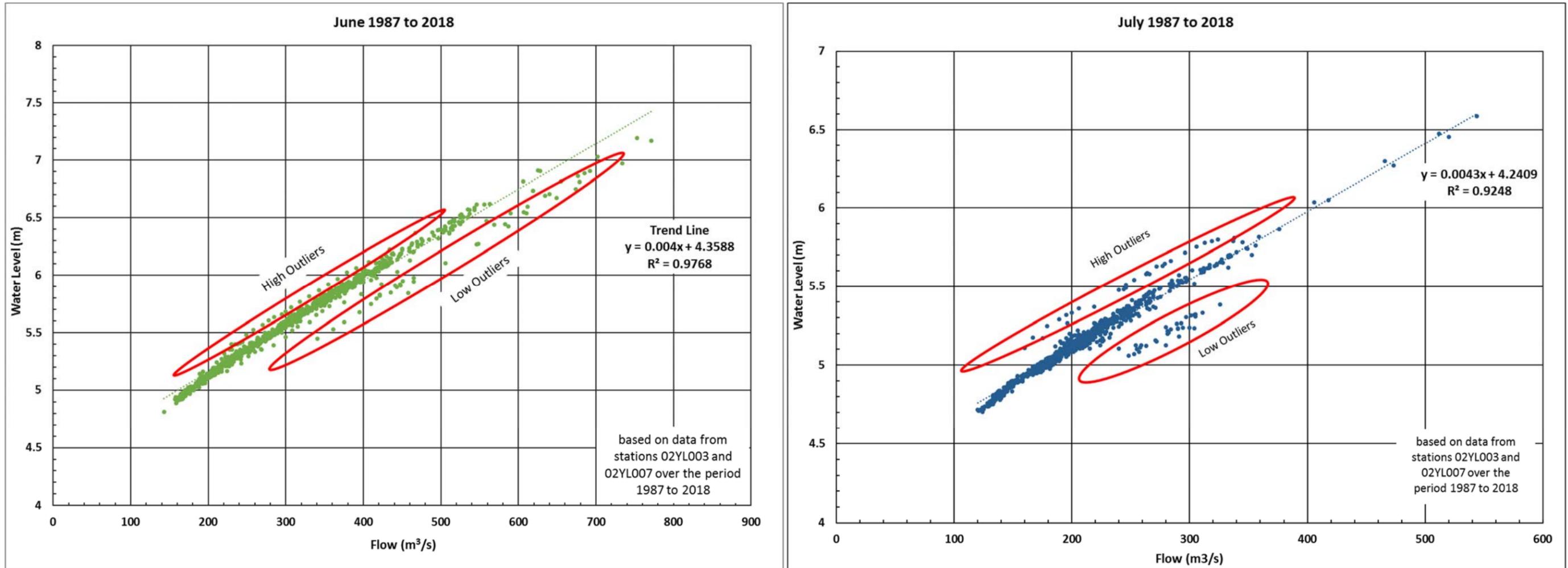
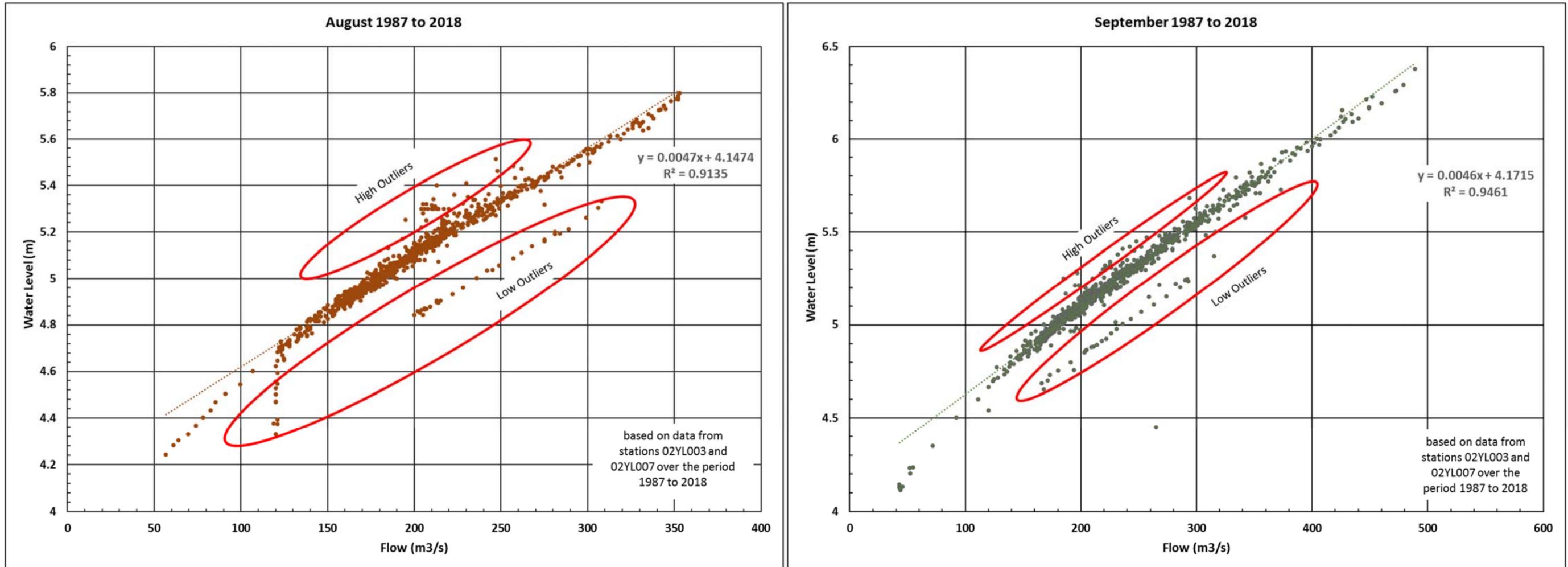


Figure 6-9: Deer Lake Stage-Discharge Curve based on data from Stations 02YL003 (Flow) and 02YL007 (Stage) for the months of August and September 1987 to 2018

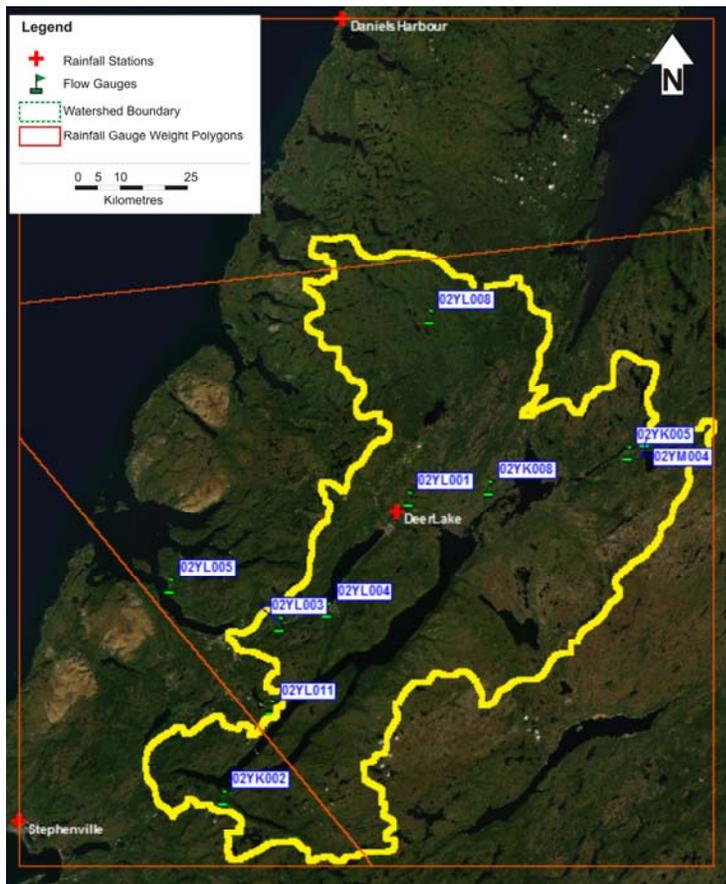


### 6.3.1.4 Rainfall Inputs

For this study, the analyses were completed using the current climate IDF and projected climate change IDF for the 2080 period.

Environment and Climate Change Canada publishes Intensity Duration Frequency (IDF) relationships which are estimates of rainfall return period amounts in the form of frequencies between 2-years and 1 in 100-years and for durations of 5 minutes to 24 hours. Three rainfall stations (ref Figure 6-10) were selected for use for this study, namely Daniels Harbour (ID 8401405); Deer Lake (ID 8401501); and Stephenville (ID 8403801). The area of influence of these gauges has been divided using a Thiessen (Gage Weight) polygon approach. As can be seen from Figure 6-10, most of the watershed, for modelling purposes is associated with the Deer Lake station.

As required by the Terms of Reference for this study, the current climate condition was defined by review of the latest intensity duration frequency (IDF) curve from Environment and Climate Change Canada and the 2015 report “Intensity-Duration-Frequency Curve Update for Newfoundland and Labrador” (CRA, 2015). Further, a review of the published IDF, from the noted sources, was completed to ensure the information was no more than 5 years old from the start of this project.



**Figure 6-10: Rainfall Stations and Gage Weight Polygons**

At the outset of this study, the most up to date published IDF data available from Environment and Climate Change Canada was version 2.3, dated December 21, 2014. The 2014 published information based the IDF information for Daniels Harbour, Deer Lake and Stephenville on recorded precipitation data to 1995, 2002, and 2012, respectively. The next release of IDF data from Environment was version 3.00 dated February 27, 2019. This published information indicated no change to the previously published IDF data (i.e. v2.3) for Daniels Harbour and Deer Lake. However, the IDF information for Stephenville had been updated to include recorded precipitation data to 2017.

The current climate IDF information, documented in the 2015 Conestoga-Rovers & Associates (CRA) assessment of IDF curves for Newfoundland and Labrador (CRA, 2015), added to the v2.3 Environment Canada IDF data to include recorded precipitation data to 1996-2014, and 2003-2014 for Daniels Harbour and Deer Lake, respectively. The CRA assessment for Stephenville used Environment Canada version 2.3 IDF data.

Therefore, the current conditions IDF data for Daniels Harbour and Deer Lake was based on the IDF information presented in (CRA, 2015); and the IDF data for Stephenville was based on the Environment Canada v3 published IDF data. Therefore, the requirement to independently update IDF data for this study was not required.

Climate change influenced IDF relationships for the median IDF and the 2080 90<sup>th</sup> percentile IDF were developed. The IDF data were obtained from the report *"Projected Impacts of Climate Change for the Province of Newfoundland & Labrador: 2018 Update"* (Finnis and Daraio, 2018). Tables 6-13, 6-14 and 6-15 summarize 1 in 20-year and 1 in 100-year AEP IDF curves for the noted scenarios and stations, respectively. The 1 in 20-year AEP precipitation amounts were estimated by interpolation (using the logarithmic function trending option in Microsoft Excel<sup>TM</sup>).

**Table 6-13: Current Climate and Climate Change IDF data – Daniels Harbour**

IDF Scenario	Event Duration								
	5 min	10 min	15 min	30 min	1 hour	2 hour	6 hour	12 hour	24 hour
<b>1 in 20-year AEP Total Rainfall (mm)</b>									
<b>Current Climate</b>									
CRA 2015	8.8	11.6	13.3	17.5	24.7	31.1	51.0	69.0	97.7
<b>Projected IDF</b>									
2050 Median	10.9	14.1	16.0	21.1	29.5	36.2	59.5	80.6	115.9
2080 Median	12.5	16.2	18.3	23.9	33.4	40.4	66.4	90.1	130.8
2080 90 <sup>th</sup> Percentile	16.4	20.8	23.2	30.5	42.2	49.8	81.8	111.4	164.1
<b>1 in 100-year AEP Total Rainfall (mm)</b>									
<b>Current Climate</b>									
CRA 2015	12.0	15.5	17.5	23.0	32.1	39.1	64.1	87.1	126
<b>Projected IDF</b>									
2050 Median	14.7	18.8	21.1	27.7	38.4	45.7	75.2	102.2	149.8
2080 Median	17.3	21.9	24.4	32.0	44.3	52.1	85.5	116.5	172.1
2080 90 <sup>th</sup> Percentile	23.4	29.2	32.3	42.5	58.4	67.1	110.3	150.5	225.4

**Table 6-14: Current Climate and Climate Change IDF data – Deer Lake**

IDF Scenario	Event Duration								
	5 min	10 min	15 min	30 min	1 hour	2 hour	6 hour	12 hour	24 hour
<b>1 in 20-year AEP Total Rainfall (mm)</b>									
<b>Current Climate</b>									
CRA 2015	8.1	11.1	12.9	16.3	21.1	31.5	44.3	56.3	70.3
<b>Projected IDF</b>									
2050 Median	10.3	14.6	17.0	21.7	26.5	39.9	58.4	73.3	89.5
2080 Median	12.1	17.3	19.9	25.1	30.5	46.0	66.9	83.7	102.5
2080 90 <sup>th</sup> Percentile	13.5	19.2	22.2	27.8	33.4	50.6	73.4	91.5	112.3
<b>1 in 100-year AEP Total Rainfall (mm)</b>									
<b>Current Climate</b>									
CRA 2015	10.8	14.7	16.7	20.5	26.2	39.7	54.3	68.5	86.8
<b>Projected IDF</b>									
2050 Median	13.6	19.3	22.3	27.9	33.5	50.8	73.7	91.8	112.6
2080 Median	16.1	22.9	26.3	32.6	38.7	59.1	85.3	105.9	130.2
2080 90 <sup>th</sup> Percentile	18.3	26.0	29.8	36.8	43.4	66.5	95.6	118.3	145.8

**Table 6-15: Current Climate and Climate Change IDF data – Stephenville**

IDF Scenario	Event Duration								
	5 min	10 min	15 min	30 min	1 hour	2 hour	6 hour	12 hour	24 hour
<b>1 in 20-year AEP Total Rainfall (mm)</b>									
<b>Current Climate</b>									
Environment Canada v3	8.4	12.6	15.4	22.1	29.4	39.0	65.3	79.1	102.2
<b>Projected IDF</b>									
2050 Median	9.3	14.4	17.6	25.5	33.5	42.4	71.8	88.1	116.1
2080 Median	11.5	17.8	21.7	31.6	41.0	51.2	86.9	106.5	141.6
2080 90 <sup>th</sup> Percentile	13.0	20.3	24.6	35.9	46.4	57.6	97.6	119.7	159.9
<b>1 in 100-year AEP Total Rainfall (mm)</b>									
<b>Current Climate</b>									
Environment Canada v3	10.9	16.4	19.9	28.7	37.7	49.5	82.8	99.7	130.3
<b>Projected IDF</b>									
2050 Median	12.0	18.7	22.7	33.0	42.9	53.4	90.5	110.9	147.7
2080 Median	15.1	23.6	28.5	41.6	53.5	65.8	111.8	136.9	183.7
2080 90 <sup>th</sup> Percentile	17.5	27.4	33.1	48.4	61.9	75.7	128.5	157.3	212.0

### 6.3.2 Rainfall Hyetograph Development

The 1 in 20-year and 1 in 100-year rainfall hyetographs were estimated by using the Alternating Block method. The alternating block design storm is an artificial hyetograph constructed from the IDF data. Precipitation depths for time intervals, or blocks, are calculated in such a way that the aggregate depth over any time duration at the center of the storm is equal to the depth from the IDF curve for that duration. In this way the design storm has intensity at its center equal to the critical rainfall from the IDF curve no matter what the duration. Hyetographs for the purposes of HEC-HMS climate change conditions modelling were also generated using the alternating block method using the 2080 90<sup>th</sup> percentile projected IDF data and applying the resultant mass rainfall curve to the data. Rainfall was input to the HEC-HMS model in the form of a hyetograph (rainfall amount over time).

### 6.3.3 Model Calibration and Validation

Model calibration and validation are required to ensure that generated peak flows from the HEC-HMS model are considered to be within an acceptable range of actual observed data. Unfortunately, it was not possible to conduct a conventional calibration process in this study due to insufficient, on a storm by storm basis, measured flow, precipitation data and dam operation data for the study area. Additional information, in this regard, is detailed in Section 6.3.5. It is also noteworthy that no operational or flow data was available to this study for Grand Lake Dam. Model calibration requires accurate measured flow data at points of interest in the watershed for comparison with corresponding computed flows from deterministic modelling.

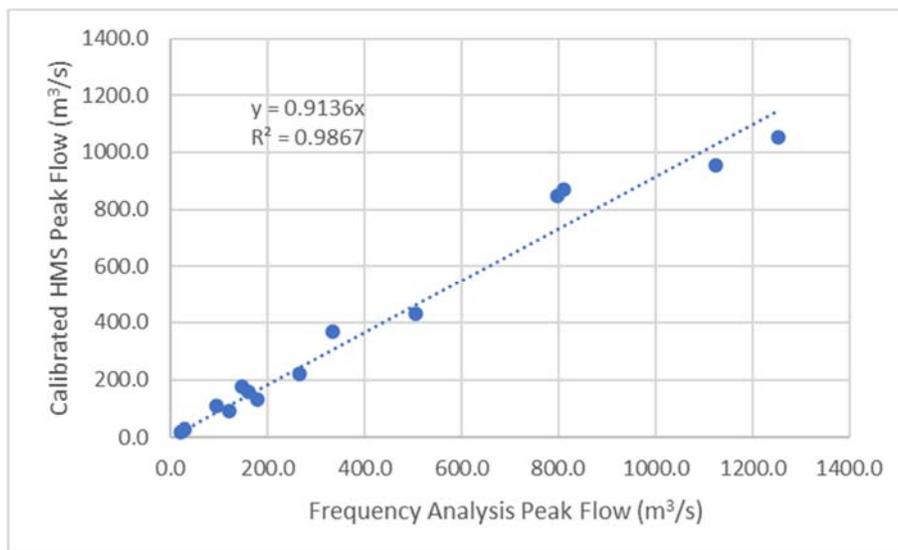
The existing development and current climate scenario HEC-HMS model was therefore calibrated by comparing the model simulated peak flows with the single station frequency analysis results for the 1 in 20-year and 1 in 100-year AEP events at key locations in the watershed. Select model parameters (i.e. CN, Initial Abstraction, and lag times) were adjusted during the calibration process. Table 6-16 and Figure 6-11 present the calibrated HEC-HMS peak flows and comparison with the frequency flows at selected flow gauge locations.

The calibration results indicate that the simulated peak flows are generally comparable to the frequency peak flows. The calibrated HEC-HMS model marginally underestimates the 1 in 20-year AEP peak flows and marginally overestimates the 1 in 100-year AEP peak flows. The differences for the 1 in 20-year AEP peak flow at Station 02YL004 and the 1 in 100-year AEP peak flows at Station 02YK005 and Station 02YK002 are somewhat larger. For Station 02YL004, the simulated 1 in 20-year AEP peak flow is close to the frequency analysis 95% upper confidence limit and the difference between the 1 in 100-year AEP peak flows is negligible. Station 02YK005 and Station 02YK002 are located far upstream of the Grand Lake Dam. As such, the results for Stations 02YK005 and 2YK002 are not considered significant for those areas of the watershed slated for new flood plain mapping.

Figure 6-11 compares the calibrated peak flows and frequency analysis peak flows for both the 1 in 20-year AEP and 1 in 100-year AEP floods at all stations. The graph illustrates that there is strong correlation between the frequency analysis peak flows and the simulated flows generated by the calibrated HEC-HMS model. Consequently, the calibrated HEC-HMS hydrologic model is considered representative for the existing land use and current climate scenario.

**Table 6-16: Humber River HEC-HMS Model Calibration**

Station ID	Frequency Analysis based Peak Flow (m <sup>3</sup> /s)			HEC-HMS Computed Peak Flows (m <sup>3</sup> /s)	% difference (Frequency Analysis based Peak Flow vs. HEC- HMS Computed Flow)
	95% Lower Confidence Limit	Peak Flow	95% Upper Confidence Limit		
<b>1 in 20-year AEP</b>					
02YL004	75.9	91.4	118.7	119.8	+31%
02YL003	796.8	845.8	917.7	798.1	-6%
02YL001	810.5	868.6	947.6	811.5	-7%
02YL008	329.8	366.6	426.4	334.6	-9%
02YK008	16.7	20.0	25.7	19.8	-1%
02YK005	97.5	109.3	127.0	93.9	-14%
02YK002	159.5	174.7	196.6	147.1	-16%
<b>1 in 100-year AEP</b>					
02YL004	122.6	160.0	236.5	160.9	+1%
02YL003	884.4	953.7	1,061.8	1,124.8	+18%
02YL001	963.2	1,052.9	1,181.6	1,252.7	+19%
02YL008	379.8	432.3	524.1	506.2	+17%
02YK008	22.6	28.5	39.8	29.1	+2%
02YK005	115.0	131.7	158.4	179.3	+36%
02YK002	194.8	218.9	255.8	265.3	+21%



**Figure 6-11: Comparison between Frequency Analysis Peak Flows and Calibrated HEC-HMS Peak Flows**

The results confirm reasonable alignment between the HEC-HMS computed peak flows and the peak flows computed using single station frequency analysis. The calibrated flows are within the 95% confidence levels, with the 1 in 20-year AEP flows generally lower and the 1 in 100-year AEP flows generally higher compared with the frequency analysis flows. Subcatchment parameters for the existing development and current climate scenario, as well as a summary table for calibrated model parameters are provided in Appendix M.

### 6.3.4 Comparison of HEC-HMS Results with Previous Studies

A comparison of the HEC-HMS model peak flow computations with peak flows used for previous hydrotechnical studies in the Humber River study area was completed (ref. Table 6-17). The previous studies are:

- Hydrotechnical Study of the Deer Lake Area, Cumming Cockburn Limited, 1987
- Hydrotechnical Study of the Steady Brook Area, Nolan Davis & Associates Limited and Cumming Cockburn & Associates Limited, 1984

It is noted from the information presented in Table 6-17 that the 100-year AEP peak flow estimates are very comparable. While the comparison between the 20-year AEP flows does highlight some differences, these are considered reasonable given the different methodologies applied within the hydrologic models as well as the available background data, to the noted studies, as outlined briefly below.

**Table 6-17: Comparison of Computed Flows - Previous Studies with 2020 Results**

Location	1 in 20-year AEP		1 in 100-year AEP	
	Previous Studies (SSARR)	2020 (HEC-HMS)	Previous Studies (SSARR)	2020 (HEC-HMS)
<b>Comparison with the 1987 Deer Lake Study</b>				
Inlet to Deer Lake	1,160.0	803.9	1,370.0	1,268.5
<b>Comparison with the 1984 Steady Brook Study</b>				
Outlet of Deer Lake	948.0	818.5	1,180.0	1,325.8
Humber River D/S of confluence with Steady Brook	957.0	780.6	1,180.0	1,115.0
Steady Brook at confluence with Humber River	105.0	86.9	134.0	127.3

#### Hydrotechnical Study of the Steady Brook Area (1984)

At the time of the 1984 Steady Brook study, the available streamflow record for the Humber River at Humber Village was considered too short for single station frequency assessment. As well, there was no recorded streamflow data along Steady Brook. As such, the estimation of streamflow was based on deterministic models and regional techniques. Flow estimation was based on a deterministic model for the Humber River and regional techniques for Steady Brook.

The 1984 study utilized the SSARR model for modelling of the Humber River. The model was executed in a continuous mode to establish a time series of computed flows, based on recorded rainfall that could

then be used to as input to single station frequency analysis to estimate AEP flows. It is noted in the reporting that the meteorological data available to the 1984 study was “marginally sufficient”.

The model of the watershed was based on eleven (11) subwatershed of which five (5) were gauged. The five (5) gauged subwatersheds are identified from Figures B.2 through B.5 in Appendix B of the 1984 report as:

- Lewaseechjeech Brook
- Hinds Brook
- Sheffield Brook
- Indian Brook
- Upper Humber River

It is noted that the hydrometric gauge downstream from Deer Lake only had, at the time of the study, 2 years of recorded streamflow data. Calibration was based on the gauged subwatersheds. From the calibration comparison plots available in the reporting, it can be inferred that calibration and validation was a significant effort with the best comparisons, at times, being 100's of m<sup>3</sup>/s higher or lower than observed.

Significant instabilities are also documented with regard to the simulation of Grand Lake. It was noted that in some cases computed flows were highly erratic when compared with published records and in some cases negative flows generated by the deterministic model.

Regional Flood Frequency Analysis was applied to estimate flows for Steady Brook. The analysis was based on available regional equations documented in the Regional Flood Frequency Analysis for the island of Newfoundland (Panu et al, 1984). It is noted that the drainage area to the Humber River at the outlet of Deer Lake where flow estimates were determined exceeded the upper limit of drainage area size recommended by for the application of the Regional equations.

A HYMO model was also developed as a secondary flow estimation technique based on a one subcatchment.

### **Hydrotechnical Study of the Deer Lake Area (1987)**

Hydrologic modelling for this study was based on the SSARR model developed for Steady Brook (1984) study. The comments provided regarding the 1984 study are also applicable to this 1987 study with respect to modelling of the Humber River watershed.

### **Current Study**

The current study uses HEC-HMS as the hydrologic simulation program for flow estimation. The model developed is based, overall, on 200+ subwatersheds. The Steady Brook watershed itself based on 12 subwatersheds. Similar techniques for calibration and validation were employed, although the current study has available to it much longer streamflow records for more locations throughout the watershed. Additional comparison of the Steady Brook flow modelling results is provided in Section 9.5.2.4.

### 6.3.5 Comparison of Results with Measured Flows at Gauges

A direct comparison of the HEC-HMS computed peak flows and recorded maximum instantaneous streamflow events for streamflow stations 02YL001 and 02YL003 yielded no meaningful results. A summary of high streamflow events at these stations is summarized in Table 6-18. The noted events are multi-day events, which does not align with the 24-hour rainfall event duration adopted for this study. As well, most of the events are associated with cold weather months which also does not align with the single IDF based rainfall event approach which is generally associated with warm weather months.

**Table 6-18: Maximum Instantaneous Flow and Rainfall Comparison**

Event		Precipitation (mm)	Maximum Instantaneous Flow (m <sup>3</sup> /s)
Start Date	End Date		
<b>Station 02YL001</b>			
5/8/2016 1:00	5/14/2016 20:00	18.53	431.9
6/8/2016 17:00	6/13/2016 15:00	46.98	298.2
6/13/2016 6:00	6/20/2016 0:00	39.90	257.2
6/28/2016 0:00	7/17/2016 0:00	77.46	93.3
9/8/2016 0:00	9/15/2016 0:00	73.27	265.8
10/22/2016 12:00	10/29/2016 19:00	51.65	394.4
11/20/2016 0:00	11/27/2016 0:00	32.82	201.6
4/6/2017 12:00	4/23/2017 12:00	37.92	160.1
9/27/2017 12:00	10/5/2017 13:00	45.32	260.6
11/6/2017 12:00	11/15/2017 0:00	40.91	289.9
11/26/2017 6:00	12/6/2017 6:00	20.56	158.3
1/12/2018 18:00	1/23/2018 6:00	89.90	1196.4
4/25/2018 6:00	5/9/2018 13:00	68.07	610.2
5/15/2018 18:00	5/19/2018 23:00	15.19	403.3
6/18/2018 12:00	6/30/2018 0:00	53.95	264.
7/28/2018 12:00	8/6/2018 12:00	20.65	66.8
9/6/2018 6:00	9/11/2018 18:00	22.83	127.5
9/28/2018 5:00	10/5/2018 16:00	34.42	228.5
10/16/2018 1:00	10/21/2018 4:00	43.30	266.0
10/21/2018 4:00	10/24/2018 12:00	42.44	454.3
10/28/2018 0:00	11/3/2018 12:00	63.04	394.2
12/22/2018 0:00	1/3/2019 12:00	57.88	98.7
1/21/2019 12:00	2/8/2019 13:00	63.11	187.6
6/21/2019 6:00	6/29/2019 0:00	49.59	393.9
9/24/2019 0:00	10/6/2019 0:00	58.70	137.2
10/31/2019 12:00	11/5/2019 18:00	75.25	666.2
11/6/2019 6:00	11/11/2019 6:00	33.06	208.7
11/12/2019 6:00	11/22/2019 12:00	73.36	299.6
<b>Station 02YL003</b>			
6/6/2016 0:00	6/25/2016 0:00	72.40	340.1
9/8/2016 0:00	9/17/2016 0:00	72.40	340.1

Event		Precipitation (mm)	Maximum Instantaneous Flow (m <sup>3</sup> /s)
Start Date	End Date		
<b>Station 02YL001</b>			
10/9/2016 0:00	10/19/2016 0:00	76.71	353.8
10/19/2016 0:00	10/31/2016 0:00	81.12	419.3
11/18/2016 0:00	12/8/2016 0:00	62.60	344.6
9/26/2017 0:00	10/7/2017 0:00	57.13	342.1
10/13/2017 0:00	11/2/2017 0:00	43.41	349.5
11/5/2017 0:00	11/19/2017 0:00	41.34	311.4
1/11/2018 0:00	1/27/2018 0:00	111.67	773.0
10/12/2018 0:00	11/27/2018 0:00	323.02	532.9
12/10/2019 0:00	12/25/2019 0:00	99.86	458.0

### 6.3.6 Comparison of Results with Regional Flood Frequency Equations

The most current regional flood frequency equations for Newfoundland and Labrador were developed in 2014 (AMEC, 2014). The 2014 RFFA Update, like four (4) previous studies (1971, 1984, 1990, 1999), has derived a set of equations for estimating return period flood flows in ungauged watersheds in the Province. Table 6-19 outlines the chronology of the RFFA updates in Newfoundland and Labrador.

**Table 6-19: Chronology of Regional Flood Frequency Analysis Updates for Newfoundland and Labrador**

Year	Authors	Regions included in the Analysis	Regional Equations based on	
			Gauged Watersheds	Regions
2014	AMEC (now Wood)	Newfoundland and Labrador	78 in Newfoundland 12 in Labrador	4 in Newfoundland 1 in Labrador
1999	Rollings	Newfoundland	50	4
1990	Beersing	Newfoundland	39	4
1984	Panu et al	Newfoundland	21	2
1971	Poulin	Newfoundland	17	1

It has been noted previously (ref. Section 6.2.4) that application of the RFFA was not considered necessary for quantification of flows along the main Humber River. Notwithstanding, the one-parameter RFFA equations were used to develop estimates of return period flows at gauge station locations for completeness. It is noted that based on Figure 3.1 from (AMEC, 2014), all of the Humber River watershed gauge stations lie within the North-West Region. The 2014 RFFA one-parameter equations for the north-west region are presented in Table 6-20.

**Table 6-20: North-West Region of Newfoundland - One Parameter Equations**

Return Period (years)	North-West Region One Parameter Equations
20	$1.519 \times DA^{0.795}$
100	$2.216 \times DA^{0.761}$

As documented in the RFFA guide, for the North-West Region, the maximum and minimum drainage areas for which the equations are considered valid are 2,110 km<sup>2</sup> and 13 km<sup>2</sup>, respectively. It is not recommended that the regression equations be used if the parameters are outside the recommended range as the extrapolation of the results beyond the extremes used in regression equation development reduces the accuracy of the resultant estimates significantly. The resultant RFFA estimates of flows at gauge locations in the study area are summarized in Table 6-21; please note that the drainage area associated with station 02YL003 is much larger than the maximum recommended for the RFFA equations and the drainage area associated with station 02YL001 is equal to the maximum recommended drainage for application of the RFFA equations. As such, these RFFA peak flow estimate associated with station 02YL003 is not considered valid; similarly, the peak flow estimate associated with station 02YL001 should be considered with caution.

As can be interpreted from the information presented in Table 6-21, the RFFA estimates only in some instances align with the single station frequency analysis results and the HEC-HMS computed peak flows.

**Table 6-21: Comparison of Computed Flows – Regional Flood Frequency Analysis**

Station ID	Drainage Area (km <sup>2</sup> )	Frequency Analysis based Peak Flow (m <sup>3</sup> /s)			HEC-HMS Computed Peak Flows (m <sup>3</sup> /s)	RFFA, 2014 (based on the 1-Parameter Equation)
		95% Lower Confidence Limit	Peak Flow	95% Upper Confidence Limit		
<b>20 Year AEP</b>						
02YL004	58.5	75.9	91.4	118.7	119.8	38.6
02YL003	7860 <sup>2</sup>	796.8	845.8	917.7	798.1	n/a
02YL001	2110 <sup>3</sup>	810.5	868.6	947.6	811.5	667.4
02YL008	471	329.8	366.6	426.4	334.6	202.6
02YK008	20.4	16.7	20.0	25.7	19.8	16.7
02YK005	391	97.5	109.3	127.0	93.9	174.7
02YK002	470	159.5	174.7	196.6	147.1	202.2
<b>100 Year AEP</b>						
02YL004	58.5	122.6	160.0	236.5	160.9	49.0
02YL003	7860	884.4	953.7	1,061.8	1,124.8	n/a
02YL001	2110	963.2	1,052.9	1,181.6	1,252.7	750.5
02YL008	471	379.8	432.3	524.1	506.2	239.7
02YK008	20.4	22.6	28.5	39.8	29.1	22.0
02YK005	391	115.0	131.7	158.4	179.3	208.1
02YK002	470	194.8	218.9	255.8	265.3	239.4
Notes:						
1. Information from Table 6-16 has been replicated in Table 6-21 for comparison purposes.						
2. The drainage area associated with station 02YL003 is much larger than the maximum recommended for application of the RFFA equations, therefore use of the associated RFFA peak flow estimate is not considered valid.						
3. The drainage area associated with station 02YL001 is equal to the maximum recommended drainage for application of the RFFA equations, therefore use of the associated RFFA peak flow estimate should be considered with caution.						

### 6.3.7 Future Development Scenario HEC-HMS Model Development

The calibrated existing development and current climate scenario HEC-HMS model formed the basis for development of the future development or fully developed HEC-HMS model. To reflect future land cover conditions, the CN and Initial Abstraction values defined in the calibrated model were updated based on future municipal development/land use plans for the communities of Deer Lake, Pasadena, Reidville and Steady Brook as available from the Newfoundland and Labrador Department of Environment and Climate Change website<sup>16</sup>.

Subcatchment parameters for the future development scenario HEC-HMS model are provided in Appendix M.

Table 6-19 provides a summary of key model parameters across the base, calibrated and future development models.

**Table 6-22: Summary of Key HEC-HMS Model Parameters across the Existing Development Scenario Base and Calibrated and Future Development Scenario Models**

Statistic	Curve Number (CN)	Initial Abstraction (mm)	Manning's Roughness Coefficient (routing)	Basin Lag (min)
<b>Base Parameters</b>				
<b>Range</b>	52.04 to 90.02	5.63 to 46.82	0.035	5.72 to 304.06
<b>Mean</b>	77.22	15.31	0.035	130.81
<b>Calibrated Parameters</b>				
<b>Range</b>	52.04 to 90.29	5.46 to 46.82	0.050 to 0.080	5.72 to 304.06
<b>Mean</b>	74.73	17.91	0.052	109.22
<b>Future Development Parameters</b>				
<b>Range</b>	52.04 to 99.00	0.51 to 46.82	0.050 to 0.080	5.72 to 304.06
<b>Mean</b>	78.83	14.52	0.052	109.22

### 6.3.8 HEC-HMS Modelled Scenarios

The newly developed HEC-HMS models were used to estimate 1 in 20-year and 1 in 100-year AEP peak flows in study area locations for the following scenarios:

- current climate and current development conditions;
- current climate and future development conditions;
- climate change and current development conditions; and
- climate change and future development conditions.

The future/climate change influenced climate was assessed for three possible futures, namely: 2050 mean, 2080 mean, and 2080 90<sup>th</sup> percentile.

<sup>16</sup> Source website <https://www.gov.nl.ca/eccm/registry/reglist/>

The HEC-HMS computed peak flows were extracted for 114 locations along main Humber River and tributary watercourses as the input for the hydraulic analyses.

## 6.4 Conclusions and Recommendations

The 1 in 20-year and 1 in 100-year AEP flood flows were estimated for the subject watershed, namely: Humber River, using both statistical and deterministic methodologies. Comparative assessment of the flow estimates over the range of methodologies concluded that the deterministic model results provided a reasonable estimate of streamflow for these watersheds. The streamflow estimates generated through the deterministic analysis were carried forward for use in the hydraulic model.

The development of a deterministic watershed simulation model for the Humber River was based on best available data, engineering judgment and parameterization founded upon field collected watershed data such as LiDAR and satellite and orthophoto imagery. The peak flows computed using the HEC-HMS model compared very well with independently determined peak flows at the Environment and Climate Change Canada gauge locations in the watershed and using streamflow estimates based on application of the RFFA equations. It is, therefore, recommended that the streamflow estimates generated through the deterministic analysis be carried forward to the hydraulic analysis for computation of flood levels across the study areas.

It is recommended that local municipalities in the study area engage in a field-based program to measure water levels at designated structures during flood events. This will provide for the development of a database of information which could support both hydrologic and hydraulic modelling in the future.

It is also recommended that the program focused on unregulated streamflow data collection continue for the Humber River and its associated tributaries. Additional recording stations at strategic locations (e.g., outflow from each of the unregulated tributary areas) would provide a foundation of data that would enhance the hydrologic model calibration/validation process.

It is recommended that WRMD engage in a program to collect and develop stage-storage-discharge curves and operational data including rules curves, gates settings and reservoir water levels for all dams in the Province. Significant resources were utilized with the current project to first determine the ownership of the data (i.e. the contact person within the dam owner organization) and also to deal with delays that resulted from the time that was found to be necessary to obtain the information, once the most appropriate contact was established. If this information was already available through WRMD at the outset of the project, the development of the hydrologic model would have been more efficient.

Finally, it is recommended that that HEC-GeoHMS and HEC-HMS be used in future watershed and flood studies as these tools both simplify the development of deterministic models and provide for the generation of a significant warehouse of information that can be used for other purposes beyond hydrologic assessment.

## 7.0 Hydraulic Investigations and Modelling

Synopsis: Hydraulic investigations and modelling focus on converting estimated flows from hydrologic modelling to represent water levels along a watercourse. Modelling inputs include river cross-sections, hydraulic structure (including culverts, bridges, weirs, dams, etc.) information, hydraulic coefficients, channel resistance coefficients and boundary conditions. The terrain model data for this project was developed using the LiDAR database also developed for this project. Hydraulic modelling for the Humber River study area was developed using the River Analysis System (HEC-RAS), an industry standard program developed by the US Army Corps of Engineers Hydrologic Engineering Center. The outcomes of the hydraulic investigations and modelling component of this study were used to delineate the extent of the flood plain for a number of land use and AEP flood scenarios. The collection and processing of data, computational procedures and analysis of computed profiles is compliant with Canadian federal and Province of Newfoundland and Labrador and industry criteria and guidelines.

The hydraulic modelling outcomes of this study have also supported an ice jam assessment for the community of Steady Brook and on the upper Humber River at the Town of Deer Lake. These communities have experienced flooding resulting from ice jams. This assessment was primarily interested in understanding the meteorological and hydraulic circumstances that caused ice jams, specifically for the event in Deer Lake in January of 2018. The RIVICE program was used to develop a river-ice hydraulic model that clarified the connection between ice jams and water level.

### 7.1 Overview

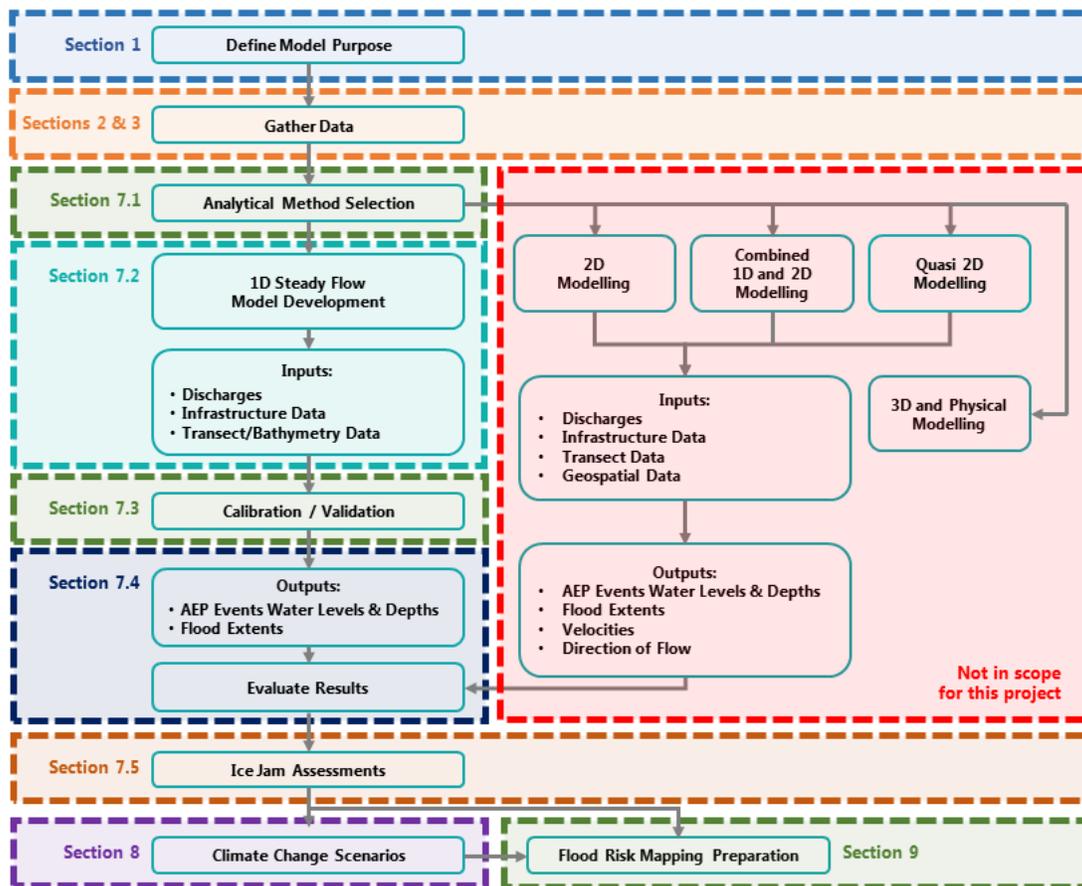
The collection and processing of data, computational procedures and analysis of computed profiles is compliant with criteria and guidelines published by the Hydrologic Engineering Center in the User's Manual and Training Documents (ref. USACE, 2016; 2018; 2019), the Hydrologic and Hydraulic Procedures for Flood Plain Delineation (Environment Canada, 1976) as well as the new Federal Flood Mapping Guidelines Series<sup>17</sup>, the Terms of Reference for this study which includes the Technical Document for Flood Risk Mapping Studies (provided as Appendix B in the RFP).

The objective of the hydraulic analysis was estimation of water surface elevations resulting from the 1 in 20-year and 1 in 100-year AEP flow estimates. The computed water surface elevations are used in conjunction with the LiDAR database and other relevant mapping to visualize the limits of the flooding on flood risk maps. To determine the water surface profile for a given flood condition, a backwater analysis is generally necessary. The US Army Corps of Engineers (USACE) HEC-RAS one-dimensional backwater analysis program was selected for this study.

The following sections describe the development and calibration of the HEC-RAS hydraulic model, as well as the details associated with the results of the hydraulic simulation of various flood events.

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<sup>17</sup> (Canada, n.d.). Available via URL <https://www.publicsafety.gc.ca/cnt/mrgnc-mngmnt/dsstr-prvntn-mtgrn/ndmp/fldpln-mppng-en.aspx>



**Figure 7-1: Hydraulic Investigations and Modelling Task Flow and Project Linkages**

(Please note that this flow chart was adapted from the federal flood mapping guidelines [Canada, n.d.]

## 7.2 Hydraulic Model Development

### 7.2.1 HEC-RAS

HEC-RAS (River Analysis System), the successor to HEC-2, is a hydraulic modelling computer program developed by the USACE to simulate water surface profiles for steady and gradually varied flow in open channel watercourses. The computational procedures used by HEC-2 and HEC-RAS to model steady state flow are generally similar and are based on solving the one-dimensional energy equation. The HEC-RAS computational software estimates water surface elevations and related output along a channel reach under sub-critical, supercritical or mixed flow regimes. The program is capable of modelling complicated networks with multiple reaches and tributaries. Flow through culverts, bridges, weirs and gated spillways can also be accommodated. Levees, blocked obstructions and ineffective flow areas can also be modelled, as can ice jam and debris flow conditions.

In simple terms, the model uses surface water flow rates to predict water surface elevations. These elevations can then be transferred to a DTM or topographic map to identify the limits of flood-prone areas.

HEC-RAS requires a terrain model with three-dimensional attributes (x, y, and z) for the area of interest. The terrain model commonly used in hydrologic modelling is a DTM. HEC-GeoRAS is a pre- and post-processing program developed co-operatively by the Hydrologic Engineering Center (HEC) of the USACE and Environmental Systems Research Institute Inc. (ESRI) to:

- extract geometric data from a DTM for input into HEC-RAS, and;
- use output from the hydraulic model and generate a water surface elevation DTM that can be superimposed on the terrain DTM to identify flood-prone areas.

The DTM for this project was developed from the LiDAR database developed for this project, as described previously.

The HEC-GeoRAS 10.2 extension, for ArcGIS 10.2 and HEC-RAS 5.0.7, was utilized to complete the one-dimensional hydraulic modeling component of this project. HEC-RAS 5.0.7 represents the most up-to-date version of the software at the time of hydraulic model development for this project

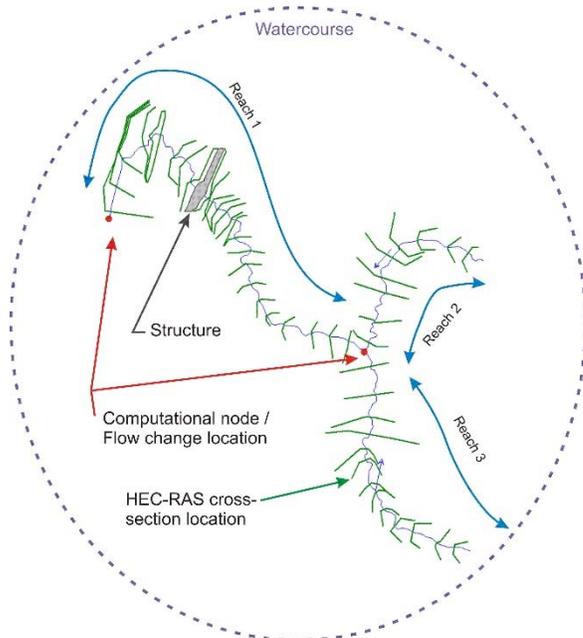
HEC-RAS is an approved model for flood plain calculations in Newfoundland and Labrador and was identified as the preferred modelling platform in the Terms of Reference for this project.

### 7.2.2 Cross Sections

Hydraulic sections were located in accordance with HEC-RAS modelling guidelines (USACE, 2016) and other noted reference and guidance documents. Cross section data was abstracted from the LiDAR base mapping developed for this project supplemented with field surveyed cross-section data, as outlined in Section 3.0 of this report.

The locations of the sections are illustrated on the flood risk maps (ref. Appendices E, F, G, and H). The first cross-section of the hydraulic model is located on Humber River Reach 001 at section 5.00. This location was selected to ensure appropriate establishment of the downstream model boundary condition (ref. Section 7.2.6) and represents the first river location where bathymetry data was available from the field survey effort (ref. Section 3).

The watercourses to be modelled were defined using the IMA&SN and are considered to include the reach of the Humber River from its mouth in the Bay of Islands to Upper Humber River just north of Reidville, plus perennial streams within the official of the municipalities of Steady Brook, Pasadena, Reidville and Deer Lake. Using this definition, the IMA&SN was defined to include eighteen (18) watercourses defined using ninety-six (96) separate reaches compiled into a single HEC-RAS dataset. The watercourses are named in the HEC-RAS dataset as noted in Table 7-1.



**Table 7-1: HEC-RAS Watercourse Naming and Associated Reaches**

HEC-RAS Watercourses	
Blue Gulch Brook (1 reach segment)	Reidville (3 reach segments)
Deer Lake (15 reach segments)	River_17 (1 reach segment)
Humber River (25 reach segments)	River_18 (1 reach segment)
Humber Village (5 reach segments)	River_19 (1 reach segment)
Junction Brook (4 reach segments)	Rocky Brook (1 reach segment)
Lanes Brook (2 reach segments)	South Brook (10 reach segments)
Matthews Brook (1 reach segment)	Steady Brook (4 reach segments)
Nichols Brook (9 reach segments)	Transmission Brook (1 reach segment)
Pasadena (8 reach segments)	Trout Brook (3 reach segments)

In the upper reaches of some tributaries of the Humber River, cross sections extended beyond the high-resolution DEM developed for this project. For these areas the high-resolution DEM was supplemented with the 10 m contour data as available from 1:50,000 scale National Topographic Series and 2 m contour data as available from the 1:2,500 scale community mapping, negating the need for supplementary field surveying.

As noted in Section 3.0, the below waterline survey data was integrated into the hydraulic models of the subject watercourses.

An overview of the completed hydraulic model for the study area is as follows:

- ▶ Overall study reach length of approximately 178 km (based on the sum of channel inter-section reach lengths)
- ▶ 1,481 hydraulic sections across 96 watercourse reaches
- ▶ Minimum and maximum channel elevations at the start and end of the watercourses are summarized in Table 7-2.
- ▶ Average inter-section reach length of about 128 m
- ▶ Maximum inter-section reach length of about 2483 m; longer intersections distances were defined for the section of the model through Deer Lake.
- ▶ 340 sections, or about 23%, have inter-section reach length greater than 100 m
- ▶ 1044 sections, or about 70%, have inter-section reach length less than 100 m
- ▶ 658 sections, or about 44%, have inter-section reach length less than 50 m
- ▶ 325 sections, or about 22%, have inter-section reach length less than 25 m

Please note also, that all HEC-RAS modelling was completed using a Subcritical flow regime.

**Table 7-2: Minimum/Maximum Channel Elevations by HEC-RAS Watercourse**

HEC-RAS Watercourse	Channel Elevation (m)		HEC-RAS Watercourse	Channel Elevation (m)	
	Minimum	Maximum		Minimum	Maximum
Blue Gulch Brook	6.31	50.05	<b><i>Pasadena area</i></b>		
Humber River	-10.19	14.90	Pasadena 001	8.11	91.37
Junction Brook	-2.37	50.00	Pasadena 002	9.45	50.15
Matthews Brook	4.52	38.74	Pasadena 003	6.00	104.20
Nichols Brook	6.14	55.70	Pasadena 004	6.21	27.38
River_17	6.51	42.67	Pasadena 005	6.21	37.83
River_18	9.49	79.40	Pasadena 006	6.14	84.47
River_19	8.27	71.32	<b><i>Lanes Brook area</i></b>		
Rocky Brook	6.16	38.00	Lanes Brook 001	6.46	55.73
South Brook	6.01	118.00	Lanes Brook 002	6.14	46.00
Transmission Brook	10.11	114.00	<b><i>Deer Lake area</i></b>		
Trout Brook	6.31	32.00	Deer Lake 001	6.03	8.60
<b><i>Steady Brook area</i></b>			Deer Lake 002	6.22	74.08
Steady Brook 001	2.39	12.48	Deer Lake 003	4.04	48.63
Steady Brook 002	5.66	11.28	Deer Lake 012	6.07	48.96
Steady Brook 003	3.56	34.97	Deer Lake 015	6.85	13.35
Steady Brook 004	4.85	21.70	<b><i>Reidville area</i></b>		
<b><i>Humber Village area</i></b>			Reidville 001	7.36	44.00
Humber Village 001	4.75	59.04	Reidville 002	6.88	33.26
Humber Village 002	3.86	21.18	Reidville 003	6.35	19.30
Humber Village 005	6.08	20.18			

Notes:

1. Please note that the maximum channel elevation may reference a connected reach.

## 7.2.3 Hydraulic Structures

### 7.2.3.1 Watercourse Crossings / Bridges

As-built information was gathered for six (6) bridges and field survey completed for nine (9) bridges to obtain dimensions and elevations for each watercourse crossing within the study area for hydraulic modelling for this project, as described in Section 3.4. Each of the surveyed structures was included in the hydraulic model.

In addition to the fifteen (15) bridges noted above, one (1) additional bridge and seventy-nine (79) culverts have also been included in the hydraulic model. These structures were visually inspected in the field and manually measured. Field measurements were integrated within elevation data abstracted from the DEM to estimate structure characteristics.

The rating curve, as generated by the hydraulic model, is included along with basic bridge survey data

(invert, obvert, etc.) as components of the watercourse crossing information which allows for interpolation of bridge opening capacities (see Appendix C). Although the 1 in 20-year and 1 in 100-year AEP flows may exceed this value, the structure may still not be overtopped. This result is because the structures can become surcharged to gain additional head to pass the flow and/or there is a change in the flow regime whereby a higher flow results in a lower water level. Indication of overtopping of any watercourse crossing or bridge included in the hydraulic model is summarized in Table 7-8.

### 7.2.3.2 Dams

No dams are located within the study area for hydraulic modelling for this project.

## 7.2.4 Lateral Structures

One (1) lateral structure was coded in the HEC-RAS model; located on Deer Lake Reach 2 between sections 1043.76 and 1292.89. This area, generally to the west of the TransCanada Highway and south-west of The Viking Trail/ Old Bonne Bay Road, lies on a side slope with the down slope transitioning to the main Humber River to the west. Preliminary modelling in this area identified that at high flow, flood waters would breach the banks of the watercourse. Given the general topography in the area, flood waters would spill down slope directly to the main Humber River and not follow the Deer Lake Reach 2 watercourse which generally flows to the north. The lateral structure embankment elevations were extracted from the LiDAR DEM.

Computed water surface elevations, from the preliminary modelling effort, through this spill zone are significantly higher if the lateral structure is not modelled (ref. Table 7-3). It was concluded from this assessment that a lateral weir would support a more realistic computation of flood water elevations for this area. As such, a lateral weir was included in the model in this reach. Notwithstanding, it is recommended that a two-dimensional (2D) modelling assessment be completed for this area to provide a detailed assessment of spill flow paths and, potential, related impacts to public and private assets.

## 7.2.5 Energy Loss Coefficients

Energy loss coefficients are used in the HEC-RAS program to calculate changes in the water surface elevation between sections. The coefficients include Manning roughness coefficients, expansion and contraction coefficients, and weir and pressure coefficients for road / rail crossings. These coefficients were estimated based on published information, field reconnaissance and engineering judgment.

### 7.2.5.1 Expansion and Contraction Coefficients

Expansion and contraction coefficients for normal channel cross-section were set at 0.1 and 0.3, respectively, and 0.5 and 0.8 for cross-sections at hydraulic structures, respectively. These ratios are used by HEC-RAS in the computation of energy losses due to flow contraction and expansion between adjacent cross sections. The noted values are consistent with those recommended in the HEC-RAS Technical Reference Manual.

**Table 7-3: Deer Lake Reach 2 – Comparison of Computed Water Levels with / without Lateral Weir  
 (comparison based on Existing Condition Land Use with Climate Change IDF scenario)**

HEC-RAS Section	1 in 100-year AEP Computed Water Surface Elevations (m)		Change (m)
	Without Lateral Structure	With Lateral Structure	
992.54	23.57	18.93	4.64
1043.76	23.97	19.14	4.83
1078.98	23.97	19.59	4.38
1114.21	23.97	19.71	4.26
1155.46	23.97	20.01	3.96
1196.7	23.97	20.27	3.70
1237.95	23.97	20.75	3.22
1279.19	23.97	20.87	3.10
1292.89	23.97	20.86	3.11
1313.44	23.97	20.88	3.09
1333.99	23.97	20.93	3.04
1347.69	23.97	21.50	2.47
1361.39	23.97	22.49	1.48
1362.6	23.97	22.48	1.49
1363.81	23.97	22.49	1.48
1365.02	23.97	22.49	1.48
1366.23	23.97	22.49	1.48
1424.25	23.97	22.69	1.28
1433.92	23.97	22.71	1.26
1451.6	23.97	22.71	1.26
1481.1	23.97	22.71	1.26
1590.4	23.97	22.6	1.37
1656.93	23.97	23.10	0.87
1666.21	23.97	23.17	0.80
1692.34	23.99	23.97	0.02
1693.28	23.99	23.97	0.02
1694.23	23.98	23.96	0.02
1695.17	23.98	23.96	0.02

### 7.2.5.2 Roughness Coefficients

Estimation of Manning roughness coefficients was based on field observation, satellite imagery review (available via Google Maps™) and orthophotos, engineering judgment, previous modeling experience, and comparison of reach characteristics with the “Roughness Characteristics of Natural Channels” (Barnes, 1967).

Starting roughness coefficients defined in the hydraulic model were in the range 0.035 to 0.050 for channels and 0.025 to 0.080 for overbank areas. Channels through the study area range from clean, gravel bottom to large boulders with debris (represented by the low and high range of roughness coefficients). For the overbank areas, the lower range is associated with asphalt and concrete surfaces and the middle range represents grassed areas clear of significant vegetation and the upper range represented forested overbank areas. The upper range representing areas of denser vegetation.

### 7.2.5.3 Weir Flow Coefficients

The CivilGeo website<sup>18</sup> provides a review of HEC-RAS Bridge High Flow Computations including details regarding estimation of weir coefficients. The following was abstracted from the CivilGeo website.

*Under free flow conditions (discharge independent of tailwater) the coefficient of discharge C, ranges from 2.5 to 3.1 (1.38 - 1.71 for metric units<sup>19</sup>) for broad-crested weirs depending primarily upon the gross head on the crest (C increases with head). Increased resistance to flow caused by obstructions such as trash on bridge railings, curbs, and other barriers would decrease the value of C.*

*Tables of weir coefficients, C, are given for broad-crested weirs in Brater and King's Handbook (Brater and King, 1963), with the value of C varying with measured head (H) and breadth of weir. For rectangular weirs with a breadth of 15 feet and H of 1 foot or more, the given value is 2.63 (1.45 for metric units). Trapezoidal shaped weirs generally have a larger coefficient with typical values ranging from 2.7 to 3.08 (1.49 to 1.70 for metric units).*

*The "Hydraulics of Bridge Waterways" document (FHWA, 1978) provides a curve of C versus the head on the roadway. The roadway section is shown as a trapezoid and the coefficient rapidly changes from 2.9 for a very small H to 3.03 for H = 0.6 feet. From there, the curve levels off near a constant value of 3.05 (1.69 for metric units).*

As well, the Connecticut Department of Transportation - Drainage Manual, Chapter 8, Section 8 (CONNDot, 2000) provides another means of estimating the weir coefficient.

The Ontario Technical Guidelines for Flood Hazard Mapping (EWRG, 2017) suggests a calibration range of 1.4 to 1.7 for bridge weir flow coefficients.

Bridge weir coefficients were defined in the range 1.4 to 1.7 for the current study HEC-RAS model, representing typical bridges and elevated decks, respectively.

For a flood plain mapping assignment with the Toronto and Region Conservation Authority, Wood completed a sensitivity analysis of bridge weir coefficients (Wood, 2020) to better understand the influence of the typical range of weir coefficients on computed water surface elevations. The results of this analysis demonstrated that water surface elevation and weir flow computations are insensitive to changes in the weir flow coefficient for the structures evaluated (which represented a range of configurations and range of overtopping depths). This conclusion is reflected in the results with the change in computed water surface elevations ranging from -0.05 to 0.09 m.

### 7.2.6 Starting Water Surface Elevations

Table 7-4 presents maximum tidal elevations for the study area. The sources of the values reported are noted at the bottom of the table. Tide table values are taken from a particular port (e.g. Corner Brook), or estimated from nearby ports, (e.g. Port Aux Basques or Harrington Harbour on the southern Quebec shore).

<sup>18</sup> Please refer to <https://www.civilgeo.com/knowledge-base/hec-ras-bridge-high-flow-computations/>

<sup>19</sup> To convert an English weir coefficient to an equivalent SI weir coefficient, multiply the English weir coefficient by 0.552

For orientation, Figure 7-2 illustrates the relation between tidal surfaces (MWL<sup>20</sup>, HHWMT<sup>21</sup>, HHWLT<sup>22</sup>), charting datums, and physical features. Probable maximum storm surge is estimated from inspection of the 40-year return period hindcast values by Bernier and Thompson (2006) as illustrated in Figure 7-3. Future predictions for sea level rise are made based on predictions presented in Batterson and Liverman (2010) which include Intergovernmental Panel on Climate Change (IPCC) sea level predictions, potential accelerated ice melt, and regional trends of crustal rebound.

In the absence of an extremal analysis of water level measurements, it is noted that the HHWMT/LT (tidal water level, i.e. without surge) values quoted are generally representative of a 1 in 20-year AEP event (as they are based on 19 years of predictions) while the recorded extreme value (Recorded Extreme, HHW) from the Department of Fisheries and Oceans (DFO) tide tables are for the historical record at Port Aux Basques (1935 to 2012 or 67 years record) is reflective of a 1 in 100-year return period.

For the purposes of this study, the starting water surface elevation was computed as the maximum high tide (large tide for higher high water - HHWLT) of 2.1 m (chart datum) plus a storm surge of 0.7 m for the Corner Brook area for existing conditions. It should be noted that, in the absence of tide and surge observations specifically at the downstream limits of the hydraulic models, both parameters were assumed to be the same as observed by the Canadian Hydrographic Service (CHS) at the locations noted in Table 7-4. This provides a combined total of 2.8 m (chart datum) for the Corner Brook area which was used as the downstream boundary condition in the existing conditions hydraulic models for the 1 in 20-year and 1 in 100-year AEP flood simulations. This approach is consistent with previous hydrotechnical studies completed for WRMD such as the Flood Risk Mapping Project for Shearstown / Bay Roberts Area (Hatch 2012) and the Flood Risk Mapping Project for Corner Brook and Petrie's Brook (AMEC, 2012b).

The inclusion of a surge component in the estimation of starting water levels is considered reasonable for the Corner Brook area. The surge from the Gulf would easily propagate into the Bay of Islands all the way to the head of the inlets. There could even be some amplification in the narrow inlets. The assessment of the amplification component would require modelling that resolves the Bay of Islands and the inlets which the Bernier model does not include. As such, the surge elevation estimate of 0.7 m for the Corner Brook area is not considered overly conservative.

The future conditions model (2080 tri-decade period) also incorporates a sea level rise component resulting in a starting water surface elevation of 3.36 m, respectively.

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<sup>20</sup> MWL: is the height above chart datum of the mean of all hourly observations used for the tidal analysis and that particular place (DFO, 2012a), or, the average of all hourly water levels over the available period of record (Forrester, 1983).

<sup>21</sup> HHWMT: is higher high water, mean tide, which is the average of all the higher high waters from 19 years of predictions (Forrester, 1983).

<sup>22</sup> HHWLT: is higher high water, large tide, which is the average of the highest high waters, one from each of 19 years of predictions (Forrester, 1983).

**Table 7-4: Tidal Elevations**

Description	Elevation (m)
MWL (m)	1.2 <sup>(1)</sup>
HHWMT (m)	1.8 <sup>(2)</sup>
HHWLT (m)	2.1 <sup>(3)</sup>
Recorded Extreme, HHW (m)	2.9 <sup>(3)</sup>
Probable Maximum Surge (m) <sup>(4)</sup>	0.7
Sea level rise 2020 (m) <sup>(5)</sup>	0.05
Sea level rise 2050 (m) <sup>(5)</sup>	0.23
Sea level rise 2080 (m) <sup>(5)</sup>	0.56

Notes:

1. Source: Corner Brook (DFO, 2012b)
2. Source: Harrington-Harbour (DFO, 2012b)
3. Source: mean of Harrington-Harbour (DFO, 2012b), Port Aux Basques (DFO, 2012a)
4. Source: Figure 10 in Bernier and Thompson (2006)
5. Source: Table 3 and Figure 4 in Batterson and Liverman (2010); Zone 2 for Humber River.

Acronyms (from Forrester, 1983):

MWL: is the height above chart datum of the mean of all hourly observations used for the tidal analysis and that particular place (DFO, 2012a), or, the average of all hourly water levels over the available period of record

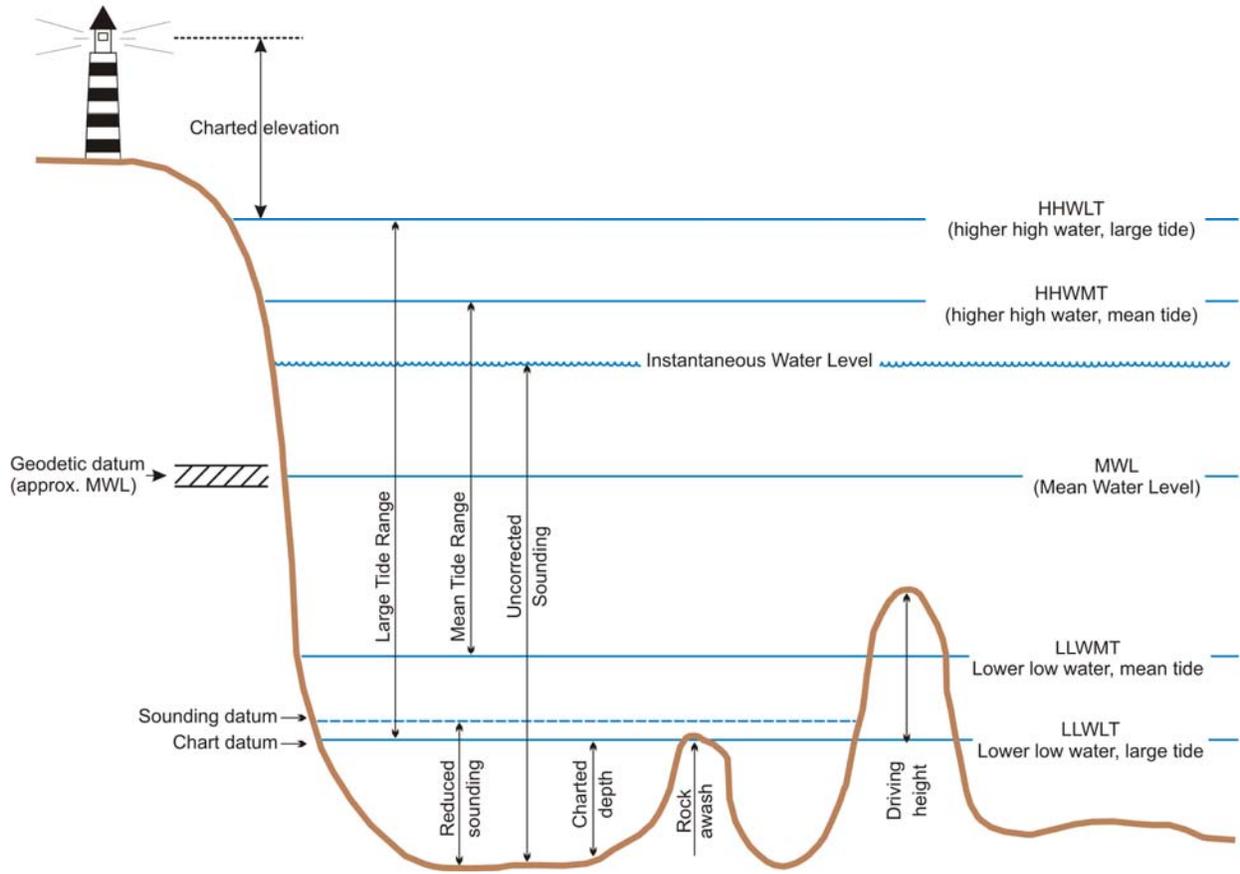
HHWMT: is higher high water, mean tide, which is the average of all the higher high waters from 19 years of predictions

HHWLT: is higher high water, large tide, which is the average of the highest high waters, one from each of 19 years of predictions

HHW: higher high water

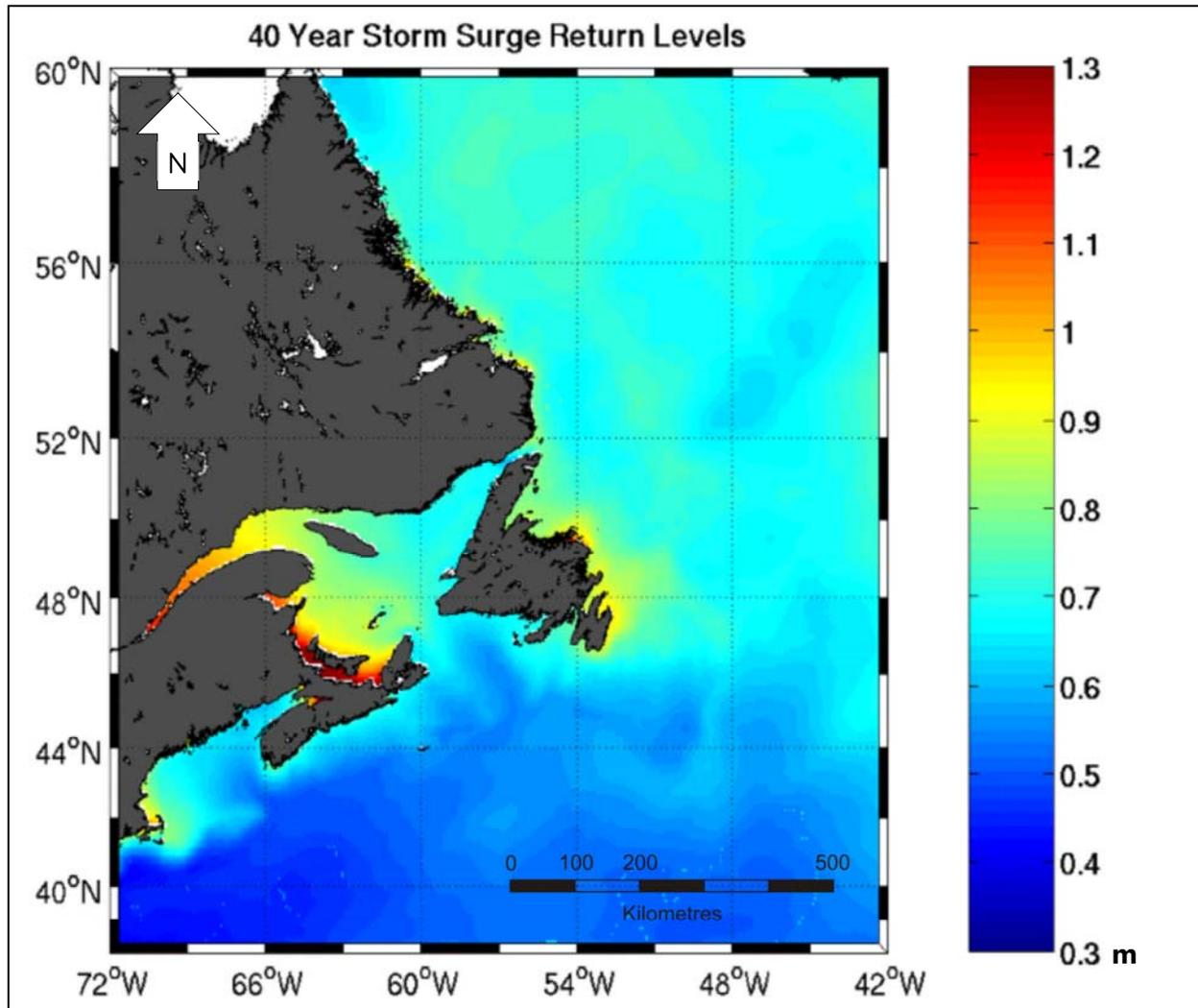
As noted in Section 2.1, published tides data in Canada is referenced to chart datum. However, use of tides data in the project modelling required conversion of chart datum to CGVD-2013. The conversion factor was determined to be -1.609 m (ref. Appendix E). As such, for modelling purposes, the following starting water surface elevations were defined for the various hydraulic modelling scenarios:

Modelling Scenario	Chart Datum	CGVD-2013
<ul style="list-style-type: none"> <li>Existing development and current IDF</li> <li>Full development and current IDF</li> </ul>	2.80 m	1.19 m
<ul style="list-style-type: none"> <li>Existing development and climate change IDF</li> <li>Full development and climate change IDF</li> </ul>	3.36 m	1.75 m



**Figure 7-2: Relation between tidal surfaces, charting datums and physical features**

(Source: reconstructed from Forrester, 1983)



**Figure 7-3: 40-year return level of extreme storm surges**

(Source: Bernier and Thompson, 2006)

### 7.3 Model Calibration and Verification

Model calibration is completed by adjusting the selected parameters, such as Manning's roughness coefficient, in the hydraulic model to obtain a best fit between the model calculations and observed field data; in this case measured streamflow data.

The calibration and validation effort for the HEC-RAS model developed for the Humber River study area was founded on the observed water surface elevation and flow data available for the Environment and Climate Change Canada flow gauging stations located within the study area. The channel/floodplain Manning's roughness coefficient was found to be the most sensitive hydraulic parameter (ref. Section 8) with respect to the model calibration. Therefore, the model calibration was completed by modifying the Manning's roughness coefficient of upstream cross sections iteratively until the model simulated water surface elevation reasonably agreed with the corresponding observed water surface elevations at each gauging station for several water level-flow pairs. The starting roughness coefficient values (ref. Section 7.2.5.2) were modified through the calibration process to yield final values in the range of 0.025 to 0.08 for the left and right overbanks, and 0.03 to 0.045 for the channel. The calibrated model was then used to simulate water surface elevations for additional events as a means of model validation.

Observed water level and flow data at four (4) gauging stations (02YL001, 02YL003, 02YL004 and 02YL012) was obtained from Environment and Climate Change Canada to support the calibration and validation effort. Stations 02YL001 (Upper Humber River near Reidville) and 02YL003 (Humber River at Humber Village Bridge) are situated on the main Humber River; while the stations 02YL004 (South Brook at Pasadena) and 02YL012 (Steady Brook above Confluence to Humber River) are situated in the South Brook Reach 4 and Steady Brook Reach 1, respectively.

#### 7.3.1 Station 02YL001 - Upper Humber River near Reidville

The observed data at station 02YL001 was used to calibrate the model parameters upstream of HEC-RAS cross section 2428.85 of the Humber River Reach 25. Four (4) events with flow values ranging from 273 m<sup>3</sup>/s to 822 m<sup>3</sup>/s were selected for the model calibration. An iterative process of adjusting the main channel Manning's roughness coefficient, while comparing the observed and simulated water surface elevations for the selected calibration events, was employed. Through this process, a main channel roughness value of 0.045 was determined to provide the most reasonable balancing of the resulting computed water surface elevations at station 02YL001; with preference given to the events with the highest observed peak flows. The comparison of the observed and simulated water surface elevations for calibration and validation events are summarized in Table 7-5.

The results indicate that the calibrated model yielded water levels within a range of -0.02 m to 0.33 m of those observed at Station 02YL001 for the calibration and validation events. The 1 in 20-year and 1 in 100-year flow rates at this location were estimated to be 664 m<sup>3</sup>/s and 1,252 m<sup>3</sup>/s, respectively. The difference in the simulated water surface elevations for flood events greater than the 10-year event was found to be less than 0.05 m ±. Therefore, the calibrated model was deemed to be capable of reasonably simulating the flood water levels at station 02YL001 for the noted range of peak flows.

**Table 7-5: Observed and Simulated Water Surface Elevation at Station 02YL001  
(Upper Humber River near Reedville - Humber River Reach 025 Cross Section 2428.85)**

Event Type	Date	Event	Observed		Simulated WSE (m)	Difference (m)
			Flow (m <sup>3</sup> /s)	WSE <sup>1</sup> (m)		
Calibration	2013-04-28 21:30	A	822	12.12	12.10	-0.02
	2019-11-03 01:00	B	667	11.76	11.81	0.05
	2019-11-14 20:35	C	300	10.71	11.01	0.31
	2019-11-14 09:20	D	273	10.61	10.94	0.33
Validation	2020-06-02 03:30	E	723	11.90	11.92	0.02
Notes:						
1. The observed water surface elevations were converted to CGVD-2013 vertical datum.						

### 7.3.2 Station 02YL003 - Humber River at Humber Village Bridge

Similarly, calibrating the HEC-RAS model using the observed data at station 02YL003, a main channel Manning's roughness value of 0.04 was determined to provide the most reasonable balancing of the resulting computed water surface elevations at station 02YL003; again, with preference given to the events with the highest observed peak flows. Observed and simulated water surface elevations for calibration and validation events are summarized in Table 7-6.

**Table 7-6: Observed and Simulated Water Surface Elevation at Station 02YL003 (Humber River at Humber Village Bridge - Humber River Reach 006 Cross Section 6748.05)**

Event Type	Date	Event	Observed		Simulated WSE (m)	Difference (m)
			Flow (m <sup>3</sup> /s)	WSE <sup>1</sup> (m)		
Calibration	2013-04-30 04:30	A	817	5.22	5.24	0.02
	2019-06-07 19:45	B	540	4.09	4.11	0.02
	2019-06-25 23:00	C	468	3.76	3.74	-0.02
	2019-10-01 21:45	D	288	2.83	2.78	-0.05
Validation	2019-08-18 00:00	E	198	2.28	2.22	-0.06
	2020-06-04 00:30	F	842	5.31	5.33	0.02
Notes:						
1. The observed water surface elevations were converted to CGVD-2013 vertical datum.						

As noted in Table 7-6, the difference in the simulated and observed water surface elevations were found to be in the range of -0.06 m to 0.02 m for the selected calibration and validation events. Therefore, the calibrated model was deemed to be capable of reasonably simulating the flood water levels at station 02YL003 for the noted range of peak flows.

### 7.3.3 Station 02YL012 - Steady Brook above Confluence to Humber River

The gauging station 02YL012 is situated about 560 m ( $\pm$ ) upstream of the confluence of the Steady Brook Reach 1 with the main Humber River (Steady Brook Reach 1 at cross section 563.18). The channel invert elevation at the gauging station is 2.46 m ( $\pm$ ). Analysing the computed water surface elevations at the main Humber River at cross section 6525.97, situated immediately downstream of the confluence, suggests that the observed water levels at the station 02YL012 may be influenced by water levels in the Humber River when the peak flow rate in the main Humber River is above 384 m<sup>3</sup>/s ( $\pm$ ). Therefore, the calibration events selected for the Steady Brook Reach 1 were selected whereby the corresponding Humber River peak flow rate was less than the threshold value of 384 m<sup>3</sup>/s. After calibrating the main channel Manning's roughness coefficient, the roughness value of 0.045 was found to be a suitable value for the Steady Brook Reach 1 cross sections. Observed and simulated water surface elevations for model calibration and validation events are summarized in Table 7-7.

**Table 7-7: Observed and Simulated Water Surface Elevation at Station 02YL012 (Steady Brook above Confluence to Humber River - Steady Brook Reach 1 Cross Section 563.18)**

Event Type	Date	Event	Observed		Simulated WSE (m)	Difference (m)
			Flow (m <sup>3</sup> /s)	WSE <sup>1</sup> (m)		
Calibration	2018-02-06 14:00	A	104.8	4.41	4.47	0.06
	2019-01-04 17:00	B	35.5	3.77	3.89	0.13
	2019-04-22 18:00	C	33.1	3.73	3.85	0.12
	2017-12-14 07:00	D	12.4	3.35	3.33	-0.02
Validation	2019-10-13 09:00	E	5.1	3.11	3.02	-0.09
Additional	2020-06-03 23:00	F	180.7 <sup>2</sup>	4.87	4.66	-0.21
Notes:						
1. The observed water surface elevations were converted to CGVD-2013 vertical datum.						
2. Corresponding Humber River peak flow is above the threshold values of 384 m <sup>3</sup> /s						

As noted in Table 7-7, the difference in observed and simulated water surface elevations are in the range of -0.02 m to 0.13 m for the selected calibration events and -0.09 m for the selected validation event. Therefore, the calibrated model was deemed to be capable of reasonably simulating the flood water levels at station 02YL012 for the noted range of peak flows. Based on these results, the calibrated model was deemed to reasonably simulate the flood water levels at Station 02YL012.

The potential interaction between water levels in the main Humber River as an influencing factor for information at the Steady Brook station 02YL012 should be better understood. As such, it is recommended that a detailed investigation and assessment be completed to determine conclusively if main Humber River water levels do influence data recorded at station 02YL012. A further objective of such an assessment should be to determine if station 02YL012 should be moved upstream from its current location, along Steady Brook, to negate any potential main Humber River water level influences.

## 7.4 Simulation of the 1 in 20-year and 1 in 100-year AEP Flood Events

Peak flows through the study reaches were computed using the calibrated and validated deterministic hydrologic model (HEC-HMS) developed for this project. The computed peak flows were inputted to a steady state hydraulic model (HEC-RAS) for the purpose of estimating the water surface profiles corresponding to the 1 in 20-year and 1 in 100-year AEP flood events for the following scenarios:

- Existing development and current IDF
- Full development and current IDF
- Existing development and climate change IDF
- Full development and climate change IDF

The resultant water level output from the HEC-RAS model was used to delineate the extent of flooding on maps as discussed in Section 9. HEC-RAS output defining computed water surface elevations for the 1 in 20-year and 1 in 100-year AEP events is provided in Appendix N.

### 7.4.1 Capacity of the Stream Crossing Structures

A summary of modelled culverts and bridges in the study reach and the associated computed water surface elevations, as a means of identifying which structures are overtopped or not, is provided as Tables 7-8, 7-9 and 7-10. Table 7-8 provides a high-level summary of structures that are or are not overtopped for the 1 in 20-year AEP and 1 in 100-year AEP floods. The general conclusions are that a significant number of structures would be overtopped during a 1 in 20-year AEP flood. Future development and climate change have the potential to exacerbate the situation.

Detailed hydraulic information, on a structure by structure basis, is provided in Tables 7-9 and 7-10 for the 1 in 20-year AEP and 1 in 100-year AEP floods, respectively.

**Table 7-8: Watercourse Crossings – Structure Overtopping Summary –  
Humber River and Tributaries**

Watercourse Crossing Flood Condition	1 in 20-year AEP				1 in 100-year AEP			
	Current Development		Fully Development		Current Development		Fully Development	
	Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change
Not Overtopped	51	28	40	25	36	18	33	15
Overtopped	44	67	55	70	59	77	62	80

**Table 7-9: Watercourse Crossings - Overtopping Summary – Humber River and Tributaries – 1 in 20-year AEP Flood**

Structure #	Structure Name / Location	Structure Type	Watercourse	HEC-RAS Tributary	HEC-RAS Structure Number	Low Chord (m)	Top of Road (m)	Flow Data (m³/s)				Computed Water Surface Elevation (m) by Scenario				Overtopping Depth (+ve) / Freeboard Available (-ve) (m)			
								Current Development		Fully Developed		Current Development		Fully Developed		Current Development		Fully Developed	
								Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change
<b>1 in 20-year AEP Flood</b>																			
Trout Brook-001	Reidville Road	Culvert	Trout Brook	Reach 1	1533.17	11.83	15.09	23.2	57.7	26.3	62.3	15.19	15.88	15.32	15.94	0.10	0.79	0.23	0.85
TransmissionBr-002	Main Street	Bridge	TransmissionBr	Reach 1	1075	34.33	35.2	16.9	37.3	18.9	39.9	35.56	35.88	35.58	36	0.36	0.68	0.38	0.8
Steady Brook-003	Steady Brook (Thistle Drive - Bridge to Marble Village)	Bridge	Steady Brook	Reach 1	1142.11	21	21.5	89.2	205.7	90.3	207.2	15.13	16.45	15.14	16.46	-6.37	-5.05	-6.36	-5.04
Steady Brook-004	Steady Brook TCH Bridges (TCH-124 and TCH-064)	Bridge	Steady Brook	Reach 1	1000.34	15.3	17.2	89.2	205.7	90.3	207.2	11.27	12.81	11.29	12.82	-5.93	-4.39	-5.91	-4.38
Steady Brook-005	Steady Brook (Marble Drive Bridge)	Bridge	Steady Brook	Reach 1	742.21	8	9.48	89.2	205.7	90.3	207.2	6.13	7.52	6.15	7.63	-3.35	-1.96	-3.33	-1.85
Steady Brook-006	TransCanada Highway	Culvert	Steady Brook	Reach 2	513.65	11.49	12.96	2.2	5.7	2.5	6	11.72	13.14	11.85	13.14	-1.24	0.18	-1.11	0.18
Steady Brook-007	TransCanada Highway	Culvert	Steady Brook	Reach 4	285	10.68	11.86	14.5	35.9	14.5	35.9	5.14	5.14	5.14	5.14	-6.72	-6.72	-6.72	-6.72
Steady Brook-008	TransCanada Highway	Culvert	Steady Brook	Reach 3	53.5	8	9	9	24.8	9	24.8	9.27	9.63	9.27	9.63	0.27	0.63	0.27	0.63
South Brook-009	Midland Row	Culvert	South Brook	Reach 6	2137.38	35.27	35.54	11.3	30.1	16.7	37.7	35.17	35.68	35.85	35.92	-0.37	0.14	0.31	0.38
South Brook-010	Hodder Drive	Culvert	South Brook	Reach 6	2011.6	33.55	33.84	11.3	30.1	16.7	37.7	33.66	34.06	34.23	34.37	-0.18	0.22	0.39	0.53
South Brook-011	Birchview Drive	Culvert	South Brook	Reach 6	1918.07	33.1	33.24	11.3	30.1	16.7	37.7	33.13	33.12	34.24	33.17	-0.11	-0.12	1	-0.07
South Brook-012	Dawson Drive	Culvert	South Brook	Reach 6	1827.4	31.46	31.66	11.3	30.1	16.7	37.7	31.89	32.03	31.95	31.98	0.23	0.37	0.29	0.32
South Brook-013	Earle Drive	Culvert	South Brook	Reach 6	1668	30.07	30.05	11.3	30.1	16.7	37.7	31.79	31.98	31.87	32.01	1.74	1.93	1.82	1.96
South Brook-014	Main Street	Culvert	South Brook	Reach 6	1454.64	28.28	31.58	11.3	30.1	16.7	37.7	31.79	31.98	31.87	32.01	0.21	0.4	0.29	0.43
South Brook-015	Church Street	Culvert	South Brook	Reach 6	1028.26	24.48	24.98	11.3	30.1	16.7	37.7	24.81	25.31	25.24	25.36	-0.17	0.33	0.26	0.38
South Brook-016	1 Avenue	Culvert	South Brook	Reach 6	693.5	21.33	21.56	11.3	30.1	16.7	37.7	22.02	22.02	22.02	22.02	0.46	0.46	0.46	0.46
South Brook-017	TransCanada Highway	Culvert	South Brook	Reach 6	177	13.37	18.1	11.3	30.1	16.7	37.7	16.98	18.15	18.05	18.29	-1.12	0.05	-0.05	0.19
South Brook-018	Forest Drive	Culvert	South Brook	Reach 5	739	41.8	42.16	5.5	13.9	7	16.1	42	42.57	42.28	42.7	-0.16	0.41	0.12	0.54
South Brook-019	Main Street	Culvert	South Brook	Reach 5	402	23.63	25.9	5.5	13.9	7	16.1	24.53	26.03	25.65	26.1	-1.37	0.13	-0.25	0.2
South Brook-020	Main Street	Bridge	South Brook	Reach 4	766.5	16.66	17.68	119.8	230	157.3	266.7	16.62	18.64	17.66	18.76	-1.06	0.96	-0.02	1.08
South Brook-021	Church Street	Bridge	South Brook	Reach 4	697	16	17	119.8	230	157.3	266.7	16.02	18.38	16.77	18.52	-0.98	1.38	-0.23	1.52
South Brook-022	PA 44 Pasadena (South Brook Bridges - TCH 162)	Bridge	South Brook	Reach 2	823	11.1	13.38	124.6	239	162.7	276.6	9.86	11.51	10.36	12	-3.52	-1.87	-3.02	-1.38
Rocky Brook-023	Old Rocky Brook Road	Bridge	Rocky Brook	Reach 1	3623.35	20	21.04	95	229.5	95.4	230.2	15.17	16.2	15.17	16.2	-5.87	-4.84	-5.87	-4.84
River_19-024	Riverside Drive	Culvert	River_19	Reach_19	658.1	40.64	41.51	0.6	1.8	0.6	1.8	40.11	40.69	40.11	40.69	-1.40	-0.82	-1.4	-0.82
River_18-025	Riverside Drive	Culvert	River_18	Reach_18	642.8	39.24	39.17	10	24.4	10	24.4	39.84	40.3	39.84	40.3	0.67	1.13	0.67	1.13
River_18-026	Unnamed Road in Humber Valley Resort	Culvert	River_18	Reach_18	570.4	33.28	34.29	10	24.4	10	24.4	34.95	35.29	34.95	35.29	0.66	1	0.66	1

Structure #	Structure Name / Location	Structure Type	Watercourse	HEC-RAS Tributary	HEC-RAS Structure Number	Low Chord (m)	Top of Road (m)	Flow Data (m³/s)				Computed Water Surface Elevation (m) by Scenario				Overtopping Depth (+ve) / Freeboard Available (-ve) (m)			
								Current Development		Fully Developed		Current Development		Fully Developed		Current Development		Fully Developed	
								Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change
<b>1 in 20-year AEP Flood</b>																			
River_18-027	Unnamed Road in Humber Valley Resort	Culvert	River_18	Reach_18	102.31	13.29	17.05	10	24.4	10	24.4	15.12	17.68	15.12	17.68	-1.93	0.63	-1.93	0.63
River_17-028	TransCanada Highway	Culvert	River_17	Reach_17	451.7	32.02	36.99	7.9	19.2	8.1	19.5	36.99	36.99	36.99	36.99	0	0	0	0
River_17-029	Newfoundland T'Railway	Culvert	River_17	Reach_17	115	9.32	11.14	7.9	19.2	8.1	19.5	11.39	11.53	11.39	11.54	0.25	0.39	0.25	0.4
Reidville-030	Old Rocky Brook Road	Culvert	Reidville	Reach 1	1747.09	20.74	23.41	5.4	13.6	5.8	14.2	23.71	23.95	23.73	23.96	0.30	0.54	0.32	0.55
Reidville-031	Reidville Road	Culvert	Reidville	Reach 2	102.25	11.74	17.86	3.3	7.9	3.6	8.4	11.86	14.51	11.95	15.05	-6.00	-3.35	-5.91	-2.81
Reidville-032	Reidville Road	Culvert	Reidville	Reach 3	462.12	15.5	16.2	8.2	20.3	8.6	20.8	16.65	17.15	16.7	17.18	0.45	0.95	0.5	0.98
Pasadena-033	TransCanada Highway	Culvert	Pasadena	Reach 1	145.11	29.15	30.59	4.9	12.8	5.9	14.2	30.76	30.9	30.78	30.92	0.17	0.31	0.19	0.33
Pasadena-034	TransCanada Highway	Culvert	Pasadena	Reach 2	108.9	35.76	35.88	2.9	7.3	3.5	8.1	35.97	36.09	35.99	36.09	0.09	0.21	0.11	0.21
Pasadena-035	Newfoundland T'Railway	Culvert	Pasadena	Reach 2	61.5	22.4	22.7	2.9	7.3	3.5	8.1	22.86	22.95	22.88	22.94	0.16	0.25	0.18	0.24
Pasadena-036	Midland Row	Culvert	Pasadena	Reach 3	2404.5	40.78	40.88	10.7	25.8	13.1	29.2	40.93	41.01	40.91	41.04	0.05	0.13	0.03	0.16
Pasadena-037	Trail	Culvert	Pasadena	Reach 3	2283.5	38	38.04	10.7	25.8	13.1	29.2	38.44	38.73	38.49	38.78	0.40	0.69	0.45	0.74
Pasadena-038	Main Street	Culvert	Pasadena	Reach 3	1040.5	25.4	27.06	10.7	25.8	13.1	29.2	27.09	27.32	27.16	27.34	0.03	0.26	0.1	0.28
Pasadena-039	TransCanada Highway	Culvert	Pasadena	Reach 3	137.38	15.85	22.78	10.7	25.8	13.1	29.2	18.07	22.97	19.7	23	-4.71	0.19	-3.08	0.22
Pasadena-040	TransCanada Highway	Culvert	Pasadena	Reach 4	154.15	20.97	23.64	4.3	10.3	5.8	12.3	23.64	23.64	23.64	23.64	0.00	0	0	0
Pasadena-041	TransCanada Highway	Culvert	Pasadena	Reach 5	452.23	18.44	19.74	21.8	52.8	26.1	59	19.87	20.19	20.97	20.22	0.13	0.45	1.23	0.48
Pasadena-042	Newfoundland T'Railway	Culvert	Pasadena	Reach 5	92.83	10.3	12.28	21.8	52.8	26.1	59	12.33	12.56	12.4	12.58	0.05	0.28	0.12	0.3
Pasadena-043	TransCanada Highway	Culvert	Pasadena	Reach 6	664	24.34	29.39	4.5	14.6	9.7	21.9	24.31	29.39	25.97	29.4	-5.08	0	-3.42	0.01
Nichols Brook-044	Grace Avenue	Culvert	Nichols Brook	Reach 9	122.34	34.18	36.09	0.8	1.7	0.8	1.7	33.41	33.77	33.41	33.57	-2.68	-2.32	-2.68	-2.52
Nichols Brook-045	Grace Avenue	Culvert	Nichols Brook	Reach 7	470.45	25.67	32.89	2.3	7.7	4.1	10.5	25.47	28.32	26.04	32.48	-7.42	-4.57	-6.85	-0.41
Nichols Brook-046	Driveway Crossing	Culvert	Nichols Brook	Reach 7	262.6	21.54	30.25	2.3	7.7	4.1	10.5	21.34	24.19	21.91	26.82	-8.91	-6.06	-8.34	-3.43
Nichols Brook-047	George Aaron Drive	Culvert	Nichols Brook	Reach 1	634.04	11.87	17.2	24.5	70.1	28.9	77.3	12.33	17.5	12.67	17.63	-4.87	0.3	-4.53	0.43
Matthews Brook-048	Bonnell Drive	Culvert	Matthews Brook	Reach 1	710.5	24.78	26.89	17.3	37	20.7	41	26.02	27.18	26.97	27.24	-0.87	0.29	0.08	0.35
Matthews Brook-049	TransCanada Highway	Culvert	Matthews Brook	Reach 1	240.35	12.65	16.65	17.3	37	20.7	41	16.52	17.23	16.73	17.29	-0.13	0.58	0.08	0.64
Matthews Brook-050	Strawberry Loop	Culvert	Matthews Brook	Reach 1	144.17	9.3	13.87	17.3	37	20.7	41	14.06	14.4	14.11	14.46	0.19	0.53	0.24	0.59
Matthews Brook-051	Strawberry Lane	Culvert	Matthews Brook	Reach 1	44.9	6.55	8.46	17.3	37	20.7	41	8.81	9.26	8.92	9.33	0.35	0.8	0.46	0.87
Lanes Brook-052	TransCanada Highway (Little Harbour)	Culvert	Lanes Brook	Reach 1	171	17.99	19.73	5.7	15.6	7.3	18	19.73	19.73	20.93	19.73	0.00	0	1.2	0
Lanes Brook-053	TransCanada Highway (Little Harbour)	Culvert	Lanes Brook	Reach 2	189.6	18.73	20.7	19.3	47.2	24.8	54.8	19.18	20.83	20.65	20.91	-1.52	0.13	-0.05	0.21
Humber Village-054	Maple Street	Culvert	Humber Village	Reach 4	457	17.6	17.6	15.9	37.8	15.9	37.8	18.08	18.31	18.08	18.31	0.48	0.71	0.48	0.71
Humber Village-055	Maple Street	Culvert	Humber Village	Reach 4	106.9	9.17	10.16	15.9	37.8	15.9	37.8	10.01	10.72	10.01	10.72	-0.15	0.56	-0.15	0.56



Structure #	Structure Name / Location	Structure Type	Watercourse	HEC-RAS Tributary	HEC-RAS Structure Number	Low Chord (m)	Top of Road (m)	Flow Data (m³/s)				Computed Water Surface Elevation (m) by Scenario				Overtopping Depth (+ve) / Freeboard Available (-ve) (m)			
								Current Development		Fully Developed		Current Development		Fully Developed		Current Development		Fully Developed	
								Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change
<b>1 in 20-year AEP Flood</b>																			
Humber Village-056	Marble View Drive	Culvert	Humber Village	Reach 1	1062.5	38.76	38.97	6.9	17.1	6.9	17.1	39.48	39.77	39.48	39.77	0.51	0.8	0.51	0.8
Humber Village-057	Driveway Crossing	Culvert	Humber Village	Reach 1	679	16.52	17.93	6.9	17.1	6.9	17.1	18.17	18.33	18.17	18.33	0.24	0.4	0.24	0.4
Humber Village-058	Driveway Crossing	Bridge	Humber Village	Reach 1	191	15.22	15.72	6.9	17.1	6.9	17.1	8.27	8.72	8.27	8.72	-7.45	-7	-7.45	-7
Humber Village-060	Driveway Crossing	Culvert	Humber Village	Reach 5	182.4	18.04	20.55	2	4.9	2	4.9	20.75	20.95	20.75	20.95	0.20	0.4	0.2	0.4
Humber River-061	Viking Trail / Route 430 Bridge	Bridge	Humber River	Reach 020	1770.09	10.2	11.78	780.7	2050	785.2	2061.5	7.59	10.3	7.65	10.39	-4.19	-1.48	-4.13	-1.39
Humber River-062	Nicholsville Bridge	Bridge	Humber River	Reach 019	23104.33	10	11.33	772.1	2027.4	776.6	2039.3	7.16	9.74	7.24	9.85	-4.17	-1.59	-4.09	-1.48
Humber River-063	Humber Valley Resort Bridge (to Lakeside Drive)	Bridge	Humber River	Reach 010	12854.08	10	12.28	820	1709.4	856.5	1753.8	6.92	9.59	7.01	9.71	-5.36	-2.69	-5.27	-2.57
Humber River-064	Humber Village (Tamarack Street) Bridge	Bridge	Humber River	Reach 006	6785.7	7.7	9	803.1	1692.3	815.9	1736.3	5.18	8.05	5.24	8.18	-3.82	-0.95	-3.76	-0.82
Humber River-065	Ballam Bridge (North Shore Highway)	Bridge	Humber River	Reach 001	1830.94	3.17	4.27	766.2	1658.1	782	1702.3	1.39	2.44	1.4	2.48	-2.88	-1.83	-2.87	-1.79
Deer Lake-066	TransCanada Highway	Culvert	Deer Lake	Reach 7	754.5	27.83	28.85	6.91	16.56	7.26	17.01	29.17	29.17	29.17	29.17	0.32	0.32	0.32	0.32
Deer Lake-067	Airport Road	Culvert	Deer Lake	Reach 6	248.9	12.52	16.2	8.9	21.3	10.5	23.1	16.2	16.2	16.2	16.2	0.00	0	0	0
Deer Lake-068	Airport Road	Culvert	Deer Lake	Reach 10	23.87	10.56	11.23	6.1	13.6	9.5	17.5	10.68	11.45	11.31	11.51	-0.55	0.22	0.08	0.28
Deer Lake-069	Airport Avenue Extension	Culvert	Deer Lake	Reach 5	3605	32.54	37.5	14.1	31.4	15.6	33.3	37.17	37.64	37.4	37.66	-0.33	0.14	-0.1	0.16
Deer Lake-070	TransCanada Highway	Culvert	Deer Lake	Reach 5	1253.05	13.39	18.56	14.1	31.4	15.6	33.3	18.11	18.72	18.56	18.74	-0.45	0.16	0	0.18
Deer Lake-071	Goose Arm Road	Culvert	Deer Lake	Reach 13	365.45	34.57	34.35	0.3	1.9	1	3.2	33.51	34.23	33.89	34.44	-0.84	-0.12	-0.46	0.09
Deer Lake-072	Scott Drive	Culvert	Deer Lake	Reach 13	256.64	31.17	32.15	0.3	1.9	1	3.2	30.11	30.83	30.49	31.25	-2.04	-1.32	-1.66	-0.9
Deer Lake-073	Goose Arm Road	Culvert	Deer Lake	Reach 14	247.58	34.95	34.98	1.4	6.1	3.1	9	35.11	35.28	35.19	35.34	0.13	0.3	0.21	0.36
Deer Lake-074	Nicholsville Road	Culvert	Deer Lake	Reach 1	524.1	8.8	9.73	5.1	10.9	7.3	13.3	9.87	9.99	9.92	10.03	0.14	0.26	0.19	0.3
Deer Lake-075	Mosses Lane	Culvert	Deer Lake	Reach 1	164.12	7.75	8.7	5.1	10.9	7.3	13.3	8.72	9.86	8.72	9.97	0.02	1.16	0.02	1.27
Deer Lake-076	Main Street South	Culvert	Deer Lake	Reach 2	3197.7	45.27	45.97	8	17.3	12.1	21.9	46.32	46.42	46.39	46.45	0.35	0.45	0.42	0.48
Deer Lake-077	Mayor Avenue	Culvert	Deer Lake	Reach 2	2720	36.73	36.74	8	17.3	12.1	21.9	37.43	37.44	37.43	37.72	0.69	0.7	0.69	0.98
Deer Lake-078	High Street	Culvert	Deer Lake	Reach 2	2674.5	35.39	36.71	8	17.3	12.1	21.9	37.04	37.31	37.18	37.4	0.33	0.6	0.47	0.69
Deer Lake-079	4 Avenue	Culvert	Deer Lake	Reach 2	2485.5	33.79	35.47	8	17.3	12.1	21.9	35.85	36.13	35.99	36.24	0.38	0.66	0.52	0.77
Deer Lake-080	Shears Place	Culvert	Deer Lake	Reach 2	2174.61	29.69	30.01	8	17.3	12.1	21.9	30.01	30.1	30.01	30.18	0	0.09	0	0.17
Deer Lake-081	5 Avenue Extension	Culvert	Deer Lake	Reach 2	1772.28	23.45	24.1	8	17.3	12.1	21.9	24.12	24.13	24.12	24.95	0.02	0.03	0.02	0.85
Deer Lake-082	Driveway Crossing	Culvert	Deer Lake	Reach 2	1716.5	23.21	23.78	8	17.3	12.1	21.9	23.97	24.09	24.02	24.94	0.19	0.31	0.24	1.16
Deer Lake-083	Reids Lane	Culvert	Deer Lake	Reach 2	1682.83	23.07	23.71	8	17.3	12.1	21.9	23.97	24.08	24.01	24.93	0.26	0.37	0.3	1.22
Deer Lake-084	Wights Road	Culvert	Deer Lake	Reach 2	1395.24	20.96	22.43	8	17.3	12.1	21.9	23.96	24.07	23.99	24.93	1.53	1.64	1.56	2.5
Deer Lake-085	Driveway Crossing	Culvert	Deer Lake	Reach 2	1354.54	20.78	21.81	8	17.3	12.1	21.9	23.95	24.07	23.98	24.92	2.14	2.26	2.17	3.11



Structure #	Structure Name / Location	Structure Type	Watercourse	HEC-RAS Tributary	HEC-RAS Structure Number	Low Chord (m)	Top of Road (m)	Flow Data (m³/s)				Computed Water Surface Elevation (m) by Scenario				Overtopping Depth (+ve) / Freeboard Available (-ve) (m)			
								Current Development		Fully Developed		Current Development		Fully Developed		Current Development		Fully Developed	
								Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change
<b>1 in 20-year AEP Flood</b>																			
Deer Lake-086	Old Bonnie Bay Road	Culvert	Deer Lake	Reach 2	908.5	19.73	23.92	8	17.3	12.1	21.9	18.91	18.95	18.93	18.96	-5.01	-4.97	-4.99	-4.96
Deer Lake-087	TransCanada Highway	Culvert	Deer Lake	Reach 2	602	13.87	17.35	8	17.3	12.1	21.9	16.52	17.41	16.73	17.45	-0.83	0.06	-0.62	0.1
Deer Lake-088	TransCanada Highway (Ramp)	Culvert	Deer Lake	Reach 2	492.24	12.49	16.61	8	17.3	12.1	21.9	16.61	16.66	16.61	16.7	0	0.05	0	0.09
Deer Lake-089	Amanda Avenue	Culvert	Deer Lake	Reach 12	247.15	13.67	13.96	1.9	8.5	4.8	13.5	13.34	13.65	14.08	14.4	-0.62	-0.31	0.12	0.44
Deer Lake-090	Driveway Crossing	Culvert	Deer Lake	Reach 12	143.14	7.48	7.1	1.9	8.5	4.8	13.5	7.28	9.77	7.48	9.89	0.18	2.67	0.38	2.79
Blue Gulch Br-091	Midland Row	Culvert	Blue Gulch Br	Reach 1	3715	41.51	41.56	27.6	65.2	30.8	69.6	41.75	41.78	41.8	41.78	0.19	0.22	0.24	0.22
Blue Gulch Br-092	Bonnell Drive	Culvert	Blue Gulch Br	Reach 1	3317	36.19	36.3	27.6	65.2	30.8	69.6	36.19	36.3	36.4	36.3	-0.11	0	0.1	0
Blue Gulch Br-093	Main Street	Bridge	Blue Gulch Br	Reach 1	2889.5	31.9	32.38	27.6	65.2	30.8	69.6	32.51	32.76	32.68	32.78	0.13	0.38	0.3	0.4
Blue Gulch Br-094	Church Street	Bridge	Blue Gulch Br	Reach 1	2663.5	28.2	28.65	27.6	65.2	30.8	69.6	29.29	29.21	29.32	29.21	0.64	0.56	0.67	0.56
Blue Gulch Br-095	TransCanada Highway	Culvert	Blue Gulch Br	Reach 1	1947	17.36	23.28	27.6	65.2	30.8	69.6	22.75	23.56	23.28	23.59	-0.53	0.28	0	0.31
Blue Gulch Br-096	Newfoundland T'Railway	Culvert	Blue Gulch Br	Reach 1	1728.5	12.54	16.73	27.6	65.2	30.8	69.6	16.87	17.3	16.95	17.34	0.14	0.57	0.22	0.61

**Table 7-10: Watercourse Crossings - Overtopping Summary – Humber River and Tributaries – 1 in 100-year AEP Floods**

Structure #	Structure Name / Location	Structure Type	Watercourse	HEC-RAS Tributary	HEC-RAS Structure Number	Low Chord (m)	Top of Road (m)	Flow Data (m³/s)				Computed Water Surface Elevation (m) by Scenario				Overtopping Depth (+ve) / Freeboard Available (-ve) (m)			
								Current Development		Fully Developed		Current Development		Fully Developed		Current Development		Fully Developed	
								Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change
<b>1 in 100-year AEP Flood</b>																			
Trout Brook-001	Reidville Road	Culvert	Trout Brook	Reach 1	1533.17	11.83	15.09	35.4	87.7	39.1	92.9	15.49	16.11	15.57	16.16	0.40	1.02	0.48	1.07
TransmissionBr-002	Main Street	Bridge	TransmissionBr	Reach 1	1075	34.33	35.2	24.3	54	26.6	56.8	35.62	35.95	35.64	35.97	0.42	0.75	0.44	0.77
Steady Brook-003	Steady Brook (Thistle Drive - Bridge to Marble Village)	Bridge	Steady Brook	Reach 1	1142.11	21	21.5	130.9	304	132.2	305.7	15.64	17.35	15.66	17.37	-5.86	-4.15	-5.84	-4.13
Steady Brook-004	Steady Brook TCH Bridges (TCH-124 and TCH-064)	Bridge	Steady Brook	Reach 1	1000.34	15.3	17.2	130.9	304	132.2	305.7	11.88	13.24	11.9	13.27	-5.32	-3.96	-5.3	-3.93
Steady Brook-005	Steady Brook (Marble Drive Bridge)	Bridge	Steady Brook	Reach 1	742.21	8	9.48	130.9	304	132.2	305.7	6.49	10.04	6.5	10.17	-2.99	0.56	-2.98	0.69
Steady Brook-006	TransCanada Highway	Culvert	Steady Brook	Reach 2	513.65	11.49	12.96	3.4	8.6	3.8	9	12.45	13.3	12.95	13.32	-0.51	0.34	-0.01	0.36
Steady Brook-007	TransCanada Highway	Culvert	Steady Brook	Reach 4	285	10.68	11.86	22.1	54.2	22.1	54.2	6.32	6.32	6.32	6.32	-5.54	-5.54	-5.54	-5.54
Steady Brook-008	TransCanada Highway	Culvert	Steady Brook	Reach 3	53.5	8	9	14.5	38.8	14.5	38.8	9.44	9.85	9.44	10.01	0.44	0.85	0.44	1.01
South Brook-009	Midland Row	Culvert	South Brook	Reach 6	2137.38	35.27	35.54	17.9	47.6	24.2	55.7	35.98	35.77	35.55	35.83	0.44	0.23	0.01	0.29
South Brook-010	Hodder Drive	Culvert	South Brook	Reach 6	2011.6	33.55	33.84	17.9	47.6	24.2	55.7	33.99	33.89	33.82	34.07	0.15	0.05	-0.02	0.23
South Brook-011	Birchview Drive	Culvert	South Brook	Reach 6	1918.07	33.1	33.24	17.9	47.6	24.2	55.7	33.14	33.24	33.76	33.29	-0.10	0	0.52	0.05
South Brook-012	Dawson Drive	Culvert	South Brook	Reach 6	1827.4	31.46	31.66	17.9	47.6	24.2	55.7	31.97	32.07	32	32.2	0.31	0.41	0.34	0.54
South Brook-013	Earle Drive	Culvert	South Brook	Reach 6	1668	30.07	30.05	17.9	47.6	24.2	55.7	31.79	31.98	31.87	32.01	1.74	1.93	1.82	1.96
South Brook-014	Main Street	Culvert	South Brook	Reach 6	1454.64	28.28	31.58	17.9	47.6	24.2	55.7	31.88	32.05	31.94	32.08	0.30	0.47	0.36	0.5
South Brook-015	Church Street	Culvert	South Brook	Reach 6	1028.26	24.48	24.98	17.9	47.6	24.2	55.7	25.33	25.42	25.26	25.47	0.35	0.44	0.28	0.49
South Brook-016	1 Avenue	Culvert	South Brook	Reach 6	693.5	21.33	21.56	17.9	47.6	24.2	55.7	22.02	22.01	21.62	22.01	0.46	0.45	0.06	0.45
South Brook-017	TransCanada Highway	Culvert	South Brook	Reach 6	177	13.37	18.1	17.9	47.6	24.2	55.7	18.05	18.45	18.05	18.49	-0.05	0.35	-0.05	0.39
South Brook-018	Forest Drive	Culvert	South Brook	Reach 5	739	41.8	42.16	8.4	21.2	10.3	23.7	42.41	42.8	42.55	42.86	0.25	0.64	0.39	0.7
South Brook-019	Main Street	Culvert	South Brook	Reach 5	402	23.63	25.9	8.4	21.2	10.3	23.7	24.48	26.23	25.64	26.28	-1.42	0.33	-0.26	0.38
South Brook-020	Main Street	Bridge	South Brook	Reach 4	766.5	16.66	17.68	160.9	316.7	198.6	351.2	17.81	18.92	18.51	19.02	0.13	1.24	0.83	1.34
South Brook-021	Church Street	Bridge	South Brook	Reach 4	697	16	17	160.9	316.7	198.6	351.2	17.08	18.66	18.25	18.73	0.08	1.66	1.25	1.73
South Brook-022	PA 44 Pasadena (South Brook Bridges - TCH 162)	Bridge	South Brook	Reach 2	823	11.1	13.38	167.1	329.1	205.6	364.5	10.41	14.6	10.95	14.67	-2.97	1.22	-2.43	1.29
Rocky Brook-023	Old Rocky Brook Road	Bridge	Rocky Brook	Reach 1	3623.35	20	21.04	142.6	345.9	143.1	346.7	15.57	16.92	15.57	16.92	-5.47	-4.12	-5.47	-4.12
River_19-024	Riverside Drive	Culvert	River_19	Reach_19	658.1	40.64	41.51	1	2.9	1	2.9	40.32	41.18	40.32	41.18	-1.19	-0.33	-1.19	-0.33
River_18-025	Riverside Drive	Culvert	River_18	Reach_18	642.8	39.24	39.17	15.1	36.7	15.1	36.7	39.9	40.61	39.9	40.61	0.73	1.44	0.73	1.44
River_18-026	Unnamed Road in Humber Valley Resort	Culvert	River_18	Reach_18	570.4	33.28	34.29	15.1	36.7	15.1	36.7	35.09	35.47	35.09	35.47	0.80	1.18	0.8	1.18



Structure #	Structure Name / Location	Structure Type	Watercourse	HEC-RAS Tributary	HEC-RAS Structure Number	Low Chord (m)	Top of Road (m)	Flow Data (m <sup>3</sup> /s)				Computed Water Surface Elevation (m) by Scenario				Overtopping Depth (+ve) / Freeboard Available (-ve) (m)			
								Current Development		Fully Developed		Current Development		Fully Developed		Current Development		Fully Developed	
								Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change
<b>1 in 100-year AEP Flood</b>																			
River_18-027	Unnamed Road in Humber Valley Resort	Culvert	River_18	Reach_18	102.31	13.29	17.05	15.1	36.7	15.1	36.7	17.32	17.98	17.32	17.98	0.27	0.93	0.27	0.93
River_17-028	TransCanada Highway	Culvert	River_17	Reach_17	451.7	32.02	36.99	11.9	28.9	12.2	29.3	36.99	36.99	36.99	36.99	0.00	0	0	0
River_17-029	Newfoundland T'Railway	Culvert	River_17	Reach_17	115	9.32	11.14	11.9	28.9	12.2	29.3	11.44	12.2	11.45	12.35	0.30	1.06	0.31	1.21
Reidville-030	Old Rocky Brook Road	Culvert	Reidville	Reach 1	1747.09	20.74	23.41	8.3	20.7	8.8	21.4	23.83	24.05	23.85	24.06	0.42	0.64	0.44	0.65
Reidville-031	Reidville Road	Culvert	Reidville	Reach 2	102.25	11.74	17.86	4.9	11.8	5.3	12.4	12.02	18.07	12.19	18.09	-5.84	0.21	-5.67	0.23
Reidville-032	Reidville Road	Culvert	Reidville	Reach 3	462.12	15.5	16.2	12.4	30.7	12.9	31.3	16.89	17.42	16.89	17.43	0.69	1.22	0.69	1.23
Pasadena-033	TransCanada Highway	Culvert	Pasadena	Reach 1	145.11	29.15	30.59	7.7	19.6	8.9	21.3	30.82	30.99	30.84	31.01	0.23	0.4	0.25	0.42
Pasadena-034	TransCanada Highway	Culvert	Pasadena	Reach 2	108.9	35.76	35.88	4.5	11.1	5.1	12	36.02	36.14	36.03	36.16	0.14	0.26	0.15	0.28
Pasadena-035	Newfoundland T'Railway	Culvert	Pasadena	Reach 2	61.5	22.4	22.7	4.5	11.1	5.1	12	22.92	22.91	22.94	22.89	0.22	0.21	0.24	0.19
Pasadena-036	Midland Row	Culvert	Pasadena	Reach 3	2404.5	40.78	40.88	16.1	38.7	19	42.5	40.93	41.12	40.93	41.14	0.05	0.24	0.05	0.26
Pasadena-037	Trail	Culvert	Pasadena	Reach 3	2283.5	38	38.04	16.1	38.7	19	42.5	38.55	38.92	38.63	38.9	0.51	0.88	0.59	0.86
Pasadena-038	Main Street	Culvert	Pasadena	Reach 3	1040.5	25.4	27.06	16.1	38.7	19	42.5	27.23	27.41	27.28	27.43	0.17	0.35	0.22	0.37
Pasadena-039	TransCanada Highway	Culvert	Pasadena	Reach 3	137.38	15.85	22.78	16.1	38.7	19	42.5	22.82	23.08	22.88	23.1	0.04	0.3	0.1	0.32
Pasadena-040	TransCanada Highway	Culvert	Pasadena	Reach 4	154.15	20.97	23.64	6.4	15.3	8.2	17.4	23.64	23.64	23.64	23.64	0.00	0	0	0
Pasadena-041	TransCanada Highway	Culvert	Pasadena	Reach 5	452.23	18.44	19.74	32.8	79.5	37.9	86.3	19.97	20.3	20.04	20.32	0.23	0.56	0.3	0.58
Pasadena-042	Newfoundland T'Railway	Culvert	Pasadena	Reach 5	92.83	10.3	12.28	32.8	79.5	37.9	86.3	12.46	12.67	12.49	12.69	0.18	0.39	0.21	0.41
Pasadena-043	TransCanada Highway	Culvert	Pasadena	Reach 6	664	24.34	29.39	7.9	24.2	14.1	32.2	25.13	29.42	28.95	29.48	-4.26	0.03	-0.44	0.09
Nichols Brook-044	Grace Avenue	Culvert	Nichols Brook	Reach 9	122.34	34.18	36.09	1.1	2.4	1.1	2.4	33.54	33.8	33.54	33.8	-2.55	-2.29	-2.55	-2.29
Nichols Brook-045	Grace Avenue	Culvert	Nichols Brook	Reach 7	470.45	25.67	32.89	4.1	12.7	6.4	16.3	26.04	33.13	27.23	33.23	-6.85	0.24	-5.66	0.34
Nichols Brook-046	Driveway Crossing	Culvert	Nichols Brook	Reach 7	262.6	21.54	30.25	4.1	12.7	6.4	16.3	21.91	30.06	23.1	30.34	-8.34	-0.19	-7.15	0.09
Nichols Brook-047	George Aaron Drive	Culvert	Nichols Brook	Reach 1	634.04	11.87	17.2	40.2	111.9	45.8	120.4	14.19	18.01	15.28	18.08	-3.01	0.81	-1.92	0.88
Matthews Brook-048	Bonnell Drive	Culvert	Matthews Brook	Reach 1	710.5	24.78	26.89	24.5	53	28.2	57.1	27.06	27.38	24.9	27.42	0.17	0.49	-1.99	0.53
Matthews Brook-049	TransCanada Highway	Culvert	Matthews Brook	Reach 1	240.35	12.65	16.65	24.5	53	28.2	57.1	16.89	17.45	17.01	17.5	0.24	0.8	0.36	0.85
Matthews Brook-050	Strawberry Loop	Culvert	Matthews Brook	Reach 1	144.17	9.3	13.87	24.5	53	28.2	57.1	14.2	14.6	14.26	14.64	0.33	0.73	0.39	0.77
Matthews Brook-051	Strawberry Lane	Culvert	Matthews Brook	Reach 1	44.9	6.55	8.46	24.5	53	28.2	57.1	8.96	11.34	9.03	11.48	0.50	2.88	0.57	3.02
Lanes Brook-052	TransCanada Highway (Little Harbour)	Culvert	Lanes Brook	Reach 1	171	17.99	19.73	9.1	24.5	11.1	27.2	19.73	19.73	20.93	19.73	0.00	0	1.2	0
Lanes Brook-053	TransCanada Highway (Little Harbour)	Culvert	Lanes Brook	Reach 2	189.6	18.73	20.7	29.2	71	35.7	79.3	20.65	21.07	20.68	21.15	-0.05	0.37	-0.02	0.45
Humber Village-054	Maple Street	Culvert	Humber Village	Reach 4	457	17.6	17.6	23.7	56.2	23.7	56.2	18.17	18.31	18.17	18.31	0.57	0.71	0.57	0.71
Humber Village-055	Maple Street	Culvert	Humber Village	Reach 4	106.9	9.17	10.16	23.7	56.2	23.7	56.2	10.49	11.01	10.49	11.03	0.33	0.85	0.33	0.87



Structure #	Structure Name / Location	Structure Type	Watercourse	HEC-RAS Tributary	HEC-RAS Structure Number	Low Chord (m)	Top of Road (m)	Flow Data (m³/s)				Computed Water Surface Elevation (m) by Scenario				Overtopping Depth (+ve) / Freeboard Available (-ve) (m)			
								Current Development		Fully Developed		Current Development		Fully Developed		Current Development		Fully Developed	
								Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change
<b>1 in 100-year AEP Flood</b>																			
Humber Village-056	Marble View Drive	Culvert	Humber Village	Reach 1	1062.5	38.76	38.97	10.5	25.8	10.5	25.8	39.62	39.92	39.62	39.92	0.65	0.95	0.65	0.95
Humber Village-057	Driveway Crossing	Culvert	Humber Village	Reach 1	679	16.52	17.93	10.5	25.8	10.5	25.8	18.24	18.44	18.24	18.44	0.31	0.51	0.31	0.51
Humber Village-058	Driveway Crossing	Bridge	Humber Village	Reach 1	191	15.22	15.72	10.5	25.8	10.5	25.8	8.45	10.22	8.45	10.38	-7.27	-5.5	-7.27	-5.34
Humber Village-060	Driveway Crossing	Culvert	Humber Village	Reach 5	182.4	18.04	20.55	3	7.3	3	7.3	20.83	21.05	20.83	21.05	0.28	0.5	0.28	0.5
Humber River-061	Viking Trail / Route 430 Bridge	Bridge	Humber River	Reach 020	1770.09	10.2	11.78	1216.2	3254.3	1223.4	3271.2	8.68	12.71	8.73	12.79	-3.10	0.93	-3.05	1.01
Humber River-062	Nicholsville Bridge	Bridge	Humber River	Reach 019	23104.33	10	11.33	1202.2	3225.8	1209.5	3243.6	8.22	12.36	8.28	12.47	-3.11	1.03	-3.05	1.14
Humber River-063	Humber Valley Resort Bridge (to Lakeside Drive)	Bridge	Humber River	Reach 010	12854.08	10	12.28	1145.5	2674	1167.4	2736.9	8	12.02	8.06	12.18	-4.28	-0.26	-4.22	-0.1
Humber River-064	Humber Village (Tamarack Street) Bridge	Bridge	Humber River	Reach 006	6785.7	7.7	9	1132.7	2642.4	1154.4	2704.8	6.33	10.43	6.41	10.58	-2.67	1.43	-2.59	1.58
Humber River-065	Ballam Bridge (North Shore Highway)	Bridge	Humber River	Reach 001	1830.94	3.17	4.27	1106.6	2574.5	1129.5	2637.2	1.6	2.87	1.62	3.62	-2.67	-1.4	-2.65	-0.65
Deer Lake-066	TransCanada Highway	Culvert	Deer Lake	Reach 7	754.5	27.83	28.85	10.36	24.71	10.72	25.16	29.17	29.16	29.17	29.16	0.32	0.31	0.32	0.31
Deer Lake-067	Airport Road	Culvert	Deer Lake	Reach 6	248.9	12.52	16.2	13.3	31.9	15	33.8	16.2	16.2	16.2	16.2	0.00	0	0	0
Deer Lake-068	Airport Road	Culvert	Deer Lake	Reach 10	23.87	10.56	11.23	8.8	19.7	12.5	23.7	11.26	12.95	11.4	13.03	0.03	1.72	0.17	1.8
Deer Lake-069	Airport Avenue Extension	Culvert	Deer Lake	Reach 5	3605	32.54	37.5	20.3	45.6	22.1	47.7	37.38	37.79	37.35	37.81	-0.12	0.29	-0.15	0.31
Deer Lake-070	TransCanada Highway	Culvert	Deer Lake	Reach 5	1253.05	13.39	18.56	20.3	45.6	22.1	47.7	18.61	18.83	18.64	18.85	0.05	0.27	0.08	0.29
Deer Lake-071	Goose Arm Road	Culvert	Deer Lake	Reach 13	365.45	34.57	34.35	0.8	3.5	1.7	5.2	33.8	34.45	34.16	34.47	-0.55	0.1	-0.19	0.12
Deer Lake-072	Scott Drive	Culvert	Deer Lake	Reach 13	256.64	31.17	32.15	0.8	3.5	1.7	5.2	30.4	31.34	30.76	31.9	-1.75	-0.81	-1.39	-0.25
Deer Lake-073	Goose Arm Road	Culvert	Deer Lake	Reach 14	247.58	34.95	34.98	2.9	10.8	5.1	14.5	35.18	35.37	35.25	35.44	0.20	0.39	0.27	0.46
Deer Lake-074	Nicholsville Road	Culvert	Deer Lake	Reach 1	524.1	8.8	9.73	7.2	15.6	9.5	18.1	9.92	12.24	9.96	12.39	0.19	2.51	0.23	2.66
Deer Lake-075	Mosses Lane	Culvert	Deer Lake	Reach 1	164.12	7.75	8.7	7.2	15.6	9.5	18.1	8.72	12.23	8.72	12.38	0.02	3.53	0.02	3.68
Deer Lake-076	Main Street South	Culvert	Deer Lake	Reach 2	3197.7	45.27	45.97	11.4	24.9	15.8	29.4	46.38	46.44	46.42	46.42	0.41	0.47	0.45	0.45
Deer Lake-077	Mayor Avenue	Culvert	Deer Lake	Reach 2	2720	36.73	36.74	11.4	24.9	15.8	29.4	37.46	37.76	37.38	37.8	0.72	1.02	0.64	1.06
Deer Lake-078	High Street	Culvert	Deer Lake	Reach 2	2674.5	35.39	36.71	11.4	24.9	15.8	29.4	37.16	37.42	37.27	37.47	0.45	0.71	0.56	0.76
Deer Lake-079	4 Avenue	Culvert	Deer Lake	Reach 2	2485.5	33.79	35.47	11.4	24.9	15.8	29.4	35.97	36.3	36.09	36.4	0.50	0.83	0.62	0.93
Deer Lake-080	Shears Place	Culvert	Deer Lake	Reach 2	2174.61	29.69	30.01	11.4	24.9	15.8	29.4	30.01	30.23	30.07	30.31	0.00	0.22	0.06	0.3
Deer Lake-081	5 Avenue Extension	Culvert	Deer Lake	Reach 2	1772.28	23.45	24.1	11.4	24.9	15.8	29.4	24.12	25.5	24.12	26.27	0.02	1.4	0.02	2.17
Deer Lake-082	Driveway Crossing	Culvert	Deer Lake	Reach 2	1716.5	23.21	23.78	11.4	24.9	15.8	29.4	24	25.49	24.06	26.26	0.22	1.71	0.28	2.48
Deer Lake-083	Reids Lane	Culvert	Deer Lake	Reach 2	1682.83	23.07	23.71	11.4	24.9	15.8	29.4	24	25.48	24.06	26.25	0.29	1.77	0.35	2.54
Deer Lake-084	Wights Road	Culvert	Deer Lake	Reach 2	1395.24	20.96	22.43	11.4	24.9	15.8	29.4	23.98	25.47	24.03	26.24	1.55	3.04	1.6	3.81
Deer Lake-085	Driveway Crossing	Culvert	Deer Lake	Reach 2	1354.54	20.78	21.81	11.4	24.9	15.8	29.4	23.97	25.46	24.02	26.24	2.16	3.65	2.21	4.43

Structure #	Structure Name / Location	Structure Type	Watercourse	HEC-RAS Tributary	HEC-RAS Structure Number	Low Chord (m)	Top of Road (m)	Flow Data (m³/s)				Computed Water Surface Elevation (m) by Scenario				Overtopping Depth (+ve) / Freeboard Available (-ve) (m)			
								Current Development		Fully Developed		Current Development		Fully Developed		Current Development		Fully Developed	
								Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change	Current Climate	Climate Change
<b>1 in 100-year AEP Flood</b>																			
Deer Lake-086	Old Bonnie Bay Road	Culvert	Deer Lake	Reach 2	908.5	19.73	23.92	11.4	24.9	15.8	29.4	18.93	18.97	18.94	18.99	-4.99	-4.95	-4.98	-4.93
Deer Lake-087	TransCanada Highway	Culvert	Deer Lake	Reach 2	602	13.87	17.35	11.4	24.9	15.8	29.4	16.6	17.47	17.4	17.5	-0.75	0.12	0.05	0.15
Deer Lake-088	TransCanada Highway (Ramp)	Culvert	Deer Lake	Reach 2	492.24	12.49	16.61	11.4	24.9	15.8	29.4	16.61	16.73	16.64	16.76	0.00	0.12	0.03	0.15
Deer Lake-089	Amanda Avenue	Culvert	Deer Lake	Reach 12	247.15	13.67	13.96	3.9	15.2	7.7	21.4	14.01	14.59	14.28	14.76	0.05	0.63	0.32	0.8
Deer Lake-090	Driveway Crossing	Culvert	Deer Lake	Reach 12	143.14	7.48	7.1	3.9	15.2	7.7	21.4	8.17	12.21	8.23	12.36	1.07	5.11	1.13	5.26
Blue Gulch Br-091	Midland Row	Culvert	Blue Gulch Br	Reach 1	3715	41.51	41.56	41	97	44.8	101.9	42.09	42.07	41.84	42.09	0.53	0.51	0.28	0.53
Blue Gulch Br-092	Bonnell Drive	Culvert	Blue Gulch Br	Reach 1	3317	36.19	36.3	41	97	44.8	101.9	36.3	36.3	36.3	36.32	0.00	0	0	0.02
Blue Gulch Br-093	Main Street	Bridge	Blue Gulch Br	Reach 1	2889.5	31.9	32.38	41	97	44.8	101.9	33.02	32.87	32.68	32.88	0.64	0.49	0.3	0.5
Blue Gulch Br-094	Church Street	Bridge	Blue Gulch Br	Reach 1	2663.5	28.2	28.65	41	97	44.8	101.9	29.29	29.21	29.32	29.21	0.64	0.56	0.67	0.56
Blue Gulch Br-095	TransCanada Highway	Culvert	Blue Gulch Br	Reach 1	1947	17.36	23.28	41	97	44.8	101.9	23.34	23.73	23.39	23.75	0.06	0.45	0.11	0.47
Blue Gulch Br-096	Newfoundland T'Railway	Culvert	Blue Gulch Br	Reach 1	1728.5	12.54	16.73	41	97	44.8	101.9	16.89	17.53	17.07	17.56	0.16	0.8	0.34	0.83

## 7.5 Ice Jam Assessments

### 7.5.1 Deer Lake – January 2018

Heavy rain, fast-melting snow and ice jams led to flooding which caused significant damage to communities and other infrastructure along the Humber River in January 2018 (ref. Figure 7-4). It was noted in conversation with representatives from the Town of Deer Lake (ref. Section 2.4) that the ice damming/flooding event that occurred in January 2018 was an anomalous event for the community. It was noted that “people have lived on the river for 70 years and have never seen what happened last year”.

This report section describes the meteorological and hydraulic conditions that potentially led to and influenced the January 2018 ice-jam flood event along the upper Humber River at the Town of Deer Lake. The methodology to calculate the severity of the event with regards to water level staging and flooding along with simulated results are also provided. All data used for the ice jam assessments is in accordance with the CGVD-2013 datum.

This ice jam flood event assessment and associated reporting was completed by Dr. Karl-Erich Lindenschmidt, Associate Professor at the School of Environment and Sustainability, at the University of Saskatchewan.<sup>23</sup>



**Figure 7-4: Ice was flowing down the Humber River near the Nicholville Bridge**  
(Source: CBC News, 2018c)

<sup>23</sup> Source: <https://sens.usask.ca/people/faculty/core-faculty/lindenschmidt-karl.php>

### 7.5.1.1 Meteorological Conditions

During the beginning of January 2018, air temperatures at the Town of Deer Lake were below freezing (ref. Figure 7-5). A warm spell occurred during the time frame January 11 to 13, 2018, when air temperatures reached the positive double-digit values causing much snowmelt and runoff.

The warm spell was accompanied by over 40 mm of rain and there was approximately 60 cm of snow recorded on the ground at the Deer Lake meteorological station, much of which melted (~90%) during the warm period (ref. Figure 7-6). Both the rain and the snowmelt would have contributed to high runoff in the catchment area.

Figure 7-7 shows a generalised extreme value GEV distribution of the maximum flows recorded in January for the years 1930 – 1933 and 1938 – 2020 (87 years) for the Upper Humber River near Reidville station. There is uncertainty in the distribution because it potentially may consist of a mix of both open-water and ice-induced maximum flows. For instance, the maximum daily-averaged open-water flow on January 15, 2018 was 1,118.5 m<sup>3</sup>/s. However, it is assumed that ice did not influence the hydraulics of the river until the following day when the daily-average flow was 724 m<sup>3</sup>/s, corresponding to an annual exceedance probability (AEP) of approximately 1 in 80 years.

The large runoff volume from the Deer Lake catchment area led to a rapid rise in the water level elevation of the lake, as evident in Figure 7-8. Water levels rose over 2.25 m during the warm spell in January 2018 to an elevation of approximately 7.5 m.a.s.l. This was the highest elevation recorded in January during the 32-years of records between 1987 and 2018 (ref. Figure 7-9), with an AEP of over 1 in 100-years.

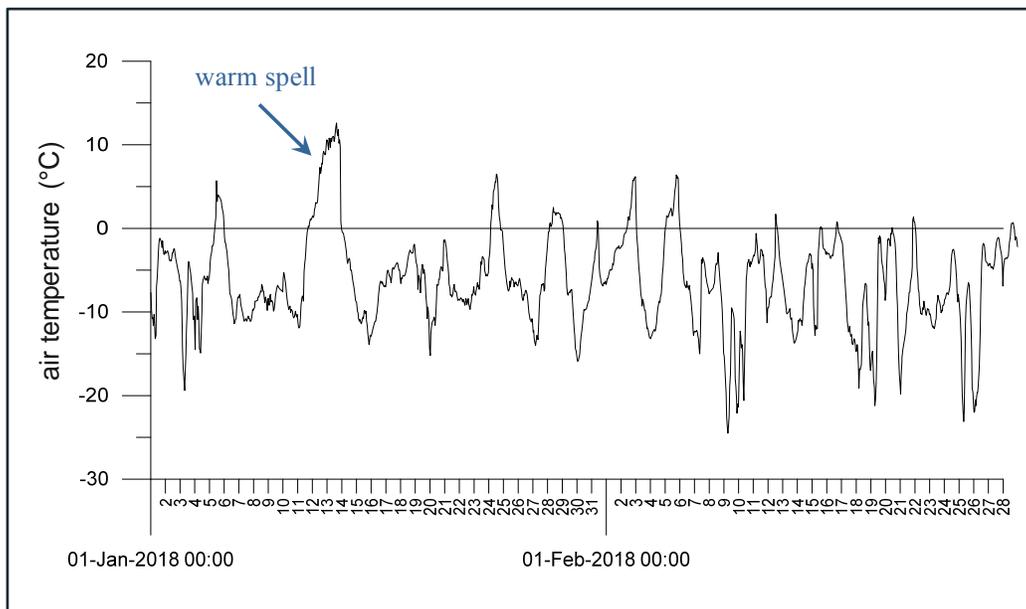


Figure 7-5: Air temperatures recorded at Deer Lake in January and February 2018

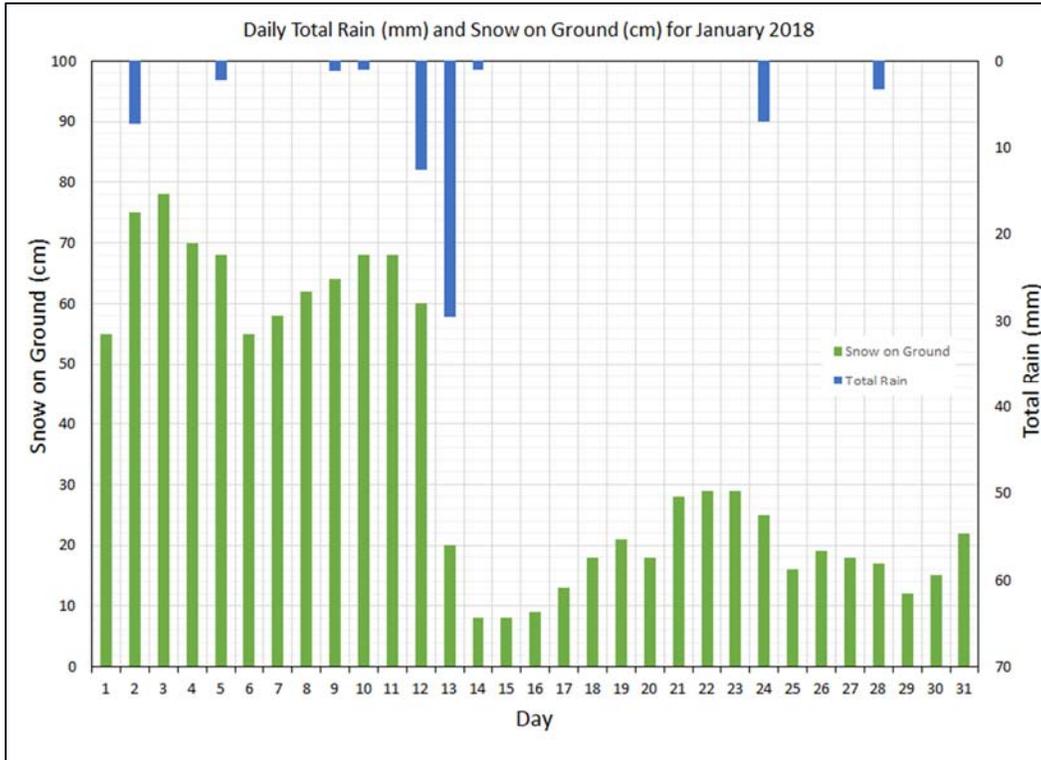


Figure 7-6: Total Rain and Snow-on-Ground for January 2018 at Deer Lake Airport

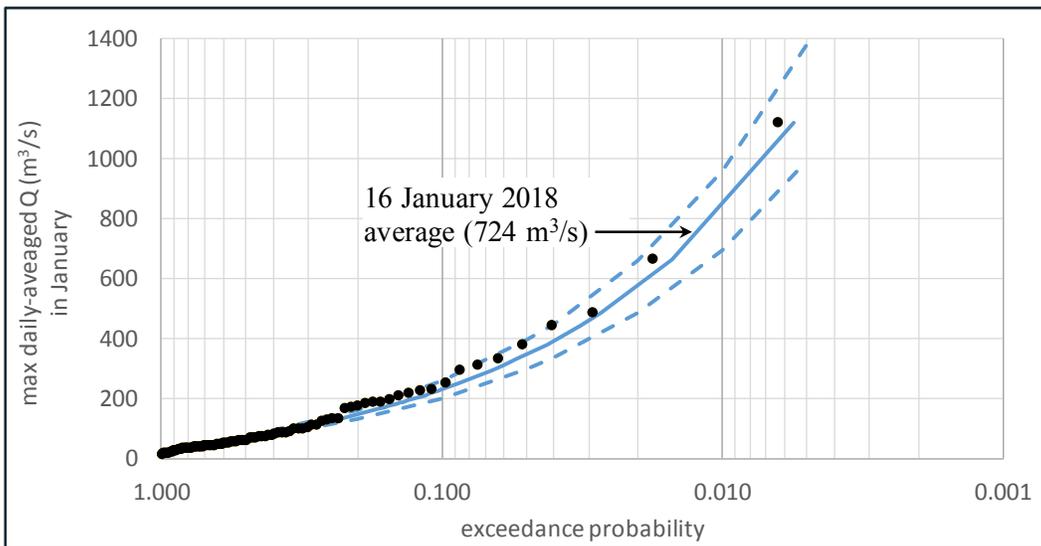
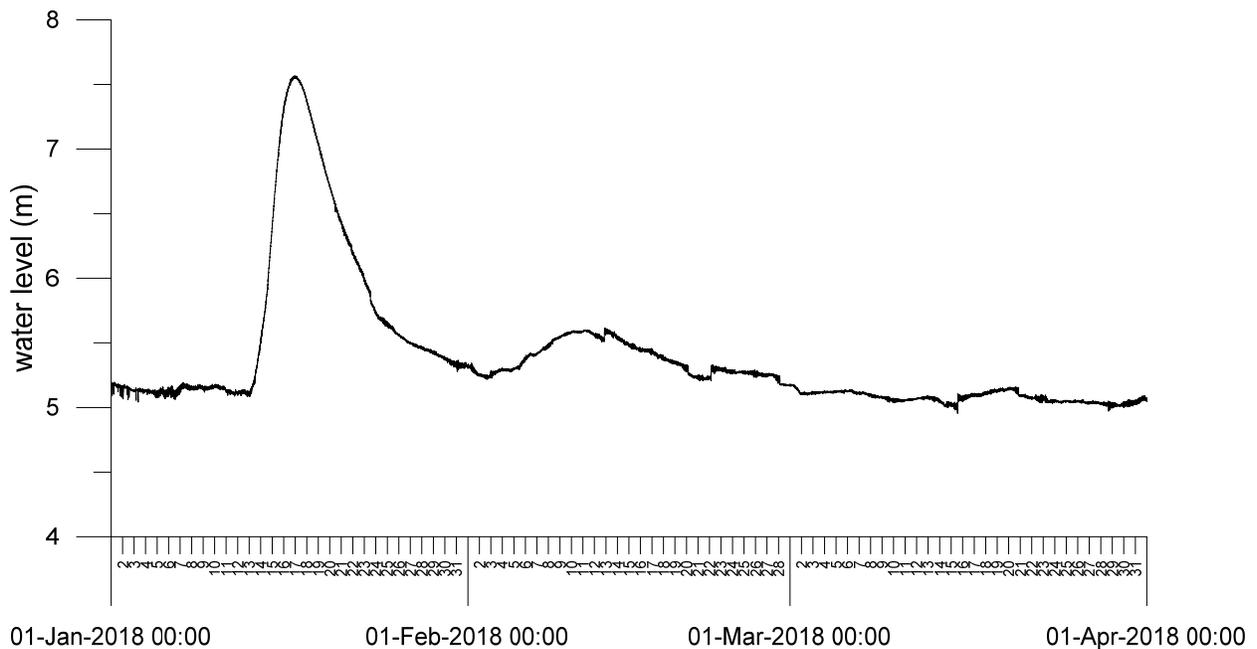
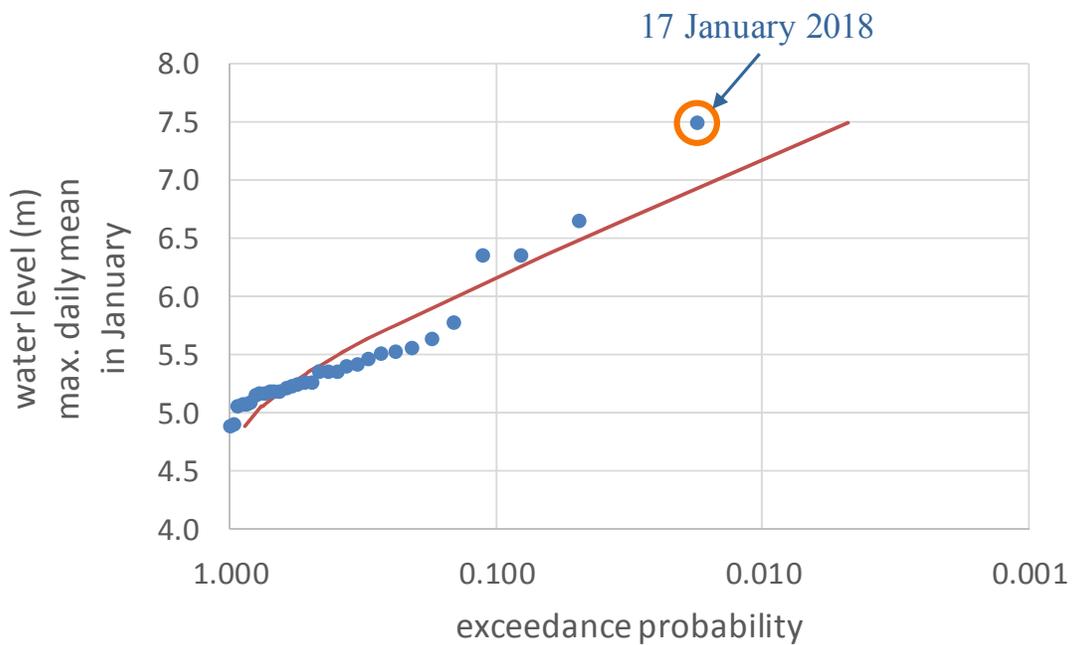


Figure 7-7: Generalised extreme value (GEV) distribution with 95% confidence band of maximum daily-averaged flows recorded in the months of January between 1930 and 2020 (except 1934 – 1937) at the gauge "Upper Humber River near Reidville"



**Figure 7-8: Water level elevations recorded at the Deer Lake gauge near generating station for the first three months of 2018**

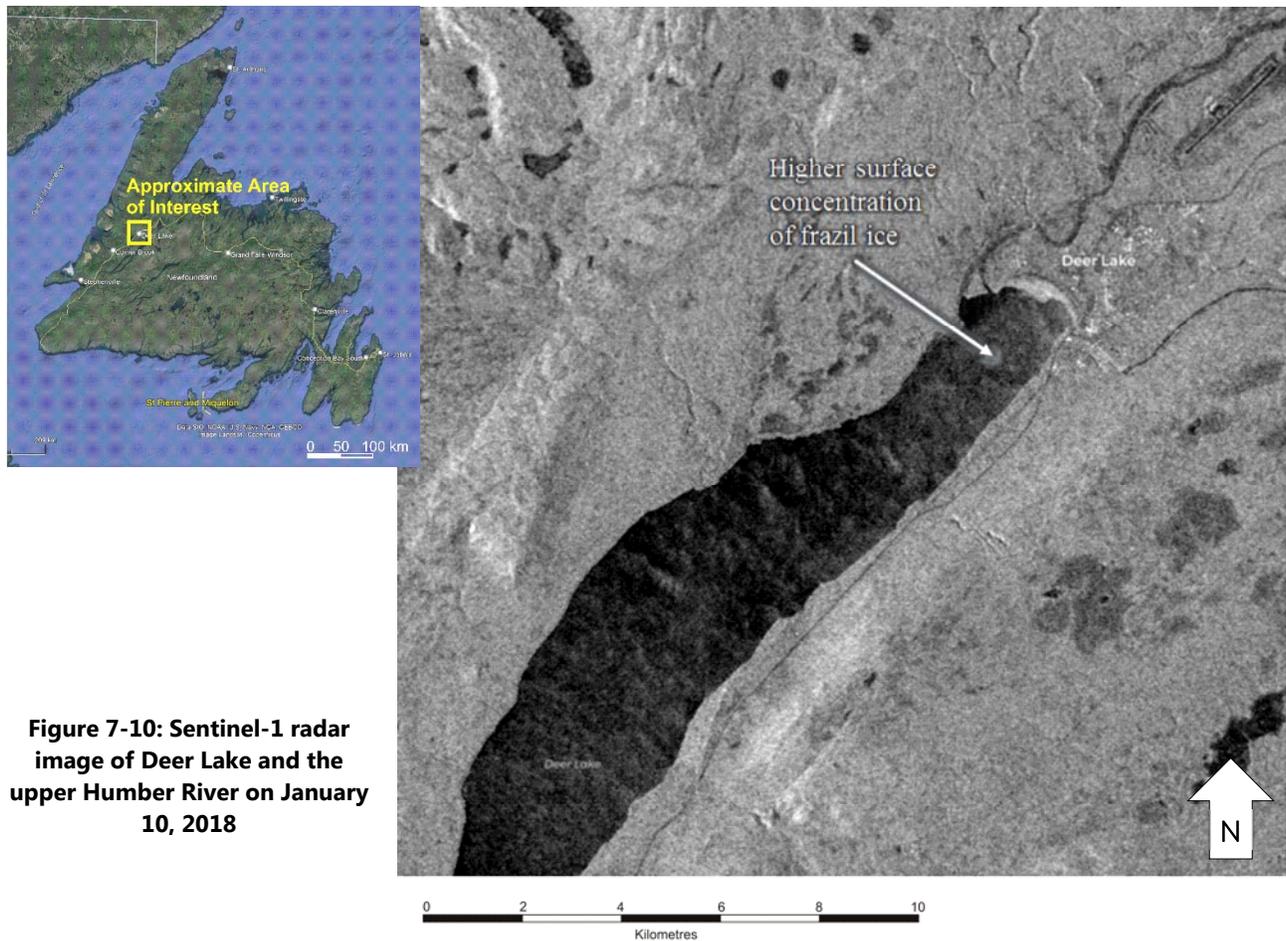


**Figure 7-9: Extreme value I (Gumbel) distribution of maximum daily mean water level elevations recorded at the Deer Lake gauge near the generating station in all months of January between 1987 and 2018**

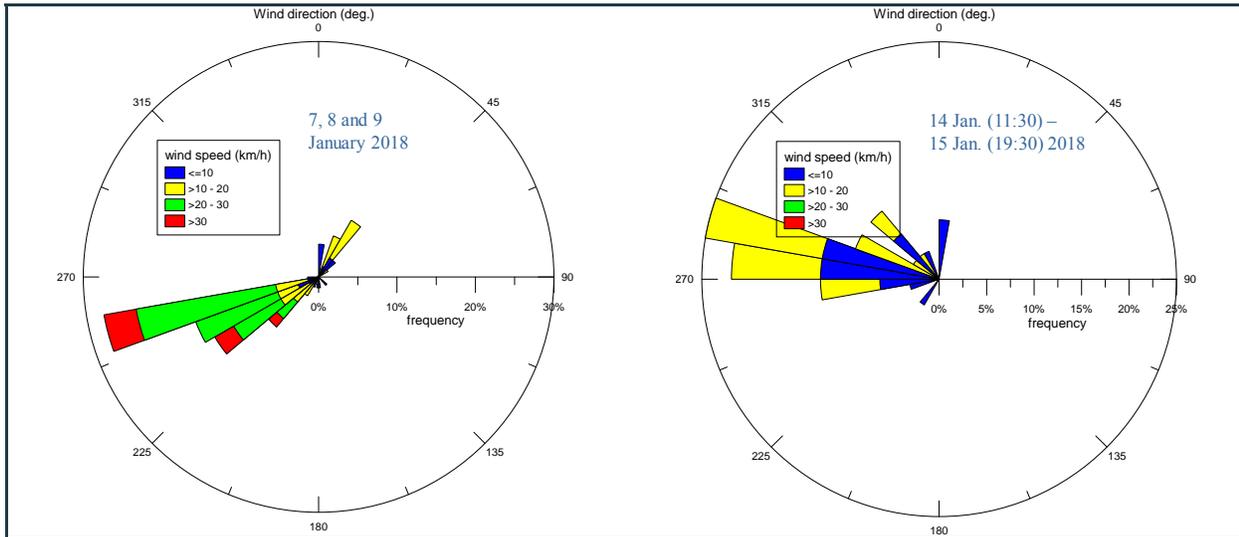
### 7.5.1.2 Ice Conditions

Figure 7-10 shows the Deer Lake water surface on January 10, 2018, an image acquired by the European Space Agency’s radar satellite Sentinel-1. The image was acquired when air temperatures were still well below freezing (ref. Figure 7-5), just before the warm spell of January 11 to 13, 2018. A higher concentration of frazil ice is evident in the northeast portion of the lake, after high winds persisted from the west-southwest and southwest (ref. Figure 7-11, left panel) across the fetch of the lake. The cold wind would have caused frazil ice to form and accumulate at the downwind side area of the lake. The persistent wind in the northeast direction may have formed a seiche with water levels set up higher at the lake’s northeast end compared to its southwest end.

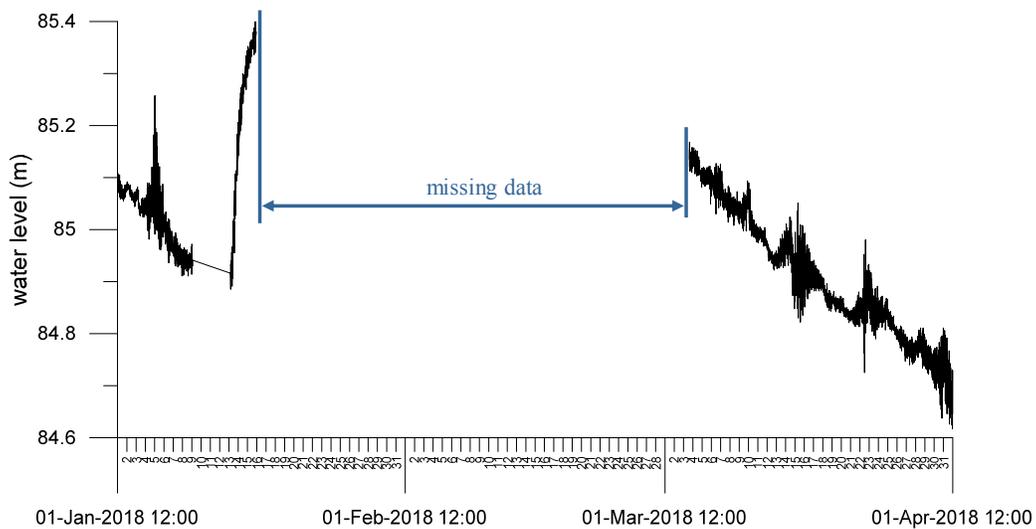
The water level also rose in Grand Lake, as recorded on the lake’s gauge east of Grand Lake Brook (see Figure 7-12), as a result of the high runoff in that lake’s catchment area.



**Figure 7-10: Sentinel-1 radar image of Deer Lake and the upper Humber River on January 10, 2018**



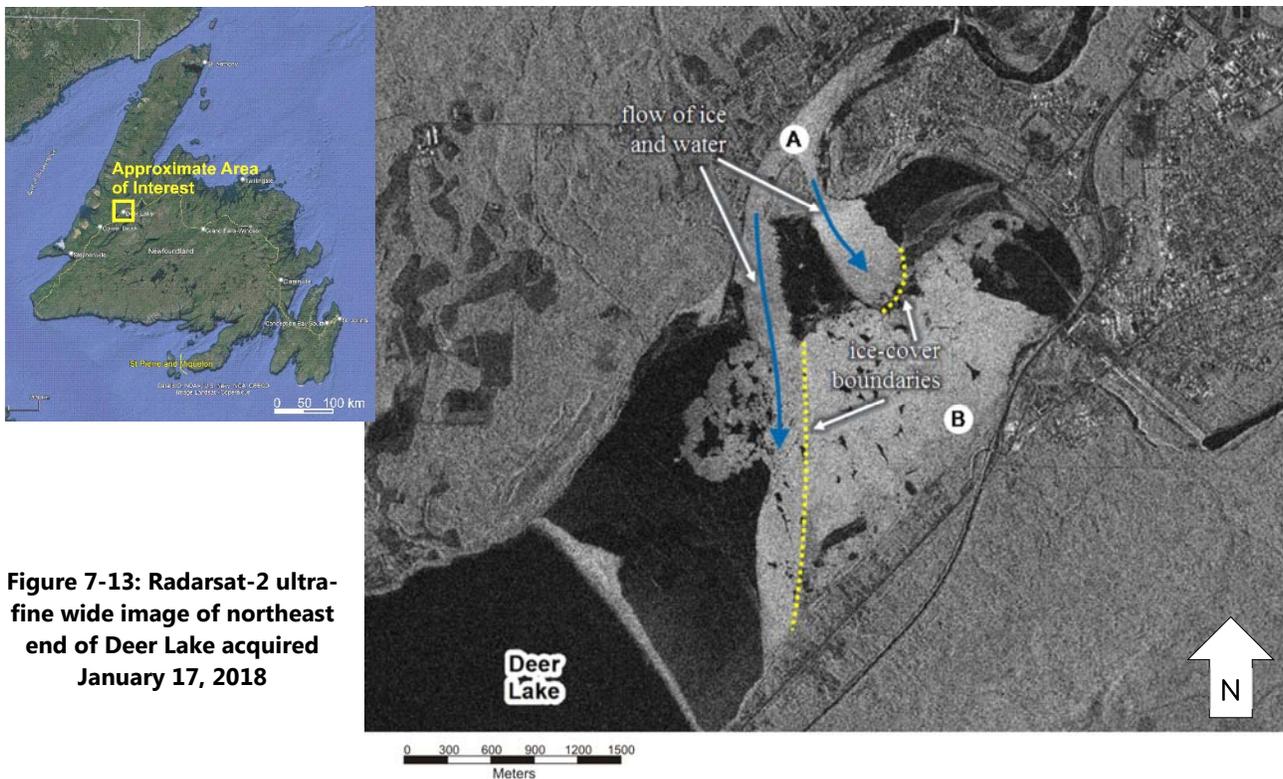
**Figure 7-11: Wind roses for January 7 to 9, 2018 (left panel) and January 14 & 15, 2018 (right panel)**



**Figure 7-12: Water level elevations recorded at the Grand Lake gauge east of Grand Lake Brook for the January, February and March 2018**

Figure 7-13 shows a Radarsat-2 image of the ice cover on Deer Lake on January 17, 2018. The ice cover in area "B" appears to consist of ice of different origin than the ice along the arrows from the upper Humber River at "A". The yellow lines indicate boundaries of the two different ice covers. Persistent wind from the west-northwest direction (see Figure 7-11, right panel) may have pushed and accumulated frazil ice onto the east shore at the generating plant. It is unknown how much water may have been spilled through the generating plant's spillway from Grand Lake to Deer Lake after the high runoff event, when air temperatures again dropped

below freezing. In such a case, high spill flow velocities could increase water turbulence in Deer Lake to create additional frazil ice. Figure 7-14 provides evidence of the turbulence that can be created when one of the spillway gates are opened. Figure 7-15 shows turbulent water discharged from the powerhouse. The frazil ice cover indicated by "B" in Figure 7-13 could then potentially block ice from "A" to flow further into the lake causing some ice and water to back up as it is flowing down and exiting the upper Humber River into Deer Lake. The Canadian Broadcasting Corporation (CBC) reported that "The mouth of the Humber River, where it flows into Deer Lake, is blocked by an ice obstruction that stretches across to the eastern side of the lake" (CBC, 2018a). The high flows in the upper Humber River, the elevated lake water level and the wind setup will still have been major contributors to the severity of the ice-jam flood event of January 2018.



**Figure 7-13: Radarsat-2 ultra-fine wide image of northeast end of Deer Lake acquired January 17, 2018**

### 7.5.1.3 River Ice Hydraulic Modelling

A river-ice hydraulic model was developed for the upper Humber River. The software package RIVICE is a hydraulic river ice model that mimics important ice processes both during river freeze-up and ice-cover breakup (Lindenschmidt, 2017; ECCO, 2013). RIVICE is a one-dimensional (variations in the longitudinal direction) hydrodynamic model that dynamically simulates the progression of ice-cover and ice-jam formation and collapse. Hence, not only equilibrium jams but under-developed jams and temporarily over-shot jams can be simulated. The progression, shoving and collapse of an ice cover or ice jam is determined by tracking the

balance of forces applied to the jam ice cover.

Cross-sections from a bathymetric survey carried out in November 2018 were used to set up the model. An open-water case using flows and water level elevations during the survey was first simulated to calibrate Manning's roughness coefficients  $n$  along the modelled reach (ref. Figure 7-16). A high roughness of  $n = 0.080$  at a bridge section was calibrated. Roughness coefficients 0.025 and 0.030 were calibrated for the river stretches, respectively upstream and downstream of the bridge.



**Figure 7-14: Spillway on Grand Lake Main Dam**

(Source: NTV, 2016)

The frazil ice cover along the Humber River extended to approximately chainage 5,800 m of the model domain, an example of which is shown in Figure 7-17. Unfortunately, high-water marks were not available and the gauge on the upper Humber River near Reidville was impacted by ice locally with a lodgement created immediately downstream from the gauge at a set of rapids, as shown in the Sentinel-1 image in Figure 7-17 acquired January 19, 2018. Ice effects had already occurred on January 16, 2018 as shown by the stage hydrograph in Figure 7-18. Hence, the local jamming and ice-cover formation distorts the signal that may be due to the ice-cover formation further downstream at Deer Lake making it difficult to directly relate those water level readings into the modelling results. Additionally, there is a set of rapids between the gauge location and the upstream-most surveyed cross-section. Without additional cross-sections upstream of the rapids, the geomorphology, in particular the increase in bed slope, cannot be captured in the model setup. Hence, only ice-cover extent could be used for model calibration causing model results to have a high degree of uncertainty. A simulation of the ice-cover formation is provided in Figure 7-19, which matches the ice-cover extent of January 17, 2018 (ref. Figure 7-13). The model results in Figure 7-19 include the open-water profile simulated with the same discharge as that used to simulate the ice-cover gives an indication of the potential staging that occurred through the ice jamming.



Figure 7-15: "Turbulent waters constantly churning out of the Deer Lake Power plant ..."

(Source: Telegram, 2018)

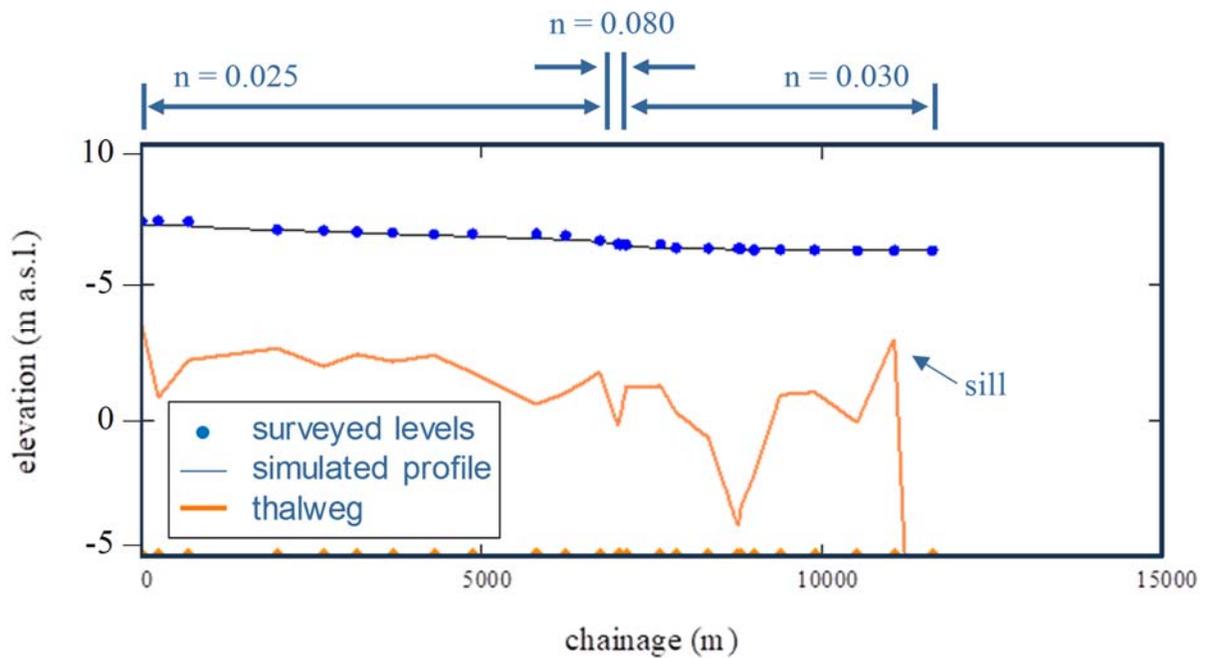


Figure 7-16: Open-water calibration with varying Manning's roughness coefficients  $n$  along the modelled reach of the upper Humber River

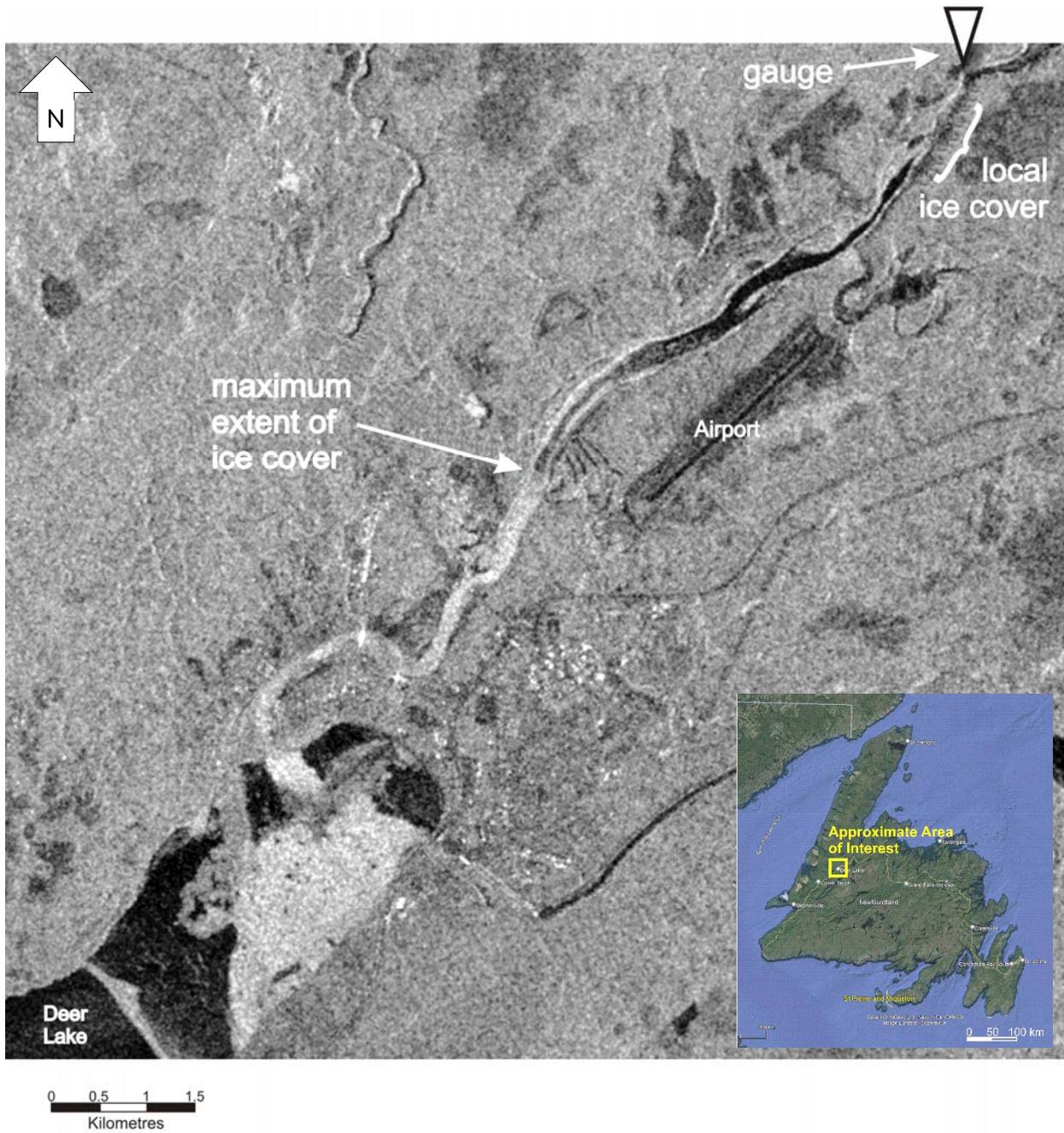
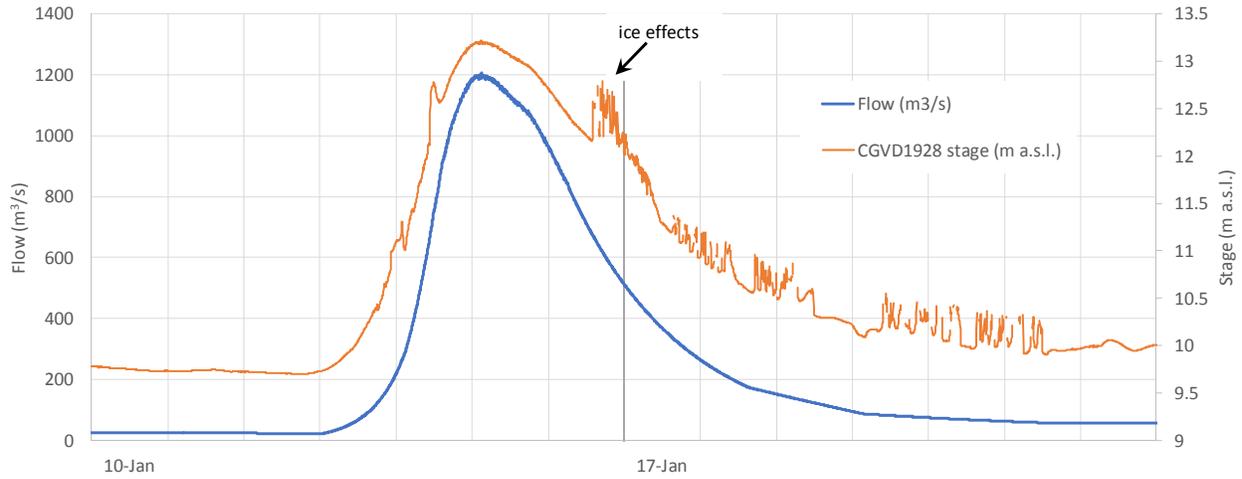
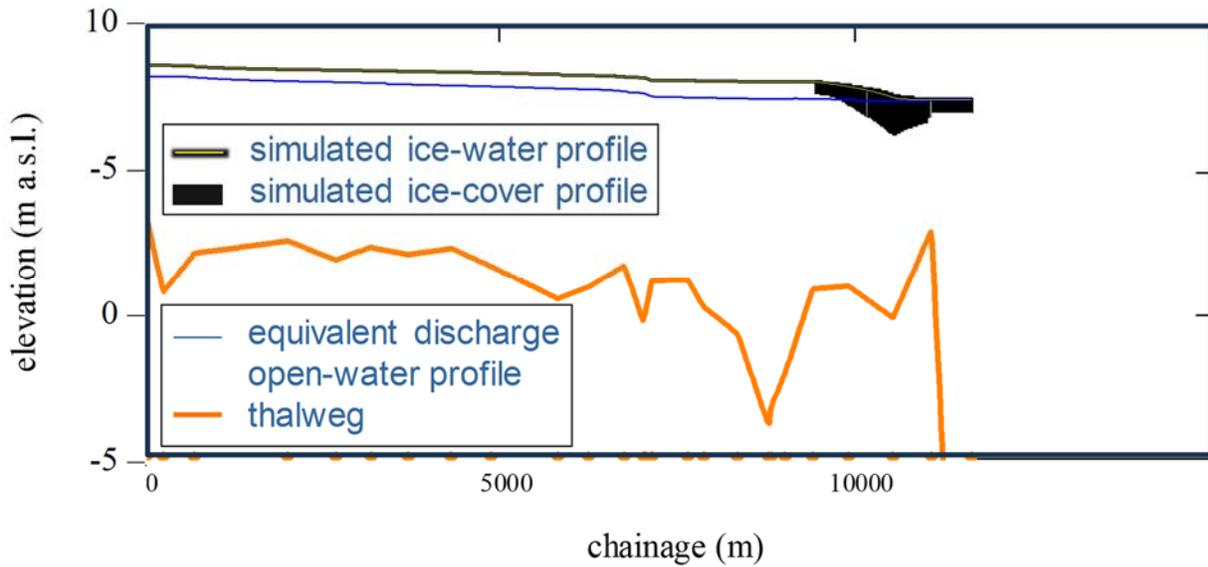


Figure 7-17: Sentinel-1A image of the upper Humber River acquired on January 19, 2018



**Figure 7-18: Flow and stage hydrographs recorded at the Humber River gauge near Reidville  
(Please note: ice effects on the recorded stage on January 16, 2018)**

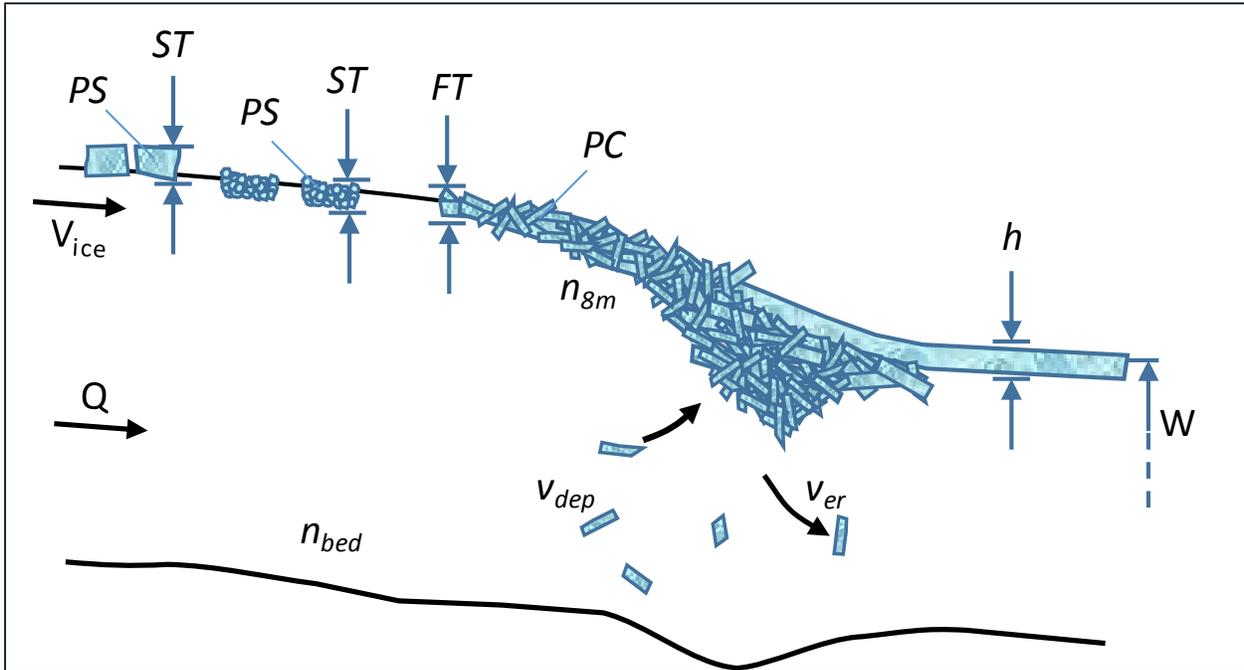


**Figure 7-19: Ice-cover simulation of the January 2018 event**

A local sensitivity analysis was carried out on the backwater profile of a fully extended ice cover along the modelling domain of the upper Humber River. The parameters and boundary conditions included in the analysis are as follows and are depicted in Figure 7-20:

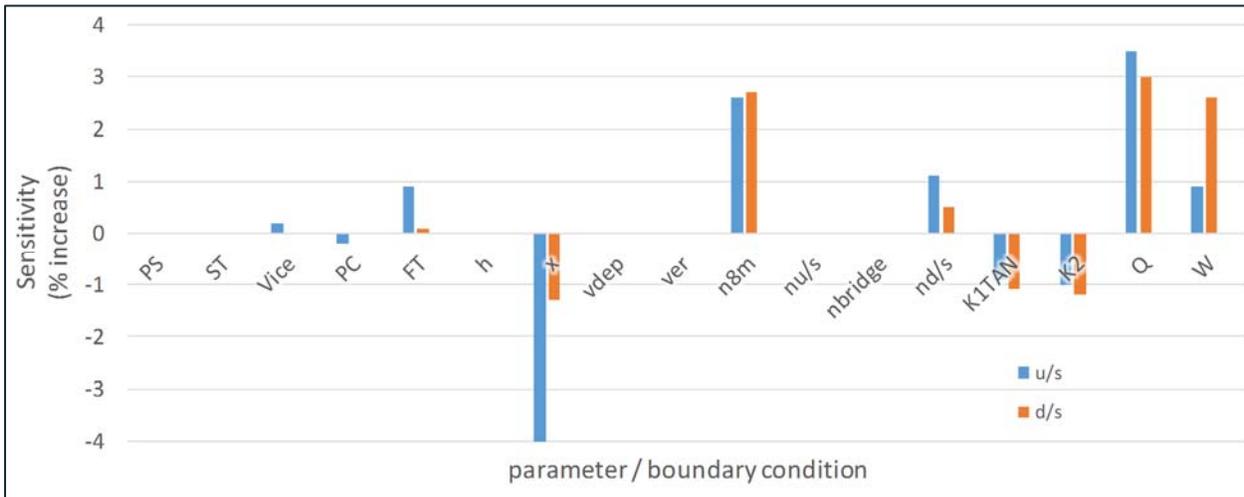
$PS$	– porosity of slush ice pans
$ST$	– thickness of slush ice pans
$V_{ice}$	– volume of inflowing ice
$PC$	– porosity of ice-jam cover
$FT$	– thickness of ice-jam front
$h$	– thickness of intact ice cover downstream of ice jam
$x$	– location of ice-jam lodgement
$v_{dep}$	– flow velocity threshold for ice deposition
$v_{er}$	– flow velocity threshold for ice erosion
$n_{8m}$	– ice-cover roughness parameter
$n_{u/s}$	– Manning’s roughness coefficient upstream of bridge
$n_{bridge}$	– Manning’s roughness coefficient at bridge with piers in water
$n_{d/s}$	– Manning’s roughness coefficient downstream of bridge
$K1TAN$	– lateral distribution of ice-cover forces as friction along ice cover and banks
$K2$	– internal ice-cover resistance to external forces
$Q$	– discharge of water from upstream boundary condition
$W$	– downstream water level boundary condition

Figure 7-21 summarises the results of the sensitivity analysis. The location of the ice-jam lodgement  $x$  is quite sensitive to backwater levels. This may be due to the sill (ref. Figure 7-16) that is present at the mouth of the upper Humber River before a sharp drop occurs from the river into Deer Lake. The proximity of the ice-jam lodgement to the sill can influence how much water flowing in the river is constricted before it exits into the lake. The ice-cover roughness parameter  $n_{8m}$  is also sensitive to backwater levels, as is the roughness coefficient along the lower reach  $n_{d/s}$  of the upper Humber River. Strength parameters  $K1TAN$  and  $K2$  are both sensitive to backwater staging. Both boundary conditions,  $Q$  and  $W$ , are positively sensitive to backwater staging (i.e., increases in these values increases staging). Hence, high runoff volumes and high Deer Lake water levels will exacerbate backwater staging and flooding from ice along the upper Humber River.



**Figure 7-20: Depiction of parameters and boundary conditions used for the sensitivity analysis of the upper Humber River ice model**

(Source: Sheikholeslami et al., 2017)



**Figure 7-21: Sensitivities of parameters and boundary conditions on the backwater profile of a fully extended ice cover along the upper Humber River**

### 7.5.1.4 Monte-Carlo Analysis

A Monte-Carlo analysis (MOCA) was carried out on the ice model in which 1,000 simulations were executed. Extending this analysis beyond the noted number of simulations did not change the conclusions. Each simulation had a different set of parameter and boundary condition values. Parameter values were generated randomly from uniform distributions, whereas the upstream discharge  $Q$  and the downstream water-level boundary  $W$  were extracted from the extreme value distributions illustrated in Figure 7-7 and Figure 7-9, respectively. The resulting ensemble of backwater simulations is illustrated in Figure 7-22. The backwater profile of the January 2018 simulation from Figure 7-19 is juxtaposed as a cyan line on Figure 7-22. The 99<sup>th</sup>, 99.5<sup>th</sup> and 99.8<sup>th</sup> percentiles, which correspond respectively to the AEP 1 in 100-year, 1 in 200-year and 1 in 500-year return periods, are also indicated in the figure. For most of the model domain, the January 2018 profile extends above the 0.998 percentile line, classifying this event as a most extreme case.

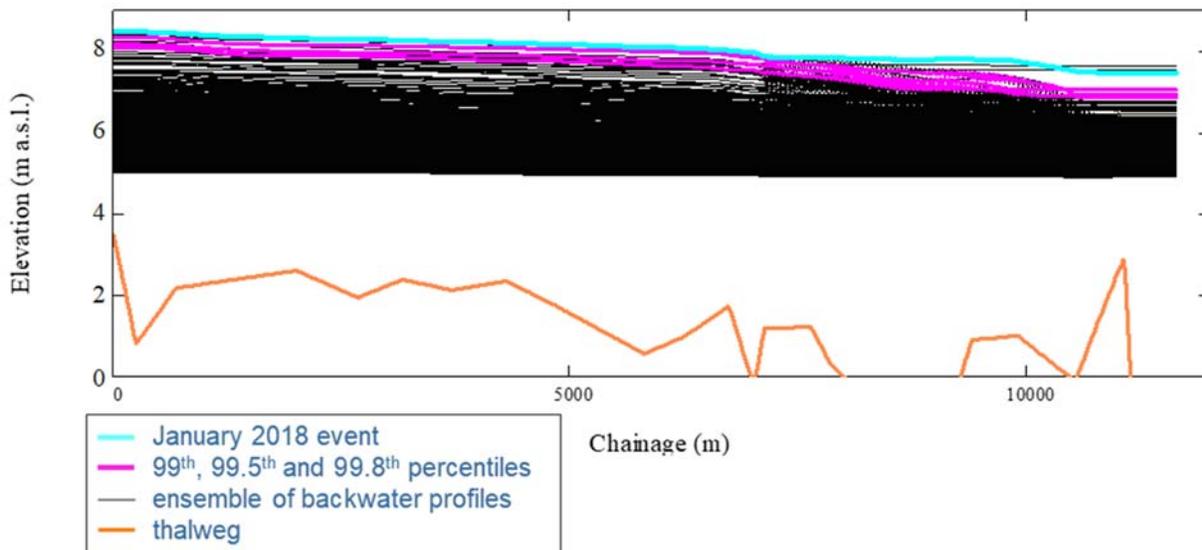


Figure 7-22: Ensemble of 1,000 Backwater Profiles

## 7.5.2 Steady Brook

The Town of Steady Brook, situated along the lower Humber River in western Newfoundland, floods periodically, causing damages to property and even requiring evacuations from residences in the area. This section provides a high-level assessment of some of the causes of these floods and to determine if patterns are present between the ice, hydraulic and meteorological regimes of the brook, its basin and surrounding region.

### 7.5.2.1 Floods inventory

The flood events inventory records several floods along Steady Brook; two (2) in the winter, three (3) in the spring and one (1) in autumn. An additional flood occurred at the beginning of June 2020 and is included in the spring floods inventory summary (ref. Table 7-11).

**Table 7-11: Steady Brook Ice Assessment – Floods Summary**

Winter Floods				
Flood Event Details				Description
When	27/28 January 1976	Damages	\$100,000	Ice amassed up at the mouth of Clark's Brook causing some problems. Several road washouts had occurred, one resident on Massey Drive was reported to have lost his driveway. Steady Brook was plugged with ice causing the water to back up inundating four (4) homes and threatening ten (10) others. Several road washouts reported. Homes in Frenchman's Cove, Benoit's Cove and Lark Harbour were also damaged by flood waters.
Season	Winter	Displaced	2 families	
Cause	Rain on snow	Source	Flooding Events in Newfoundland and Labrador - A Historical Perspective. Hydrotechnical Study of the Deer Lake Area	
When	January 1977	Damages	N/A	Two (2) homes in the community were flooded according to a newspaper report.
Season	Winter	Displaced	N/A	
Cause	Rain on snow	Source	Flooding Events in Newfoundland and Labrador - A Historical Perspective. Hydrotechnical Study of the Deer Lake Area	
Spring Floods				
Flood Event Details				Description
When	19 – 21 May 1969	Damages	\$40,000	Several basements and some outside properties were flooded; several homes were flooded, two (2) were considered to require replacement; three (3) houses were flooded and a section of the highway was flooded.
Season	Spring	Displaced	N/A	
Cause	Rainfall	Source	Hydrotechnical Study of Steady Brook Area. Environment Canada, 8 January 8th, 1976.	
When	17 – 20 May 1978	Damages	N/A	Humber River was overflowing at Steady Brook; Bowater reported as not having spilled water from the main dam.
Season	Spring	Displaced	N/A	
Cause	Snowmelt	Source	Flooding Events in Newfoundland and Labrador - A Historical Perspective. Hydrotechnical Study of the Deer Lake Area	
When	4 – 10 May 1982	Damages	N/A	Some property damage reported in the community of Steady Brook.
Season	Spring	Displaced	N/A	
Cause	Rainfall	Source	Flooding Events in Newfoundland and Labrador - A Historical Perspective. Hydrotechnical Study of the Deer Lake Area	
When	June 2020	Damages	N/A	Many properties flooded in Steady Brook near the confluence to the Humber River. "...run off from a harsh Newfoundland winter [was] causing the mighty Humber River to overflow its banks into the Town of Steady Brook ..."
Season	Spring	Displaced	N/A	
Cause	Snowmelt & Runoff	Source	<a href="https://www.facebook.com/scott.dalley.1/posts/10163516174510153">https://www.facebook.com/scott.dalley.1/posts/10163516174510153</a>	
Autumn Floods				
Flood Event Details				Description
When	28 November 2013	Damages	N/A	Streets and homes were flooded. Corner Brook stream raging. Trans-Canada Highway south branch closed. Streams and brooks overflowing. Many schools closed in Western Newfoundland, and power was gone in Pasadena, Steady Brook, Flat Bay area, Humber Village, Steady Brook, Little Rapids and the Stephenville-Port Aux Basques area. Reports of a hydro pole breaking off. Road shoulder washouts, basement flooding, bridge was closed.
Season	Autumn	Displaced	N/A	
Cause	Rainfall	Source	Hydrotechnical Study of Steady Brook Area. Environment Canada, 8 January 8th, 1976.	

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### 7.5.2.2 Winter floods

The stream bed of the Steady Brook consists mostly of bedrock, boulders and coarse gravel (ref. Figure 7-23); hence, there is a propensity of the stream to form anchor ice in winter. Figure 7-24 shows the locations where the photos were taken. The banks are relatively steep in the upper surveyed stretch and flatten and widen out in the lower reach before the brook empties into the lower Humber River. Just upstream of the most upstream cross-section surveyed is Steady Brook Falls, which can form frazil ice and aufeis (a sheet-like mass of layered ice that forms from successive freezing of thin flows of water on existing ice) during frigid conditions (ref. Figure 7-25).

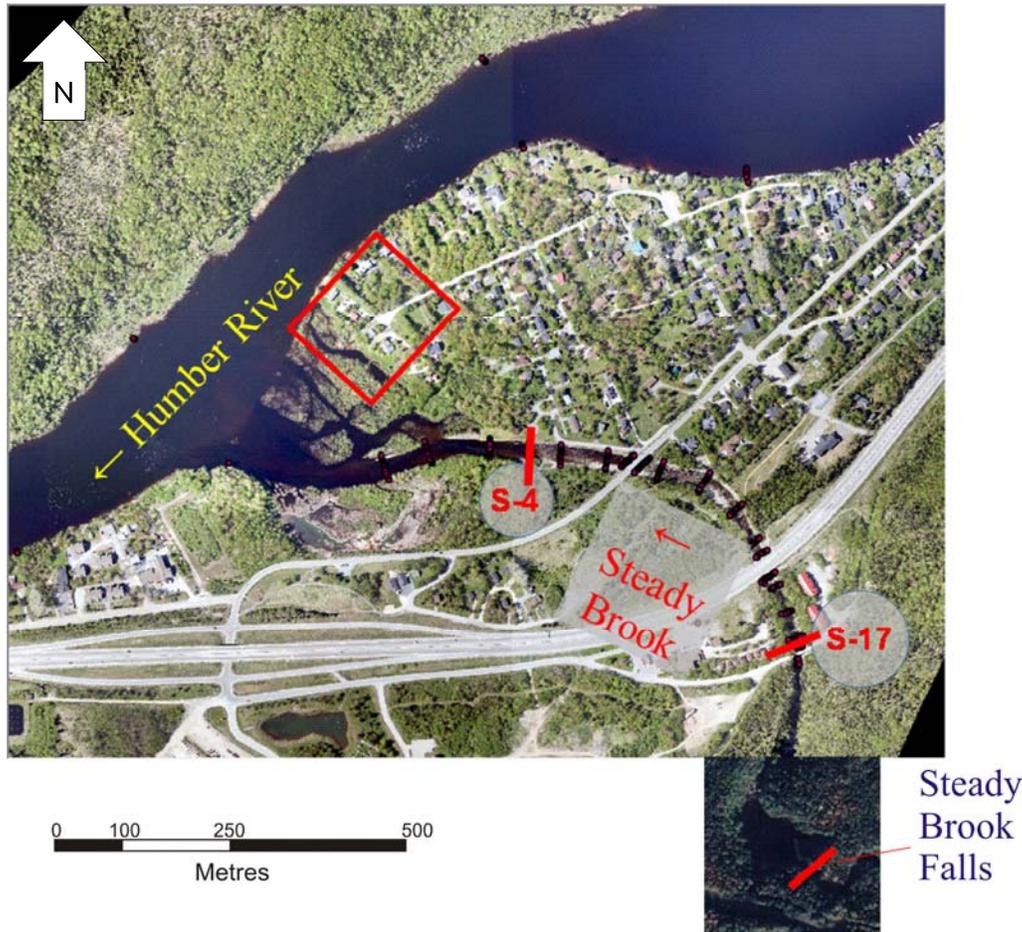


**Figure 7-23: Selected locations of surveyed reach of Steady Brook**

***left panel: upper course (cross-section #S-17, looking downstream)***

***right panel: lower course (cross-section #S-4, looking downstream)***

The winter floods that occurred during the month of January for the years 1976 and 1977 were likely caused by rain-on-snow events. Figure 7-26 provides meteorological data recorded at Corner Brook for January 1976. At the end of the month on 27 – 28 January 1976, when flooding in the Town of Steady Brook was reported, a total of 21.1 mm of rain fell on 19.1 cm of snow that had accumulated over the previous 4 days. In January 1977 (see Figure 7-27), 18.8 mm of rain fell on 52 cm of snow that had accumulated since the middle of that month. In both months, air temperature had dropped to below  $-10^{\circ}\text{C}$ , during which time anchor ice and a suspended frazil ice cover may have formed along the Steady Brook. Anchor ice can form ice dams that persist for the duration of the winter season and maintain increased backwater levels (Dubé et al., 2015). Breakup events of the ice cover can lead to ice jamming, which was documented by Nafziger et al. (2011) for other streams in Newfoundland. An example is shown in Figure 7-28.



**Figure 7-24: Surveyed section of the Steady Brook and Steady Brook Falls**  
**Box outlined in red indicates flooded area shown by an aerial view in Figure 7-33**

Cumulative degree days of freezing (CDDF) are shown in Figure 7-29 and were calculated using the following algorithm (Lindenschmidt, 2020):

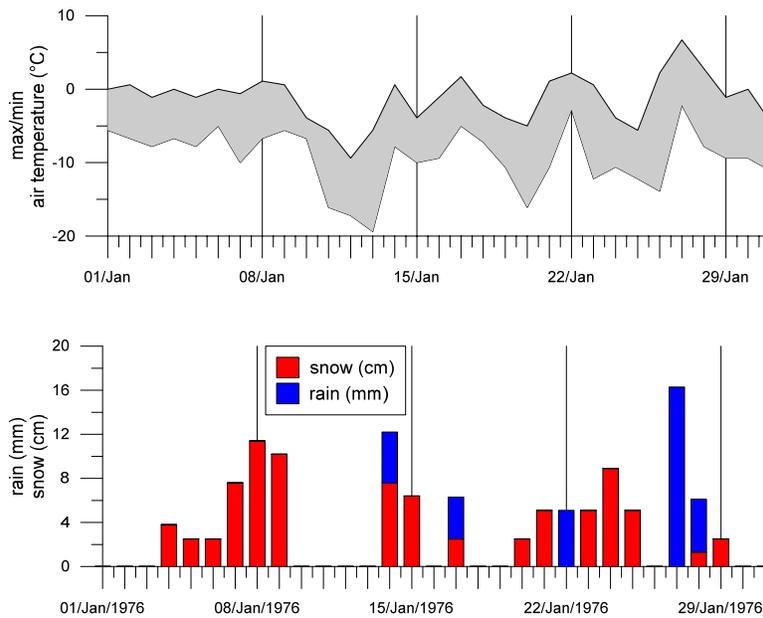
$$\begin{aligned} & \text{if } (MeanAirTemp_i < 0^\circ C) \\ & \text{then } CDDF_i = CDDF_{i-1} - MeanAirTemp_i \\ & \text{else } CDDF_i = CDDF_{i-1} \end{aligned}$$

where  $MeanAirTemp_i$  is the mean air temperature for a particular day  $i$  and  $i-1$  is the previous day. In both winters, the CDDF reached approximately 200 °C-day by mid-January and 250 – 300 °C-day by the end of January. For these values, it can be expected that the stream width is at least 70 – 80% ice covered, particularly in the pool sections (see Figure 7-30 for an example from the Rimouski River in Quebec.). Unfortunately, flows are not available for this timeframe in order to make correlations between ice behaviour and hydraulic conditions in the Steady Brook.

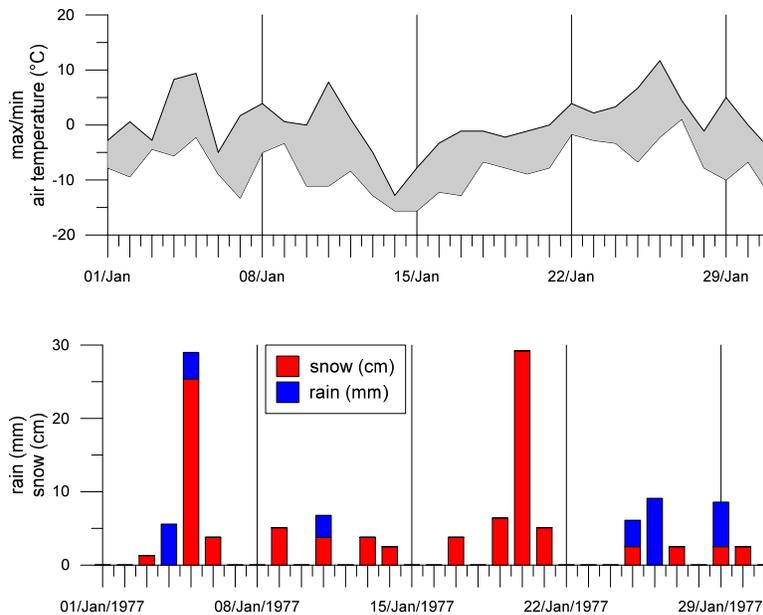


**Figure 7-25: Steady Brook Falls in September 2018 (left panel) and January 2018 (right panel)**

Climate Change Flood Risk Mapping Study and the  
Development of a Flood Forecasting Service: Humber River Communities  
Volume 1: Flood Risk Mapping Development



**Figure 7-26: Meteorological data recorded at Corner Brook in January 1976**  
*top panel: ranges between daily maximum and minimum air temperatures*  
*bottom panel: daily snowfall (cm) and rainfall (mm) depths*

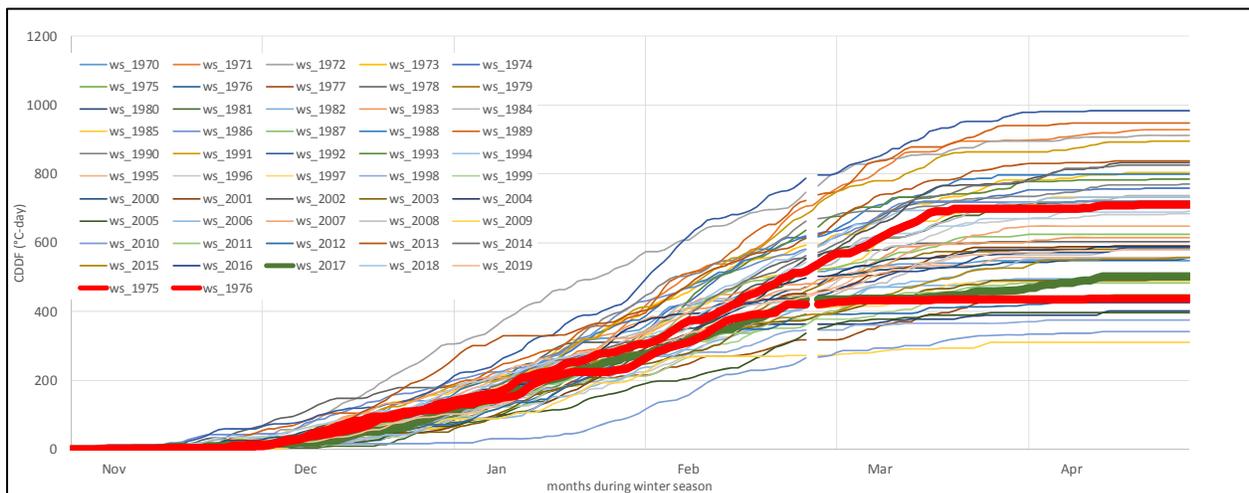


**Figure 7-27: Meteorological data recorded at Corner Brook in January 1977**  
*top panel: ranges between daily maximum and minimum air temperatures*  
*bottom panel: daily snowfall (cm) and rainfall (mm) depths*



**Figure 7-28: Small ice jam on the Twillick Brook  
in the Upper Salmon Area of south-central Newfoundland**

(Source: Nafziger et al., 2011)



**Figure 7-29: Cumulative degree days of freezing (CDDF)**

***“ws” in legend indicates winter starting in November of a particular year  
mean air temperature data recorded at Corner Brook***

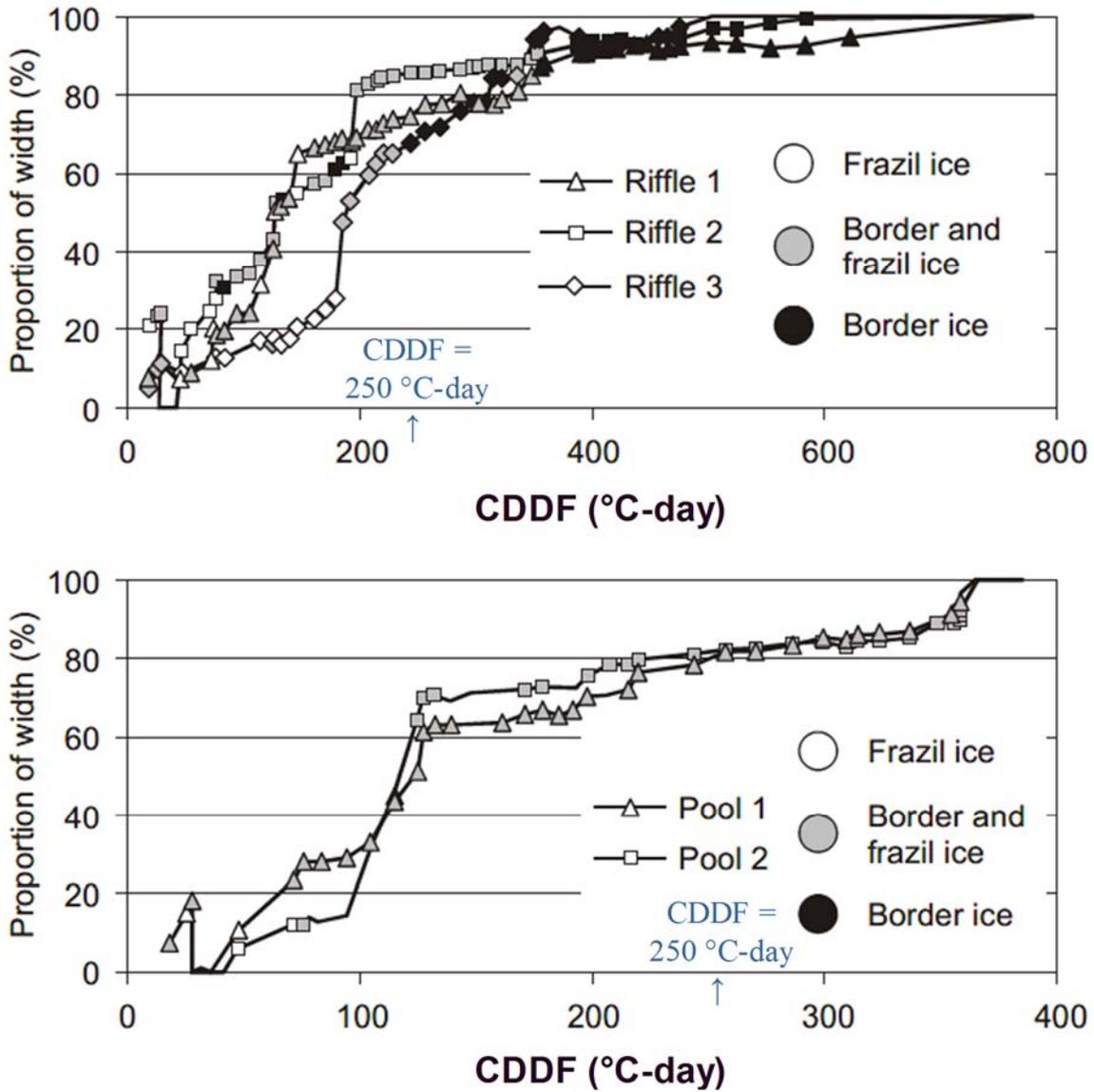
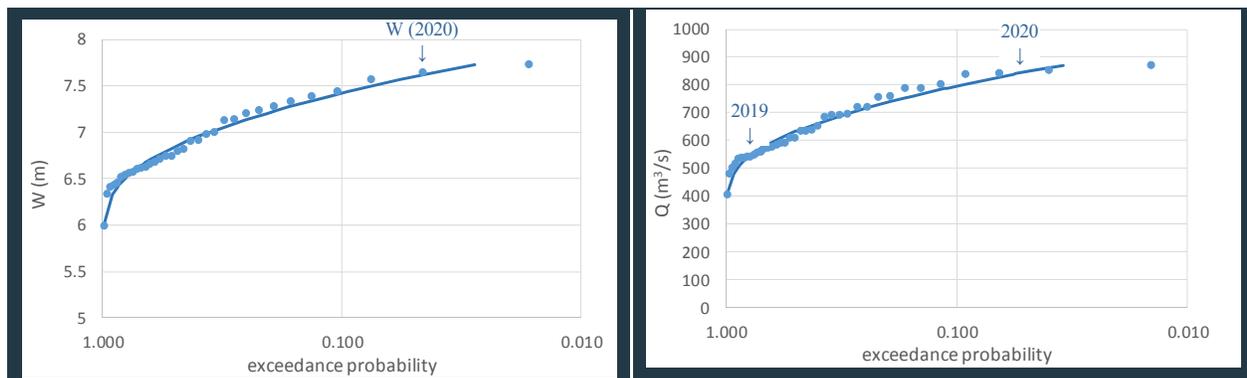


Figure 7-30: Ice cover growth curves in riffles (top panel) and pools (bottom panel) on the Rimouski River (width ~ 50 m)

(Source: Beltaos, 2013, p. 397)

### 7.5.2.3 Spring Floods

Record snowfall depths in Newfoundland during the 2019 – 2020 winter led to high snowmelt runoff in the spring of 2020. For the months of May and June, water levels in Deer Lake were the third highest on record (see Figure 7-31, left panel) and flows along the lower Humber River were the second highest on record (see Figure 7-31, right panel). Although the maximum values recorded during May and June of 2020 had return periods of approximately 1 in 20-years (1 in 17 years for the Deer Lake water level; 1 in 24 years for flow along the lower Humber River), the coincidence of the high flows in Steady Brook may have caused the flooding at the Humber River/Steady Brook confluence to be more extreme. Although the length of record of the flows in the Steady Brook is too short to construct a valid frequency distribution, the time series does reveal the extremity of the discharges in the Steady Brook for the spring of 2020 compared to the previous 5 years of recordings (see Figure 7-32).



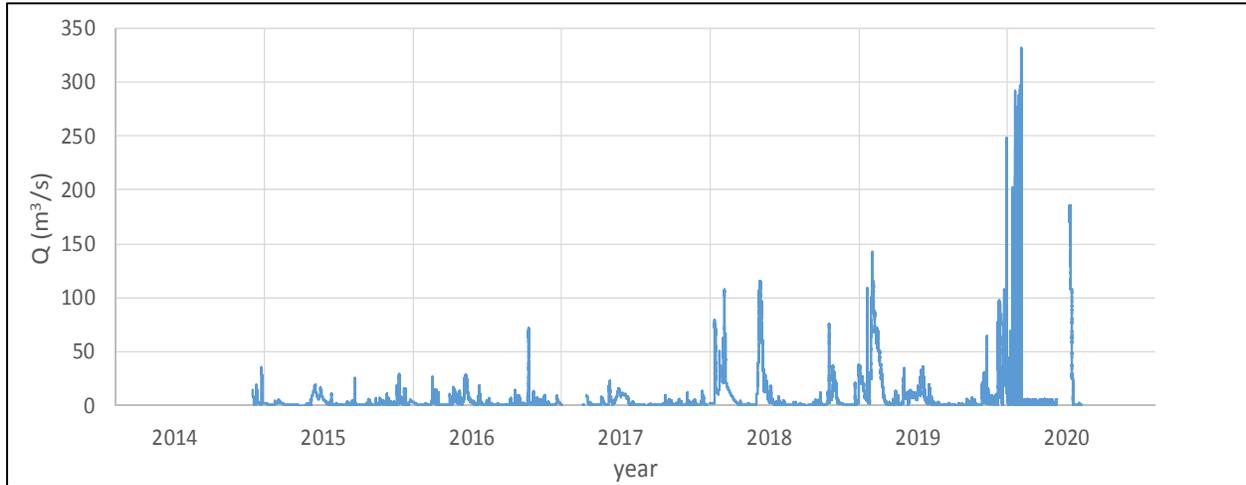
**Figure 7-31: Frequency distributions of Maximum Water Level and Daily Mean Discharge for Stations 02YL007 and 02YL003**

*left panel:* maximum water levels recorded at Deer Lake near the generating station (gauge 02YL007) in May – June for the years 1987 to 2020 (n = 34) and

*right panel:* maximum daily mean discharges of the Humber River recorded at the Humber Village Bridge (gauge: 02YL003) in May – June for the years 1982 to 2020 (n = 39)

Many properties were flooded at the confluence as indicated by an aerial photograph shown in Figure 7-33. The area depicted in the photograph is indicated in red in Figure 7-24. The flooded area is in a very flat and low lying area along the banks of the lower Humber River, as indicated by the DEM when compared with the ortho-photograph in Figure 7-34. The DEM was developed from LiDAR data that was acquired in June 2019 when the maximum daily mean flow was very low, with a flow return period for May and June of approximately 1 in 1.2 years (see right panel of Figure 7-31). Flood maps for Steady Brook<sup>24</sup>, from studies carried a few decades ago, also show the same problematic area for flooding.

<sup>24</sup> Source: <https://www.gov.nl.ca/mae/files/waterres-flooding-steady-brook-large.jpg>

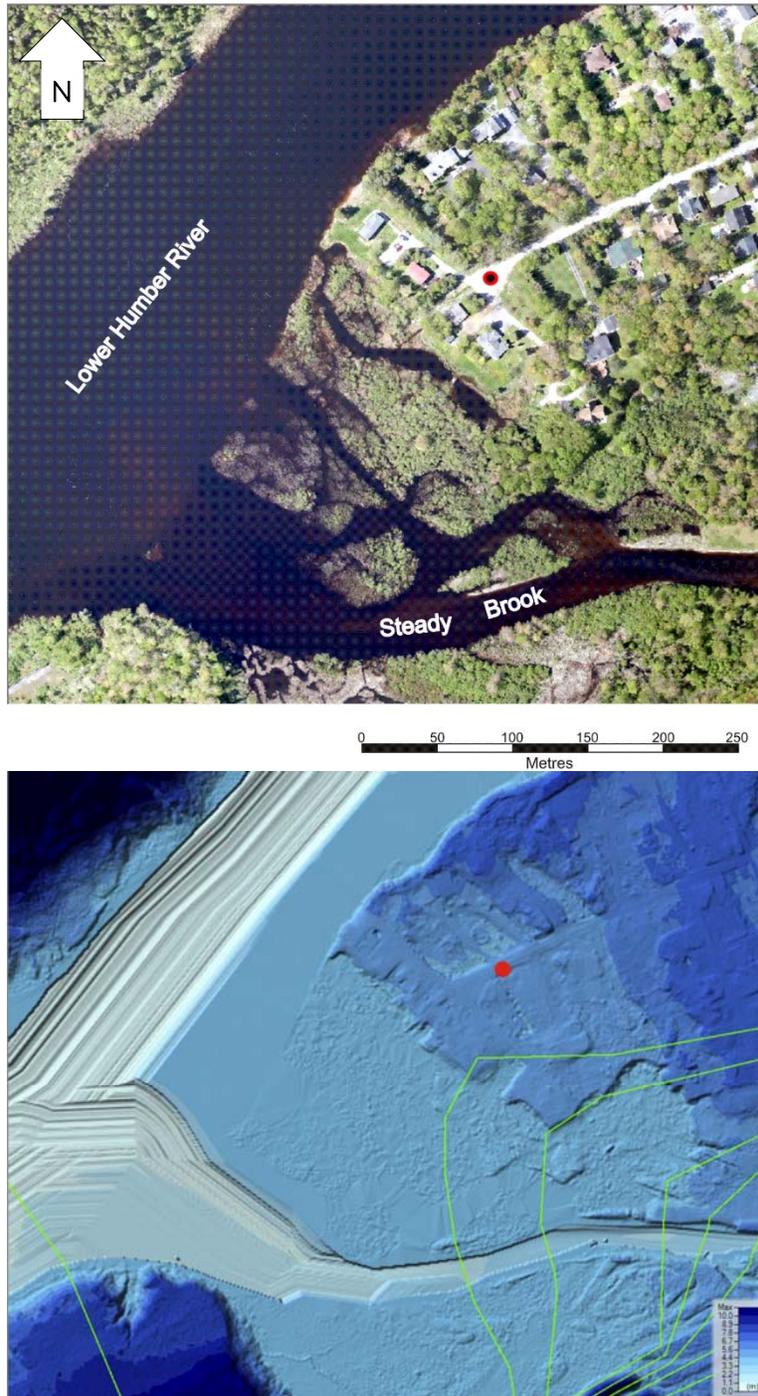


**Figure 7-32: Flows recorded at Steady Brook above its confluence to the lower Humber River (gauge: 02YL012)**



**Figure 7-33: Area of Steady Brook flooded during the spring 2020 event**

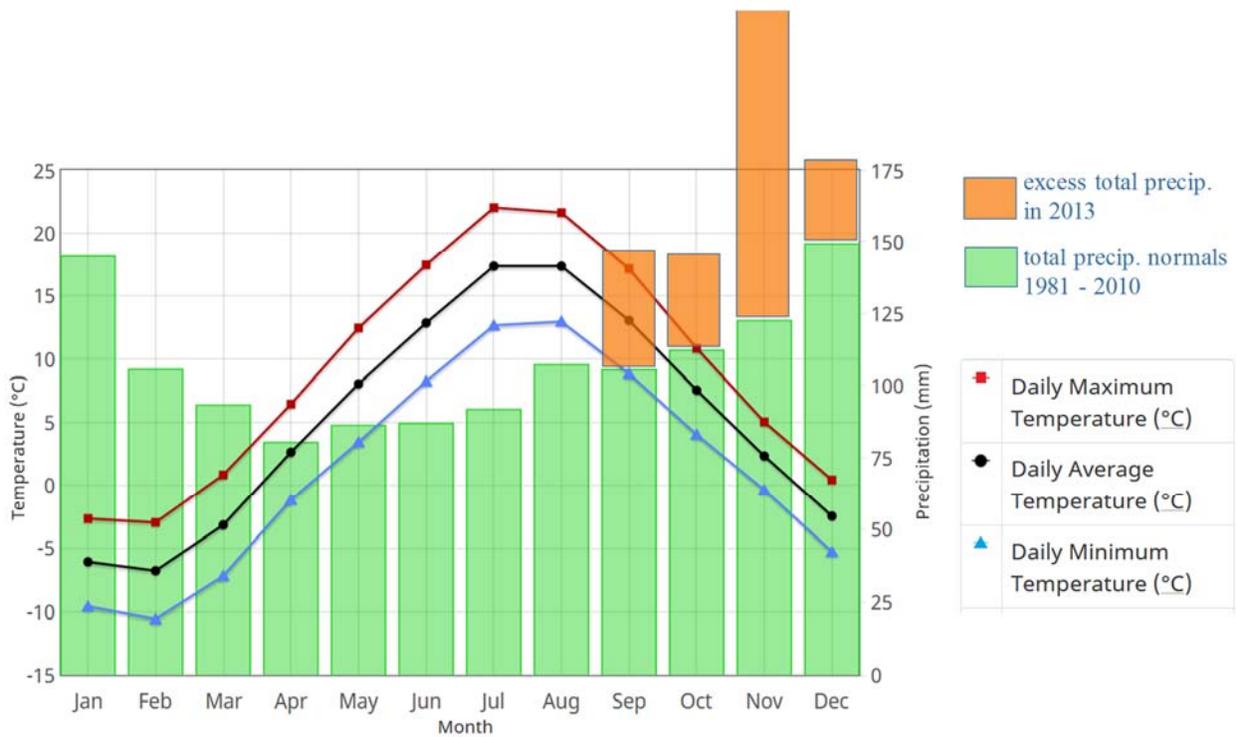
*(See area outlined in red in Figure 7-24)*



**Figure 7-34: Ortho-photograph (top panel) and DEM (bottom panel) of the lower Humber River/Steady Brook confluence**

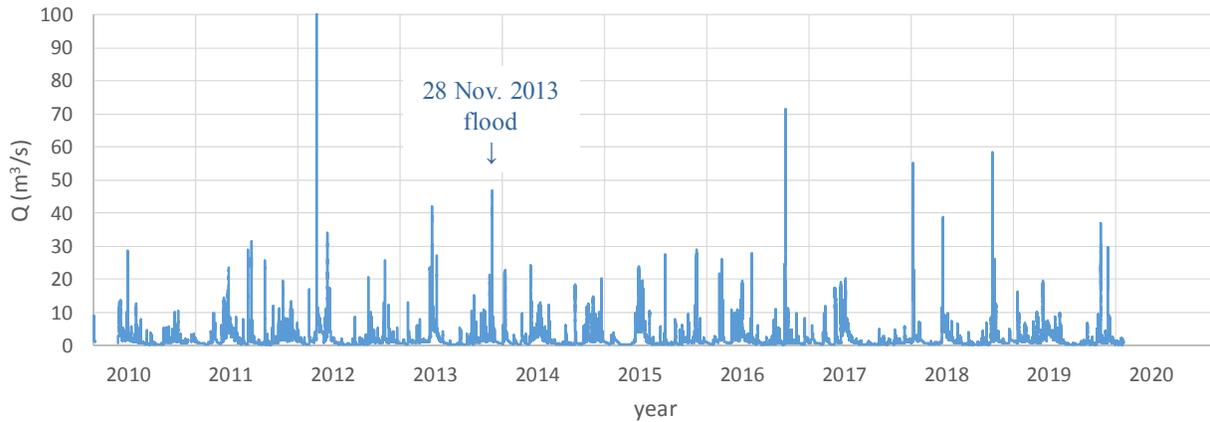
### 7.5.2.4 Autumn flood

Flooding occurred in the Town of Steady Brook at the end of November 2013. From the description of the flood inventory (ref. Table 7-10), it appears that flooding was widespread throughout western Newfoundland and not particular to the Town of Steady Brook. Moisture conditions recorded at Corner Brook were far wetter than normal values, as indicated in Figure 7-35. The gauge on the Steady Brook had not yet been installed at this time, but a gauge on a similar brook, the South Brook at Pasadena (gauge 02YL004) approximately 17 km northeast of the Town of Steady Brook, can be used here as a proxy for Steady Brook flow magnitudes. Flows were relatively high in South Brook (see Figure 7-36) and, according to the regional extent of the large rainfall conditions, it is assumed that the flows in the Steady Brook were also high.



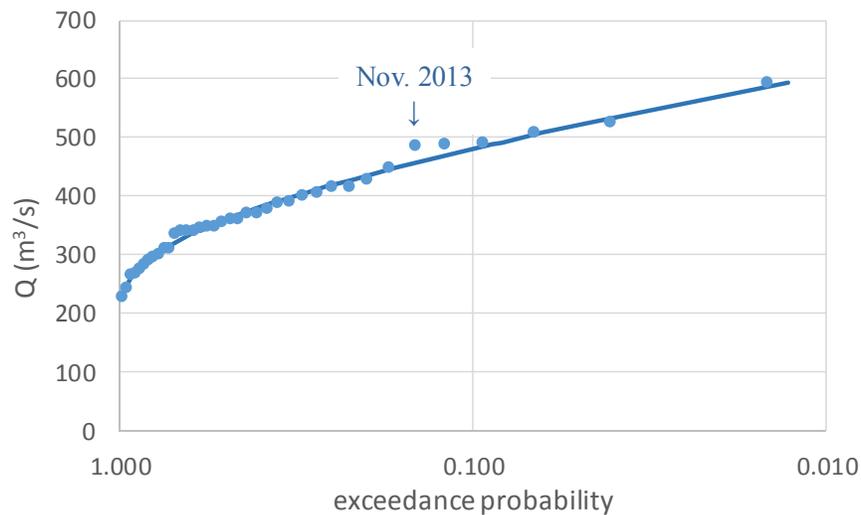
**Figure 7-35: Air temperature and precipitation normals for 1981 to 2010 at Corner Brook**

*Please note that any total precipitation excesses are superimposed only for the latter half of 2013*

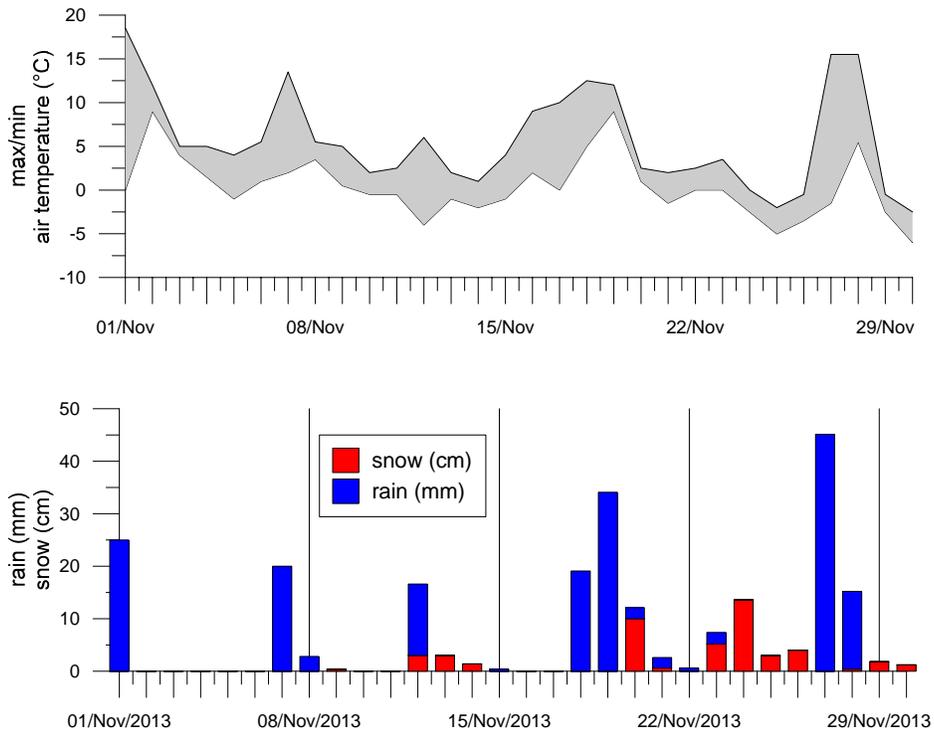


**Figure 7-36: Flows recorded in the South Brook at Pasadena (gauge: 02YL004) used here as a proxy for the magnitude of flows in the Steady Brook**

The maximum daily-mean flow in the lower Humber River was not that extreme in November 2013, less extreme than a 1:10 year return period (ref. Figure 7-37), so it is difficult to determine if coincidence of the flow peaks of the lower Humber River and the Steady Brook at their confluence caused the flooding in the Town of Steady Brook. The high antecedent moisture conditions (ref. Figure 7-35), the heavy rains on 27 and 28 November 2013 (total rain = 60 mm shown in Figure 7-38) and the 36.8 cm of snow that fell during the week prior to the heavy rains (ref. Figure 7-38) will have contributed to the higher flows and potentially may have led to some pluvial flooding in the flat, low-lying areas along the fluvial water bodies.



**Figure 7-37: Maximum daily mean discharges of the Humber River recorded at the Humber Village Bridge (gauge: 02YL003) in November for the years 1982 to 2019 (n = 38)**



**Figure 7-38: Meteorological data recorded at Corner Brook in Nov. 2013**

*top panel: ranges between daily maximum and minimum air temperatures  
bottom panel: daily snowfall (cm) and rainfall (mm) depths*

Mean daily air temperatures hovered just above freezing for most of November 2013 (ref. Figure 7-38) and the CDDF was < 15 °C-day by the end of the month; hence, very little ice would have been generated in the stream at this time.

## 7.6 Summary, Conclusions and Recommendations

### 7.6.1 Summary

A hydraulic model, based on the USACE program HEC-RAS, was developed for a reach of the Humber River, and select tributaries, covering a linear distance of approximately 178 km (with 96 watercourse reaches and 1,481 cross-sections). The model was developed based on field surveyed bathymetric data conducted between November 2018 and December 2019 and LiDAR survey conducted in June 2019. The new hydraulic model also includes sixteen (16) bridges and seventy-nine (79) culverts. Coding of structures was supported by topographic field survey, visual inspection and measurement.

Observed water level and flow data at four (4) gauging stations (02YL001, 02YL003, 02YL004 and 02YL012) was obtained from Environment and Climate Change Canada to support calibration and validation of the new

hydraulic model.

A detailed assessment of the river ice event of January 2018 in Deer Lake was completed. The ice damming/flooding event was considered an anomalous event for the community and it was noted that “people have lived on the river for 70 years and have never seen what happened last year”. The one-dimensional hydrodynamic simulation software RIVICE was used for the development of the river-ice hydraulic model to support the assessment of this event.

A high-level assessment of the river ice formation in the Steady Brook was also completed. This assessment concluded that there are potential ice conditions in winter, snowmelt and rain-on-snow events in spring and high precipitation and flows accompanied by high antecedent moisture conditions in the autumn.

The ice jam assessments, completed by Dr. Karl-Erich Lindenschmidt (Associate Professor at the School of Environment and Sustainability, at the University of Saskatchewan), were focused on development of an understanding of the meteorological and hydraulic circumstances that contributed to the development of ice jams on the upper Humber River at the Town of Deer Lake in January 2018 and generally, along the Steady Brook.

The hydrologic and hydraulic models developed for this study and relevant support data are included with the Project CD materials attached to this report. The models may be used in the future to evaluate the impact on water levels resulting from any structural changes to the subject watercourses, structures, or floodplain / overbank areas.

## 7.6.2 Conclusions and Recommendations

### Hydraulic Modelling

It is recommended that the water levels for existing conditions for the 1 in 20-year and 1 in 100-year AEP water surface profiles, associated with the fully developed and current IDF scenario, as defined on the flood plain maps and as provided in tabular form in Appendix N, be adopted for regulatory and management purposes.

It is recommended that HEC-RAS, and associated tools such as Geo-HECRAS and HEC-GeoRAS, be used in future watershed and flood studies as it both simplifies the development of deterministic models as well as provides for the generation of a significant warehouse of information that can be used for several ancillary purposes beyond hydraulic assessment.

### Ice Jam Assessment

#### Deer Lake

It was concluded from the ice assessment results that the January 2018 event was the result of a unique set of snow cover, wind, frazil ice, temperature and other conditions. The ice jam assessment further concluded that the January 2018 ice jam event was a most extreme case, approximating a 1 in 500-year event.

Given the results of the ice jam assessment, it was also concluded that integration of river ice modelling (i.e. the RIVICE simulation model) into the flood forecasting system (ref. Section 11) was not necessary.

A program focused on field-based collection of ice thickness/accumulation data should be implemented in areas when ice jamming occurs. It was noted previously that no ice thickness data was available for the study area. A database of ice thickness/accumulation data would enhance and provide additional confidence the ice modelling process and results.

#### Steady Brook

It was concluded that the reasons for flooding in the Town of Steady Brook are multifaceted: potential ice conditions in winter, snowmelt and rain-on-snow events in spring and high precipitation and flows accompanied by high antecedent moisture conditions in the autumn.

It has also been concluded that the currently available Steady Brook streamflow gauge record does not cover a sufficient time period to allow for the determination of patterns between the ice, hydraulic and meteorological regimes of the watercourse. It is therefore recommended, for future study beyond the present work scope, that the continuous HEC-HMS model developed for the flood forecasting component of this study (ref. Section 11 and Volume 2 reporting) be augmented to model the Steady Brook watershed discretely. Using this tool, in conjunction with the available long-term meteorological record, the available streamflow time series may be extended providing a longer dataset upon which to base the foregoing assessment and its associated conclusions.

## 8.0 Sensitivity Analysis and Climate Change

**Sensitivity Analysis Synopsis:** The hydrologic and hydraulic models developed for this study were based on available data and selection of appropriate input data. Deterministic modelling, generally, has an inherent potential for errors or uncertainty to be associated with the selection of input variables which can affect the resulting flood flows and computation of associated water levels. Sensitivity analysis supports a better understanding on model uncertainty and increases confidence in simulation model results and ensuring the model is accurately reflecting watershed conditions and responses.

**Climate Change Synopsis:** Due to the influence of climate change, Newfoundland and Labrador is expected to experience weather that is warmer, wetter and stormier. Increased frequency and severity of storms and sea level rise are expected to exacerbate existing flood risk in many areas of the Province, cause increased damages to homes and infrastructure, and increase risk to public safety. To support estimation of climate change influenced future flood risk the hydrologic and hydraulic models developed through this study were used in conjunction with estimates of future precipitation and future sea level rise. The estimates of future precipitation and future sea level rise were based on up-to-date information provided by the Province. Climate change scenarios for 1 in 20 and 1 in 100-year AEP flood profiles were assessed for current development conditions and fully developed watershed conditions. The results indicate increasing flood risk in the future with about 10.4 hectares of additional lands flooded by the 1 in 100-year AEP flood for under fully developed/ climate change scenario.

**Figure 8-1: Sensitivity Analysis and Climate Change Summary**



## 8.1 Sensitivity Analysis

As required by the Terms of Reference for this study, a sensitivity analysis of the hydrologic and hydraulic model inputs was completed to determine the effects of changing model parameters on the resulting flood levels.

The hydrologic and hydraulic models were developed based on a review of available data and selection of appropriate input data. However, as is the case in all numerical modelling of physical processes, there is the inherent potential for errors or uncertainty to be associated with the selection of input variables which could affect the resulting flood flows and subsequent computation of associated water levels. Sensitivity analysis can, hence, be useful for a range of purposes, including:

- Testing the robustness of simulation model results in the presence of uncertainty.
- Increasing the understanding of the relationships between input and output variables in the simulation models.
- Increasing confidence in simulation model results by identifying model inputs that cause significant uncertainty in the output. Increased attention to these specific model inputs can then be applied to ensure proper definition and/or parameterization.
- Ensuring the model is accurately reflecting watershed conditions and responses by identifying errors in the model output as reflected by unexpected relationships between inputs and outputs.

The sensitivity analysis has considered the effects of  $\pm 10\%$ ,  $\pm 20\%$  and  $\pm 30\%$  isolated changes in each required parameter and determined their effects on computed peaks flow and water surface elevations. Factors which were considered for sensitivity analysis have included:

- HEC-HMS
  - SCS Curve Number
  - Manning's roughness coefficient (routing reaches)
- HEC-RAS
  - Manning's roughness coefficient
  - Peak discharge
  - Starting water surface elevation

Imperviousness was not included in sensitivity analysis given the very limited urbanization in the watershed.

### 8.1.1 Sensitivity to Hydrologic Model Inputs

This aspect of the sensitivity analysis was completed using the final calibrated Existing Development and Current IDF model scenario.

#### 8.1.1.1 SCS Curve Numbers

As previously described, a SCS Curve Number is required for each sub-basin within the hydrologic model. The Curve Number for a sub-basin is a function of soil type, land use, and antecedent runoff conditions. The Curve Number defines the amount of runoff and infiltration, for the pervious portion of the catchment, based on a

given rainfall amount. The Curve Number for each sub-basin within the HEC-HMS model was increased and decreased by 10%, 20% and 30% for the 1 in 20-year and 1 in 100-year AEP events (ref Table 8-1). The results of this analysis are presented in Table 8-2. The results of the sensitivity analysis highlight the following:

- the generated peak flows are very sensitive to the selection of Curve Number; as demonstrated by a 10% change in Curve Number resulting in a change in peak flow of 17% to 36%;
- positive changes result in greater changes than negative changes;
- positive changes in Curve Number result in an increase in peak flow estimation, while a negative change results in decrease in simulated peak flows;
- the variability in percentage change in simulated peak flows may also be influenced by associated changes in peak flows timing and flow accumulation as the peak moves in a downstream direction;
- percentage changes in simulated peak flows for the 1 in 20-year AEP event are greater than the percentage changes in simulated peak flows for the 1 in 100-year AEP event, for the same change in roughness value.

Given this result, the input variables, associated with generation of the Curve Number grid (soils and land use), developed for the HEC-HMS model were reviewed. This review confirmed that the soils information used for model development was the best currently available; sourced from the Government of Canada. The land use data was based on the land classification project completed for this project. This assessment was based on 10-meter resolution SPOT imagery. With coarser resolution, spectral mixing exists meaning some pixels contain a mixture of different features and cover types, compared to higher resolution images where individual pixel values represent more homogenous materials. The overall impact of the satellite imagery resolution on land use classification is difficult to quantify. Impacts in sub-catchment where the predominant land forest is forest (which represents a significant portion of the watershed) would not be expected to be significant. However, a greater degree of impact may be anticipated in urban areas where the 10 m resolution may not adequately capture impervious areas, resulting in potentially lower Curve Numbers, potentially leading to under-estimation of runoff.

**Table 8-1: HEC-HMS Sensitivity Analysis - SCS Curve Number – Range of Values**

Statistic	Existing Condition +30%	Existing Condition +20%	Existing Condition +10%	Base Condition	Existing Condition -10%	Existing Condition -20%	Existing Condition -30%
Minimum	67.65	62.45	57.24	52.04	46.84	41.63	36.43
Mean	95.38	90.85	84.01	76.42	68.78	61.14	53.50
Maximum	99.00	99.00	99.00	98.34	88.51	78.67	68.84

Notes:

1. Please note that a maximum CN value of 99 was applied if the changed value was greater than 100

**Table 8-2: HEC-HMS Sensitivity Analysis - SCS Curve Number - Results**

Location	Base Case Flow (m³/s)	Adjustment to base estimate of SCS Curve Number											
		30%		20%		10%		-10%		-20%		-30%	
		Flow (m³/s)	% Diff	Flow (m³/s)	% Diff	Flow (m³/s)	% Diff	Flow (m³/s)	% Diff	Flow (m³/s)	% Diff	Flow (m³/s)	% Diff
<b>1 in 20-year AEP</b>													
02YL008	334.6	786.3	135.0%	604	80.5%	442.4	32.2%	257.6	-23.0%	199.8	-40.3%	155	-53.7%
02YL001	811.5	1893.1	133.3%	1454.3	79.2%	1073.2	32.2%	620.5	-23.5%	475.7	-41.4%	362.7	-55.3%
02YL003	798.1	1491	86.8%	1261.1	58.0%	1000.5	25.4%	597.9	-25.1%	451	-43.5%	339.8	-57.4%
02YL004	119.8	160.6	34.1%	160.6	34.1%	159.8	33.4%	88.1	-26.5%	65.7	-45.2%	49.5	-58.7%
02YK008	19.8	41.8	111.1%	38.1	92.4%	27	36.4%	14.9	-24.7%	11.4	-42.4%	8.7	-56.1%
02YK002	147.1	253.1	72.1%	211.8	44.0%	177	20.3%	121.4	-17.5%	99	-32.7%	79.4	-46.0%
02YK005	93.9	192.7	105.2%	148.9	58.6%	117.5	25.1%	75.3	-19.8%	60.5	-35.6%	48.2	-48.7%
<b>1 in 100-year AEP</b>													
02YL008	506.2	1028.9	103.3%	841.5	66.2%	647.6	27.9%	399.3	-21.1%	315.7	-37.6%	248.5	-50.9%
02YL001	1252.7	2585	106.4%	2076.1	65.7%	1601.6	27.9%	985	-21.4%	772.7	-38.3%	600.7	-52.0%
02YL003	1124.8	1940.8	72.5%	1639.8	45.8%	1360.1	20.9%	960.5	-14.6%	759.6	-32.5%	579.2	-48.5%
02YL004	160.9	201.7	25.4%	201.7	25.4%	201	24.9%	123.6	-23.2%	95.1	-40.9%	73.1	-54.6%
02YK008	29.1	53.1	82.5%	49.8	71.1%	37.9	30.2%	22.6	-22.3%	17.6	-39.5%	13.7	-52.9%
02YK002	265.3	423.2	59.5%	363.2	36.9%	311.1	17.3%	224.5	-15.4%	187.8	-29.2%	154.7	-41.7%
02YK005	179.3	344.3	92.0%	274	52.8%	220.9	23.2%	145.7	-18.7%	118	-34.2%	94.8	-47.1%

**8.1.1.2 River Reach Roughness**

The river reach roughness is an input parameter to the hydrologic model which is used to determine the shape of the resulting hydrograph through the effect of channel routing from one basin to the next downstream computational node. The Manning’s Roughness coefficients were increased and decreased by 10%, 20% and 30% for the 1 in 20-year and 1 in 100-year AEP events (ref. Table 8-3). The results of the analysis are presented in Table 8-4. As suggested by the results, the selection of the river reach roughness coefficient has a less significant impact, than subcatchment SCS Curve Number, on the resulting peak flows. Further, in some cases the changes make almost no difference at all.

**Table 8-3: HEC-HMS Sensitivity Analysis – Manning’s Roughness – Range of Values**

Statistic	Existing Condition +30%	Existing Condition +20%	Existing Condition +10%	Base Condition	Existing Condition -10%	Existing Condition -20%	Existing Condition -30%
Minimum	0.065	0.060	0.055	0.050	0.045	0.040	0.035
Mean	0.067	0.062	0.057	0.052	0.047	0.041	0.036
Maximum	0.104	0.096	0.088	0.080	0.072	0.064	0.056
Notes:							
1. Please note that the changed values have not been deemed to exceed a reasonable range							

**Table 8-4: HEC-HMS Sensitivity Analysis - Manning’s Roughness Coefficient - Results**

Location	Base Case Flow (m³/s)	Adjustment to base estimate of Manning’s Roughness Coefficient											
		30%		20%		10%		-10%		-20%		-30%	
		Flow (m³/s)	% Diff	Flow (m³/s)	% Diff	Flow (m³/s)	% Diff	Flow (m³/s)	% Diff	Flow (m³/s)	% Diff	Flow (m³/s)	% Diff
<b>1 in 20-year AEP</b>													
02YL008	334.6	323.9	-3.2%	327.3	-2.2%	330.8	-1.1%	338.5	1.2%	342.7	2.4%	347.3	3.8%
02YL001	811.5	688.7	-15.1%	726.5	-10.5%	767.4	-5.4%	858.4	5.8%	908.6	12.0%	963.5	18.7%
02YL003	798.1	641.8	-19.6%	678.7	-15.0%	733	-8.2%	876.6	9.8%	953.7	19.5%	989.2	23.9%
02YL004	119.8	Please note that the drainage areas upstream of stations 02YL004 and 02YK008 are represented with a single subcatchment in the HEC-HMS model. As such, the model results are not impacted by changes to Manning’s ‘n’ values at these locations.											
02YK008	19.8												
02YK002	147.1	124.6	-15.3%	132	-10.3%	139.6	-5.1%	154.5	5.0%	161.4	9.7%	167.9	14.1%
02YK005	93.9	93.2	-0.7%	93.5	-0.4%	93.7	-0.2%	94	0.1%	94.1	0.2%	94.1	0.2%
<b>1 in 100-year AEP</b>													
02YL008	506.2	488.9	-3.4%	494.3	-2.4%	500.1	-1.2%	512.8	1.3%	519.9	2.7%	527.6	4.2%
02YL001	1252.7	1072	-14.4%	1128.2	-9.9%	1188.3	-5.1%	1322.7	5.6%	1399.5	11.7%	1485.8	18.6%
02YL003	1124.8	970.5	-13.7%	1012.3	-10.0%	1065.3	-5.3%	1190.1	5.8%	1259.5	12.0%	1316.3	17.0%
02YL004	160.9	Please note that the drainage areas upstream of stations 02YL004 and 02YK008 are represented with a single subcatchment in the HEC-HMS model. As such, the model results are not impacted by changes to Manning’s ‘n’ values at these locations.											
02YK008	29.1												
02YK002	265.3	234.1	-11.8%	244.5	-7.8%	254.9	-3.9%	275.9	4.0%	287.4	8.3%	300.1	13.1%
02YK005	179.3	177.5	-1.0%	178.2	-0.6%	178.8	-0.3%	179.7	0.2%	180	0.4%	180.2	0.5%

### 8.1.1.3 Summary of Hydrologic Model Sensitivity

Changes in computed peak flows resulting from the sensitivity runs demonstrate the HEC-HMS model computations are sensitive to Curve Number. Percentage changes to this parameter manifest as greater than the parameter percentage change in the resultant peak flow computations, generally. Conversely, the HEC-HMS model computations are not particularly sensitive to the Manning’s Roughness Coefficient of reach routing elements. Percentage changes to this parameter manifest as less than the parameter percentage change in the resultant peak flow computations, generally.

Standard HEC-HMS output tables, associated with hydrologic computations detailed for the sensitivity analysis, are provided in Appendix O.

### 8.1.2 Sensitivity of Hydraulic Model Inputs

This aspect of the sensitivity analysis was completed using the final calibrated Existing Development and Current IDF model scenario.

#### 8.1.2.1 Manning’s Roughness

The Manning’s Roughness input parameter of the hydraulic model defines the relative roughness of the main channel and floodplain areas. A higher Manning’s Roughness coefficient will increase flooding levels and reduce velocities. The Manning’s Roughness for the channel and overbank at each cross section were increased

and decreased by 10%, 20% and 30% for the 1 in 20-year and 1 in 100-year AEP events. The results of the analysis are presented in Table 8-5.

The selection of Manning's Roughness coefficient generally has a limited overall impact. However, significant impacts in localized reaches is demonstrated through this analysis where changes in flow regime occur as a result of roughness variation (i.e. from supercritical to subcritical or vice-versa). Large changes in water surface can also occur in cross-sections near (typically upstream) critical culvert and bridge locations where flow changes from open surface flow to surcharged or overtopping situations. The analysis has demonstrated that altering of Manning's Roughness coefficient by 20% (positive or negative) results in an average change in computed water surface elevation of between about -10 cm to +10 cm. Similarly, a change of 30% (positive or negative) results in an average change in computed water surface elevation of between about -9 cm to +13 cm.

A comparative assessment of the occurrence of critical depth at cross-sections was also completed (ref. Table 8-6). The results indicate that variation of Manning's Roughness co-efficient can have a considerable influence on critical depth occurrence across the model. As would be expected, an upward change in this variable tends to decrease the number of sections where critical depth is the resultant computed water surface elevation when compared with the occurrence of critical depth in the base model. Similarly, a downward change in Manning's roughness tends to increase the occurrence of critical depth.

**Table 8-5: HEC-RAS Sensitivity Analysis - Manning's Roughness Coefficient - Results**

Event (AEP)	Change in Computed Water Surface Elevation (m)					
	Maximum Decrease	Average	Maximum Increase	Maximum Decrease	Average	Maximum Increase
	<b>Manning's n - 10%</b>			<b>Manning's n + 10%</b>		
1 in 20-year	-0.340	-0.032	0.110	-0.070	0.033	0.300
1 in 100-year	-0.460	-0.041	0.210	-0.100	0.042	0.350
	<b>Manning's n - 20%</b>			<b>Manning's n + 20%</b>		
1 in 20-year	-0.580	-0.062	0.080	-0.150	0.066	0.540
1 in 100-year	-0.740	-0.082	0.350	-1.220	0.086	1.510
	<b>Manning's n - 30%</b>			<b>Manning's n + 30%</b>		
1 in 20-year	-0.880	-0.091	0.040	-0.380	0.099	0.760
1 in 100-year	-1.270	-0.120	0.350	-1.220	0.130	0.960

**Table 8-6: HEC-RAS Sensitivity Analysis - Manning's Roughness Coefficient – Change in Critical Depth Occurrence**

Scenario	Critical Depth Occurrence by AEP Event	
	20-year	100-year
Manning's n -30%	787	756
Manning's n -20%	755	724
Manning's n -10%	710	687
<b>Base Model</b>	<b>664</b>	<b>649</b>
Manning's n +10%	603	607
Manning's n +20%	557	551
Manning's n +30%	521	516
Notes:		
1 The values presented in this table are the number of computational cross-sections in the HEC-RAS model where critical depth is the resultant computed water surface elevation.		

### 8.1.2.2 Peak Discharge

To determine the impact of the changes in peak flows on the resulting water surface profile, the peak flows for the 1 in 20-year and 1 in 100-year AEP events were increased and decreased by 10%, 20%, and 30%. Table 8-7 summarizes the changes in water levels for the modelled AEP events associated with the varying peak flow conditions.

Similar to the results for Manning's Roughness, the selection of peak discharge generally has a limited impact on average (<0.3 m). However, significant impacts in localized reaches is demonstrated through this analysis where changes in flow regime occur (i.e. from supercritical to subcritical or vice-versa). Large changes in water surface can also occur in cross-sections near (typically upstream of) critical culvert and bridge locations where flow changes from open surface flow to surcharged or overtopping situations.

A comparative assessment of the occurrence of critical depth at cross-sections was also completed (ref. Table 8-8). The results indicate that variation of flow has a minimal influence on critical depth occurrence across the model.

**Table 8-7: HEC-RAS Sensitivity Analysis - Peak Discharge**

Event (AEP)	Change in Computed Water Surface Elevation (m)					
	Maximum Decrease	Average	Maximum Increase	Maximum Decrease	Average	Maximum Increase
	<b>Peak Discharge - 10%</b>			<b>Peak Discharge + 10%</b>		
1 in 20-year	-1.270	-0.085	3.040	-1.610	0.076	0.860
1 in 100-year	-4.560	-0.109	1.420	-3.370	0.083	1.060
	<b>Peak Discharge - 20%</b>			<b>Peak Discharge + 20%</b>		
1 in 20-year	-3.400	-0.204	0.430	-1.020	0.147	1.550
1 in 100-year	-3.270	-0.196	0.930	-3.380	0.165	1.600
	<b>Peak Discharge - 30%</b>			<b>Peak Discharge + 30%</b>		
1 in 20-year	-5.710	-0.309	1.470	-2.540	0.199	2.120
1 in 100-year	-4.370	-0.283	3.440	-3.380	0.255	2.520

**Table 8-8: HEC-RAS Sensitivity Analysis – Peak Discharge – Change in Critical Depth Occurrence**

Scenario	Critical Depth Occurrence by AEP Event	
	1 in 20-year	1 in 100-year
Peak Discharge -30%	672	655
Peak Discharge -20%	667	661
Peak Discharge -10%	663	653
<b>Base Model</b>	<b>664</b>	<b>649</b>
Peak Discharge +10%	658	645
Peak Discharge +20%	659	641
Peak Discharge +30%	660	630

Notes:  
 2 The values presented in this table are the number of computational cross-section in the HEC-RAS model where critical depth is the resultant computed water surface elevation.

### 8.1.2.3 Starting Water Surface Elevation

The downstream boundary condition for the Current IDF and Climate Change IDF modelling scenarios was estimated as 1.19 m (CGVD-2013) and 1.75 m (CGVD-2013), respectively. These water levels are comprised of the maximum high tide and storm surge as previously documented in Section 7.2.6, plus sea level rise for climate change modelling which reflects the 2080 tri-decade period.

For sensitivity analyses modelling purposes, the HEC-RAS model downstream boundary condition was decreased and increased by 0.5 m and 1.0 m for the 1 in 20-year and 1 in 100-year AEP events for existing

development conditions. This range of starting water level values, established albeit somewhat arbitrarily, was estimated to reflect the potential impact, on computed water surface elevations, from varying tides and the uncertainty associated with sea level rise estimates. The results of this analysis are presented in Table 8-9.

The resulting changes in computed water surface elevations are consistent with the incremental change in the downstream boundary condition. The maximum change is limited to the starting cross section for all scenarios. Moving in an upstream direction, the influence of the initial perturbation decreases. In all results, the impact of the increase in the downstream boundary condition is relatively localized. However, the changes in computed water surface elevations can extend a significant distance upstream, although the majority of the changes, at any cross-section, are less than 10 cm over the entire reach where changes were computed.

**Table 8-9: HEC-RAS Sensitivity Analysis – Starting Water Surface Elevation**

Event (AEP)	Change in Computed Water Surface Elevation (m) along the lower Humber River					
	Maximum Decrease	Average	Maximum Increase	Maximum Decrease	Average	Maximum Increase
	<b>Starting Water Surface Elevation -0.5 m</b>			<b>Starting Water Surface Elevation +0.5 m</b>		
1 in 20-year	-0.500	-0.005	0.010	-0.010	0.006	0.500
1 in 100-year	-0.500	-0.005	0.000	0.000	0.006	0.500
	<b>Upstream propagation to &lt;10 cm change (m)</b>		<b>Maximum extend of upstream propagation (m)</b>	<b>Upstream propagation to &lt;10 cm change (m)</b>		<b>Maximum extend of upstream propagation (m)</b>
1 in 20-year	4,635		16,675	4,930		19,525
	Humber River-Reach 001		Humber River-Reach 007	Humber River-Reach 001		Humber River-Reach 011
1 in 100-year	3,600		17,262	4,300		18,316
	Humber River-Reach 001		Humber River-Reach 008	Humber River-Reach 001		Humber River-Reach 009
	<b>Starting Water Surface Elevation -1.0 m</b>			<b>Starting Water Surface Elevation +1.0 m</b>		
1 in 20-year	-1.000	-0.010	0.010	-0.020	0.014	1.000
1 in 100-year	-1.000	-0.008	0.010	-0.010	0.012	1.000
	<b>Upstream propagation to &lt;10 cm change (m)</b>		<b>Maximum extend of upstream propagation (m)</b>	<b>Upstream propagation to &lt;10 cm change (m)</b>		<b>Maximum extend of upstream propagation (m)</b>
1 in 20-year	17,572		52,155	14,220		53,075
	Humber River-Reach 008		Humber River-Reach 024	Humber River-Reach 007		Humber River-Reach 025
1 in 100-year	18,316		50,655	9,040		53,075
	Humber River-Reach 009		Humber River-Reach 023	Humber River-Reach 003		Humber River-Reach 025

#### 8.1.2.4 Summary of Hydraulic Model Sensitivity

Average changes in computed water levels resulting from the sensitivity runs were close to base case results. More significant changes in computed water levels were attributed to changes in flow regime (i.e. from supercritical to subcritical or vice-versa) or changes in flow conditions around bridges and culverts (i.e. changes from open surface flow to surcharged or overtopping situations).

Standard HEC-RAS output tables, associated with hydraulic computations detailed for the hydraulic model sensitivity analysis, are provided in Appendix O.

#### 8.1.3 Sensitivity Analysis Conclusions

As noted previously, sensitivity analysis is used to:

- *Test the robustness of simulation model results in the presence of uncertainty and increasing the understanding of the relationships between input and output variables in the simulation models.*

Five (5) input variables were tested with the following results:

- HEC-HMS model:
  - Sensitive to changes in Curve Number,
  - Limited sensitivity to changes in river reach roughness, and;
- HEC-RAS model:
  - Not sensitive to changes in Manning's roughness coefficient
    - Please note that this comment is in reference to average changes in computed water surface elevations across the entire hydraulic model. It has been noted that significant impacts in localized reaches has been demonstrated through this analysis where changes in flow regime occur as a result of roughness variation (i.e. from supercritical to subcritical or vice-versa). Large changes in water surface can also occur in cross-sections near (typically upstream) critical culvert and bridge locations where flow changes from open surface flow to surcharged or overtopping situations.
  - Sensitive to changes in peak discharge
  - Limited sensitivity to changes in starting water surface elevation

Some benefit may be gained regarding improved confidence in Curve Number estimation through the use of higher resolution satellite imagery for land classification. However, the difference between the two methods (i.e. use of low- or high-resolution data) in terms of Curve Number estimation cannot be quantified without parallel assessments.

- *Increasing confidence in simulation model results by identifying model inputs that cause significant uncertainty in the output thereby focusing increased attention towards estimation of these specific model inputs.*

The sensitivity analysis results did not justify any additional effort towards refining initial model estimates for these parameters. However, given hydraulic model sensitivities to peak flows, continued effort to

collect streamflow data that can support hydrologic modelling calibration and AEP flow estimation is recommended.

- *Ensuring the model is accurately reflecting watershed conditions and responses by identifying errors in the model output as reflected by unexpected relationships between inputs and outputs.*

The sensitivity analysis results did not demonstrate any unexpected relationships or model errors.

Overall, the model input parameters were selected based on reliable and available background information, engineering judgment and field measured data and are considered to be a good and supportable reflection of watershed conditions. The sensitivity analysis results of the hydrologic models did suggest opportunities for future potential enhancement regarding Curve Number estimation but, overall, did not suggest a need to alter the parameterization of the hydrologic models for the present study.

The sensitivity analysis results associated with the hydraulic model indicate a general insensitivity to changes in input parameters when viewed as average changes to computed water surface elevations. Some specific locations do experience larger variation in computed water levels, but these are associated with changes in the flow regime between sub-critical flow and super-critical flow (and vice versa) and changes in bridge hydraulics associated with open water to pressure flow situations (and vice versa).

The sensitivity analysis results of the hydraulic models did not suggest a need to alter the parameterization of the hydraulic models for the present study.

#### **8.1.4 Sensitivity Analysis Recommendations**

It was noted that better estimates of Curve Number may be possible with the use of higher resolution satellite imagery to support the classification of land cover in the watersheds. This should be a consideration for future watershed modeling efforts.

As well, continued effort to collect streamflow data that can support hydrologic modelling calibration and AEP flow estimation is recommended.

## **8.2 Climate Change Influences on Flood Risk**

The Province of Newfoundland and Labrador is expected to experience changes in temperature, precipitation, sea level and other factors in the future as a result of climate change. These factors can influence the flood risk faced by a community directly or indirectly and climate change influences may result in communities which are not presently at risk of flooding being included in the list of potential candidates for new flood plain mapping.

The climate change assessment for this project focused on the development of flood plain mapping for the future 2080 tri-decade period. It should be noted that this period is not meant to represent exactly this year but the more general time frame of today 2066 to 2095.

### 8.2.1 Hydrologic Modelling

The HEC-HMS model of Humber River, developed for this project, was used to assess the impact of climate change by using projected rainfall data for the future 2080 time period. It can be argued that other parameters are also relevant in this analysis such as continued urban development and change of land cover.

Watershed runoff response will also be influenced by changes in land cover that may result from community development (increased imperviousness as a result of new roads, buildings, paved areas, etc.) or changes in terrestrial communities (such as a forest changing to an open meadow or vice versa). The land cover analysis completed as a component of this project was focused on two time periods, namely existing development and fully developed conditions. Fully developed conditions, for the purposes of this study, were defined using information available from the province's Department of Environment and Climate Change Land Use Planning Registry for the communities of Deer Lake, Pasadena, Reidville and Steady Brook.

Broader changes in land cover as a result of changing terrestrial communities due to climate change are addressed in Vasseur and Catto (2008). However, the sensitivity and vulnerability of forest communities in Atlantic Canada is considered to be low to moderate. Further, given that the Vasseur and Catto (2008) assessment of climate change influences on forest systems provided no specific guidance on regional variation of potential impacts across the Province, there was not any means making projections regarding hydrologic model parameterization for future periods to reflect potential land cover changes. As such, terrestrial land cover, not associated with changing community development, was maintained across the existing development and fully developed watershed conditions HEC-HMS models.

#### 8.2.1.1 Precipitation Projections

Precipitation projections resulting from climate change as documented in the report "*Projected Impacts of Climate Change for the Province of Newfoundland & Labrador: 2018 Update*" (Finnis and Daraio, 2018) were used to define future precipitation for this study.

As noted in the report, precipitation projections were developed using Representative Concentration Pathway (RCP) 8.5 based on an ensemble of twelve (12) climate realizations (six (6) dynamically downscaled, six (6) statistically downscaled). The ensemble median, 10<sup>th</sup> percentile, and 90<sup>th</sup> percentile IDF relationships are documented. The median is considered the most likely outcome, and a comparison of the 10<sup>th</sup> and 90<sup>th</sup> percentiles provides an indication of projection uncertainty.

The hyetographs representing the projected climate change rainfall conditions were input to the HEC-HMS model to simulate the 1 in 20-year and 1 in 100-year AEP flows for the future climate change influenced scenarios. These flows have then been used in the HEC-RAS model to simulate the inundation zones for the future climate change influenced scenarios.

#### 8.2.1.2 Hydrologic Summary

As noted previously, the existing conditions HEC-HMS model for the Humber River study watershed was used to determine peak flows for the 2080 tri-decade future period, based on rainfall estimates for this future period as documented in (Finnis and Daraio, 2018). Table 8-9 provides a summary of the calculated flows.

### 8.2.2 Hydraulic Modelling

The flows determined for the future period were then input to the HEC-RAS hydraulic model to evaluate the potential impact of climate change on computed water levels in the study reaches. Table 8-10 provides a summary of the changes in computed water surface elevations (from existing conditions/current climate) associated with each of the other scenarios. A full listing of the HEC-RAS results for the future periods (and existing) is provided in Appendix N).

**Table 8-9: Streamflow Summary for Existing and Future Conditions**

Scenario	Streamflow (m <sup>3</sup> /s)	
	Humber River (at the model terminus)	
	1 in 20-year AEP	1 in 100-year AEP
Current IDF – Existing Conditions	766.2	1106.6
Climate Change IDF – Existing Conditions	1658.1	2574.5
Current IDF – Fully Developed Conditions	782.0	1129.5
Climate Change IDF – Fully Developed Conditions	1702.3	2637.2

**Table 8-10: Comparison of Existing and Future Computed Water Surface Elevations**

Scenario	Changes in Computed Water Surface Elevation (m)
	Average Change
<b>1 in 20-year AEP Flood</b>	
Current IDF – Existing Conditions	Base condition
Climate Change IDF – Existing Conditions	0.82
Current IDF – Fully Developed Conditions	0.25
Climate Change IDF – Fully Developed Conditions	1.00
<b>1 in 100-year AEP Flood</b>	
Current IDF – Existing Conditions	Base condition
Climate Change IDF – Existing Conditions	1.10
Current IDF – Fully Developed Conditions	0.14
Climate Change IDF – Fully Developed Conditions	1.20

### 8.2.3 Projected Sea Level Rise

As directed by the RFP for this study, sea level for future climate conditions was defined by the projections contained in the Batterson-Liverman report: *“Past and Future Sea-Level Change in Newfoundland and Labrador: Guidelines for Policy and Planning”* (Batterson and Liverman, 2010). Sea level rise alone will not cause an increase in stream flow but will cause an increase in watercourse water level within the zones influenced by tides.

The analysis conducted to establish starting water surface elevations for the hydraulic modelling is documented in Section 7.2.6 of this report volume.

The analysis conducted to assess potential impact from tides and uncertainty associated with sea level rise estimates is documented in Section 8.1.2.3 of this report volume.

### **8.3 Conclusions and Recommendations**

An evaluation of the potential impacts of climate change on flood risk was completed. Estimates of flood plains for the 2080 tri-decade period were computed and delineated

It should be noted that there is a great deal of uncertainty with all climate models, statistical downscaling and projection of rainfall to point locations. The quantification of rainfall and, subsequently, flood plain estimates should not be interpreted as an accurate portrayal of possible future events. These estimates provide a good indication of upward and downward trends and general sense of the magnitude of the potential change but should not be considered absolute.

#### **8.3.1 Conclusions**

It is concluded from this assessment that future development and climate change have the potential to increase flood risk in the Humber River study area.

#### **8.3.2 Recommendations**

It is recommended that meteorological conditions in the Humber River area be monitored towards determination of changing trends in rainfall and generally extreme weather.

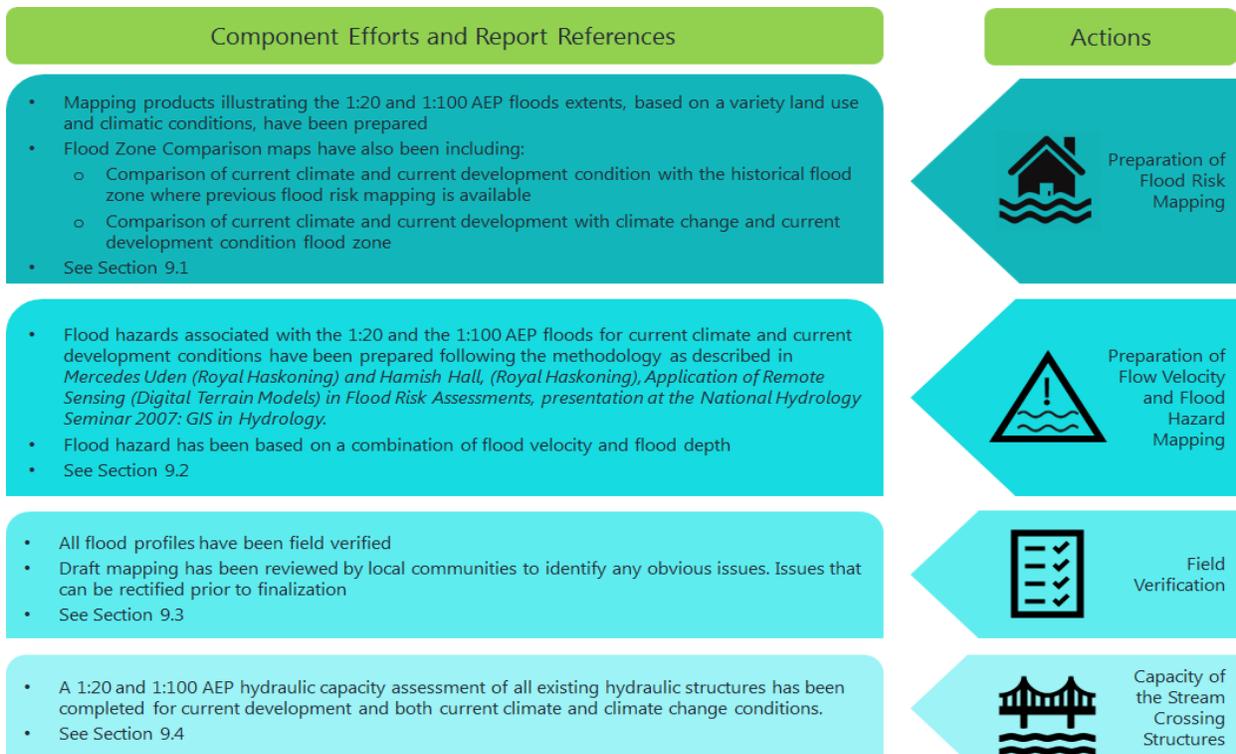
It is further recommended that climate change be integrated into municipal planning in those areas where increasing flood risk is relevant such as infrastructure and emergency planning.

## 9.0 Flood Risk Mapping Preparation

Synopsis: The best and most cost-effective method of minimizing the impact of floods is proper management and planning of known flood plains. Flood plain management typically involves the adoption of land use regulations that limit human exposure to areas prone to flooding events. The Province’s Policy for Flood Plain Management, administered through the Water Resources Act, 2002, regulates development in designated flood plains. In 2010, climate change flood plains were added to the policy. Flood risk maps in the Province are based on flood events associated with the 1 in 20 and 1 in 100 Annual Exceedance Probability (AEP). The 1 in 20 and 1 in 100 AEP floods correspond to the 5% and 1% risk of flooding in any one year. Since 2009, flood risk mapping studies have incorporated climate change projections by adding climate change flood plains for the 1 in 20 and 1 in 100 AEP floods. The Province’s flood risk mapping studies are publicly available, accessible through the Newfoundland and Labrador Water Resources Portal at [maps.gov.nl.ca/water/](https://maps.gov.nl.ca/water/). The studies and maps are also available online via the Water Resources Management Division website at [www.env.gov.nl.ca/env/waterres/flooding/frm/](https://www.env.gov.nl.ca/env/waterres/flooding/frm/).

For the Humber River project, over 700 maps comprise the overall complete flood plain and flood risk mapping set for the project.

**Figure 9-1: Flood Risk Mapping Preparation Summary**



### 9.1 Preparation of Flood Risk Mapping

A key means of communicating more complete flood risk information and to inform actions that can be taken to mitigate flood risk is to provide detailed information on flood extents, depth of flooding, probability of flooding, and other flooding characteristics in the form of hardcopy and/or digital maps and GIS compatible datasets. Based on the modelling results and using the HEC-GeoRAS extension, over 700 maps comprise the overall complete flood plain and flood risk mapping set for the project. The set of map deliverables is summarized in Table 9-1.

**Table 9-1: Flood Mapping Deliverables Summary**

Flood Map Theme	Map Reference Code	Ortho-Photography by AEP	
		1 in 20 year	1 in 100 year
Current Climate and Current Development Condition (CC-CD) Flood Zone (FZ)	FZM-CCCD	Y	Y
CC-CD Inundation	FDM-CCCD	Y	Y
CC-CD Velocity	FVM-CCCD	Y	Y
CC-CD Hazard	FHM-CCCD	Y	Y
Current Climate and Fully Developed Condition (CC-FD) FZ	FZM-CCFD	Y	Y
Climate Change and Current Development Condition (CLC-CD) FZ	FZM-CLCCD	Y	Y
Climate Change and Fully Developed Condition (CLC-FD) FZ	FZM-CLCFD	Y	Y
Comparison of CC-CD with historical FZ only if/where previous FRM is available	FZM-CCCD_HIST	Y	Y
Comparison of CC-CD with CLC-CD FZ	FZM-CCCD_CLCCD	Y	Y

Please note the following:

- Flood Zone (FZ) maps illustrate the extent of the flood plain.
- Flood inundation maps illustrate the spatial distribution of flood depth across the flood plain.
- Flood velocity maps illustrate the spatial distribution of the velocity of flow across the flood plain.
- Flood hazard maps represent a combination of the flood depth and flood velocity data to present a depiction of the potential hazard associated with a flood scenario.

The development of Community Mapping versions of the flood map products was envisioned in the RFP. Review of the available vector Community Mapping base confirmed that it was out of date and the expected effort required to update the information to reflect current anthropogenic features was beyond the scope of the current project. It was therefore, agreed with WRMD that all flood map products would be produced using the Ortho-Photography format as it was the most up to date base available to this project.

The 1 in 20-year and 1 in 100-year AEP water surface profiles were used to develop flood risk mapping using the outputs of the hydraulic model. Flows used as input to the hydraulic model are based on outputs from the hydrologic model. Flood risk maps illustrate the extent of flooding that is expected under the 1 in 20-year and 1 in 100-year AEP flood events and are available for use by all levels of government, private companies and other stakeholders. Additionally, climate change analyses were carried out for 2080 tri-



decade period, as outlined in Section 7, for both the 1 in 20-year AEP and 1 in 100-year AEP scenarios. Associated flood risk mapping was prepared for the most severe climate change water levels anticipated for the 1 in 20-year and 1 in 100-year AEP flood events.

HEC-GeoRAS enables the conversion of HEC-RAS results into GIS-based flood risk mapping. The program creates a polyline feature class to which the maximum water surface elevations are attributed. From this, triangulation is carried out which interpolates the water surface elevation between adjacent cross sections. A volumetric cut-fill analysis is then performed between the water surface and the topography to arrive at the resultant inundated area. The generic functionality for the automated flood line generation routines within HEC-GeoRAS is based on a gridded approach to DTM processing. The gridded approach attempts to represent the terrain using a "smooth" mathematical model across the entire terrain surface. Gridded DTM processing has a tendency for over- and under-shoot (i.e. the grid elevation at a point is over or under the known elevation at that same point) in zones of rapidly changing terrain. The terrain in the subject watersheds, particularly in the flood plain, is considered rapidly varying. Initial results with the generic automated flood plain functionality yielded less than desirable results. As such, a manual procedure mimicking the generic HEC-GeoRAS functionality was employed with the exception that the DTM processing was based on the Triangulated Irregular Network representation of the terrain. The resultant flood lines were significantly improved in terms of the accuracy of their placement relative to the known terrain and associated elevations.

LiDAR was acquired for the entire study area for which flood mapping was to be developed and, as such, was used to accurately represent basin topography for the purposes of flood mapping development.

It should be noted that, although the automatically generated inundation polygon provides reliable inundation at each cross section location, manual post-processing is required to ensure that the water surface elevation between cross sections is represented properly. The following issues were noted as requiring manual post-processing:

- In areas where a tributary enters the main watercourse between cross sections, the triangulated water surface often overestimates the extent of flooding up the tributary which is caused by an increase in water level along the main watercourse.
- It is also common for low lying areas, which are located off the main watercourse and which would not realistically be inundated, to appear inundated as a result of the cut-fill analysis.
- Similarly, backwater areas, where flooding of low lying areas located off the main watercourses is reasonable, can be falsely extended if the extent of the backwater area traverses upstream sections beyond the point connection to the main watercourse.
- 0.5 m contours were created from the LiDAR so that post processing in these areas can be carried out to approximately the same level of accuracy as is inherent in the LiDAR DTM.

Flood plain maps illustrating the extent of flooding expected under the 1 in 20-year and 1 in 100-year AEP flood events for the Humber River (and tributaries) study area are provided in Appendices E, F, G and H. Overview maps providing an index to the map sheets coverage across the study area are provided as Figures 9-2 to 9-5. Flood risk map examples are provided as Figures 9-6 and 9-7.

It should be noted that hydraulic structures that are overtopped are covered by the flood polygon on the flood plain maps. If the structure is not overtopped, there is a break in the flood polygon so that the bridge deck is visible. Tables 7-8 and 7-9 detail flood levels at all structures included in the modelling and provide additional details regarding structure overtopping (where this occurs).

The information on the flood plain maps provides explicit cross-section referencing for each section in the HEC-RAS model. Using this cross-section reference, flood plain map users can access secondary hydraulic data, provided in Appendix N, for all hydraulic sections which comprise the overall HEC-RAS model. The flood plain maps also identify the 1 in 20-year and 1 in 100-year AEP water levels at each cross-section.

A summary of the flooded areas depicted on the flood plain mapping developed for this study is provided in Table 9-2. As the percent change values indicate, future development has a minor influence on changing flood risk in comparison to climate change which has the potential to exert a more significant influence. The exception to this, regarding future development influences on floodplains, is noted for Pasadena where future development results in expansion of floodplains by up to about 11% (over existing landuse conditions). For this community, areas planned for future development (i.e. not yet developed) represent a larger portion of the drainage areas contributing to the four watercourses traversing the community than is the case for other communities (i.e. Steady Brook, Deer Lake and Reidville) in the study area.

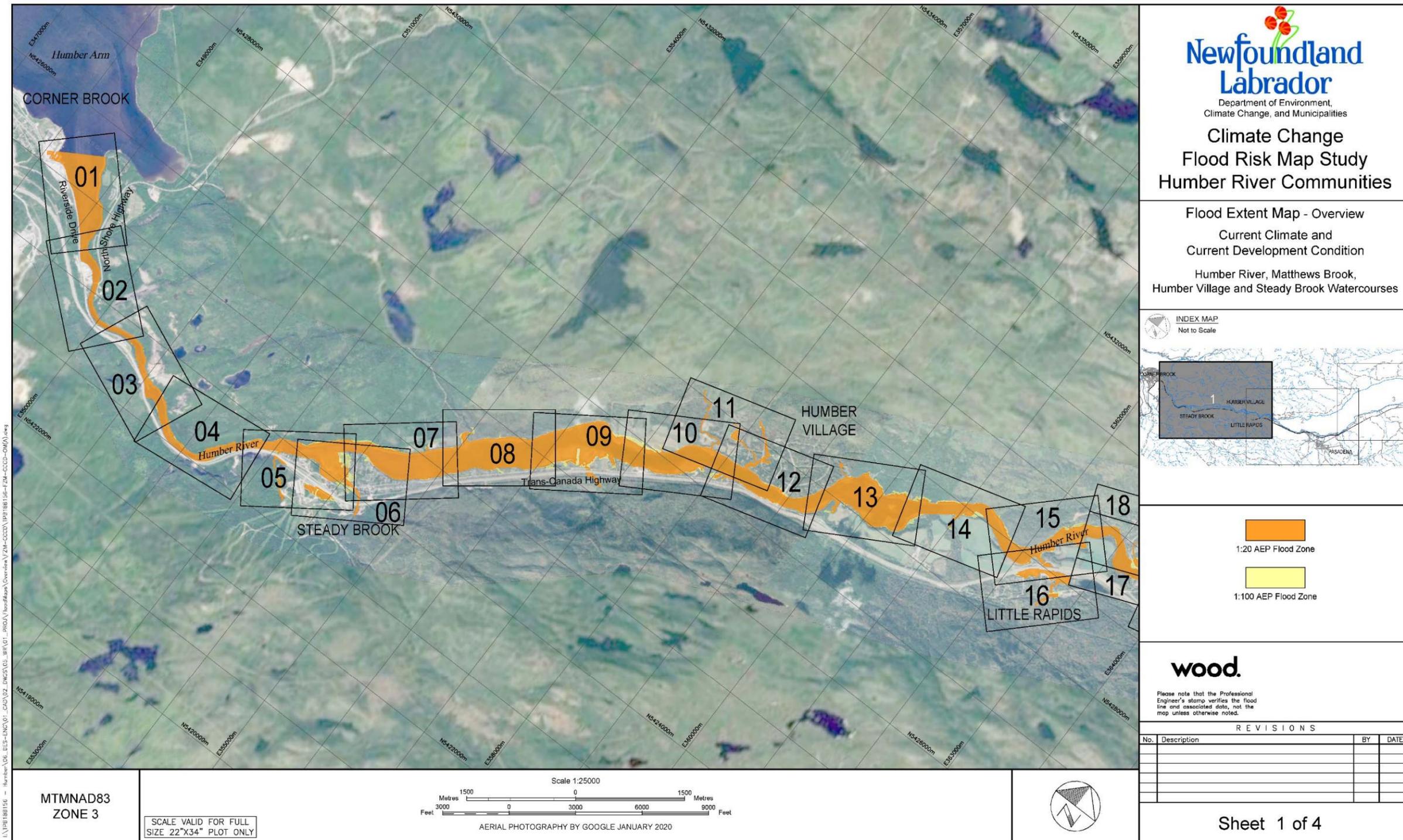
### 9.1.1 Comparison of Current Climate/Current Development to Historical Maps

Historical flood zones were delineated using public information maps<sup>25</sup> from the 1984 Steady Brook Hydrotechnical Study and the 1987 Deer Lake Hydrotechnical Study. The public information maps were spatially located in an AutoCAD environment using visual referencing and the new mapping and aerial photography prepared for this study. This approach was utilized as georeferenced digital vector or GIS compatible information is not available from these studies. Given this approach the historical floodlines should be considered approximate and within  $15\pm m$  of their true location and should be used for qualitative comparison only to other flood delineations (ref. Appendix J).

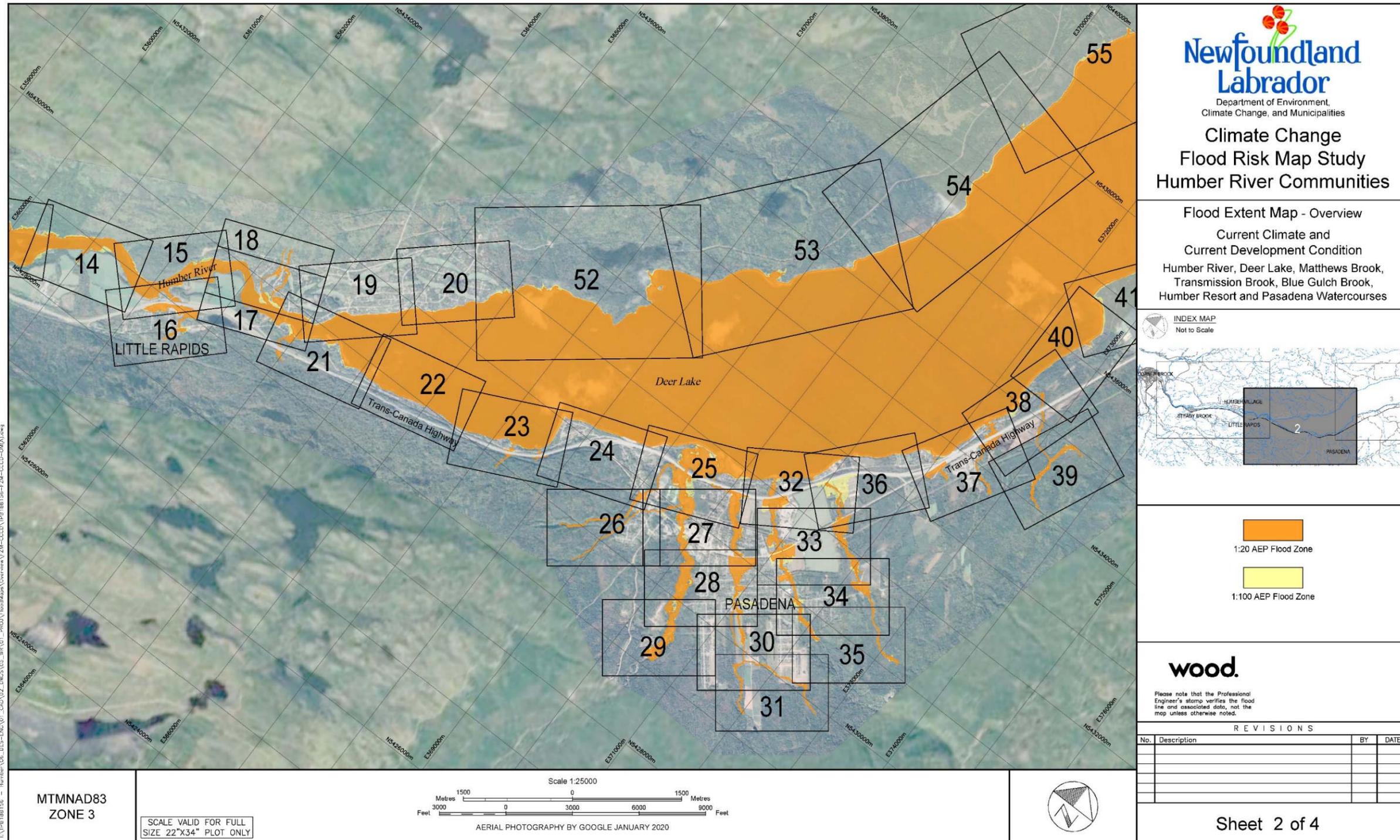
An alternate approach was also adopted for the areas of Steady Brook where in the computed water surface elevations were abstracted from the 1984 report and delineated directly using the new topographic mapping. Using this approach, the position of flood line aligns with the underlying contour information. However, as noted in Section 9.5.2.4, comparison of the flood lines based on the new contour information and those approximated (as described above) indicates differences which are not simply reflective of an offset, but the flood delineations follow different paths which is indicative of the underlying contour information being different between the 1984 study and the current study.

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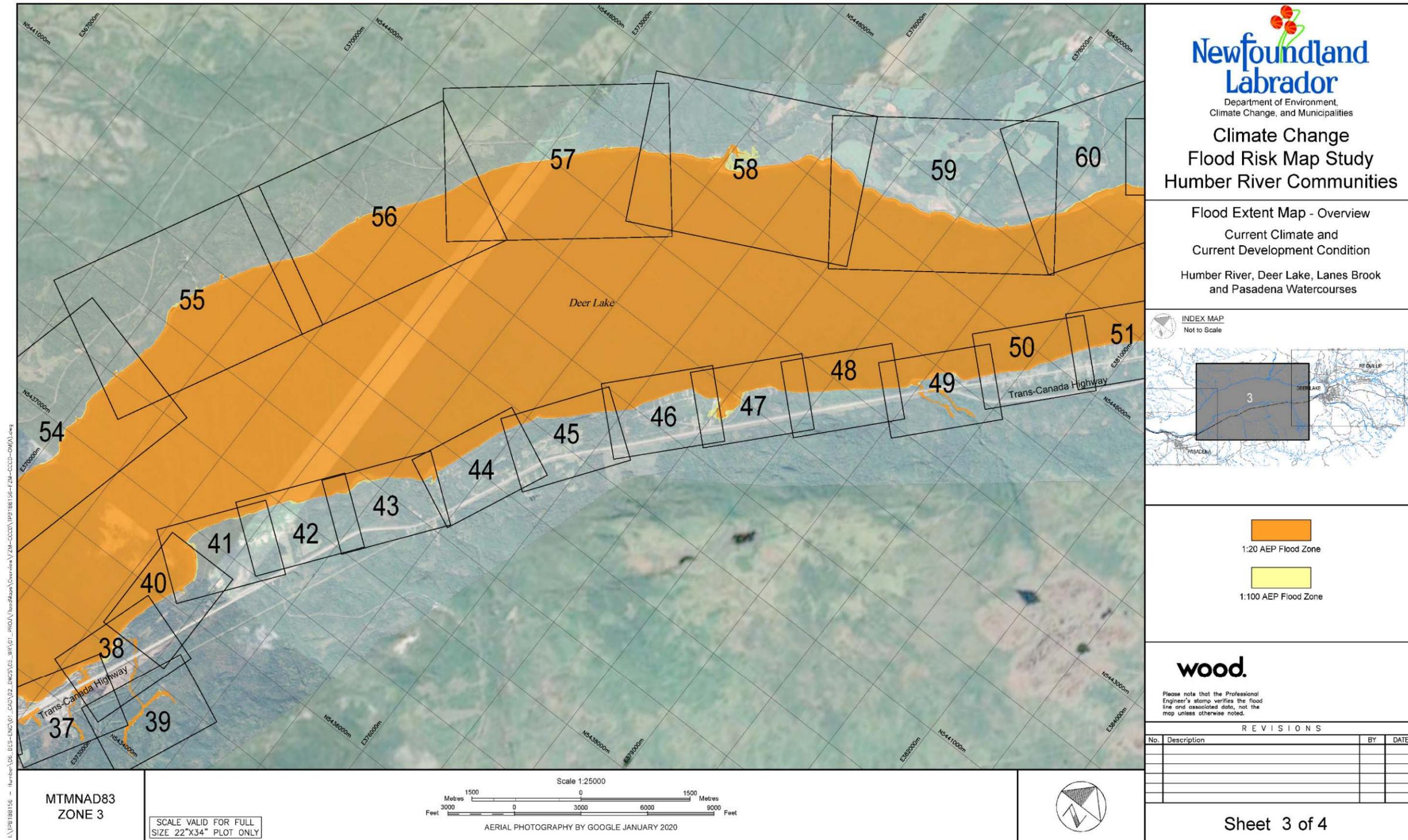
<sup>25</sup> Available via URL <https://www.gov.nl.ca/ecc/waterres/flooding/fm/>



**Figure 9-2: Flood Map  
Extent Overview – Map  
1 of 4**

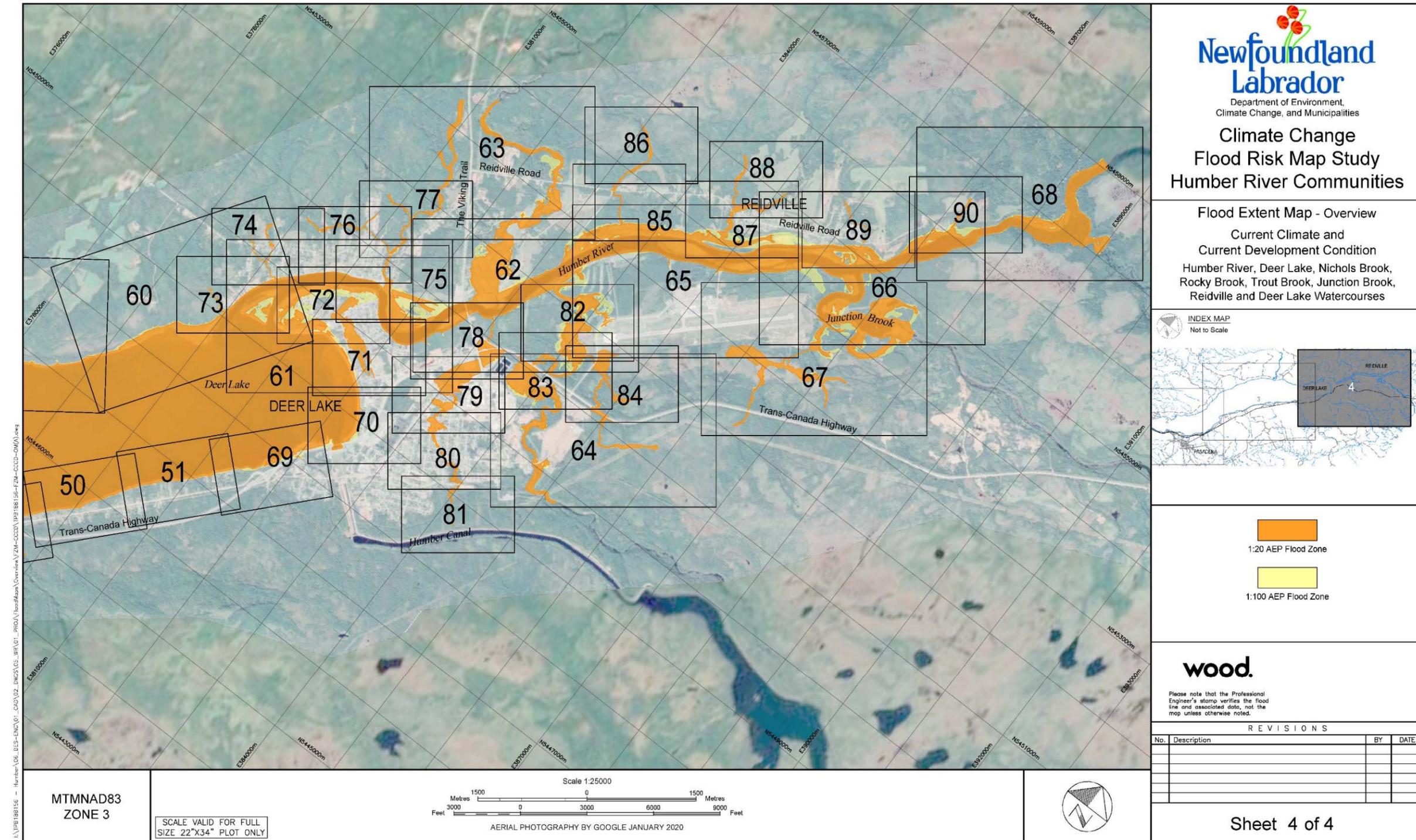


**Figure 9-3: Flood Map  
Extent Overview – Map 2  
of 4**



**Figure 9-4: Flood Map  
Extent Overview – Map 3  
of 4**

Figure 9-5: Flood Map  
Extent Overview – Map 4  
of 4



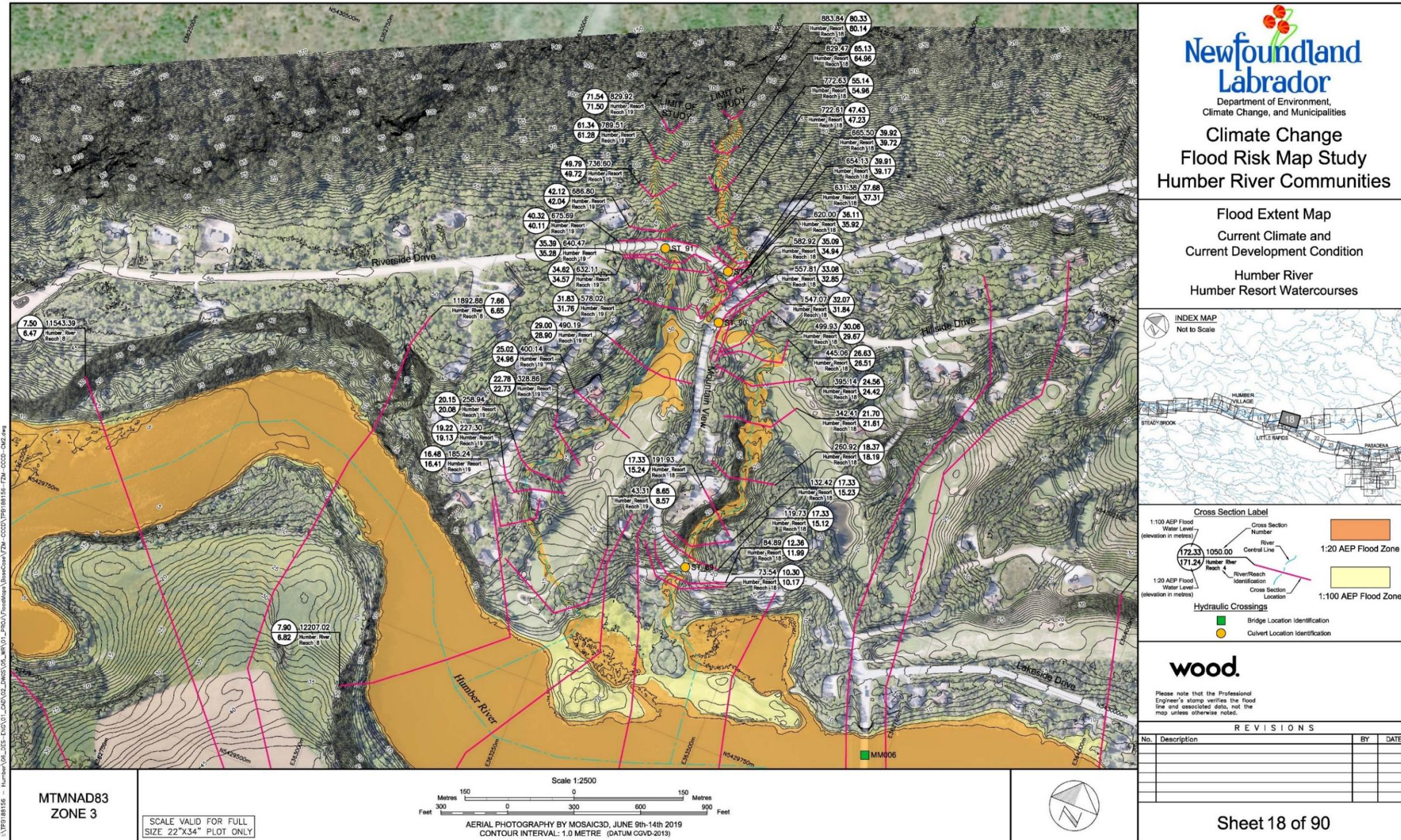
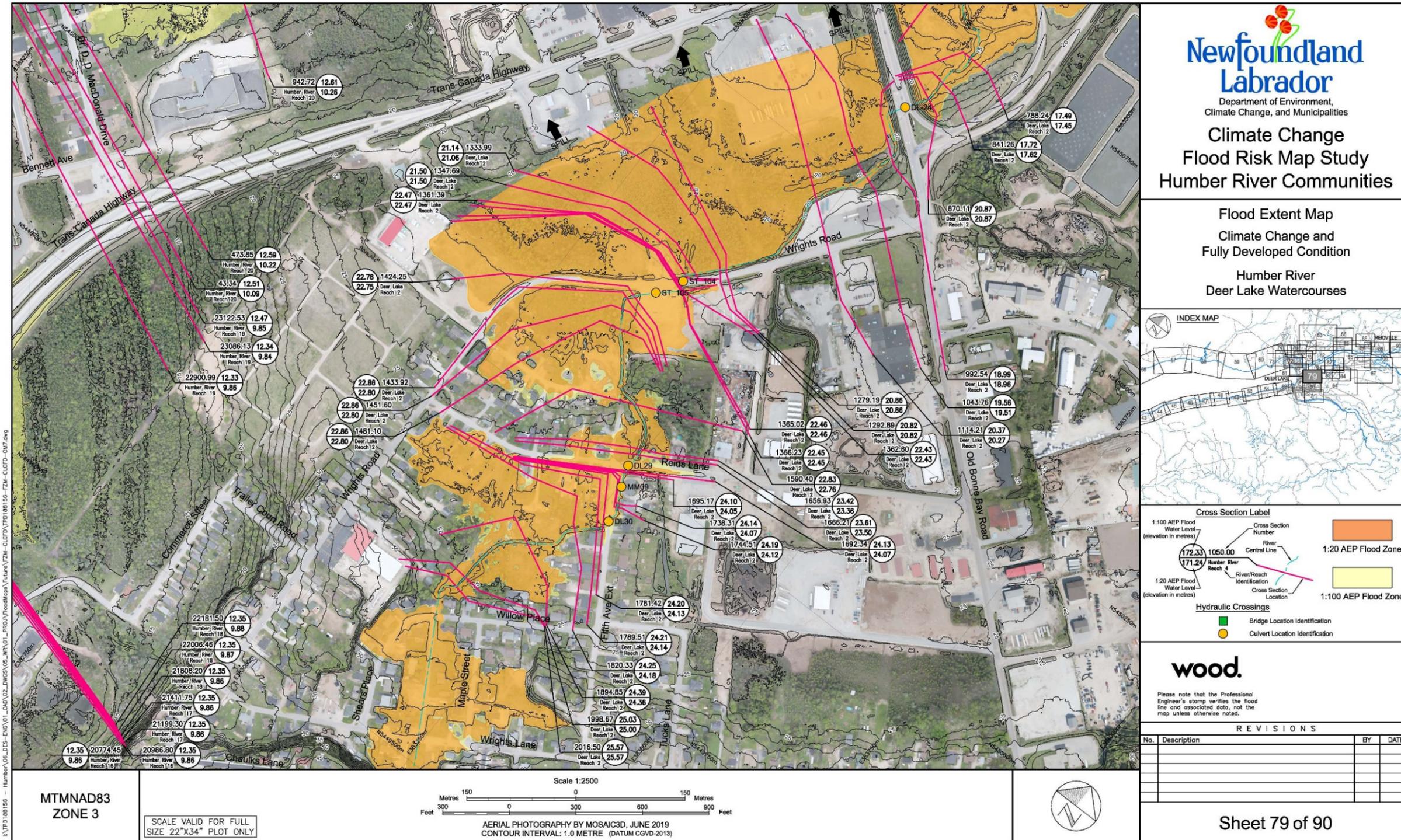


Figure 9-6: Example Floodplain Map - Current Climate and Current Development Condition



**Figure 9-7: Example  
Floodplain Map –  
Climate Change and  
Fully Developed  
Condition**

**Table 9-2: Summary of Flooded Area**

Event (AEP)	Flooded Area (km <sup>2</sup> ) / Percent Change from Current Climate & Existing Development			
	Existing Development		Fully Developed	
	Current Climate (CCCD)	Climate Change (CLCCD)	Current Climate (CCFD)	Climate Change (CLCFD)
<b>Over the Entire Study Area</b>				
20-year	81.6	87.9 / 7.7%	81.9 / 0.4%	88.4 / 8.3%
100-year	84.1	94.2 / 15.4%	84.4 / 3.4%	94.7 / 16.1%
<b>Deer Lake / Reidville (including areas upstream from Reach 16 section 20986.80)</b>				
20-year	7.4	11.4 / 53.3%	7.9 / 6.4%	10.7 / 35.4%
100-year	9.0	14.1 / 57.9%	9.1 / 1.1%	14.2 / 57.1%
<b>Pasadena (including South Brook, Blue Gulch Brook and HEC-RAS Watercourse Reach 3)</b>				
20-year	1.0	1.5 / 48.4%	1.1 / 10.8%	1.6 / 38.8%
100-year	1.4	1.7 / 24.4%	1.4 / 4.3%	1.7 / 20.3%
<b>Steady Brook</b>				
20-year	0.1	0.3 / 85.3%	0.1 / 0.1%	0.3 / 97.2%
100-year	0.2	0.3 / 53.9%	0.2 / 1.1%	0.4 / 70.8%

## 9.2 Flood Depth Mapping Development

Flood Depth Mapping was produced for the 1 in 20-year and 1 in 100-year AEP floods for the current climate and current development conditions scenario.

The water surface elevations computed by HEC-RAS were used at the associated cross-section locations to generate a DEM (Digital Elevation Model) of the flood surface. The underlying LiDAR data, obtained for the flood plain mapping assignment, was used to generate a DEM of the current topography within the area to be flood plain mapped. GIS was used to intersect the two DEM's. The flood plain limit can be contoured as elevation zero (this is basically how automated flood plain delineation functions). Additionally, flood depths were determined using this approach.

Limitations to the proposed flood depth map product relate to the extent of the available LiDAR and bathymetry data collected for this study. LiDAR data does not extend into areas covered by water; however, the LiDAR data was collected during a period of low flow water levels in the study area. Below waterline bathymetry data was collected at discrete locations along the major watercourses in scope for this study as described in Section 3. As such, the accuracy of flood depth computations and visualizations is variable as follows:

- in the nearshore area, and other areas, of overbanks and at locations where bathymetry data was surveyed, computations and visualizations are considered accurate;

- along watercourses which typically experienced shallow depth of flow during low flow conditions is considered accurate;
- along the major watercourses (such as the main Humber River) between locations where below waterline bathymetry data was collected is considered approximate.

Notwithstanding, the flood depth and related products are considered to have adequate accuracy for their intended purpose.

### 9.3 Flow Velocity Mapping Development

Flood Velocity Mapping was produced for the 1 in 20-year and 1 in 100-year AEP floods for the current climate and current development conditions scenario (ref. Appendix L). These maps were developed following guidance from the following reference documents:

- FEMA (2012). Recommended Procedures for Flood Velocity Data Development; and
- FEMA (2020). Guidance for Flood Risk Analysis and Mapping - Flood Depth and Analysis Rasters, Guidance Document 14.

### 9.4 Flood Hazard Mapping Preparation

Flood Hazard Mapping was produced for the 1 in 20-year and 1 in 100-year AEP floods for the current climate and current development conditions scenario. These maps were developed following guidance from Uden and Hall (2007) and other related documents as described in this report section.

The hazard rating outlined in Uden and Hall (2007) was originally described in Defra (2005). The flood hazard rating is based on the following equation:

$$\text{Flood Hazard Rating} = ((v + 0.5) * D) + DF$$

where:

v = velocity (m/s)

D = depth (m)

DF = debris factor defined as follows:

- 0.5 where flood depth is less than or equal to 0.25 m
- 1.0 where flood depth is greater than 0.25 m

This equation was used to develop the information presented in Table 9-3.

The flood hazard ratings ranges associated with the degrees of flood hazard are further described in Surendran et al (2008). The ranges noted in Table 9-4 were taken from Surendran et al (2008, ref. Table 4). The colour coding provided in Table 9-3, identifying the degree of flood hazard, is based on the ranges provided in Table 9-4. The exception to this is for the *Extreme* degree of flood hazard for flood depth of 2 m and velocity of 0 m/s which aligns with the RFP and not with Surendran et al (2008).

**Table 9-3: Flood Hazard Ratings**

(source: Uden and Hall (2007), Surendran et al (2008))

Flood Velocity (m/s)	Flood Hazard Ratings											
	Debris Factor											
	0.5	0.5	0.5	1	1	1	1	1	1	1	1	1
	Flood 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
0.0	0.53	0.55	0.60	1.15	1.20	1.25	1.30	1.40	1.50	1.75	2.00	2.25
0.1	0.53	0.56	0.62	1.18	1.24	1.30	1.36	1.48	1.60	1.90	2.20	2.50
0.2	0.54	0.58	0.65	1.23	1.30	1.38	1.45	1.60	1.75	2.13	2.50	2.88
0.5	0.55	0.60	0.70	1.30	1.40	1.50	1.60	1.80	2.00	2.50	3.00	3.50
1.0	0.58	0.65	0.80	1.45	1.60	1.75	1.90	2.20	2.50	3.25	4.00	4.75
1.5	0.60	0.70	0.90	1.60	1.80	2.00	2.20	2.60	3.00	4.00	5.00	6.00
2.0	0.63	0.75	1.00	1.75	2.00	2.25	2.50	3.00	3.50	4.75	6.00	7.25
2.5	0.65	0.80	1.10	1.90	2.20	2.50	2.80	3.40	4.00	5.50	7.00	8.50
3.0	0.68	0.85	1.20	2.05	2.40	2.75	3.10	3.80	4.50	6.25	8.00	9.75
3.5	0.70	0.90	1.30	2.20	2.60	3.00	3.40	4.20	5.00	7.00	9.00	11.00
4.0	0.73	0.95	1.40	2.35	2.80	3.25	3.70	4.60	5.50	7.75	10.00	12.25
4.5	0.75	1.00	1.50	2.50	3.00	3.50	4.00	5.00	6.00	8.50	11.00	13.50
5.0	0.78	1.05	1.60	2.65	3.20	3.75	4.30	5.40	6.50	9.25	12.00	14.75
6.0	0.83	1.15	1.80	2.95	3.60	4.25	4.90	6.20	7.50	10.75	14.00	17.25
7.0	0.88	1.25	2.00	3.25	4.00	4.75	5.50	7.00	8.50	12.25	16.00	19.75
8.0	0.93	1.35	2.20	3.55	4.40	5.25	6.10	7.80	9.50	13.75	18.00	22.25
9.0	0.98	1.45	2.40	3.85	4.80	5.75	6.70	8.60	10.50	15.25	20.00	24.75
10.0	1.03	1.55	2.60	4.15	5.20	6.25	7.30	9.40	11.50	16.75	22.00	27.25
11.0	1.08	1.65	2.80	4.45	5.60	6.75	7.90	10.20	12.50	18.25	24.00	29.75
12.0	1.13	1.75	3.00	4.75	6.00	7.25	8.50	11.00	13.50	19.75	26.00	32.25
13.0	1.18	1.85	3.20	5.05	6.40	7.75	9.10	11.80	14.50	21.25	28.00	34.75
14.0	1.23	1.95	3.40	5.35	6.80	8.25	9.70	12.60	15.50	22.75	30.00	37.25
15.0	1.28	2.05	3.60	5.65	7.20	8.75	10.30	13.40	16.50	24.25	32.00	39.75
16.0	1.33	2.15	3.80	5.95	7.60	9.25	10.90	14.20	17.50	25.75	34.00	42.25
17.0	1.38	2.25	4.00	6.25	8.00	9.75	11.50	15.00	18.50	27.25	36.00	44.75
18.0	1.43	2.35	4.20	6.55	8.40	10.25	12.10	15.80	19.50	28.75	38.00	47.25
19.0	1.48	2.45	4.40	6.85	8.80	10.75	12.70	16.60	20.50	30.25	40.00	49.75
20.0	1.53	2.55	4.60	7.15	9.20	11.25	13.30	17.40	21.50	31.75	42.00	52.25
21.0	1.58	2.65	4.80	7.45	9.60	11.75	13.90	18.20	22.50	33.25	44.00	54.75
22.0	1.63	2.75	5.00	7.75	10.00	12.25	14.50	19.00	23.50	34.75	46.00	57.25
23.0	1.68	2.85	5.20	8.05	10.40	12.75	15.10	19.80	24.50	36.25	48.00	59.75
24.0	1.73	2.95	5.40	8.35	10.80	13.25	15.70	20.60	25.50	37.75	50.00	62.25
25.0	1.78	3.05	5.60	8.65	11.20	13.75	16.30	21.40	26.50	39.25	52.00	64.75

The following text is taken from Defra (2006) as a narrative to provide context to the information presented in Table 9-4:

*“People are often unaware of the power of floodwater and may be swept away. Adults are unable to stand in still floodwater with a depth of about 1.5 m or greater, although this is obviously affected by the height of the person. The depth of flowing floodwater where people are unable to stand is much less. For example, some people will be at risk when the water depth is only 0.5 m if the velocity is 1 m/s. If the velocity increases to 2 m/s, some people will be unable to stand in a depth of water of only 0.3 m. Most people will be unable to stand when the velocity is 2 m/s and the depth is 0.6 m.”*

It is noted that the maximum computed channel velocities for the Humber River, as computed using the HEC-RAS model developed for this study, range from about 5.5 m/s to about 8.5 m/s, for the existing development / current climate 1 in 20 year AEP flood and the future development / climate change 1 in 100 year AEP flood, respectively.

**Table 9-4: Flood Hazard Matrix**

(source: Uden and Hall (2007), Surendran et al (2008))

Degree of Flood Hazard	Flood Hazard Rating Range	Colour Codes	RGB Colour Model			Hazard to People Classification
			R	G	B	
Low	< 0.75		146	208	80	Very low hazard - Caution
Moderate	0.75 to 1.25		255	255	0	Danger for Some includes children, the elderly and the infirm
Significant	1.25 to 2.00		255	192	0	Danger for Most includes the general public
Extreme	> 2.00		255	0	0	Danger for all includes the emergency services

## 9.5 Verification of Draft Flood Delineations

### 9.5.1 Field Verification

The flooded areas as illustrated on the flood plain developed for this study were field verified through field reconnaissance.

### 9.5.2 Community Review of Draft Flood Maps

As a required component of this study, Wood consulted with every formal community in the study area to review draft floodplain mapping products relevant to the individual community. Community specific draft maps were provided to each community for review and comment. Wood also provided opportunity to each community for virtual meetings to address any issues and/or questions the communities wished to explore or have answered. Outreach to the communities was facilitated in July and August 2020.

Draft maps, relevant to each community (ref. Table 9-5), were shared via Wood's SharePoint/OneDrive system. System confirmation of successful access to the data was confirmed for each community.

**Table 9-5: Community Flood Mapping**

Community	Relevant Map Sheets
Pasadena (South Brook)	21 - 40
Steady Brook	5, 6
Reidville	62-63, 65-68, 85-90
Deer Lake	50,51 / 60-67, 69 / 70-79 / 80-84

### 9.5.2.1 Town of Deer Lake

Wood representatives engaged with the Town Manager and Town Superintendent – Public Works. It was noted that:

- Town staff were able to print the draft flood maps, provided by Wood, and completed a thorough review of the information.
- Town staff noted that the flooding extents, as depicted on the draft flood maps, were not significantly different from the previous flood lines. Differences that were noted were not deemed to be of a magnitude that would affect the Town's current municipal plan.
- Town staff also noted that areas that historically flood, namely Pine Tree Drive and Nicholsville Road, were reasonably represented on the draft flood maps.

### 9.5.2.2 Town of Reidville

Wood representatives engaged with the Town Clerk. The Town Clerk, in conversation with Wood staff, indicated that a review of the draft maps had been completed and no items of concern identified. The Town Clerk also indicated to Wood that the draft maps were shared with Town councillors for their review and comment in advance of a council meeting. No concerns regarding the draft flood maps were communicated to Wood.

### 9.5.2.3 Town of Pasadena

Wood provided the Town of Pasadena access to the draft flood plain maps in July 2020. Outreach to the Chief Administrative Officer was actioned on multiple occasions via multiple media (e.g. email, office phone [left messages], and cell phone [left messages]). No response was received.

### 9.5.2.4 Town of Steady Brook

Wood, at the request of the Town of Steady Brook, met with Town representatives on August 6, 2020 in support of their review of the draft flood plain maps. The Mayor, Deputy Mayor, Town Manager, Town Clerk and five (5) councilors were invited to the meeting.

The focus of this meeting was to provide the Town with an overview of the study and explanation of the preparation of the draft flood maps and the various climate and land use scenarios that are depicted.

It was noted by the Town that the draft maps, as had been printed by the Town, were not visually optimal and the colouring difficult to interpret. As such, Wood provided the Town with hardcopy maps, customized to the Town review needs. Further, Wood also provided Google Earth Pro™ (i.e. Keyhole Markup language Zipped [KMZ]) files of the draft flood plain delineations. This information was provided in August 2020.

The Town also provided Wood with a number of images of properties within the Town under flooded and not flooded conditions (ref. Figure 9-8). The flooded conditions photos taken during the June 2020 flood. The “no flood” pictures of the properties were taken by Town staff on August 6, 2020. Examples of these images are presented as Figure 9-9 (please also reference Appendix P for other photos).

The reader is also directed to Figure 7-33 for an aerial view of the June 2020 flood events for highlighting the Forest Drive area.

The Town of Steady Brook, upon review of the information provided by Wood, provided a letter response dated August 28, 2020. A number of comments are documented in the letter as follows:

- “The mapping product provided by the consultant Wood plc does not match up with historical or recent flood events within the community. From observations, all concerned believe the Flood Risk Mapping Study that was undertaken did not consider all hydrological or environmental factors in our community, specifically ‘Steady Brook Stream’ itself.”
- “We are curious about what field surveys and modelling of the watershed was done for the Steady Brook Area.
- “There are multiple locations not identified on these new maps that are predisposed to flooding.”
- “... residences have commented that all of the draft mapping is incorrect.”
- “... map colouring of the layers confusing and should be more transparent”
- “... multiple spelling errors in the names of streets, for example ‘Wilson Street’ correct name is ‘Wilton Street’ and ‘Woodlawn Avenue’ is ‘Woodland Avenue’.”<sup>26</sup>
- “... these maps do not accurately depict the flooding that occurs within the Town of Steady Brook.”

Areas of flood concern identified in the August 28, 2020 letter are Falls Avenue, Forest Drive and the Steady Brook’s boat launch. Wood notes that these locations were not identified as areas of concern for the Town in the January 30, 2019 community consultation meeting with the Town (ref. Section 2.4).

Wood notes that the full project report was in development at the time of the community engagement and only a summary brief was provided to communities for review. This full project technical report is key to addressing the technical issues raised by the Town of Steady Brook.

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<sup>26</sup> It is noted that “Woodland Avenue” is noted as “Woodland Place” per Google Maps.

**Figure 9-8: Steady Brook Flood Photos from June and August 2020**



(Background image source Google Earth Pro™)



**Figure 9-9: Town of Steady Brook Photos from June and August 2020 for select Properties**  
(Photos courtesy of the Town of Steady Brook)

Notwithstanding, the issues raised by the Town prompted Wood to complete a comprehensive review of the hydrological and hydraulic modelling of the Steady Brook area with a focus on the June 2020 flood event.

### Hydrologic Modelling Review

The maximum peak flow in Steady Brook, as measured at station 02YL012, was 184.7 m<sup>3</sup>/s in June 2020<sup>27</sup>. The corresponding maximum peak flow in the main Humber River was 843.6 m<sup>3</sup>/s<sup>28</sup>, greater than the threshold value noted previously, whereby water levels from the main Humber River may be an influencing consideration for measurements at the Steady Brook station.

Table 9-6 provides a comparison of the flow values used for modelling in the *Hydrotechnical Study of the Steady Brook Area* (Cumming-Cockburn, 1984), and the current study. As previously noted, the 1984 peak flow estimates for Steady Brook were based on Regional Flood Frequency Equations (RFFA) (Panu et al, 1984). The current study has based peak flow estimates on detailed deterministic hydrological modelling (ref. Section 6). As noted, the flows determined for the current study are somewhat less than those used in the 1984 study. As well, the 1984 study documents the range associated with the AEP estimates, given by the 95<sup>th</sup> percentile range, as 65.2 m<sup>3</sup>/s to 155.0 m<sup>3</sup>/s for the 1 in 20-year AEP peak flow; similarly for the 1 in 100-year AEP peak flow the range is documented as 76.8 m<sup>3</sup>/s to 206.0 m<sup>3</sup>/s. The 1984 range of estimates encompasses the current study estimates, although it is concluded that the range is quite broad.

To further explore options for peak flow estimation, the 1990, 1999 and 2014 regional equations were applied to the Steady Brook watershed. As summarized in Table 9-7, the 1990 peak flow estimates would not be recommended for use given that a number of the RFFA equation parameters lie outside of the recommended range (including watershed area, slope, fraction of watershed area covered by lakes and swamps and fraction of watershed area controlled by lakes and swamps). Further, the estimates provided by the 1999 and 2014 RFFA equations demonstrate greater consistency.

**Table 9-6: Comparison of 1984 and Current Study Flow Data**

AEP Event	1984 Study	Current Study	Comments
<b>Humber River Flows</b>			
1 in 20-year	957	785.9	Calibrated SSARR model used to generate flow. Calibration peak flows based on single station frequency analysis.
1 in 100-year	1180	1122.9	
<b>Steady Brook Flows</b>			
1 in 20-year	105	89.2	Calibration peak flows based on Regional Flood Frequency Analysis equations.
1 in 100-year	134	130.9	

<sup>27</sup> From [https://www.mae.gov.nl.ca/wrmd/ADRS/v6/Template\\_Station.asp?station=02YL012](https://www.mae.gov.nl.ca/wrmd/ADRS/v6/Template_Station.asp?station=02YL012)

<sup>28</sup> From [https://www.mae.gov.nl.ca/wrmd/ADRS/v6/Template\\_Station.asp?station=NF02YL0012](https://www.mae.gov.nl.ca/wrmd/ADRS/v6/Template_Station.asp?station=NF02YL0012)

**Table 9-7: Estimation of Steady Brook AEP Peak Flows using various Regional Flood Frequency Equations**

AEP Event	Peak Flow Estimates (m <sup>3</sup> /s) by Regional Flood Frequency Equations			
	1990	1999	2014	
<b>Steady Brook Flows</b>				
1 in 20-year	317.3	47.9	47.9	60.0
1 in 100-year	483.9	61.5	60.3	76.0
Comments	Multiple parameters outside of the recommended range – use of flow estimates not recommended	Using the Northwest Region equations	Using the Northwest Region 1 parameter equation	Using the Northwest Region 2 parameter equation

At study initiation in 2018, the streamflow station on Steady Brook (02YL012) had been in operation for only about 4 years. As such, the period of record of available annual peak flow information was considered too short for use for single station frequency analysis and support of the development of the hydrological modelling component of this study. However, at the end of the study, this period of record encompasses 6 years of information. A general rule of thumb is that estimation of AEP flood values based on twice the record length is reasonable (UCAR, 2010). However, it should be noted that times series of only 10 years have supported single station frequency assessment of AEP peak flows up to 1 in 100-year (AMEC, 2014). In consideration of the general rule, the 6 year time series for station 02YL012 is too short to be considered for estimation of the 1 in 100-year AEP flood peak flow, however, it can be considered reasonable for estimation of the 1 in 10 year AEP flood and can provide some direction regarding the magnitude of the 1 in 20 year AEP flood. This analysis was completed using HEC-SSP (USACE, 2019) and the results, and supporting annual peak flow data, summarized in Table 9-8 and the results illustrated as Figure 9-10. This analysis does not provide any confirmation of a specific peak flow estimate but does support the understanding of the variability of flow estimation for this watercourse and inherent uncertainty embodied in flood frequency estimation using limited time series.

The spectrum of peak flow analysis methods applied for Steady Brook yield 1 in 20-year AEP flow estimates in the range 12.3 m<sup>3</sup>/s to 155.0 m<sup>3</sup>/s. Similarly, the range is 60.3 m<sup>3</sup>/s to 206.0 m<sup>3</sup>/s for the 1 in 100-year AEP flow. The variability of estimates from the methods employed demonstrates the need for continued support for streamflow measurement on Steady Brook. It is further recommended that the 1 in 20-year AEP flow estimate be re-assessed after 2024 when 10 year of recorded data will be available.

It was concluded that the newly developed HEC-HMS model provides reasonable estimates of watershed response based on the available actual flow data/frequency analysis and other review information.

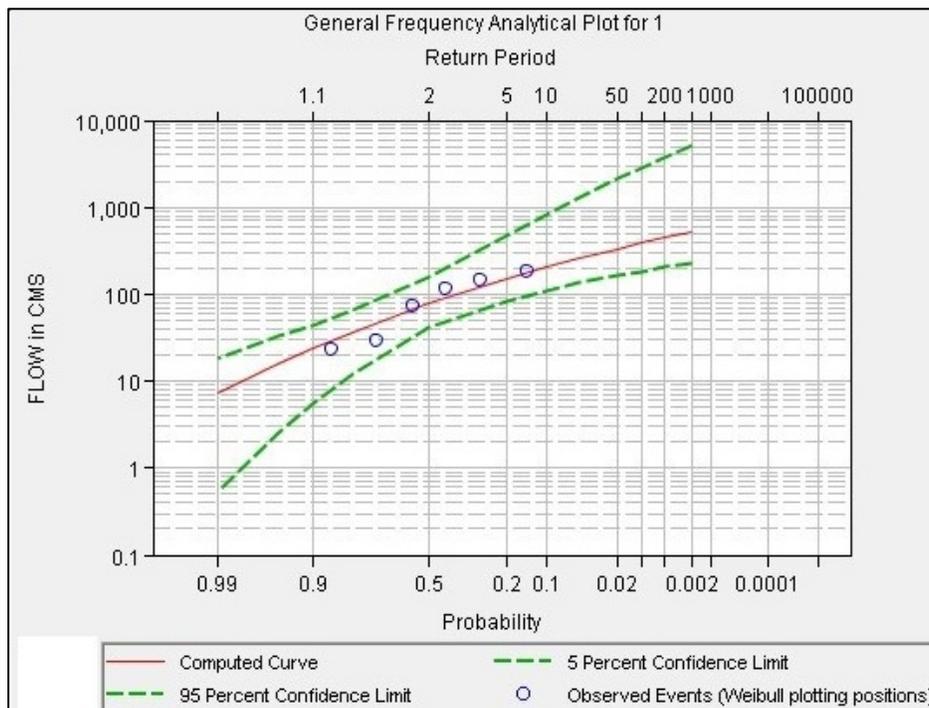
**Table 9-8: Summary of Single Station Frequency Analysis for Steady Brook above Confluence with Humber River (02YL012)**

AEP Event	Estimated Peak Flow (m <sup>3</sup> /s)	Confidence Limits		Supporting Peak Flow Data	
		5%	95%	Year	Peak Flow (m <sup>3</sup> /s)
1 in 20-year	260.9	1299.2	135.1	2015	29.2
1 in 10 year	205.9	824.1	111.3	2016	71.7
1 in 5 year	151.2	464.2	84.7	2017	23.4
Annual	7.4	18.5	0.5	2018	115.2
				2019	142.2
				2020	184.7

Notes:

1. The supporting peak flow data for 2019 represents a warm weather condition. Other higher peak flows are noted in the data, but these occur in cold periods and the flow measurements were assumed to be influenced by ice conditions, and therefore not appropriate for use in this analysis.

**Figure 9-10: Graphical representation of Single Station Frequency Analysis for Steady Brook above Confluence with Humber River (02YL012)**



### Hydraulic Modelling Review

The calibrated HEC-RAS model, developed for the current study, was used to model various flow scenarios. These scenarios are described below and illustrated as Figure 9-11:

- June 2020 flood event based on recorded streamflow (Humber River - 832.9 m<sup>3</sup>/s; Steady Brook – 180.6 m<sup>3</sup>/s)
  - The results, as noted in Table 7-7 (Event F), indicate the model marginally underestimates observed water levels by about 20 centimetres.
- Flood limits based on current study 1 in 20-year AEP flood estimates
- Flood limits based on current study 1 in 20-year AEP flood estimates plus and minus 10%

A comparative review of the various scenarios depicted in Figure 9-11 leads to the following comments:

- Flooding in area of the Town near the confluence of the Humber River and Steady Brook is more sensitive to Humber River flows than Steady Brook flows.
- The flood inundation limits representing the current study 1 in 20-year AEP flood estimates plus 10% encompasses the flood limits associated with all of the other scenarios.

**Figure 9-11: Sensitivity Assessment of Flood Delineations associated with the June 2020 Flood**

(Image source: Google Earth Pro™)

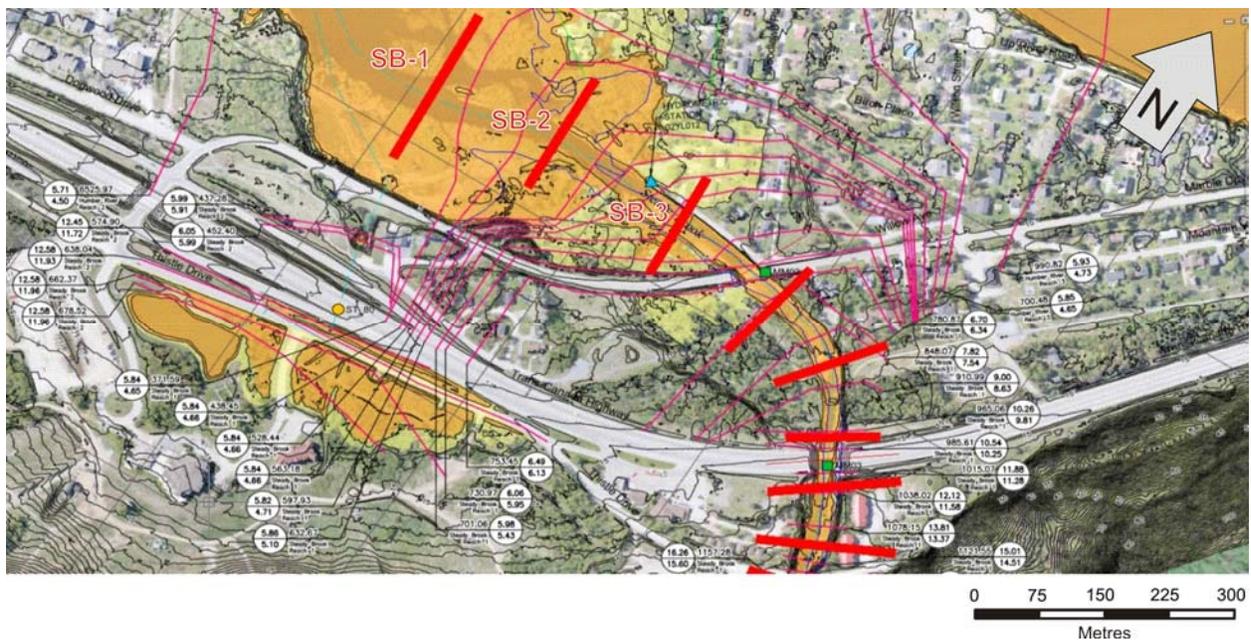


- June 2020 recorded flood flows (Humber River – 832.9 m<sup>3</sup>/s; Steady Brook – 180.6 m<sup>3</sup>/s)
- Current study 1 in 20 year AEP Flows minus 10% (Humber River – 707.3 m<sup>3</sup>/s; Steady Brook – 80.3 m<sup>3</sup>/s)
- Current study 1 in 20 year AEP Flows unadjusted (Humber River – 785.9 m<sup>3</sup>/s; Steady Brook – 89.2 m<sup>3</sup>/s)
- Current study 1 in 20 year AEP Flows plus 10% (Humber River – 864.5 m<sup>3</sup>/s; Steady Brook – 98.1 m<sup>3</sup>/s)

- The flat topography of this area of the Town results in the representation of flood limits being very sensitive to flood flow estimates.
- It is anticipated that there would be some internal micro-drainage features in the flooded prone area which are not being captured by the project DEM and were not observed during field reconnaissance.

It was concluded that the flood inundation limits, reflecting the modelled June 2020 flood, based on the current study HEC-RAS model, reasonably agrees with the actual flood experience as depicted in the photos provided by the Town.

A comparison of the hydraulic modelling cross-sections used for the 1984 Steady Brook Hydrotechnical, Study (Cumming-Cockburn, 1984 [Volume 2, Appendix C]) was also completed. As a first step, the section locations from the 1984 study were coordinated with the modelling sections for the current study (ref. Figure 9-12). Please note that current practice is to spatially define the section over its entire length. The sections, as defined in the 1984 report provide general location only and do not necessarily depict the actual spatial location and/or orientation of the section.



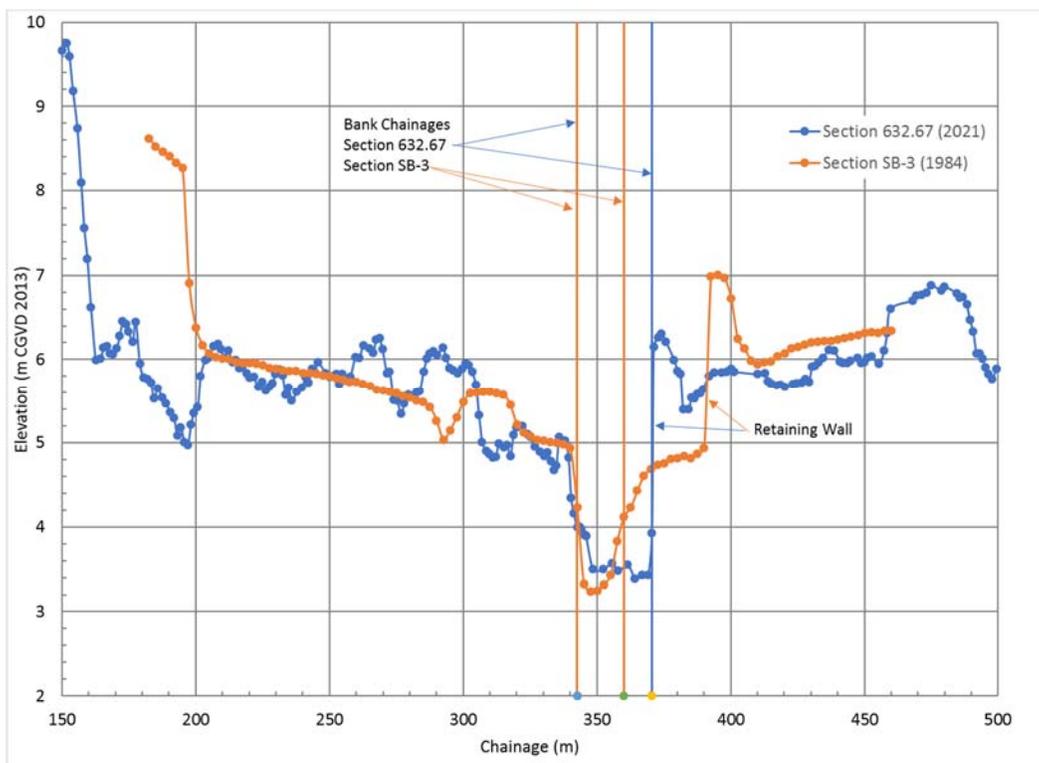
**Figure 9-12: Section Location Comparison Cumming-Cockburn (1984) to Current Study**

(Note: 1984 study section locations in red / current study section locations in magenta)

Section SB-3 (from the 1984 study) and section 632.67 (from the current study) are near one another (within about 5 m). Figure 9-13 illustrates a comparison of the two sections. Data for section SB-3 was abstracted from the graphical illustration of the section in Volume 2 Appendix C of the 1984 report. The section, as illustrated in the 1984 report, was depicted looking upstream as the retaining wall on the north side of the river was recognizable. Conversely, sections for the current study are coded in HEC-RAS with the left bank looking downstream; for Steady Brook the left bank is the south side of the watercourse. Further, as the

sections are defined with different lengths, it was assumed the left bank chainage could be assumed to be coincident between the two sections as a means of orienting the sections relative to one another.

It was also assumed that the section data for the 1984 study was coordinated to CGVD-1928. As such, a conversion of the 1984 section elevation data was required. This conversion was completed using NRCan’s online application GPS-H<sup>29</sup>. This application, amongst other functionality, supports conversion of elevations between the CGVD-1928 to CGVD-2013 vertical datums. Using this tool, the conversion from CGVD-1928 to CGVD-2013 based elevations, at the noted sections, was determined as +0.26 m. This adjustment was added to the SB-3 section elevations to allow direct comparison with current study section data.



**Figure 9-13: Section Comparison - Cumming-Cockburn (1984) to Current Study**

While the section data illustrated in Figure 9-13 do not directly align with one another, the comparative data can be visually interpreted as being aligned, accounting for differing orientations. In general, the depth of the channel at both sections is comparable. However, comparison of the channel configurations suggests some scour may have occurred over the years on the right bank at the base of the retaining wall.

<sup>29</sup> Source: <https://www.nrcan.gc.ca/maps-tools-publications/maps/tools-applications/10925>

It is also noted that the current LiDAR data should be considered more accurate of existing topography than the 1980's vintage topographic information that would have been used for the 1984 study.

### **Flood Mapping Review**

A final check of the 1984 flood mapping in comparison to the current flood delineations was completed. The objective of this effort was to highlight differences between the base mapping used for the 1984 mapping and the current DEM. This comparison is illustrated as Figure 9-14.

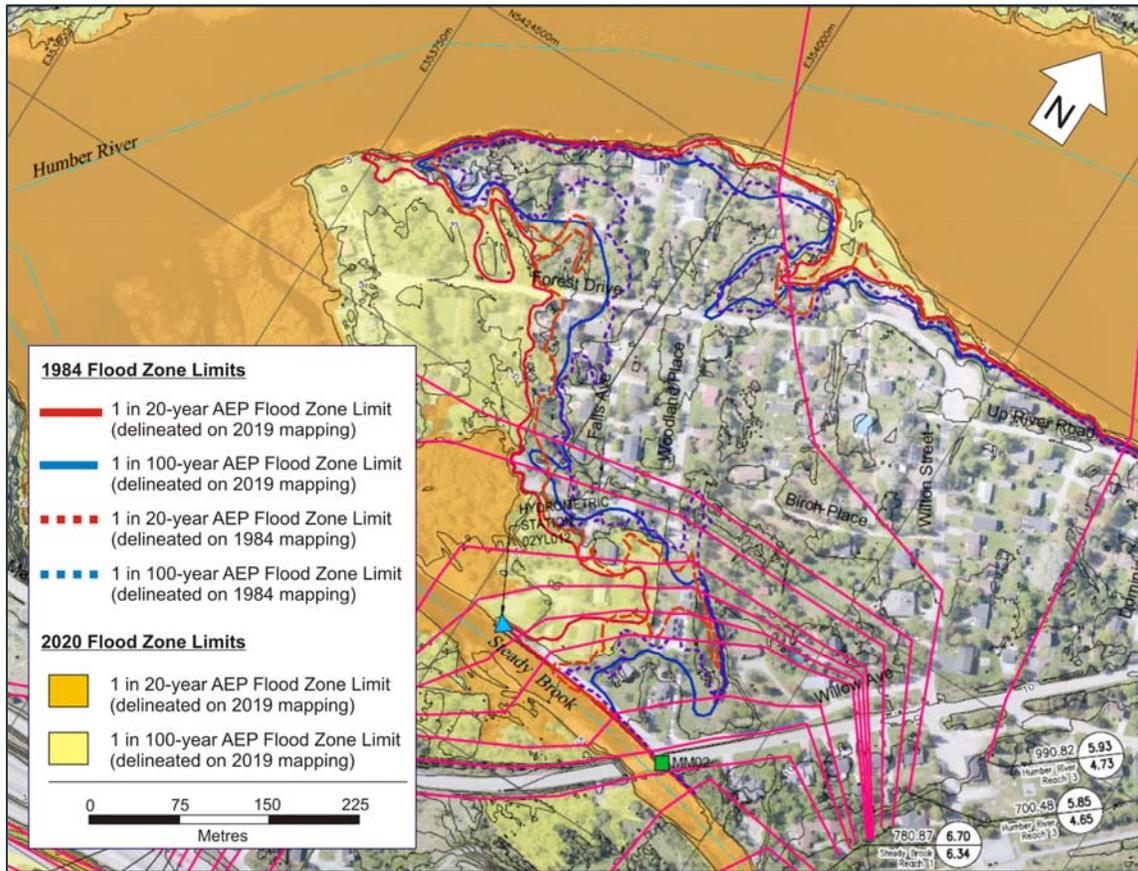
Figure 9-14 illustrates the flood delineations from the 1984 Steady Brook Flood Study in two (2) forms. Firstly, the delineations developed for the 1984 study have been transposed unchanged to the new mapping prepared for this study. Secondly, the computed water surface elevations from the 1984 study have been newly delineated using the 2019 DEM developed for the current study. This comparison demonstrates differences between the two mapping bases, resulting in some areas becoming flood plain and some other being shown to no longer be within an inundation zone.

It is concluded that the updated base mapping is also contributes to the change in flood inundation limits when compared to the 1984 flood inundation zones.

### **Conclusions**

Wood has made significant efforts to address the concerns of the Town of Steady Brook regarding the newly developed flood plain mapping for Steady Brook and the Humber River. This has included:

- Multiple meetings with the Town
- Provision of customized map products to facilitate review by Town representatives
- Town comments regarding visual presentation (e.g. colouring and transparency) and of the new flood plain mapping of maps have been addressed.
- Town comments regarding in correct nomenclature used on the new flood plain mapping of maps have been addressed.
- Comparison of flood inundations limits from the current study, previous studies and areas mapped based on flood imagery provided by the Town was completed.
- A detailed review of the hydrologic modelling developed for the new study was completed and further comparisons made to previous studies and statistical modelling results.
- A detailed review of the hydraulic modelling developed for the new study was completed and further comparisons made to flood inundation limits associated the June 2020 flood event based on recorded streamflow.
- A review of hydraulic data from the current and 1985 hydrotechnical study was completed.
- A check of the 1984 flood mapping in comparison to the current flood delineations was completed with the objective to highlight differences between the base mapping used for the 1984 mapping and the current DEM.



**Figure 9-14: Steady Brook – Current to 1984 Flood Delineation Comparison**

An overall conclusion of this detailed information and modelling review concluded that the modelling and mapping reasonably represent the characteristics of Steady Brook near the confluence with the Humber River.

Notwithstanding the additional effort to address the Town’s concerns, it maintained that it would not accept the flood plain mapping developed as a component of the current study.

As a path forward, the Town has been advised that it would be within its jurisdiction to designate areas of municipality as flood zones based on previous flooding history in their land zoning. In so doing, the Town would be able to regulate development in the designated flood zones. Additionally, the Town has the ability to add their own buffer to the flood risk mapping and regulate development within it. As an example, the City of St. Johns adds a 15 m buffer to flood risk mapping and regulates development within the buffer zone. Further, The Water Resources Management Division does not issue a Section 48 permit without municipal approval for work within municipal boundaries. It as suggested that the Town of Steady Brook contact the Local Governance and Land Use Planning Division of the Government of Newfoundland and Labrador to better understand its rights and responsibilities with respect to land zoning and regulation.

### 9.5.2.5 Community Review of Draft Flood Maps - Summary

As has been noted, Wood consulted with every formal community in the study area to review draft floodplain mapping products relevant to the individual community. Community specific draft maps were provided to each community for review and comment and Wood also provided opportunities to engage directly with municipal officials to support their review process. Table

**Table 9-9: Summary of Community Engagement Supporting Review of Draft Floodplain Mapping**

Community	Flood Mapping Review Outcome
Pasadena (South Brook)	No response from Town officials
Steady Brook	Not Accepted (Alternate approach for flood zone regulation presented)
Reidville	Accepted
Deer Lake	Accepted

## 9.6 Assessment of Stream Crossing Capacity

Please refer to Section 7.4.1, as well as, Tables 7-8, 7-9 and 7-10.

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## 10.0 Map to Map Workflow

Synopsis: The RFP for this project identified the requirement to develop a Map to Map Implementation Workflow to facilitate re-running the historical case model for climate change scenarios. Through the course of the project, it was recognized that the Map to Map linkages between the HEC-HMS and HEC-RAS models could be reasonably replicated using a traditional manual process. It was further recognized that the development of the Humber River Flood Forecasting System (HRFFS) was a prioritized component of the overall Humber River project scope. As such, WRMD agreed to remove the Map to Map technical scope from the overall project and allocate additional effort to the development of the HRFFS.

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## 11.0 Flood Forecasting Service

Synopsis: Flood forecasting is a process of estimating and predicting the magnitude, timing and duration of flooding based on known characteristics of a river basin, with the objective of preventing damages to human life, property, infrastructure and the environment. The newly developed Humber River Flood Forecasting System (HRFFS) is an automated web-based water forecasting application for predicting streamflows and water elevations along the study reach of the Humber River including Steady Brook and South Brook. The HRFFS compiles hydrometric data (i.e. gauged streamflow and water levels, tidal forecast data), retrieves numerical weather prediction (i.e. NWP) and Canada precipitation analysis (CaPA) data and integrates this data with the hydrologic and hydraulic models (i.e. HEC-HMS, and HEC-RAS) developed for this study to support 3-day forecasts of river flows and water levels for open water conditions. The application also provides automated notification on status of system processes and changing river conditions through alert notifications.

### 11.1 Overview

The Humber River Flood Forecasting System (HRFFS), developed as a component of the Humber River Communities Project is an automated web-based water forecasting application. To produce the forecasts, existing software was modified to compile hydrometric data (i.e. gauged streamflow and water levels, tidal forecast data), retrieve numerical weather prediction (i.e. NWP) and Canada precipitation analysis (CaPA) data with project developed hydrologic and hydraulic models (i.e. HEC-HMS, and HEC-RAS) for predicting river flows and water levels for open water conditions daily for a 3-day forecast. The application also provides notification on status of system process and changing river conditions through alert notification.

The development of HRFFS utilizes 4DM Inc.'s flood forecast web-based framework named HydrologiX to enable the forecasting application. HydrologiX is developed based on open source technology and utilizes Canadian Geospatial Data Infrastructure standards and technology. In addition, HRFFS incorporated elements of the Churchill River Forecast System (CRFFS) (developed via a separate project by others) that included Office of the Chief Information Officer (OCIO) security scan modifications.

The development and implementation of the HRFFS is a collaborative effort between all parties including Wood, 4DM, WRMD and the OCIO. Wood is responsible for the hydrologic and hydraulic model development, while 4DM focused on enabling the HEC-HMS and HEC-RAS rating curve table model runners, hydro-meteorological and gauge data retrieval and processing, as well as the web users interface design and the internal workings of the HRFFS application. WRMD provided user acceptance testing and approval of the system. OCIO enabled integration of the HRFFS onto government IT infrastructure.

The HRFFS application includes numerous data and numerical processes for preparing near real time water information and forecast weather data for model inputs, performing data management in geospatial-temporal database, run models, present results in web environment, send notifications and securing access to web application.

The reader is directed to Volume 2 of the Project report for fulsome details regarding the HRFFS.

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## 12.0 Summary and Recommendations

### 12.1 Summary

Key outcomes of the study are described below:

#### Background Information

- A review of the historical flooding events in the study watershed identified forty-six (46) flood events in the Humber River study area for the period 1944 to 2013. Flood events have occurred in this area in all seasons of the year and all months of the year. Of the noted flood events, three (3) identified ice jamming as a primary cause. Based on the review of the materials available, five (5) additional flood events were added to the inventory.
- The Humber River study area, or portion thereof, was previously assessed for flood risk in 1984 (Steady Brook) and 1987 (Deer Lake).

#### Field Program

- Bathymetry along the main Humber River and several tributaries was collected.
- A high-resolution LiDAR DTM of the Humber River study area upon which flood plain mapping was developed was collected in June 2019.
- The field survey was completed for major structures in the study area.
- The Humber River watershed is influenced by two (2) dams, namely Grand Lake and Hinds Lake. Deer Lake is an unregulated, natural reservoir. Information for these features was obtained and integrated into the current study.

#### Hydrologic Assessment

- The 1 in 20-year and 1 in 100-year AEP streamflows were estimated for the Humber River watershed using both statistical and deterministic methodologies. Comparative assessment of the flow estimates over the range of methodologies concluded that the deterministic model results provided a good estimate of streamflow for these watersheds. The methods used in the current study led to comparable flood flow estimates which provide confidence in the results.
- The HEC-GeoHMS and HEC-HMS models developed for this study are included with the Project CD materials attached to this report. These models may be used in the future to evaluate the impact on streamflows resulting from changes to the watershed.

#### Hydraulic Assessment

- A hydraulic model based on the USACE program HEC-RAS was developed for reaches of the Humber River covering a linear distance of approximately 178 km (with almost 1500 cross-sections).

- The model was developed based on field surveyed bathymetric data and a LiDAR survey conducted in the Fall 2018 and Spring 2019.
- The hydraulic model developed for this study was also used to evaluate the potential flood conditions (i.e. resultant water levels) associated with ice jamming events in the Deer Lake area and along Steady Brook.
- It was concluded from the Deer lake ice assessment results that the January 2018 event was the result of a unique set of snow cover, wind, frazil ice, temperature and other conditions. The ice jam assessment further concluded that the January 2018 ice jam event was a most extreme case, approximating a 1 in 500-year event. Given the results of the ice jam assessment, it was also concluded that integration of river ice modelling into the flood forecasting system was not necessary.
- It was concluded that the reasons for flooding in the Town of Steady Brook are multifaceted: potential ice conditions in winter, snowmelt and rain-on-snow events in spring and high precipitation and flows accompanied by high antecedent moisture conditions in the autumn. It has also been concluded that the currently available Steady Brook streamflow gauge record does not cover a sufficient time period to allow for the determination of patterns between the ice, hydraulic and meteorological regimes of the watercourse.
- The HEC-GeoRAS and HEC-RAS models developed for this study are included with the Project CD materials attached to this report. The model may be used in the future to evaluate the impact on water levels resulting from any structural changes to the subject watercourses or floodplain / overbank areas.

### Sensitivity Analysis

- It is understood that the hydrologic model is sensitive to a variety of input parameters including rainfall and Curve Number. These parameters were developed upon the best available information from Environment and Climate Change Canada, as well as, soils and land cover data; the latter reflecting current conditions in 2019.
- Since all hydraulic input parameters were selected based on reliable background information, it is expected that the error and uncertainty associated with model output is minimal.

### Climate Change Assessment

- Climate change analysis was completed using the 2080 tri-decade period for both the 1 in 20-year and 1 in 100-year AEP flood events.
  - Projected rainfall data was sourced from *Climate Change for the Province of Newfoundland & Labrador: 2018 Update* (Finnis and Daraio, 2018).
  - Projections for climate change influenced sea level rise were defined by the projections documented in *Past and Future Sea-Level Change in Newfoundland and Labrador: Guidelines for Policy and Planning* (Batterson and Liverman, 2010).

- It was concluded from this assessment that climate change has the potential to increase flood risk in the Humber River study area.

### **Flood Risk Mapping**

- All information necessary to complete the Flood Risk Mapping Project for this project was available either through information provided by WRMD, available background reports, contact with local municipalities or based on the comprehensive field data collection program.
- Flood risk mapping was developed using high resolution mapping in combination with the LiDAR DTM, and orthophoto imagery. These maps were based on the results of both the hydrologic and hydraulic analysis and can be used by both the communities located within the study watershed for municipal planning and WRMD for flood risk identification.
- Flood mapping representing four (4) scenarios were developed as deliverables for this study, namely:
  - Current climate rainfall and existing land use / development
  - Current climate rainfall and full development
  - Climate change rainfall and existing land use / development
  - Climate change rainfall and full development
- A comparison of the current climate and full development scenario to the climate change and full development scenario quantified a 0.4% and 3.4% increase in inundated lands for the 1 in 20 -year AEP and 1 in 100-year AEP floods, respectively.
- Climate change flood lines were delineated for the most severe climate change precipitation scenarios (i.e. 2080 tri-decade RCP 8.5 90<sup>th</sup> percentile) for existing and fully developed conditions. The flooded area associated with future climate conditions represented an increase area of about 7.7% and 15.4%, respectively, for the 1 in 20 -year AEP and 1 in 100-year AEP floods (under existing development conditions).

## **12.2 Recommendations**

Key recommendations stemming from the assessments completed for this study are outlined below:

1. A series of recommendations specific to the continued development of the Flood Events Inventory are detailed with the objective of increasing the usability and integrity of the database.
2. It is recommended that the municipalities located within the study area adopt the flood lines developed by the current study for their municipal plan and development regulations.
3. It is recommended that the municipalities located within the study area and their partners make use of the up-to-date LiDAR topographic data and orthophotography which was collected for this study for relevant municipal initiatives.

4. It is recommended that the municipalities located within the study area engage in a program to measure water levels at designated watercourse crossing structures during flood events. This will expand the database of information which could be used to support both hydrologic and hydraulic modelling in the future.
5. It is recommended that a program focused on unregulated streamflow data collection be developed for Humber River and its associated tributaries. Additional recording stations at strategic locations (e.g., outflow from each of the unregulated tributary areas) would provide a foundation of data that would enhance the hydrologic model calibration and validation processes.
6. It is noted that gauging station 02YL012, located on the Steady Brook, may be influenced by the main Humber River when water levels are high. It is recommended that this situation be investigated in greater detail.
7. It is recommended that WRMD engage in a program to collect and develop stage-storage-discharge curves and operational data including rules curves, gate(s) settings and reservoir water levels for all dams in the Province. Significant resources were utilized with the current project to first determine the ownership of the data (i.e. the contact person within the dam owner organization) and also to deal with delays that resulted from the time that was found to be necessary to obtain the information, once the most appropriate contact was established. If this information was already available through WRMD at the outset of the project, the development of the hydrologic model would have been more efficient.
8. It is recommended that that HEC-GeoHMS, HEC-HMS, HEC-GeoRAS and HEC-RAS continue to be used in future watershed and flood studies as their use both simplifies the development of deterministic models, as well as provides for the generation of a significant warehouse of information that can be used for other ancillary purposes beyond hydrologic assessments.
9. The Deer Lake Reach 2 watercourse between cross-sections 1043.76 and 1292.89 experiences a spill to the west. This area, generally to the west of the TransCanada Highway and south-west of The Viking Trail/ Old Bonne Bay Road, lies on a side slope with the down slope transitioning to the main Humber River to the west. Given the general topography in the area, flood waters would spill down slope directly to the main Humber River and not follow the Deer Lake Reach 2 watercourse which generally flows to the north. While the HEC-RAS 1D modelling approach applied for this project is considered appropriate for flood mapping purposes, the design of any mitigation strategies (e.g. enhanced and/or additional conveyance for spill waters) may benefit from the application of a HEC-RAS 2D modelling approach.
10. It is recommended that two-dimensional (2D) hydraulic analysis be considered for the confluence of the Humber River with Steady Brook to characterize flooding mechanisms in this area in greater detail.
11. It is recommended that a program focused on field-based collection of ice thickness/accumulation data should be implemented in areas when ice jamming occurs. A database of ice thickness/accumulation data would enhance and provide additional confidence the ice modelling process and results.

12. It is recommended, for future study beyond the present work scope, that the continuous HEC-HMS model developed for the flood forecasting component of this study be augmented to model the Steady Brook watershed discretely and in greater detail. Using this tool, in conjunction with the available long-term meteorological record, the available streamflow time series may be extended providing a longer dataset upon which to base the ice jamming assessment and its associated conclusions.
13. It is recommended that the municipalities located within the study area consider stream and/or structure rehabilitation in the areas where water levels exceed the river banks during the 1 in 100-year AEP flood and spill over land. This will confine extreme flood flows to the river channel and avoid the risk of overland flooding.
14. It is recommended that meteorological conditions in the Humber River study area be monitored towards determination of increasing trends in rainfall and generally extreme weather.
15. It is recommended that climate change be integrated into municipal planning in those areas where increasing flood risk is relevant such as infrastructure and emergency planning.
16. It is recommended that this study should be revisited in approximately ten (10) years, after which time additional detail may be available from rainfall and streamflow gauges in the basin. An interim review of streamflow data for the Steady Brook station may be warranted when 10 years of data have been collected at the station with the objective to provide another estimate of the return period flow regime for the watercourse near the confluence with the Humber River.
17. It is recommended that LiDAR topographic survey and orthophoto databases continue to be used for future flood risk mapping studies as they provide an accurate means of collecting high quality topography information over large areas.

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## 13.0 References

- Acres (1999). Main Dam at Grand Lake Inundation Study – Volume 1 Main Report, prepared for Deer Lake Power; a Division of Corner Brook Pulp and Paper Limited by Acres International, July 1999.
- Agriculture Canada (1991). Reconnaissance Soil Surveys of Stephenville – Port-Aux-Basques 1991 - Report No. 12 (I2 B), Agriculture Canada, Newfoundland Soil Survey, 1991. Available via URL: <https://sis.agr.gc.ca/cansis/publications/surveys/nf/index.html>
- Agriculture Canada (1988). Soils of the Red Indian Lake – Burgeo Area 1988 - Report No. 9 (I2 A), Agriculture Canada, 1988. Available via URL: <https://sis.agr.gc.ca/cansis/publications/surveys/nf/index.html>
- Amani et al (2017a). Wetland Classification in Newfoundland and Labrador Using Multi-Source SAR and Optical Data Integration. Meisam Amani, Bahram Salehi, Sahel Mahdavi, Jean Granger, and Brian Brisco, GIScience & Remote Sensing 54 (6): 779–96, 2017.
- Amani et al (2017b). Wetland Classification Using Multi-Source and Multi-Temporal Optical Remote Sensing Data in Newfoundland and Labrador, Canada, Meisam Amani, Bahram Salehi, Sahel Mahdavi, Jean Elizabeth Granger, Brian Brisco, and Alan Hanson, Canadian Journal of Remote Sensing 43 (4): 360–73, 2017.
- Amani et al (2018). Spectral Analysis of Wetlands Using Multi-Source Optical Satellite Imagery. Meisam Amani, Bahram Salehi, Sahel Mahdavi, and Brian Brisco, ISPRS Journal of Photogrammetry and Remote Sensing 144: 119–36, 2018.
- AMEC (2012a). Flood Event Inventory (1950-2011) for Newfoundland and Labrador, prepared for the Government of Newfoundland and Labrador by AMEC [now Wood], 2012.
- AMEC (2012b). Flood Risk Mapping Project for Corner Brook and Petrie’s Brook, AMEC [now Wood], 2012. Available via URI <https://www.gov.nl.ca/eccm/waterres/flooding/frm/>
- AMEC (2014). Regional Flood Frequency Analysis for Newfoundland and Labrador - 2014 Update, prepared for the Government of Newfoundland and Labrador by AMEC [now Wood], 2014.
- Barnes (1967). Roughness Characteristics of Natural Channels, USGS Numbered Series, Water Supply Paper 1849, Harry H. Barnes, Jr., U.S. Govt. Print. Office, vi, 213 p., illus. (part col.), 1967.
- Batterson and Liverman (2010). Past and Future Sea-Level Change in Newfoundland and Labrador: Guidelines for Policy and Planning. Batterson, M. and D. Liverman, Current Research (2010) Newfoundland and Labrador Department of Natural Resources, Geological Survey, Report 10-1, p. 129-141. Available via URL <http://nlhfrp.ca/wp-content/uploads/2015/01/Past-and-Future-Sea-Level-Change-in-NL...pdf>

- Beersing (1990). Regional Flood Frequency Analysis for the Island of Newfoundland, Beersing, A. K., Government of Newfoundland and Labrador, Department of Environment and Labour, Water Resources Division, January 1990.
- Beltaos (2013). River ice formation. Committee on River Ice Processes and Environment, S. Beltaos, CGU-HS. ISBN 978-0-9920022-0-6, 2013.
- Bernier and Thompson (2006). Predicting the frequency of storm surges and extreme sea levels in the northwest Atlantic, Bernier, N.B., and K.R. Thompson, J. Geophys. Res., 111, C10009, doi:10.1029/2005JC003168. Available via URL  
<https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2005JC003168>
- Brater and King (1963). Handbook of Hydraulics for the Solution of Hydraulic Engineering Problems, Brater, E.F., and King, H.W., McGraw-Hill Book Company, 6<sup>th</sup> ed, 1963.
- Bush and Lemmen (2019). Canada's Changing Climate Report. Bush, E. and Lemmen, D.S., editors Government of Canada, Ottawa, ON. 444 p. Available via URL  
[https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/energy/Climate-change/pdf/CCCR\\_FULLREPORT-EN-FINAL.pdf](https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/energy/Climate-change/pdf/CCCR_FULLREPORT-EN-FINAL.pdf)
- Cai (2010). Flood Forecasting on the Humber River Using an Artificial Neural Network Approach. H. Cai, Thesis, Memorial University. 2010. Retrieved July 2018 via:  
[www.mae.gov.nl.ca/waterres/flooding/Cai\\_2009\\_NeuralNetworkModel\\_Humber.pdf](http://www.mae.gov.nl.ca/waterres/flooding/Cai_2009_NeuralNetworkModel_Humber.pdf)
- Canada (n.d.). Federal Flood Mapping Guidelines Series, Public Safety Canada. Available via URL  
<https://www.publicsafety.gc.ca/cnt/mrgnc-mngmnt/dsstr-prvntn-mtgtn/ndmp/fldpnl-mppng-en.aspx>
- CBC News (2018a). 'Scary, unreal': 2 families told to leave homes as Deer Lake ice threatens. Canadian Broadcasting Corporation, January 2018. Retrieved July 2019 via:  
<https://www.cbc.ca/news/canada/newfoundland-labrador/deer-lake-more-ice-concerns-upper-humber-1.4493180>
- CBC News (2018b). Flooding in Pasadena forces evacuation of 5 residents Saturday. Canadian Broadcasting Corporation, February 2018. Retrieved February 2019 via:  
<https://www.cbc.ca/news/canada/newfoundland-labrador/flooding-pasadena-evacuation-5-1.4518381>
- CBC News (2018c). A look at the flood, ice damage on Newfoundland's west coast, Canadian Broadcasting Corporation, Jan 20, 2018. Retrieved February 2019 via:  
<https://www.cbc.ca/news/canada/newfoundland-labrador/water-damage-roads-washed-out-west-coast-newfoundland-1.4488529>

- CBPPL (2016). Brief History of the Deer Lake Power Company. Corner Brook Pulp and Paper Ltd. Kruger Industrial, 2016. Retrieved July 2018 via: [www.cbpl.com/wp-content/uploads/2016/06/Brief-History-Of-The-Deer-Lake-Power-Company.pdf](http://www.cbpl.com/wp-content/uploads/2016/06/Brief-History-Of-The-Deer-Lake-Power-Company.pdf)
- CONNDot (2000). Connecticut Department of Transportation - Drainage Manual, Chapter 8, Section 8, 2000. Available URL <https://portal.ct.gov/DOT/Hydraulics-and-Drainage/Drainage-Manual-Chapters-8-thru-10>
- CRA (2015). Final Report - Intensity-Duration-Frequency Curve Update for Newfoundland and Labrador, prepared for the Office of Climate Change and Energy Efficiency, Government of Newfoundland and Labrador by Conestoga-Rovers & Associates, April 14, 2015. Report available via URL [http://www.exec.gov.nl.ca/exec/occ/publications/idf\\_curve\\_2015.pdf](http://www.exec.gov.nl.ca/exec/occ/publications/idf_curve_2015.pdf)
- Cumming-Cockburn (1984). Hydrotechnical Study of the Steady Brook Area. Volumes 1 and 2, Cumming-Cockburn Ltd, 1984. Retrieved July 2018 via:  
[www.canal.gov.nl.ca/reports/frm/FRM\\_Steady%20Brook/Hydrotechnical%20Study%20of%20the%20Steady%20Brook%20Area\\_Vol1.pdf](http://www.canal.gov.nl.ca/reports/frm/FRM_Steady%20Brook/Hydrotechnical%20Study%20of%20the%20Steady%20Brook%20Area_Vol1.pdf)  
[www.canal.gov.nl.ca/reports/frm/FRM\\_Steady%20Brook/Hydrotechnical%20Study%20of%20the%20Steady%20Brook%20Area\\_Vol2.pdf](http://www.canal.gov.nl.ca/reports/frm/FRM_Steady%20Brook/Hydrotechnical%20Study%20of%20the%20Steady%20Brook%20Area_Vol2.pdf)
- Cumming-Cockburn (1987). Hydrotechnical Study of the Deer Lake Area. Cumming-Cockburn Ltd, 1987. Retrieved July 2018 via:  
[www.canal.gov.nl.ca/reports/frm/FRM\\_Deer%20Lake/Hydrotechnical%20Study%20of%20the%20Deer%20Lake%20Area\\_Vol1\\_Main%20Report.pdf](http://www.canal.gov.nl.ca/reports/frm/FRM_Deer%20Lake/Hydrotechnical%20Study%20of%20the%20Deer%20Lake%20Area_Vol1_Main%20Report.pdf)
- DAE-WRD (1982). Report on the May 1981 Flooding of the Steady Brook Area, Department of Environment - Water Resources Division, December 1982.
- Defra (2005). Flood Risk Assessment Guidance for New Development Phase 2 Framework and Guidance for Assessing and Managing Flood Risk for New Development – Full Documentation and Tools R&D Technical Report FD2320/TR2, October 2005. Available via URL [http://sciencesearch.defra.gov.uk/Document.aspx?Document=FD2320\\_3364\\_TRP.pdf](http://sciencesearch.defra.gov.uk/Document.aspx?Document=FD2320_3364_TRP.pdf)
- Defra (2006). Flood and Coastal Defence R&D Programme - R&D Outputs: Flood Risks To People - Phase 2, FD2321/TR2 Guidance Document, HR Wallingford, March 2006. Available via URL [http://randd.defra.gov.uk/Document.aspx?Document=FD2321\\_3437\\_TRP.pdf](http://randd.defra.gov.uk/Document.aspx?Document=FD2321_3437_TRP.pdf)
- DFO (2012a). *Canadian Tide and Current Tables. Volume 1 Atlantic Coast and Bay of Fundy*, Fisheries and Oceans Canada, 2012, Ottawa, ON. 88 p.
- DFO (2012b). *Canadian Tide and Current Tables. Volume 2 Gulf of St. Lawrence*, Fisheries and Oceans Canada, 2012, Ottawa, ON. 89 p.

- Dubé et al (2015.). Steep channel freeze-up processes: understanding complexity with statistical and physical models. M. Dubé, B. Turcotte, and B. Morse, Canadian Journal of Civil Engineering 42(9): 622-633, 2015. Retrieved December 2019 via: <https://doi.org/10.1139/cjce-2014-0412>
- ECCC (2013). RIVICE Model – User’s Manual. Environment and Climate Change Canada. Retrieved December 2019 via: [http://giws.usask.ca/rivice/Manual/RIVICE\\_Manual\\_2013-01-11.pdf](http://giws.usask.ca/rivice/Manual/RIVICE_Manual_2013-01-11.pdf)
- Environment Canada (1976). Hydrologic and Hydraulic Procedures for Flood Plain Delineation. Water Planning and Management Branch, Inland Waters Directorate, Environment Canada, Ottawa, 1976.
- Environment Canada (1980). Flooding Events in Newfoundland and Labrador – An Historical Perspective, Environment Canada, prepared by A.D. Kindervater, Inland Waters Directorate, Halifax, Nova Scotia. 80-WPMB-4. July 1980.
- ESA (2018). Science Toolbox Exploitation Platform (step), 2018. “SNAP.” European Space Agency (ESA). 2018. Retrieved July 2019 via: <http://step.esa.int/main/toolboxes/snap/>.
- ESA (2019a). Sentinel Online, 2019a. “Sentinel-2.” European Space Agency (ESA). 2019. Retrieved July 2019 via: <https://sentinel.esa.int/web/sentinel/missions/sentinel-2>.
- ESA (2019b). “MultiSpectral Instrument (MSI) Overview.” European Space Agency (ESA). 2019. Retrieved July 2019 via: <https://earth.esa.int/web/sentinel/technical-guides/sentinel-2-msi/msi-instrument>.
- ESA (2019c). Sentinel Online, 2019c. “Sentinel-2 Level 1C Data.” European Space Agency (ESA). 2019. Retrieved July 2019 via: <https://earth.esa.int/web/sentinel/user-guides/sentinel-2-msi/product-types/level-1c>.
- ESA (2019d). Sentinel Online, 2019d. “Sen2Cor.” European Space Agency (ESA). 2019. Retrieved July 2019 via: <http://step.esa.int/main/third-party-plugins-2/sen2cor/>.
- ESA (2019e). Sentinel Online, 2019e. “Sen2Three.” European Space Agency (ESA). 2019. Retrieved July 2019 via: <http://step.esa.int/main/third-party-plugins-2/sen2three/>.
- EWRG (2017). Technical Guidelines for Flood Hazard Mapping, Environmental Water Resources Group Ltd, March 2017.
- FEMA (2012). Recommended Procedures for Flood Velocity Data Development, Federal Emergency Management Agency, Department of Homeland Security, Washington, DC, USA, November 2012. Available via URL <https://www.hsd.org/?abstract&did=727033>
- FEMA (2020). Guidance for Flood Risk Analysis and Mapping - Flood Depth and Analysis Rasters, Guidance Document 14, Federal Emergency Management Agency, Department of Homeland Security, Washington, DC, USA, December 2020. Available via URL [https://www.fema.gov/sites/default/files/documents/fema\\_flood-depth-and-analysis-guidance.pdf](https://www.fema.gov/sites/default/files/documents/fema_flood-depth-and-analysis-guidance.pdf)

- Fisheries and Oceans Canada (n.d.). Vertical Tides. Available via URL  
<https://www.tides.gc.ca/eng/info/verticaldatums>
- FHWA (1978). Hydraulics of Bridge Waterways, U.S. Department of Transportation, Federal Highway Administration, Office of Engineering, Bridge Division, Hydraulics Branch, 1978.
- Finnis (2013). Projected Impacts of Climate Change for the Province of Newfoundland & Labrador. Office of Climate Change, Energy Efficiency & Emissions Trading, J. Finnis, 2013.
- Finnis and Daraio (2018). Projected Impacts of Climate Change for the Province of Newfoundland & Labrador: 2018 Update, prepared by Dr. Joel Finnis (Department of Geography) and Dr. Joseph Daraio (Faculty of Engineering), Memorial University of Newfoundland, March 29, 2018.  
Report available via URL [https://www.exec.gov.nl.ca/exec/occ/publications/Final\\_Report\\_2018.pdf](https://www.exec.gov.nl.ca/exec/occ/publications/Final_Report_2018.pdf)
- Forrester (1983). Canadian Tidal Manual. Department of Fisheries and Oceans, W.D. Forrester, Canadian Hydrographic Service, Ottawa, ON, 1983, 138 p. Available via URL  
<http://www.charts.gc.ca/documents/publications/Tidal%20Manual%20E.pdf>
- Golder (2017a). Inventory and Assessment of Dams in Newfoundland and Labrador – Year Two. Report Number 1668487-01-Rev 0., Golder Associates Limited, 2017. Retrieved July 2018 via:  
[www.mae.gov.nl.ca/waterres/reports/dam\\_safety/NL\\_dam\\_inventory\\_year\\_2\\_final\\_report.pdf](http://www.mae.gov.nl.ca/waterres/reports/dam_safety/NL_dam_inventory_year_2_final_report.pdf)
- Golder (2017b). Dam Breach Study and Stability Analysis of Deer Lake Structures (Draft), Golder Associates, Report No. 1656802 (Rev A), May 2017.
- Hatch (2012). Flood Risk Mapping Project for Shearstown / Bay Roberts Area, Hatch, 2012. Available via URL <https://www.gov.nl.ca/eccm/waterres/flooding/frm/>
- Lindenschmidt (2017). RIVICE – a non-proprietary, open-source, one-dimensional river-ice and water-quality model. K-E. Lindenschmidt, Water 9, 314, 2017.
- Lindenschmidt (2020). River ice processes and ice flood forecasting – a guide for practitioners and students. K-E. Lindenschmidt, Springer Nature Switzerland AG. 267 pp, 2020. Retrieved December 2019 via: <https://doi.org/10.1007/978-3-030-28679-8>
- MacLaren (1972). Humber River Flooding of Steady Brook Area. MacLaren Ltd., December 1972.
- MAE (2018). Monitoring Snow Extent and Snow Water Equivalent on the Island of Newfoundland. Municipal Affairs and Environment, Government of Newfoundland and Labrador, 2018. Retrieved July 2018 via: [www.mae.gov.nl.ca/waterres/flooding/snow\\_monitoring.html](http://www.mae.gov.nl.ca/waterres/flooding/snow_monitoring.html)
- Mahdavi et al (2017). Object-Based Classification of Wetlands in Newfoundland and Labrador Using Multi-Temporal PolSAR Data. Sahel Mahdavi, Bahram Salehi, Meisam Amani, Jean Elizabeth Granger, Brian Brisco, Weimin Huang, and Alan Hanson, Canadian Journal of Remote Sensing 43 (5): 432–50, 2017.

- Nafziger et al (2011). Freeze-up, breakup, and winter ice observations on four small regulated and unregulated streams in Newfoundland, Canada. J. Nafziger, J. Morley, F. Hicks, T. Linnansaari, A. Fraser, C. Pennell and R. Cunjak, CGU HS Committee on River Ice Processes and the Environment, 16th Workshop on River Ice, Winnipeg, Manitoba, September 18 – 22, 2011. Retrieved December 2019 via: <http://www.cripe.ca/docs/proceedings/16/Nafziger-et-al-2011a.pdf>
- NLHYDRO (2018). Hinds Lake Hydroelectric Generating Station. NL Hydro – A Nalcor Energy Company. Retrieved July 2018 via: [nlhydro.com/operations/hydroelectric-generating-stations/hinds-lake-hydroelectric-generating-station/](http://nlhydro.com/operations/hydroelectric-generating-stations/hinds-lake-hydroelectric-generating-station/)
- NTV (2016). Unfollowed recommendations raise concerns about Main Dam on Grand Lake. Picture at time 1:10 (minute:second) extracted from video <http://ntv.ca/unfollowed-recommendations-raise-concerns-about-main-dam-on-grand-lake/> (Retrieved December 2019)
- Panu et al (1984). Regional Flood Frequency Analysis for the Island of Newfoundland, Canada- Newfoundland Flood Damage Reduction Program, Panu, U. S., Smith, D. A., and Ambler D. C., Newfoundland and Labrador Department of Environment and Lands, St. John's; Environment Canada, Dartmouth, 1984.
- Philips (1996). Development of a GIS Database for Use in an Integrated Approach to Water Resources Management in the Humber River Watershed and Humber Arm, Government of Newfoundland and Labrador and Environment Canada, prepared by Philips Consultants [now Wood], 1996.
- Picco (1997). A Comparative Study of Flow Forecasting in the Humber River Basin using a Deterministic Hydrologic Model and a Dynamic Regression Statistical Model. R. Picco, R, Thesis. Memorial University, 1997. Retrieved July 2018 via: [www.collectionscanada.gc.ca/obj/s4/f2/dsk2/ftp01/MQ34219.pdf](http://www.collectionscanada.gc.ca/obj/s4/f2/dsk2/ftp01/MQ34219.pdf)
- Public Safety Canada, (2019). Federal Flood Mapping Guidelines Series. Available via URL <https://www.publicsafety.gc.ca/cnt/mrgnc-mngmnt/dsstr-prvntn-mtgtn/ndmp/fldpln-mppng-en.aspx>
- Rollings (1999). Regional Flood Frequency Analysis for the Island of Newfoundland. Rollings, K., Government of Newfoundland and Labrador, Department of Environment and Labour, Water Resources Management Division, Hydrologic Modelling Section, December 1999.
- Shawmont, (1969). Report on high Flows in May 1969 in Humber River System, SM-3-71. Prepared for the Bowater Power Company Ltd, Shawmont Newfoundland Ltd., 1969.
- Sheikholeslami et al (2017). Improved understanding of river ice processes using global sensitivity analysis approaches. R. Sheikholeslami, F. Yassin, K-E. Lindenschmidt and S. Razavi, Journal of Hydrologic Engineering 22(11): 04017048, 2017. Retrieved June 2019 via: [https://doi.org/10.1061/\(ASCE\)HE.1943-5584.0001574](https://doi.org/10.1061/(ASCE)HE.1943-5584.0001574)

- Sinergise (2019). Sentinel Science Hub, 2019, <https://scihub.copernicus.eu/dhus/#/home>, Sinergise Ltd.
- Surendran et al (2008). Supplementary Note on Flood Hazard Ratings and Thresholds for Development Planning and Control Purpose – Clarification of the Table 13.1 of FD2320/TR2 and Figure 3.2 of FD2321/TR1. Suresh Surendran and Geoff Gibbs (Environment Agency), Steven Wade and Helen Udale-Clarke (HR Wallingford), May 2008. Available via URL [http://randd.defra.gov.uk/Document.aspx?Document=FD2321\\_7400\\_PR.pdf](http://randd.defra.gov.uk/Document.aspx?Document=FD2321_7400_PR.pdf)
- Telegram (2018). Slideshow: a peek inside Deer Lake Power. Retrieved June 2019 via: [https://www.thetelegram.com/media/photologue/photos/cache/x-WS-05-27122018-DLPowerWater9-gk\\_large.JPG](https://www.thetelegram.com/media/photologue/photos/cache/x-WS-05-27122018-DLPowerWater9-gk_large.JPG)
- Tom (2010). Adapting Remotely Sensed Snow Data for Daily Flow Modelling on the Upper Humber River, Newfoundland and Labrador. M. Tom, Thesis. Memorial University, 2010. Retrieved July 2018 via: [www.mae.gov.nl.ca/waterres/flooding/adapting\\_remotely\\_sensed\\_snow\\_data.pdf](http://www.mae.gov.nl.ca/waterres/flooding/adapting_remotely_sensed_snow_data.pdf)
- UCAR (2010). Flood Frequency Analysis. Available via URL [http://ftp.comet.ucar.edu/memory-stick/hydro/basic\\_int/flood\\_frequency/print.htm#page\\_2.1.0](http://ftp.comet.ucar.edu/memory-stick/hydro/basic_int/flood_frequency/print.htm#page_2.1.0)
- Uden and Hall (2007). Application of Remote Sensing (Digital Terrain Models) in Flood Risk Assessments, Mercedes Uden (Royal Haskoning) and Hamish Hall, (Royal Haskoning), presentation at the National Hydrology Seminar 2007: GIS in Hydrology. Available via URL <http://hydrologyireland.ie/wp-content/uploads/2018/11/6-Application-of-remote-sensing.pdf>
- USACE (2013). HEC-GeoHMS Geospatial Hydrologic Modeling Extension – User Manual – version 10.1, US Army Corps of Engineers, Hydrologic Engineering Center’s (HEC), February 2013. Available via URL [https://www.hec.usace.army.mil/software/hec-geohms/documentation/HEC-GeoHMS\\_Users\\_Manual\\_10.1.pdf](https://www.hec.usace.army.mil/software/hec-geohms/documentation/HEC-GeoHMS_Users_Manual_10.1.pdf)
- USACE (2016). HEC-RAS River Analysis System – User Manual - Version 5.0, U.S. Army Corps of Engineers, Hydrologic Engineering Center’s (HEC), February 2016.
- USACE (2018). Hydrologic Modeling System (HEC-HMS) – User Manual – Version 4.4, U.S. Army Corps of Engineers, Hydrologic Engineering Center’s (HEC), November 2018
- USACE (2019). Statistical Software Package (HEC-SSP) v2.2, U.S. Army Corps of Engineers, Hydrologic Engineering Center’s (HEC), June 2019. Retrieved July 2019 via: <https://www.hec.usace.army.mil/software/hec-ssp/download.aspx>
- USGS (n.d.). The 100-Year Flood, United States Geological Survey, no date. Available via URL [https://www.usgs.gov/special-topic/water-science-school/science/100-year-flood?qt-science\\_center\\_objects=0#qt-science\\_center\\_objects](https://www.usgs.gov/special-topic/water-science-school/science/100-year-flood?qt-science_center_objects=0#qt-science_center_objects)

- Vasseur and Catto (2008): Atlantic Canada; in From Impacts to Adaptation: Canada in a Changing Climate 2007, Vasseur, L. and Catto, N., edited by D.S. Lemmen, F.J. Warren, J. Lacroix and E. Bush; Government of Canada, Ottawa, ON, p. 119-170. Available via URL <https://www.nrcan.gc.ca/impacts-adaptation-canada-changing-climate/10253>
- Warren and Lemmen (2014). Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation, Natural Resources Canada. Available via URL <https://www.nrcan.gc.ca/climate-change/impacts-adaptations/canada-changing-climate-sector-perspectives-impacts-and-adaptation/16309>
- Western Star (2018). Deer Lake neighbourhood worried about losing property to the Humber River, The Western Star, January 2018. Available via URL: <https://www.thewesternstar.com/news/local/deer-lake-neighbourhood-worried-about-losing-property-to-the-humber-river-178990/>
- Wood (2020). Technical Report Rouge River Floodplain Mapping Update – Phase 1, prepared by Wood Canada Limited for the Toronto and Region Conservation Authority, Contract #10009716, January 2020.