Water Resources Management Division
Climate Change Flood Risk Mapping Study and Development of a Flood Forecasting Service: Exploits River Communities

Final Report

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1. Introduction

1.1 Project Overview

The Water Resources Management Division (WRMD) of the Department of Municipal Affairs and Environment (now Department of Environment and Climate Change), Government of Newfoundland and Labrador, commissioned Hatch in 2018 to carry out a climate change flood risk mapping study and develop a flood forecasting service for the communities along the Exploits River, including Badger, Grand Falls-Windsor and Bishop’s Falls.

Flooding is a concern for communities on the Exploits River. The Exploits River communities have a long history of flooding due to various factors including heavy rainfall, rapid winter or spring melts, and, in some locations, ice jams.

This report describes the work done to create the flood maps and the flood forecasting system.

First, background information was reviewed about past floods in the Exploits River area. A field survey program was carried out by Sikumiut Environmental Management (SEM) to collect information on the Exploits River and the streams in the community areas. Measurements of bridges and culverts along these streams and rivers were also taken. Leading Edge Geomatics (LEG) collected Light Detection and Ranging (LiDAR) data in the Exploits River community areas. The LiDAR data was used to make high quality maps of the ground shape. LEG also took high-quality aerial photos of the community areas that were used in the flood maps.

Satellite imagery of the entire Exploits River basin was used to organize the basin into different classes, such as waterbodies, forests, pastures and urban areas.

Hatch developed a model (described in the hydrological analysis chapter) to simulate how rainfall and snowmelt on the Exploits River basin is converted to flows in the Exploits River and the streams in the community areas. The peak flood flows from the model were used in another model (described in the hydraulic analysis chapter), which estimates the resulting water levels on the Exploits River and the streams which feed into it during those flood events.

The peak water levels from the flood models were used to create flood maps that show the flood boundaries, flood depths, water velocities and flood hazard areas in the Exploits River communities. These maps were created for 1:20 annual exceedance probability (AEP) and 1:100 AEP floods based on the current climate. A 1:20 AEP flood is a flood that has a 5% probability of happening in any given year. A 1:100 AEP flood has a 1% probability of happening in any given year. Since climate change may have an impact on the Exploits River, the 1:20 and 1:100 AEP future floods due to climate change and sea level rise were also mapped.

The models that were created by Hatch were used by WEST Consultants to develop a system that helps to predict floods up to 48 hours in advance. This flood forecasting system collects observed and forecasted information about rain, snow, and temperature and converts them into flows in the rivers and streams using the models developed earlier. It then estimates how high the water levels will be in those rivers and streams. The flood forecasting system helps communities plan what flood protection or emergency measures should be carried out, if any. **Figure 1-1** gives an overview of the report structure and layout.

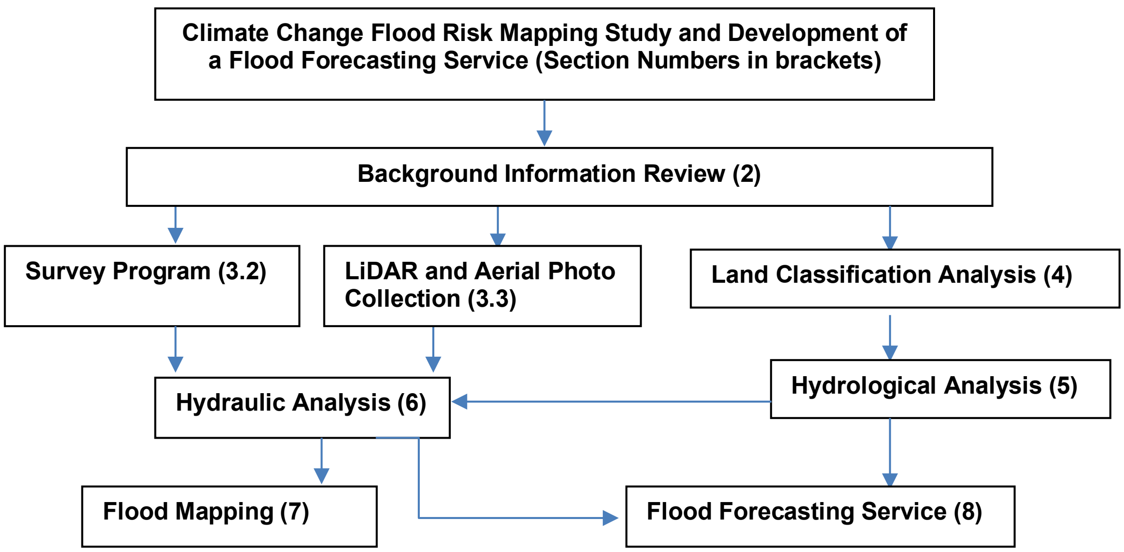

Figure 1-1: Report Overview

1.2 Objectives and Study Scope

The major objectives of this study include the following:

- Water level estimates, flow estimates and flood risk maps showing floodplains for:
  - 1:20 and 1:100 AEP current climate and current development condition
  - 1:20 and 1:100 AEP current climate and fully developed watershed condition
  - 1:20 and 1:100 AEP climate change and current development condition
  - 1:20 and 1:100 AEP climate change and fully developed watershed condition.
- Maps indicating the change of floodplains associated with historical 1:20 and 1:100 AEP and new current climate and development conditions.
- Maps indicating the change of floodplains associated with current climate and climate change 1:20 and 1:100 AEP conditions.
- Maps indicating flood velocity, flood inundation and flood hazard associated with 1:20 and 1:100 AEP current climate and development conditions.
- Linked hydro fabric, including datasets and models used to develop the flood risk maps.
- Implementation of a flood forecasting service for the study area using hydraulic and hydrologic models. This will include updates to WRMD's in-house Badger ice progression model and implementation of the RIVICE river ice model.
- Setup of flood forecasting service and training of WRMD staff.
- Hydraulic capacity assessment of hydraulic structures for 1:20 and 1:100 current and climate change conditions.

1.3 Study Area Description

The Exploits River watershed is located in the central part of the island portion of the province of Newfoundland and Labrador as shown in **Figure 1-2** and has a contributing area of about 11,000 km^2. The river begins at the outlet of Red Indian Lake and drains into the Atlantic Ocean through the Bay of Exploits for a total reach length of approximately 175 km.

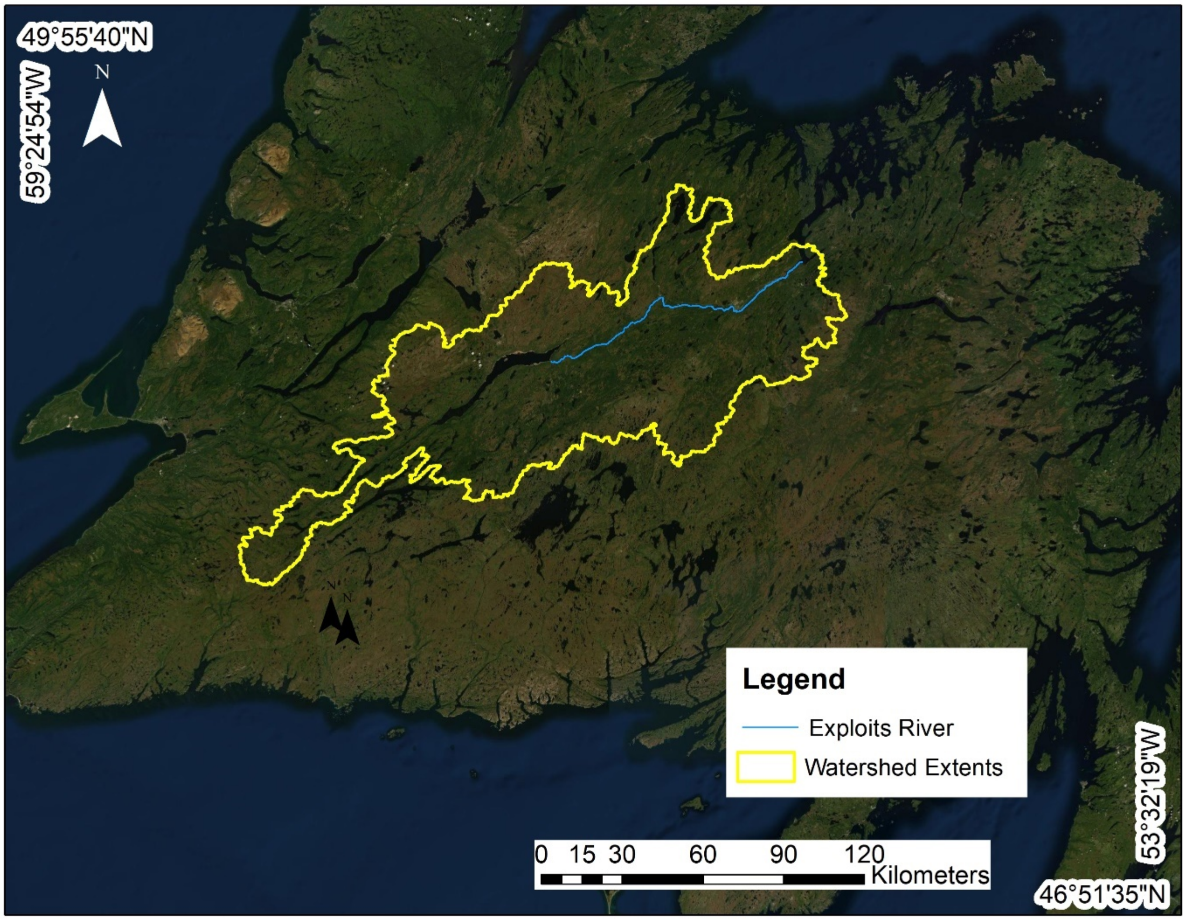

Figure 1-2: Project Watershed Location

Communities and dams located in the project area are shown in **Figure 1-3**. The study area includes the communities of Badger, Grand Falls-Windsor and Bishop's Falls, as well the residential area of Rushy Pond. In addition to the Exploits River, thirteen streams were identified in the communities from 1:50,000 topographic maps and are included in the flood risk mapping area. These are shown in **Figure 1-4**.

The Exploits River is dammed at four points along its length for the purpose of producing hydroelectric power. The uppermost dam is Millertown Dam (also known as Exploits Dam), at the mouth of Red Indian Lake, which is the main storage reservoir. Proceeding downriver, the next dam is Goodyear's Dam, located upstream of the Town of Grand Falls-Windsor. Goodyear's Dam is a free-overflow structure that serves to restrict the amount of river ice reaching the hydroelectric generating stations downstream. The third dam is Grand Falls Dam at the Grand Falls Generating Station in Grand Falls-Windsor. The final dam is Bishop's Falls Dam at the Bishop's Falls Generating Station in the Town of Bishop's Falls. These dams and generating stations are operated by Nalcor Energy. More detailed information about the dams, including dimensions and elevations, is provided in the hydraulic analysis chapter (**Section 6.2.3**).

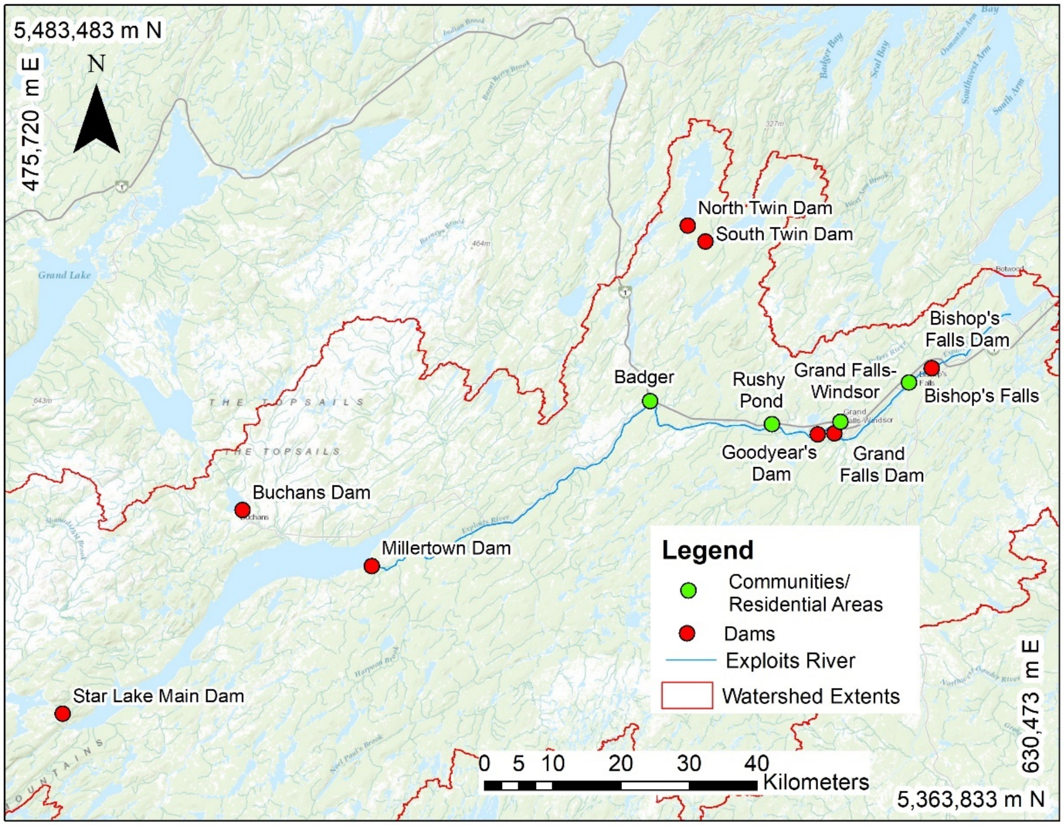

Figure 1-3: Dams and Communities in Project Area

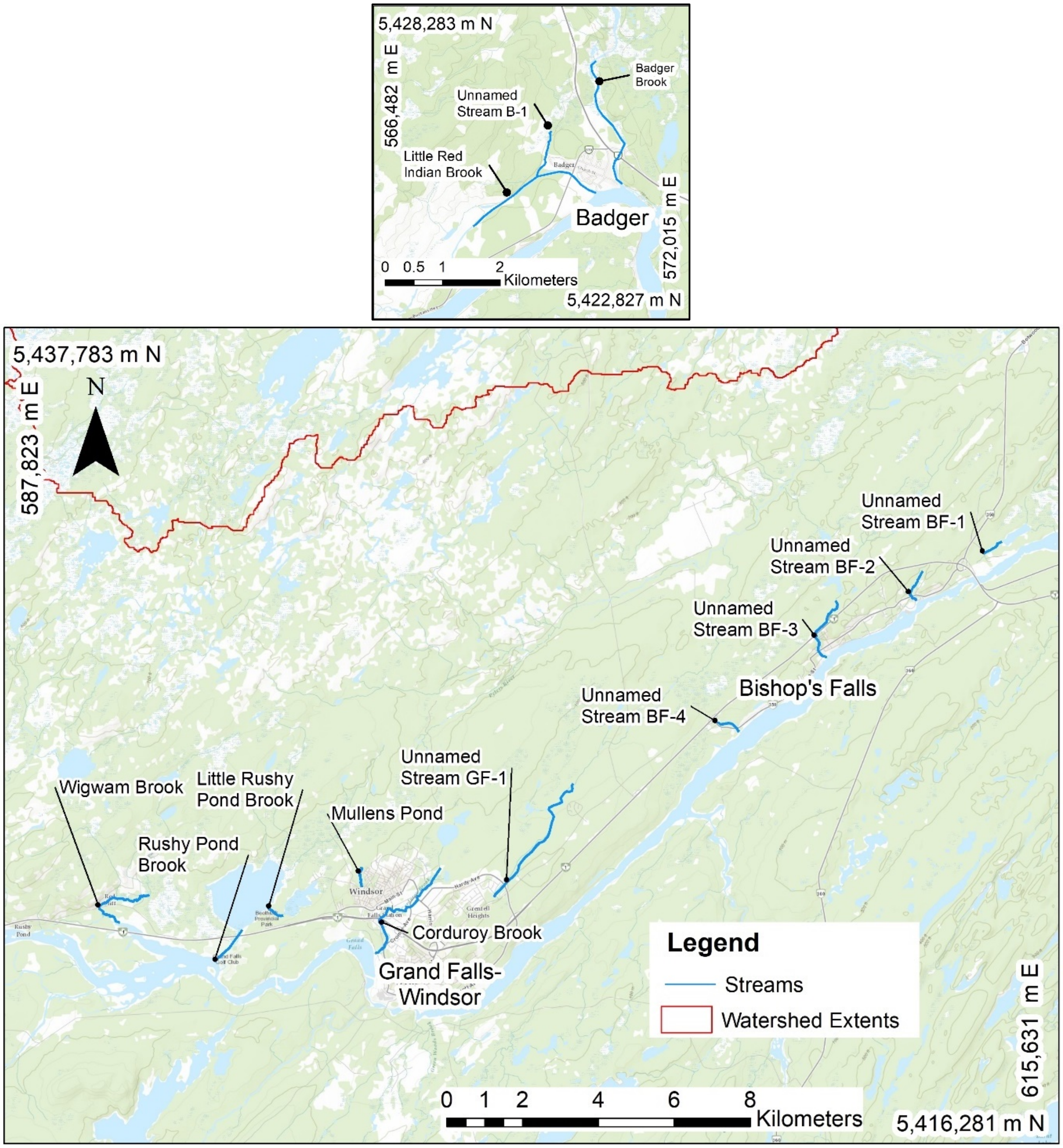

Figure 1-4: Streams in Community Extents

1.4 Geodetic Datum

All elevations in this report are related to the Canadian Geodetic Vertical Datum of 2013 (CGVD2013), which is the current standard and supersedes the Canadian Geodetic Vertical Datum of 1928 (CGVD28), which was the datum used for previous studies in this area. In the study area, CGVD2013 elevations are 0.2 to 0.3 m lower than CGVD28 elevations. Elevations in the flood forecasting system are also referenced to CGVD2013.

For historic reasons, the elevations of several dam structures are related to local operating datums for internal use by Nalcor. The conversions of local elevations to CGVD2013, based on currently available information, are provided in **Table 1-1** below.

Table 1-1: Local Elevation Datums

Local Elevation	Required Adjustment to Local Elevation to Convert to CGVD28	Required Adjustment to Local Elevation to Convert to CGVD2013	Reference
Grand Falls	-27.4 m	-27.694 m	Exploits River Flood and Dam Break Studies (Acres 1996)
Bishop's Falls	-27.12 m	-27.418 m	Exploits River Flood and Dam Break Studies (Acres 1996)

In this report, the convention for the terms “left” and “right” in reference to the watercourses and structures are with respect to facing downstream.

The 2019 field survey data collected by SEM was originally taken in CGVD28 as the benchmarks are all in that datum. SEM then converted their data to CGVD2013 for use in the model.

The 2019 LiDAR data collected by LEG was referenced to CGVD2013. LiDAR data previously acquired by LEG in the study area in 2016 was referenced to CGVD28; LEG converted this data to CGVD2013 for use in this study.

All data from previous projects including field survey and models was in CGVD28. Data was converted to CGVD2013 using tools provided by the National Research Council of Canada.

1.5 Horizontal Coordinate System

Horizontal coordinates in this study are given with respect to the Universal Transverse Mercator (UTM) projection, zone 21N. Use of the UTM projection was necessitated by constraints of the flood forecasting system software.

2. Background Information Review

2.1 Introduction

Hatch reviewed information about past flooding events to better understand how flooding happens in the Exploits River communities. Hatch made a list of past floods in the Exploits River community areas from a history of provincial flood events. Hatch also read reports that have been written about floods in the Exploits River communities. This information is used to show where areas are likely to flood. The survey and LiDAR programs were adjusted using this information to be sure that data was collected in these areas. It should be noted that this section only includes background information about past flood events. Background information about water levels and flows in the rivers and streams, weather data, dam operation rules, sea levels and ice cover is found in **Section 5** and **Section 6**. **Figure 2-1** provides an overview of the section.

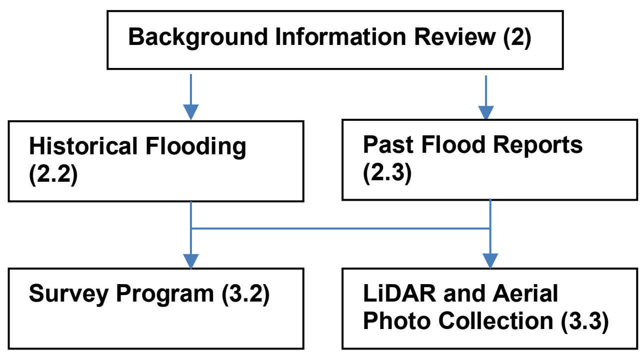

Figure 2-1: Field Data Section Overview

2.2 Historical Flooding

WRMD has created a flood events inventory database for the province of Newfoundland and Labrador (WRMD, 2014). Floods in the Exploits River communities of Badger, Rushy Pond, Grand Falls–Windsor and Bishop's Falls were reviewed. **Table 2-1** describes the flood events that have occurred in the area since 1900. It should be noted that elevations in this table are presented as reported in the original source data and have not been corrected to CGVD2013. Part of Hatch's scope for this project was to update the inventory to include the most recent flooding events in the Exploits River community areas. Municipal authorities informed Hatch of three significant flooding events since the inventory was last updated, two of which are related to Hurricane Matthew in October 2016, and one related to a heavy rainfall event in 2018. These are noted in italic font in **Table 2-1**. References for **Table 2-1** are provided in the flood events inventory database (WRMD, 2014) and are not repeated in this report.

Table 2-1: Flood Events at Exploits River Communities

Description of Flood Event	Area Affected	Date	Cause
The railway bridge at the Exploits was carried away by a large freshet, which piled the ice above the bridge, raising the water over 38 feet.	Exploits Bridge	March 22, 1900	Ice Jam
Rail line rerouting completed at Red Cliff; possibly initiated because of flooding earlier that year.	Badger, Rushy Pond	Winter 1903 (est.)	Not specified
Rail trestle at Leech Brook destroyed by ice (good possibility that contributing ice was from Leech Brook itself).	Badger	Winter 1913	Ice Jam
Flood at Badger approached intersection of church street and School Road and almost up to CNR tracks. Flood elevation estimated to be 100.15 m.	Badger	1916	Not specified
Ice jam formed below Grand Falls. At that time the ice backed up through the gorge below the Terrance, and the grinder room was flooded to a depth 6.7 meters.	Grand Falls	January 1927	Ice Jam
Ice jam at or below Rushy Pond community. Exploits River discharge approximately 708 m^3/s on April 22 rising to 988 m^3/s on April 23 and over 1325 m^3/s on April 29.	Rushy Pond	April 22, 1934	Ice Jam
Ice jam at Badger raised water height to an elevation about 99.80 m; water was at the houses in Badger.	Badger	February 21, 1937	Ice Jam
Flooding in Badger; flood elevation about 99.9 m. River banks at Badger are reported to have previously been reduced by almost 1 m due to logging work.	Badger	February 1943	Ice Jam
Winter ice conditions raised flood elevation to 99.05 m. River plugging noted on January 8, 1945 but no location given.	Badger	1945	Ice Jam
Ice and wood jams on Exploits caused flooding.	Coach Road, possibly in Rushy Pond Area	March 9, 1949	Ice and Wood Jam
Inundated a portion of the uncompleted Trans Canada Highway for about 500 ft.	Grand Falls	June 5, 1965	Rainfall
Ice cover and high water flows raised the level of Rushy Pond to road level	Grand Falls	December 30, 1971	Not specified
Flooding in the streets was extensive, storm damage was quite extensive and a section of the highway in the Exploits region near Grand Falls was underwater.	Grand Falls	December 22, 1975	Rainfall and Snowmelt

Description of Flood Event	Area Affected	Date	Cause
Flooding from Rushy Pond caused by spring runoff caused damages to the highway, Two people were drowned when their vehicle went off the highway and into 3 m of water.	Grand Falls	May 4, 1976	Rainfall
Three rivers overflowed their banks and flowed into Badger, only 8 of the evacuated houses had several inches of water in them	Badger	January 17, 1977	Ice Jam
Some flooding to basements and some tenants were forced out of their homes	Grand Falls	December 27, 1977	Snowmelt
A river flowing through the town overflowed causing considerable damage to dwellings. Bridges, culverts, and streets were also washed out.	Bishops Falls	August 17, 1979	Rainfall
Heavy rain and mild temperatures caused damages to homes and roads. The Exploits River flooded its banks after 10 in rainfall.	Bishops Falls	January 11, 1983	Rainfall
Several homes were evacuated, 40 affected by flooding	Badger	February 15, 1983	Ice Jam
Flooding – details unknown	Badger	1985	Not specified
Ice jam caused 1:100 AEP flood water level in Badger. Severe flooding caused $2.63 M in damages including damages to houses, public buildings and water and sewer systems.	Badger	February 15, 2003	Ice Jam
Heavy rain. Water levels were close to flooding the Trans-Canada Highway west of Grand-Falls Windsor.	Grand Falls-Windsor	May 10, 2003	Rainfall
Remnant of Hurricane Leslie passed over Newfoundland; Badger declared a state of emergency as a precautionary measure	Badger	September 10, 2012	Rainfall
Water came up two roads in the town and several homes had to be evacuated. The stadium and ball field were flooded. Event was close to a 1:20 AEP.	Badger	February 7, 2013	Ice Jam
Corduroy Brook culvert at Lincoln Road and Cromer Avenue was washed out during Hurricane Matthew.	*Grand Falls-Windsor*	*October 10-11, 2016*	*Rainfall*
Hurricane Matthew resulted in flooding of 20+ houses on Main Street. The culvert crossing at Sunset Drive was washed out.	*Bishop's Falls*	*October 10-11, 2016*	*Rainfall*
Gorge Park and golf course in Grand Falls - Windsor flooded after heavy rainfall.	*Grand Falls-Windsor*	*April 30, 2018*	*Rainfall*

Overall, ice jams, rainfall and snow melt have been the major causes contributing to flooding in the Exploits River communities, with ice jamming as the most common cause of flooding. The most recent three events were due to rainfall.

2.3 Past Flood Reports

Available reports on previous floods in the community areas as provided by WRMD have been reviewed. The following sections provide a brief summary of each report. It should be noted that elevations in this section are presented as reported in the original source data and have not been corrected to CGVD2013.

2.3.1 Flood of 1983 in Central Newfoundland

The flood in January 1983, affecting central and south coast areas in Newfoundland was caused by a combination of storm rainfall and rapid snowmelt. The Town of Bishop’s Falls was significantly affected. The flow from the lower Exploits River had an estimated return period of more than 500 years. The maximum instantaneous discharge at Grand Falls was 2,400 m^3/s, compared to the previous max of 1,430 m^3/s in 1969. Three homes and two clubs were washed away by flood waters, and 180 families were evacuated. The embankment dam at the Bishop’s Falls Generating Station was overtopped and destroyed, and the powerhouse was damaged. The “Flood of January 1983 in Central Newfoundland” report (Environment Canada, 1985) documents this event.

2.3.2 Hydrotechnical Study of the Badger and Rushy Pond Areas

The “Hydrotechnical Study of the Badger and Rushy Pond Areas” (Fenco, 1985) took place in 1984. The study reviewed the causes of flooding in the Badger and Rushy Pond areas using high quality field data. The report predicted 1:20 and 1:100 AEP flood levels for both areas and evaluated the flood damage reduction alternatives at Badger.

The report noted that flooding at Badger has only taken place during ice cover formation in January, or in one instance of reformation in February 1983. River discharges during these events average about 150 m^3/s (5,300 cfs) at Millertown (Exploits) Dam. Winter flooding at Badger is caused by very rapid production of frazil slush which obstructs the flow on the Exploits Rivers and causes overtopping of the banks. These conditions were modelled using a numerical ice progression model. Historical flood levels were also used to give another estimate of the 1:20 and 1:100 AEP flood levels. The 1:20 and 1:100 AEP levels generated using historical data were in close agreement with the flood levels given by the frequency analysis. The 1:100 AEP level was predicted to cause flood damage to 73 buildings in Badger. It was recommended that areas which are prone to flooding be zoned for special attention or design considerations, that the communication and warning system continue to be up to date, that the ice progression model be set up for early warning, and that a winter monitoring program be implemented.

Flooding in the Rushy Pond area was usually considered to be caused by high flow during open water conditions. This was proven in some historical events that have been modelled using a validated backwater model (HEC-2). However, the highest flood level (1983) up to the time of the study as well as majority of other past floods occurred when ice was present on the river. The area most affected by ice accumulations is the reach between the Red Cliff Overpass and the mouth of Sandy Brook. Using historical information it was found that the 1:20 and 1:100 AEP levels with winter ice were slightly higher (approximately 0.5 m) than the open water flood levels for the same return periods. Mathematical modelling was not done in this area. It was recommended that additional information be collected on ice levels and ice conditions.

The hydrologic analysis included maximum annual and winter monthly peak flows for the Exploits Dam (Millertown Dam) and the Grand Falls Dam from 1934 to 1983 and frequency analysis discharge results for the 1:2, 1:20 and 1:100 AEP flows for Red Indian Lake and Grand Falls. The open water hydraulic analysis included results for 1:20 and 1:100 AEP flows and water surface elevations. The ice progression model analysis included ice volumes passing through Badger and durations of ice passage as well as thicknesses and elevations of ice.

2.3.3 River Ice Modelling Exploits River at Badger

In 1983, an ice jam occurred on the Exploits River and flooded the Town of Badger. A hydrotechnical study was done in 1985 (Fenco, 1985) to delineate the flood risk areas and confirm the ice jam flood levels. The Province committed to following the recommendations from the study and continue the monitoring program which included the collection of real time data. In 1993, the governments of Canada and the province of Newfoundland and Labrador joined in the “General Agreement Respecting Water Resources Management”, one element of which identified the importance of flood forecasting and specifically included Badger as a location where it would be beneficial. In 1994, an updated approach for flood forecasting at Badger was initiated under this program. The objectives of the study were to evaluate the existing data collection program and ice modelling, review available data and recommend improvements to the flood/ice forecasting at Badger. The “River Ice Modelling, Exploits River at Badger” report (Fenco MacLaren, 1995) summarizes the findings from this study.

Some of the recommendations from the study suggested the monitoring program increase its frequency for ice progression observations and gauge readings, eliminate ice thickness measurements, and continue compilation of historical data. It was recommended that non-proprietary models (the Ice Cover Evolution Module of RIVICE and RIVJAM) be used to determine if the existing ice model can be improved, and that RIVJAM and the ice cover evolution module of RIVICE be reviewed in regards to improvements into the ice cover thickening process, transport, stability and erosion in the area downstream of Badger.

It was observed that snowfall has an influence on frazil ice production, and that wind direction (along the axis of the river channel) increases surface water cooling and the potential for frazil ice production.

The modelling and analysis portion of the study concluded that decreases in water levels around 2 m result in significant frazil ice blockages downstream of Badger. As well, modelling results confirmed the validity of the 1:100 AEP flood level at Badger and recommended that the 1:20 AEP flood level be slightly higher than historical modelling. It was also suggested that exceptionally high volumes of frazil ice generation on a single day may contribute to higher than normal forecasted water levels at Badger. It was recommended that forecasted elevations be increased by ~0.7 m when the single day frazil ice generation rate exceeds 2.9 million m^3 in the reach between Badger Chute and Badger.

2.3.4 Ice Analysis and Flood Risk Mapping Study of Bishop's Falls

The "Ice Analysis and Flood Risk Mapping Study of Bishop's Falls" report (Fenco Newfoundland, 1990) described the 1983 flood and hydrologic modelling of the 1:20 AEP and 1:100 AEP flood flows. Hydraulic analysis was also done using those flows to determine flood levels and the effect of ice buildup. Prior to the 1983 flood, this area did not have a history of flooding. Additional spillway gates were added to the main Ambursen Dam after the 1983 flood. This new addition allows the dam to have the capacity to pass the 1983 flood and the plotted flood lines showed that the flood risk area is very small at Bishop's Falls.

The report recommended approaches which could prevent or reduce flood damages. Some of these approaches included floodplain regulations, flood proofing and flood control dams.

Conclusions of the study suggested dynamic ice forces and action played a very small role in the failure of the earth dam during 1983. The presence of ice contributed to the slightly higher backwater levels and the ice resulted in an increase in flood levels by about 0.2 m.

2.3.5 Regional Water Resources Study of the Notre Dame Bay Area and Central Newfoundland Region

The "Regional Water Resources Study of the Notre Dame Bay Area and Central Newfoundland Region" (Nolan, 1991) was carried out to provide both new and updated information on the management and study of the freshwater resources from the Baie Verte Peninsula (Burlington Peninsula) south to Buchans, and eastward to the Gander River. This study was released in March 1991.

At the time, the region's economy depended mostly on pulp and paper and fish processing. Abundant fresh water has supported both of these industries. Groundwater availability varied but was usually sufficient. More than 10% of the communities (105 in total) relied on groundwater wells for their main water source.

Surface water quality was generally good with the exception of the lower Exploits River which was polluted by the Grand Falls-Windsor pulp and paper mill (closed in 2009) and municipal discharges. Groundwater quality was generally good with occasional pH and colour problems.

The main uses of the water in the region were hydropower, fishery, recreational and commercial fishing, water recreation, withdrawal uses, and municipal and industrial wastewater.

The abundance of high-quality water is a major asset to the region. Some environmental remediation recommendations were made for the lower Exploits River.

2.3.6 Badger Flood 2003 – Situation Report

The Badger Flood 2003 Situation Report (WRMD, 2003) described the 2003 flood event at Badger, which to that point in time was the most severe event with respect to depth of inundation and damages to the town.

Based on the data from the water level gauge at Badger, the 2003 flood started on February 15, and the water level rose 2.3 m in the first hour. The rate of water level increase was much faster than any of the major flooding events recorded at Badger since 1916. The flood led to the evacuation of the town and the declaration of a State of Emergency. The flood waters reached a maximum elevation of 100.5 m at the gauge near the arena. This level was slightly above the 1:100 AEP flood level of 100.42 m for the Main Street area. Immediately following the flood, temperatures fell and the floodwaters froze in the town, causing additional damage and impeding repairs. Of the 353 houses in Badger, 147 did not receive any damage, 68 received minor damage, 59 received major damage and at the time of writing the report, 79 had yet to be inspected but were likely to have suffered major damage.

The mechanism and progression of ice movement in 2003 was different than previous flood events. The report recommended that the mechanism of ice movement that led to the flooding be further investigated, and that the validity of the 1:20 and 1:100 AEP historical levels be checked.

This flood highlighted a number of limitations to the flood forecasting system, including location of the ice front, regression of the ice front and water temperature monitoring. The flood forecasting system was not designed to forecast floods that occurred with the rapidity of the event that occurred on February 15, 2003 and it was recommended that improvements to the system be made, including installation of a real time transmitter that can warn authorities when the water level changes rapidly.

2.3.7 Badger Flooding Event – Field Report February 2013

The “Badger Flooding Event - Field Report, February 2013” document (WRMD, 2013) described the flood event of 2013. After the 2003 flood, the flood forecasting service used for the Town of Badger was improved by using satellite RADAR imagery to monitor ice in the Exploits. The flood forecasting service for Badger uses a space satellite based river ice service, in conjunction with an Ice Progression Model and a series of monitoring stations.

On the morning of February 7, 2013, an ice jam caused a flood event approaching the 1:20 AEP level in Badger. Some residents were evacuated. The report summarizes the extents of the flood and compares them to 1:20 and 1:100 AEP extents.

2.3.8 Flood Information Maps

Flood information maps are available for Badger and Rushy Pond which include the extents of the normal water surface, the 1:20 AEP flood extents and the 1:100 AEP flood extents

(Canada-Newfoundland Flood Damage Reduction Program, n.d.). The date of preparation is not indicated on the maps; however it is assumed that the flood extents are derived from Fenco (1985).

A flood information map for Bishop's Falls includes the 1:20 AEP flood extents and the 1:100 AEP flood extents as well as the January 1983 flood levels (Canada-Newfoundland Flood Damage Reduction Program, 1990). This map was prepared in September 1990, presumably derived from Fenco Newfoundland (1990).

2.3.9 Exploits River Near Real Time Data

WRMD maintains an Exploits River Near Real Time Data web page (MAE, n.d.) containing real time data from eight stations on the Exploits River and its tributaries, as well as RADAR and webcam images of the Exploits River. The station names, WRMD and Water Survey of Canada (WSC) gauge ID numbers, and collection details are provided in **Table 2-2**. Further information about stations which collect streamflow data are found in **Table 5-1**, and stations which collect water level elevation data are summarized in **Table 6-8**. WRMD also produces publicly available snow cover extent maps (MAE, n.d., 2).

Table 2-2: Real Time Data Stations

WRMD Gauge ID	WSC Gauge ID	Gauge Name	Flow	Stage	Climate	Water Temperature	Snow	Camera
02YO019	02YO019	Badger Brook Below Foot Bridge	Y	Y	N	N	N	N
02YO013B	02YO013	Exploits River at Badger	Y	Y	N	N	N	N
NLENCL0002	n/a	Exploits River at Badger – East of Stadium	N	N	Y	N	Y	Y
NLENCM0001	n/a	Exploits River at Badger Steps	N	N	N	N	N	Y
NLENHM0003	n/a	Exploits River at Bishop's Falls Trestle	N	Y	N	N	N	Y
02YO018	02YO018	Exploits River at Charlie Edwards Brook	Y	Y	N	N	N	N
02YO011	02YO011	Exploits River Below Noel Pauls Brook	Y	Y	Y	Y	N	N
02YO016	02YO016	Exploits River Near Millertown	Y	Y	N	Y	N	N

3. Field Data Collection Program

3.1 Introduction

It is important to have information about the topography and river network. A field survey program was carried out by Sikumiut Environmental Management (SEM) to collect information on the Exploits River and its tributaries. The survey program also took measurements of bridges and culverts along these streams and rivers. Leading Edge Geomatics (LEG) collected Light Detection and Ranging (LiDAR) data in the Exploits River community areas. The LiDAR data was used to prepare high-resolution topographic maps. LEG also took high-quality aerial photos of the community areas that were used in the flood maps.

LiDAR and survey data had also been collected in previous years in the Exploits River area.

The LiDAR and survey data were used in the construction of one of the models that make up the flood forecasting system (hydraulic model). **Figure 3-1** provides an outline of this section.

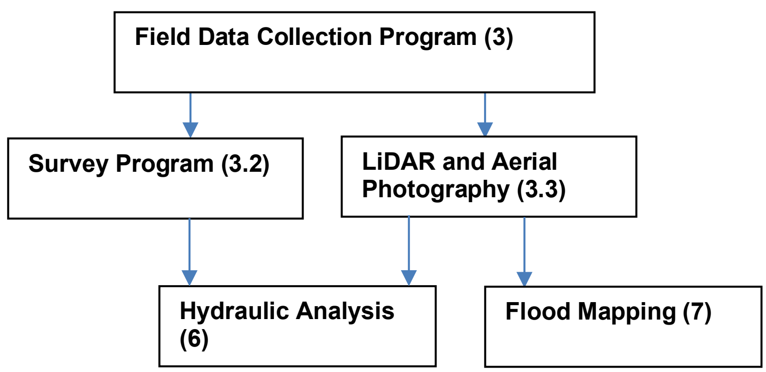

Figure 3-1: Field Data Section Overview

3.2 Survey Program

3.2.1 Previous Field Survey Programs

Several field survey programs have been executed in the study area over the past 8 years. Surveyed cross-sections of the Exploits River have been assigned a field ID with a prefix code that distinguishes the survey source.

As part of a Hydrotechnical Design Study of the Sir Robert Bond Bridge conducted by Hatch in 2012 for the NL Department of Transportation and Works (DTW), bathymetric surveys were carried out along the Exploits River downstream of Bishop’s Falls (RB prefix). Bathymetric surveys were also carried out along the Exploits River in 2013 (R prefix), and along the Exploits River in 2016 (E prefix) for Nalcor flood studies conducted by Hatch. Hatch used 100 of these recently collected cross-sections for the present study and received permission from Nalcor to use the sections from their studies. Previously existing survey cross-sections are shown in green in **Figure 3-2**. A list of tributaries is provided in **Table 3-1.**

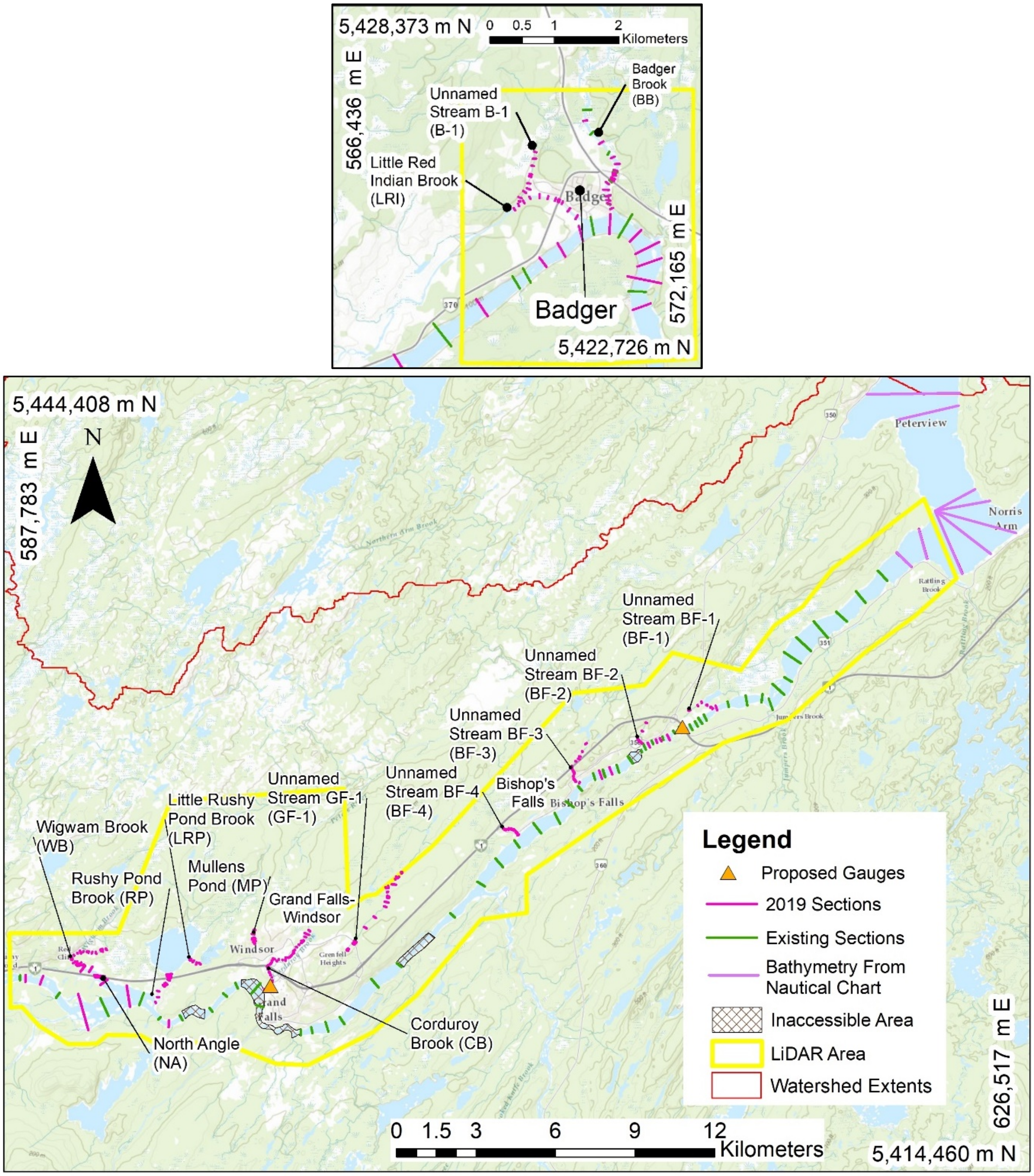

Figure 3-2: Field Survey Locations

Table 3-1: Tributary List

Tributary Name	Tributary Abbreviation
Little Red Indian Brook	LRI
Unnamed Stream B-1	B-1
Badger Brook	BB
Wigwam Brook	WB
Rushy Pond Brook	RP
Little Rushy Pond Brook	LRP
Mullen’s Pond	MP
Corduroy Brook	CB
Unnamed Stream GF-1	GF-1
Unnamed Stream BF-4	BF-4
Unnamed Stream BF-3	BF-3
Unnamed Stream BF-2	BF-2
Unnamed Stream BF-1	BF-1

3.2.2 2019 Survey Program

Bathymetric surveys were required along the 13 tributaries in the study area communities, as well as in a few locations along the Exploits River for enhanced detail in the hydraulic modeling. These are shown in pink in **Figure 3-2**. Field IDs were assigned to tributary cross-sections with prefix codes based on tributary name. It should be noted that North Angle is located at the downstream end of Wigwam Brook. For the purposes of the field survey, flood maps and models in this study, North Angle is considered to be part of Wigwam Brook. New cross-sections on the Exploits River were assigned field IDs that fit with existing section field ID numbering in each area.

A number of gauges exist in the study area, including several WSC gauges on the Exploits River and one WRMD gauge on Badger Brook. To better define conditions in the model, two additional flow and water level measurement locations were identified: one on Corduroy Brook, and one on the Exploits River at the Sir Robert Bond Bridge just downstream of Bishop’s Falls. These are shown in orange on **Figure 3-2** and again in **Figure 5-2**.

SEM was responsible for obtaining all bathymetric and ground-based topographic survey data, as well as installing the water level instruments and taking flow measurements. They were also responsible for previous bathymetric and topographic surveys of the study area in 2016 and were therefore familiar with the area. They conducted the field work on the project from April 5, 2019 to September 4, 2019.

They used a variety of equipment to gather the data, including a 6.1 m (20 ft) fiberglass boat and a canoe.

At the two water level monitoring locations, pressure transducers were installed at the beginning of April with water levels recorded for 68 days over the spring freshet. Flow measurements were taken at both locations. Water levels were recorded on an hourly basis.

A Van Essen TD Diver was installed at each location to sample pressure and temperature. A Van Essen Baro Diver was used to take measurements of atmospheric pressure; this compensates for variations in atmospheric pressure measured by the other divers.

The Corduroy Brook TD Diver was attached to a piece of rebar in the stream. The Exploits River TD Diver was more challenging. There was concern at this location that ice upstream in the rivers and lakes could destroy the installation upon breakup. It had been planned to install two divers – one on a piece of rebar and one on an anchor to avoid ice spans knocking the post and losing the sensor. It was not possible to install it on a piece of rebar as the shoreline for this area was rocky and mostly bedrock, which prevented secure installation. Therefore, only one diver was installed on an anchor and tethered to a tree for recovery. Unfortunately, when SEM tried to retrieve the instrument in June, the tether was cut at the base of the tree about 5 m inside the tree line. It seems likely that someone noticed the tether, pulled in the rope, and took the anchor diver.

SEM conducted bathymetric surveys in their boats and shallow water surveys using chest waders. Occasionally a canoe was used where transects were too deep for chest waders but too shallow for bathymetric surveying equipment. In addition to bathymetric surveys along the larger waterways, survey points were taken a minimum of 5 m onto the overbank to allow the survey data to tie into the LiDAR. Photographs at each cross-section were taken at the time of survey.

Approximately 312 survey transects were taken by SEM; section locations were sometimes modified in the field or cancelled if the location of a stream Hatch had identified on the maps was inaccurate. In total, Hatch used 304 of the SEM survey transects in the hydraulic model. These transects are tabulated in **Appendix A** and plotted in **Appendix B**.

SEM also surveyed 18 bridges and 27 culverts along the tributaries. Measurements were taken of the top of bridge deck, underside of bridge deck, culvert invert and top of culvert elevations, as well as culvert diameters. The bridges and culverts are shown in **Figure 6-5** and summarized in **Table 6-6** and **Table 6-7.**

The bridge and culvert data sheets are provided in **Appendix C** and **Appendix D**.

The surveyed water levels and thalweg are provided in **Figure 3-3** to **Figure 3-18**. The watercourses are ordered alphabetically. River stationing is in ascending order from downstream to upstream as is the convention in HEC-RAS.

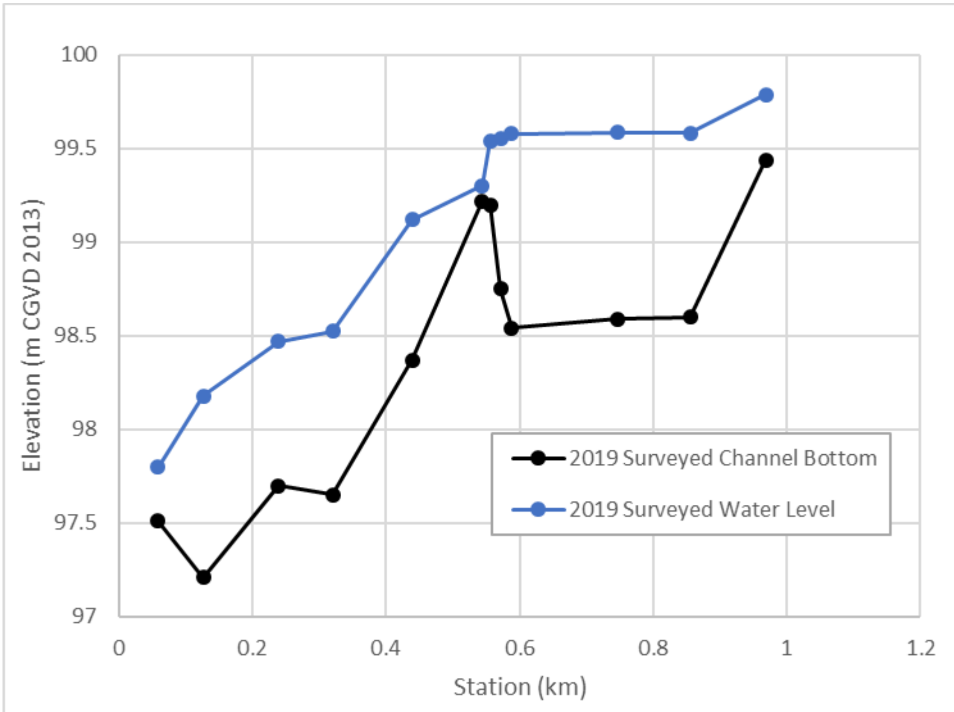

Figure 3-3: Unnamed Stream B-1 Surveyed Water Surface and Minimum Channel Bed Profiles

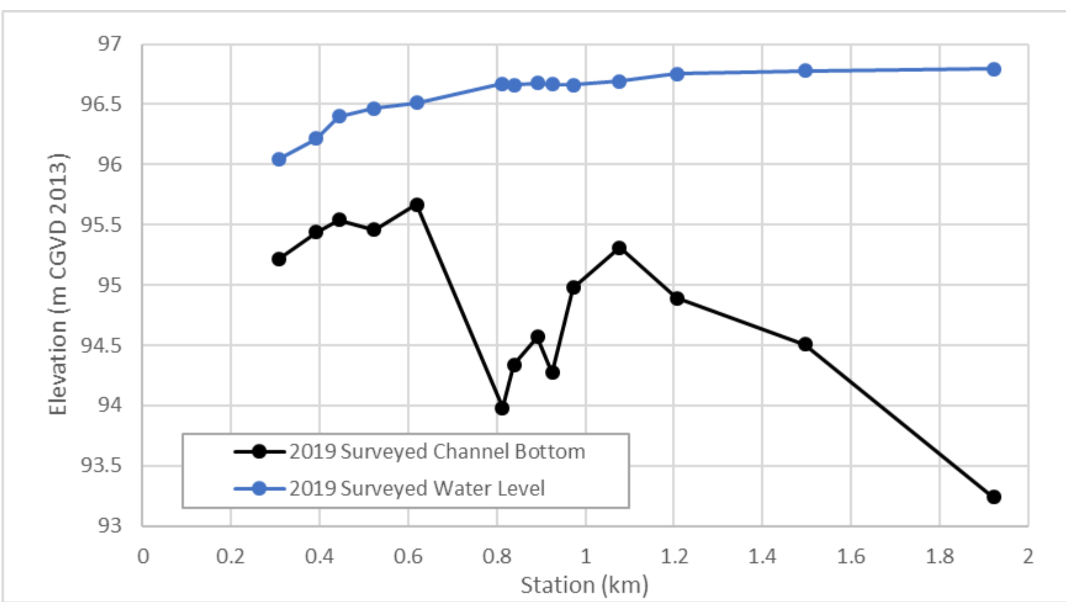

Figure 3-4: Badger Brook Surveyed Water Surface and Minimum Channel Bed Profiles

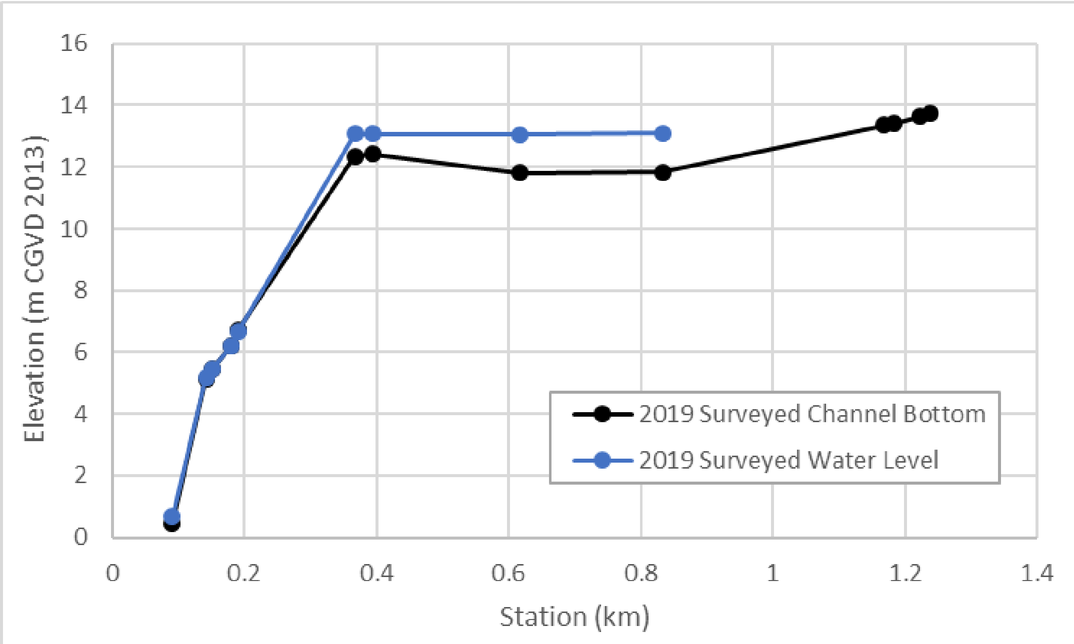

Figure 3-5: Unnamed Stream BF-1 Surveyed Water Surface and Minimum Channel Bed Profiles

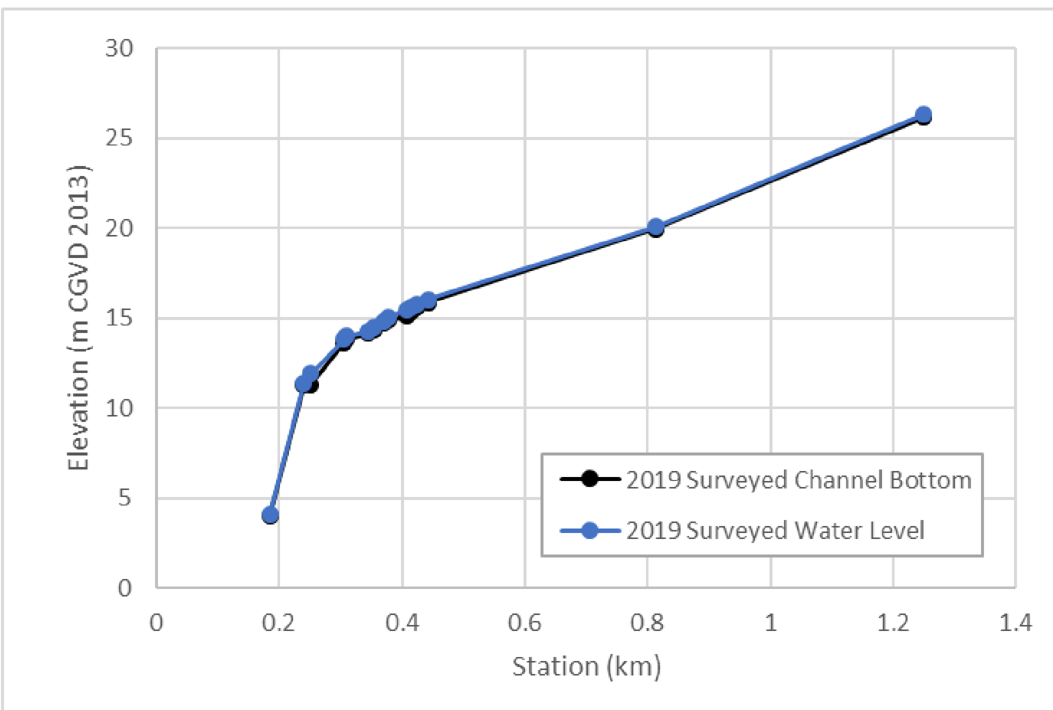

Figure 3-6: Unnamed Stream BF-2 Surveyed Water Surface and Minimum Channel Bed Profiles

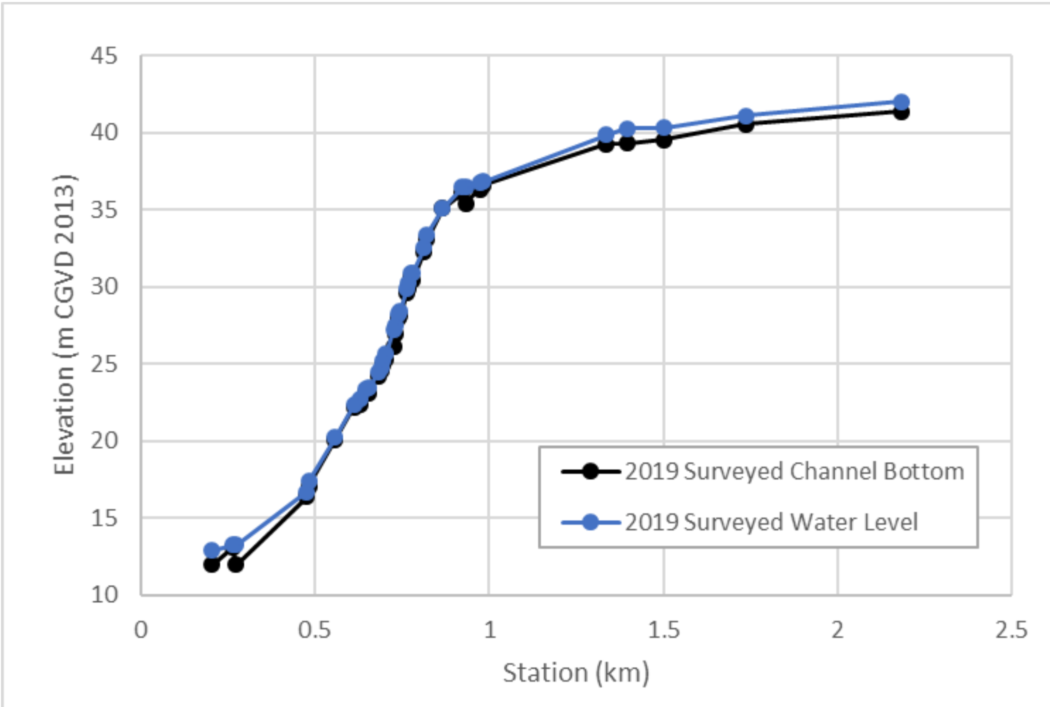

Figure 3-7: Unnamed Stream BF-3 Surveyed Water Surface and Minimum Channel Bed Profiles

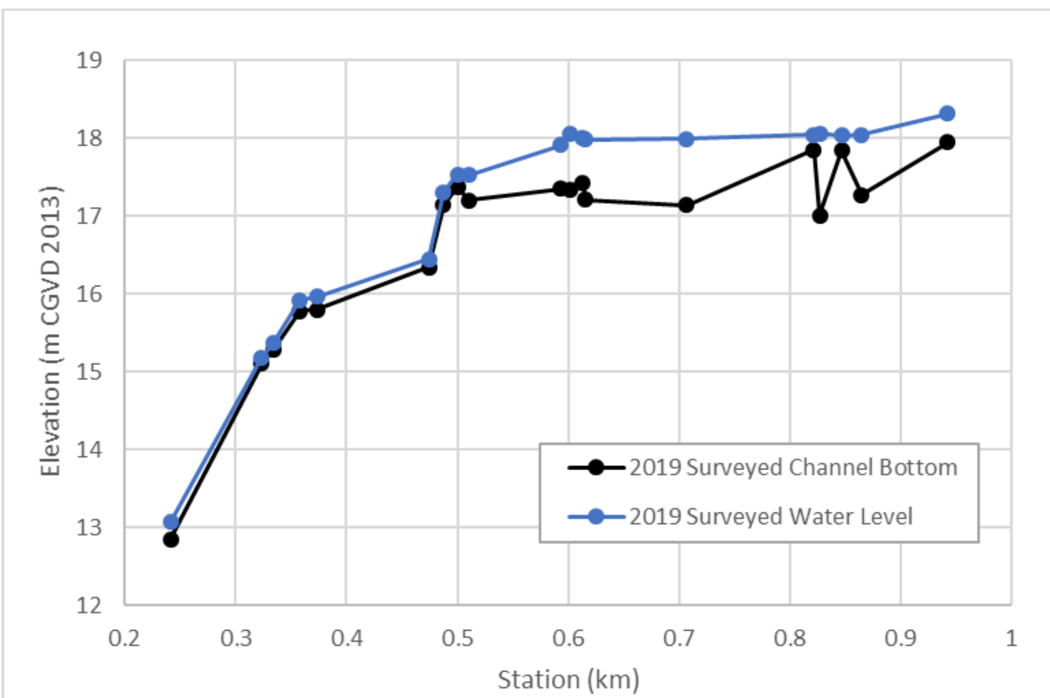

Figure 3-8: Unnamed Stream BF-4 Surveyed Water Surface and Minimum Channel Bed Profiles

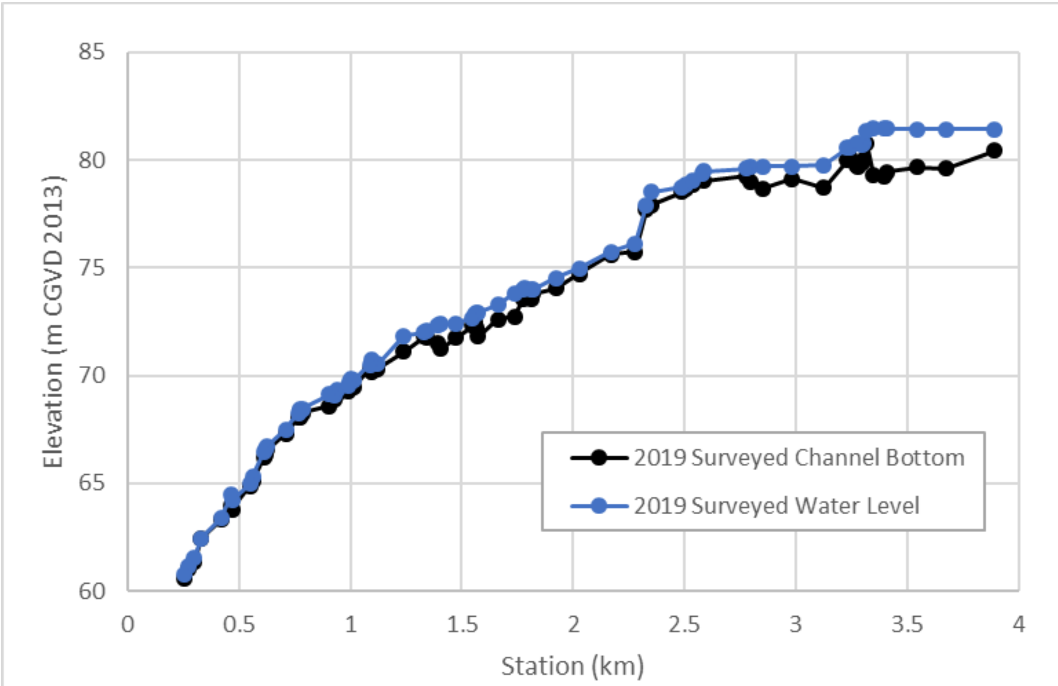

Figure 3-9: Corduroy Brook Surveyed Water Surface and Minimum Channel Bed Profiles

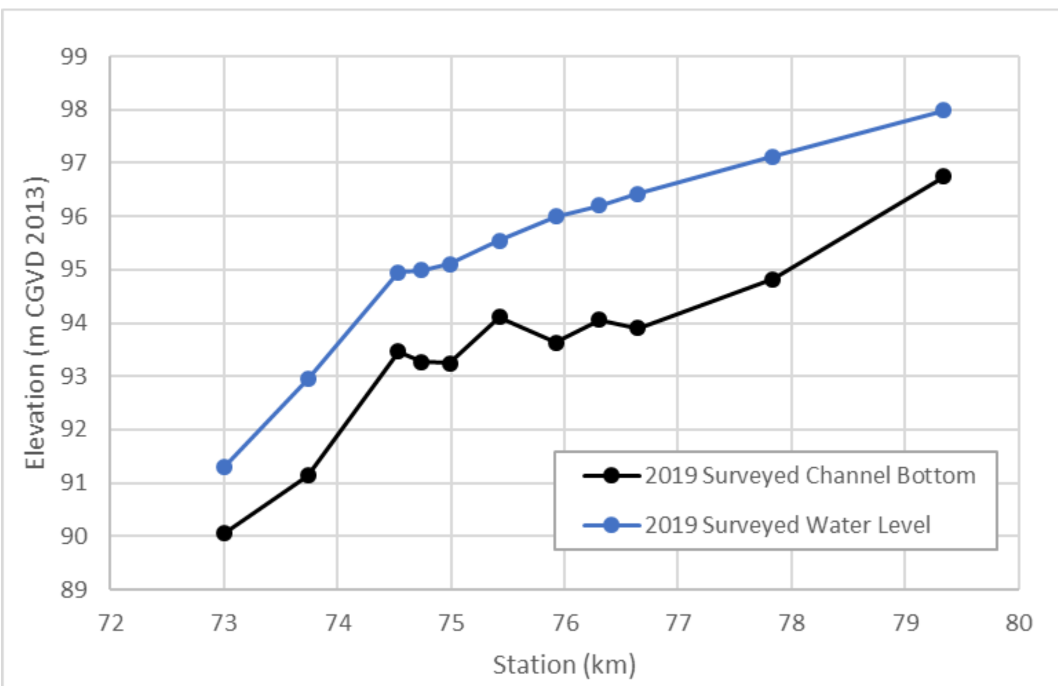

Figure 3-10: Exploits River – Badger Area Surveyed Water Surface and Minimum Channel Bed Profiles

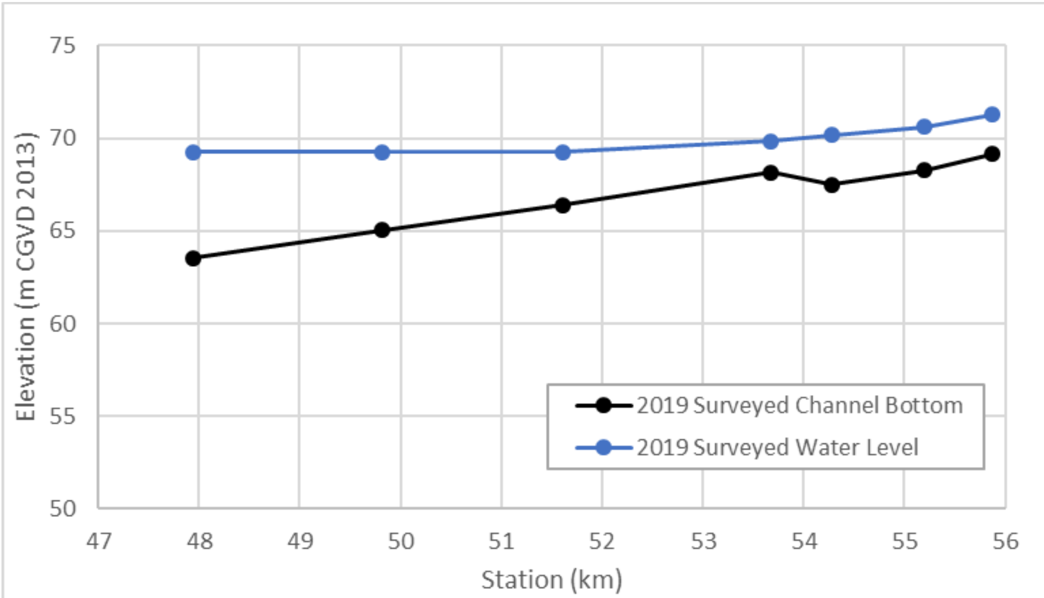

Figure 3-11: Exploits River – Rushy Pond Area Surveyed Water Surface and Minimum Channel Bed Profiles

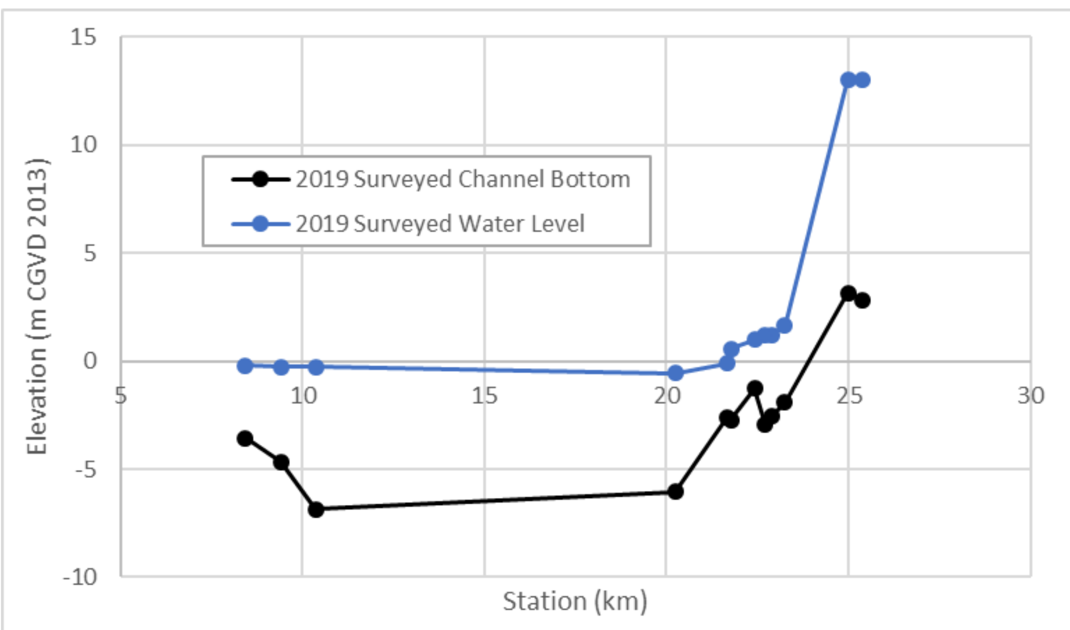

Figure 3-12: Exploits River - Bishops Falls Area Surveyed Water Surface and Minimum Channel Bed Profiles

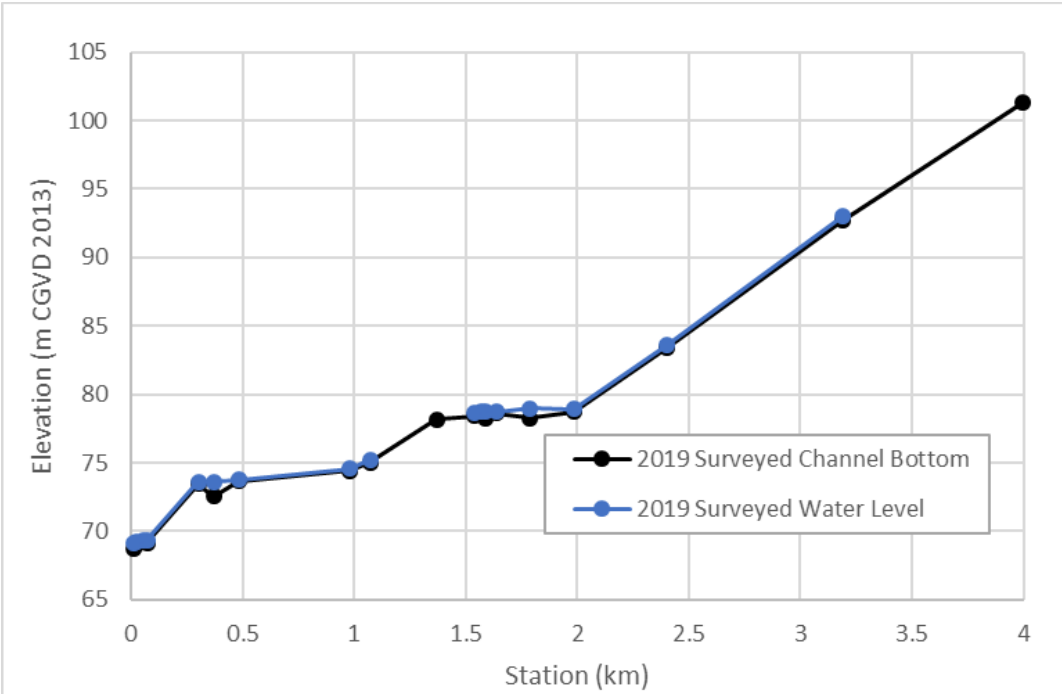

Figure 3-13: Unnamed Stream GF-1 Surveyed Water Surface and Minimum Channel Bed Profiles

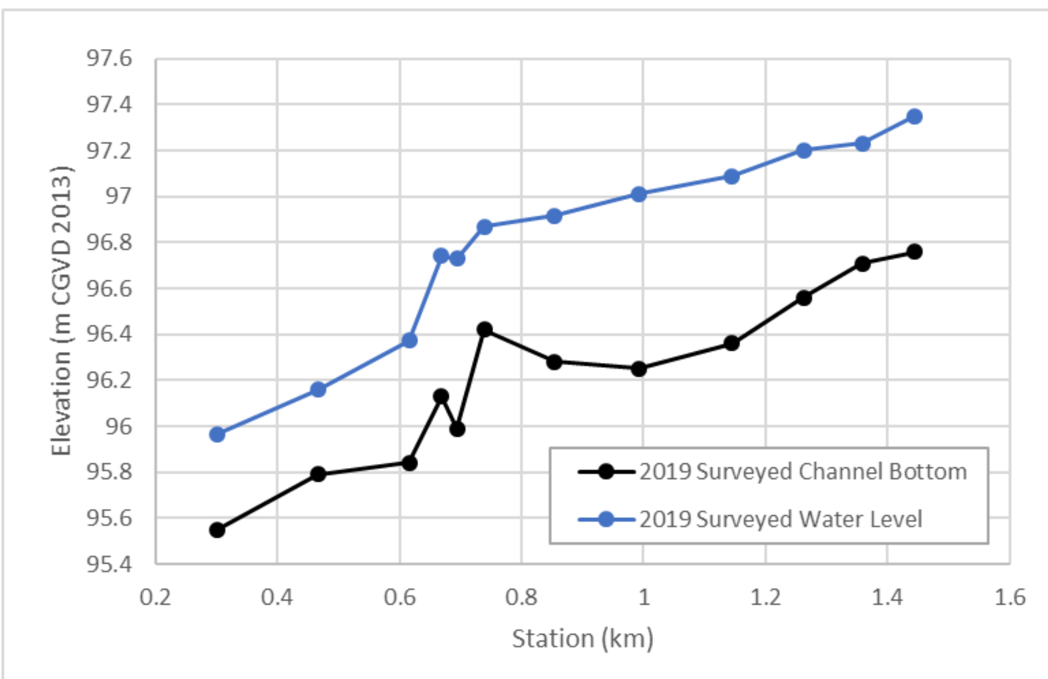

Figure 3-14: Little Red Indian Brook Surveyed Water Surface and Minimum Channel Bed Profiles

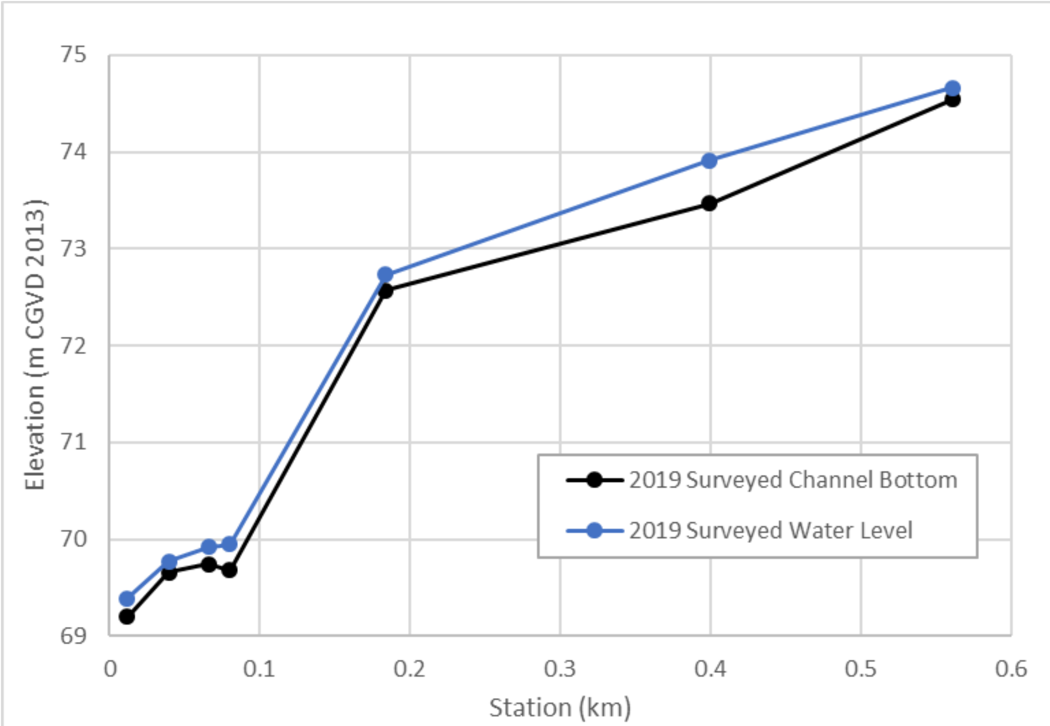

Figure 3-15: Little Rushy Pond Brook Surveyed Water Surface and Minimum Channel Bed Profiles

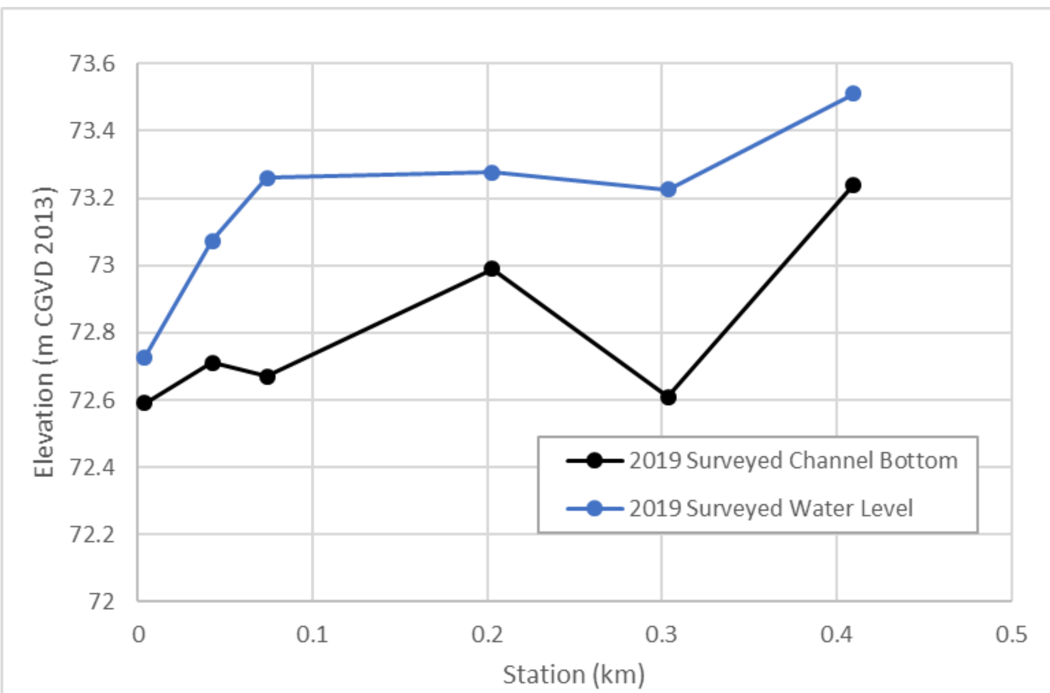

Figure 3-16: Mullen's Pond Surveyed Water Surface and Minimum Channel Bed Profiles

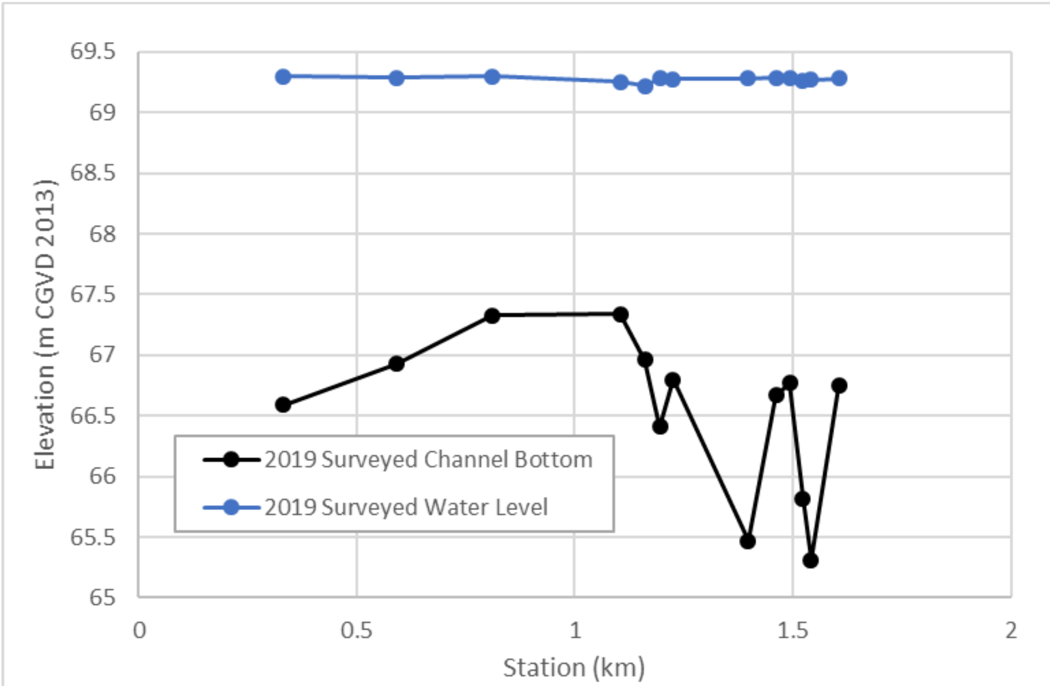

Figure 3-17: Rushy Pond Brook Surveyed Water Surface and Minimum Channel Bed Profiles

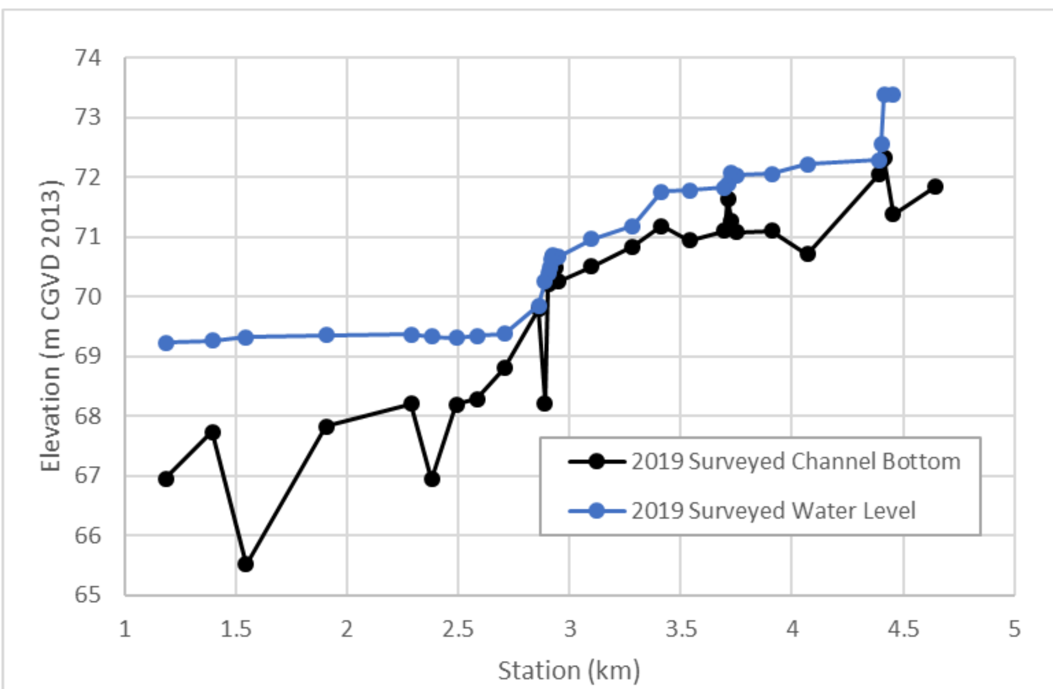

Figure 3-18: Wigwam Brook Surveyed Water Surface and Minimum Channel Bed Profiles

3.3 LiDAR and Aerial Photography Collection Program

3.3.1 2016 LiDAR Digital Elevation Model

LEG had completed a LiDAR survey in the Exploits River area in 2016 for use in a flood and dam break study conducted by Hatch for Nalcor (Hatch, 2017). The extents of the 2016 LiDAR digital elevation model (DEM) are shown in **Figure 3-19.** Permission was obtained from Nalcor to use the survey data for the current study. This survey was used in the hydrologic analysis to better define the terrain in the Badger area, and in the hydraulic analysis for flood routing from Millertown Dam to Badger, and from Badger to the Rushy Pond area (Charlie Edwards Point).

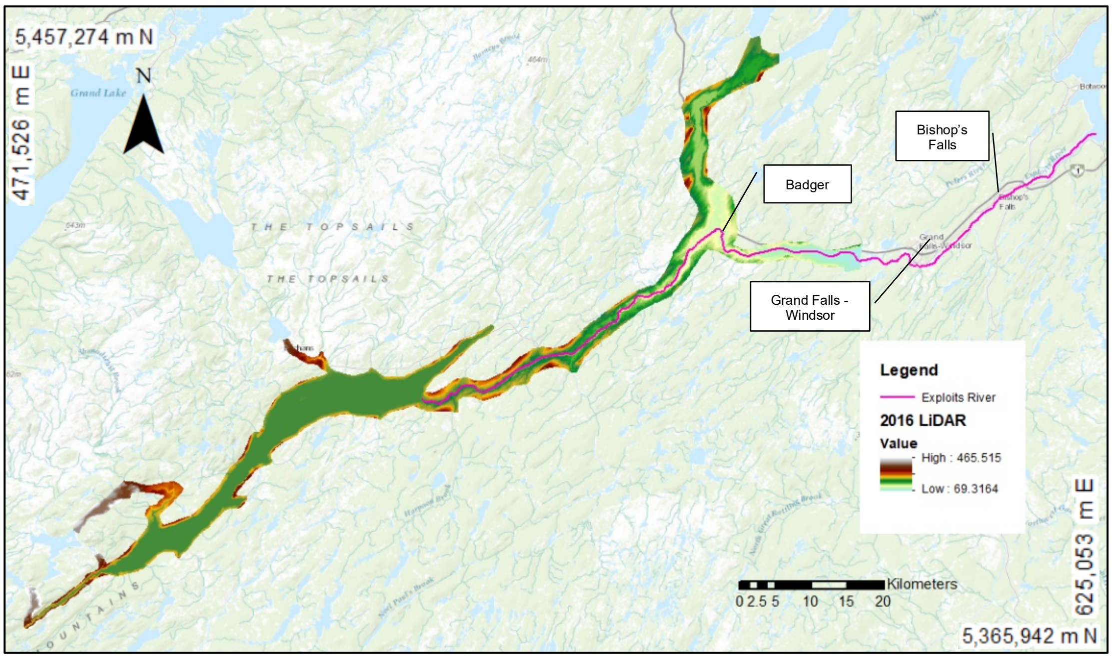

Figure 3-19: 2016 LiDAR DEM

3.3.2 2019 LiDAR Digital Elevation Model and Aerial Photographs

LEG completed a LiDAR survey of the communities of interest for the study area on August 15 and 16, 2019 and delivered a DEM of the area as shown in **Figure 3-20** to Hatch in November, 2019. Elevations range from -0.8 m to 243.3 m. LEG also took aerial photography of the same study area on July 25-26, 2019. LEG's report is provided in **Appendix E**.

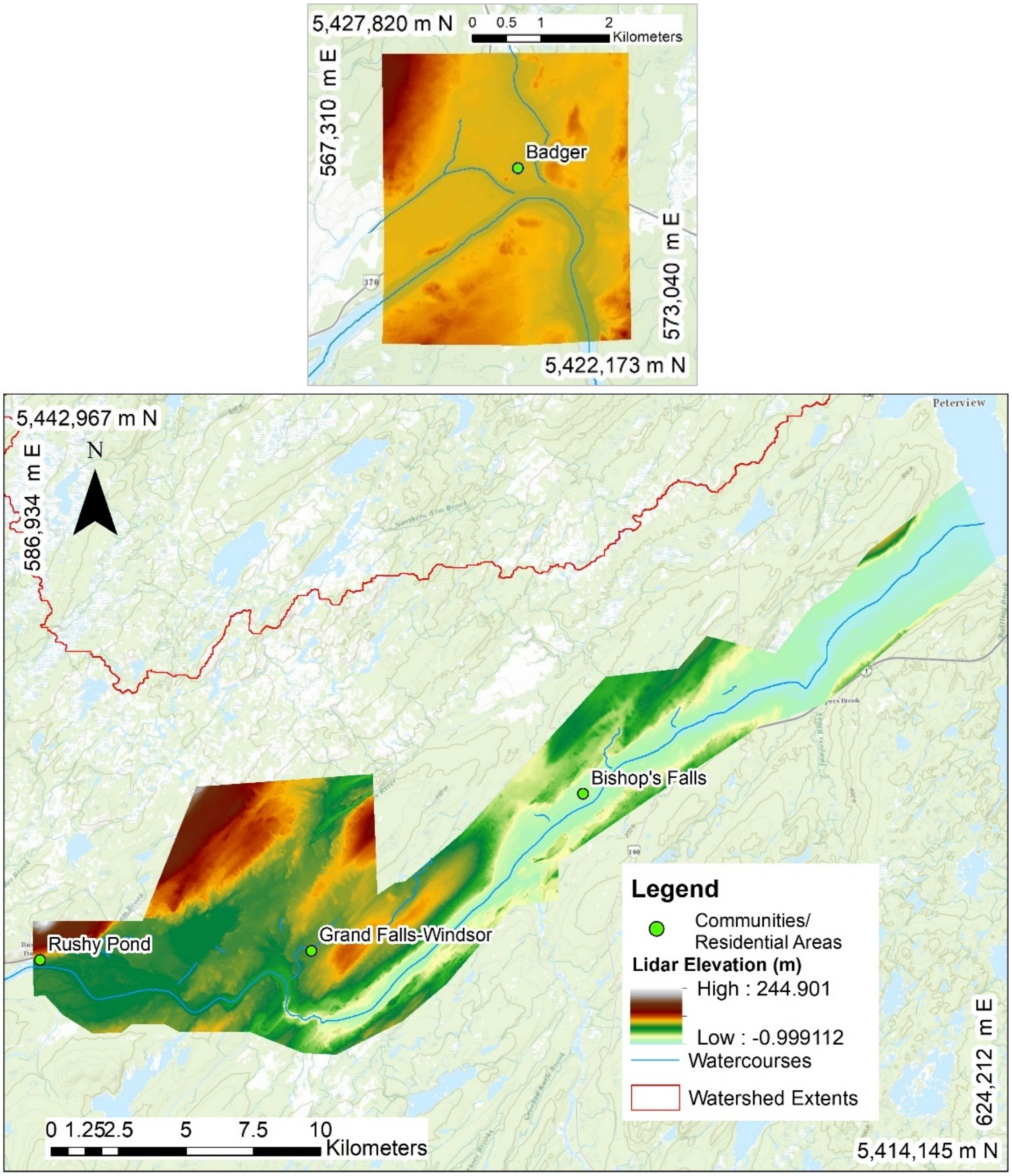

Figure 3-20: 2019 LiDAR DEM

The total size of the acquisition area was about 208 km^2.The flights were spatially positioned using a base station set up over Canadian Base Network station 96G7003 in Grand Falls. 43 lines and two cross strips were flown to get LiDAR coverage. Seven lines were flown to get aerial photo coverage. During the flights, the crew monitored the weather and atmospheric conditions, with acquisition occurring only when no conditions were present that would adversely affect the data collection. The pilot monitored the aircraft course, position, pitch, roll and yaw. The sensor operator monitored the sensor, status of potential error, weather and cloud locations. Where unfavorable conditions affected a flight line, that line was reflown immediately or at a more optimal time.

The LiDAR data was processed using RIEGL's RiProcess suite of software, where it was exported in LAS format, checked, separated into 1 km^2 tiles, classified and checked again. A DEM and 0.25 m contours were produced from this data. The imagery data was developed, triangulated and orthorectified. The images were seamed, colour balanced and separated into 1 km^2 tiles.

The LiDAR vertical Non-Vegetated Accuracy (NVA) was 12.31 cm at a 95% confidence level. This was tested using 101 control points. All control points were tested on non-vegetated surfaces in accordance with federal LiDAR collection guidelines. The LiDAR collection had a 55% overlap between adjacent swaths. The highest point density frequency on non-vegetated surfaces was 10.4 ppm, and the highest point density frequency on vegetated surfaces was 3.5 ppm.

The aerial photograph horizontal accuracy was checked using Real Time Kinematic and/or Fast Static GPS survey points, as well as LiDAR derived check points. The tested Root Mean Square Error (RMSE) was 0.139 m.

The DEM was used in the hydraulic model primarily to determine the cross-section elevations in overbank areas (**Section 6**), and the contours and aerial photography were used in the flood maps (**Section 6.8**).

4. Land Classification Analysis

4.1 Introduction

The Exploits River basin boundaries were set as part of the hydrological modelling work.

Satellite imagery of the entire Exploits River basin was used to organize the basin into different classes, such as waterbodies, forests, pastures and urban areas. This was done using ESRI ArcGIS, a Geographical Information System (GIS) software. For most of the basin, lower-resolution Sentinel-2 satellite imagery could be used because the area has very few people living in it. Sentinel-2 satellite imagery is freely available, but it has a low resolution and shouldn't be used in areas where people are living as it is hard to see the changes in how land is used around groups of houses. In areas where people are living, Hatch bought higher-resolution SPOT-7 data. The accuracy of the classification was checked.

These classes were used in one of the tools (hydrological model) that is part of the flood forecasting system. **Figure 4-1** provides an overview of this section.

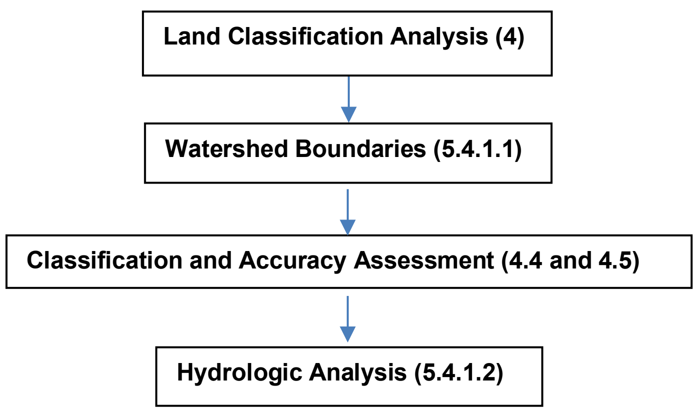

Figure 4-1: Land Classification Section Overview

4.2 Flood Watersheds

The delineation of watershed boundaries is described in **Section 5**. The 48 drainage sub-basins that were analyzed in this study form a continuous area with no overlap or gaps between sub-basins. As the remote sensing activity was conducted in parallel with the development of the watersheds, initial watershed boundaries were buffered by 20 km to ensure that the land cover classification data provided full coverage for the watershed.

4.3 Imagery and Data Sources

The land cover classification was completed using high-resolution optical satellite imagery acquired by Hatch. The majority of the study area was analyzed using Sentinel-2 satellite imagery, which is freely available from the European Space Agency. Sentinel-2 imagery is collected frequently, with a new set of imagery available every five days between the two satellites (Sentinel-2A and Sentinel-2B). The Sentinel-2 imagery offers 13 spectral bands of information, each with varying resolutions. Four of the bands (red, blue, green and near infrared) have a resolution of 10 m, six bands have a resolution of 20 m (various vegetation red edge, short wave infrared, coastal aerosol, water vapour) and the remaining three bands have a resolution of 60 m.

The imagery was acquired during the peak of the vegetation period (July 14, 2018) for a period with little cloud cover. Four imagery sets were used to minimize the areas obstructed by cloud cover. An image of the area was produced using the visible light bands from the Sentinel-2 imagery (B2, B3 and B4), but other combinations of the 12 bands (B1 to B12) were combined to help delineate the various areas. Multiple tiles were stitched together to create two orthorectified and mosaicked images of the whole study area. Due to the size of the study area, it was necessary to compile the Sentinel-2 data into two mosaics representing the east and west sides of the study area . Sentinel-2 images were delivered orthorectified in both JPEG and full resolution GEOTIFF formats.

In the urban areas where increased resolution was required, SPOT 7 imagery (acquired on August 1, 2018) with a 0.5 m resolution was purchased by Hatch from Harris Geospatial. This imagery consisted of previously orthorectified datasets of 10 m accuracy including fused (1.5 m panchromatic sharpened) and 6.0 m 4-band multispectral imagery. The data was provided in GEOTIFF format. Two SPOT 7 mosaics were created with a total area of 117.2 km^2: one over Badger, and one over the Grand Falls-Windsor, Rushy Pond and Bishop’s Falls areas. The imagery coverage extents are shown in **Figure 4-2**.

The multispectral imagery was used for training and classification, while additional layers were used for points of reference.

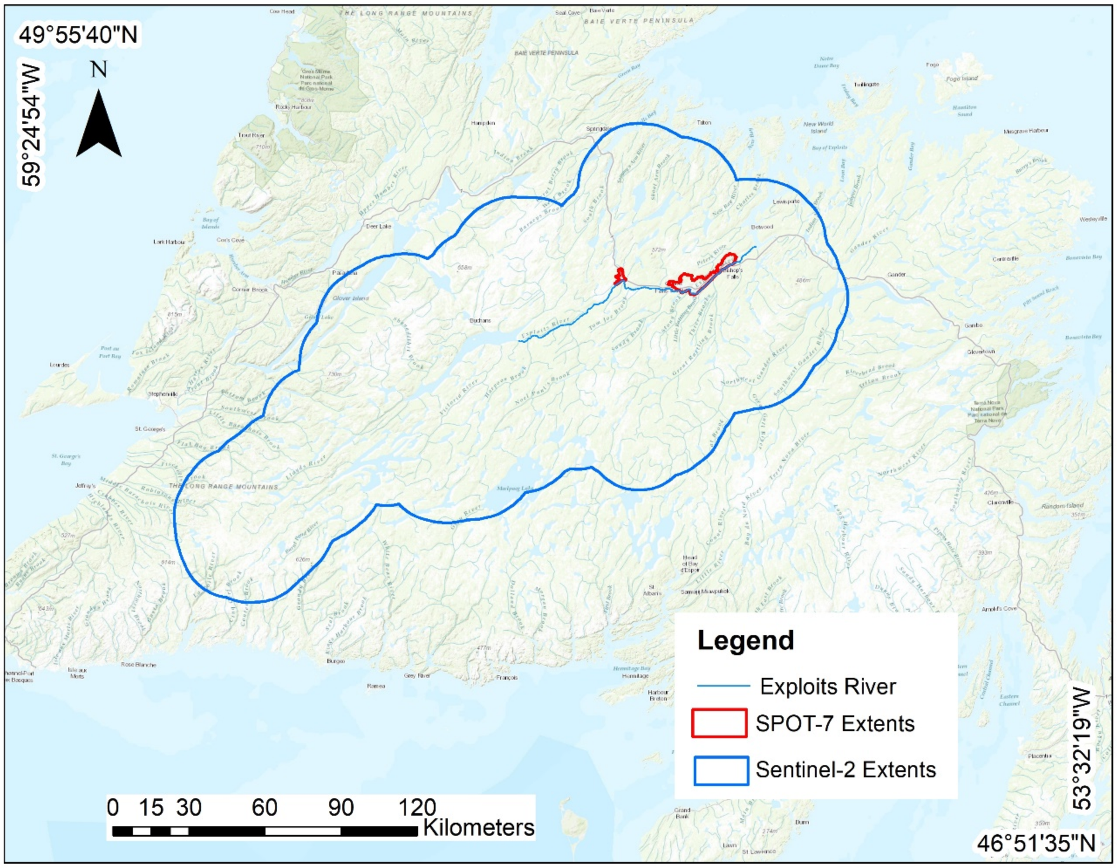

Figure 4-2: Imagery Coverage

4.4 Classification Methodology

4.4.1 Methodology

A supervised classification was performed using ESRI ArcMap by developing "training areas" for each of the land cover classifications listed in **Table 4-1**. These "training areas" were drawn in areas where the land classification was known. This included some of trial and error to get the best land cover delineation. Land cover classification was performed through a multi-step process outlined below and shown in **Figure 4-3**:

- Image preprocessing and mosaic production.
- ISO cluster unsupervised classification and aggregation.
- Classification corrections and manual edits.
- Land cover tabulations.
- Accuracy assessment (summarized in **Section 4.5.2**).

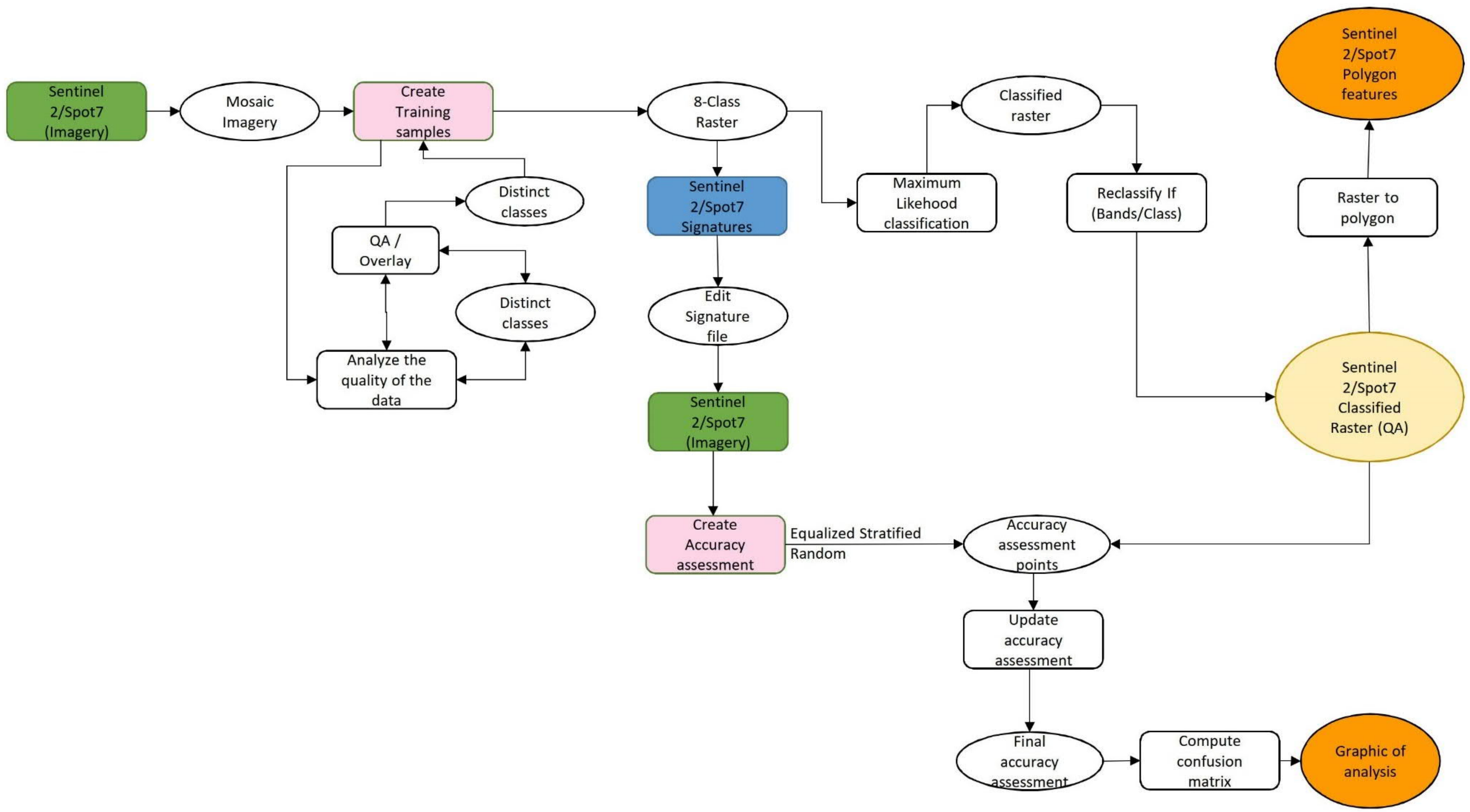

Figure 4-3: Graphical Model of Land Cover/Land Use Classification Methods Used in this Study

4.4.2 Land Cover Classification Categories

The land cover classifications were assigned using eight classes as shown in **Table 4-1**, based on those specified by WRMD. The Urban Area classification included both residential and commercial areas as it was found to be impractical to separate residential from commercial land use; a similar approach was taken by AMEC (2015). Waterbodies and swamps/wetlands were identified separately in this analysis.

Table 4-1: Land Cover Classification

Land Cover Class	Examples
Barren land	Non-vegetated areas.
Deforested areas	Patches of treed and un-treed areas adjacent to forest roads, areas with open green fields in forested zones.
Fields/pastures/open spaces	Agricultural areas, farmer fields; parks, cemeteries, golf courses, etc. within urban area, low lying grass areas near airport, vegetated areas.
Forest	Forests.
Urban Area	Small homes and subdivisions. Large building and parking lots, schools, shopping malls, industries, plants, etc.
Unclassified	No data, cloud, shadow, snow/ice.
Waterbodies	Lakes, ponds, and rivers.
Swamps/wetlands	Swamps; wetlands.

4.4.3 Classification and Aggregation

Either supervised or unsupervised classification methods can be used to classify a multi-band raster image. Spectral signatures, also known as reflectance values, are used in the supervised classification method. These are obtained from training samples, which are polygons that represent a distinct sample area of each land cover type to be classified. These samples are defined by the GIS analyst to classify the image.

The unsupervised classification method allows the software to find the spectral classes, also called clusters, in the multi-band image without the GIS analyst’s intervention without supervision. The GIS analyst then needs to identify what each cluster represents, such as water, bare earth or dry soil. The ESRI Spatial Analyst toolset is used to create training samples and signature files. A signature file is used in supervised classification to record the spectral signatures of different classes across a series of bands. The signature file also provides a central location to conduct supervised and unsupervised classifications.

4.4.4 Manual Corrections and Final Land Cover

Scatterplots representing each training sample were compared to ensure that the training samples are properly defined. A total area of 9,468.55 ha was used in the training areas.

Initial results were converted to polygon shapefiles and reviewed. Where obvious errors were identified, pixels were manually assigned to the correct class. This was mostly performed in barren land, deforested area and open spaces. Datasets were incorporated after verifying the alignment with original imagery (Sentinel-2 or SPOT 7). The spatial analyst tool was used to refine and clean the data by reducing single pixel classification results. This algorithm reclasses land cover data to their probabilistically more correct class as shown in the figure below by smoothing the boundary between zones. For urban area features, the land cover classification was reviewed with the higher resolution SPOT 7 data.

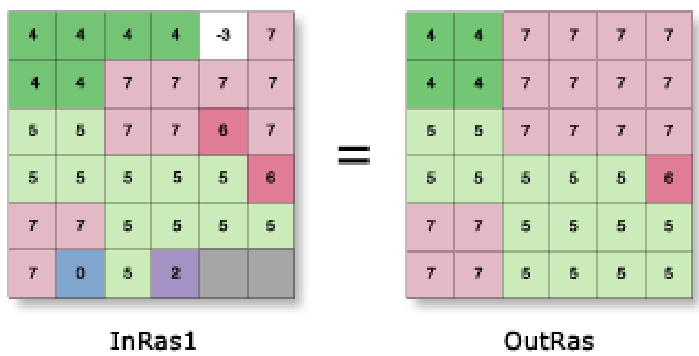

Figure 4-4: Boundary Smoothing (Image courtesy of ESRI)

4.5 Results and Accuracy Assessment

4.5.1 Results

Overall classification results are presented in **Table 4-2** and **Table 4-3** with the overall land classification shown for the project area on **Figure 4-5**. It should be noted that the total land cover area in **Table 4-2** is significantly greater than the watershed area of 11,000 km^2 because the watershed boundaries were buffered by 20 km to ensure that the land cover classification covered the entire project area.

Table 4-2: Sentinel-2 Land Cover Metrics

<table>
<tr><th>Land Cover Class</th><th colspan="2">Land Cover (km^2)</th><th>% Area</th></tr>
<tr><td>Barren Land</td><td colspan="2">762</td><td>3</td></tr>
<tr><td>Deforested Areas</td><td colspan="2">1,035</td><td>4</td></tr>
<tr><td>Fields/Pastures/Open Spaces</td><td colspan="2">6,237</td><td>24</td></tr>
<tr><td>Forest</td><td colspan="2">7,186</td><td>28</td></tr>
<tr><td>Waterbodies</td><td>2,459</td><td rowspan="2">9,101</td><td rowspan="2">35</td></tr>
<tr><td>Wetlands</td><td>6,643</td></tr>
<tr><td>Unclassified</td><td colspan="2">1,835</td><td>7</td></tr>
<tr><td>**Total**</td><td colspan="2">**26,156**</td><td>**100**</td></tr>
</table>

Table 4-3: SPOT 7 Land Cover Metrics

<table>
<tr><th>Land Cover Class</th><th colspan="2">Land Cover (km^2)</th><th>% Area</th></tr>
<tr><td>Barren Land</td><td colspan="2">0.17</td><td>0.1</td></tr>
<tr><td>Fields/Pastures/Open Spaces</td><td colspan="2">20</td><td>17.4</td></tr>
<tr><td>Forest</td><td colspan="2">53</td><td>45.3</td></tr>
<tr><td>Urban Area</td><td colspan="2">21</td><td>18.3</td></tr>
<tr><td>Waterbodies</td><td>8</td><td rowspan="2">22</td><td>6.8</td></tr>
<tr><td>Wetlands</td><td>14</td><td>12.1</td></tr>
<tr><td>**Total**</td><td colspan="2">**117**</td><td>**100.0**</td></tr>
</table>

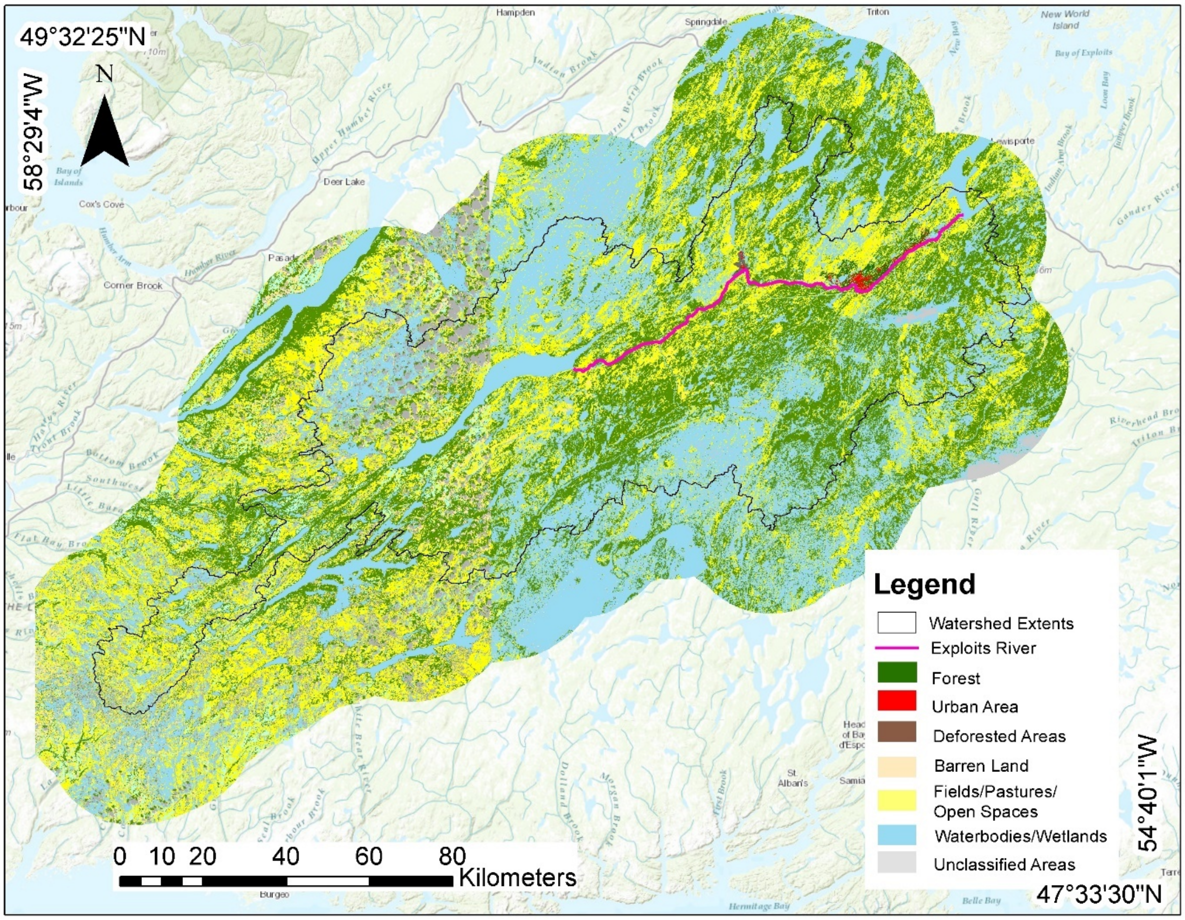

Figure 4-5: Land Cover Classification

4.5.2 Accuracy Assessment

An accuracy assessment was completed to measure the effectiveness of the land classification exercise for both the Sentinel-2 and SPOT 7 imagery. The accuracy assessment was done for each of the two Sentinel-2 and two SPOT 7 mosaics due to the different levels of detail in each mosaic.

The accuracy assessment was conducted by comparing ESRI base imagery with the classified land cover at each assessment point as shown in **Figure 4-6**.


Base Imagery (Variable Resolution)


Sentinel-2 (20 m Resolution)

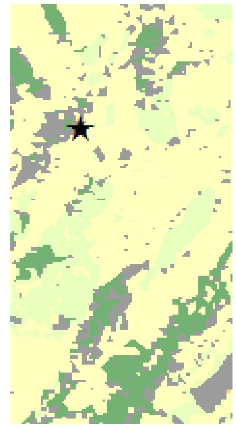
Classification Land Cover (20 m Resolution)

Figure 4-6: Base Imagery, Sentinel-2 and Classified Land Cover Example

4.5.2.1 Methodology

50 points per class were distributed randomly throughout each imagery type, with the exception of 25 points distributed for the Unclassified class. This resulted in a total of 325 points for the Sentinel-2 mosaics, and 300 points for each of the SPOT 7 mosaics as no unclassified data was present in the SPOT 7 mosaics.

These points were assessed as to whether the assigned land cover matched the land cover shown on base imagery. The urban class points defined using the SPOT 7 imagery were carefully reviewed given the level of interpretation involved in identifying these classification results; features may be interpreted differently on Sentinel-2 imagery.

4.5.2.2 Results

Table 4-4, **Table 4-5** and **Table 4-6** present a “standard error” or “confusion matrix” based on the land cover at the location of each point. The columns represent the classified land cover for each point; there are 50 for each class with the exception of 25 for the unclassified class. These were distributed randomly over each class. The rows represent the ground truthing results showing the class for each point as determined with the base imagery. The values in green along the diagonal show the agreement between the ground truth and classified values.

For example, out of the 50 points classified as “Forest” in the Sentinel-2 land classification exercise, 47 of them were confirmed during ground truthing to have been correctly identified as “Forest”. One of the remaining three points was found to have been in the “Deforested Area” class, one in the “Fields/Pastures/Open Spaces” class, and one in the “Wetland” class. In addition, there were three points in the “Deforested Areas” class, three in the “Unclassified” class and one in the “Wetland” class which should have also been classified as “Forest”.

Overall, the 238 of the 325 Sentinel-2 points were correctly classified, resulting in an overall accuracy of 73%.

One accuracy assessment was conducted for each SPOT 7 mosaic, with 262 and 260 of the total 300 points correctly classified, respectively. This resulted in overall accuracies of 87.3% and 86.7%. The SPOT 7 imagery was divided into two areas: the west side of the study area over Badger, and the east side of the study area over Grand Falls-Windsor and Bishop's Falls.

Table 4-4: Sentinel-2 Accuracy Assessment

	Barren Land	Deforested Area	Fields/Pastures/ Open Spaces	Forest	Unclassified	Waterbodies	Wetland	**Total**	Accuracy
Barren Land	32	0	0	0	0	0	1	**33**	97.0%
Deforested Area	0	29	4	1	0	0	1	**35**	82.9%
Fields/Pastures/Open Spaces	12	14	38	1	1	0	5	**71**	53.5%
Forest	0	3	0	47	3	0	1	**54**	87.0%
Unclassified	6	2	4	0	4	0	2	**18**	22.2%
Waterbodies	0	0	0	0	8	49	1	**58**	84.5%
Wetland	0	2	4	1	9	1	39	**56**	69.6%
Total	**50**	**50**	**50**	**50**	**25**	**50**	**50**	**325**	
Accuracy	64.0%	58.0%	76.0%	94.0%	16.0%	98.0%	78.0%		

SUM of diagnosis (corrects)	238
N (Total Points Assessed)	325
Overall Accuracy	73.2%

Table 4-5: SPOT 7 Accuracy Assessment - West

	Barren Land	Fields/Pastures/ Open Spaces	Forest	Urban Areas	Waterbodies	Wetland	**Total**	Accuracy
Barren Land	33	0	0	1	0	0	**34**	97.1%
Fields/Pastures/Open Spaces	7	40	0	4	0	1	**52**	76.9%
Forest	0	6	50	0	0	1	**57**	87.7%
Urban Areas	8	1	0	45	0	2	**56**	80.4%
Waterbodies	0	0	0	0	48	0	**48**	100.0%
Wetland	2	3	0	0	2	46	**53**	86.8%
Total	**50**	**50**	**50**	**50**	**50**	**50**	**300**	
Accuracy	66.0%	80.0%	100.0%	90.0%	96.0%	92.0%		

SUM of diagnosis (corrects)	262
N (Total Points Assessed)	300
Overall Accuracy	87.3%

Table 4-6: SPOT 7 Accuracy Assessment - East

	Barren Land	Fields/Pastures/ Open Spaces	Forest	Urban Areas	Waterbodies	Wetland	**Total**	Accuracy
Barren Land	27	0	0	0	0	0	**27**	100.0%
Fields/Pastures/Open Spaces	1	35	0	0	0	0	**36**	97.2%
Forest	0	1	50	0	0	0	**51**	98.0%
Urban Areas	19	4	0	50	0	2	**75**	66.7%
Waterbodies	0	0	0	0	50	0	**50**	100.0%
Wetland	3	10	0	0	0	48	**61**	78.7%
Total	**50**	**50**	**50**	**50**	**50**	**50**	**300**	
Accuracy	54.0%	70.0%	100.0%	100.0%	100.0%	96.0%		

SUM of diagnosis (corrects)	260
N (Total Points Assessed)	300
Overall Accuracy	86.7%

It is important to note that this accuracy assessment was conducted with an equal number of points given to each class, and therefore it is not representative of the overall accuracy of the land classification data. For example, the accuracy in the tables above for the “Barren Land” class is in the order of 54% to 66%. However, “Barren Land” represents less than 3% of the entire study area and therefore is not as significant in the overall accuracy of the entire classification exercise. It should also be noted that the “Barren Land” class is a highly interpretive class with results that may be viewed differently between users and producers of remote sensing data. Many impervious features were mistakenly represented as “Barren land” in this schema; however, soil curve numbers tend to be very similar between deforested area and barren land (soil type dependent) features. **Figure 4-7**, **Figure 4-8** and **Figure 4-9** show the classes proportionally by the area of watershed. **Figure 4-8** and **Figure 4-9** show the classes in the west and east sides, respectively. The column height represents the total area of the soil classification as a percentage of the watershed. The orange portion of the column represents the portion that was incorrectly classified. This factor tends to make these lower accuracy results slightly less significant. An equal number of points was set to avoid prioritizing one class over another and to have consistent results between classes. The results obtained give a complementary analysis showing the obtained results versus the percentage of each class's area.

In contrast, the accuracy results for Forest and Waterbodies were very high for all three accuracy assessments, and these combined classes represent 37% and 61% of the Sentinel-2 and SPOT 7 data, respectively. In **Table 4-4**, **Table 4-5** and **Table 4-6**, Water and Forest generally have the highest accuracy, while non-forest vegetation and barren land classes have the lowest.

Of the 50 accuracy assessment points falling on areas classified as barren land in **Table 4-4**, 32 were verified as barren land, 12 were fields, pasture and open spaces, and six were unclassified (64% correct). When the accuracy is plotted as a function of the area in **Figure 4-7** below, the relative significance of these results is apparent. **Figure 4-7**, **Figure 4-8** and **Figure 4-9** help to ensure that the accuracy of a given classification is not misrepresented.

It is also evident from **Figure 4-7**, **Figure 4-8** and **Figure 4-9** that the accuracy increases greatly with the SPOT 7 imagery. However, due to the size of the watershed, the remote areas represented by the Sentinel-2 imagery produce a sufficient and reasonable land cover classification.

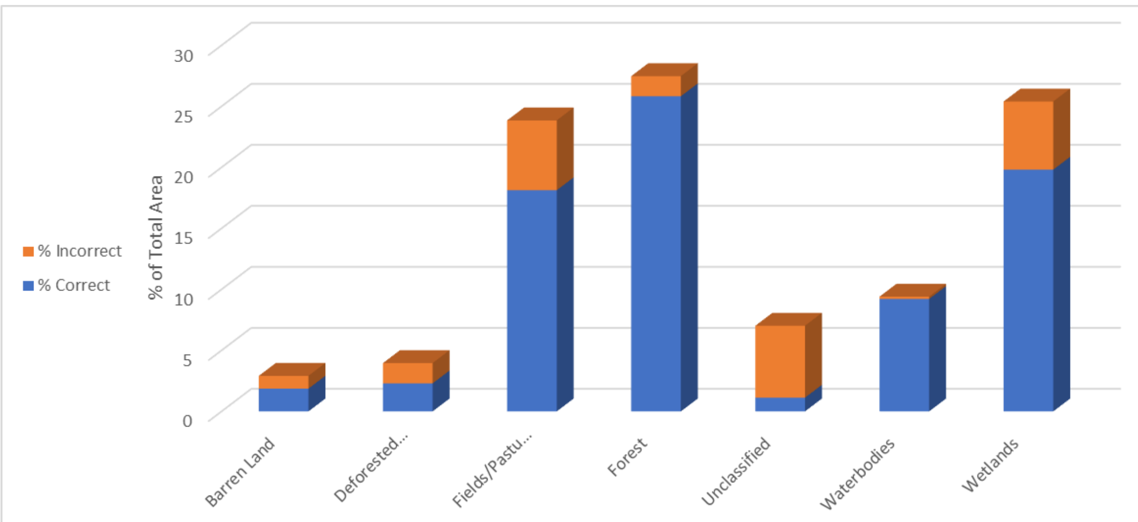

Figure 4-7: Land Cover Classification Sentinel-2 by Area of Class

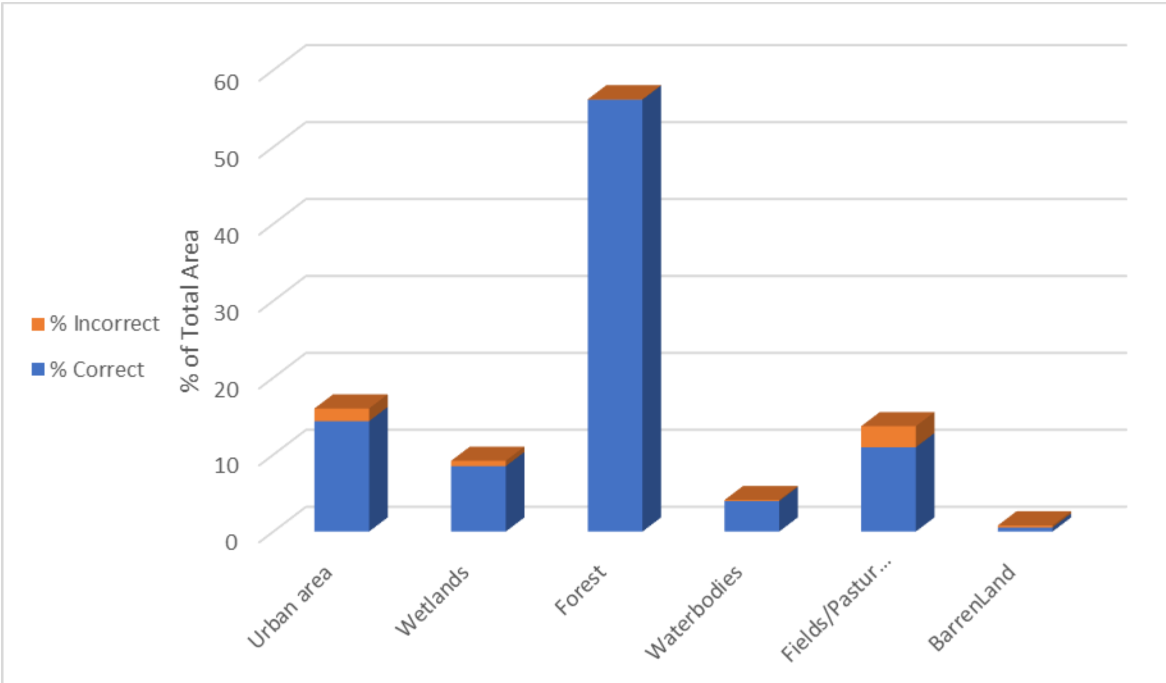

Figure 4-8: Land Cover Classification SPOT 7-West by Area of Class

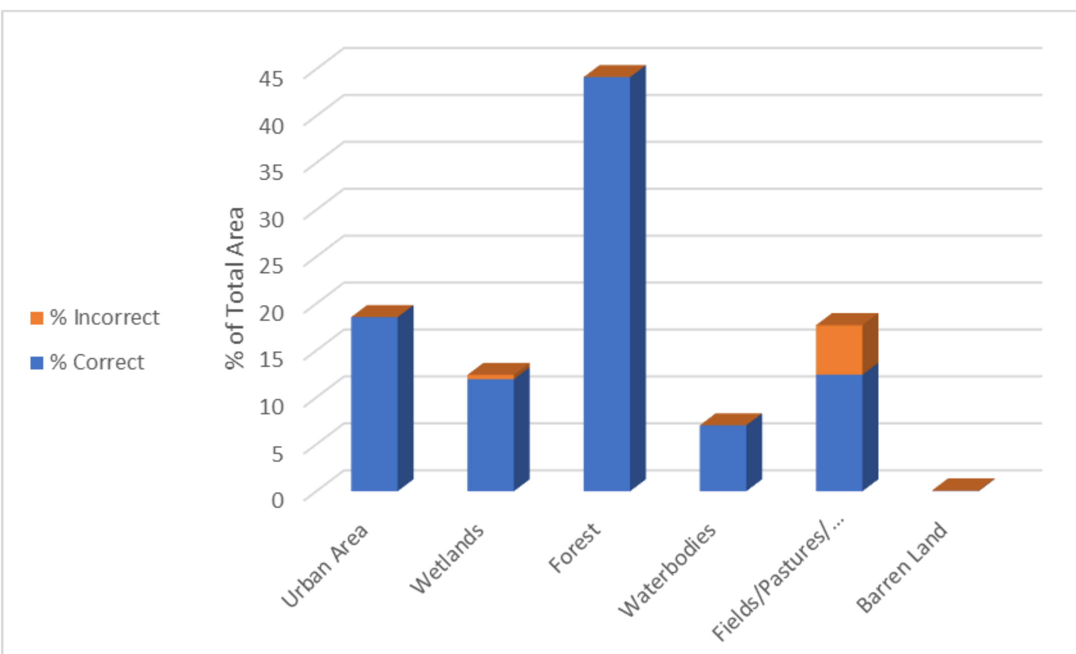

Figure 4-9: Land Cover Classification SPOT 7-East by Area of Class

4.6 Land Classification Conclusions and Recommendations

In conclusion, given the large size of the watershed, the ground cover analysis has a good success rate and is adequate for the purposes of this study. In urban areas where future development will affect the runoff potential, higher accuracy with very good quality control is achieved with the SPOT 7 data.

5. Hydrological Analysis

5.1 Introduction

Hydrology studies how water falls from the sky as rain or snow, and then how it seeps into the ground and evaporates back into the atmosphere. The extra water that does not seep into the ground or evaporate runs over the ground and into streams and rivers.

The goal of the hydrological analysis was to estimate how much water flows into the Exploits River and other streams during the 1:20 and 1:100 annual exceedance probability (AEP) floods. Two different ways were used to estimate the amount of water: a deterministic model and a stochastic analysis.

The deterministic model is a computer program that simulates how the rain and snow that falls on the Exploits River basin is converted to flows in the Exploits River and the streams which feed into it. It is called a deterministic model because the results are determined by the model inputs and the conditions used at the start of the model run. The deterministic model was built using the U.S. Army Corps of Engineers (USACE) HEC-HMS (Hydrologic Engineering Center - Hydrologic Modelling System) software which is a tool that is commonly used for this type of analysis. The physiography, or physical geography, of the watershed determines how rainfall and snowmelt move over the land into streams and rivers. The physiographic characteristics of the Exploits River area were developed using Geographical Information System (GIS) tools. The watershed boundary was drawn and the Digital Elevation Model (DEM) showing ground surface elevations across the watershed was built. The stream network in the watershed was drawn, and the soil type and land use types in the watershed were set.

Intensity-Duration-Frequency (IDF) curves were used to find out how much rain has fallen in storms that have occurred in the past in this area. Historic rainfall and snow information in the Exploits River basin was collected to calibrate the model. Calibration was done to make sure that the model was set up properly. Rain and snow amounts which led to major flood events in the past were input into the model. The flows that the model produced were compared to the flows that really happened. The model settings were adjusted until the flow amounts that the model produced (simulated runoff) were similar to the flows that were measured at hydrometric stations situated along the river (observed runoff). The model was then said to be calibrated and useful for predicting floods in the future. Using the model, estimates of 1:20 and 1:100 AEP rainfall from the IDF curves were converted into estimates of 1:20 and 1:100 AEP floods.

The stochastic analysis was done by looking at available measurements of floods which happened in the past on the Exploits River and other rivers in the area. Five gauges along the Exploits River were used to estimate the 1:20 and 1:100 AEP floods using a method called the single station flood frequency analysis (SSFFA). The 1:20 and 1:100 AEP floods had also been estimated using a method called the regional flood frequency analysis (RFFA).

The RFFA uses a number of gauges on rivers that are about the same size as the Exploits River and the streams which flow into it. Hatch updated these RFFA results with more recent streamflow data and were used to estimate the peak flows on the Exploits River and 13 of its tributaries. The peak flows from the SSFFA and RFFA were compared.

Finally, the floods from the deterministic model and the stochastic analysis were compared in order to choose the best way to estimate the 1:20 and 1:100 AEP floods in the Exploits River and the streams that flow into it.

Climate change and future development in the communities may have an impact on the amount of water that flows into the streams and rivers. The larger future floods that are expected to have a 5% chance of happening each year (1:20 AEP) and a 1% chance of happening each year (1:100 AEP) from climate change and future development were calculated.

These flows will be used in the hydraulic models to make flood risk maps. The deterministic model will be an important part of the flood forecasting service. **Figure 5-1** gives an overview of the section structure and layout.

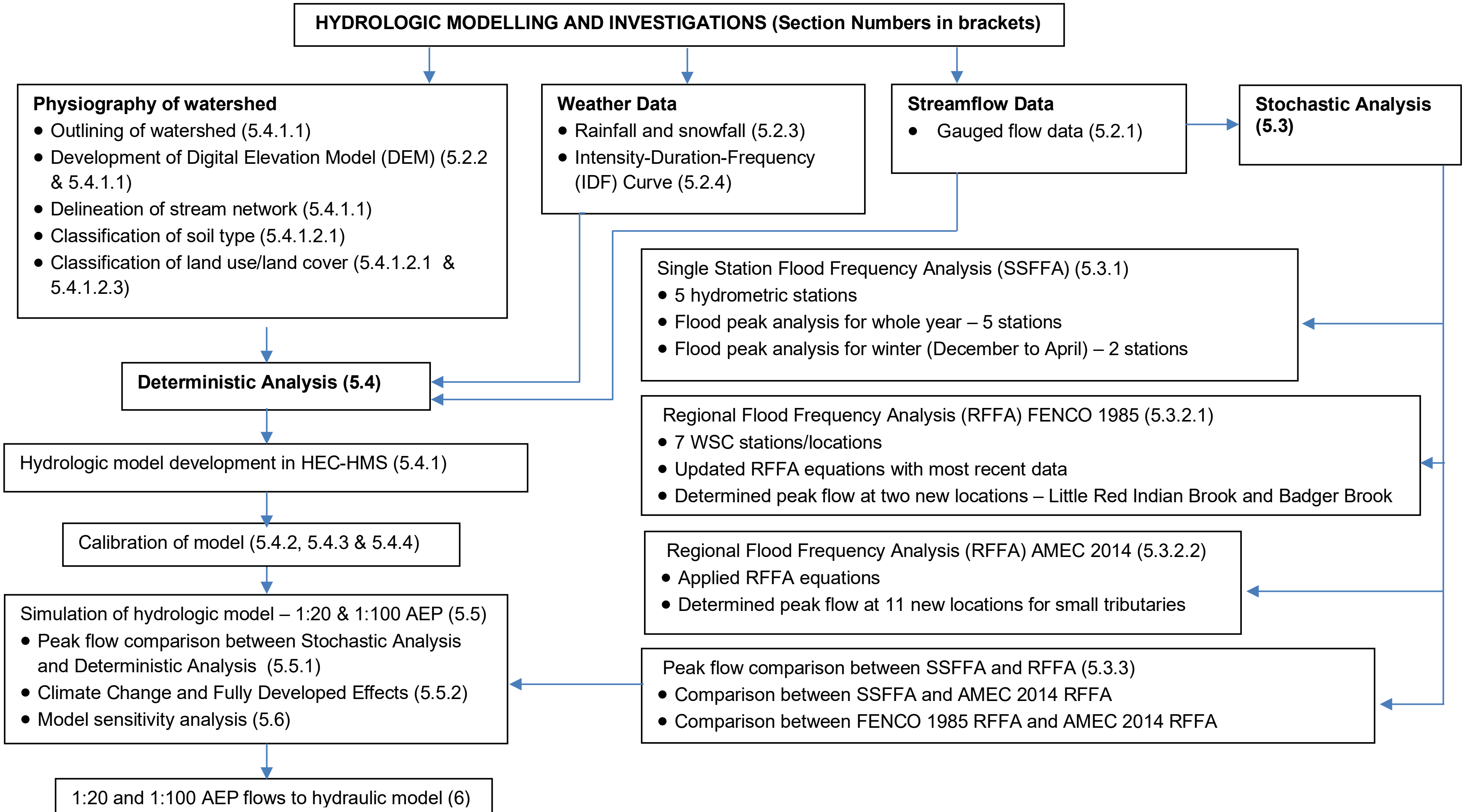

Figure 5-1: Hydrological Analysis Section Overview

5.2 Data Collection

Prior to undertaking the hydrologic analysis, it was necessary to collect relevant information from the watershed and study area. This data is summarized in the sections that follow.

5.2.1 Streamflow Records

Flow and water level measurement data in and around the Exploits River watershed was retrieved from WSC records. Selected records were used to calibrate the model output, to aid in determining average basin yield estimates for the ungauged portions of the watershed, and for deriving the statistical estimates of flood peaks. The records of interest included active WSC hydrometric gauges, as well as inactive gauges with records suitable for calibrating the model to historical events. The selected streamflow gauges are found in **Table 5-1** and **Figure 5-2**. A WRMD/WSC gauge on Badger Brook is also included in the table and figure for reference. Data from this gauge was not used in this study as it was only installed in 2018. Outflow is also measured independently by Nalcor at Millertown Dam and at Grand Falls Dam; these records were used where gaps existed in WSC data. The SSFFA and the RFFA used instantaneous peak flow data. The winter flood analysis, HEC-HMS modeling and the flow duration curve analysis used mean daily flow data.

Table 5-1: Hydrometric Gauges Used in Hydrologic Analysis

Gauge ID	Gauge Name	Active?	Latitude (°N)	Longitude (°W)	WSC Drainage Area (km^2)	Record Period
02YK002	Lewaseechjeech Brook at Little Grand Lake	Y	48.62	57.93	470	1952-Present
02YK008	Boot Brook at Trans-Canada Highway	Y	49.27	57.10	20	1985-Present
02YN002	Lloyds River Below King George IV Lake	Y	48.24	57.83	469	1981-Present
02YN004	Star Brook Above Star Lake	Y	48.63	57.31	276	2000-Present
02YO001	Exploits River At Grand Falls	N	48.93	55.67	8,390	1944-2010 (see note 2)
02YO004	Sandy Brook At Sandy Brook Powerhouse	N	48.89	55.82	508	1964-2010
02YO005	Exploits River Below Stony Brook	N	48.92	55.66	8,640	1968-1996
02YO006	Peters River Near Botwood	Y	49.10	55.40	177	1981-Present
02YO007	Leech Brook Near Grand Falls	N	48.95	55.83	88	1984-1996
02YO008	Great Rattling Brook Above Tote River Confluence	Y	48.83	55.53	773	1984-Present
02YO010	Junction Brook Near Badger	N	48.98	56.02	62	1985-1997
02YO011	Exploits River Below Noel Pauls Brook	Y	48.84	56.27	6,300	1985-Present
02YO012	Southwest Brook at Lewisporte	Y	49.22	55.05	59	1989-Present
02YO013	Exploits River At Badger	Y	48.97	56.03	6,620	2004-Present
02YO014	Tributary to Gill's Pond Brook	Y	48.64	56.53	8	2006-Present
02YO016	Exploits River Near Millertown	Y	48.76	56.58	4,810	2007-Present
02YO018	Exploits River At Charlie Edwards Point	Y	48.94	55.79	7,810	2009-Present
02YO019	Badger Brook Below Foot Bridge	Y	48.98	56.03	717 (see note 1)	2018-Present
02YP001	Shoal Arm Brook Near Badger Bay	N	49.37	55.81	64	1982-1997

Notes:
1. Drainage area for 02YO019 taken from hydrologic DEM. All others taken from WSC metadata.
2. Extended to 2018 using Nalcor record at Grand Falls Generating Station.

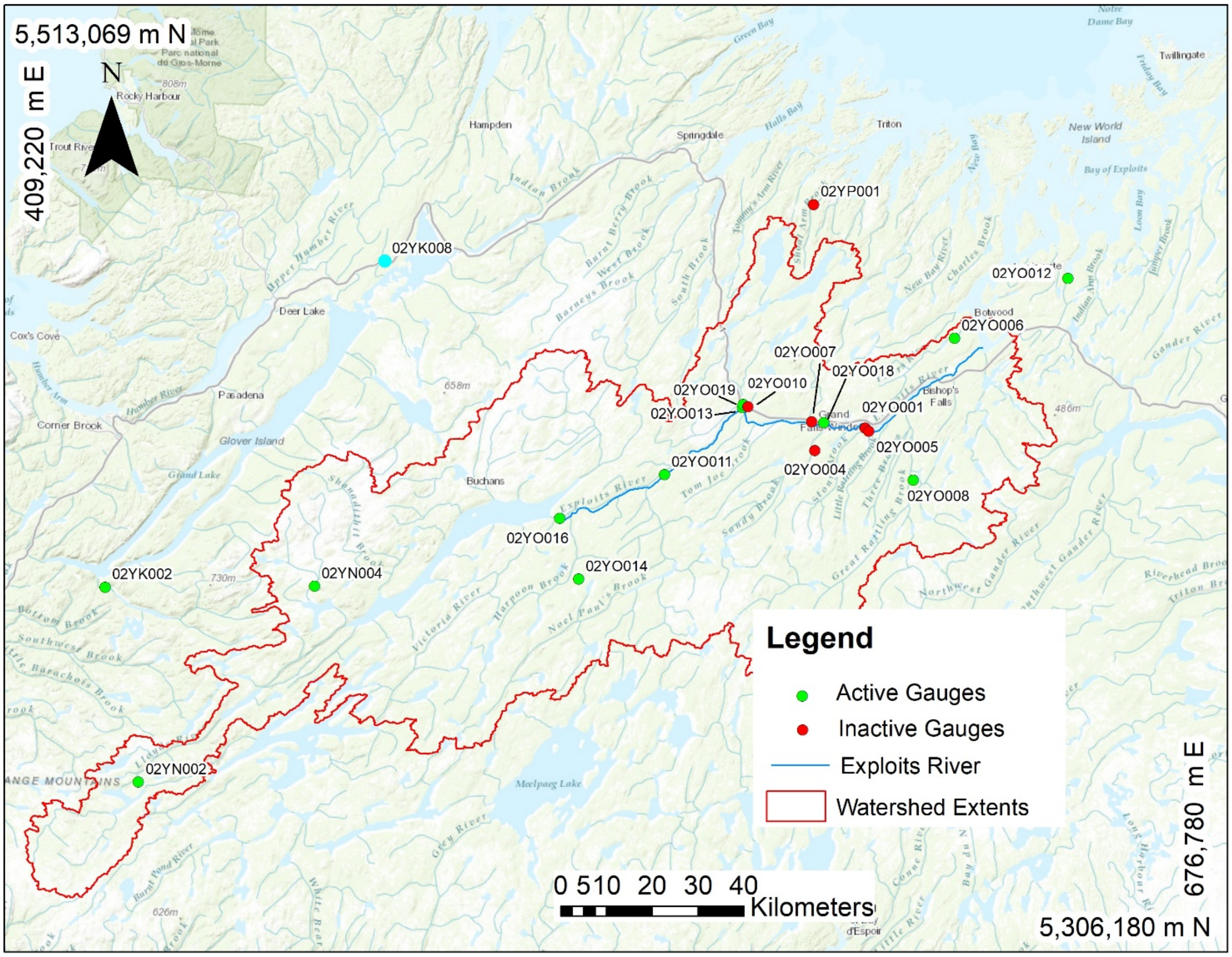

Figure 5-2: Hydrometric Gauges Used in Hydrologic Analysis

5.2.2 *Digital Elevation Model*

A DEM of the watershed was created from the Canadian Digital Surface Model (CDSM), which is produced by Natural Resources Canada. The CDSM is based on one-arc-second Shuttle Radar Topography Mission (SRTM) information and has been sampled to a 0.75-arc-second resolution resulting in a raster cell size of about 20 m with vertical accuracy of 5.5 m. The DEM around the minor tributary B-1 in the Badger area was supplemented with previously-acquired LiDAR data from Nalcor's Exploits River Flood Study (Hatch 2017), due to the need to enhance the DEM in this area for sub-basin delineation.

The elevation of the DEM ranged from approximately 0 m (near the Bay of Exploits) to 700 m (in the Long Range Mountains, along the western edge of the watershed). The watershed DEM is shown in **Figure 5-3**.

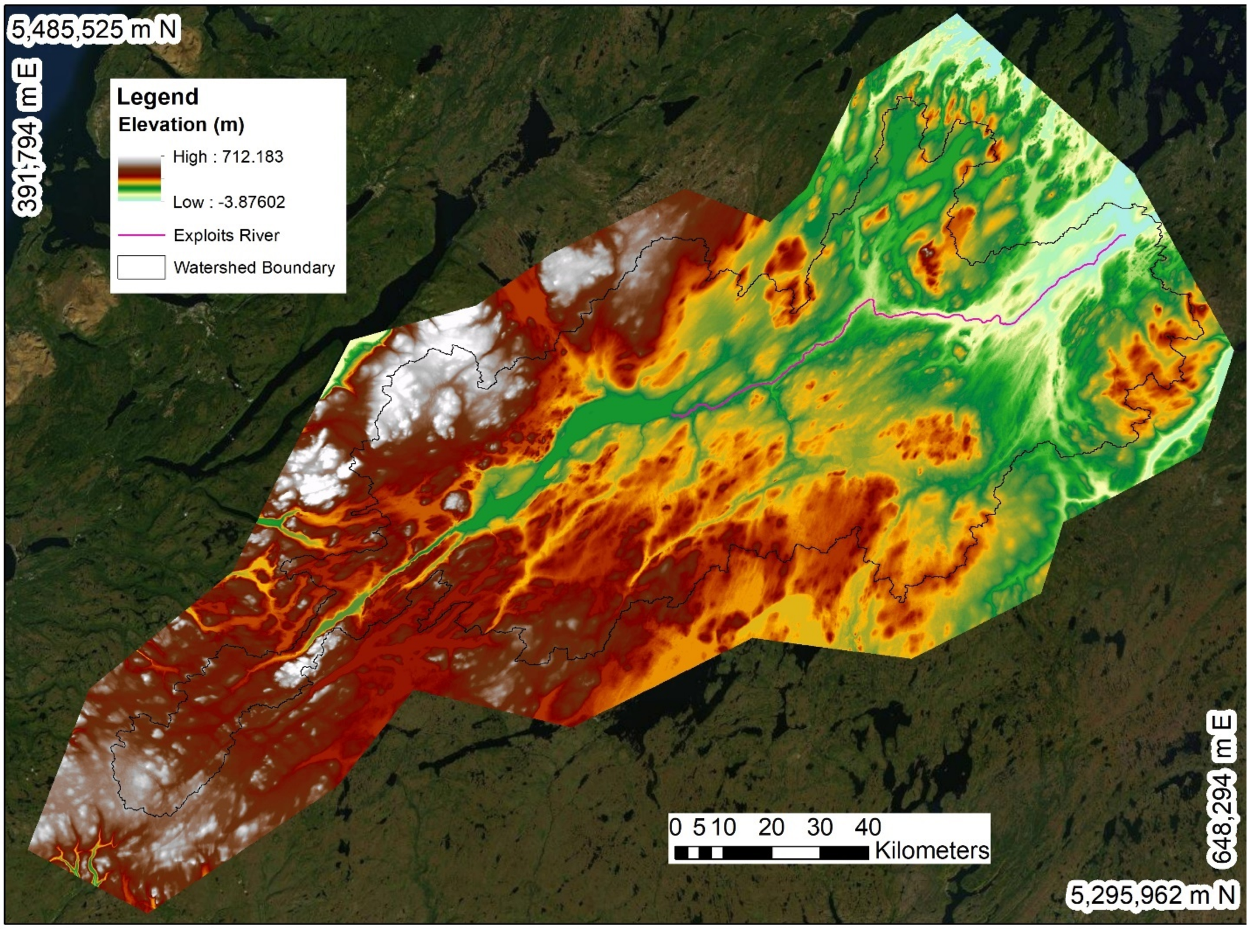

Figure 5-3: Watershed DEM

5.2.3 Meteorological Data

Precipitation and temperature data was obtained from Environment Canada records. A total of 26 climate stations were used in the calibration and validation activities as shown in **Figure 5-4** and **Table 5-2**.

All stations are operated by Environment Canada, with the exception of the WRMD climate station Granite Lake at East End, which was used for the 2016 and 2018 calibration events. At Millertown Dam, there was a five-year gap between the end of station record 8401550 ("Exploits Dam") in 2008 and the start of station record 8402757 ("Millertown RCS") in 2013. Data for this intermediate period was infilled by using temperature and precipitation observations obtained from Nalcor Energy.

In an attempt to increase the runoff produced by the Hurricane Igor calibration event in 2010, rainfall from additional stations was used for this event.

For the 1983 precipitation event, 6-hour precipitation readings at meteorological stations were used as summarized in the Environment Canada and Government of Newfoundland and Labrador report "The Flood of January 1983 in Central Newfoundland" (1985).

Calibration event precipitation and temperature data was available in point data format, however, the HEC-RTS software to be used for the flood forecasting system uses gridded data. Therefore, the deterministic hydrologic model required meteorological data such as precipitation, temperature and snow water equivalent (SWE) to be obtained in gridded formats or otherwise converted to gridded format. The USACE program GageInterp was used to interpolate between precipitation and temperature point data to develop gridded files that could be read by HEC-HMS. For Hurricanes Igor and Matthew in 2010 and 2016, historical gridded precipitation data from the Canadian Precipitation Analysis (CaPA) system was available and was obtained from Environment Canada by special request to better capture the spatial distribution of the precipitation over the watershed during the storm.

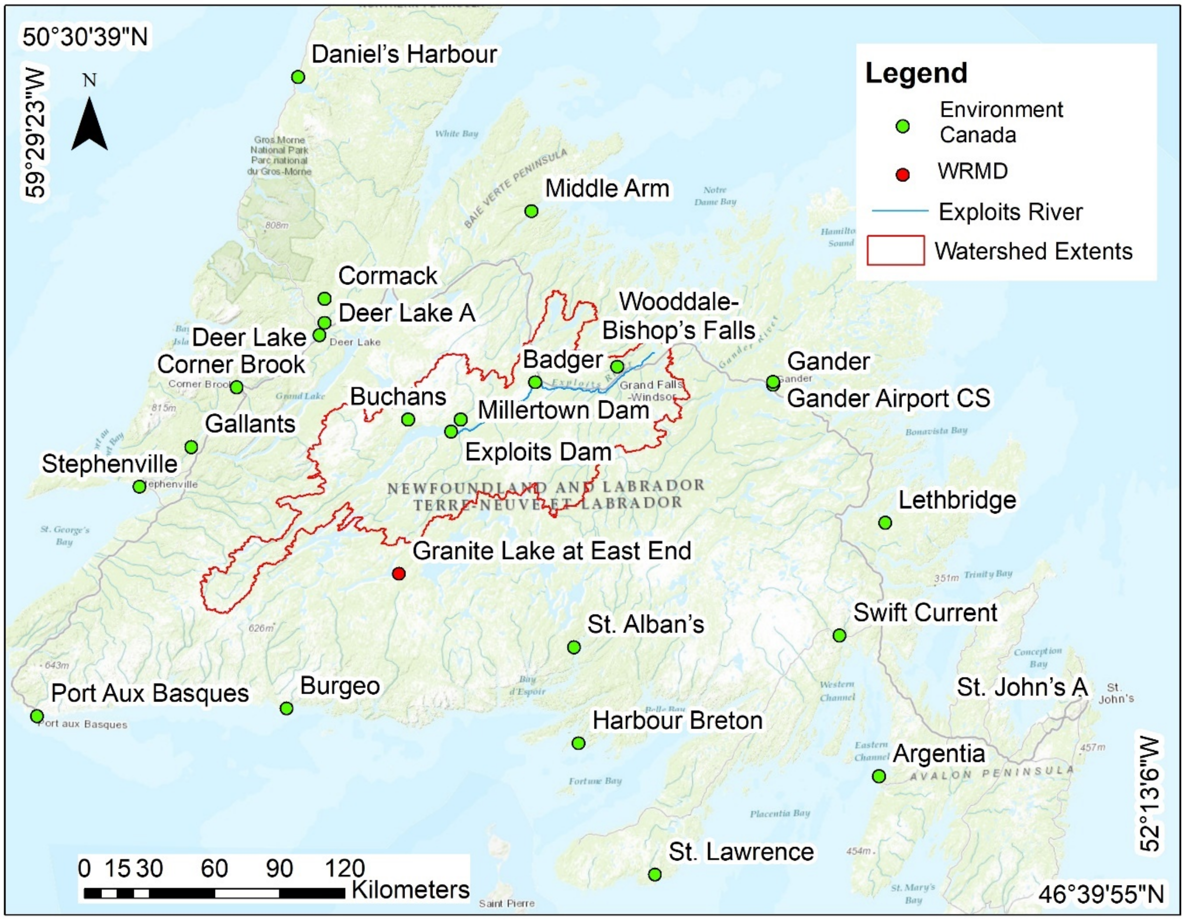

Figure 5-4: Climate Stations

Table 5-2: Climate Stations Used for Calibration/Validation Events

Location	Operator	ID	Period of Record	Latitude (˚N)	Longitude (˚W)	Elevation (m)	Continuous 2013-2017	1983	2003	2010	2016	2018
Argentia	Env. Canada	8400100/ 8400102	1945-1986	47.30	54.00	15.5		Y				
Badger	Env. Canada	8400301	1973-Present	48.97	56.07	102.7	Y		Y	Y	Y	Y
Buchans	Env. Canada	8400698	1965-2011	48.82	56.87	269.7		Y				
Burgeo	Env. Canada	8400800 / 8400801	1939-Present	47.62	57.62	10.6	Y	Y	Y	Y	Y	Y
Cormack	Env. Canada	8401286	1980-2016	49.32	57.40	153.9				Y		
Corner Brook	Env. Canada	8401300	1933-Present	48.95	57.95	4.6	Y		Y	Y	Y	Y
Daniel's Harbour	Env. Canada	8401400/ 8401405	1953-Present	50.24	57.58	19.0		Y				
Deer Lake	Env. Canada	8401500	1933-Present	49.17	57.43	10.7		Y		Y		
Deer Lake A	Env. Canada	8401501/ 8401502	1965-Present	49.22	57.40	21.9				Y		
Englee	Env. Canada	8401538	1993-Present	50.72	56.11	30.30				Y		
Exploits Dam	Env. Canada	8401550	1956-2008	48.77	56.60	153.6		Y				
Gallants	Env. Canada	8401642	1982-2016	48.70	58.23	143.0				Y		
Gander	Env. Canada	8401700/ 8401703	1937- Present	48.94	54.57	151.2	Y	Y	Y	Y	Y	Y
Gander Airport CS	Env. Canada	8401705	2005-Present	48.95	54.57	151.0				Y		
Granite Lake at East End	WRMD	02ZC004	2006-Present	48.18	56.93	311.0					Y	Y
Harbour Breton	Env. Canada	8402071	1983-Present	47.47	55.83	30.0	Y		Y	Y	Y	Y
Lethbridge	Env. Canada	8402544	1954-Present	48.35	53.90	15.2				Y		
Middle Arm	Env. Canada	8402644	1988-Present	49.68	56.08	47.8				Y		
Millertown Dam	Env. Canada	8401550/ 8402757	1956-Present	48.82	56.54	152.0			Y		Y	Y
Port Aux Basques	Env. Canada	8402975 /8402980	1909-Present	47.57	59.15	39.7		Y		Y		
St. Alban's	Env. Canada	8403290	1968-1983	47.87	55.85	13.4		Y				
St. Lawrence	Env. Canada	8403615/ 8403616 /8403619	1966-Present	46.92	55.38	48.5		Y				
St. John's A	Env. Canada	8403506	1942-2012	47.62	52.74	140.5		Y				
Stephenville	Env. Canada	8403800/ 8403801	1942-Present	48.53	58.55	24.7		Y		Y		
Swift Current	Env. Canada	8403825	1984-Present	47.89	54.21	18.2				Y		
Wooddale-Bishop's Falls	Env. Canada	8404310	1974-2011	49.03	55.55	45.7		Y	Y	Y		

5.2.4 Intensity-Duration-Frequency Curves

5.2.4.1 Current Conditions

The Intensity-Duration-Frequency (IDF) curves for Newfoundland and Labrador were updated in 2015 by Conestoga-Rovers & Associates (2015). Hatch did not make any further updates to these curves. It was agreed with WRMD that addition of the data for the intervening years was unlikely to make a significant change to the results, given the long period of record that is available at each location.

The 1:20 and 1:100 AEP rainfall hyetographs were developed from the Gander Airport IDF curve using the alternating block method. The Gander Airport station was used as it best represented conditions in the Exploits Basin due to its close proximity to the watershed. The 24-hour 1:20 and 1:100 AEP hourly rainfall hyetographs are shown in **Figure 5-5** below with maximum rainfall amounts by duration shown in **Table 5-3**. Precipitation grids in 5 minute increments representing the precipitation shown in the table below were developed and applied over the entire watershed. It was assumed that the spatial distribution of the rainfall is uniform across all subbasins.

Table 5-3: Gander Airport IDF Rainfall Amounts

	1:20 AEP (mm)		1:100 AEP (mm)	
Duration	Current Condition	Climate Change (2071-2100)	Current Condition	Climate Change (2041-2070)
5 min	8.9	11.6	11.7	15.07
10 min	13.0	16.6	17.1	21.45
15 min	15.9	20.2	21.0	26.19
30 min	21.6	26.6	28.5	34.39
1 h	25.6	30.5	33.2	38.84
2 h	32.8	38.7	41.7	48.57
6 h	52.6	59.9	66.2	74.59
12 h	69.4	78.7	88.0	98.37
24 h	92.3	100.2	119.8	126.29

5.2.4.2 Climate Change

The IDF curves are expected to be affected by climate change as defined in Finnis & Daraio's "Projected Impacts of Climate Change for the Province of Newfoundland & Labrador: 2018 Update" (2018). The median projected 1:20 and 1:100 AEP rainfall hyetographs for the Gander Airport IDF curves are shown in **Figure 5-6** below with maximum rainfall amounts by duration shown above in **Table 5-3**.

This document provides climate change projections for two periods: 2041-2070 and 2071-2100. For the Gander Airport, the 2071-2100 time period has a larger projected 1:20 AEP event than the 2041-2070 time period, while the 2041-2070 time period has a larger projected

1:100 AEP event than the 2071-2100 time period. Therefore, the 2071-2100 time period was used for the 1:20 AEP event and the 2041-2070 time period was used for the 1:100 AEP event. It was assumed that the spatial distribution of the rainfall is uniform across all subbasins.

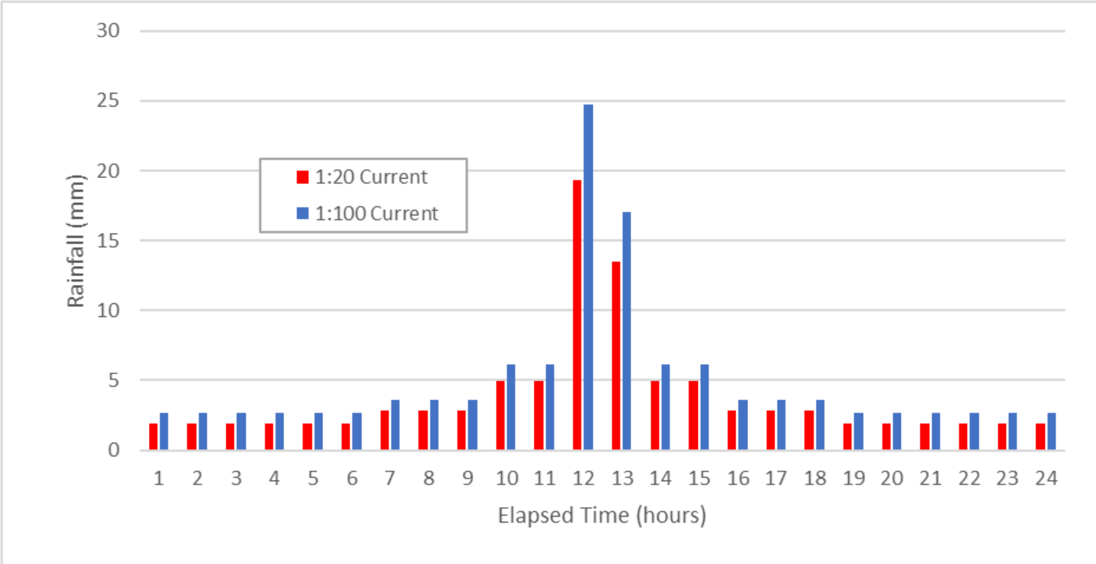

Figure 5-5: 1:20 and 1:100 AEP Hourly Rainfall Hyetographs – Current Condition

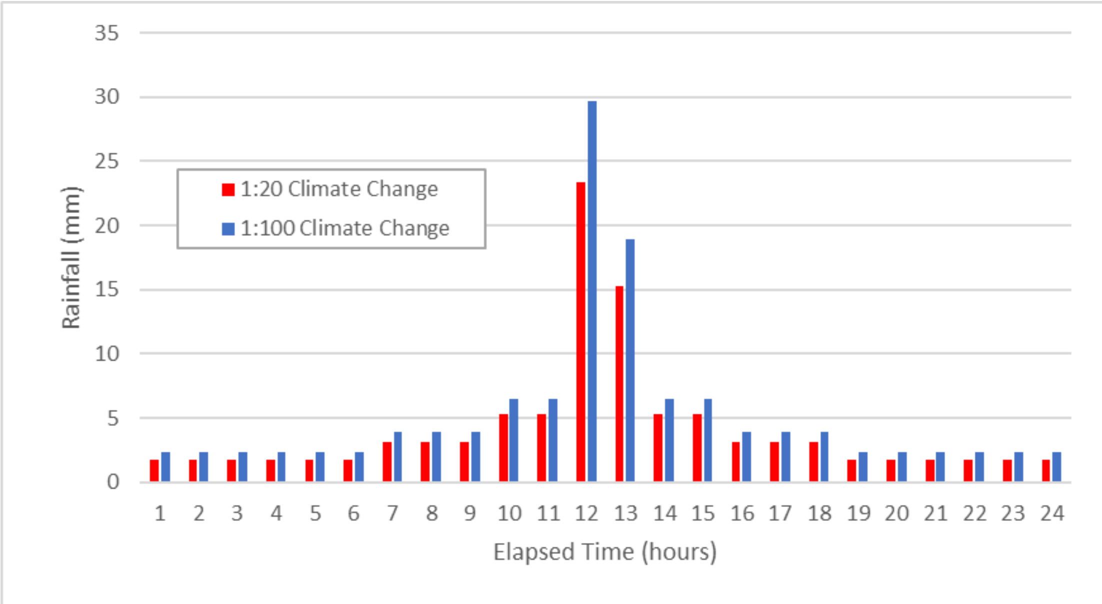

Figure 5-6: 1:20 and 1:100 AEP Hourly Rainfall Hyetographs – Climate Change Condition

5.3 Stochastic Analysis

The objectives of the stochastic analysis component of the study were to develop statistically-derived flow estimates at specific locations identified as key nodes in the study area for the hydraulic modelling and flood risk mapping. The required estimates were as follows:

- Updated 1:20 and 1:100 AEP peak flows for the main stem of the Exploits River:
  - Badger (above Badger Brook confluence)
  - Badger (below Badger Brook confluence)
  - Goodyear's Dam
  - Grand Falls Dam
  - Bishop's Falls Dam.
- 1:20 and 1:100 AEP peak flows for Little Red Indian Brook and Badger Brook in Badger.
- Exploits River winter flood estimates, for ice jam modelling at Badger.
- 1:20 and 1:100 AEP peak flows for 11 minor tributary streams identified in the communities.

Similar stochastic analyses were previously undertaken by Fenco in their analyses of floods on the Exploits River at Bishop's Falls and Badger (Fenco 1985, 1990). These two studies were reviewed in detail before undertaking the current analyses. The datasets available to the Fenco studies were updated and extended with the latest records from the WSC hydrometric data archive for use in the current stochastic analyses.

Flood frequency analyses were undertaken using two-parameter and three-parameter distributions, depending on the length of record available, using the Consolidated Frequency Analysis software CFA3.1 from Environment Canada (2000).

Flood peaks for Little Red Indian Brook and Badger Brook were estimated using regional flood frequency analysis techniques, since no flow records were available for these tributaries.

Flood peaks for all points of interest were estimated also using the regional regression equations developed by AMEC (2014). In the case of the 11 minor tributary streams (all with drainage area less than 25 km^2), this was the only statistical approach available, since no flow records were available for these tributaries, and there was an insufficient number of similarly-sized gauged basins in the immediate area on which to conduct a new regional frequency analysis.

5.3.1 *Single Station Flood Frequency Analysis*

Single station flood frequency analysis was undertaken for each active flow record on the main stem of the Exploits River below Red Indian Lake, as well as the available historical record at Bishop's Falls:

- 02YO011 Exploits River Below Noel Paul's Brook.
- 02YO013 Exploits River at Badger.
- 02YO018 Exploits River at Charlie Edwards Point.
- 02YO001 Exploits River at Grand Falls.
- Bishop's Falls (Fenco 1990).

The annual flood series (maximum daily flow) for the Exploits River at Bishop's Falls for the period 1933 to 1983 was extracted from Fenco (1990), who derived the outflows from operating records of Abitibi-Price Inc., the owner of the plant at the time. Nalcor does not maintain a record of flow at Bishop's Falls and the plant records that were available for more recent years were not sufficient for attempting to extend the series further.

The flow record 02YO001 (Exploits River at Grand Falls) consists of data from the Grand Falls Generating Station contributed to WSC by the plant operator. WSC has published the flows for the period 1944 to 2010. Data for 2011 to 2018 was obtained by Hatch directly from Nalcor.

Fenco (1985) limited its frequency analysis of the flood record for the Exploits River at Grand Falls to the period 1970 onward, due to the diversion of Victoria Lake in 1968. The natural outflow of Victoria Lake was formerly via the Victoria River to Red Indian Lake. The diversion directed the drainage area of Victoria Lake (1,056 km^2, about 9 percent of the drainage area of the Exploits River to Bishop's Falls) into the Bay d'Espoir Hydroelectric System.

However, for the current study, screening analysis of the full Grand Falls flood record (1944 to 2018) detected no significant trend or non-homogeneity in flood peaks between the pre- and post-diversion periods. Consequently, the full period of record has been retained. Fenco (1990) demonstrated that, although the flood volumes at Bishop's Falls after 1969 have decreased, peak inflows from Millertown Dam arrive too late to have a significant effect on the flood peak at Bishop's Falls. Hydrograph analysis confirmed that the flood peaks on the lower part of the Exploits River are driven mainly by runoff from the uncontrolled drainage area below Red Indian Lake, and are relatively insensitive to changes in typical operations at Millertown Dam. It was concluded that for the purpose of frequency analysis of historical flows, the available flood records can be treated as natural flow series.

The maximum daily flows at Grand Falls and Bishop's Falls were multiplied by 1.04 and 1.026, respectively, to yield the series of peak flows (maximum instantaneous), based on the ratios of peak to daily flow determined in Fenco (1985) and Fenco (1990). Records of hourly flow at Grand Falls and Bishop's Falls are no longer collected. However, indirect checks using Nalcor hourly tailwater level data are consistent with the previous findings.

The selected flood peak records were screened to ensure the data are random, statistically independent and stationary, using the following tests:

- Run test for general randomness.
- Spearman test for independence.
- Spearman test for trend.
- Mann-Whitney split sample test for homogeneity.

The data series passed all tests at the 5 percent significance level, with the exception of the Grand Falls record which did not pass the randomness and independence tests at the 5 percent significance level but did pass at the 1 percent significance level. The null hypothesis of the statistical test for randomness is that the data are random. If the dataset passes the test at the 5% significance level the data are considered random. If the dataset does not pass the test at the 1% significance level the data are not random and should be rejected. If the dataset does not pass the test at the 5% significance level, but passes the test at the 1% significance level, the data are considered to be somewhat random and should be examined further. On further review of the Grand Falls record there was no obvious reason to reject the data, especially in the absence of any non-stationarity, such as trend, that could invalidate the frequency estimates.

The seasonality of the flood data was also reviewed for evidence of non-homogeneity with respect to flood runoff processes that could invalidate treatment of the data as representing a single population (e.g., events driven by snowmelt vs. events driven by rainfall on snow-free ground). In the Grand Falls record (75 years), 61 of the annual flood peaks (81 percent) occurred in the December to May period (representing snowmelt-driven events). This included all of the largest events on record with empirical probabilities of 5 percent (1:20 AEP) or less. It was concluded that for the purpose of frequency analysis of historical flows, a combined population analysis is not warranted. Since the flood processes at the other locations on the Exploits River would be driven by the same processes as at Grand Falls, it was concluded that separate distributions were not required, which agrees with the findings of Fenco (1985).

Instantaneous flood peak records (infilled from annual maximum daily flows using average peaking factor when the instantaneous peaks were missing) with more than 20 years of data were analysed using 3-parameter frequency distributions (3-parameter lognormal (3LN) and log Pearson type 3 (LP3), using maximum likelihood parameter fitting, and the generalized extreme value (GEV), using L-moments[1] parameter fitting).

Instantaneous flood peak records (infilled as described above) with less than 20 years of data were analysed using two-parameter frequency distributions (EV-1 (Gumbel), Normal and Lognormal) to avoid the influence of possibly non-representative skewness exhibited by the flood record. The only records in this category (Badger and Charlie Edwards Point, with 9 years and 8 years respectively) were expected to be too short for reliable extrapolation to the AEPs of interest, but were included for comparison.

The 1983 flood at Bishop's Falls has not been exceeded in the subsequent 35 years, so the historic information option in CFA3.1 was used to extend the effective time span to 86 years with a single peak over the threshold 3,340 m^3/s (the 1983 approximate flood peak).

Table 5-4 shows the five locations on the Exploits River for which instantaneous flood peak frequency analysis was undertaken, the best fit distributions adopted and the 1:20 and 1:100 AEP flood peak estimates resulting from the analysis.

Table 5-4: Exploits River Instantaneous Flood Peak Frequency Analysis Results

Gauge ID	Location	Drainage Area (km^2) (Note 1)	No. of Years	Frequency Distribution	1:20 AEP (m^3/s)	1:100 AEP (m^3/s)
02YO011	Below Noel Pauls Brook	6,357	34	3LN	1,340	1,650
02YO013	At Badger	6,602	9	EV-1	1,205	1,509
02YO018	At Charlie Edwards Point	7,782	8	EV-1	1,243	1,517
02YO001	At Grand Falls	8,459	75	3LN	1,500	1,820
Fenco (1990)	At Bishop's Falls	10,176	51 (Note 2)	3LN	2,220	2,810

Note:
1. Drainage areas from hydrologic DEM.
2. Effective time span of record extended to 86 years.

Table 5-4 suggests that the short periods of record available for the Exploits River at Badger and at Charlie Edwards Point may not be representative of the long-term frequency distributions at these locations. The peaks at these locations are too small relative to their respective drainage areas compared to the neighboring gauges on the Exploits River.

[1] Hosking, quoted in Environment Canada (2000), "has demonstrated that the probability weighted moments (L-moments) approach yields more accurate quantile estimates than the maximum likelihood approach when fitting GEV parameters, for sample sizes common in flood hydrology". As a result, L-moments is the preferred parameter fitting approach for the GEV distribution used in the CFA3.1 software.

A potential adjustment to the 1:20 and 1:100 AEP flood peak estimates was considered by plotting daily flows at Badger and at Charlie Edwards Point against the corresponding daily flows below Noel Pauls Brook to establish trendline relationships. These trendlines could then be used to adjust flood peaks below Noel Pauls Brook to Badger and Charlie Edwards Point. Flows were first ranked to adjust for travel times.

Figure 5-7 shows that the ratio of flow at Badger to flow below Noel Pauls Brook is virtually unchanged throughout the observed range of low, medium and high flow conditions.

In contrast **Figure 5-8** shows that the ratio of flows at Charlie Edwards Point to flows below Noel Pauls Brook drops significantly at flood flow levels. This is likely due to the attenuation of flood flows in Badger Brook by North and South Twin Lakes, plus four smaller lakes, which effectively delay the contribution of Badger Brook until after the peak in the Exploits River has passed Badger.

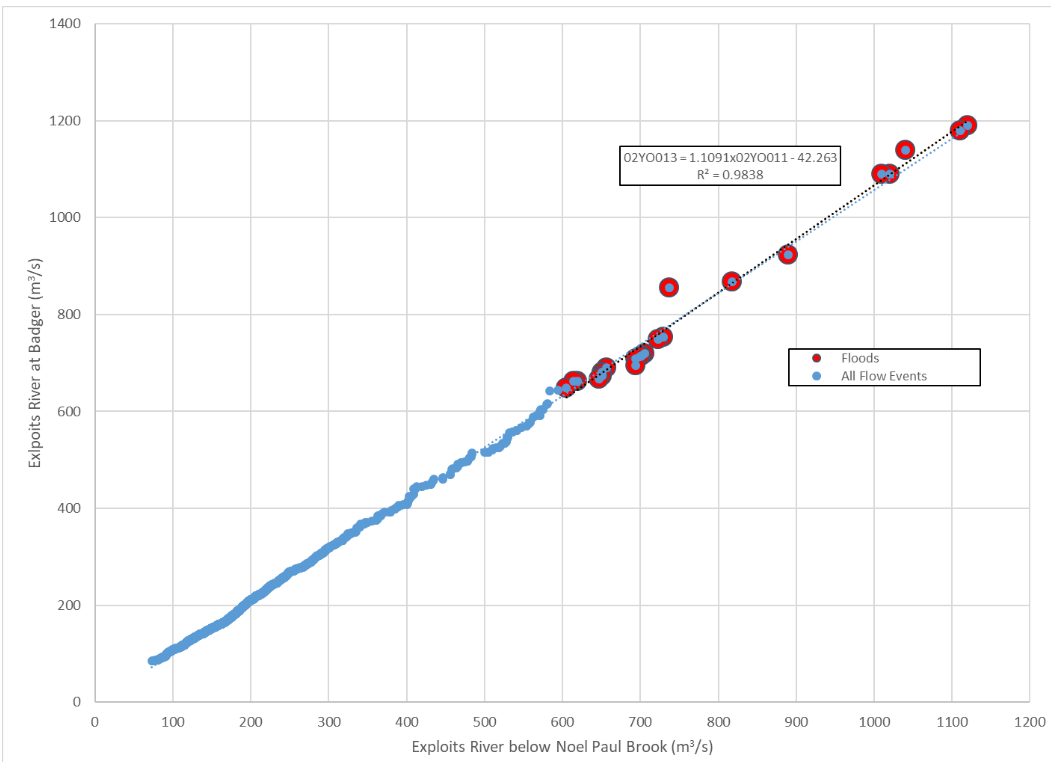

Figure 5-7: Exploits River at Badger vs. Below Noel Pauls Brook Daily Flows

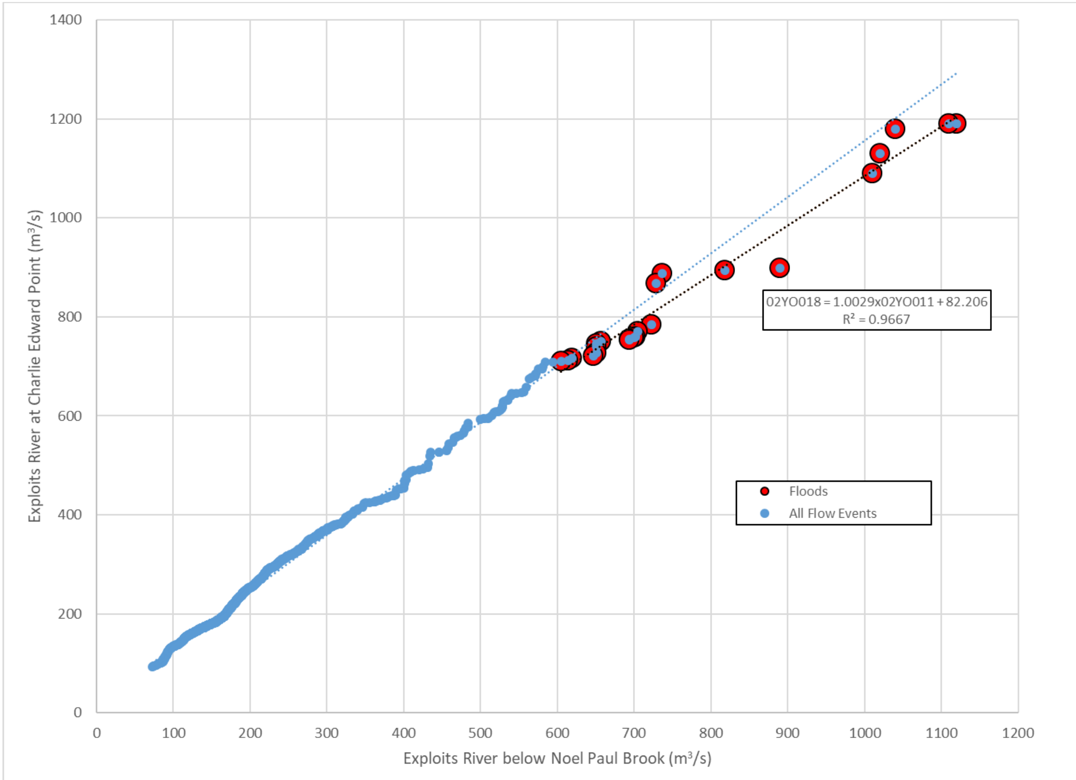

Figure 5-8: Exploits River at Charlie Edwards Point vs. Below Noel Pauls Brook Daily Flows

Table 5-5 presents a second version of **Table 5-4**, revised to reflect estimates that were refined based on the trendline analyses described above. Flood peaks at Badger, downstream from Badger Brook confluence, and at Goodyear's Dam have been interpolated based on drainage area from the locations upstream and downstream.

Table 5-5: Exploits River Flood Peak Frequency Analysis Results

Gauge ID	Location	Drainage Area (km^2) (Note 1)	No. of Years	Frequency Distribution	1:20 AEP (m^3/s)	1:100 AEP (m^3/s)
02YO011	Below Noel Pauls Brook	6,357	34	3LN	1,340	1,650
02YO013	At Badger	6,602	9	Revised from 02YO011	1,400	1,715
-	At Badger below Badger Brook	7,320	-	Interpolated	1,418	1,730
02YO018	At Charlie Edwards Point	7,782	8	Revised from 02YO011	1,430	1,740
-	At Goodyear's Dam	8,444	-	Interpolated	1,498	1,818
02YO001	At Grand Falls	8,459	41	3LN	1,500	1,820
Fenco (1990)	At Bishop's Falls	10,176	51 (Note 2)	3LN	2,220	2,810

Notes:
1. Drainage areas from hydrometric DEM.
2. Effective time span of record extended to 86 years.

5.3.1.1 *Winter Floods*

Fenco (1985) estimated 1:20 AEP and 1:100 AEP peak flows on the Exploits River for the winter months of December to April, for use in the analysis of ice jam flooding. However, Fenco ultimately found that the ice cover at Badger is not stable at peak flows of these magnitudes. At winter peak flows as low as 1:20 AEP, the ice cover is swept downstream without incident, and at higher flow rates, the ice cover cannot advance into the Badger area.

A review of the updated flood history confirmed the previous finding by Fenco that damaging floods at Badger were associated with ice cover formation and progression, which are processes that occurs generally in months of December to February in relatively steady flow conditions.

Taking into consideration these complexities, it was necessary to test a variety of cases to identify a scenario resulting in maximum winter water levels for the 1:20 and 1:100 AEP events.

The Fenco (1985) estimates of winter peak flows for the Exploits River at Badger were updated as follows.

- Flood frequency analysis for Exploits River below Noel Pauls Brook (02YO011) for the months December, January, February, March and April individually, plus the flood maxima for each winter (December to April).

- The selected flood peak records were screened for independence, trend, randomness and homogeneity using the CFA3.1. All the selected records passed the tests at the 5 percent significance level.
- Proration of the estimated 1:20 and 1:100 AEP flood peaks to Badger using **Figure 5-7**.
- The GEV distribution, using L-moments parameter fitting, was found to give the best fit to all five monthly cases, which are shown in **Table 5-6**.

Table 5-6: Exploits River – Winter Flood Peak Frequency Analysis Results

Month/Period	02YO011 Below Noel Pauls Brook		02YO013 At Badger	
	1:20 AEP (m^3/s)	1:100 AEP (m^3/s)	1:20 AEP (m^3/s)	1:100 AEP (m^3/s)
January	432	687	454	720
February	412	759	432	800
March	412	613	432	638
April	862	1,170	914	1,255
December	786	1,510	829	1,632
Winter (Dec - Apr)	1,030	1,340	1,100	1,444

In addition, a frequency analysis of ice formation flows was carried out. This was taken as the three-month (December to February) mean flow at Badger.

- The series of December-February 3-month mean flows at Badger (02YO013) was extended from 9 to 33 years (1986 to 2018) via correlation to Noel Paul's Brook (02YO011) as shown in **Figure 5-9**.
- The flow series was screened for independence, trend, randomness and homogeneity. All the selected records passed the tests at the 5 percent significance level.
- The flows were found to be normally distributed, using Maximum Likelihood, and the estimates are shown in **Table 5-7**.

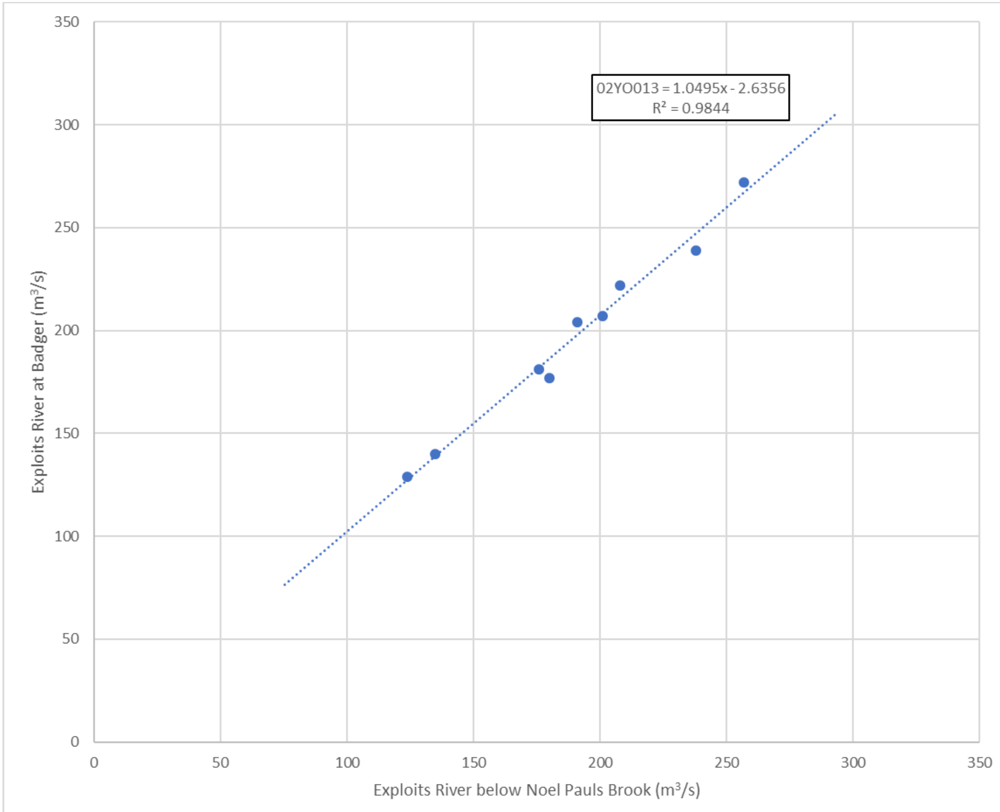

Figure 5-9: Exploits River at Badger vs. Below Noel Pauls Brook December-February Mean Flows

Table 5-7: Exploits River – December to February Mean Flow Frequency Analysis Results

AEP	02YO013 At Badger (m^3/s)
Average	195
1:20	278
1:50	298
1:100	312

5.3.2 *Regional Flood Frequency Analysis*

5.3.2.1 Little Red Indian Brook and Badger Brook

No flow records were available for Little Red Indian Brook and Badger Brook, two significant tributaries that meet the Exploits River within the Town of Badger. The drainage areas of Little Red Indian Brook and Badger Brook are 136.6 km^2 and 717.5 km^2, respectively. Fenco (1985) undertook a regional flood frequency analysis (RFFA) to estimate the required flood peak estimates for these tributaries, using data from seven WSC gauges on smaller streams and rivers in a hydrologically homogeneous region centered around Badger.

The RFFA, which Fenco termed a "sub-regional" analysis, was updated for the present study to include the additional years of available data. The selected flood peak records were screened for independence, trend, randomness and homogeneity using CFA3.1. All the selected records passed the screening tests at the 5 percent significance level.

Instantaneous flood peak records with more than 20 years of data were analysed using three-parameter frequency distributions (LN3 and LP3, using maximum likelihood parameter fitting, and GEV, using L-moments parameter fitting).

Instantaneous flood peak records with less than 20 years of data were analysed using two-parameter frequency distributions (EV-1 (Gumbel), Normal and Lognormal) to avoid the influence of possibly non-representative skewness exhibited by the flood record.

Table 5-8 shows the seven WSC hydrometric gauges included in the RFFA, the best fit distributions adopted and the 1:20 and 1:100 AEP flood peak estimates resulting from the analysis. These gauges are also shown in **Figure 5-10**.

Table 5-8: Regional Flood Peak Frequency Analysis Results

Gauge ID	Name	Drainage Area (km^2)	No. of Years	Frequency Distribution	1:20 AEP (m^3/s)	1:100 AEP (m^3/s)
02YK002	Lewaseechjeech Brook at Little Grand Lake	470	43	GEV	184	228
02YK008	Boot Brook at Trans-Canada Highway	20	32	GEV	21	32
02YO006	Peters River Near Botwood	177	36	3LN	98	139
02YO007	Leech Brook Near Grand Falls	88	12	EV1	46	57
02YO010	Junction Brook Near Badger	62	12	EV1	18	23
02YO014	Tributary to Gill's Pond Brook	8	11	EV1	4	6
02YP001	Shoal Arm Brook Near Badger Bay	64	15	EV1	41	52

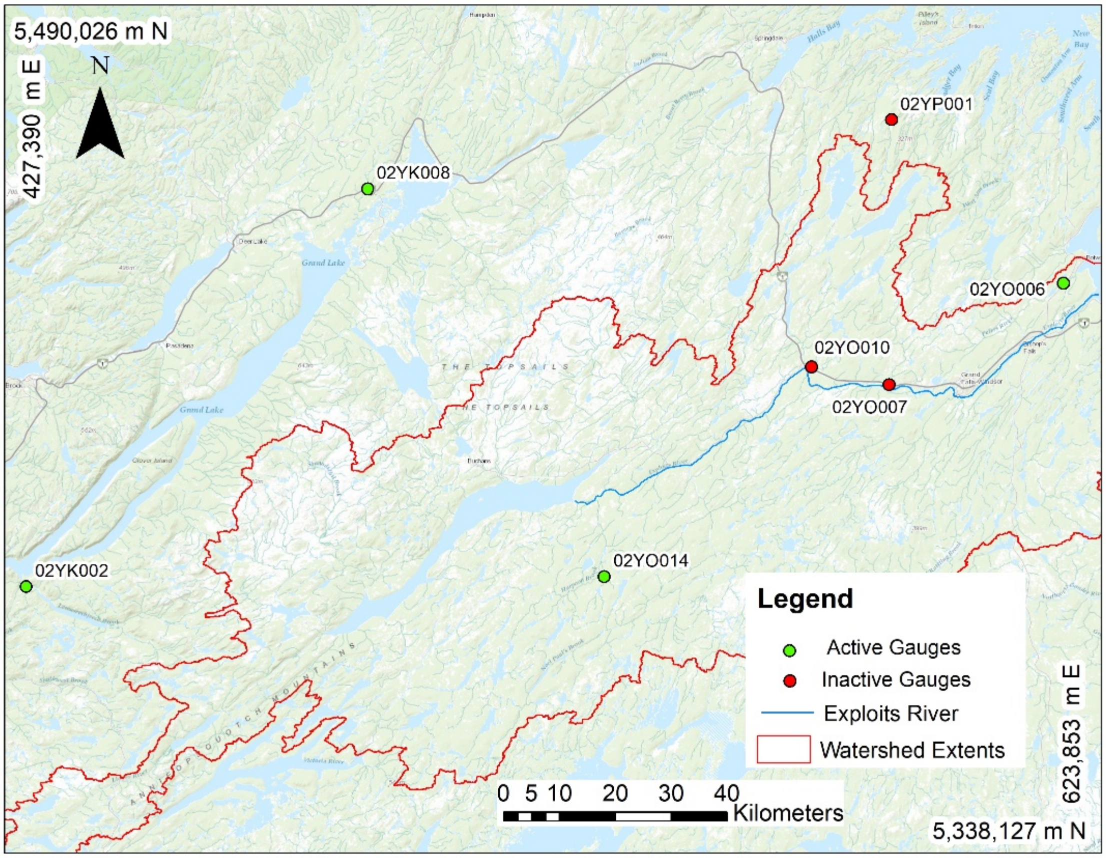

Figure 5-10: Location of Regional Flood Frequency Analysis Gauge Locations

The flood peak estimates from **Table 5-8** were then plotted against drainage area to develop fitted curve equations to estimate 1:20 and 1:100 AEP flood peaks for Little Red Indian Brook and Badger Brook.

Figure 5-11 and **Figure 5-12** show the fitted curves:

Q_{20} = $0.91*DA^{0.87}$ $R^2 = 0.91$

Q_{100} = $1.29*DA^{0.85}$ $R^2 = 0.89$

Where:

Q = instantaneous peak flow in m^3/s

DA = drainage area in km^2

Table 5-9 presents the 1:20 and 1:100 AEP flood peak estimates for Little Red Indian Brook and Badger Brook in Badger, based on the RFFA.

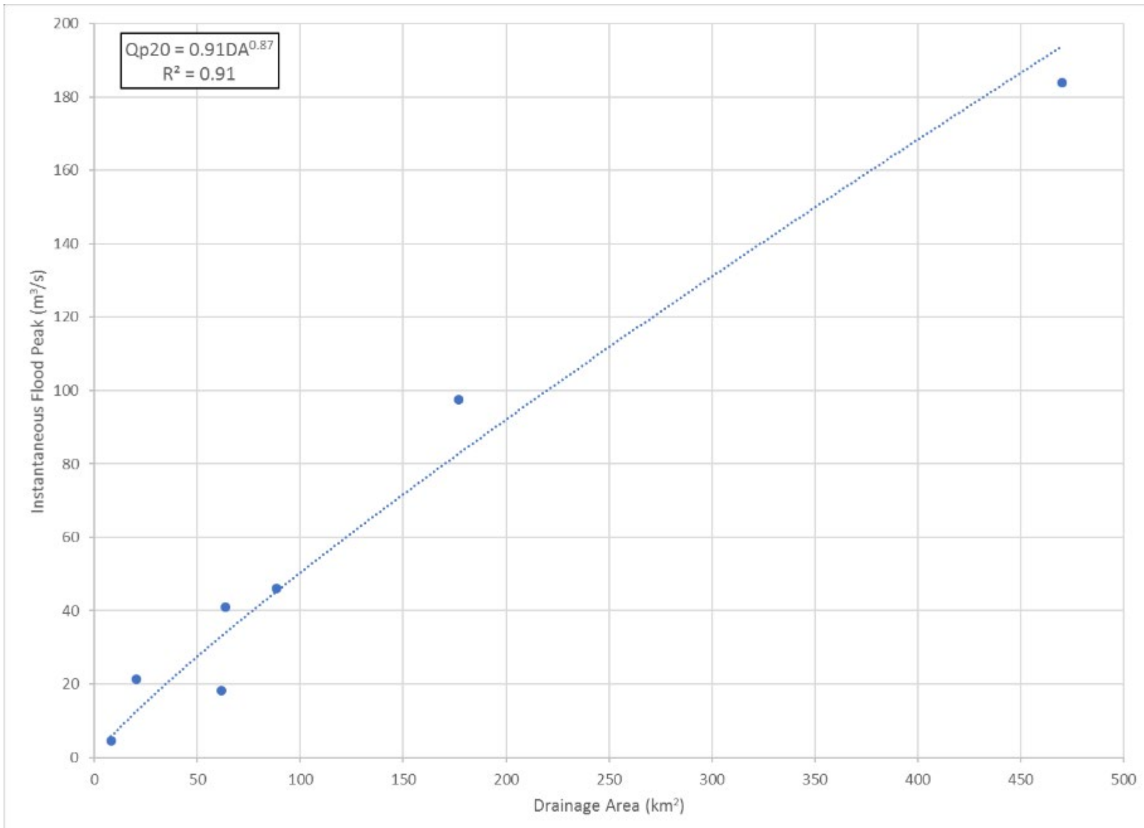

Figure 5-11: Regional Flood Frequency Plot for 1:20 AEP Flood Peaks

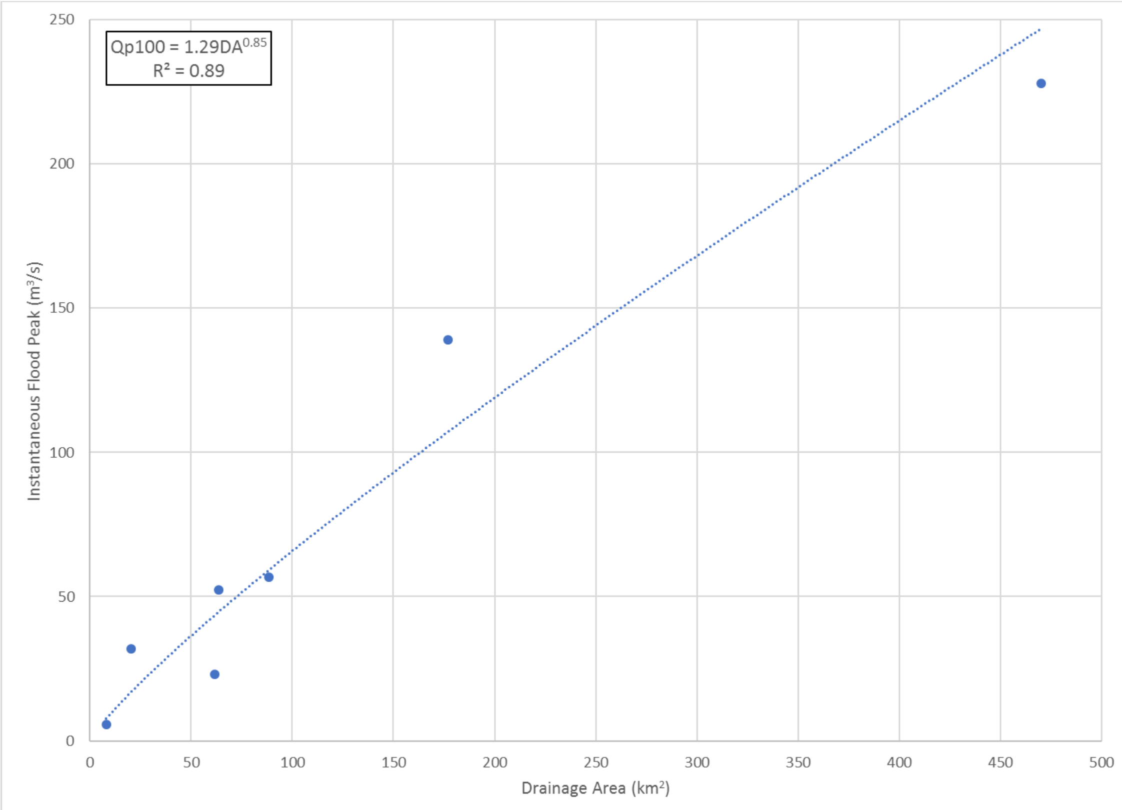

Figure 5-12: Regional Flood Frequency Plot for 1:100 AEP Flood Peaks

Table 5-9: Little Red Indian Brook and Badger Brook Flood Peak Estimates

Name	Drainage Area (km^2)	1:20 AEP (m^3/s)	1:100 AEP (m^3/s)
Little Red Indian Brook	137	66	84
Badger Brook	718	278	345

5.3.2.2 *Regional Flood Frequency Analysis for NL (from AMEC, 2014)*

Flood frequency estimates were made for each of the points of interest in the study basin using the methodology from the most recent update to the Regional Flood Frequency Analysis for Newfoundland and Labrador, last updated by AMEC in 2014. These equations were developed with the intention of estimating flood frequency on ungauged watersheds but have some limitations attached. Further details on these limitations can be found in the 2014 AMEC report accompanying the RFFA tool. These relationships were used here as a comparison and as a way of providing a second flood frequency estimate on the smaller ungauged basins in some of the communities.

The AMEC 2014 RFFA divides the province into five regions and developed regional equations for various AEP peak flows based on basin physiographic parameters. The Exploits basin is entirely within the Northeast region of the island, where the equation parameters are drainage area and lake attenuation factor, a calculated parameter which takes into account the total area of lakes as well as the portion of the basin drainage area that is controlled by the lakes. The 1:20 and 1:100 AEP peak flow relationships for the Northeast region are as follows:

$$Q_{20} = 7.568 * DA^{0.725} * LAF^{-0.317}$$

$$Q_{100} = 11.243 * DA^{0.708} * LAF^{-0.330}$$

Where:

Q = instantaneous peak flow in m^3/s

DA = drainage area in km^2

LAF = lake attenuation factor (minimum value 50)

Further details on the method can be found in the AMEC 2014 publication.

It should be noted that the AMEC 2014 equations have certain limitations. The equations are recommended for use only for unregulated drainage areas with limited urbanization. Application of these equations is also not recommended for watersheds whose physiographic parameters are outside of the range of the values used in developing the applicable regression equations. Extrapolation of the results beyond the extremes of the parameters used in regression equation development may reduce the accuracy of estimates significantly (AMEC 2014).

- The smallest basin used by AMEC in the Northeast region had a drainage area of 39 km^2, and all of the minor tributary basins in the current study are smaller than that, in some cases by one or two orders of magnitude.
- The largest basin used by AMEC in the Northeast region had a drainage area of 4,447 km^2, and the Exploits River points of interest in this study have drainage areas 1.4 to 2.3 times larger.
- The largest LAF for basins used by AMEC in the Northeast region was 881, which is exceeded by two sites (Rushy Pond Brook and Little Rushy Pond) that have large upstream lake areas relative to overall drainage area size.
- Most of the minor tributary drainage areas fall at least partially within municipal boundaries and have varying degrees of urban development.

The 1:20 and 1:100 AEP flows were estimated for the locations in **Table 5-10** below, including all gauge and dam sites on the Exploits River main stem, and all tributary streams included in the study. Values designated with an asterisk (*) are outside the regression equation parameter range, and the associated flood peak estimates should be regarded with caution.

Table 5-10: Summary of RFFA (AMEC 2014) Results

Location	DA (km^2)	LAF	1:20 AEP (m^3/s)	1:100 AEP (m^3/s)
Exploits River				
Exploits River below Noel Pauls Brook	6,357*	50	1,252	1,524
Exploits River at Badger	6,602*	50	1,287	1,565
Exploits River below Badger Brook	7,320*	50	1,387	1,683
Exploits River at Charlie Edwards Point	7,782*	50	1,450	1,758
Exploits River at Goodyear’s Dam	8,444*	50	1,539	1,863
Exploits River at Grand Falls	8,459*	50	1,541	1,865
Exploits River at Bishop’s Falls	10,176*	50	1,762	2,126
Major Tributaries				
Little Red Indian Brook	137	50	78	101
Badger Brook	718	50	257	325
Minor Tributaries				
Badger				
Unnamed Stream B-1 at Little Red Indian Brook	2.0*	50	3.6	5.0
Rushy Pond Area				
Wigwam Brook at Exploits River	20.6*	50	19.6	26.3
Rushy Pond Brook at Exploits River	23.6*	1,009*	8.4	10.8
Little Rushy Pond Brook at Rushy Pond	1.3*	2,922*	0.7	1.0
Grand Falls-Windsor				
Mullens Pond at Headwall	0.49*	239	0.8	1.1
Corduroy Brook at Exploits River	8.0*	89	8.3	11.2
Unnamed Stream GF-1 at Municipal Boundary	7.8*	50	9.7	13.2
Bishop’s Falls				
Unnamed Stream BF-1 at Exploits River	5.3*	287	4.2	5.6
Unnamed Stream BF-2 at Exploits River	2.1*	50	3.8	5.2
Unnamed Stream BF-3 at Exploits River	8.9*	168	7.3	9.8
Unnamed Stream BF-4 at Exploits River	0.4*	50	1.2	1.7

Note: * value outside regression equation parameter range

5.3.3 Comparison of Statistical Flood Frequency Estimates

Table 5-11 summarizes the statistical estimates of the 1:20 and 1:100 AEP flood peaks that were prepared for the locations on the Exploits River. The single station flood frequency estimates use long-term site-specific data and are considered to be more accurate and are preferred where available; it is noted that in general the RFFA appears to agree well with the single station frequency analysis.

Table 5-11: Summary of Flood Frequency Analysis Results – Exploits River

Location	Single Station Flood Frequency Analysis		Regional Flood Frequency Analysis (AMEC 2014 Equations)	
	1:20 AEP Peak Flow (m^3/s)	1:100 AEP Peak Flow (m^3/s)	1:20 AEP Peak Flow (m^3/s)	1:100 AEP Peak Flow (m^3/s)
Exploits River below Noel Pauls Brook	1,340	1,650	1,252	1,524
Exploits River at Badger	1,400	1,715	1,287	1,565
Exploits River below Badger Brook	1,418	1,730	1,387	1,683
Exploits River at Charlie Edwards Point	1,430	1,740	1,450	1,758
Exploits River at Goodyear's Dam	1,498	1,818	1,539	1,863
Exploits River at Grand Falls	1,500	1,820	1,541	1,865
Exploits River at Bishop's Falls	2,220	2,810	1,762	2,126

Table 5-12 summarizes the statistical estimates of the 1:20 and 1:100 AEP flood peaks that were prepared for Little Red Indian Brook and Badger Brook. In the absence of site-specific flow data, only regionally-based approaches are possible for preparing statistical estimates. For Little Red Indian Brook, the AMEC equation estimates are higher than the updated "sub-regional" estimates by 18 to 20 percent. For Badger Brook, the AMEC equation estimates are lower than the updated "sub-regional" estimates by 6 to 8 percent.

For these streams, it is expected that the AMEC equation estimates are more accurate. Of the two methodologies, AMEC (2014) better envelopes the range of drainage areas represented by Little Red Indian Brook and Badger Brook, and includes a second explanatory variable (lake attenuation factor) that together with drainage area can better account for differences in basin physiography.

Table 5-12: Summary of Flood Frequency Analysis Results – Major Tributaries

Location	Regional Flood Frequency Analysis (Update of Fenco 1985)		Regional Flood Frequency Analysis (AMEC 2014 Equations)	
	1:20 AEP Peak Flow (m^3/s)	1:100 AEP Peak Flow (m^3/s)	1:20 AEP Peak Flow (m^3/s)	1:100 AEP Peak Flow (m^3/s)
Little Red Indian Brook	66	84	78	101
Badger Brook	278	345	257	325

Table 5-13 summarizes the statistical estimates of the 1:20 and 1:100 AEP flood peaks that were prepared for the 11 minor tributaries. Due to the limitations of the AMEC 2014 equations, these estimates are subject to the caveats in **Section 5.3.2.2** and should be regarded with extreme caution.

Table 5-13: Summary of Flood Frequency Analysis Results – Minor Tributaries

Location	Regional Flood Frequency Analysis (AMEC 2014 Equations)	
	1:20 AEP Peak Flow (m^3/s)	1:100 AEP Peak Flow (m^3/s)
Badger		
Unnamed Stream B-1 at Little Red Indian Brook	3.6	5.0
Rushy Pond Area		
Wigwam Brook at Exploits River	19.6	26.3
Rushy Pond Brook at Exploits River	8.4	10.8
Little Rushy Pond Brook at Rushy Pond	0.7	1.0
Grand Falls-Windsor		
Mullens Pond at Headwall	0.8	1.1
Corduroy Brook at Exploits River	8.3	11.2
Unnamed Stream GF-1 at Municipal Boundary	9.7	13.2
Bishop's Falls		
Unnamed Stream BF-1 at Exploits River	4.2	5.6
Unnamed Stream BF-2 at Exploits River	3.8	5.2
Unnamed Stream BF-3 at Exploits River	7.3	9.8
Unnamed Stream BF-4 at Exploits River	1.2	1.7

5.4 Deterministic Hydrologic Model

The deterministic hydrologic modelling component of the study required the setup of a calibrated HEC-HMS model of the Exploits River watershed. The applications of the model mandated by WRMD were to:

- Provide deterministic estimates of 1:20 and 1:100 AEP peak flows using current 1:20 and 1:100 AEP rainfall intensity-duration-frequency (IDF) estimates.
- Provide deterministic estimates of 1:20 and 1:100 AEP climate change peak flows using future predicted 1:20 and 1:100 AEP rainfall IDF estimates.
- Provide a hydrological model for use in the flood forecasting service to be implemented for the Exploits River communities.

5.4.1 HEC-HMS Model Setup

WRMD required the use of the Geospatial Hydrologic Modelling Extension (HEC-GeoHMS) for ArcGIS for setup of the HEC-HMS model. Specifically, HEC-GeoHMS was used to prepare geometric data and to generate hydrologic inputs for import to HEC-HMS as follows:

- DEM pre-processing.

- Delineation of the watershed and component sub-basins.
- Determination of sub-basin characteristics and parameters.
- Creation of the HEC-HMS project.

The version of HEC-HMS used to develop the model was 4.2.1 due to compatibility requirements with the current version of the HEC-RTS flood forecasting platform.

The physical processes used in the model are summarized in **Table 5-14** and the sections below.

Table 5-14: Model Physical Processes

Process	Method	Comment
Canopy	Simple Canopy	Uniform canopy value for each subbasin; no gridded input needed
Surface	Simple Surface	Uniform surface values for each subbasin; no gridded input needed
Loss	Soil Moisture Accounting Loss	Best representation of conditions in watershed
Transform	Mod-Clark Transform	Required for gridded precipitation use in HEC-RTS flood forecasting software
Baseflow	Linear Reservoir	Routes infiltrated precipitation to the channel
Snowmelt	Gridded Temperature Index	Required to work with ModClark transform method
Routing	Muskingum-Cunge	Only routing method compatible with gridded meteorological data

5.4.1.1 DEM Pre-processing and Sub-Basin Delineation

Using the DEM discussed in **Section 5.2.2**, the HEC-GeoHMS preprocessing tools were used to create sub-basins by reconditioning the DEM, filling sinks, determining flow direction and accumulation, stream definition and segmentation, delineating catchment areas, and processing catchment areas and drainage lines. Initial sub-basin boundaries were reviewed using National Hydro Network data and aerial imagery. Where a stream extended over a generated sub-basin boundary, the area was reviewed using aerial imagery to determine if the boundary needed to be adjusted. If it did, adjustments were made to the DEM using the reconditioning tool and the preprocessing tools were rerun.

The basin was divided into 48 sub-basins as shown in **Figure 5-13** and **Figure 5-14**. Divisions were made at important hydrologic elements, including gauges, dams, important tributaries, and bridges and culverts where hydrologic model outputs were wanted. In community areas, sub-basins were also defined between rural and urban areas to better distinguish the rural and urban runoff characteristics.

The LiDAR DEM referenced in **Section 3.3.2** was not acquired until after development of the deterministic model. Upon comparison to the hydrologic DEM, the sub-basin delineation for Unnamed Streams BF-1, BF-2, BF-3 and BF-4 in Bishop’s Falls as well as Mullen’s Pond and

Corduroy Brook in Grand Falls-Windsor had to be adjusted using the LiDAR DEM. The LiDAR DEM was found to portray sub-basin geometry in urban areas more accurately, including changes in the natural drainage paths caused by features such as streets, lot grading, ditches, stream realignments and highway embankments.

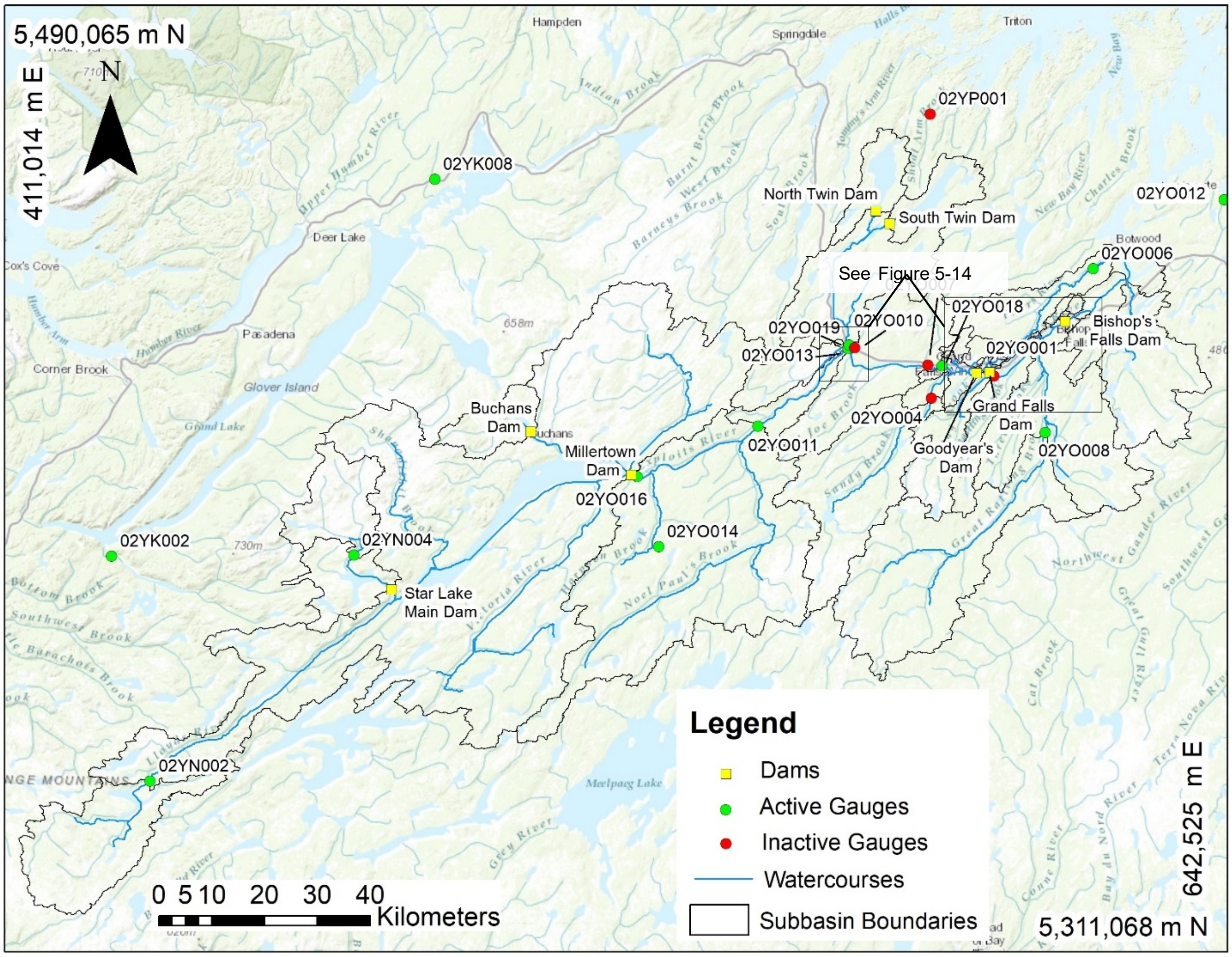

Figure 5-13: Sub-Basin Delineation for Exploits River HEC-HMS Model

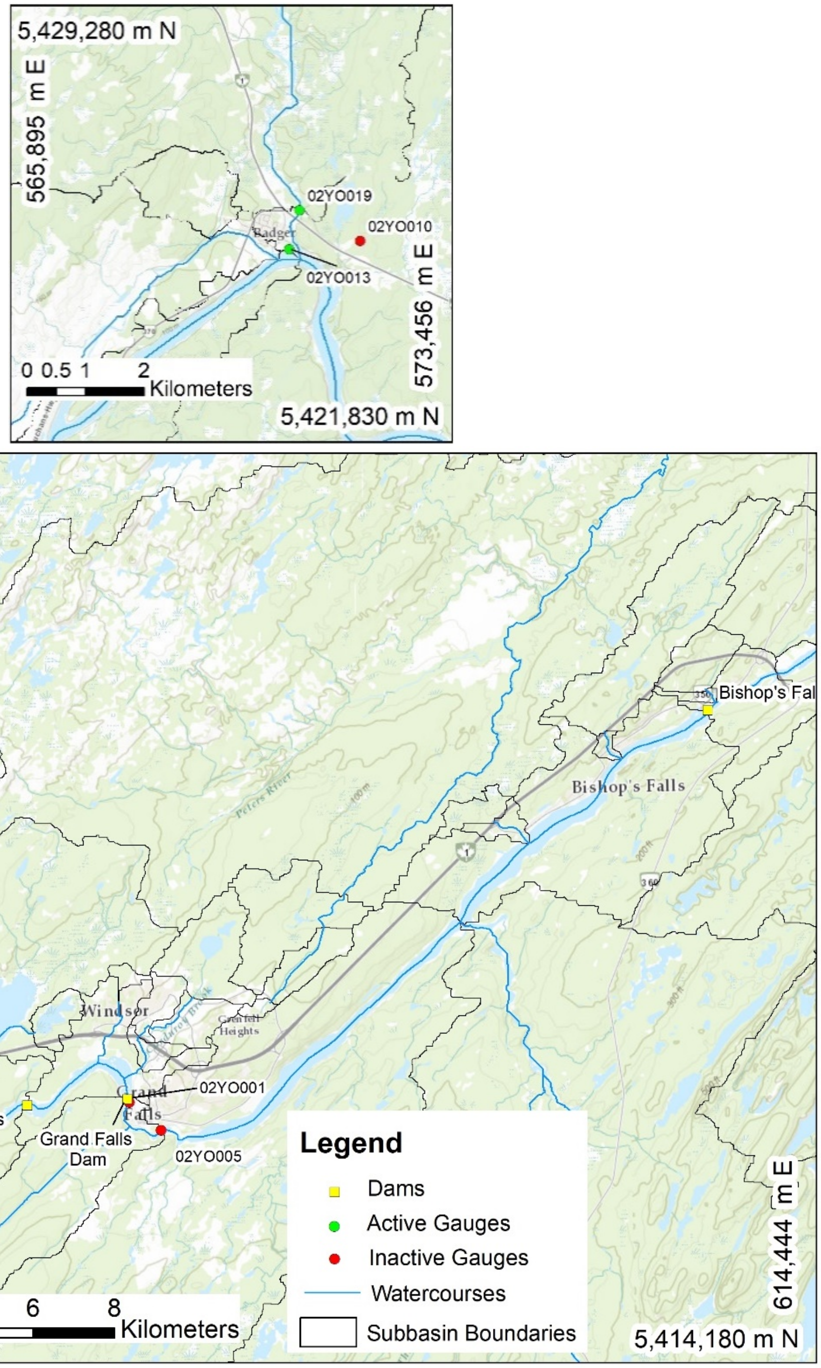

Figure 5-14: Sub-Basin Delineation for Exploits River HEC-HMS Model in Community Extents

Following sub-basin delineation, the river length and slope, basin slope, longest flowpath, basin centroid, and centroid elevation and longest flowpath were developed using HEC-GeoHMS stream and sub-basin characteristic tools.

The HEC-GeoHMS hydrologic parameter estimation tools were used to define the HMS processes, and a grid file was prepared at a 2 km x 2 km grid to be used for temperature and precipitation data processing. The 2 km x 2 km grid was determined in accordance with recommendations from the HEC-GeoHMS user manual.

Following determination of the hydrologic parameters, including CN values discussed in the following section, export functions were used to prepare the data for import into the HEC-HMS model.

5.4.1.2 SCS Curve Number

WRMD required the characterization of the watershed runoff generation potential using the US Soil Conservation Service (SCS) runoff Curve Number (CN) method [USDA, 1986]. The CN is a function of soil drainage and land cover characteristics, with higher values of CN indicative of lower permeability and higher potential for runoff generation. The CN values for the sub-basins in the watershed were determined from a remote sensing analysis that generated a land cover classification, combined with soil data from the National Soil Database.

5.4.1.2.1 Land Cover Classification

5.4.1.2.1.1 Current Development

The remote sensing analysis and land cover classification are documented in **Section 4**. The land cover classification for the Exploits River basin only is shown in **Table 5-15.**

5.4.1.2.1.2 Fully Developed

The communities of Badger, Grand Falls-Windsor and Bishop’s Falls provided future land use zoning areas to assess the impacts that future development might have on flood runoff flows.

The fully developed residential and commercial areas are shown in **Figure 5-15**. The fully developed areas were all given a land classification of urban area for a total increase in urban area land cover of 11 km^2, or 0.1% of the total watershed area as shown in **Table 5-15**.

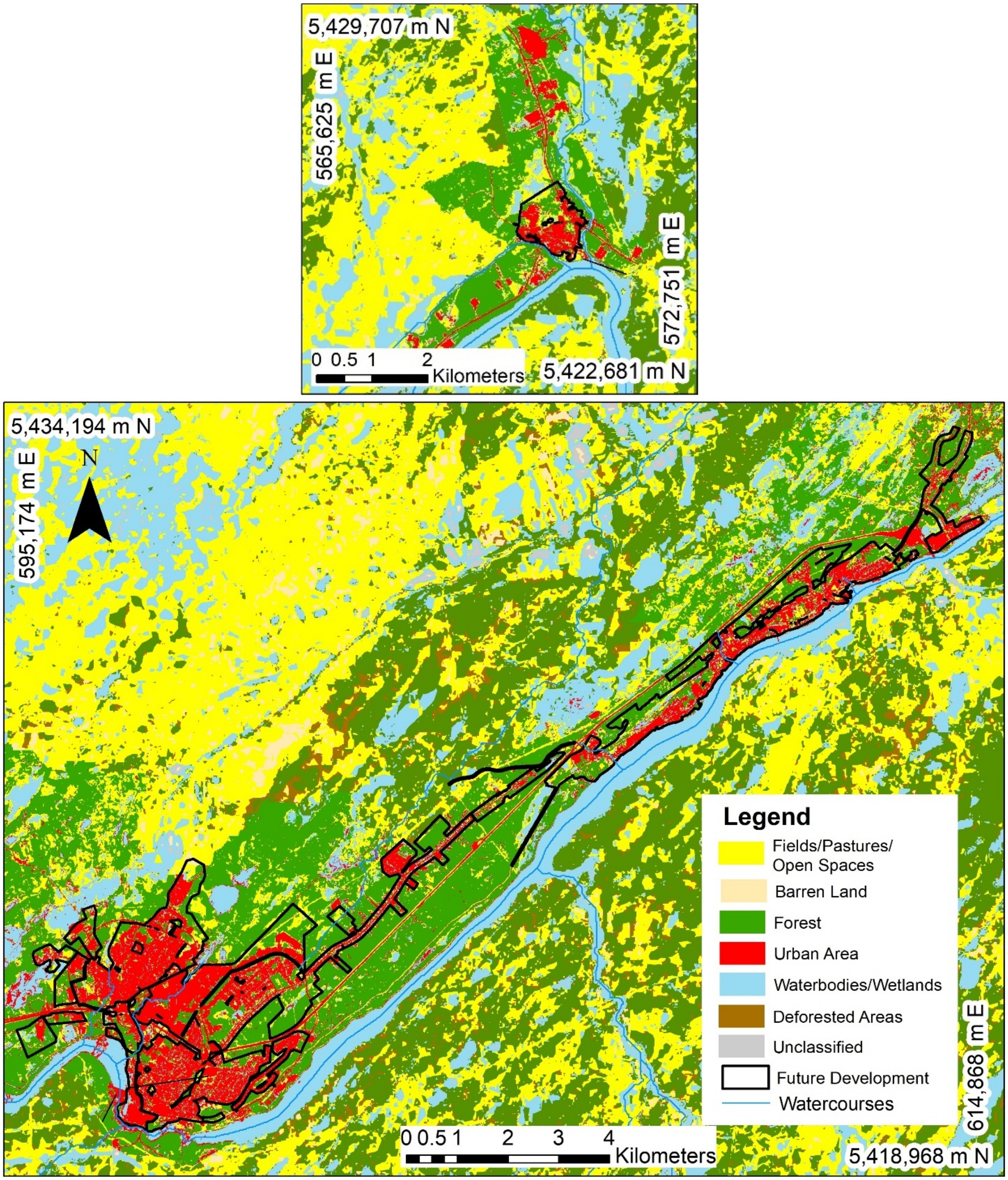

Figure 5-15: Fully Developed

A summary of the land cover areas and percentages for the Exploits River watershed only is provided in **Table 5-15** below.

Table 5-15: Land Cover Classification Summary

<table>
<tr><th></th><th colspan="3">Current Development</th><th colspan="2">Fully Developed</th><th rowspan="2">Fully – Current Development Difference (km²)</th></tr>
<tr><th>Land Cover Class</th><th colspan="2">Land Cover (km²)</th><th>% Area</th><th>Land Cover (km²)</th><th>% Area</th></tr>
<tr><td>Barren Land</td><td colspan="2">280</td><td>2.5%</td><td>280</td><td>2.5%</td><td>-0.4</td></tr>
<tr><td>Deforested Areas</td><td colspan="2">358</td><td>3.3%</td><td>358</td><td>3.3%</td><td>-0.2</td></tr>
<tr><td>Fields/Pastures/Open Spaces</td><td colspan="2">2,435</td><td>22.2%</td><td>2,432</td><td>22.1%</td><td>-2.6</td></tr>
<tr><td>Forest</td><td colspan="2">3,508</td><td>31.9%</td><td>3,502</td><td>31.9%</td><td>-6.0</td></tr>
<tr><td>Urban Areas</td><td colspan="2">21</td><td>0.2%</td><td>32</td><td>0.3%</td><td>11.0</td></tr>
<tr><td>Waterbodies</td><td>822</td><td rowspan="2">3,779</td><td rowspan="2">34.4%</td><td rowspan="2">3,778</td><td rowspan="2">34.4%</td><td rowspan="2">-1.5</td></tr>
<tr><td>Wetlands</td><td>2,957</td></tr>
<tr><td>Unclassified</td><td colspan="2">602</td><td>5.5%</td><td>602</td><td>5.5%</td><td>-0.5</td></tr>
<tr><td>Total</td><td colspan="2">10,983</td><td>100%</td><td>10,983</td><td>100%</td><td></td></tr>
</table>

5.4.1.2.2 Soil Classification

Soil data was obtained from the National Soil Database Soil Landscapes of Canada (version 3.2, March 2011) from the Canadian Soil Information Service of Agriculture Canada. The data included drainage characteristics for the various soils in the watershed.

The SCS CN method classifies soils into four hydrologic soil groups (A, B, C and D) based on their runoff potential as shown in **Table 5-16**. The following scheme was prescribed by WRMD to correlate the National Soil Database soil drainage class to SCS hydrologic soil groups.

Table 5-16: Drainage Class and SCS Soil Group

National Soil Database		SCS CN Method	
Drainage Class	**Description**	**Soil Group**	**Description**
VR	Very rapidly drained	A	These soils have low runoff potential and high infiltration rates even when thoroughly wetted. They consist chiefly of deep, well to excessively drained sand or gravel and have a high rate of water transmission.
R	Rapidly drained	A	
W	Well drained	A	
MW	Moderately well drained	A	
I	Imperfectly drained	B	These soils have moderate infiltration rates when thoroughly wetted and consist chiefly of moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission.
P	Poorly drained	C	These soils have low infiltration rates when thoroughly wetted and consist chiefly of soils with a layer that impedes downward movement of water and soils with moderately fine to fine texture.
VP	Very poorly drained	D	These soils have high runoff potential. They have very low infiltration rates when thoroughly wetted and consist chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface, and shallow soils over nearly impervious material.

The resulting SCS hydrologic soil groups are summarized in **Table 5-17** and **Figure 5-16**.

Table 5-17: Soil Classification Summary

Soil Group	Area (km^2)	% Area
A	5,298	48%
B	4,038	37%
C	918	8%
D	728	7%
Total	10,983	100%

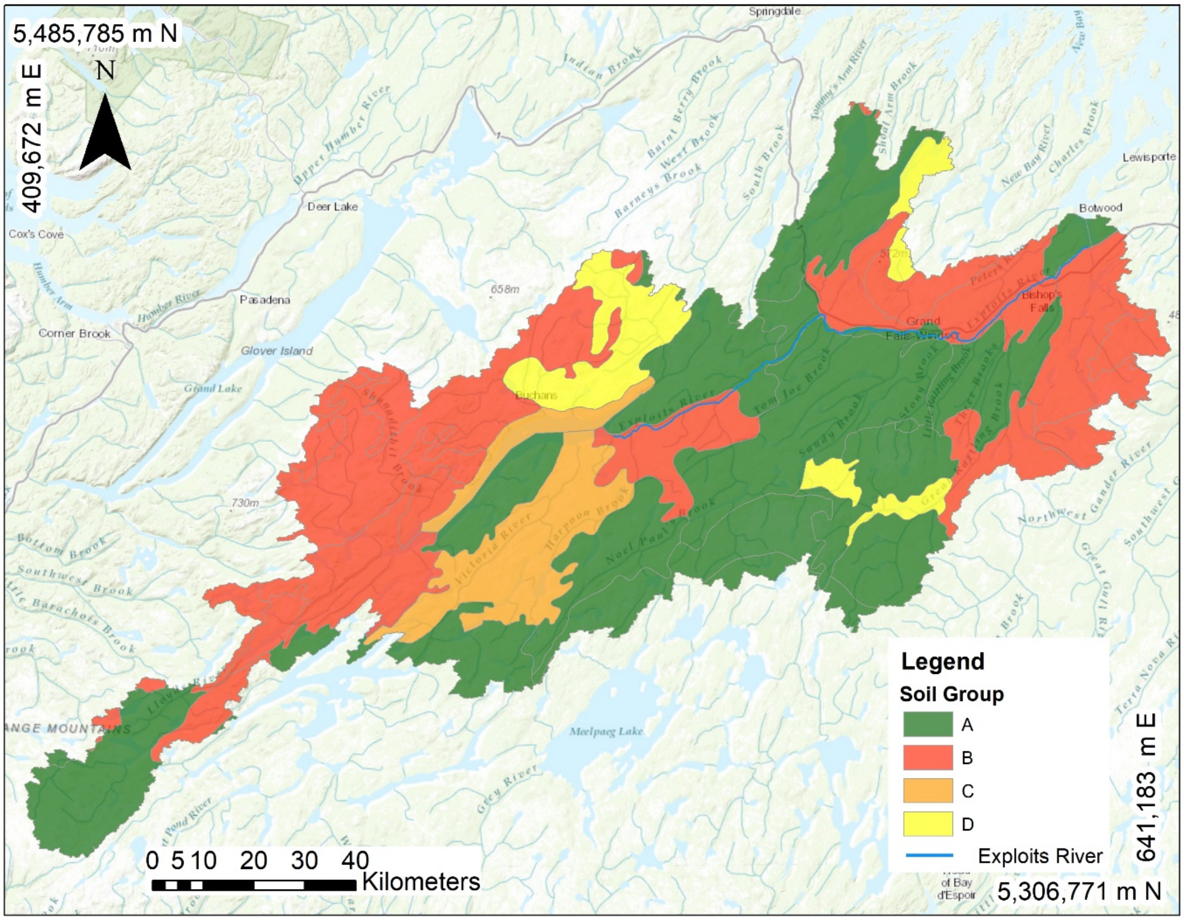

Figure 5-16: Soil Classification

5.4.1.2.3 Estimates of CN

Each combination of hydrologic soil group (soil) and land use class (cover) is associated with a particular CN value. The CN indicates the runoff potential of a soil-cover complex and is valid for periods when the soil is not frozen. CN values are empirical and are subject to causes of variability that may be characterized by the antecedent runoff condition (ARC). ARC is divided into three classes: I for dry conditions, II for average conditions, and III for wetter conditions. WRMD requires that initial estimates of CN be based on the assumption of ARC III. **Table 5-18** summarizes the CNs for soil-cover complexes based on WRMD recommended values. The CN for the urban areas land class (as noted in **Section 5.4.1.2.1**) was taken as the mean of CN values for residential and commercial areas recommended by WRMD.

Table 5-18: CN Values for Soil-Cover Complexes (ARC III)

Land Cover	A	B	C	D
Barren Land	89	94	97	98
Deforested Areas	75	87	92	94
Fields/Pastures/ Open Spaces	59	78	88	91
Forest	50	74	85	89
Waterbodies	100	100	100	100
Wetlands	100	100	100	100
Urban Areas	87	93	96	97
Unclassified	n/a	n/a	n/a	n/a

Using GeoHMS, soil areas were combined with land cover to assign the corresponding CN values from **Table 5-18**. From this, area-weighted average CN values were calculated for each sub-basin. Areas with unclassified land cover were excluded from the weighted average CN value calculation. The CN values varied from 55 to 97, with higher numbers representing more runoff potential. Higher CN values were seen in areas with wetlands and lakes, as well as in urban areas. The CN distribution for the study watershed is summarized in **Figure 5-17** and **Figure 5-18**.

The average CN values for fully developed conditions were calculated using the fully developed polygons shown in **Figure 5-15**. For the sub-basins which contained urban areas, there was a marginal increase in CN between the current and fully developed conditions ranging from 0.001 to 6.4 with an average increase of 1.5. The fully developed CN is not shown in a figure as the increase is too small to be meaningfully displayed.

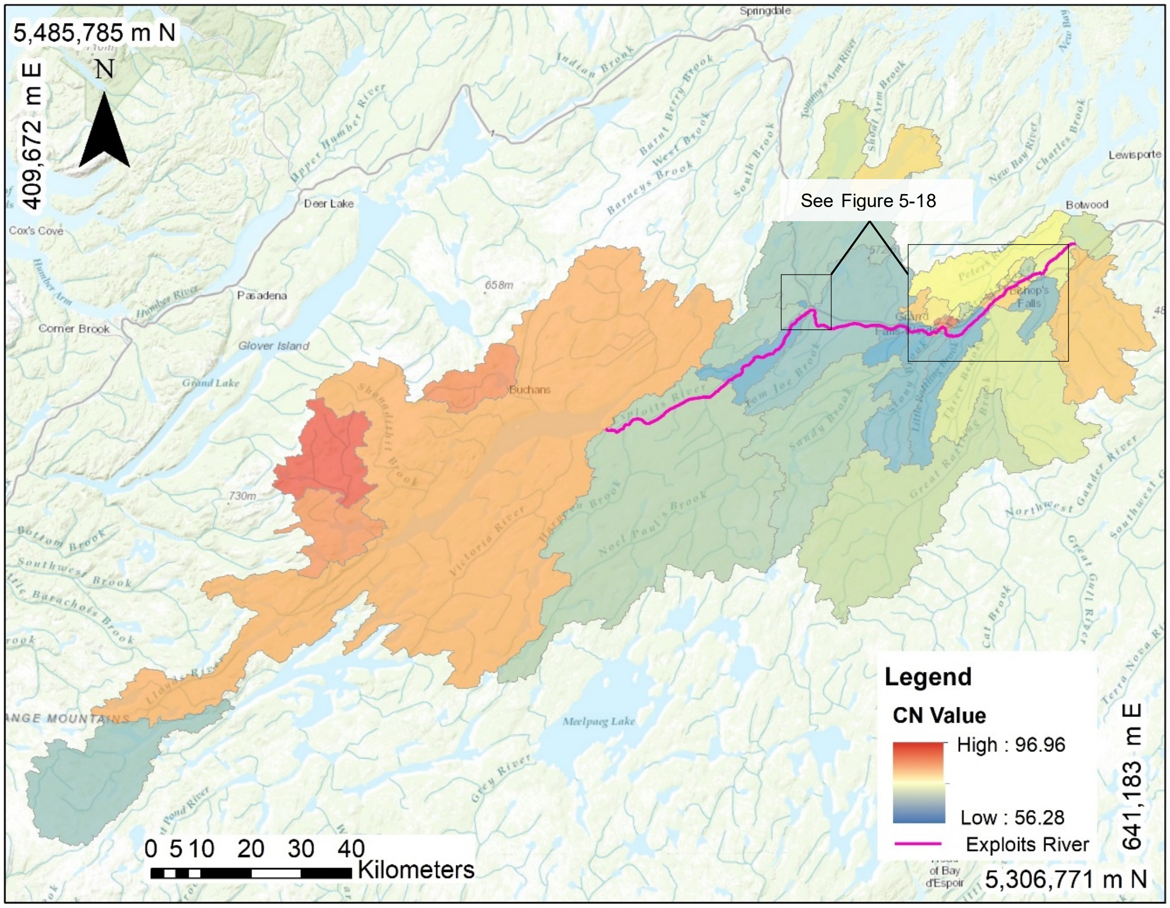

Figure 5-17: CN Distribution – Current Development

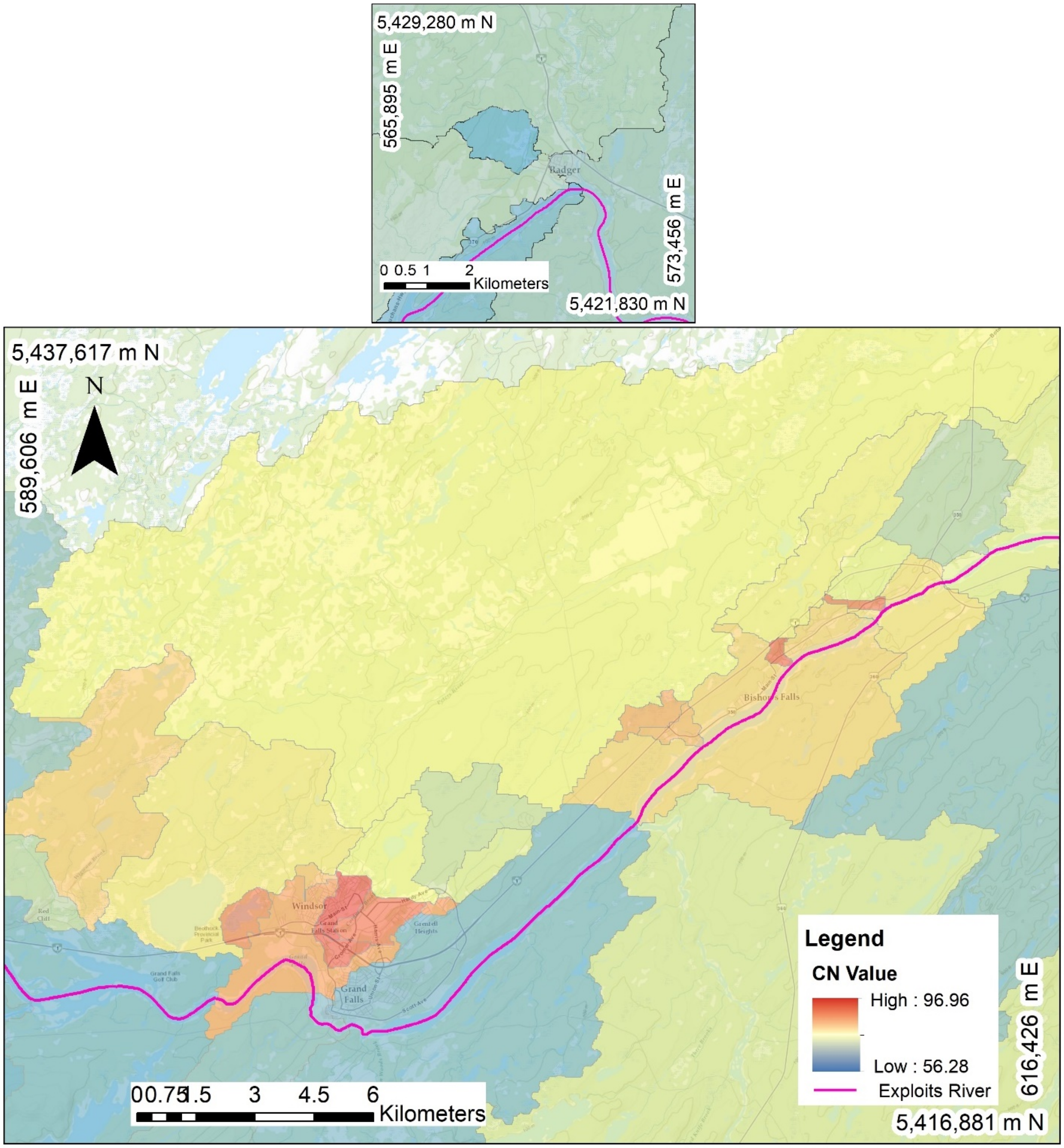

Figure 5-18: CN Distribution in Community Extents – Current Development

5.4.1.3 Loss Method

HEC-HMS computes runoff volume by computing the volume of water that is lost to interception, infiltration, surface storage, evaporation, and transpiration, and subtracting it from the precipitation. Various “loss models” are available within HEC-HMS. For long-term runoff forecasting, the HEC-HMS Technical Reference Manual (USACE, 2000) recommends the use of a continuous type of loss model, i.e., one that accounts for changes in the watershed condition between rainfall events, rather than a single-event model that requires specification of all conditions at the start of each event. The Soil Moisture Accounting (SMA) model is a continuous model whereas the other loss models available in HEC-HMS are event models (such as the SCS CN loss model).

The SMA model simulates the storage and movement of water on and through vegetation, on the soil surface, in the soil profile, and in groundwater layers. Given precipitation and potential evapotranspiration (ET_o), the model computes basin surface runoff, baseflow, groundwater flow, losses due to ET_o, and deep percolation over the entire basin.

The SMA model represents the watershed with a series of storage layers, as illustrated in **Figure 5-19**. Rates of inflow to, outflow from, and capacities of the layers control the volume of water lost or added to each of these storage components. Current storage contents are calculated during the simulation and vary continuously both during and between storms. The different storage layers in the SMA model are:

- Canopy-Interception storage. Canopy interception represents precipitation that is captured on trees and other vegetation and does not reach the soil surface. When precipitation occurs, it first fills canopy storage. Only after canopy storage is filled does precipitation become available to fill other storage volumes. Water in canopy storage is held until it is removed by evaporation.
- Surface-Interception storage. Surface depression storage is the volume of water held in shallow surface depressions. Inflows to this storage come from precipitation not captured by canopy interception and in excess of the infiltration rate. Outflows from this storage can be due to infiltration and to ET_o. Any contents in surface depression storage at the beginning of the time step are available for infiltration. If the surface storage is exceeded the excess water contributes to surface runoff as direct runoff. The resulting runoff hydrograph is computed with one of the transform methods available in HEC-HMS.
- Soil-profile storage. The soil storage represents water stored in the top layer of the soil. Inflow is via infiltration from the surface. Outflows include percolation to a groundwater layer and ET_o.
- Groundwater storage. Groundwater layers in the SMA model represent horizontal interflow processes. Water percolates into groundwater storage from the soil profile. The percolation rate is a function of a maximum percolation rate and the storage in the layers between which the water flows. Losses from a groundwater storage layer are due to groundwater flow or to percolation from one layer to another or to deep percolation, where it is lost to the system. A single groundwater storage layer was used in the Exploits

River basin model and no deep percolation loss was considered. Groundwater flow is treated as inflow to a linear reservoir model to simulate baseflow.

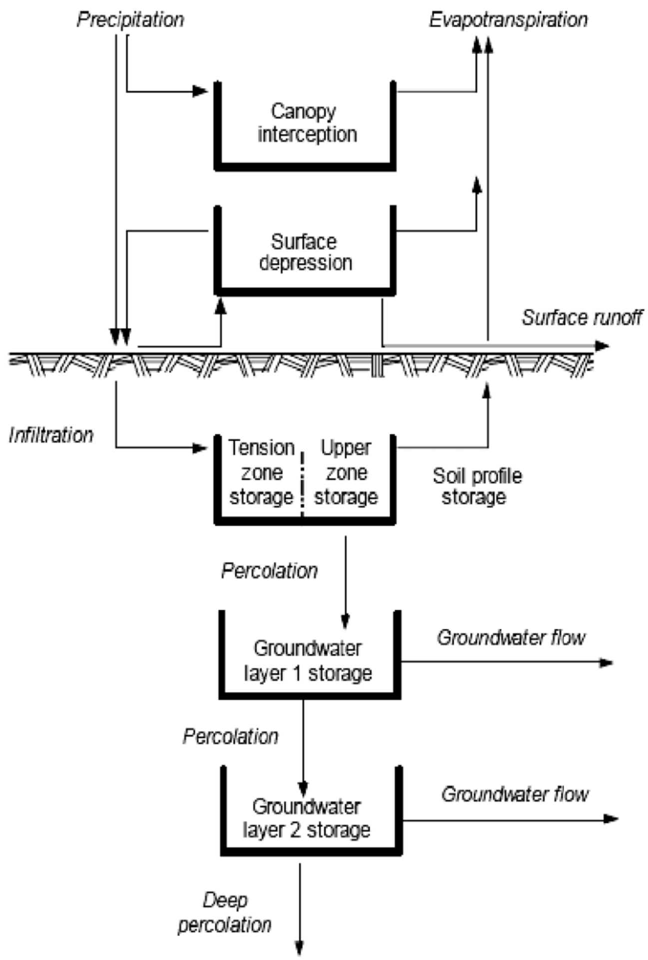

Figure 5-19: HEC-HMS Schematic of the Soil Moisture Accounting Method (Bennet, 1998)

Derivation of SMA model parameters from CN values is presented in **Section 5.4.4**.

5.4.1.4 Transform Method

The method selected to transform excess precipitation to direct runoff in the sub-basin calibration analysis is the modified version of the Clark Unit Hydrograph model (ModClark model). The ModClark method was selected for the transform method, as it is the only method in HEC-HMS that is compatible with the use of gridded precipitation and temperature as required for the flood forecasting system.

The original Clark model derives a watershed unit hydrograph by explicitly representing two critical processes in the transformation of excess precipitation to direct runoff:

- Storage attenuation or reduction of the magnitude of the discharge, as the excess is stored throughout the watershed.
- Translation or movement of the excess from its origin throughout the drainage to the watershed outlet.

Short-term storage of water throughout a watershed – in the soil, on the surface, and in the channels – plays an important role in the transformation of excess precipitation to runoff. Clark uses a linear reservoir function as a representation of this storage. With Clark's model the linear reservoir represents the aggregated impacts of all the watershed storage. The time required for water to move to the watershed outlet is accounted for by a linear channel model.

In the original Clark model, sub-basin characteristics and processes are lumped for each sub-basin. The ModClark model also simulates the storage and translation but is distributed (gridded) to explicitly capture the spatial variability of characteristics and processes within each sub-basin. The runoff volume from each grid cell is computed as the product of grid cell area and precipitation excess. Storage is accounted for with the same linear reservoir model as the Clark method. However, the translation time to the sub-basin outlet is computed for each grid cell using a grid-based travel time method.

The sub-basin input parameters are the Clark linear reservoir coefficient, the time of concentration of the sub-basin, and travel distances for each grid cell to the sub-basin outlet. Travel distances are computed from the watershed DEM by HEC-GeoHMS.

The time of concentration is calculated by HEC-GeoHMS using the Natural Resource Conservation Service (NRCS) TR-55 methodology, as the sum of travel times for overland sheet flow, shallow concentrated flow, and channel flow. Sheet flow and shallow concentrated flow occur over only short distances; given the large sizes of the sub-basins, channel flow is the dominant component. Channel flow travel time is a function of channel flowpath distance as determined in HEC-GeoHMS and user-specified Manning's n.

5.4.1.5 Baseflow Method

The linear-reservoir baseflow model is used in conjunction with the continuous SMA model. Flow out of the groundwater storage layer is routed though a linear reservoir function to simulate baseflow recession. This baseflow model simulates the storage and movement of subsurface flow as storage and movement of water through reservoirs.

5.4.1.6 Snowmelt Method

The snowmelt method in HEC-HMS is a temperature index approach that computes the liquid water available at the soil surface which is then subject to infiltration and surface runoff. The gridded form of this method is designed to work with the ModClark transform method.

5.4.1.7 Channel Routing Method

In HEC-HMS, channel flow routing through river elements can be modelled using one of several methods. The purpose of the channel flow routing is to model flood hydrograph travel time, modification and attenuation, accounting for the effects of wave speed, storage and friction as the flow passes through the river channel. The Muskingum-Cunge routing model was used as it is the only routing method compatible with gridded meteorological data, which is needed for flood forecasting in HEC-RTS. Representative channel widths and side slopes were determined from ArcGIS imagery and previously surveyed data sections in the study area. On streams other than the Exploits River, a Manning's n (roughness) of 0.045 for small streams and 0.035 for larger streams was used. On the Exploits River, a calibration/validation exercise was conducted for this value as summarized in **Section 5.4.3**.

5.4.1.8 Reservoir Storage and Discharge Characteristics

Five storage dams operated by Nalcor and their associated reservoirs were included in the HEC-HMS hydrologic model: Millertown Dam (Red Indian Lake), North Twin, South Twin, Star Lake and Buchans Lake. Goodyear's, Grand Falls and Bishops Falls Dams on the Exploits River were not represented in the hydrologic model as they are run-of-river structures with negligible storage routing (attenuation) effects on flood peaks.

HEC-HMS simulates the routing of flow through a reservoir via level-pool computations that require a known relationship between storage and discharge. Elevation-storage and storage-discharge curves for the five modelled dams were compiled from the 2017 Exploits River flood study (Hatch, 2017). Star Lake Dam has a fixed-crest overflow spillway, while Buchans, North Twin, and South Twin Dams are gated structures but are very infrequently operated. These dams have little impact on the downstream flood regime of the Exploits River as the reservoirs control relatively small portions of the overall drainage area, and two of them (Star Lake and Buchans) are located upstream of the main storage at Millertown Dam. Consequently it was reasonable to represent these dams with fixed elevation-storage-discharge relationships (HEC-HMS is not able to model gate discharges unless they are uniquely a function of storage).

However, the storage at Red Indian Lake and gate operations at Millertown Dam have significant potential to impact downstream flood flows. Historically, large floods on the Exploits River have not coincided with large releases from Millertown Dam. It was observed that historical releases from Millertown Dam varied significantly, independent of the reservoir levels in Red Indian Lake. Hatch has confirmed with Nalcor operators that the releases are dependent on a variety of factors, and that dam outflows are not based on any simple equations or operation procedures. Because of the variable operations and the unknowns, the HEC-HMS model is not able to recreate the operations at the structure. Different approaches were taken to model flow through Millertown Dam for each phase of the project:

- During calibration, known outflows from Millertown Dam as provided in Nalcor records and other historical documentation were input as specified time series of releases (i.e., a fixed internal boundary condition). This essentially forces the model with the correct flow at the upstream end of the Exploits River at all times in calibration events.

- During the model runs of the 1:20 and 1:100 AEP rainfall events, the model was run twice for each event, to represent a range of flow releases through Millertown Dam. First, the spillway gates were modelled as closed, with no spill from Red Indian Lake. Second, the spillway gates were modelled as fully open.
- During implementation of the flood forecasting system, the last recorded outflow at gauge 02YO016 at Millertown Dam will be extended to the end of the simulation.

LiDAR and field survey data were used to derive volume and discharge characteristics for lake, wetland and floodplain areas with significant storage routing effects in Corduroy Brook and Unnamed Streams BF-1 and BF-3.

5.4.2 Initial Sub-Basin Model Calibration

The first step in calibrating the HEC-HMS model of the Exploits River watershed involved the calibration of the response of individual sub-basins for the range of hydrometeorological inputs likely to be experienced during the use of the continuous flood forecasting model.

During flood events, outflows from Red Indian Lake into the Exploits River are controlled by the operation of Millertown Dam, while downstream tributary inflows to the Exploits River are largely unregulated. Thus, sub-basin calibration concentrated on unregulated tributaries where WSC maintains active hydrometric gauges.

Sub-basin calibration for a continuous hydrological model requires the following information:

- A historical flow record unaffected by upstream regulation.
- A precipitation record concurrent with the flow record.
- A temperature record to determine whether precipitation falls as rainfall or snow.
- Evapotranspiration data or estimation method.

5.4.2.1 Historical Flow Records

Historical flow records from three WSC hydrometric gauges were selected for the sub-basin calibration:

- Great Rattling Brook above Tote River Confluence (02YO008).
- Peters River near Botwood (02YO006).
- Southwest Brook at Lewisporte (02YO012).

Details for these three gauges are shown in **Table 5-1**.

5.4.2.2 Precipitation Data

Daily precipitation data were extracted from station 8400301 Badger (AUT) for the period 2013 to 2017, which is the closest Environment Canada climate station (with suitable data) to the three sub-basins listed above.

5.4.2.3 Temperature Data

Daily temperature data were extracted from climate station 8401700 Gander International Airport, elevation of 151.2 m. These temperature data were lapsed to each sub-basin using an assumed lapse rate of 6.0°C/1000 m. The lapse rate is the rate at which temperature varies with changes in elevation.

5.4.2.4 Evapotranspiration

A preliminary estimate of mean annual evapotranspiration loss of 380 mm/year for the Exploits River basin was taken from the Hydrological Atlas of Canada (Canada Surveys and Mapping Branch, 1978). This value was subsequently increased to 430 mm/year in the loss model, where it is used as potential evapotranspiration (ET_o). Monthly ET_o values were used as shown in **Table 5-19** below.

Table 5-19: Monthly Evapotranspiration Values – Initial Model

Month	Rate (mm/month)
January	0
February	0
March	0
April	0
May	29
June	112
July	113
August	92
September	57
October	27
November	0
December	0

5.4.2.5 Calibration Methodology

A review of precipitation records in and around the Exploits River basin shows that precipitation is very variable, both geographically and on a day-to-day basis. Geographically, mean annual precipitation decreases from the southwest to the northeast across the basins, although mean annual precipitation is more uniform downstream from Millertown Dam.

On a day-to-day basis it is not unusual for precipitation to vary significantly throughout the basin. This means that, with the limited precipitation gauge coverage in and around the Exploits River basin, it is difficult to estimate the precipitation received by any one sub-basin. To address precipitation uncertainty, Badger precipitation was applied to each sub-basin using a proration factor so as to maintain the water balance (match the simulated average runoff to the observed average runoff at each gauge).

Thereafter, the key variable model parameters that affect simulated sub-basin outflows were adjusted for the three WSC sub-basins, as follows:

- Baseflow method: baseflow linear reservoir coefficient.

- Loss method (SMA): Maximum infiltration rate, maximum surface storage.
- Transform method: ModClark linear reservoir coefficient.

The baseflow coefficient was adjusted so as to match the observed hydrograph recession. The maximum infiltration rate and maximum storage in the surface affect the simulated runoff volumes and were adjusted to match the observed hydrographs. The ModClark linear coefficient affects the simulated flood peak magnitudes and volume, and was adjusted to match observed peak magnitudes. Initial conditions and parameters in this model shown in **Table 5-25** were selected based on past experience in similar watersheds.

5.4.2.6 Calibration Results

5.4.2.6.1 Flow Duration Curves

Flow duration curves present the percent of time flow is greater than or equal to a specific value. Since the precipitation over each sub-basin was adjusted to reproduce the mean annual flow during the calibration period (2013 to 2017), the best measure of how well simulated flows match measured flows is by comparing flow duration curves. **Figure 5-20** to **Figure 5-22** present observed and simulated flow duration curves for WSC gauges 02YO008, 02YO006 and 02YO012.

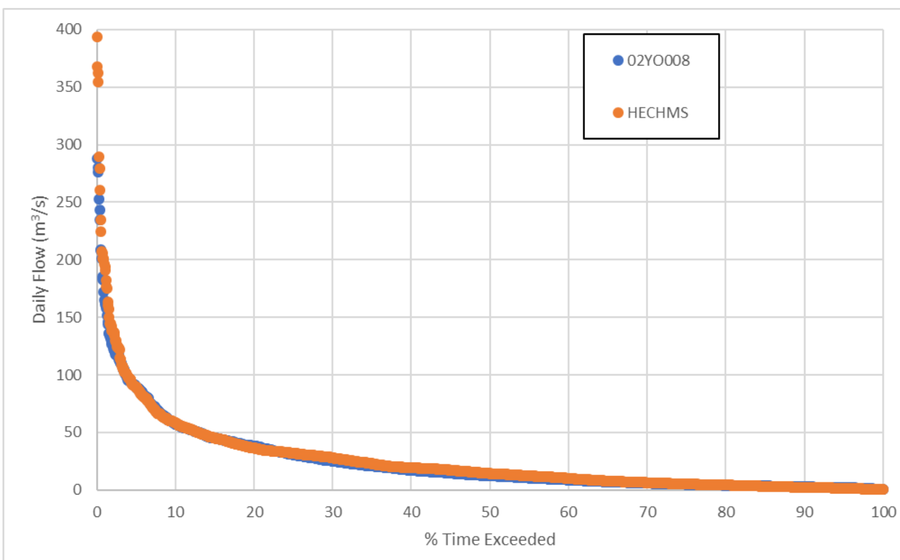

Figure 5-20: Flow Duration Curve for 02YO008

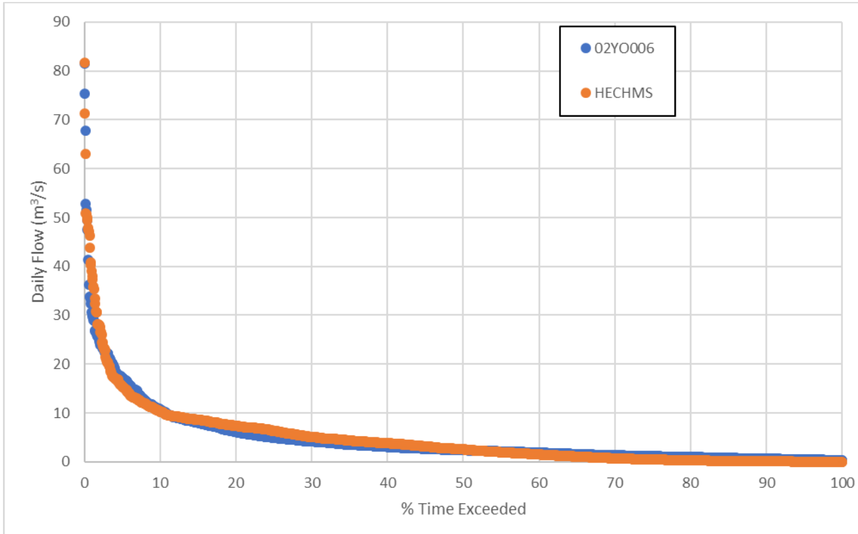

Figure 5-21: Flow Duration Curve for 02YO006

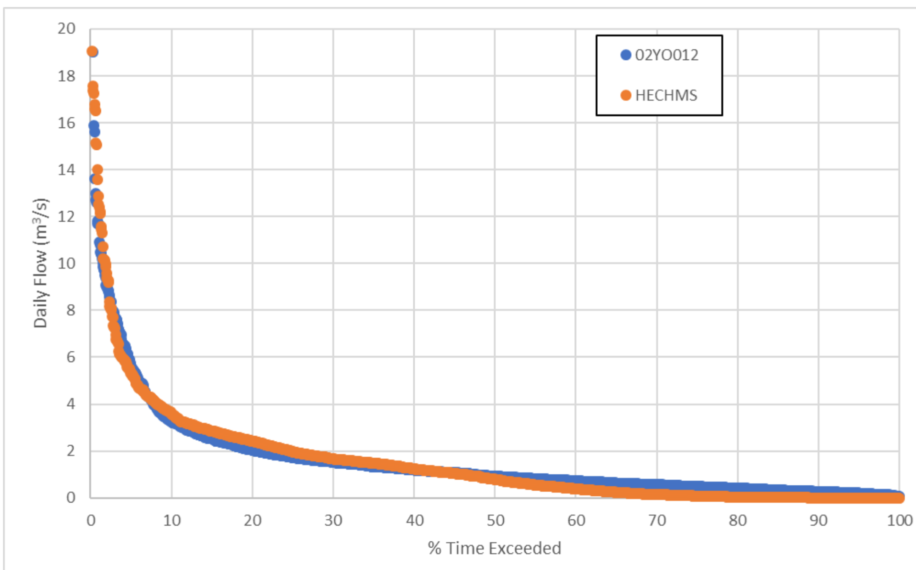

Figure 5-22: Flow Duration Curve for 02YO012

Figure 5-20 to **Figure 5-22** show that the calibrated sub-basin models reproduce the measured flow duration curves well, especially in the high flow portion of the curves, which are of principal interest for flood forecasting.

5.4.2.6.2 Daily Flow Hydrographs

Figure 5-23 to **Figure 5-25** present the recorded and simulated daily flow hydrographs for WSC gauges 02YO008, 02YO006 and 02YO012. The simulated hydrographs show similar shapes and timing as the recorded flow hydrographs, but do not always reproduce the observed flood hydrographs. As noted earlier, one contributor to model uncertainty is the difficulty in using the data from the Badger climate station to accurately capture storm events that occurred over each sub-basin.

Precipitation inputs in the final flood forecasting model will be in the form of a gridded mesh. It is anticipated that this will provide higher quality precipitation coverage for all sub-basins in the model and so enable a correspondingly improved simulation of expected flows. The routing calibration in **Section 5.4.3** and full model calibration and validation in **Section 5.4.4** further refine the model parameters to better match observed flows. R^2 values for the values in **Figure 5-23** to **Figure 5-25** are 0.37 for 02YO008, 0.55 for 02YO006 and 0.49 for 02YO012.

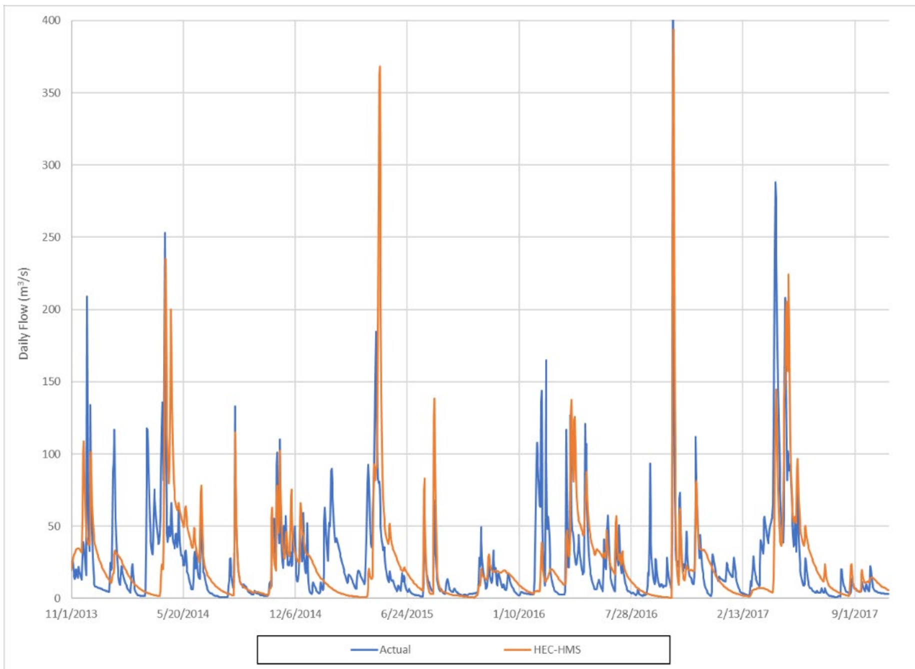

Figure 5-23: Daily Flow Hydrographs for 02YO008

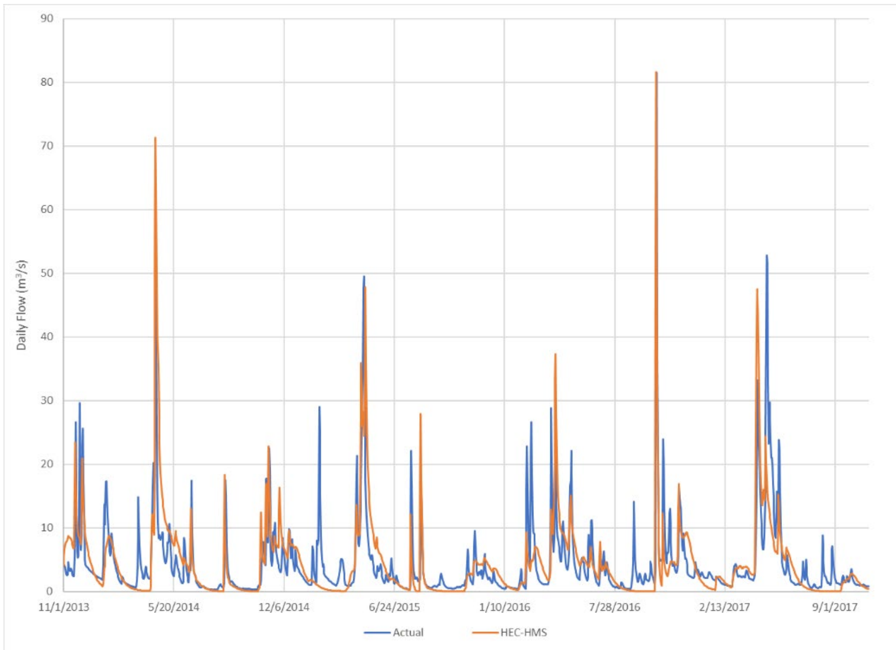

Figure 5-24: Daily Flow Hydrographs for 02YO006

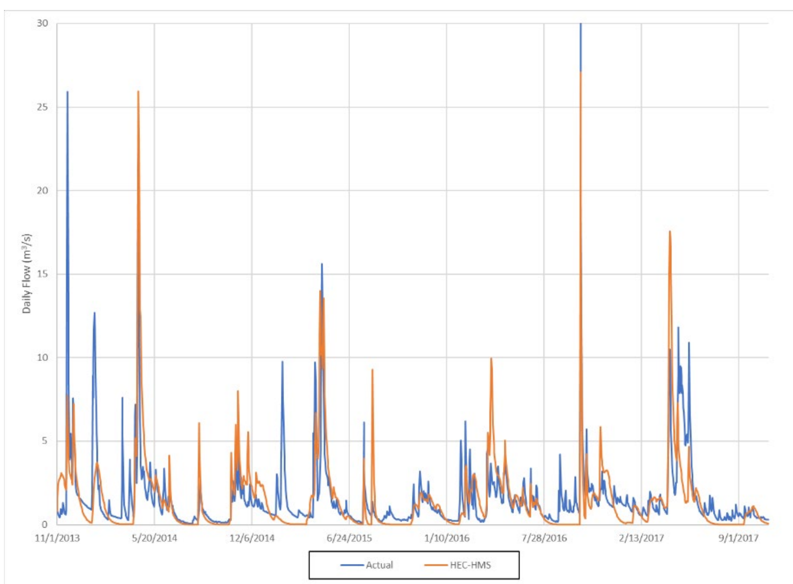

Figure 5-25: Daily Flow Hydrographs for 02YO012

5.4.3 Channel Routing Calibration

The time of the observed and modelled flood peaks should match. Major releases from Millertown Dam took place in April and May 2013. The progress of these releases down the Exploits River was tracked and the Manning's n roughness coefficient was adjusted until the time of the modelled rising limb and peak matched the observed time as shown in **Figure 5-26**. The Manning's n was set to 0.027 between Millertown Dam and Badger, and 0.032 between Badger and the outlet.

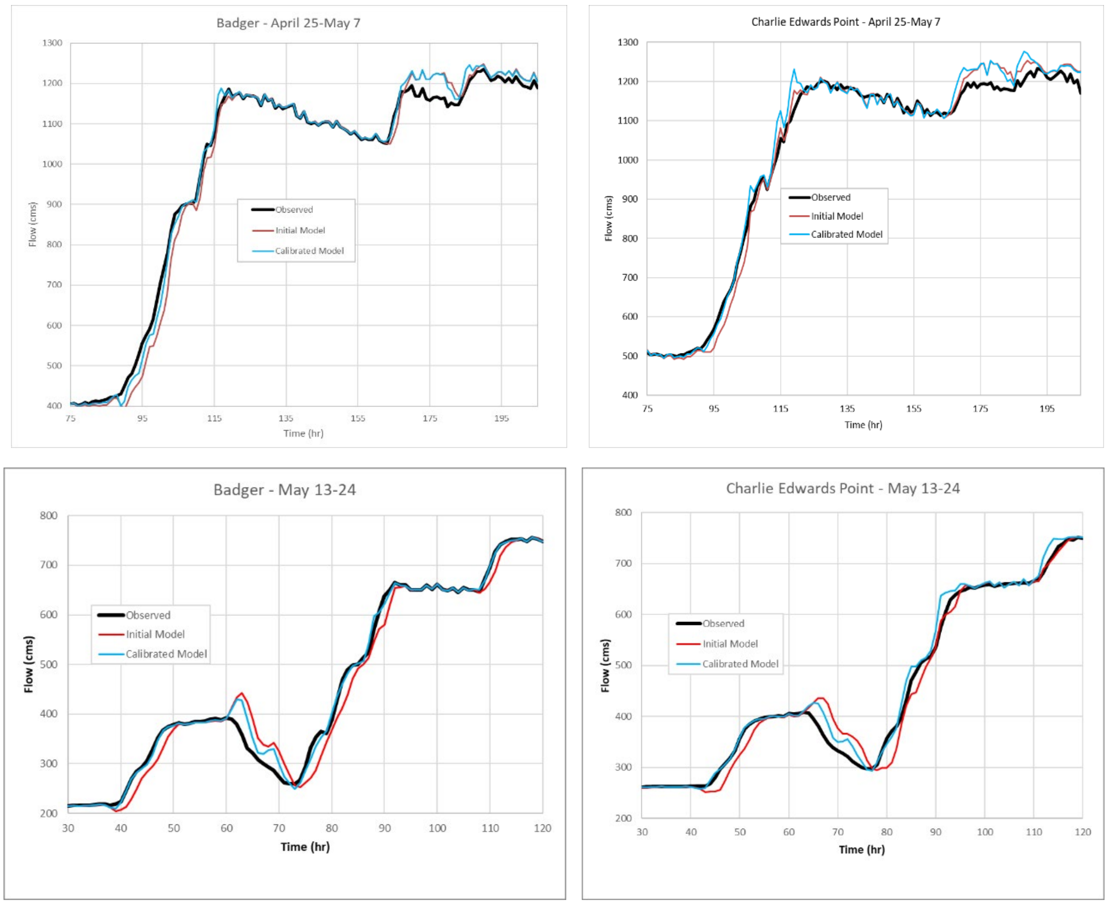

Figure 5-26: Routing Calibration Results

5.4.4 Full Model Calibration and Validation

5.4.4.1 Historic Events

The full watershed model was calibrated in HEC-HMS to two historic flood peak events:

- Fall flood event (rainfall-only, no snow): Hurricane Matthew, October 2016.
- Spring flood event (rainfall and snowmelt): April 2018.

The model was then validated against two historic flood peak events:

- Spring flood event (rainfall and snowmelt): May 2003.
- Winter flood event (rain-on-snow): January 1983.

Hurricane Igor in September 2010 was also expected to be used for validation as a fall flood event, but observed flows in general exceeded modelled flows at the gauge locations. Hurricane Igor was predominantly focused to the east of the Exploits watershed, and the precipitation was not well captured in the climate stations around the Exploits basin. Gridded precipitation data obtained from Environment Canada also did not show sufficiently high rainfall to increase modelled flows to the levels observed by WSC gauges. Due to these data limitations, Hurricane Igor was not used as a validation event.

5.4.4.2 Methodology

The full model calibration and validation included a refinement of the infiltration, tension zone storage, upper zone storage, baseflow, groundwater, evapotranspiration and temperature parameters. The ModClark time of concentration and storage parameters, as well as select temperature parameters, were adjusted through an iterative process as modelled discharge was compared to observed discharge. Fleming and Neary (2004) and Cunderlik and Simonovic (2004) were instrumental in determining which parameters should be modified.

5.4.4.2.1 Infiltration, Tension Zone Storage and Upper Zone Storage

The maximum infiltration, tension zone storage and upper zone storage parameters in the Soil Moisture Accounting Loss process were set based on CN values and soil classification as determined in **Section 5.4.1.2**.

Koren et al (2000) related CN values to upper and tension zone storage using the porosity, field capacity and wilting point of the soil. Rawls (1983) provided relationships between soil classification and the porosity, field capacity and wilting point of the soil.

The CN in Koren’s relationship used average CN conditions represented by Antecedent Runoff Conditions (ARC) Class II; the CN values developed in **Section 5.4.1.2** were developed in the wetter ARC III class. The US Department of Agriculture Natural Resources Conservation Service (NRCS) provided a relationship between ARC II and III (2004).

Maximum infiltration values were related to soil classification through a relationship provided by the US Department of Agriculture’s NRCS (2010).

The maximum infiltration values ranged from 1.1 to 10.9 mm/hr for current and fully developed conditions. Upper zone storage values ranged from 4.4 to 89.7 mm for current development conditions and 4.4 to 86.6 mm for fully developed conditions. Tension zone storage values ranged from 0.6 to 16.2 mm for current development conditions and 0.6 to 14.9 mm for fully developed conditions.

5.4.4.2.2 Baseflow and Groundwater

The Soil Percolation parameter in the Soil Moisture Accounting Loss process of 0.0244 mm/h was obtained from the mean annual baseflow in the Exploits watershed region as recorded in “Hydrogeology of Central Newfoundland” (AMEC 2013).

The initial GW 1 Baseflow parameters in the baseflow process were set by taking the mean annual runoff in the Exploits basin from the Water Resources Atlas of Newfoundland (Water Resources Division, 1992) and relating it to the drainage area of each subbasin. The initial subbasin baseflow parameters range from 0.001 to 94.2 m^3/s.

An equation correlating the baseflow GW 1 Coefficient parameter and drainage area in the baseflow process was determined using the initial sub-basin calibration. This was used to set the baseflow coefficient for each sub-basin. The subbasin coefficients range from 13.5 to 982.8 hours.

5.4.4.2.3 Evapotranspiration

A revised estimate of mean annual evapotranspiration loss of 500 mm/year for the Exploits River basin was taken from the Water Resources Atlas of Newfoundland (Water Resources Division, 1992). Monthly ET_o values were used as shown in **Table 5-20** below.

Table 5-20: Monthly Evapotranspiration Values – Full Model

Month	Rate (mm/month)
January	0
February	0
March	0
April	0
May	34
June	130
July	131
August	107
September	66
October	31
November	0
December	0

5.4.4.2.4 Time of Concentration and Storage

The time of concentration and storage parameters used in the ModClark transform process were adjusted to match observed peaks.

The time of concentration values were initially determined through HEC-GeoHMS tools. The time of concentration was then modified to match the timing of observed peaks at Noel Pauls gauge and Great Rattling gauge. Final time of concentration values ranged from 0.3 to 71.5 hours.

Storage parameter values were manually adjusted for the subbasins upstream of the Noel Pauls, Lloyds River, Star Lake, Great Rattling Brook and Peters River gauges to match modelled peaks with observed data. Sabol (1988) proposed a method for relating the Clark storage parameter to time of concentration, subbasin area and length of the longest watercourse. From this relationship, the storage parameter values for all other subbasins were estimated.

Storage parameter values ranged from 0.9 to 258.6 hours.

5.4.4.2.5 Temperature and Melt Parameters

As observed precipitation data is generally available only in mm (which may be rainfall, snow-water equivalent or a mix of both), a discrimination temperature (PX temperature) is required for the model to decide whether to simulate the precipitation as rain or snow. When the air temperature is less than the specified PX temperature, precipitation is assumed to be snow. When the air temperature is above the PX temperature, any precipitation is assumed to be rain. A base temperature is required to calculate snowmelt. If the air temperature is less than the base temperature, the amount of melt is zero. The meltrate is multiplied by the difference between the air temperature and the base temperature. The HEC-HMS manual states that the base temperature default is 0°C, and that the PX temperature can range up to 1°C. Both the PX and base temperatures were set to 0°C in the full model calibration to match observed conditions.

Meltrates were adjusted to match observed runoff. A constant dry meltrate of 2 mm/°C-day was selected, which is within the recommended range of 1-4 mm outlined in the HEC-HMS manual. The wet meltrate and rain rate limit were selected to model the effects of a rain-on-snow event. The rain rate limit determines which meltrate is applied; if more precipitation is falling than the rain rate limit, the wet meltrate is used. A rain rate limit of 20 mm/day and wet meltrate of 10 mm/°C-day were selected in order to model the accelerated meltrate observed during heavy rain-on-snow events such as observed in 1983 and 2018.

5.4.4.3 Results

Results for the four calibration and validation events are provided below. As with the initial sub-basin calibration, the simulated hydrographs show similar shapes and timing as the recorded flow hydrographs, but do not always reproduce the observed flood hydrographs. This is likely due to the difficulty in capturing storm events that occurred over each sub-basin but did not occur over the climate stations. The best match between modelled and observed data is found for the 2016 Hurricane Matthew event, which used gridded data from Environment Canada over the storm’s duration. As stated previously, precipitation inputs in the final flood forecasting model will be in the form of a gridded mesh, from Environment Canada’s High Resolution Deterministic Prediction System (HRDPS). It is expected that this will provide more precise and spatially varying precipitation coverage for all sub-basins in the model and so enable a correspondingly improved simulation of expected flows.

Model goodness-of-fit was assessed using the coefficient of determination R^2 and Nash Sutcliffe Efficiency (NSE). NSE indicates the overall agreement between modeled and observed hydrographs, and can range from negative infinity to 1, with 1 corresponding to a perfect match between modeled and observed data. For flood mapping and forecasting, the accuracy of the modeled peak flow is also of particular interest, and therefore the peak flow error and percent error are included as additional indicators.

5.4.4.3.1 Calibration Fall Event – Hurricane Matthew, October 2016

Hurricane Matthew observed data included hourly flows at Noel Pauls, Badger, Charlie Edwards Point and Great Rattling Brook gauges. Daily flows were available at Grand Falls Dam and the Lloyds River, Peters River and Star Brook gauges. Gridded 6-hour CaPA precipitation data was obtained for the storm's duration, with point temperature and precipitation data at the stations indicated in **Table 5-2** used for the remainder of the simulation.

The goodness-of-fit between the modelled and observed events is generally good for flows resulting from Hurricane Matthew, with the R^2 and Nash-Sutcliffe values ranging from 0.52 to 0.94 as shown in **Table 5-21** and **Figure 5-27** below.

Table 5-21: Maximum Observed and Modelled Flows for 2016 Event

Gauge	Maximum Flows (m^3/s)				R^2	NSE
	Modelled	Observed	Diff	% Diff		
02YO011 - Exploits River at Noel Pauls Brook	746	780	-34	-4%	0.88	0.82
02YO013 - Exploits River at Badger	824	965	-141	-15%	0.91	0.89
02YO018 - Exploits River at Charlie Edwards Point	1073	995	77	8%	0.80	0.52
02YO001 - Exploits River at Grand Falls	1286	1088	197	18%	0.83	0.68
02YN002 - Lloyds River Below King George IV Lake	152	153	-1	-1%	0.88	0.85
02YN004 - Star Brook Above Star Lake	131	134	-3	-2%	0.73	0.624
02YN008 - Great Rattling Brook Above Tote River Confluence	583	590	-7	-1%	0.94	0.88
02YN006 - Peters River Near Botwood	90	82	8	10%	0.86	0.85

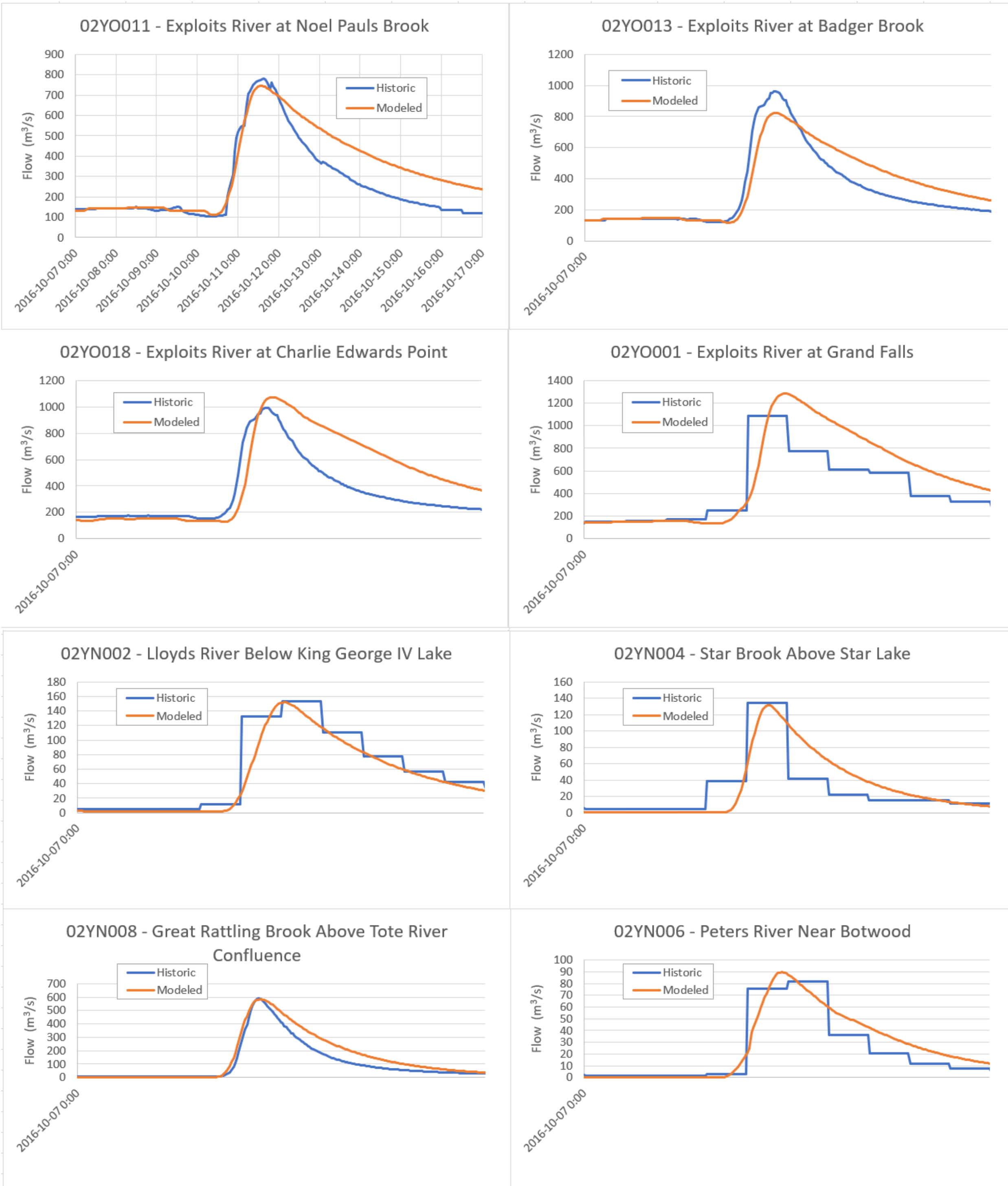

Figure 5-27: Observed and Modelled Flows for 2016 Event

5.4.4.3.2 Calibration Spring Flood Event – 2018

The observed data for the spring flood event of 2018 included hourly flows at Noel Pauls, Badger, Charlie Edwards Point and Great Rattling Brook gauges. Daily flows were available at Grand Falls Dam and the Lloyds River, Peters River and Star Brook gauges. Gridded 6-hour CaPA precipitation data was obtained for the significant rain-on-snow event on April 29, 2018, with point temperature and precipitation data at the stations indicated in **Table 5-2** used for the remainder of the simulation.

The goodness-of-fit between the modelled and observed events is generally good, with the R^2 and Nash-Sutcliffe values on the Exploits River ranging from 0.68 to 0.94 shown in **Table 5-22** and **Figure 5-28** below.

Table 5-22: Maximum Observed and Modelled Flows for 2018 Event

Gauge	Maximum Flows (m^3/s)				R^2	Nash-Sutcliffe
	Modelled	Historic	Diff	% Diff		
02YO011 - Exploits River at Noel Pauls Brook	894	849	45	5%	0.94	0.93
02YO013 - Exploits River at Badger	924	1007	-83	-8%	0.93	0.92
02YO018 - Exploits River at Charlie Edwards Point	1189	1419	-230	-16%	0.84	0.69
02YO001 - Exploits River at Grand Falls	916	1137	-221	-19%	0.70	0.68
02YN002 - Lloyds River Below King George IV Lake	188	247	-59	-24%	0.54	0.50
02YN004 - Star Brook Above Star Lake	147	172	-25	-14%	0.67	0.562
02YN008 - Great Rattling Brook Above Tote River Confluence	226	302	-77	-25%	0.47	0.43
02YN006 - Peters River Near Botwood	48	54	-6	-10%	0.51	0.43

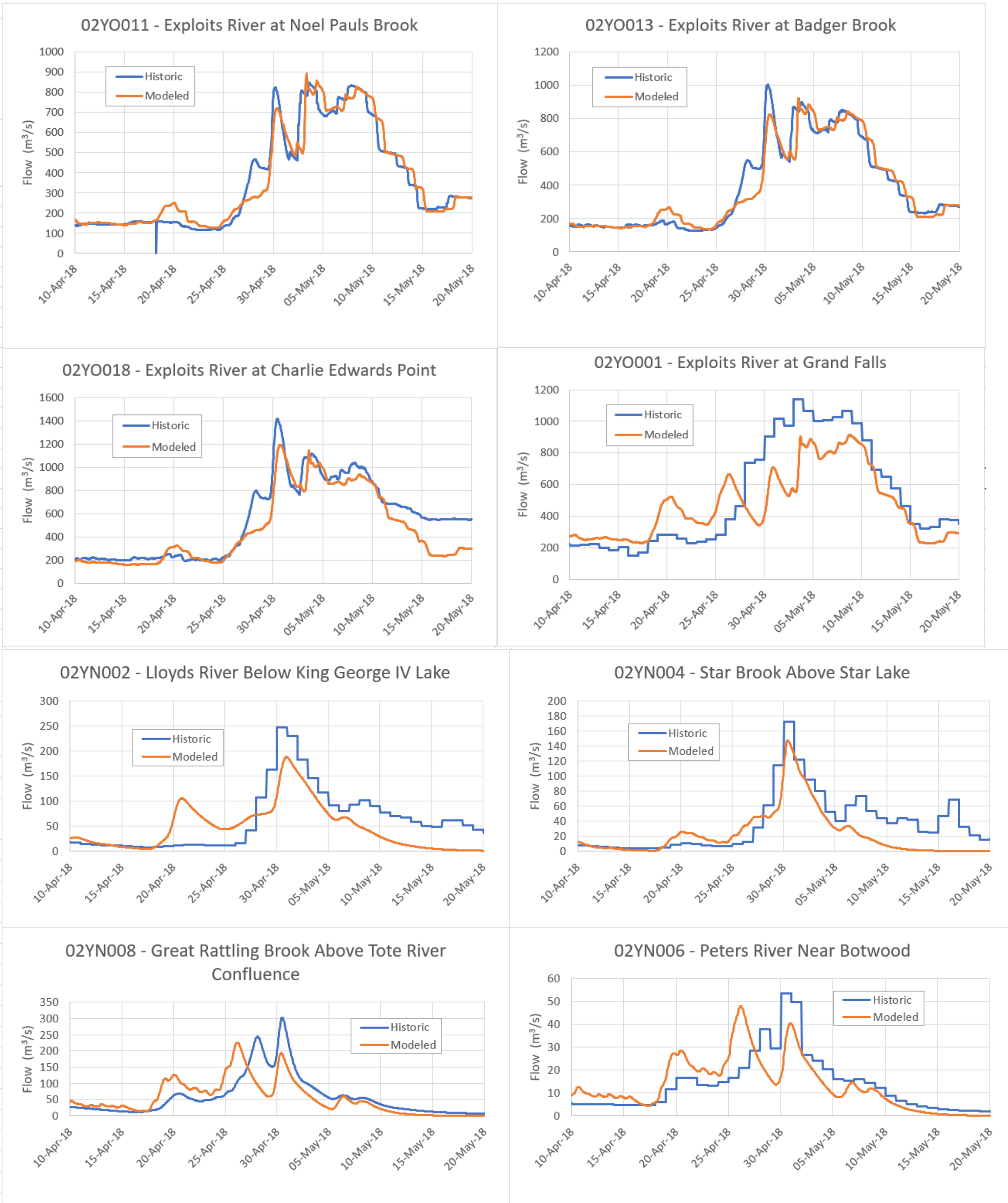

Figure 5-28: Observed and Modelled Flows for 2018 Event

5.4.4.3.3 Validation Spring Flood Event – 2003

The observed data for the spring flood event of 2003 included hourly flows at Noel Pauls and Great Rattling Brook gauges. Daily flows were available at Grand Falls Dam and the Lloyds River, Peters River and Star Brook gauges. Point temperature and precipitation data at the stations indicated in **Table 5-2** was used for the simulation.

The goodness-of-fit between the modelled and observed events is generally good on the Exploits River, with the R^2 and Nash-Sutcliffe values on the Exploits River ranging from 0.57 to 0.84 as shown in **Table 5-23** and **Figure 5-29** below. The model is less accurate at the Lloyds River and Star Brook upstream of the Millertown Dam, however, these gauges are included for comparison purposes only as the model flows are specified at Millertown Dam. It is possible that the precipitation distribution is less well captured by the available gauges for the 2003 event, which is why the modeled runoff doesn't match the historic runoff as well as for other events.

Table 5-23: Maximum Observed and Modelled Flows for 2003 Event

Gauge	Maximum Flows (m^3/s)				R^2	Nash-Sutcliffe
	Modelled	Historic	Diff	% Diff		
02YO011 - Exploits River at Noel Pauls Brook	1316	1560	-244	-16%	0.84	0.83
02YO001 - Exploits River at Grand Falls	1552	1787	-235	-13%	0.64	0.57
02YN002 - Lloyds River Below King George IV Lake	150	177	-27	-15%	0.33	0.11
02YN004 - Star Brook Above Star Lake	150	119	31	26%	0.05	-0.613
02YN008 - Great Rattling Brook Above Tote River Confluence	258	261	-3	-1%	0.38	0.19
02YN006 - Peters River Near Botwood	52	59	-7	-11%	0.41	0.18

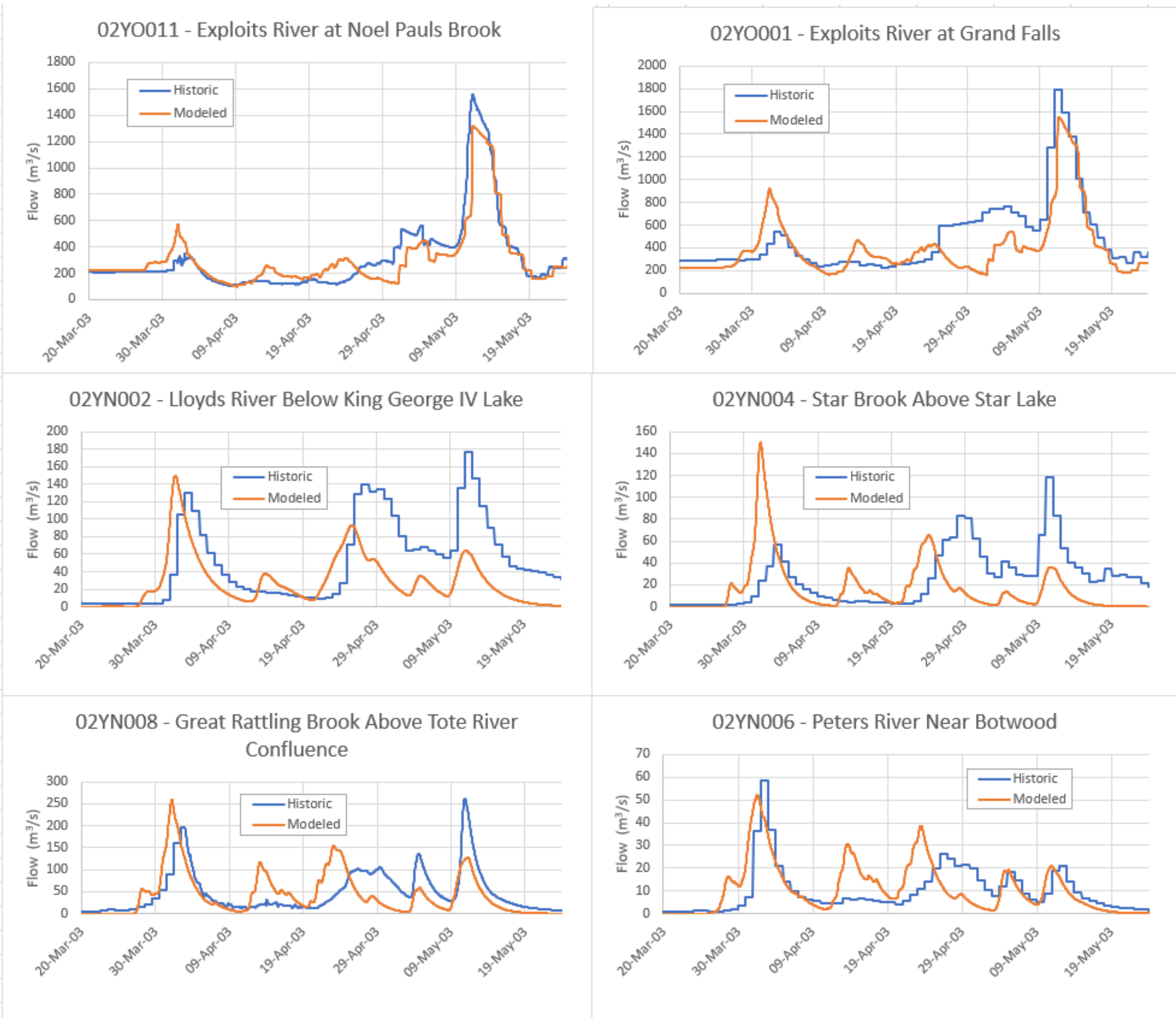

Figure 5-29: Observed and Modelled Flows for 2003 Event

5.4.4.3.4 Validation Winter Flood Event – 1983

The observed data for the winter rain-on-snow flood event of 1983 included daily flows at Grand Falls, Sandy Brook, Peters River and Lloyds River gauges. The Environment Canada and Government of Newfoundland and Labrador event report (1985) provided six-hour point precipitation observations during the event at several locations as well as isoline maps of estimated snow water equivalent on the ground at the beginning of the event. Daily point temperature and precipitation data at the stations indicated in **Table 5-2** was used for the remainder of the simulation.

The agreement between the modelled and historic events is generally good, with the R^2 and Nash-Sutcliffe values on the Exploits River around 0.85 as shown in **Figure 5-30** and **Table 5-24** below.

Table 5-24: Maximum Observed and Modelled Flows for 1983 Event

Gauge	Maximum Flows (m^3/s)				R^2	Nash-Sutcliffe
	Modelled	Historic	Diff	% Diff		
02YO005 - Exploits River Below Stony Brook	1769	2090	-321	-15%	0.86	0.85
02YN002 - Lloyds River Below King George IV Lake	182	285	-103	-36%	0.82	0.78
02YO004 - Sandy Brook At Sandy Brook Powerhouse	234	507	-273	-54%	0.93	0.682
02YN006 - Peters River Near Botwood	147	131	16	12%	0.73	0.34

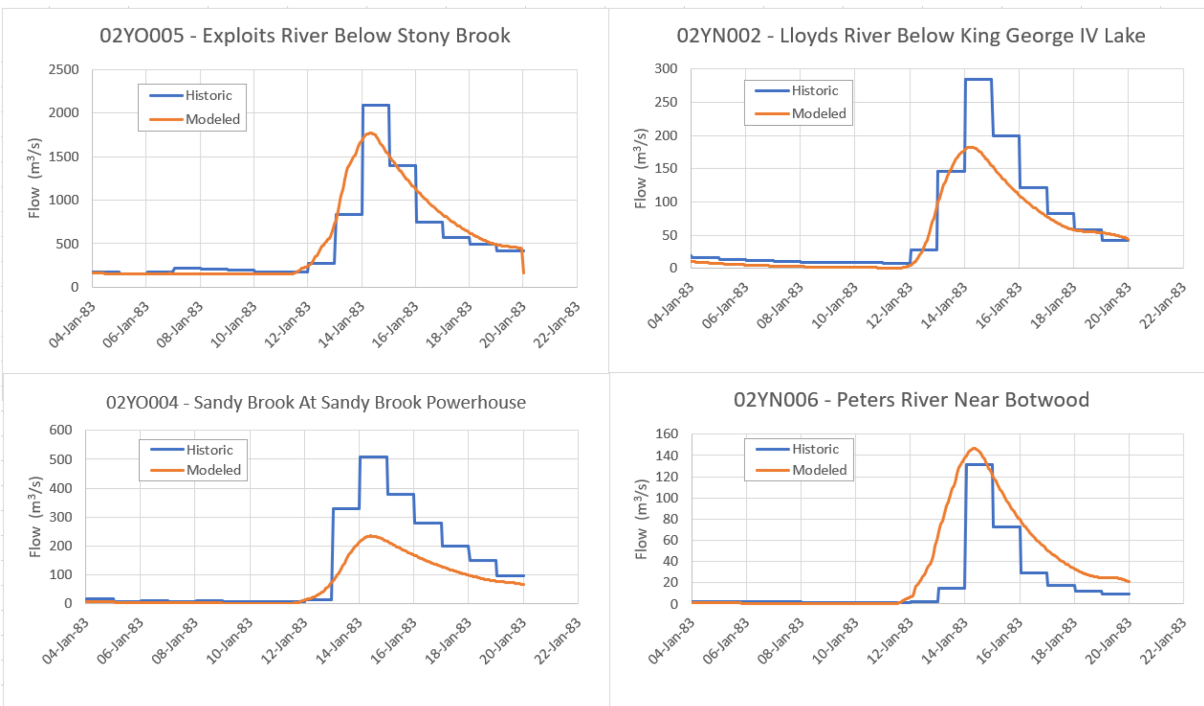

Figure 5-30: Observed and Modelled Flows for 1983 Event

5.4.4.4 *Parameter Summary*

A HEC-HMS SMA case study conducted by Cunderlik and Simonovic (2004) included a sensitivity analysis to identify sensitive parameters for flood modeling. Hatch relied on this study to select which parameters should be calibrated. Hatch did not have scope or budget to do exhaustive pre-calibration sensitivity analyses of all parameters, and the client's study plan called for sensitivity analysis of the final model.

Non-calibrated parameters that were not considered sensitive and were therefore fixed during model setup are presented in **Table 5-25**. Key parameters which were identified for calibration based on the SMA flood modeling case study sensitivity are presented in **Table 5-26**.

Table 5-25: Non-Calibrated Model Parameters

Model Process	Parameter	Unit	Model Value / Range of Values	Comment
Canopy	Initial Storage	%	100	Set during initial model calibration
	Max Storage	mm	5	Set during initial model calibration
	Crop Coefficient	-	0.95	Set during initial model calibration
	Uptake Method	-	Simple	Set during initial model calibration
Surface	Initial Surface Depression Storage	%	100	Set during initial model calibration
	Max Surface Depression Storage	mm	5	Set during initial model calibration
Loss	Initial GW 1 Saturation	%	100	Set during initial model calibration
	Initial GW 2 Saturation	%	0	Set during initial model calibration; no GW 2 layer in model
	Maximum Infiltration	mm/hr	1.1 – 10.9	Based on CN, soil and texture class for each subbasin. See **Section 5.4.4.2.1**
	Impervious	%	0	This is accounted for by the CN value
	Upper Zone Storage	mm	4.4 – 89.7 (current) 4.4 to 86.6 mm (fully dev.)	Based on CN, porosity, field capacity for each subbasin. See **Section 5.4.4.2.1**
	Tension Zone Storage	mm	0.6 – 16.2 (current) 0.6 – 14.9 mm (fully dev.)	Based on CN, porosity, field capacity and wilting point for each subbasin. See **Section 5.4.4.2.1**
	Soil Percolation	mm/hr	0.0244	From Hydrogeology of Central Newfoundland (AMEC, 2013). See **Section 5.4.4.2.2**
	GW 1 Storage	mm	0	Set during initial model calibration
	GW 1 Percolation	mm/hr	0	Set during initial model calibration
	GW1 Coefficient	hr	100	Set during initial model calibration
	GW 2 Storage	mm/hr	0	Set during initial model calibration; no GW 2 layer in model
	GW 2 Percolation	mm	0	Set during initial model calibration; no GW 2 layer in model
	GW 2 Coefficient	hr	0	Set during initial model calibration; no GW 2 layer in model
Baseflow	GW 1 Initial	m^3/s	0.001 – 94.2	Based on mean annual flow. See **Section 5.4.4.2.2**
	GW 1 Coefficient	hr	13.5 – 982.8	Based on drainage area. See **Section 5.4.4.2.2**
Routing	Channel Length	m	27 – 64,610	Determined from HEC-GeoHMS.
	Channel Slope	m/m	0.0004 – 0.05	Determined from HEC-GeoHMS.
	Channel Width	m	3 – 2,846	Determined from HEC-GeoHMS.
	Channel Side Slope	xH:1V	15 - 39	Determined from HEC-GeoHMS.
Evapor-ation & Transpir-ation	Evapotranspiration	mm	500 mm	Total 500 mm distributed from May to October. See **Section 5.4.4.2.3**
	ATI-Meltrate Coefficient	-	0.98	HEC-HMS default value

Model Process	Parameter	Unit	Model Value / Range of Values	Comment
Snow Accumul-ation & Melt	Cold Limit	mm/day	0	HEC-HMS default value
	ATI-Coldrate Coefficient	-	0.5	HEC-HMS default value
	ATI-Coldrate Function	mm/°C-day	1.32	Set during initial model calibration
	Water Capacity	%	3	Set during initial model calibration
	Groundmelt	mm/day	0.025	Set during initial model calibration

Table 5-26: Calibrated Model Parameters

Model Process	Parameter	Unit	Model Value / Range of Values	Comment
Loss	Initial Soil Saturation	%	90	Adjusted during full calibration.
Transform	Time of Concentration	hr	0.3 – 71.5	Determined in HEC-GeoHMS setup with some adjustments to match observed peaks. See **Section 5.4.4.2.4**.
	Storage Coefficient	hr	0.9 – 258.6	Matched observed peaks. See **Section 5.4.4.2.4**
Routing	Manning's n	-	0.027 – 0.045	Matched observed data. See **Section 5.4.3**
Snow Accumul-ation & Melt	PX Temperature	°C	0	Matched observed data. See **Section 5.4.4.2.5**
	Base Temperature	°C	0	Matched observed data. See **Section 5.4.4.2.5**
	Wet Meltrate	mm/°C-day	10	Matched observed data. See **Section 5.4.4.2.5**
	Rain Rate Limit	mm/day	20	Matched observed data. See **Section 5.4.4.2.5**
	Dry meltrate (ATI-Meltrate Function)	mm/°C-day	2	Matched observed data. See **Section 5.4.4.2.5**

5.5 1:20 and 1:100 AEP Flood Estimates

5.5.1 Comparison of Stochastic and Deterministic Flood Estimates

The 1:20 and 1:100 AEP precipitation hyetographs derived from the Gander Airport IDF curve as discussed in **Section 5.2.4.1** were converted to precipitation grids and applied uniformly across the study basin. These were used as the precipitation inputs for the watershed in the HEC-HMS model to determine the modelled flood flows resulting from the application of 1:20 and 1:100 AEP precipitation events across the entire watershed. This method was applied as a check on the statistical flood analysis, which included both rain and rain/snowmelt events.

As discussed in **Section 5.4.1.8**, to capture a range of possible releases from Red Indian Lake, the model was run twice for each event, once with no spill from Millertown Dam and once with the spillway gates fully open.

Along the Exploits River, the deterministic model results are compared to the stochastic flood flows obtained from the single station frequency analysis shown in **Table 5-5**. The comparison is summarized in **Table 5-27** and shown in **Figure 5-31** and **Figure 5-32**. The stochastic flows are larger than the deterministic model flows in all cases and at all locations. This is to be expected, as the record of annual maximum floods (on which the stochastic flows are based) is dominated by flood events that included snowmelt. The deterministic model estimates are based on rainfall IDF data and are representative of flood events due to rainfall only.

Table 5-27: 1:20 and 1:100 AEP Stochastic and Deterministic Peak Flow Comparison on Exploits River

WSC Station	Name	Drainage Area (km^2)	1:20 AEP (m^3/s)			1:100 AEP (m^3/s)		
			Stochastic	Deterministic		Stochastic	Deterministic	
				Millertown Gates Open	Millertown Gates Closed		Millertown Gates Open	Millertown Gates Closed
02YO011	Below Noel Pauls Brook	6,357	1,340	1,004	398	1,650	1,127	520
02YO013	At Badger Brook	6,602	1,400	1,070	464	1,715	1,214	607
	At Badger downstream from Badger Brook	7,320	1,418	1,200	594	1,730	1,383	777
02YO018	At Charlie Edwards Point	7,782	1,430	1,291	690	1,740	1,504	902
-	At Goodyear Dam	8,444	1,498	1,442	841	1,818	1,702	1,100
02YO001	At Grand Falls	8,459	1,500	1,443	841	1,820	1,702	1,100
Fenco (1990)	At Bishops Falls	10,176	2,220	2,006	1,389	2,810	2,444	1,827

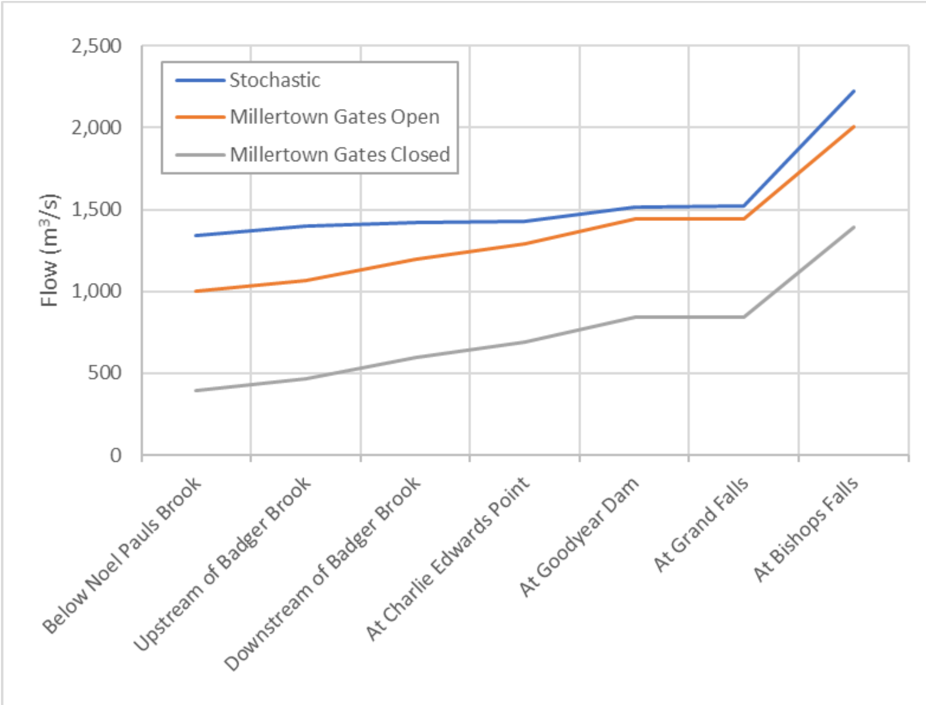

Figure 5-31: 1:20 AEP Flood Flow Comparison

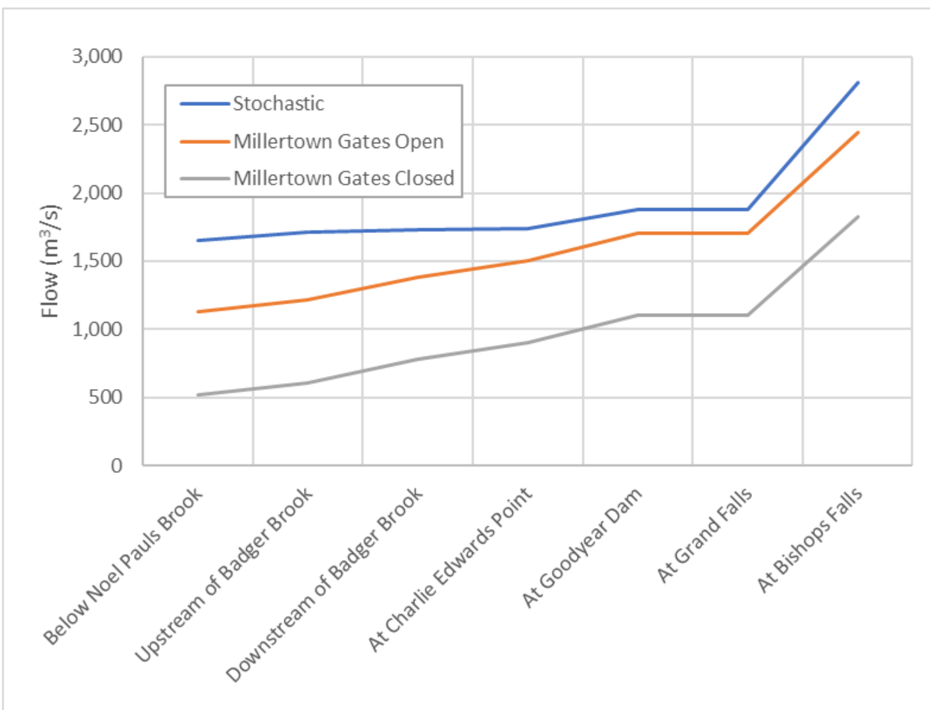

Figure 5-32: 1:100 AEP Flood Flow Comparison

For the tributaries, the deterministic model results are compared to the stochastic flood flows obtained from the RFFA conducted by AMEC (2014) as shown in **Table 5-12** and **Table 5-13**. The comparison is summarized in **Table 5-28** below; flows are referenced to the downstream outlet of each tributary. The stochastic values for the major tributaries of Little Red Indian Brook and Badger Brook were higher than the deterministic, again likely due to the influence of snowmelt on flood peaks in larger basins. For the remaining minor tributaries, the deterministic flows were generally higher. As discussed in **Section 5.3.2.2** there is less confidence in the stochastic estimates for the minor tributaries because the drainage areas are too small for the RFFA equations. Therefore, the deterministic estimates for the minor tributaries are considered more reliable.

Table 5-28: 1:20 and 1:100 AEP Stochastic and Deterministic Peak Flow Comparison on Tributary Streams

Tributary	Drainage Area (km^2)	1:20 AEP (m^3/s)		1:100 AEP (m^3/s)	
		Stochastic	Deterministic	Stochastic	Deterministic
Little Red Indian Brook	136.6	77.5	44.7	100.6	59.0
Badger Brook	717.5	257.4	131.2	325.0	170.4
Unnamed Stream B-1	2.0	3.6	5.4	5.0	7.0
Wigwam Brook	20.6	19.6	26.2	26.3	33.9
Rushy Pond Brook	23.6	8.4	22.8	10.8	29.6
Little Rushy Pond Brook	1.3	0.7	1.9	1.0	2.4
Mullens Pond	0.5	0.8	1.7	1.12	2.1
Corduroy Brook	8.0	8.3	10.2	11.2	11.5
Unnamed Stream GF-1	7.8	9.7	13.9	13.2	17.9
Unnamed Stream BF-4	0.4	1.2	1.4	1.7	1.8
Unnamed Stream BF-3	8.9	7.3	7.6	9.8	10.2
Unnamed Stream BF-2	2.1	3.8	4.8	5.2	6.2
Unnamed Stream BF-1	5.3	4.2	0.3	5.6	0.4

5.5.2 Climate Change and Fully Developed Effects

The 1:20 and 1:100 AEP climate change precipitation events from the Gander Airport IDF curve as discussed in **Section 5.2.4.2** were converted to precipitation grids and applied uniformly across the study basin. These were used as the precipitation inputs for the watershed in the HEC-HMS model to determine the modelled flood flows resulting from the application of 1:20 and 1:100 AEP precipitation events across the entire watershed.

The fully developed CN values discussed in **Section 5.4.1.2.1.2** were used in the development of a "Fully Developed" basin model. The CN values were used to update maximum infiltration, upper zone storage and tension zone storage values as discussed in **Section 5.4.4.2.1**.

The effects of climate change and fully developed on runoff flows in the basin were assessed in a series of scenarios:

- Current climate condition and current development (CC-CD).
- Current climate condition and fully developed (CC-FD).
- Climate change condition and current development (CLC-CD).
- Climate change condition and fully developed (CLC-FD).

In order to better ascertain the effects of the climate and development changes on runoff in the downstream communities, the deterministic model was run with the Millertown Dam spillway gates closed. The scenarios are presented in **Table 5-29**.

Fully developed conditions had a negligible impact on runoff with only two tributaries experiencing a 1% increase in flows in the 1:20 AEP storm and none experiencing an increase in the 1:100 AEP storm.

The changes in climate had a more significant effect, with increases of 9 to 10% on the Exploits River for the 1:20 AEP storm and 6% for the 1:100 AEP storm.

The tributary flows increased by 0 to 19% for the 1:20 AEP storm and 0 to 19% for the 1:100 AEP storm.

Table 5-29: Climate Change and Fully Developed Flows

	1:20 AEP Flows (m^3/s)							1:100 AEP Flows (m^3/s)						
	Current Climate (CC)		Climate Change (CLC)		% Difference			CC		CLC		% Difference		
	Current Development (CD)	Fully Developed (FD)	CD	FD	CC-CD to CC-FD	CC-CD to CLC-CD	CC-FD to CLC-FD	CD	FD	CD	FD	CC-CD to CC-FD	CC-CD to CLC-CD	CC-FD to CLC-FD
Exploits River														
Below Noel Pauls Brook	398	398	436	436	0%	10%	10%	520	520	551	551	0%	6%	6%
Upstream of Badger Brook	464	464	508	508	0%	10%	10%	607	607	643	643	0%	6%	6%
Downstream of Badger Brook	594	594	651	651	0%	10%	10%	777	777	823	823	0%	6%	6%
At Charlie Edwards Point	690	690	755	755	0%	9%	9%	902	902	954	954	0%	6%	6%
At Goodyear Dam	841	841	920	920	0%	9%	9%	1100	1100	1163	1163	0%	6%	6%
At Grand Falls	841	841	921	921	0%	9%	9%	1100	1100	1163	1163	0%	6%	6%
At Bishops Falls	1389	1389	1524	1524	0%	10%	10%	1827	1827	1935	1935	0%	6%	6%
Tributaries														
Little Red Indian Brook	44.7	44.7	49.3	49.3	0%	10%	10%	59.0	59.0	62.8	62.8	0%	6%	6%
Badger Brook	131.2	131.2	143.5	143.5	0%	9%	9%	170.4	170.4	180.5	180.5	0%	6%	6%
Unnamed Stream B-1	5.4	5.4	6.4	6.4	0%	19%	19%	7.0	7.0	8.1	8.1	0%	16%	16%
Wigwam Brook	26.2	26.2	29.8	29.8	0%	14%	14%	33.9	33.9	37.8	37.8	0%	12%	12%
Rushy Pond Brook	22.8	22.8	25.7	25.7	0%	13%	13%	29.6	29.6	32.7	32.7	0%	10%	10%
Little Rushy Pond Brook	1.9	1.9	2.1	2.1	0%	11%	11%	2.4	2.4	2.7	2.7	0%	13%	13%
Mullens Pond	1.7	1.7	2.0	2.0	0%	18%	18%	2.1	2.1	2.5	2.5	0%	19%	19%
Corduroy Brook	10.2	10.3	10.9	10.9	1%	7%	6%	11.5	11.5	12.3	12.3	0%	7%	7%
Unnamed Stream GF-1	13.9	14.0	15.9	15.9	1%	14%	14%	17.9	17.9	20.0	20.1	0%	12%	12%
Unnamed Stream BF-4	1.4	1.4	1.6	1.6	0%	15%	15%	1.8	1.8	2.0	2.0	0%	15%	15%
Unnamed Stream BF-3	7.6	7.6	8.6	8.6	0%	13%	13%	10.2	10.2	11.2	11.2	0%	10%	10%
Unnamed Stream BF-2	4.8	4.8	5.7	5.7	0%	18%	18%	6.2	6.2	7.2	7.2	0%	16%	16%
Unnamed Stream BF-1	0.3	0.3	0.3	0.3	0%	0%	0%	0.4	0.4	0.4	0.4	0%	0%	0%

Table 5-30 below shows the recommended flows to be used in the steady state hydraulic model for the 1:20 AEP and 1:100 AEP current climate and climate change simulations. For the Exploits River, as well as the larger tributaries Little Red Indian Brook and Badger Brook, the stochastic model current climate flows as presented in **Table 5-5** and **Table 5-12** were used in the model. To estimate climate change flows for these waterways, the percent increases between the deterministically-derived current climate and climate change flows as shown in **Table 5-29** were applied to the stochastic current climate flows. For the smaller tributaries, the deterministic flows were used as shown in **Table 5-29**.

Table 5-30: Recommended Flows for Steady State Hydraulic Model

	1:20 AEP		1:100 AEP	
	Current Climate (CC)	Climate Change (CLC)	Current Climate (CC)	Climate Change (CLC)
Exploits River				
Below Noel Pauls Brook	1,340	1,468	1,650	1,747
Upstream of Badger Brook	1,400	1,535	1,715	1,817
Downstream of Badger Brook	1,418	1,554	1,730	1,833
At Charlie Edwards Point	1,430	1,564	1,740	1,839
At Goodyear Dam	1,498	1,639	1,818	1,923
At Grand Falls	1,500	1,641	1,820	1,924
At Bishops Falls	2,220	2,436	2,810	2,975
Tributaries				
Little Red Indian Brook	77.5	85.5	101.0	107.5
Badger Brook	257.0	281.1	325.0	344.3
Unnamed Stream B-1	5.4	6.4	7.0	8.1
Wigwam Brook	26.2	29.8	33.9	37.8
Rushy Pond Brook	22.8	25.7	29.6	32.7
Little Rushy Pond Brook	1.9	2.1	2.4	2.7
Mullens Pond	1.7	2.0	2.1	2.5
Corduroy Brook	10.2	10.9	11.5	12.3
Unnamed Stream GF-1	13.9	15.9	17.9	20.0
Unnamed Stream BF-4	1.4	1.6	1.8	2.0
Unnamed Stream BF-3	7.6	8.6	10.2	11.2
Unnamed Stream BF-2	4.8	5.7	6.2	7.2
Unnamed Stream BF-1	0.3	0.3	0.4	0.4

5.6 Sensitivity Analysis

The SCS Curve Number (as represented in the SMA loss model by the tension zone and upper zone storage parameters) and channel Manning's roughness coefficient were varied by ±10%, ±20% and ±30%. As an additional check, the initial soil saturation was also reduced from 90% to 50%. The 1:100 AEP (gates closed) analysis was used to assess the effect that these changes have on the peak flows in the study areas. Key sensitivity results are shown in **Table 5-31**. The maximum variation in flows corresponding to an increase and decrease in CN of 30% is within +3% / -4%. The maximum variation in flows corresponding to an increase and decrease in Manning's n is within +1% / -1%. The maximum variation in flows corresponding to a decrease in the initial storage saturation is -13.6%.

Table 5-31: Sensitivity Analysis Results

	Base Case	Parameter Increase			Parameter Decrease			Max % increase	Max % decrease
		10%	20%	30%	-10%	-20%	-30%		
Peak Flow (m^3/s) - Sensitivity to Curve Number									
Exploits River at Badger	607.3	613.9	619.3	623.9	599.5	591.2	583.1	2.7%	-4.0%
Exploits River at Bishop's Falls	1827.3	1847.1	1863.6	1875.8	1803.6	1778.9	1754.2	2.6%	-4.0%
Badger Brook	170.4	172.3	173.8	175.1	168.2	165.9	163.6	2.8%	-4.0%
Corduroy Brook	11.5	11.5	11.5	11.5	11.4	11.4	11.4	0.0%	-0.9%
Peak Flow (m^3/s) - Sensitivity to Manning's n									
Exploits River at Badger	607.3	607.2	607.1	607.1	607.3	607.2	607.1	0.0%	0.0%
Exploits River at Bishop's Falls	1827.3	1823.3	1819.1	1815.2	1830.8	1834.1	1837.4	0.6%	-0.7%
Badger Brook	170.4	170.2	170.0	169.9	170.6	170.8	171.1	0.4%	-0.3%
Corduroy Brook	11.5	11.4	11.4	11.4	11.5	11.5	11.5	0.0%	-0.9%
Peak Flow (m^3/s) - Sensitivity to Initial Soil Saturation									
	Base Case – 90%				**Sensitivity – 50%**			**% Change**	
Exploits River at Badger	607.3				530.2			-12.7%	
Exploits River at Bishop's Falls	1827.3				1596.8			-12.6%	
Badger Brook	170.4				147.3			-13.6%	
Corduroy Brook	11.5				11.3			-1.7%	

5.7 Hydrology Conclusions and Recommendations

For the Exploits River, Badger Brook and Little Red Indian Brook, the 1:20 and 1:100 AEP peak flood flows developed using stochastic methods are generally larger than the deterministic model flows for the same AEP rainstorm due to the stochastic method's inclusion of floods originating from both precipitation and snowmelt. It is recommended that stochastic analysis outputs be used for flood flows on these rivers in the subsequent portions of the project relating to flood risk mapping. For the remainder of the tributary streams in the study, the stochastic estimates are not considered reliable due to the limitations of the methodology, and the deterministic estimates should be used. The recommended flows are summarized in **Table 5-30**.

The hydrologic model that was developed and calibrated for this study can be used in the HEC-RTS flood forecasting system to provide the flows in the watercourses arising from the rainfall in the study area.

Hatch recommends the following:

6. Installing additional precipitation gauges would help reduce uncertainty in the spatial distribution of precipitation, and could improve hydrological model calibration. It is recommended that additional stations be installed in southern part of the watershed where coverage by the existing observation network is sparse (e.g., Noel Pauls and Great Rattling sub-basins).
7. It is recommended that a means of continuous flow measurement be implemented at Bishop’s Falls as there is currently no active long term record of flow at that location. One alternative may be for Nalcor to implement discharge calculations based on hydro generation and spill at the Bishop’s Falls Generating Station or calibration of the Bishop’s Falls tailwater curve via field measurement of flow and level. Another alternative may be for WRMD to establish an independent gauge at a suitable location. A continuous record of flow at Bishop’s Falls would provide the following benefits:
   - Additional years of record in the flood series would improve the confidence of statistically-based flood estimates for future updates to this study.
   - Information from future floods in the basin could be used to improve the calibration of the hydrological model developed in the current study.
8. In addition to the use of climate change rainfall IDF projections, WRMD should consider using the calibrated deterministic hydrologic model in a continuous precipitation-runoff simulation approach, using downscaled temperature and precipitation projections from climate models. Such an approach would provide a way of making climate change flood estimates that quantitatively consider the effects of future changes in snowpack, snowmelt, and soil moisture, which are important contributors to annual flood peaks in large river basins such as the Exploits River.

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6. Hydraulic Analysis

6.1 Introduction

Hydraulics studies how water moves in channels or pipes. For this study, hydraulics looks at how water moves in streams and rivers.

Hydraulic models were developed for the Exploits River to estimate the water elevations on the Exploits River and the streams which flow into it (tributaries). Three models were developed:

- Unsteady state flood forecasting model: This model is used in the flood forecasting system to show water levels on the Exploits River, Badger Brook, Little Red Indian Brook, North Angle/Wigwam Brook and Rushy Pond Brook when there is no ice on the Exploits River. When there is no ice on the river, the river is said to be in "open-water conditions". This is an unsteady state model where the flows and water levels change with time. The model shows the rising and falling water levels during a flood.
- Steady state flood mapping model: This model shows the maximum water levels which could be expected about every 20 years and 100 years on the Exploits River and 13 tributaries when there is no ice on the Exploits River. This is a steady state model where the flows and elevations in the river do not change with time. These water levels are used to make flood maps.
- Ice model: This model is used in the flood forecasting system to show water levels on the Exploits River during the winter when there is ice on the Exploits River. It is also used to make flood maps by showing the maximum water levels which could be expected about every 20 years and 100 years on the Exploits River in the winter when there is ice on the river. This is an unsteady state model.

The unsteady state flood forecasting and steady state flood mapping models were built using the USACE HEC-RAS (Hydrologic Engineering Centre – River Analysis System) software, which is a tool that is commonly used for this type of analysis. Two models were developed for open-water conditions because the flood forecasting system and flood maps used different kinds of information. The ice model was constructed using RIVICE with the assistance of Dr. Karl-Erich Lindenschmidt.

The unsteady state flood forecasting model was built using LiDAR topographic maps, survey information, and hydraulic models which had been built for earlier projects in the area. Flows from the hydrological model were collected. Past water level elevations on the rivers and streams were collected to calibrate the model.

First, the unsteady state model was built. Flows from past flood and normal flow events were run through the model. The water levels that the model showed were compared with the water levels that actually happened during those events. The model was then said to be calibrated and can be trusted to accurately predict water levels in the future. The unsteady state model was then used to build the ice and steady state models.

The unsteady state model was used to build the ice model. Flows from past ice jam and normal winter flow events were run through the model. The water levels that the model showed were compared with the water levels that actually happened during those events. The model was changed and calibrated so that the modeled water levels matched the recorded water levels.

In the steady state model, the rest of the small streams were added and calibrated in the same way as the unsteady state model. The maximum 1:20 and 1:100 AEP flows from the hydrologic model were input to the steady state model. This gave the maximum 1:20 and 1:100 AEP water levels. The higher water levels which are expected because of climate change were also modelled.

Climate change may have an impact on the amount of water that flows into the streams and rivers. The 1:20 and 1:100 AEP future floods due to climate change and sea level rise were calculated.

Water levels between the ice and steady state models were compared to get the maximum 1:20 and 1:100 AEP water levels. These were used to make the flood maps.

The unsteady state flood forecasting model and the ice model were added to the flood forecasting system.

Figure 6-1 provides an overview of the report structure and layout.

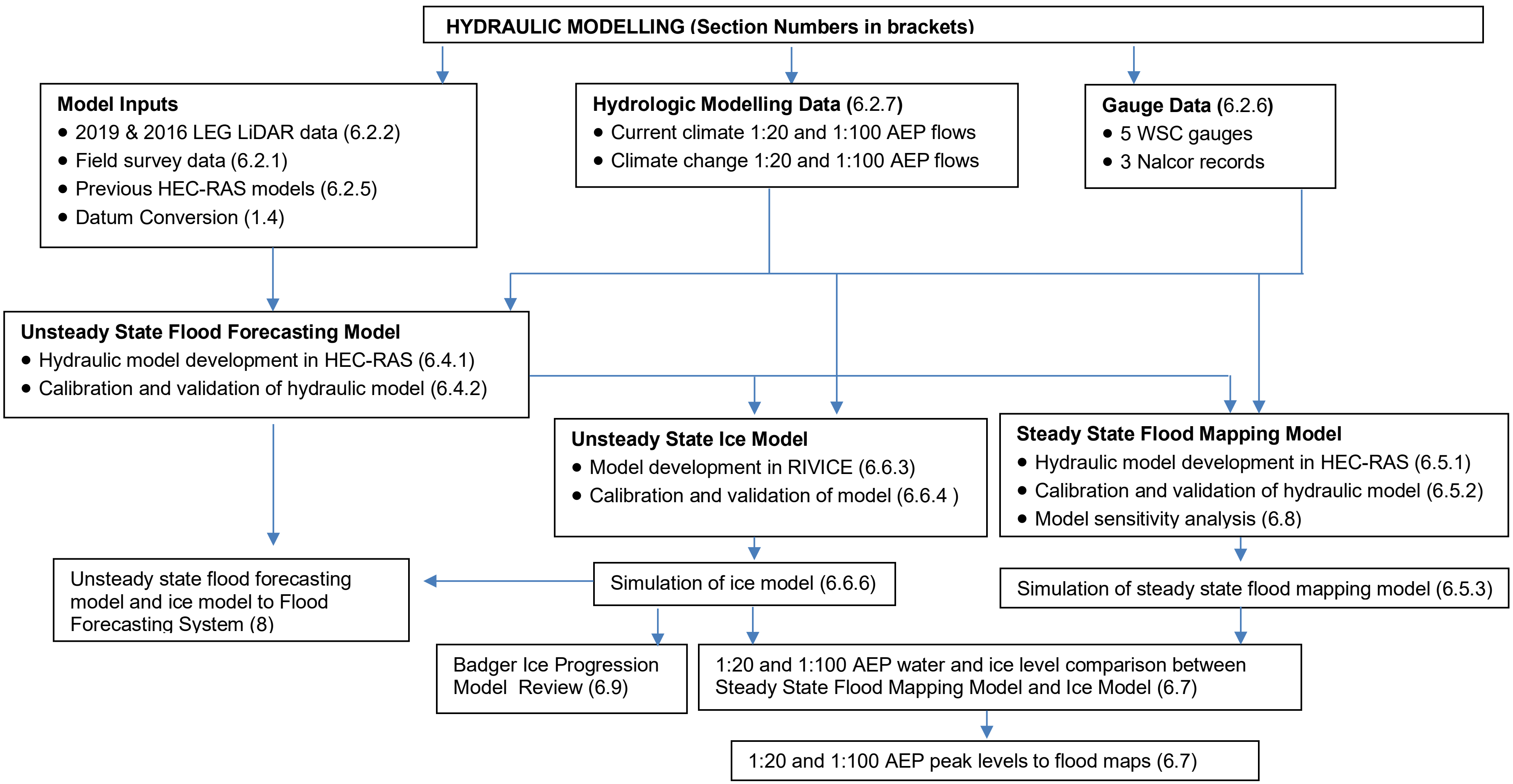

Figure 6-1: Hydraulic Analysis Section Overview

6.2 Data Collection

6.2.1 Field Survey Data

SEM conducted a field survey program as discussed in **Section 3.2.2**. Other field survey data was collected from 2012 to 2016 as discussed in **Section 3.2.1**.

6.2.2 LiDAR DEM

LEG completed LiDAR surveys of the Exploits River communities as discussed in **Section 3.3** and provided DEMs for use in the hydraulic models.

6.2.3 Dams

The Exploits River is dammed at four points along its length for the purpose of producing hydroelectric power. The uppermost dam is Millertown Dam (also known as Exploits Dam), at the mouth of Red Indian Lake, which is the main storage reservoir. Proceeding downriver, the next dam is Goodyear's Dam, located upstream of the Town of Grand Falls-Windsor. Goodyear's Dam is a free-overflow structure that serves to restrict the amount of river ice reaching the hydroelectric generating stations downstream. The third dam is Grand Falls Dam at the Grand Falls Generating Station in Grand Falls-Windsor. The final dam is Bishop's Falls Dam at the Bishop's Falls Generating Station in the Town of Bishop's Falls. These dams and generating stations are operated by Nalcor Energy.

Releases from Millertown Dam are provided by the hydrologic model, and therefore Millertown Dam was not represented in the hydraulic models. The releases from Millertown Dam are introduced at the upstream boundary of the hydraulic models which is immediately downstream of the dam structure itself.

Pertinent data for key components of the dams in the study area are provided in the following tables.

Table 6-1: Headpond Full Supply Levels

Dam	Full Supply Level (CGVD 2013)
Goodyear's Dam	69.6 m
Grand Falls	60.7 m
Bishop's Falls	13.0 m

Table 6-2: Goodyear's Dam

Timber Crib Overflow Section	
Structure Type	Timber Crib with rockfill on downstream face of repaired section
Structure Length	198 m
Nominal Maximum Height	6.4 m
Crest Elevation	68.6 to 69.0 m

South Closure Embankment	
Structure Type	Embankment
Structure Length	110 m
Nominal Maximum Height	8.9 m
Crest Elevation	71.1 to 72.4 m
Spillway Channel	
Structure Type	Rock-lined channel
Structure Width	24 m
Invert Elevation	69.9 m

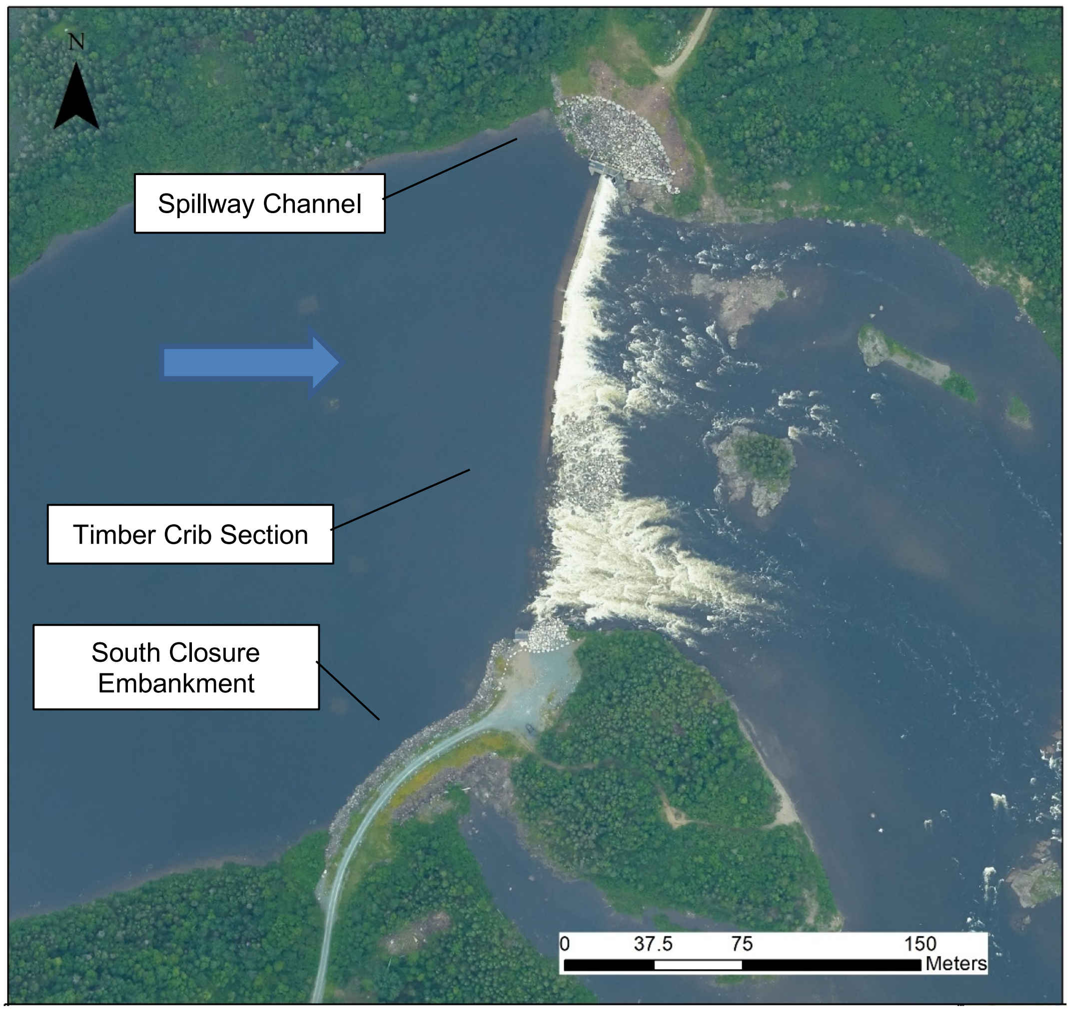

Figure 6-2: Goodyear's Dam Overview

Table 6-3: Grand Falls Main Dam

Main Dam	
Structure Type	Concrete gravity
Structure Length	250 m
Nominal Maximum Height	7.0 m
Crest Elevation	60.7 m
Discharge Facilities	Obermeyer gate Crest – 59.2 m, Length – 8.9 m Outside Sluice Gate Gate invert elevation – 54.6 m, Gate width – 6.1 m, gate height – 4.0 m

Table 6-4: Grand Falls Power Canal

Forebay Intake	
Structure Type	Concrete gravity
Deck Elevation	62.8 m
Discharge Facilities	17 gates (permanently open/non-operable) Gate invert elevation 54.6 m Gate width 2.4 m, gate height 3.7 m
RCC Dam / Spillway	
Structure Type	Roller compacted concrete (RCC) gravity
Structure Length	168 m
Nominal Maximum Height	13.4 m
Crest Elevation	59.8 m
Discharge Facilities	Uncontrolled overflow crest with flashboards Top of flashboards elevation 60.7 m Inside Sluice Gate Gate invert elevation – 54.6 m, Gate width – 4.6 m, gate height – 2.1 m
West Embankment Dam	
Structure Type	Embankment
Structure Length	293 m
Nominal Maximum Height	12.6 m
Crest Elevation	63.9 m

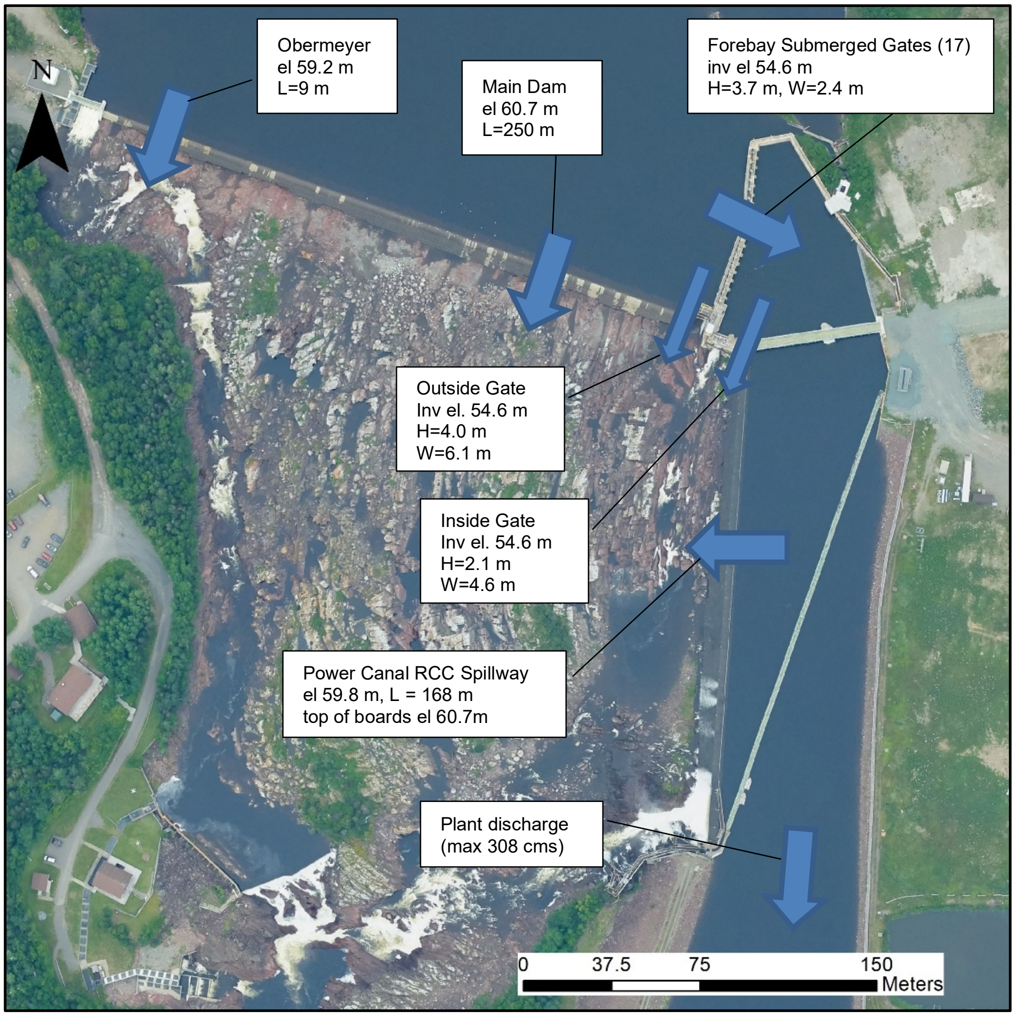

Figure 6-3: Grand Falls Dam Overview

Table 6-5: Bishop's Falls Dam

Overflow Spillway	
Structure Type	Ambursen / concrete gravity with flashboards
Structure Length	177 m
Nominal Maximum Height	13.3 m
Crest Elevation	11.7 m
Discharge Facilities	Uncontrolled overflow crest with flashboards Top of flashboards elevation 13.0 m
Gated Spillway	
Structure Type	Concrete gravity
Nominal Maximum Height	10.7 m
Deck Elevation	14.8 m
Discharge Facilities	10 sluice gates Sill elevation 4.6 m Gate width 5.5 m
Embankment Dam	
Structure Type	Embankment
Structure Length	225 m
Nominal Maximum Height	13.0 m
Crest Elevation	16.2 m

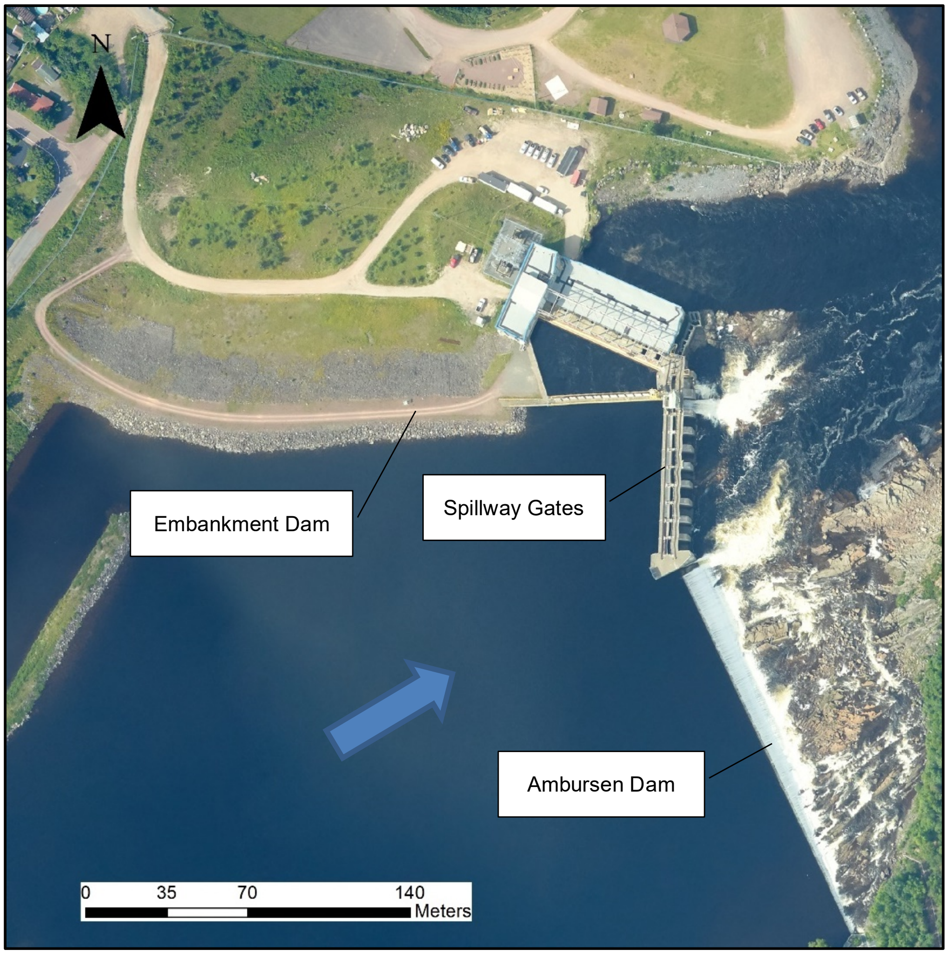

Figure 6-4: Bishop's Falls Dam Overview

6.2.4 Bridges and Culverts

A total of 10 bridges and two culverts are included in the flood forecasting system model. The flood forecasting system model includes the Exploits River and several major tributaries, including Badger Brook, Little Red Indian Brook, Rushy Pond and the downstream end of Wigwam Brook. All structures on these tributary reaches are in the flood forecasting system model. All remaining tributaries and streams in the community areas are included in the flood mapping model. Nine bridges and 27 culverts on these watercourses are added to the flood mapping model. In addition, the Mullen’s Pond watercourse discharges into a culvert that feeds into the Grand Falls-Windsor stormwater management system. A rating curve representing this culvert was used as a downstream boundary condition for this watercourse in the flood mapping model. This structure was surveyed by SEM and is included in structure figures and summary tables in this report for completeness, although it is not explicitly modeled as a culvert in the model.

Photos of surveyed structures in the community areas are provided in the field survey report (digital copy) as well as in **Appendix C** and **Appendix D** of this report.

An overview map is shown in **Figure 6-5.** Pertinent information about each bridge crossing, including river station, structure ID and name, lowest deck elevation, bridge span, condition and inclusion in the flood forecasting system model (abbreviated as FFSM) is provided in **Table 6-6**. Information about each culvert crossing, including river station, structure ID and name, lowest top of road elevation, number of barrels, upstream invert elevation, culvert diameter, condition and inclusion in the flood forecasting system model is provided in **Table 6-7**. Each structure has been assigned a three-part structure ID consisting of an abbreviated river name followed by a “CR” identifier to differentiate the crossing structure IDs from cross-section IDs, followed by a number (eg. BF2-CR-1). The numbers are assigned from downstream to upstream. The condition assessment of each structure is taken from the SEM data sheets in **Appendix C** and **Appendix D**.

It should be noted that culvert BF2-CR-4 was not surveyed by SEM and is not included in **Appendix D**. This is because the King Road crossing over Unnamed Stream BF-2 was constructed recently and was not visible on available aerial imagery when the field program was planned. Hatch obtained information on the culvert size and material type directly from the contractor who installed the culverts. In the same way, culverts BF1-CR-1 and BF1-CR-2 were not surveyed by SEM and are not included in **Appendix D**. The Sunset Drive realignment was constructed recently and was not visible on available aerial imagery when the field program was planned. Hatch obtained information on the culvert BF1-CR-2 size and material type directly from the contractor who installed the culvert. Hatch obtained information on culvert BF1-CR-1 from municipal staff in Bishop’s Falls. The surveyed culvert listed in **Appendix D** as between BF1-03 and BF1-04 captures overland flow coming from the east portion of the watershed and is not included in the model. This culvert formerly carried Unnamed Stream BF-2 flow, however, it no longer does so after the road realignment. The data sheet for this culvert has been left in the appendix for completeness.

The Grand Falls Bridge (also known as Mill Bridge) crosses the Exploits River over a narrow gorge 1.2 km downstream of Grand Falls Main Dam. The bridge provides local access from the Town of Grand Falls-Windsor to the south side of the Exploits River. The bridge span is so far above the river surface such that it is not impacted by any flood and is not included in the model.

The other three bridges crossing the Exploits River were not surveyed during this program, as survey information and other pertinent details for these bridges were available from past Hatch programs.

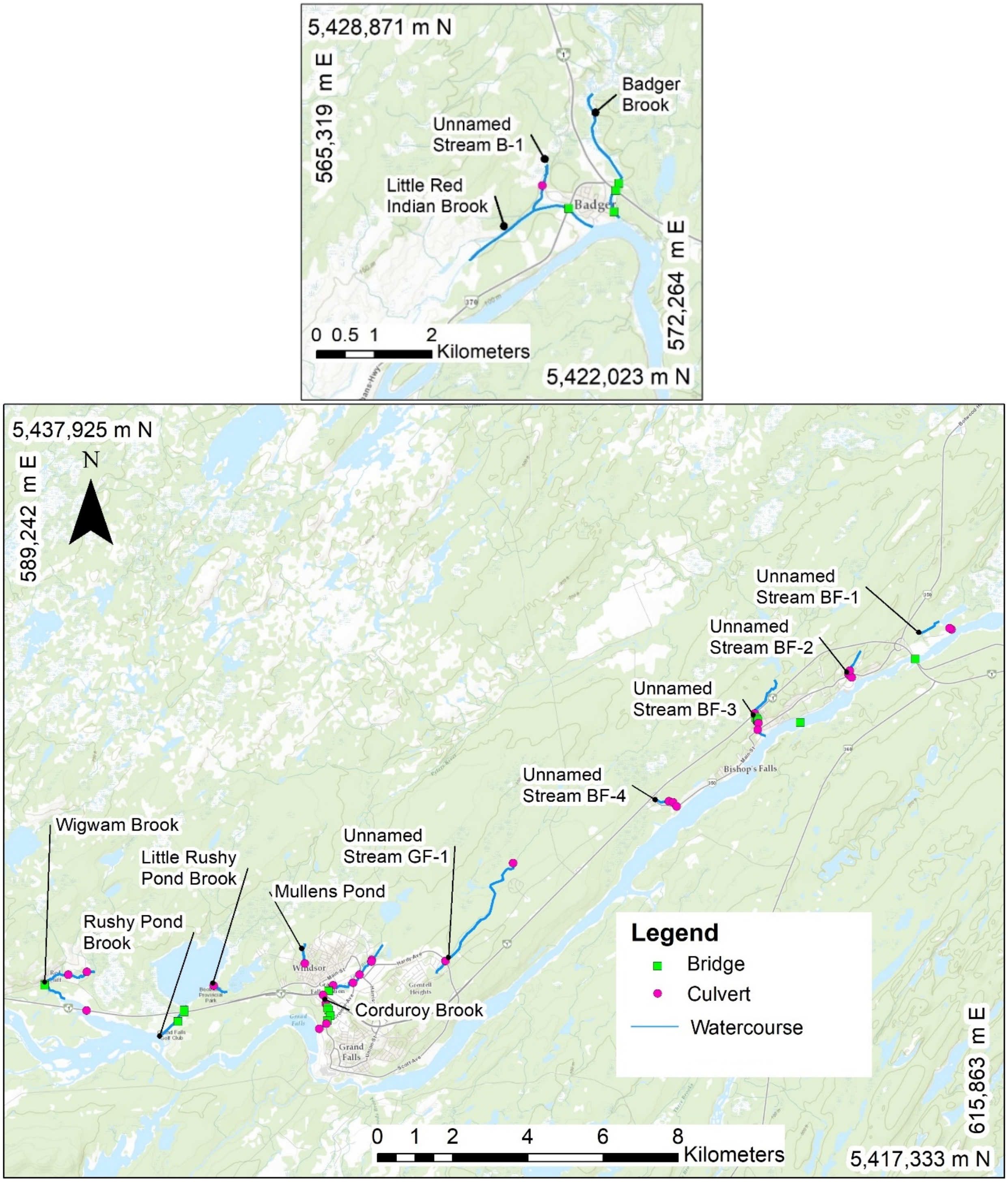

Figure 6-5: Bridges and Culverts in Community Areas

Table 6-6: Bridges in Model

River	River Station	Bridge ID	Bridge Name	Northing (UTM Zone 21)	Easting (UTM Zone 21)	Deck Elevation (m)	Span (m)	Condition	In FFSM
Badger Brook	0.383	BB-CR-1	Badger Brook T'Railway Bridge	5,425,280	570,735	100.3	58	Some rails broken, mostly good condition	Y
Badger Brook	0.793	BB-CR-2	Badger Brook TCH Bridge	5,425,648	570,771	100.9	68.9	Numerous potholes and patches	Y
Badger Brook	0.937	BB-CR-3	Badger Brook Footbridge	5,425,773	570,821	99.8	48.5	No deficiencies noted	Y
Unnamed Stream BF-3	0.692	BF3-CR-3	Beaumont Heights 2 Bridge	5,429,495	609,311	27.1	9.1	No deficiencies noted	N
Unnamed Stream BF-3	0.736	BF3-CR-4	Dominic Street 1 Bridge	5,429,525	609,281	29.8	6.2	No deficiencies noted	N
Unnamed Stream BF-3	0.771	BF3-CR-5	Dominic Street 2 Bridge	5,429,558	609,268	32.6	9.2	No deficiencies noted	N
Unnamed Stream BF-3	0.817	BF3-CR-6	Dominic Street 3 Bridge	5,429,591	609,243	34.8	7	No deficiencies noted	N
Corduroy Brook	0.616	CB-CR-3	Corduroy Brook Nature Trail 1 Bridge	5,421,513	597,853	68.2	8	No deficiencies noted	N
Corduroy Brook	0.774	CB-CR-4	Corduroy Brook Nature Trail 2 Bridge	5,421,651	597,923	70.2	10.8	Portion of wooden railing missing, pieces cracking off of bottom, looks sunken on downstream side	N
Corduroy Brook	0.933	CB-CR-5	Squires Lane 1 Bridge	5,421,804	597,885	70.9	15.3	No deficiencies noted	N
Corduroy Brook	1	CB-CR-6	Squires Lane 2 Bridge	5,421,863	597,854	71.5	11.2	No deficiencies noted	N
Corduroy Brook	1.561	CB-CR-9	Duggan Street 1 Bridge	5,422,314	597,881	73.6	8.4	No deficiencies noted	N
Exploits River	21.69	E-CR-1	Sir Robert Bond Bridge	5,431,142	613,498	9.3	218	Newly rebuilt; not surveyed in 2019	Y
Exploits River	25.262	E-CR-2	Bishop's Falls Trestle	5,429,456	610,431	20.3	295	Not surveyed in 2019	Y
Exploits River	126.7173	E-CR-3	Exploits Bailey Bridge	5,400,977	530,750	149.7	82	Not surveyed in 2019	Y
Little Red Indian Brook	0.679	LRI-CR-1	Route 370 Buchans Hwy Bridge	5,425,340	569,949	101.3	28.2	No deficiencies noted	Y
Rushy Pond Brook	1.18	RP-CR-1	Golf Course Bridge	5,421,500	593,878	73.8	45.8	No deficiencies noted	Y
Rushy Pond Brook	1.483	RP-CR-2	Rushy Pond Brook TCH Bridge	5,421,748	594,035	72.6	47.5	Potholes in asphalt road, crumbling concrete in abutments	Y
Rushy Pond Brook	1.529	RP-CR-3	Rushy Pond Brook T'Railway Bridge	5,421,800	594,038	72	24.6	Some wood chipped on deck	Y
Wigwam Brook	2.898	WB-CR-2	Wigwam Brook Newfoundland T'Railway Bridge	5,422,457	590,332	73.2	4.5	Some wood pieces splintering off, concrete crumbling on bottom of bridge	N
Wigwam Brook	2.928	WB-CR-3	Red Cliff Road Bridge	5,422,488	590,331	73.1	8.6	Concrete crumbling on underside of bridge, asphalt cracks on top of bridge	N

Table 6-7: Culverts in Model

River	River Station	Culvert ID	Culvert Name	Northing (UTM Zone 21)	Easting (UTM Zone 21)	Lowest Road El. around Culvert (m)	Number of Barrels	US Invert Elevation (m)	Diameter or Dimensions (m)	Condition	In FFSM
Unnamed Stream B-1	0.562	B1-CR-1	Stream B1 Newfoundland T'Railway Culvert	5,425,731	569,491	100.2	1	99.5	1.1	In good condition; overgrown with vegetation	N
Unnamed Stream BF-1	0.173	BF1-CR-1	Sunset Drive Culvert 1	5,431,928	614,461	9	1	7.6[1]	1.2	Not surveyed	N
Unnamed Stream BF-1	0.235	BF1-CR-1	Sunset Drive Culvert 2	5,431,961	614,410	11.7	1	9.85[1]	1.05	Not surveyed	N
Unnamed Stream BF-2	0.28	BF2-CR-1	Culvert Under Private Home	5,430,650	611,802	15	1	13.7	1.4 h, 1.8 w	Culvert compressed and somewhat rusted	N
Unnamed Stream BF-2	0.364	BF2-CR-2	BF2 Stream Main Street Culvert	5,430,702	611,754	15.7	1	14.6	1.6	In good condition	N
Unnamed Stream BF-2	0.42	BF2-CR-3	BF 2 Stream Exploits Valley and Beothuk Trail Culvert	5,430,740	611,716	17	2	15.6 / 15.7	2 – 0.9	In good condition	N
Unnamed Stream BF-2	0.54	BF2-CR-4	Kings Road Culvert	5,430,835	611,755	17.9	3	16.5[1]	1 – 1.1 / 1 – 1.1 / 1 – 0.8	Not surveyed	N
Unnamed Stream BF-3	0.29	BF3-CR-1	BF3 Stream Main St Culvert	5,429,256	609,306	17.8	1	16.4	1.9	In good condition	N
Unnamed Stream BF-3	0.637	BF3-CR-2	Beaumont Heights 1 Culvert	5,429,440	609,315	24.2	2	22.8 / 22.9	2 – 1.4	In good condition	N
Unnamed Stream BF-3	0.948	BF3-CR-7	BF3 Stream TCH Culvert	5,429,694	609,229	41.4	1	36.8	2.5 (US) – 1.7 h, 2.6 w (DS)	In good condition	N
Unnamed Stream BF-4	0.345	BF4-CR-1	BF4 Stream Main Street Culvert	5,427,220	607,143	18.5	1	15.8	0.8 h, 1.2 w	In good condition	N
Unnamed Stream BF-4	0.494	BF4-CR-2	BF4 Stream Exploits Valley and Beothuk Trail Culvert	5,427,330	607,045	18.5	2	17.4 / 17.5	2 – 0.9	Bottoms are rusted out on downstream side	N
Unnamed Stream BF-4	0.608	BF4-CR-3	BF4 Stream Newfoundland T'Railway Culvert	5,427,358	606,938	18.6	2	17.5 / 17.6	2 – 0.8	In good condition; water level on downstream side almost to top of culverts	N
Corduroy Brook	0.29	CB-CR-1	Corduroy Brook Unnamed Road Culvert	5,421,303	597,639	63.8	2	61.1 / 61.2	2 – 1.0	Minor corrosion	N
Corduroy Brook	0.51	CB-CR-2	Lincoln Road Culvert	5,421,433	597,823	67.1	2	64.8 / 65.8	1 – 0.8 / 1 – 1.8 h, 2.1 w	Left culvert compressed; otherwise in good condition	N
Corduroy Brook	1.11	CB-CR-7	Corduroy Brook Lane Culvert	5,421,965	597,808	73.3	1	70.5	1.7	Bottom has been corroded off	N
Corduroy Brook	1.375	CB-CR-8	Corduroy Brook TCH Culvert with Pedestrian Underpass	5,422,195	597,742	75.7	2	71.8 / 74.7[1]	1 – 1.7 / 1 – 2.4 h, 2.4 w[2]	Downstream culvert missing top piece; corrosion observed; pedestrian underpass not surveyed	N
Corduroy Brook	1.798	CB-CR-10	Duggan Street 2 Culvert	5,422,460	598,002	75.5	1	73.8	1.8	Culvert compressed	N
Corduroy Brook	2.41	CB-CR-11	Cromer Avenue Culvert	5,422,527	598,535	81.1	1	78.4	1.5	In good condition	N
Corduroy Brook	2.675	CB-CR-12	Harris Ave Culvert	5,422,742	598,704	82.2	1	79.3	1.8	In good condition	N
Corduroy Brook	3.252	CB-CR-13	Princess Drive Culvert	5,423,087	599,021	82.7	1	80.2	1.7	In good condition	N
Corduroy Brook	3.306	CB-CR-14	Corduroy Brook Newfoundland T'Railway Culvert	5,423,136	599,029	81.7	1	79.9	1.5	Fish ladder upstream, in good condition but fencing around it is falling over	N
GF1 Stream	0.048	GF-CR-1	GF1 Stream Newfoundland T'Railway Bridge	5,425,713	602,793	70.3	2	69.3	2 – 1.2 h, 1.2 w	In good condition	N
GF1 Stream	3.999	GF-CR-2	Hardy Avenue Culvert	5,423,105	600,998	103.2	2	101.55	1 – 0.4, 1 – 0.9	In good condition; 0.9 m barrel not surveyed	N

River	River Station	Culvert ID	Culvert Name	Northing (UTM Zone 21)	Easting (UTM Zone 21)	Lowest Road El. around Culvert (m)	Number of Barrels	US Invert Elevation (m)	Diameter or Dimensions (m)	Condition	In FFSM
Little Rushy Pond Brook	0.05	LRP-CR-1	Little Rushy Pond Stream Unnamed Road Culvert	5,422,449	594,826	70.5	1	69.7	0.7	Culvert is collapsing; overgrown vegetation on both sides	N
Mullen's Pond	0.003	MP-CR-1	Second Avenue Culvert	5,423,039	597,254	73.8	1	72.7	0.8	In good condition	Y
Wigwam Brook	1.424	WB-CR-1	Trans Canada Highway at North Angle	5,421,787	591,439	72.6	1	68.6	1.6 h, 1.6 w	Culvert filled with debris; wood is rotting	Y
Wigwam Brook	3.72	WB-CR-4	Wigwam Brook Unnamed Road 1 Culvert	5,422,741	590,951	73.4	2	71.6 / 71.8	2 – 1.4	Base of culverts have corroded away	N
Wigwam Brook	4.408	WB-CR-5	Wigwam Brook Unnamed Road 2 Culvert	5,422,819	591,455	73.6	3	72.2 / 72.3 / 72.7	1 – 1.1 h, 1.5 w / 2 – 1.1 h, 1.2 w	Upstream side of culverts have been dammed by beavers	N

Notes:

1. Based on channel elevations as measured from LiDAR.
2. Estimated from orthophotos.

6.2.5 Previous HEC-RAS Models

Hatch has extensive previous modelling experience on the Exploits River. As part of the hydraulic model development, Hatch used geometry from a previous HEC-RAS model built by Hatch for Nalcor. This model, built in 2016, was an unsteady dam breach model of the entire Exploits River watershed, including areas upstream of the current study areas such as Star Lake, Buchans Lake and Twin Lakes (Hatch, 2017). It included the Millertown, Goodyear's, Grand Falls and Bishop's Falls dams, as well as bridges along the Exploits River and Badger Brook. The model was also used for some hydraulic studies of Goodyear's Dam in 2018 with some refinements to improve calibration to observed water surfaces at cross-sections where survey data was lacking.

For the present study, the need for the hydraulic model is limited to the Exploits River below Millertown Dam and tributaries within community limits. Previous model geometry within the community areas was enhanced with the additional LiDAR and bathymetric surveys; all cross-sections within community flood risk map areas have been fully surveyed with bathymetry and LiDAR. Model cross-section geometry for the Exploits River outside of flood risk map areas but needed for unsteady flow routing in the flood forecast system (such as between Millertown Dam and Badger, and between Badger and Rushy Pond) has been retained from the 2016 model.

6.2.6 Gauge Data

Flow and water level measurement data in and around the Exploits River watershed was retrieved from WSC records. Selected records were used to calibrate the model output. The records of interest included active WSC hydrometric gauges, as well as inactive gauges with records suitable for calibrating the model to historical events. The selected streamflow gauges are found in **Table 6-8 and Figure 6-6**. A WRMD gauge installed at the Bishop's Falls Trestle Bridge as well as a WRMD/WSC gauge on Badger Brook are also included in the table and figure for reference. Data from these gauges were not used in this study as they were recently installed.

Table 6-8: Hydrometric Gauges Used in Hydraulic Analysis

Gauge ID	Gauge Name	Active?	Latitude (°N)	Longitude (°W)	WSC Drainage Area (km^2)	Record Period
02YO001	Exploits River At Grand Falls	N	48.93	55.67	8,390	1944-2010 (see note 2)
02YO008	Great Rattling Brook Above Tote River Confluence	Y	48.83	55.53	773	1984-Present
02YO011	Exploits River Below Noel Pauls Brook	Y	48.84	56.27	6,300	1985-Present
02YO013	Exploits River At Badger	Y	48.97	56.03	6,620	2004-Present
02YO016	Exploits River Near Millertown	Y	48.76	56.58	4,810	2007-Present
02YO018	Exploits River At Charlie Edwards Point	Y	48.94	55.79	7,810	2009-Present
02YO019	Badger Brook Below Foot Bridge	Y	48.98	56.03	717 (see note 1)	2018-Present
NLENHM0003 (see note 3)	Exploits River at Bishop's Falls Trestle	Y	49.08	55.49	10,167 (see note 1)	2019-Present

Notes:
1. Drainage area for 02YO019 and NLENHM0003 taken from hydrologic DEM. All others taken from WSC metadata.
2. Extended to 2018 using Nalcor record at Grand Falls Generating Station.
3. Gauge NLENHM0003 is managed by WRMD and does not have a standard WSC gauge ID.

Outflow is also measured independently by Nalcor at Millertown Dam and at Grand Falls Dam; these records were used where gaps existed in WSC data. Water levels at Grand Falls and Bishop's Falls Dam are measured by Nalcor; these were used in calibration.

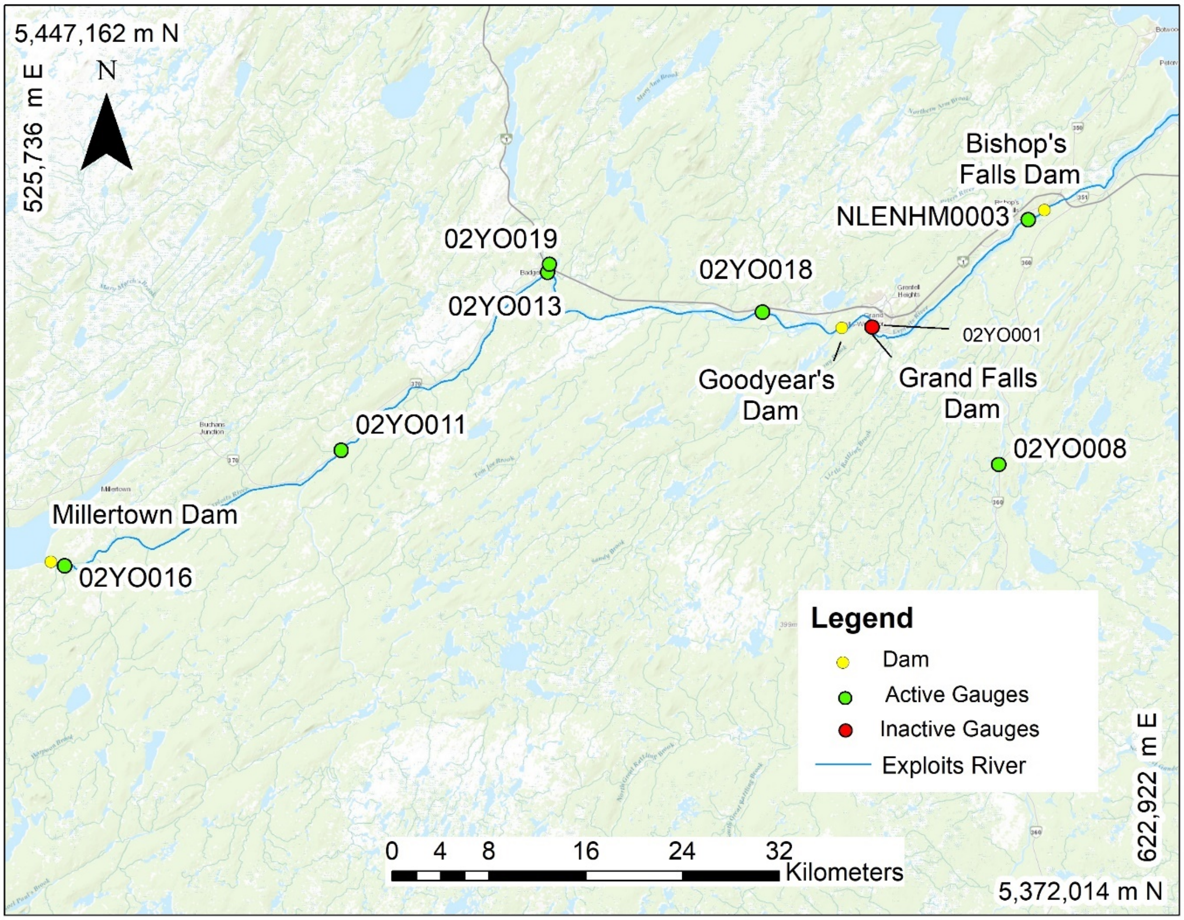

Figure 6-6: Hydrometric Gauges Used in Hydraulic Analysis

6.2.6.1 Bishop's Falls Trestle Bridge Datum Adjustment

The Bishop's Falls Trestle Bridge gauge measures elevations with respect to an assumed datum. This prevents gauge readings from being compared with forecasted water levels. The gauge is located in the Bishop's Falls Dam headpond. Using headpond water level records from Nalcor and daily water levels at the gauge from WRMD, Hatch established a rough datum for this gauge to allow correlation between gauge readings and flood forecasts. A correction of -6.15 m brings the Bishop's Falls Trestle gauge open water readings in very good sync with the Nalcor headpond readings as shown in **Figure 6-7** below. The gauge readings began on October 24, 2019. It should be noted that the gauge is mounted on the bridge and measures distance to the surface: either open water, ice or snow cover on the ice. Therefore this datum adjustment is only applicable for open water flows.

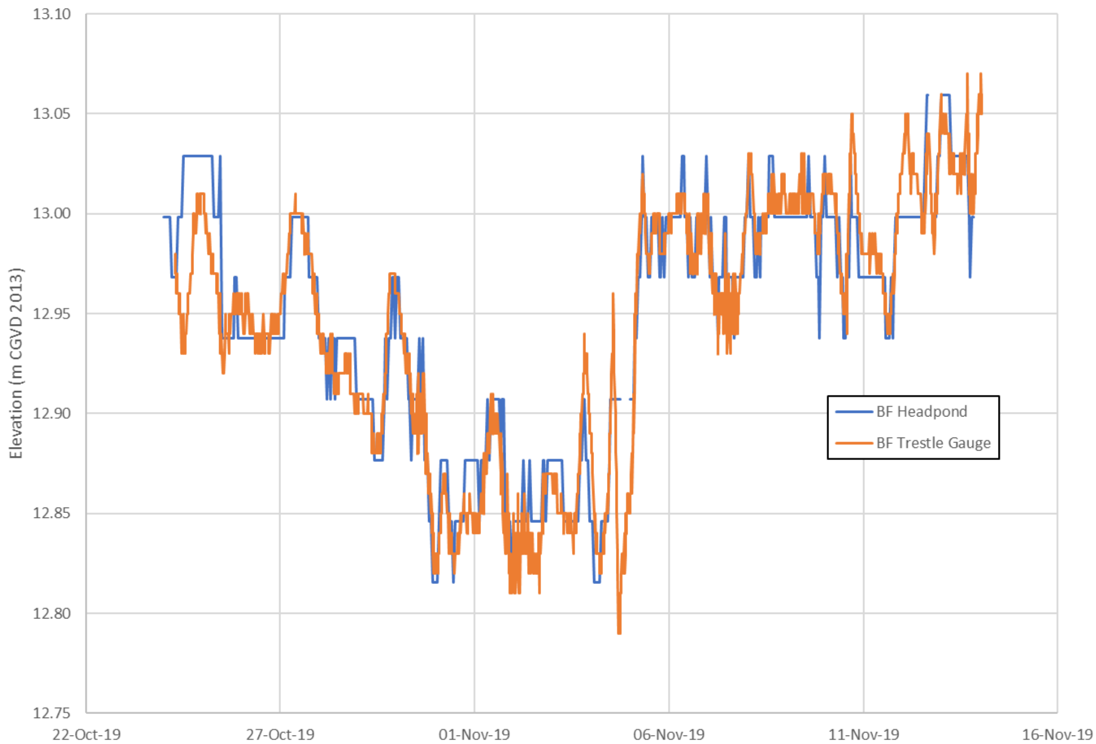

Figure 6-7: Bishop's Falls Trestle Datum Adjustment

6.2.7 Hydrologic Modelling Data

The 1:20 and 1:100 AEP flows are taken from **Table 5-29** in **Section 5.5.2** for both the current and climate change scenarios. The fully developed case scenarios are not included in the hydraulic analysis as the increase in flows is negligible between the current and fully developed cases, for the watercourses in this study. Stochastic flows were taken along the Exploits River, Badger Brook and Little Red Indian Brook. Deterministic flows were taken for all other tributaries.

6.3 Open-Water Model Development Rationale

The hydraulic modelling component of the study required the setup of a calibrated HEC-RAS model of the Exploits River and its tributaries. The application of the model mandated by WRMD was to determine the areal extents and inundation depths of flooding based on the estimated 1:20 and 1:100 AEP for current climate and climate change conditions.

Normally for the required flood risk mapping a steady state model would suffice. However, the flood forecasting system software HEC-RTS requires an unsteady hydraulic model rather than a steady state one. Given the small size of a number of the tributaries, it would have been very difficult to stabilize a model that included all thirteen of the tributaries. The small tributaries would have a negligible contribution to flooding on the Exploits River. It was therefore decided to create two models:

- An unsteady model to be used in the flood forecasting system with the Exploits River, including Badger Brook, Little Red Indian Brook, Little Rushy Pond Brook and the downstream portion of Wigwam Brook. This will ensure that flood levels are well captured in areas with historical backflooding from the Exploits River.
- A steady state model to be used for flood mapping which includes all thirteen tributaries. The peak 1:20 and 1:100 flood values adopted from the stochastic analysis or HEC-HMS model (as applicable) will be run through this model to get the flood levels needed for mapping.

Section 6.4 and **Section 6.5** outline the development of the two open-water HEC-RAS models.

6.4 Unsteady State Flood Forecasting Model

6.4.1 Model Geometry

6.4.1.1 River Reaches

The unsteady flood forecasting model includes five rivers, ordered here from upstream to downstream:

- Exploits River: 128 km reach from Millertown Dam to its outlet in the Bay of Exploits.
- Little Red Indian Brook: 1.4 km reach from west of the Town of Badger to its confluence with the Exploits River (Station 75.7).
- Badger Brook: 1.9 km reach from north of the town of Badger to its confluence with the Exploits River (Station 75.3).
- Wigwam Brook: 2.9 km reach from the Newfoundland T'Railway to its confluence with the Exploits River (Station 49.9).
- Rushy Pond Brook: 1.6 km reach from Rushy Pond to its confluence with the Exploits River (Station 48.8).

Model reaches are shown in profile view in **Figure 6-9** to **Figure 6-12**; ordered alphabetically. River stationing is in ascending order from downstream to upstream as is the convention in HEC-RAS.

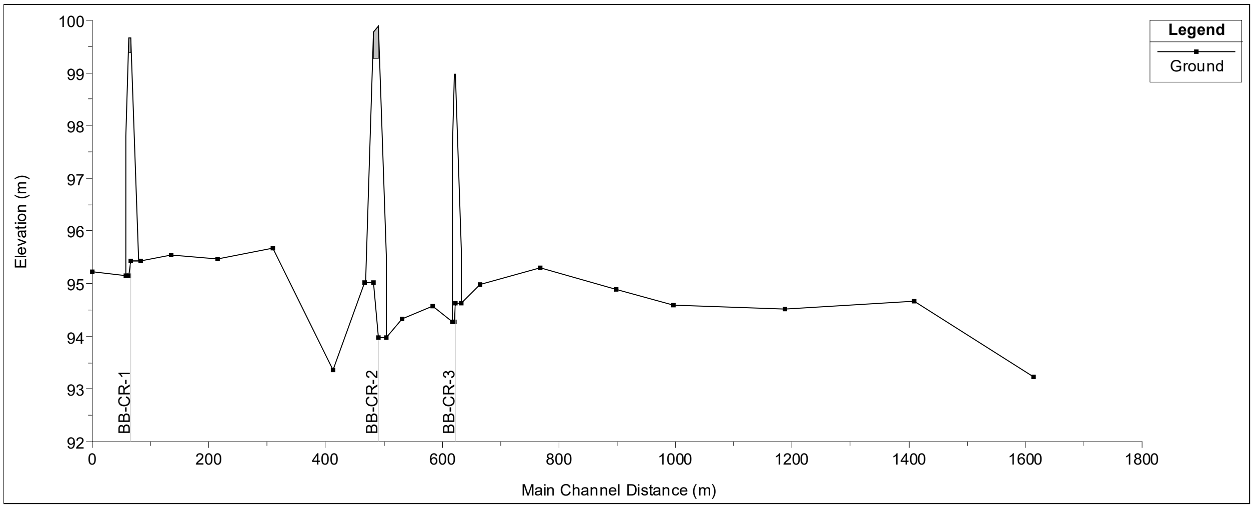

Figure 6-8: Badger Brook Profile

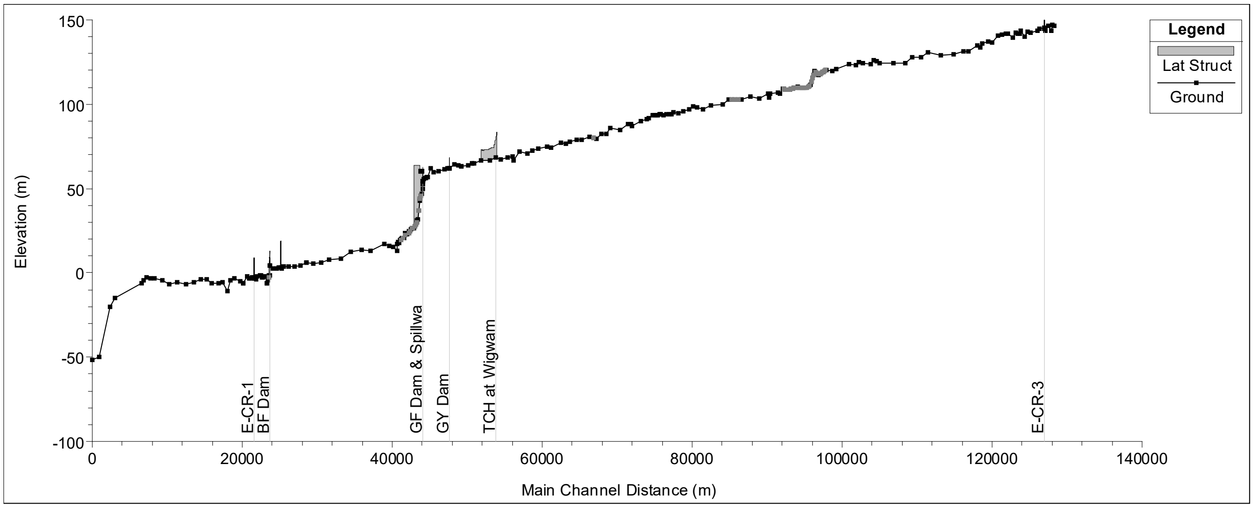

Figure 6-9: Exploits River Profile

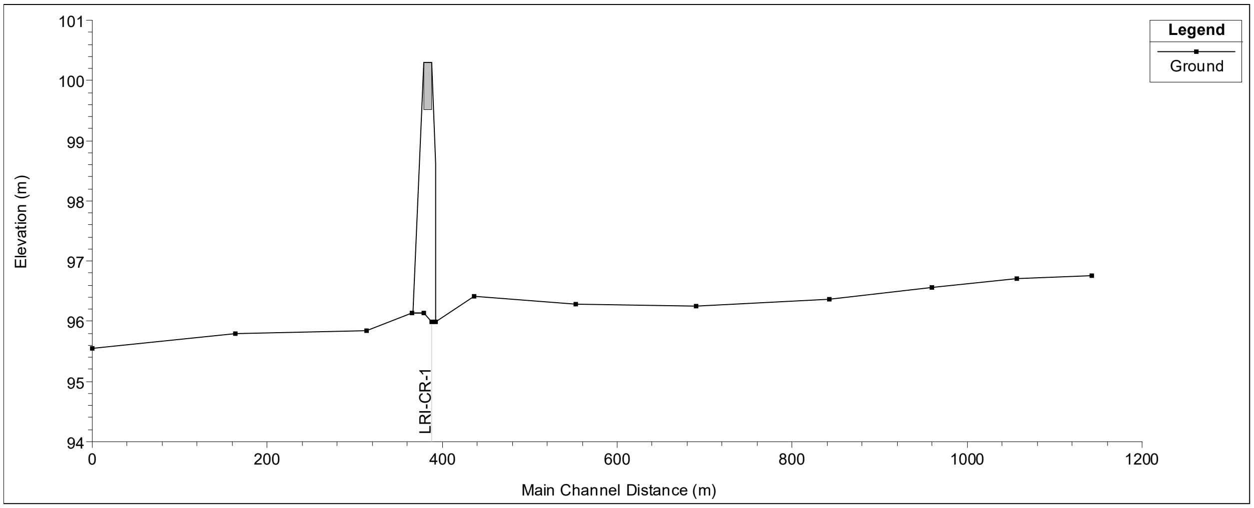

Figure 6-10: Little Red Indian Brook Profile

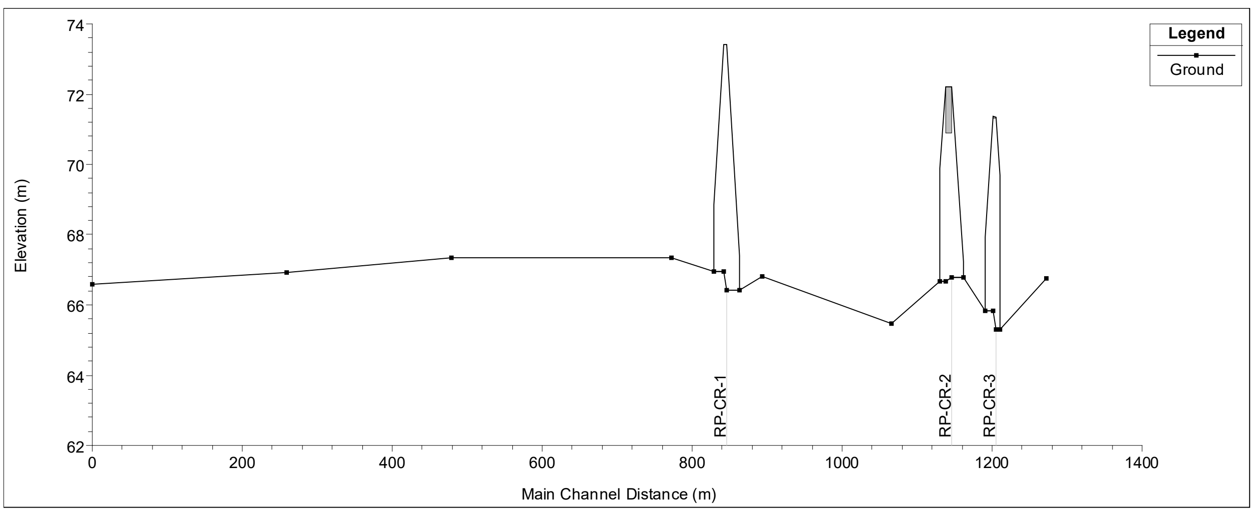

Figure 6-11: Rushy Pond Brook

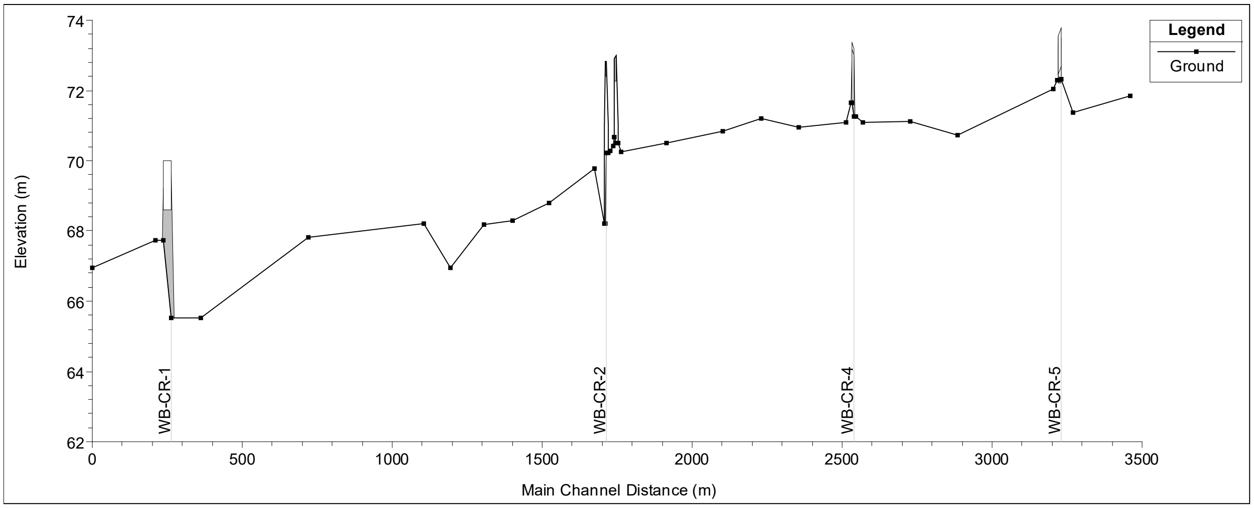

Figure 6-12: Wigwam Brook Profile

6.4.1.2 *Cross-Section*

WRMD required the use of the Geospatial Hydraulic Modelling Extension (HEC-GeoRAS) for ArcGIS for setup of the HEC-RAS model. Specifically, HEC-GeoRAS was used to prepare geometric data and to generate inputs for import to HEC-RAS as follows:

- River alignments;
- Cross-section development with stations, elevations from the DEM and bathymetry, bank locations and downstream reach lengths; and
- Creation of the HEC-RAS project.

HEC-RAS 5.0.5 is the version used to build the hydraulic model, though the model was run in Version 5.0.3 for the flood forecasting system due to compatibility requirements with HEC-RTS. For the flood mapping work, the model was run in Version 5.0.7 to take advantage of better mapping output capabilities.

HEC-RTS requires the use of the Universal Transverse Mercator (UTM) projection system and is not compatible with the Modified Transverse Mercator (MTM) projection used in Newfoundland and Labrador. Therefore a new model needed to be built in the UTM Zone 21N projection.

New cross-sections were drawn in areas where surveys had been conducted, and on tributaries that weren't included in the previous model.

The survey elevations at each of the 2019 surveyed cross-sections were added to the cross-sections. The LiDAR elevations were also added to the cross-sections. The bathymetry and LiDAR were combined using tools in HEC-RAS.

The model schematic is shown in **Figure 6-13.**

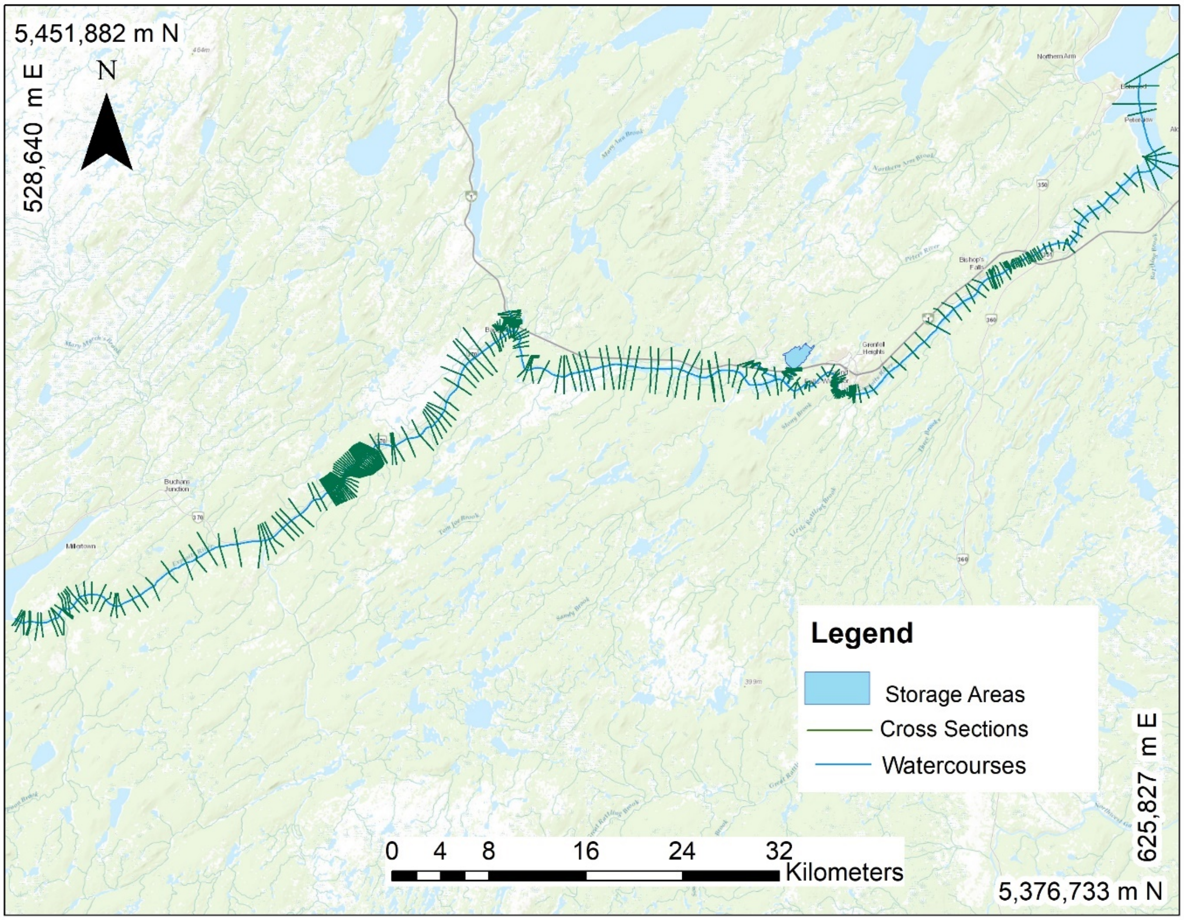

Figure 6-13: Unsteady State Model Schematic

Dams, bridges and culverts listed in **Section 6.2.3** and **Section 6.2.4** were added to the model.

6.4.1.3 Hydraulic Roughness

Manning roughness coefficient (Manning's n) characterizes the hydraulic resistance of an open channel and is a required input of HEC-RAS. The model allows separate coefficients for river channel and overbank areas as well as variation from cross-section to cross-section. Appropriate roughness coefficients were chosen from values typically used for the channel types and ground cover observed in the model reach.

The Manning's n was validated as a key factor in modelling water levels within the basin. The validation exercise is discussed in **Section** 6.4.2. Values used in the model include the following.

Exploits River

- Main channel: 0.035 (clean, straight, full, some stones and weeds).
- In Badger area (Station 77.8 to 73.0): 0.045 – adjusted during calibration to match observed water levels.
- Wigwam Brook area to Goodyear's Dam (Station 52.8 to 46.8): 0.04 – adjusted during calibration to match observed water levels.
- Between Grand Falls Main Dam and tailrace (Station to 43.2 to 42.2): 0.10 – increased for stability.
- Downstream of Grand Falls tailrace to outlet (Station 40.8 to outlet): 0.45 – adjusted during calibration to match observed water levels.

Badger Brook and Little Red Indian Brook

- Main channel: 0.040 – adjusted during calibration to match observed water levels.

Wigwam Brook and Rushy Pond Brook

- Main channel: 0.040 (clean, winding, some pools and shoals).

Overbank areas and islands

- Forested: 0.12.
- Light brush and trees/developed areas: 0.050 to 0.1.

6.4.1.4 Storage Areas

Two storage areas are included in the model: the Power Canal at Grand Falls Dam and Rushy Pond. The elevation-volume curve from previous models was used to develop the storage area for the Power Canal. The surface area of Rushy Pond was used to develop its storage area's elevation-volume curve.

The elevation-volume curves are provided in **Figure 6-14** and **Figure 6-15.** For the calibration, the initial water elevation in Rushy Pond was set as 69.3 m based on the surveyed water levels at the upstream end of Rushy Pond Brook. The initial water elevation in the Power Canal was set at 60.7 m based on the elevation of the 2019 LiDAR.

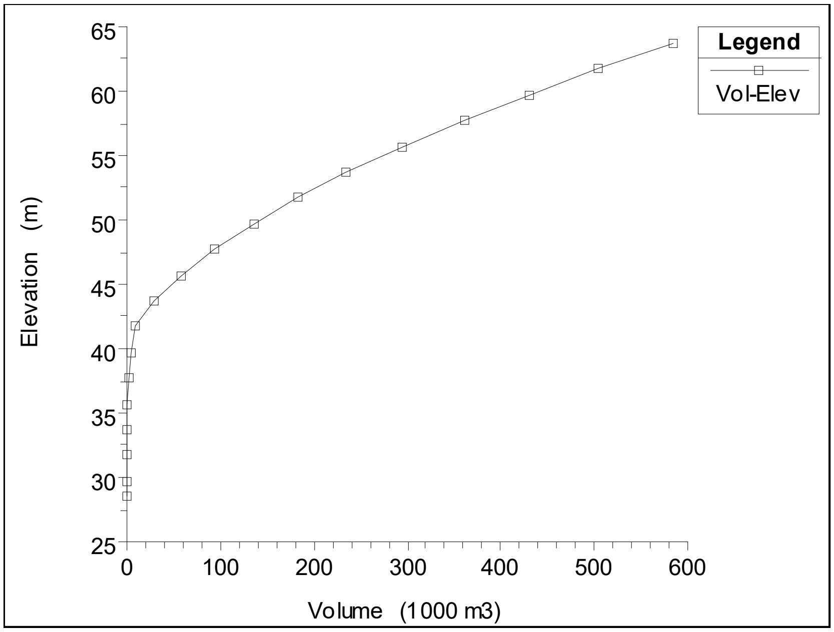

Figure 6-14: Power Canal Elevation-Volume Curve

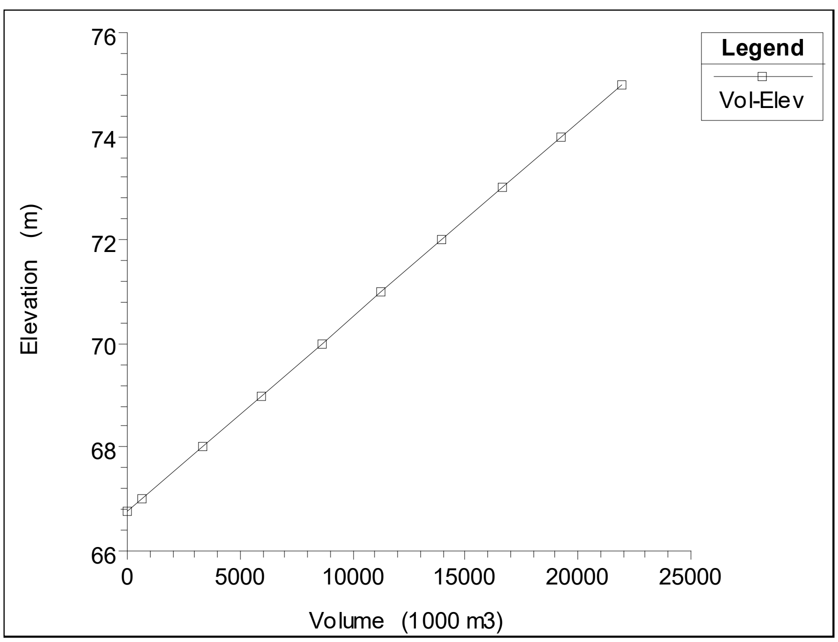

Figure 6-15: Rushy Pond Elevation-Volume Curve

6.4.1.5 Dams

The geometries of the dams and spillways listed in **Section 6.2.3** were modelled at the appropriate model cross-sections. The dimensions of the gates and crest elevations for the dams and spillways were taken from previous models. These were revised to include updates constructed in the past several years by comparing against drawings and other construction information.

Spillway and gate discharge capacities were represented in HEC-RAS by user-defined weir and orifice coefficients, as applicable. During calibration, the weir coefficient at Goodyear's Dam was adjusted to match observed water levels.

Gate operations at Grand Falls and Bishop's Falls were modelled in HEC-RAS using the "elevation controlled gate" function. This allows the gates to open and close based on set rates provided by the user, keeping the water level fluctuations within limits of a defined range of elevation. The "elevation controlled gate" function was also used to simulate the automatic release of the flashboards at Grand Falls and Bishop's Falls. The flashboards were assumed to fail once there is 0.5 m (1.5 ft) of head on the boards, as described in the Exploits Generation Operations Reference Manual.

Generation flows are omitted from the model; all flow is passed through the available spill facilities and/or over the dams. This could also be considered to represent a condition such as an interruption of generation, possibly from high tailwater levels or a transmission system failure that might occur during an extreme storm event.

6.4.1.6 Boundary Conditions

The inflow hydrographs used for the various floods were generated by the HEC-HMS model as summarized in **Table 5-29** in **Section 5.5.2**.

The downstream boundary condition of the Exploits River was set at 0.4 m, which is the Higher High Water Large Tide at Botwood, located in the Bay of Exploits. This represents the most conservative water level expected at the downstream end of the model.

6.4.1.7 Lateral Structures

Two lateral structures direct the flow from the Exploits River into and out of the Grand Falls Power Canal. These structures form part of the Grand Falls Development and are discussed in **Section 6.2.3**.

A lateral structure was added along the Exploits River at Wigwam Brook where the Trans-Canada Highway crosses through the floodplain. The lateral structure crest was cut from the 2019 LiDAR DEM, and the structure is intended to better represent how flows pass between Wigwam Brook and the Exploits River during flood conditions.

A lateral structure was added on Corduroy Brook to simulate how floodwaters spill out of the Corduroy Brook watershed over a berm into the adjacent basin. Lateral structures were also added along BF-1 and BF-2 to represent where floodwaters spill out of the watershed into adjacent basins. The crest of these structures were cut from the 2019 LiDAR DEM.

6.4.1.8 Bridges and Culverts

Bridges and culverts were added to the model with dimensions as presented in **Section 6.2.4.**

6.4.2 Calibration and Validation

Model calibration entails adjustment of parameters so that the simulated output (water level, flow travel time, etc.) reproduces observed data to an acceptable accuracy.

Two types of data were available in the calibration for the unsteady state model:

- Instantaneous water level observations on the Exploits River and tributaries to verify how model water levels compare with observed levels at a given time.
- Continuously observed water levels on the Exploits River to verify how the model water levels compare with observed levels over the course of an entire flood event on the Exploits River.

Observed flows from Water Survey of Canada gauges at Millertown Dam, Noel Pauls Brook, Badger, Charlie Edwards Point and Great Rattling Brook were used as inputs to the model, as well as Nalcor flow measurements at Grand Falls Dam. Gauge information is found in **Section 6.2.6**. Velocity observations were made by SEM during the 2019 field program; these were used to estimate the flows in the tributaries.

The model was further validated by comparing existing WSC rating curves at the Badger and Charlie Edwards Point gauges with model rating curves.

6.4.2.1 Instantaneous Observed Water Level

Three instantaneous observation sets were available in the study area:

- 2019 LiDAR observations – Water level elevations can be measured from the 2019 LiDAR DEM for the Exploits River in the community areas.
- 2019 field survey observations – Water level elevations were taken as part of the 2019 field survey on the Exploits River and tributaries. The field survey was collected between June and August, 2019. Exact dates of collection for each cross-section were available in the survey data.
- 2016 LiDAR observations – Water level elevations can be measured from the 2016 LiDAR DEM for the Exploits River between Millertown Dam and Grand Falls Dam.

The Manning’s n roughness coefficient and Goodyear’s Dam weir coefficient were adjusted to match modelled water levels to observed levels.

6.4.2.1.1 2019 LiDAR

The figures below show an average agreement between the modelled and observed water levels of approximately 12 cm. **Figure 6-16** to **Figure 6-18** show the profiles in the community areas.

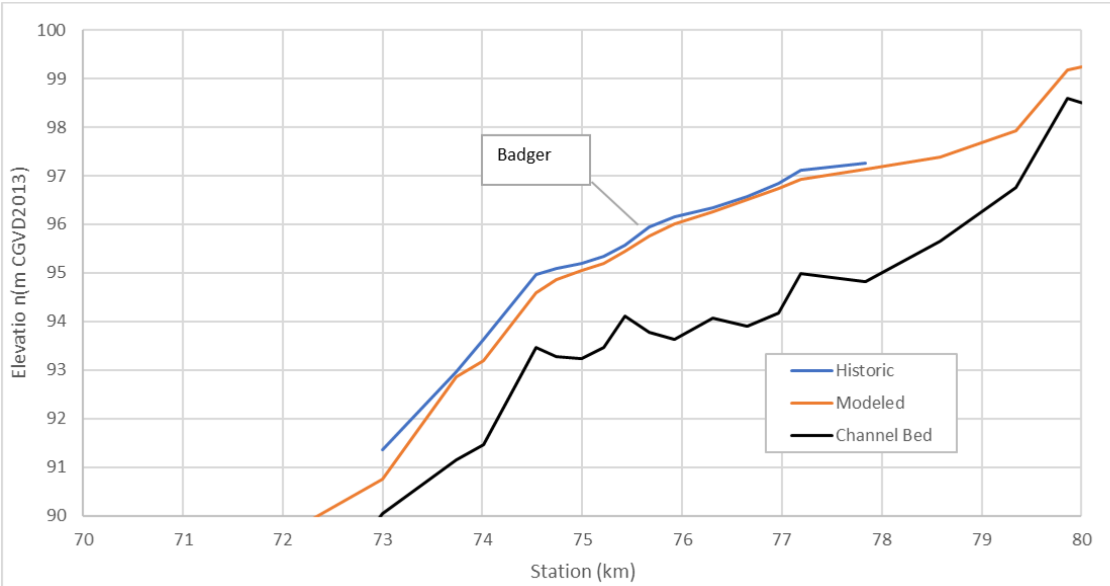

Figure 6-16: 2019 LiDAR Comparison - Badger Area

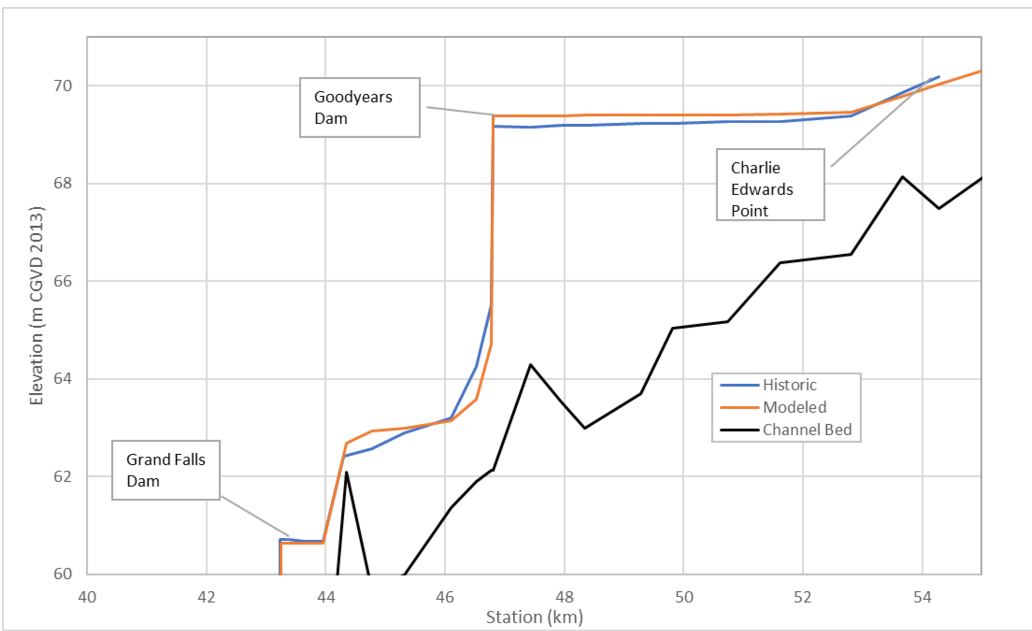

Figure 6-17: 2019 LiDAR Comparison - Grand Falls Area

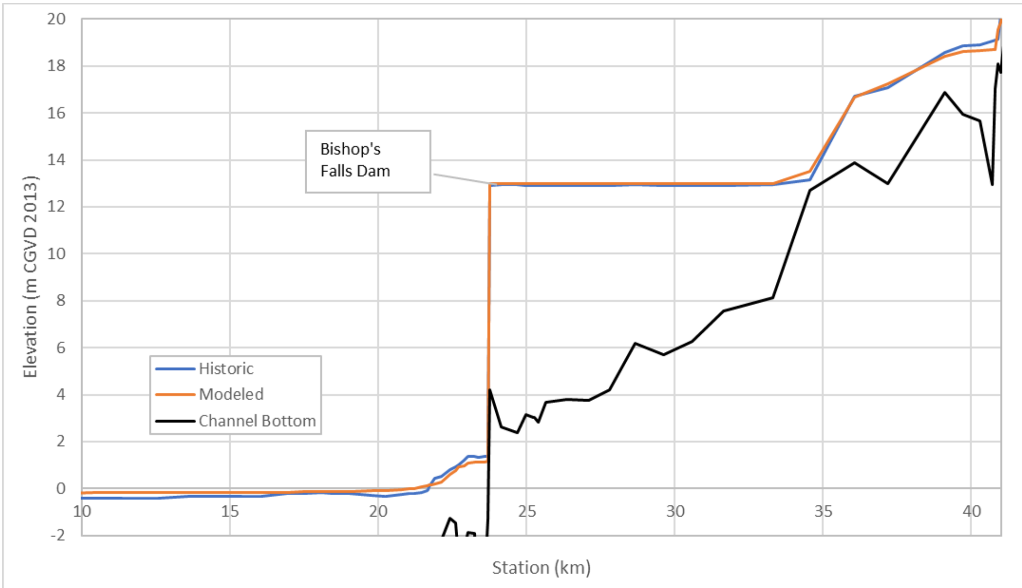

Figure 6-18: 2019 LiDAR Comparison - Bishop's Falls Area

6.4.2.1.2 2016 LiDAR

The average agreement between the modelled and observed water levels for the 2016 LiDAR is approximately 14 cm. **Figure 6-19** shows the profile from Badger to Charlie Edwards Point.

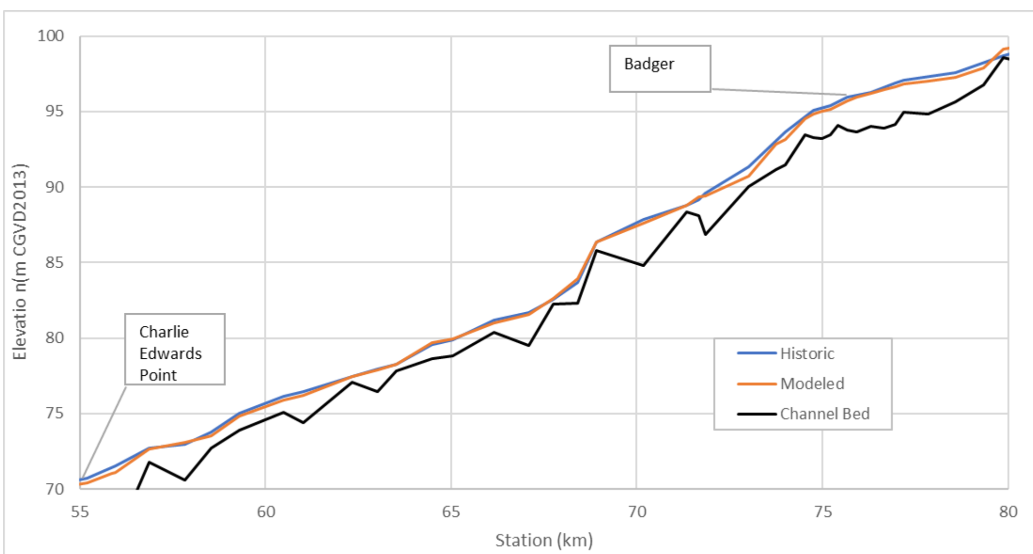

Figure 6-19: 2016 LiDAR Comparison - Badger Area

6.4.2.1.3 2019 Survey Data

The average agreement between the modelled and observed water levels for the 2019 surveyed points is approximately 4 cm for the entire model, 1 cm for the Exploits River and 8 cm for the tributaries. **Figure 6-20** to **Figure 6-24** show the comparisons between modelled and observed water levels.

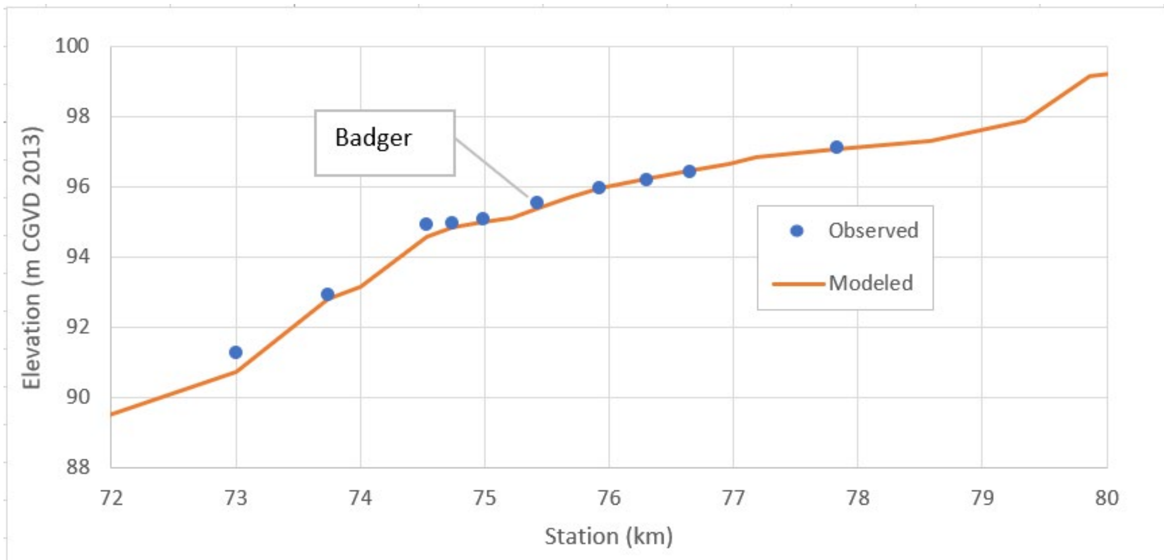

Figure 6-20: 2019 Survey Comparison - Badger Area

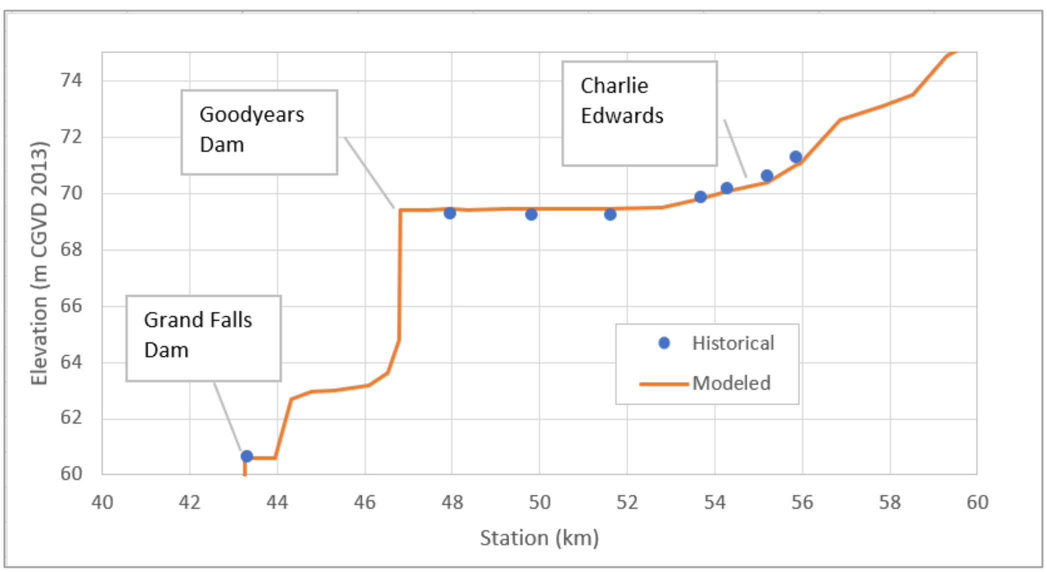

Figure 6-21: 2019 Survey Comparison - Grand Falls Area

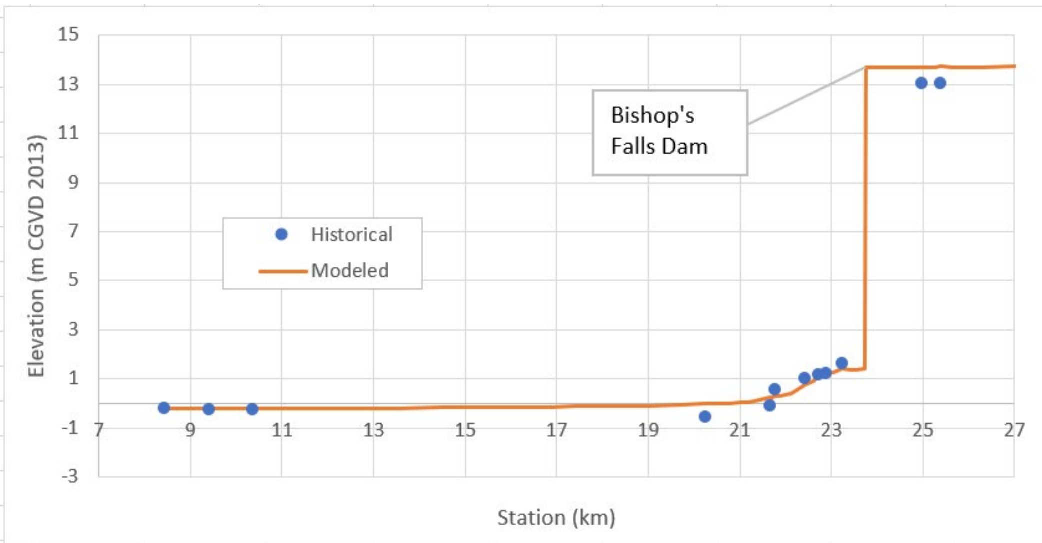

Figure 6-22: 2019 Survey Comparison - Bishop's Falls Area

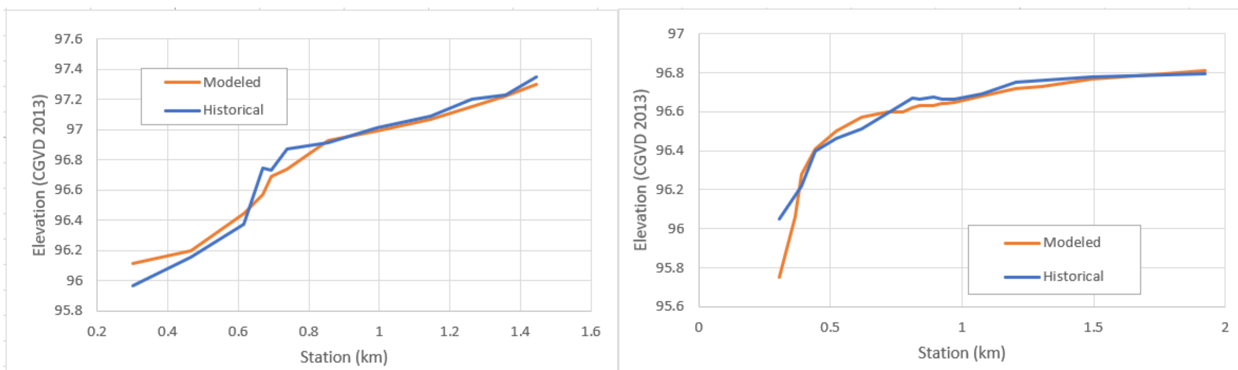

Figure 6-23: 2019 Survey Comparison - Little Red Indian Brook (left) and Badger Brook (right)

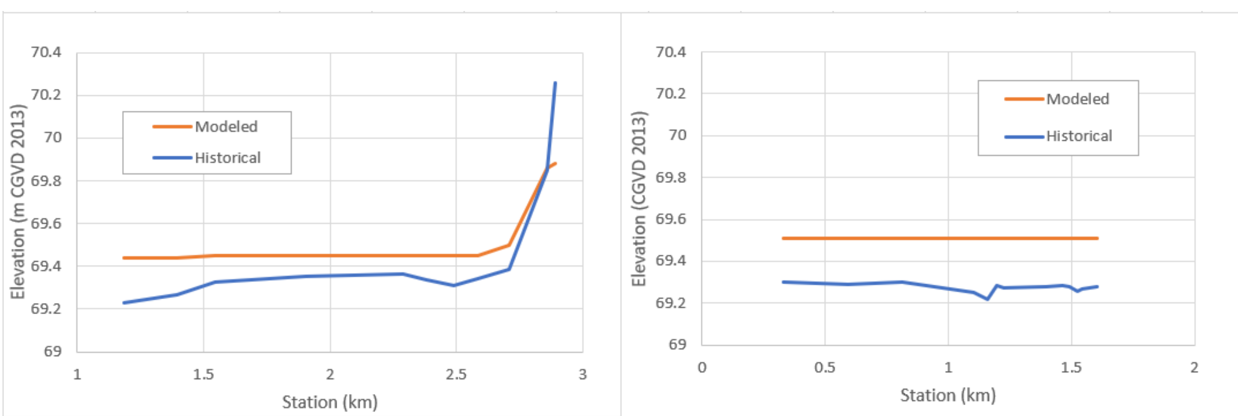

Figure 6-24: 2019 Survey Comparison - Wigwam Brook (left) and Rushy Pond (right)

6.4.2.2 *Continuous Observed Water Level*

Two continuous flood events were modelled on the Exploits River:

- October 2016 – Hurricane Matthew.
- April 25 to May 7, 2013 – During this period, there was a large release from Millertown Dam, stepping up from about 100 m^3/s to 1,130 m^3/s over the course of a few days from April 27 to May 3.

Water Survey of Canada gauges at Noel Pauls Brook, Badger and Charlie Edwards Point provided hourly water level observations on the Exploits River.

Nalcor water level readings at Grand Falls and Bishop's Falls gave hourly headwater and tailwater levels. However, the Grand Falls Dam has experienced recent reconstruction which raised the dam crest. Therefore observed water levels are lower than the modelled water levels and comparisons between historical and modelled levels are not useful in calibration.

6.4.2.2.1 2016 Event

The average difference between modelled and historical values over the flood duration and at the peak is shown in **Table 6-9**. Charlie Edwards Point did not record observations during the 2016 hurricane, and Bishop's Falls did not record over the flood peak, therefore these observation locations are not included in the comparison below. **Figure 6-25** and **Figure 6-26** compare the flood hydrographs. The R^2 ranges from 0.989 to 0.994.

Table 6-9: 2016 Comparison Results

Gauge	Difference (Modelled – Historical) (m)		R^2
	Average	Peak	
02YO011 - Exploits River at Noel Pauls Brook	-0.02	0.11	0.994
02YO013 - Exploits River at Badger	-0.21	-0.01	0.989

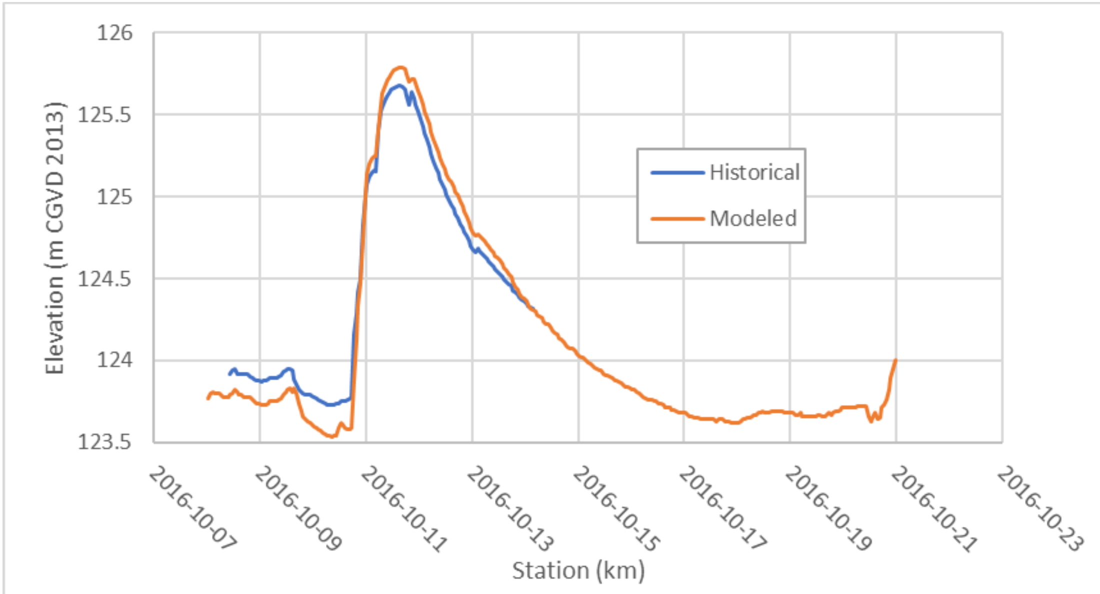

Figure 6-25: 2016 Comparison - 02YO011 - Noel Pauls Gauge

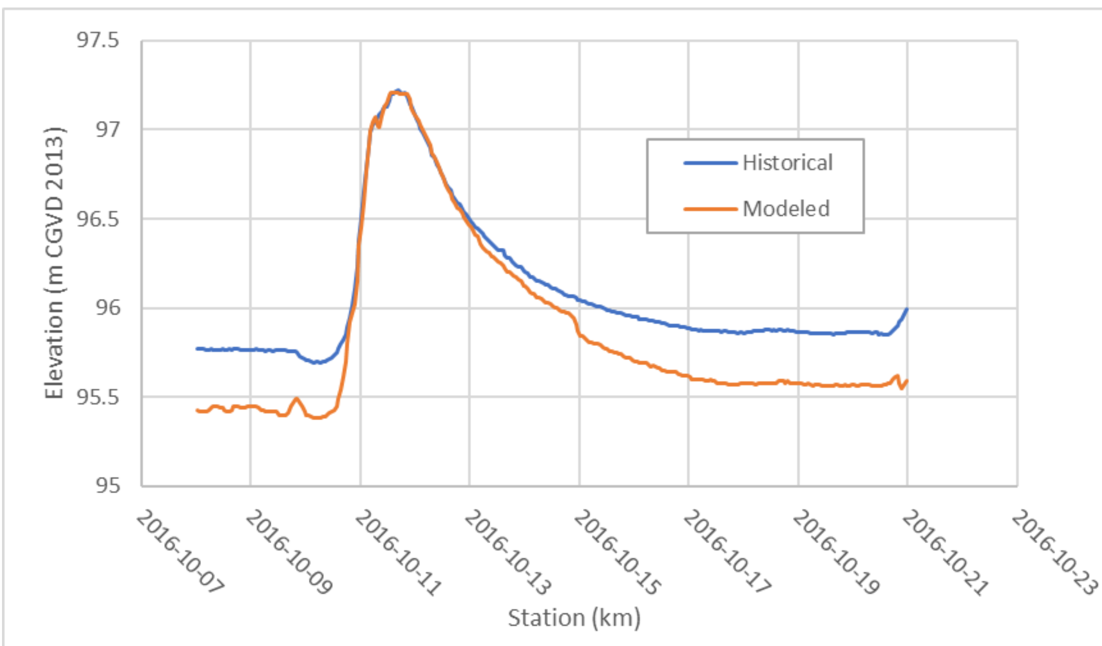

Figure 6-26: 2016 Comparison - 02YO013 - Badger Gauge

6.4.2.2.2 2013 Event

The average difference between modelled and historical values over the flood duration and at the peak is shown in **Table 6-10**. **Figure 6-27 to Figure 6-31** compare the flood hydrographs. With the exception of Bishop's Falls Headpond, the R^2 varies from 0.9 to 0.998.

Table 6-10: 2013 Comparison Results

Gauge	Difference (Modelled – Historical) (m)		R^2
	Average	Peak	
02YO011 - Exploits River at Noel Pauls Brook	0.03	0.09	0.994
02YO013 - Exploits River at Badger	0.02	0.14	0.989
02YO018 - Exploits River at Charlie Edwards Point	0.15	0.14	0.998
Bishop's Falls Dam Headpond	-0.57	0.16	0.002
Bishop's Falls Dam Tailrace	-0.69	-0.96	0.900

Several things should be noted with respect to the results presented at Bishop's Falls.

The modelled flood peaks in the headpond match the historical conditions; which indicates that the model is using the dam's available capacity as needed. Operator decisions at Bishop's Falls and Grand Falls are difficult to simulate on a real-time basis. General gate operations rules for extreme flood events have been included in the model. The 1:20 and 1:100 flood maps have been developed assuming that all gates are fully opened, which is a typical assumption at high flows and is outlined in the Nalcor operating manual. The operators will use all available discharge capacity to ensure the upstream water level rises no higher than necessary, firstly by turbining as much water as possible to maximize generation and minimize spill, then by preferentially utilizing all available gates, before finally relying on the overflow spillway, so as to reduce the risk of unsafe overtopping of the dam and minimize upstream flooding.

The modelled tailwater is consistently lower than historical conditions. This is consistent with previous modelling work at this site. Hatch modelled the tailwater levels at Bishop's Falls Dam in a study in 2019 for Newfoundland and Labrador Hydro (Hatch, 2019). In that study, the modelled levels compared well with the historical data for lower flows, which was also observed in this study as shown in **Figure 6-31**. However, for higher flows, the modelled levels were below the expected tailwater rating curve; this was also observed in this study. The modelled results seemed to fit the limited information available on the largest flood events at the site. The reason for the discrepancy was not able to be identified in the 2019 study. During discussions with Newfoundland and Labrador Hydro staff, it has been noted that the modeled results also agree with the OMS documentation at the site, while the observed values are recorded by Nalcor staff and continue to read higher than expected. The bathymetry downstream of the dam was well-defined from drawings and previous surveys, and review of the model geometry did not identify any inconsistencies. It could be associated with uncertainty in the measurement of tailwater and/or estimation of flows at Bishop's Falls. Due to the size of the watershed, there will be large variations in the spatial distribution of precipitation and runoff, and estimation of flows using measurements in other locations may not give consistent results. Since there was confidence in the model's geometry and the output was consistent with operator experience, the 2019 study recommended that the modelled tailwater curve be used.

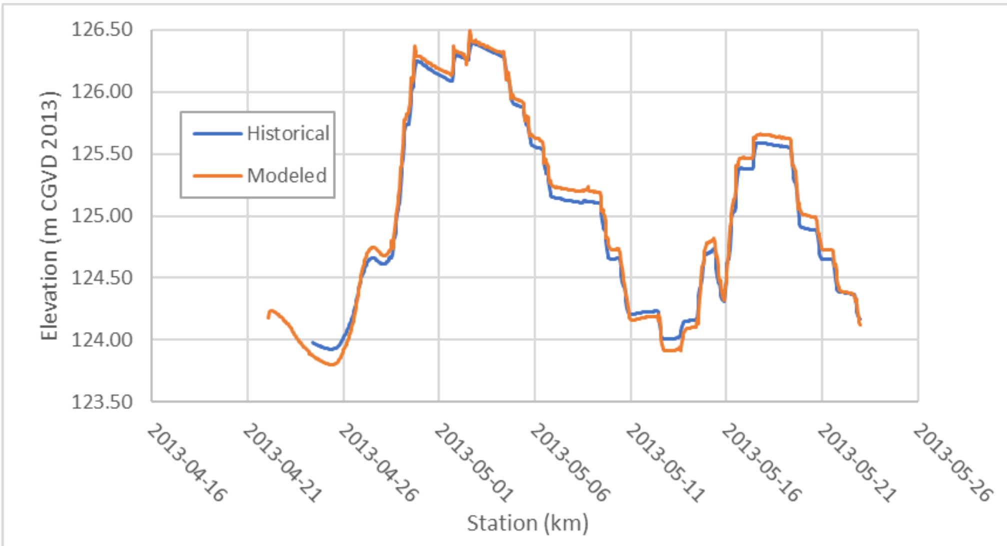

Figure 6-27: 2013 Comparison - 02YO011 - Noel Pauls Gauge

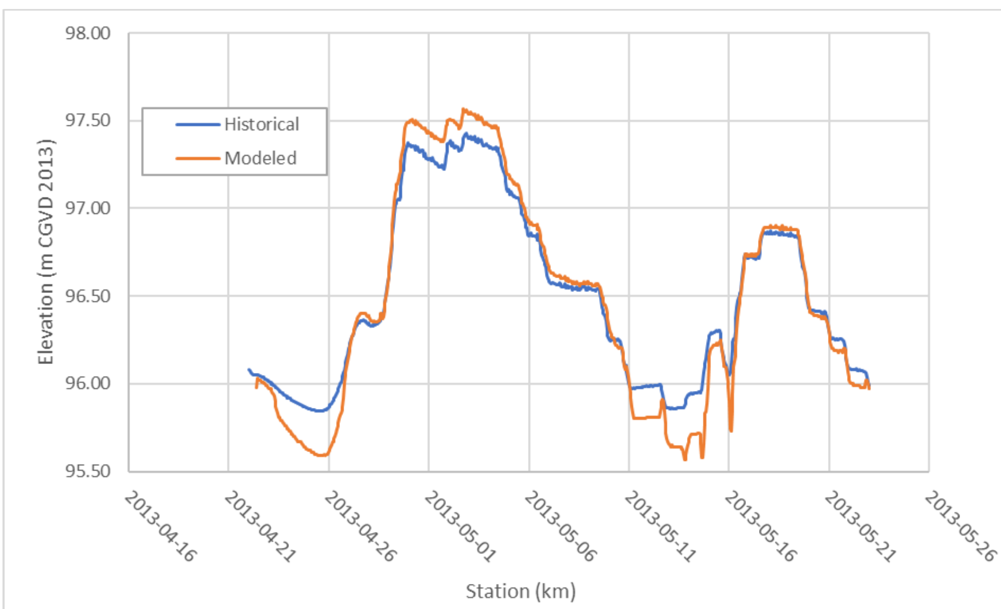

Figure 6-28: 2013 Comparison - 02YO013 - Badger Gauge

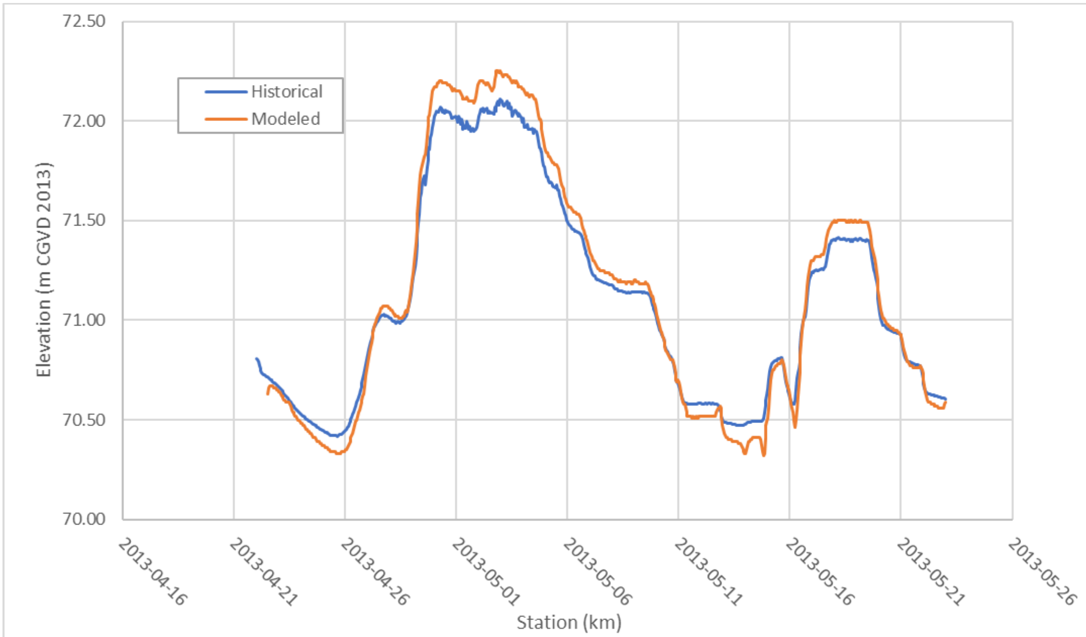

Figure 6-29: 2013 Comparison - 02YO018 - Charlie Edwards Point Gauge

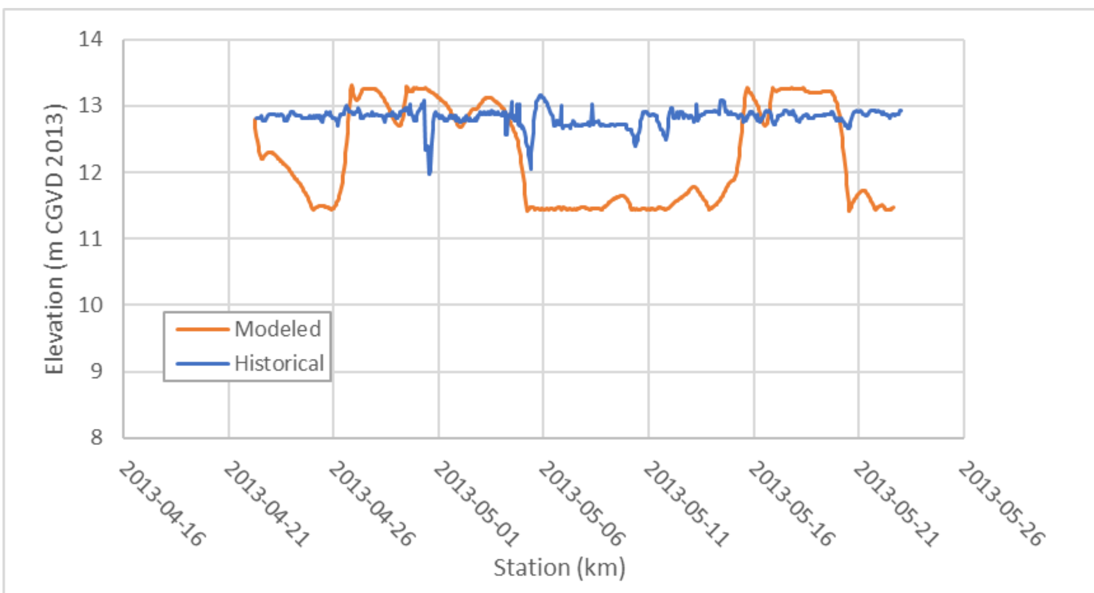

Figure 6-30: 2013 Comparison - Bishop's Falls Dam Headpond

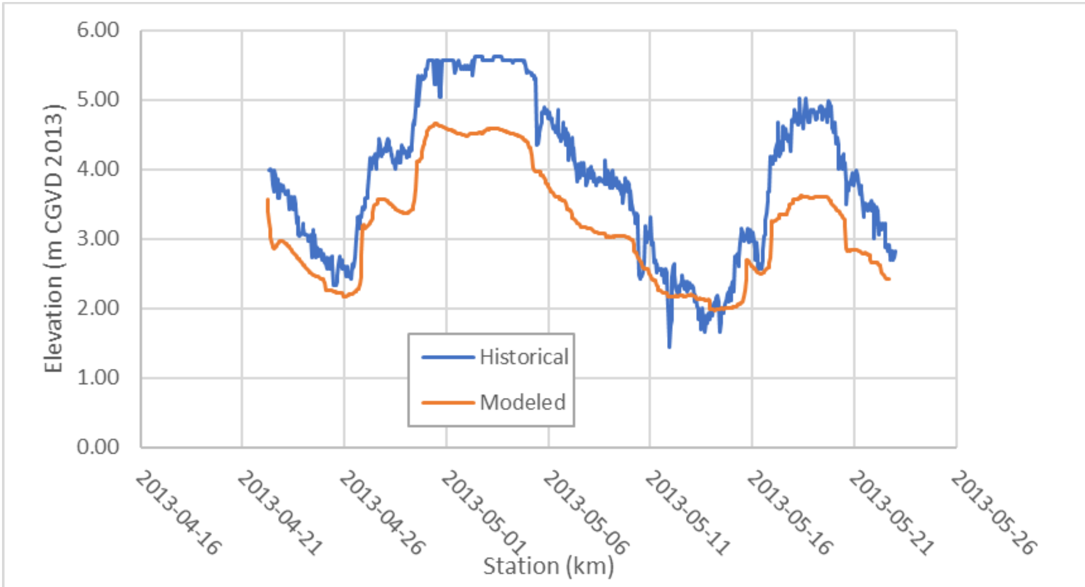

Figure 6-31: 2013 Comparison - Bishop's Falls Dam Tailrace

6.4.2.3 *Rating Curve Validation*

Rating curves for WSC gauges on the Exploits River at Charlie Edwards Point and Exploits River at Badger were compared to the model rating curves. The rating curves match very well in the flood stages of the river as shown in **Figure 6-32** and **Figure 6-33**.

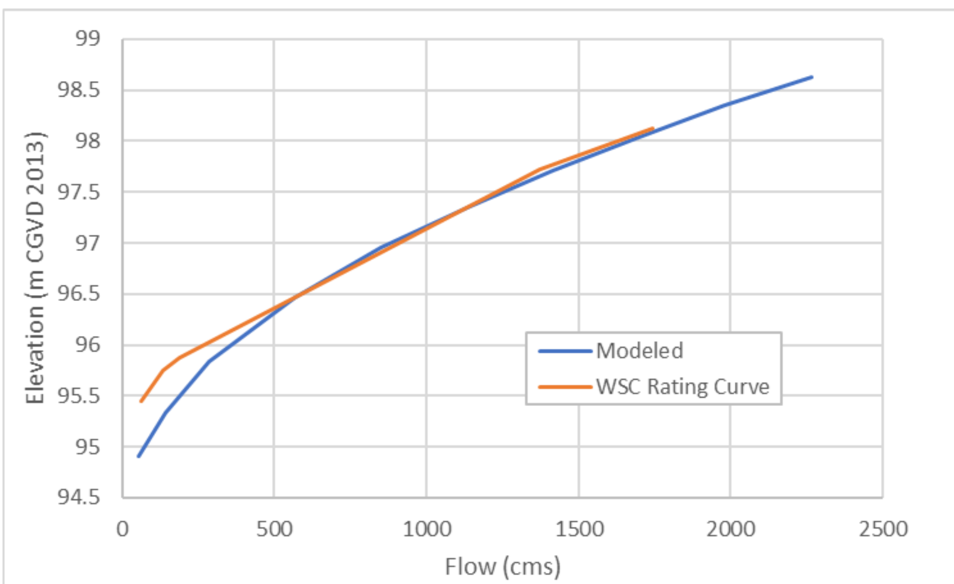

Figure 6-32: Rating Curve Comparison - 02YO013 - Badger Gauge

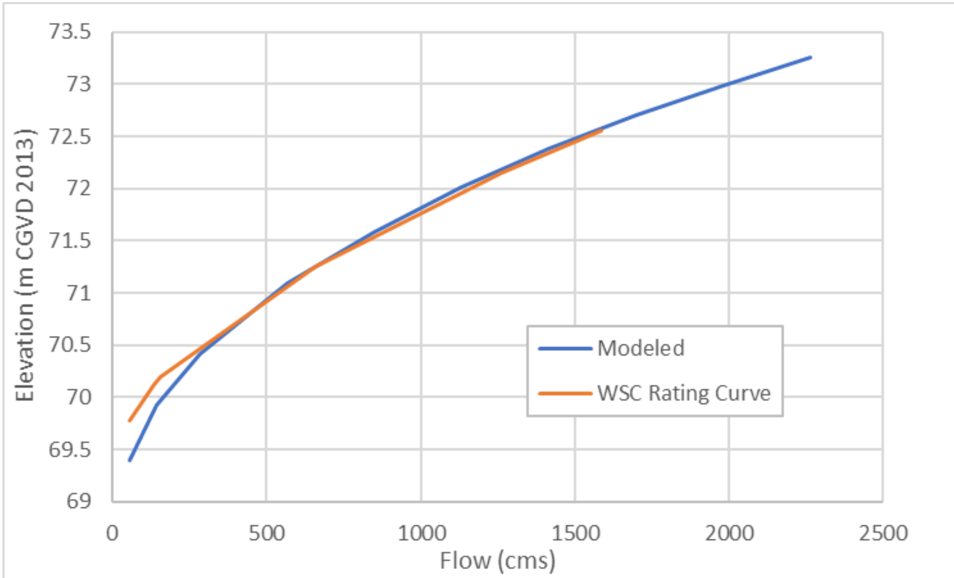

Figure 6-33: Rating Curve Comparison - 02YO018 - Charlie Edwards Point Gauge

6.5 Steady State Flood Mapping Model

6.5.1 Model Geometry

6.5.1.1 River Reaches

Following completion of the flood forecasting model, the remaining tributaries were added to create the steady state flood mapping model. This model includes thirteen rivers, ordered from upstream to downstream:

- Exploits River: 128 km reach from Millertown Dam to its outlet in the Bay of Exploits; no change from flood forecasting model.
- Unnamed Stream B-1: 1.0 km reach from its upstream end to its confluence with Little Red Indian Brook (Station 1.3).
- Little Red Indian Brook: 1.4 km reach from west of the Town of Badger to its confluence with the Exploits River (Station 75.7) ; no change from flood forecasting model.
- Badger Brook: 1.9 km reach from north of the town of Badger to its confluence with the Exploits River (Station 75.3); no change from flood forecasting model.
- Wigwam Brook: 4.6 km reach from its upstream end to its confluence with the Exploits River (Station 49.9); increased length from flood forecasting model.
- Little Rushy Pond Brook: 0.6 km reach from its upstream end to its outlet into Rushy Pond.
- Rushy Pond Brook: 1.6 km reach from Rushy Pond to its confluence with the Exploits River (Station 48.8); no change from flood forecasting model.

- Mullen's Pond: 0.4 km reach from its upstream end to its outlet into the Second Avenue Culvert. The culvert diverts the flows from the pond into the Grand Falls-Windsor sewer system.
- Corduroy Brook: 3.9 km reach from its upstream end to its confluence with the Exploits River (Station 43.7).
- Unnamed Stream GF-1: 4.0 km reach from its upstream end to the Newfoundland T'Railway. At this point, it is downstream of the community areas and is no longer modelled.
- Unnamed Stream BF-4: 0.9 km reach from its upstream end to its confluence with the Exploits River (Station 29.4).
- Unnamed Stream BF-3: 2.1 km reach from its upstream end to its confluence with the Exploits River (Station 26.2).
- Unnamed Stream BF-2: 1.2 km reach from its upstream end to its confluence with the Exploits River (Station 23.4).
- Unnamed Stream BF-1: 1.2 km reach from its upstream end to its confluence with the Exploits River (Station 20.4).

Model reaches are shown in profile view in **Figure 6-34** to **Figure 6-43**, ordered alphabetically. Reaches that were not changed between the unsteady and steady state models are not repeated below.

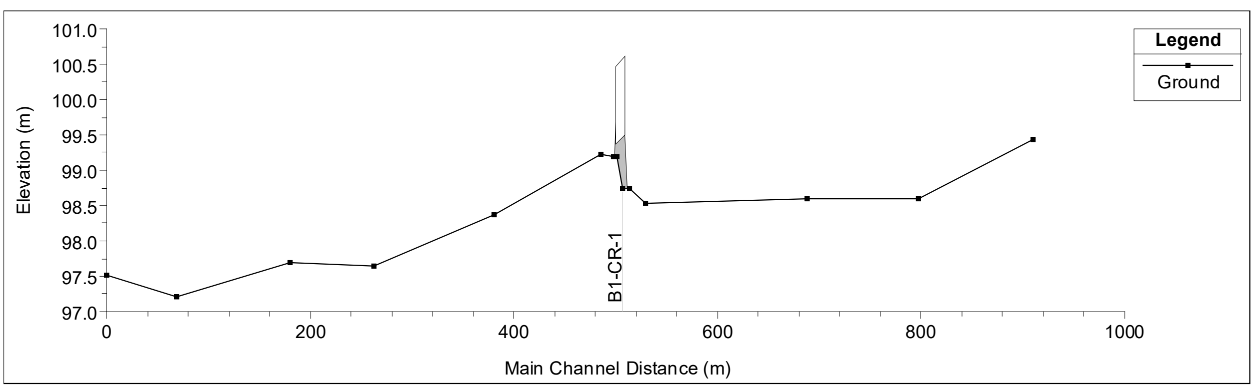

Figure 6-34: Unnamed Stream B-1 Profile

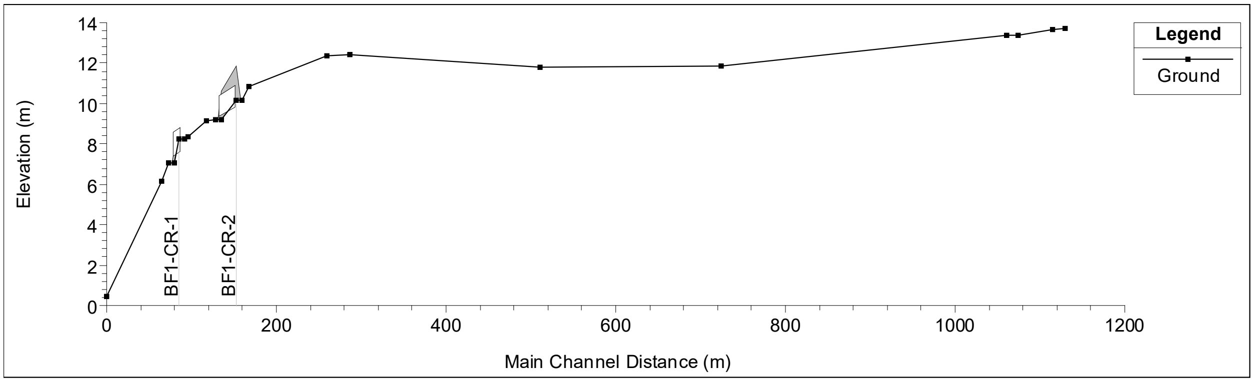

Figure 6-35: Unnamed Stream BF-1 Profile

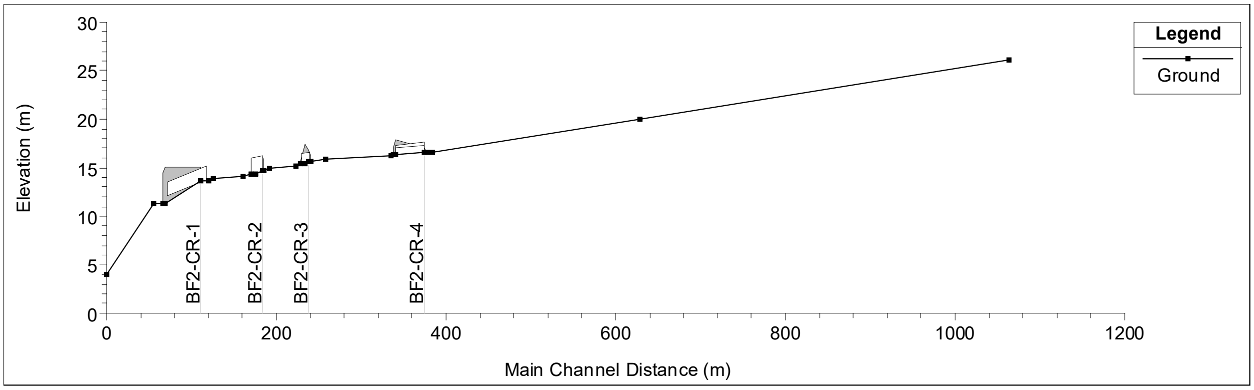

Figure 6-36: Unnamed Stream BF-2 Profile

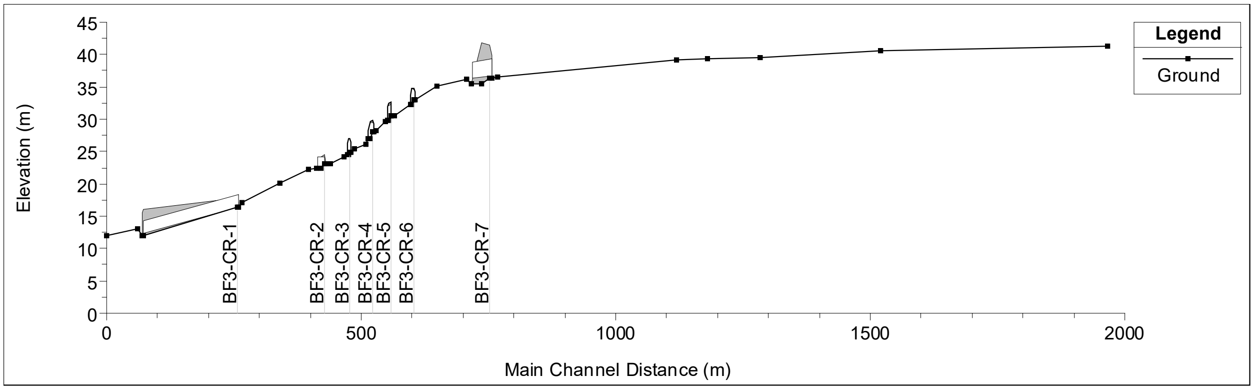

Figure 6-37: Unnamed Stream BF-3 Profile

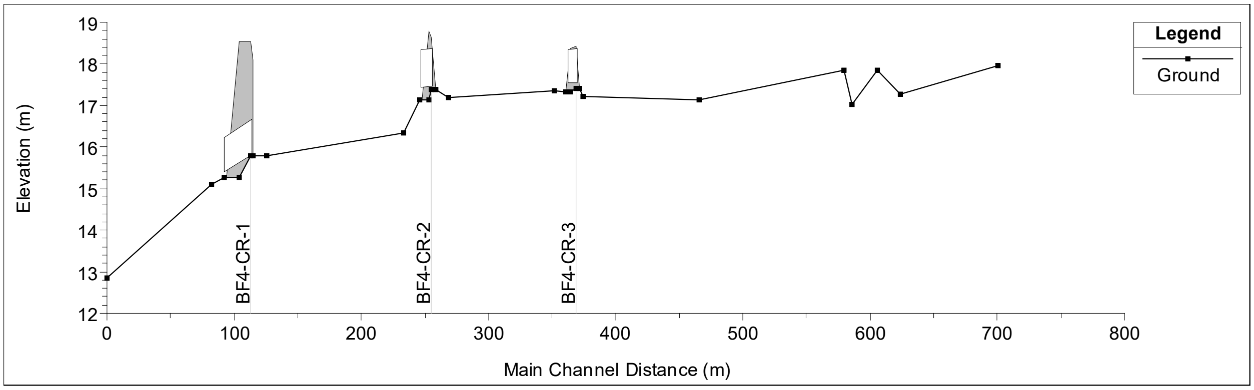

Figure 6-38: Unnamed Stream BF-4 Profile

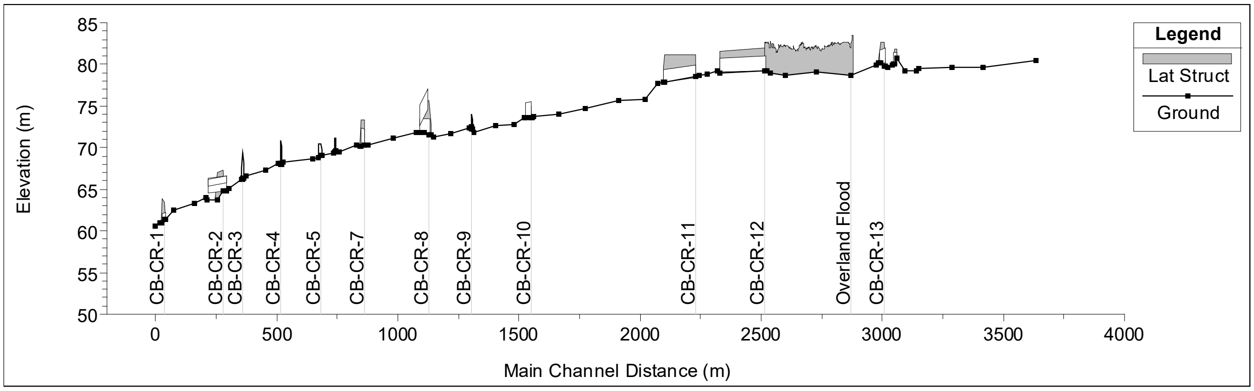

Figure 6-39: Corduroy Brook Profile

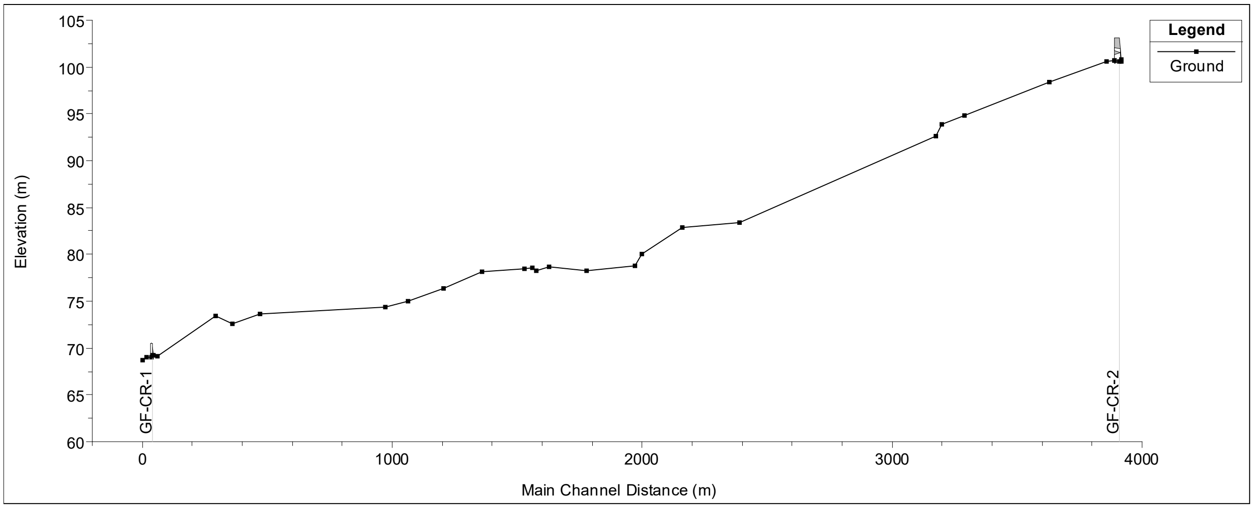

Figure 6-40: Unnamed Stream GF-1 Profile

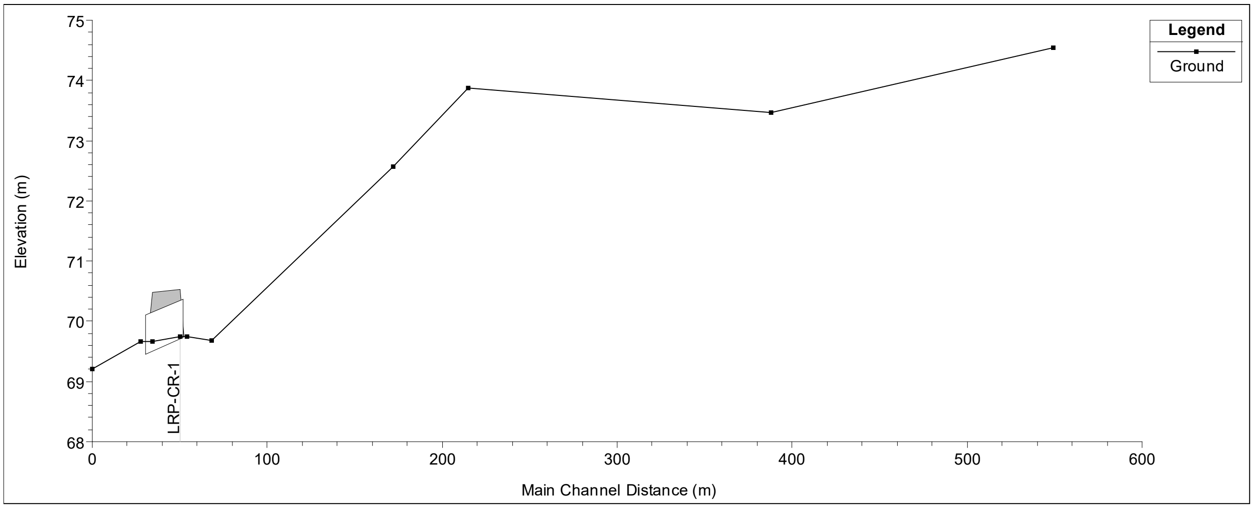

Figure 6-41: Little Rushy Pond Profile

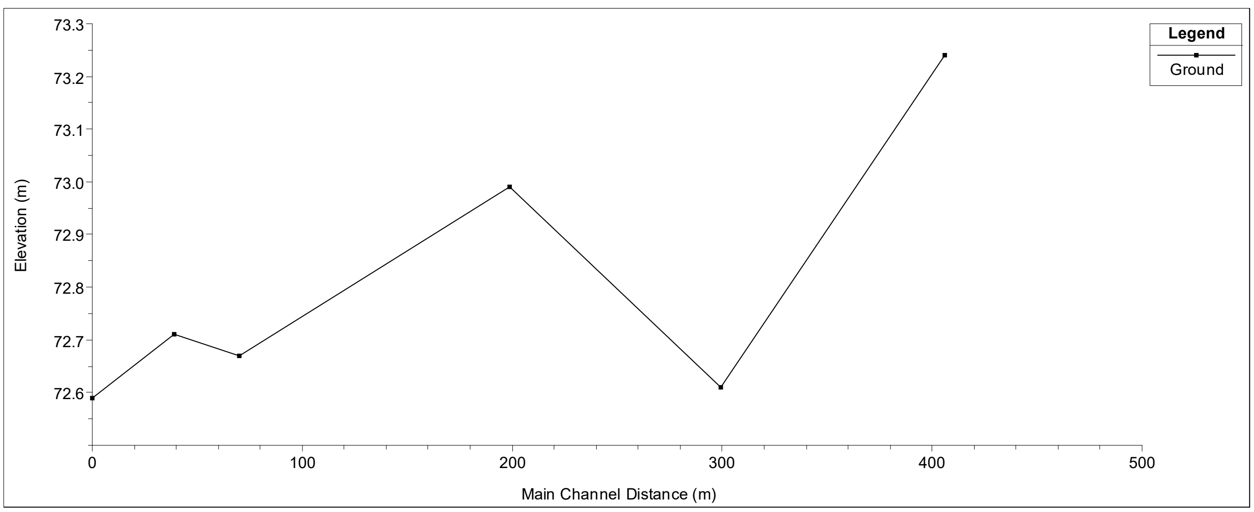

Figure 6-42: Mullen's Pond Profile

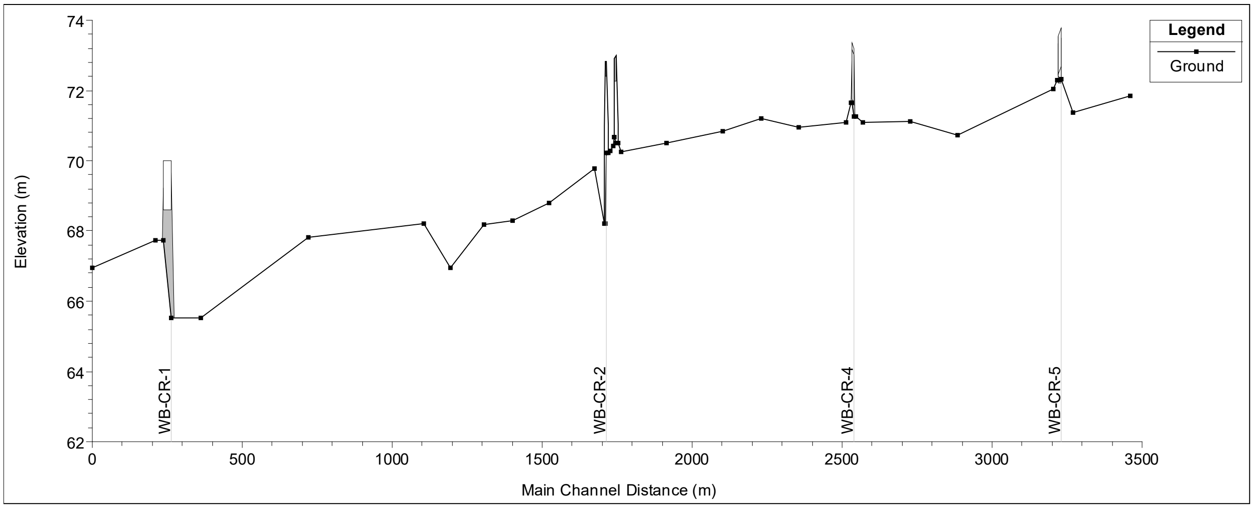

Figure 6-43: Wigwam Brook Profile

6.5.1.2 Cross-Section

In general, cross-sections from the unsteady state model were not changed in the steady state model, except where cross-sections needed to be adjusted to avoid overlapping with newly added tributaries. All cross-sections in the new reaches were created using the 2019 LiDAR and survey information with HEC-GeoRAS tools as outlined in **Section 6.4.1.2**.

The model schematic is shown in **Figure 6-44**.

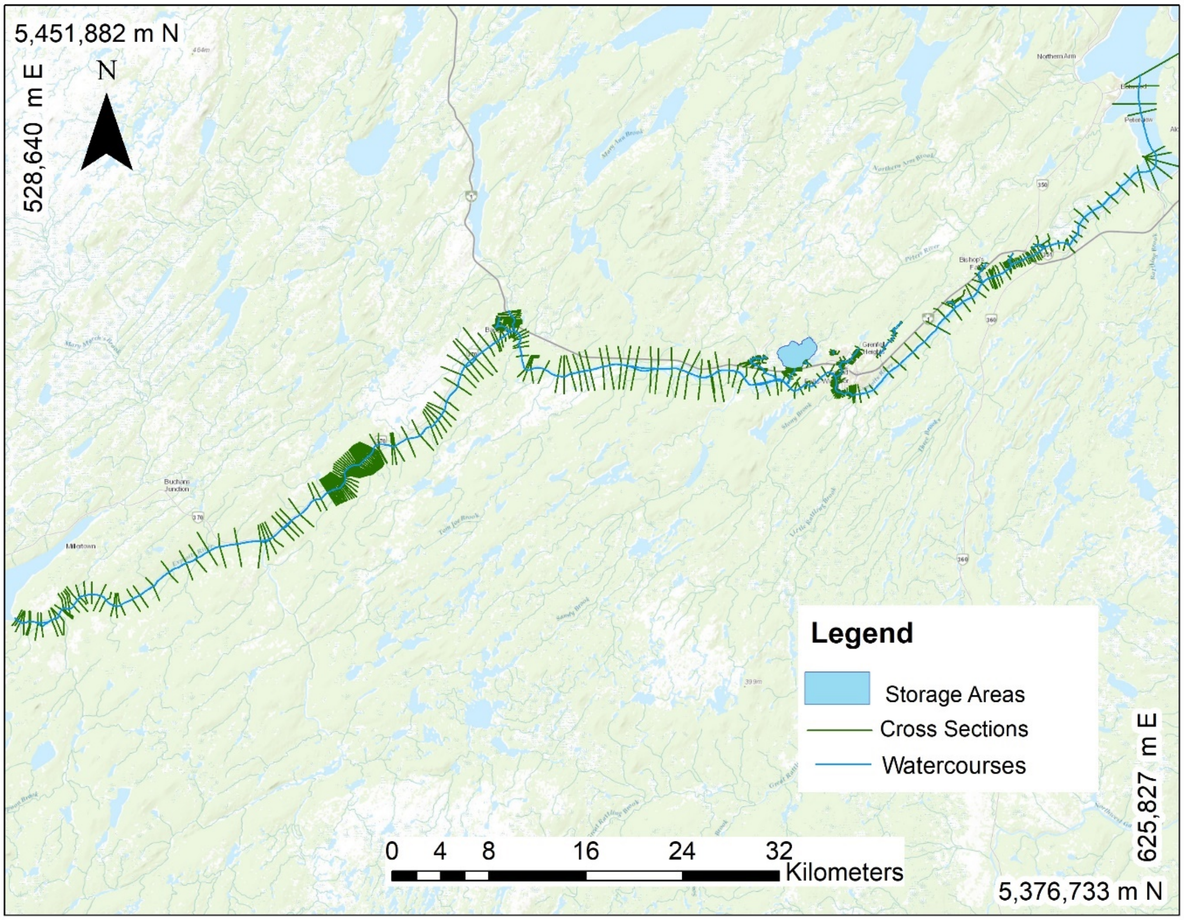

Figure 6-44: Steady State Model Schematic

6.5.1.3 *Hydraulic Roughness*

No changes were made to the roughness values developed in the unsteady state model as described in **Section 6.4.1.3**.

The overbank roughness values for the cross-sections added to the steady state model were assigned as described in **Section 6.4.1.3**.

The main channel values for the new reaches are all 0.040, corresponding to a description of clean, winding, some pools and shoals.

6.5.1.4 *Storage Areas*

No new storage areas were added to the steady state model, nor were changes were made to the existing storage areas.

6.5.1.5 *Dams*

No new dams were added to the steady state model. All gate openings were set to fully open for the steady flows.

6.5.1.6 *Boundary Conditions*

For the steady state model, the upstream boundary condition for the Exploits River was set at 146.6 m as a known water surface; this value represents a reasonable starting point for flows in the Exploits River. The upstream model boundary for the Exploits River is well upriver of the study area communities and has no impact on the simulated water levels in the mapping area in steady state mode. The upstream boundary conditions for the tributaries were set as normal depths based on their slopes.

The downstream boundary condition for the Exploits River is unchanged for the current climate condition. The downstream boundary condition of the Exploits River for the climate change condition was increased to 1.3 m based on a projected estimated sea level rise of 0.9 m by 2099 (Batterson, 2010). The downstream boundary of Unnamed Stream GF-1 is set as the normal depth based on the river slope. The downstream boundary of Mullen’s Pond is set as a rating curve to model the culvert’s discharge into the town stormwater management system.

6.5.1.7 *Lateral Structure*

No new lateral structures were added to the steady state model.

6.5.1.8 *Bridges and Culverts*

Bridges and culverts were added to the model with dimensions as presented in **Section 6.2.4.**

6.5.2 ***Validation***

The reaches added to the steady state model were validated by comparing 2019 survey observations with model results.

As discussed in the unsteady state calibration section, water level elevations were taken as part of the 2019 field survey on the Exploits River and tributaries. The field survey was collected between June and August, 2019. Exact dates of collection for each cross-section were available in the survey data.

Observed flows from Water Survey of Canada gauges at Millertown Dam, Noel Pauls Brook, Badger, Charlie Edwards Point and Great Rattling Brook were used as inputs to the model. Velocity observations were made by SEM during the 2019 field program; these were used to estimate the flows in the tributaries.

A variation in the Manning’s n produced very little change in the water levels, therefore the standard roughness of 0.04 was used for all tributaries.

The figures below show an average agreement between the modelled and observed water levels of approximately 20 cm.

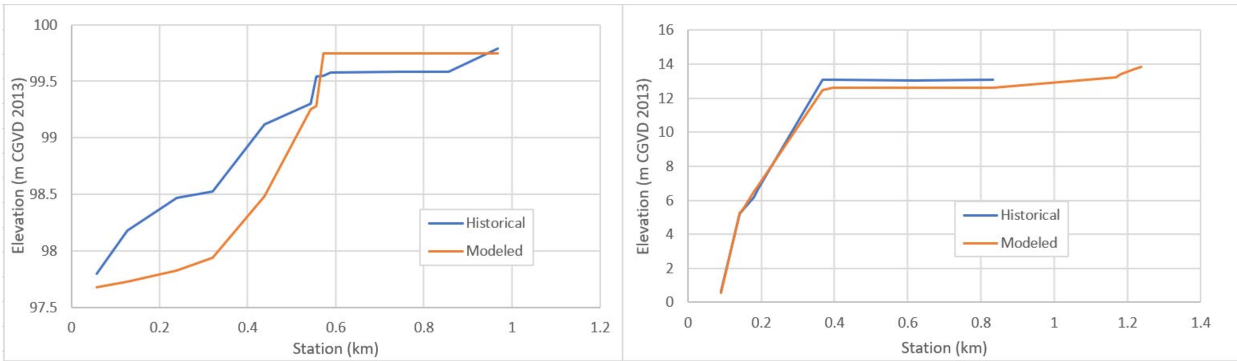

Figure 6-45: 2019 Survey Comparison: Unnamed Stream B-1 (left) and BF-1 (right)

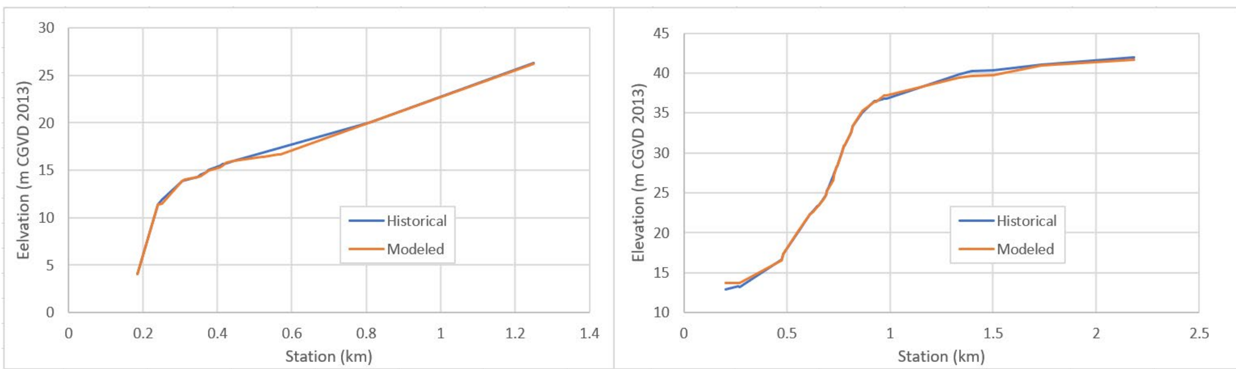

Figure 6-46: 2019 Survey Comparison: Unnamed Stream BF-2 (left) and BF-3 (right)

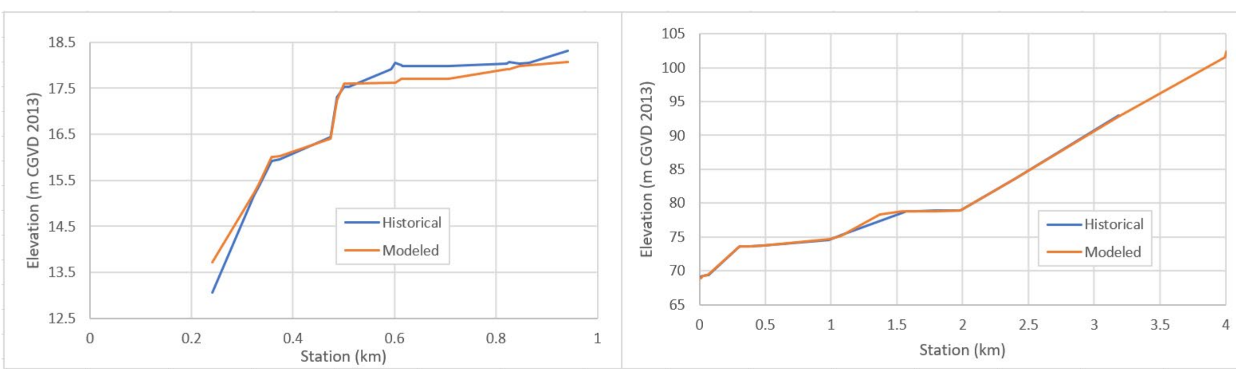

Figure 6-47: 2019 Survey Comparison: Unnamed Stream BF-4 (left) and GF-1 (right)

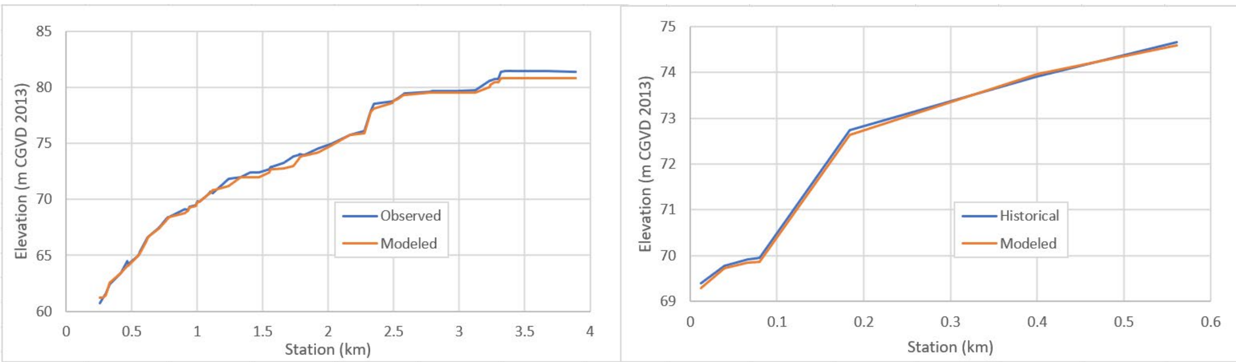

Figure 6-48: 2019 Survey Comparison - Corduroy Brook (left) and Little Rushy Pond Brook (right)

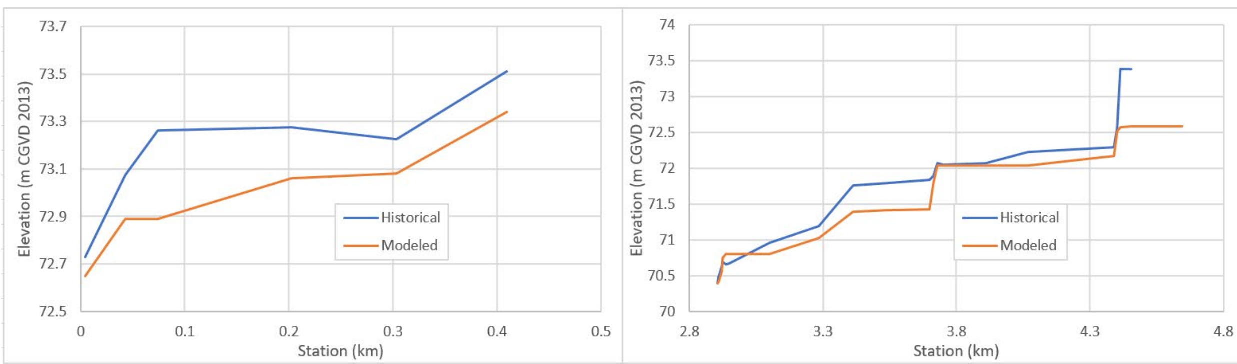

Figure 6-49: 2019 Survey Comparison - Mullens Pond (left) and Little Rushy Pond Brook (right)

6.5.3 1:20 and 1:100 AEP Simulation

The 1:20 and 1:100 AEP flows summarized in **Table 5-5, Table 5-12** and **Table 5-29** were modeled in the steady state model. Results were compared with the ice model as summarized in **Section 6.7**.

6.6 Ice Model

6.6.1 General

Ice formation processes on the Exploits River through the town of Badger can be very dynamic, and can result in significant water level increases in the townsite. The severe water levels associated with past events have been the result of the formation of an equilibrium ice jam when the ice front migrates up through the townsite. The maximum water level ultimately reached in this area is a function of the formation discharge, the local channel geometry, and the meteorological conditions experienced each winter. Once the ice front passes through the townsite, water levels typically begin to fall as the cover begins to smoothen with time. The Hydrotechnical Study of the Badger and Rushy Pond Areas [Fenco, 1985] provides an excellent overview of the historical ice jams in the area and summarizes the ice processes contributing to flooding (**Section 2.3.2**).

Clearly, being able to simulate ice formation within the study reach is critical to defining the ice-related flood hazards throughout the study domain. Fortunately, these processes have been studied in the past, and significant information has been collected on the ice processes in this reach to allow for the calibration and use of physically based numerical models to simulate the impacts of these types of ice events.

To assess the hazard of flooding induced by ice accumulation on the Exploits River near Badger, the RIVICE model was used, as requested by the study Terms of Reference. After reviewing the available data records, three recorded ice events were selected for winter calibration of the model: the 2013/14 winter, the 2002/2003 winter, and the 2009/2010 winter. The latter two events represent two of the highest ice stages in recent history, while the third event represents a year with limited ice production. It was included to validate the model's performance under warmer winter scenarios. The following sections summarize the model setup, and the results of the calibration and validation simulations.

6.6.2 RIVICE Model

RIVICE is a non-proprietary ice formation model developed by Environment Canada. Development of the model began in 1989, initiated by a consortium of engineering firms and utilities, who had noted the lack of a universally available ice model in industry, and had prepared an unsolicited proposal for the development of a non-proprietary hydro-dynamic numerical model of river ice processes. The model was developed over many years under the direction of a steering committee, and has been improved in several stages, with careful attention paid to the principles of hydraulics and ice mechanics. The current version is a fully dynamic, one-dimensional program which is able to simulate the formation process at freeze-up and parts of the breakup process under a wide variety of conditions and types of rivers. The model is well documented and not difficult to apply, although a thorough understanding of river ice processes is required to ensure that the model results are correctly interpreted. The dynamic engine of the model builds off of the original "ONE-D" hydrodynamic model software.

RIVICE has been formulated to permit the simulation of river ice cover development, primarily in swift rivers that do not permit the orderly formation of a smooth, stable, thermally developed ice cover like that on in a more stationary situation such as a lake. As such, the model considers the various ice processes that can affect the winter water surface profile along a river:

- Rate of ice generation
- Ice cover advance by frontal progression
- Ice deposition and transport
- Ice erosion
- Border ice growth

- Ice retreat by shoving, or mechanical thickening
- Ice cover advance by staging
- Melting of the cover in the spring

In a RIVICE or ONE-D model, each channel is divided into segments of assumed similar hydraulic characteristics called reaches. Each reach has a node at each end. Reaches can have any length and are connected by nodes. For purposes of calculation by the finite difference method, each reach is further subdivided into segments of equal length called mesh spaces. The length of the mesh spaces can vary from one reach to another. The boundaries between adjacent mesh spaces are called mesh points, and it is for these point locations that the program computes water levels and discharges over a period of time. The physical properties of the channel at mesh points are interpolated from adjacent surveyed or derived cross-sections.

The program achieves a dynamic solution by solving the equations governing fluid motion for the entire system at one instant in time, then solving them again for one increment of time, or time step, later. The process is repeated until the desired period of simulation is completed. Time steps are set by the user, and have a direct effect on the length of computation time required to complete a run. Time step length also has an effect on the stability and the accuracy of the numerical results generated by the program.

It is noted that the program does not have a “hot start” capability which would allow it to save the results of a previous run and begin part of the way through a winter season. Instead, the program must start from the beginning of the winter season each time a simulation is run to advance the cover and estimate it’s downstream thickness. This significantly increases the run time. Addition of a “hot start” capability is recommended to facilitate adjustment of parameters in the model from a given point in the winter season. It is also noted that the RIVICE model does not have a routine to simulate the natural smoothing of the underside of an ice cover that will occur after initial cover formation. This will result in a slow drop in water levels as the cover becomes more smooth with time. It is recommended that an algorithm such as that proposed by Nezhikhovskiy (1964) be implemented to the code to augment its ability to simulate this effect.

6.6.3 RIVICE Model Setup

The HEC-RAS model formed the basis for the set up of the RIVICE model used in this assessment. Cross-sections in the HEC-RAS model were exported for input into the RIVICE model for the full reach from Goodyear’s Dam up to Millertown Dam at the outlet of Red Indian Lake. Based on available data on recorded ice formation events on the Exploits River, this model reach should be more than adequate to allow simulation of historical ice events on the Exploits River in the Badger area.

As noted, cross-sections were extracted from the HEC-RAS model and transformed into an appropriate format for input and use in the RIVICE model. The final model boundaries and base cross-sections provided from HEC-RAS are shown in **Figure 6-50.**

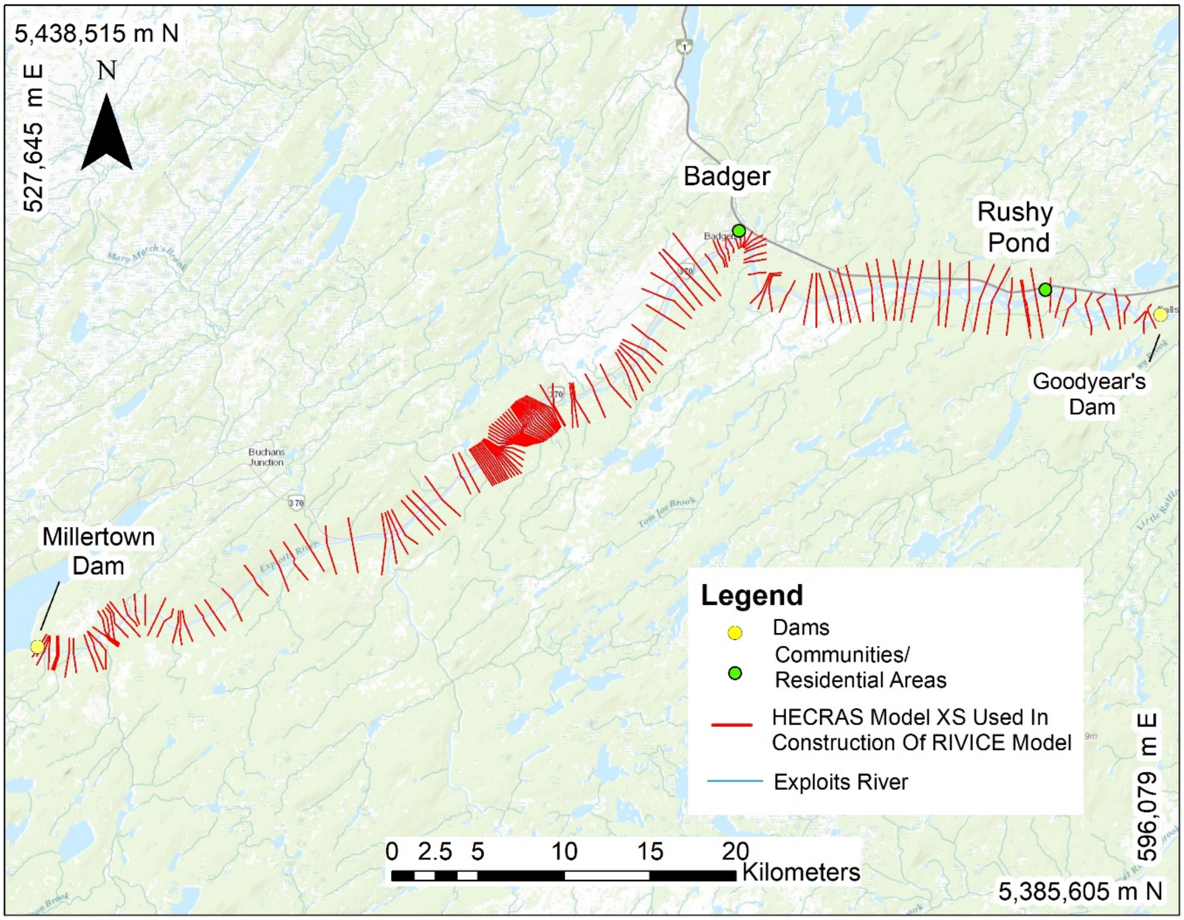

Figure 6-50: RIVICE Extents and Input XS

Compared to open water modelling requirements, ice models generally require a tighter cross-sectional spacing to better define the geometry of the ice jam toe and sections of the ice jam profile that are particularly complex in nature. Additional cross-sections are needed to provide a smoother flow transition and to allow for a more refined calculation of ice jam profiles, particularly at toe locations. Tighter spacing is also required to maintain the overall numerical stability of the model. RIVICE is a fully dynamic model, and therefore an appropriate time step for simulation had to be selected in combination with the selected cross-section spacing. Final parameters utilized in the model were based on a 175 m nodal spacing and a 15 second time step.

6.6.4 Calibration

6.6.4.1 Open Water Calibration

Once the model had been set up, open water simulations were performed to ensure that the RIVICE profile was able to match the results of the original HEC-RAS model. Both models were used to simulate water levels for a range of typical formation flows and the simulated water levels were compared for both models. A Manning's n bed roughness of 0.042 was used for the model.

Figure 6-51 summarizes the results of the model comparison for the stage discharge rating curve for the WSC gauge located within the community of Badger (WSC Gauge 02YO013). The match was quite reasonable, and the model was then considered ready for its calibration to historical ice events on the river.

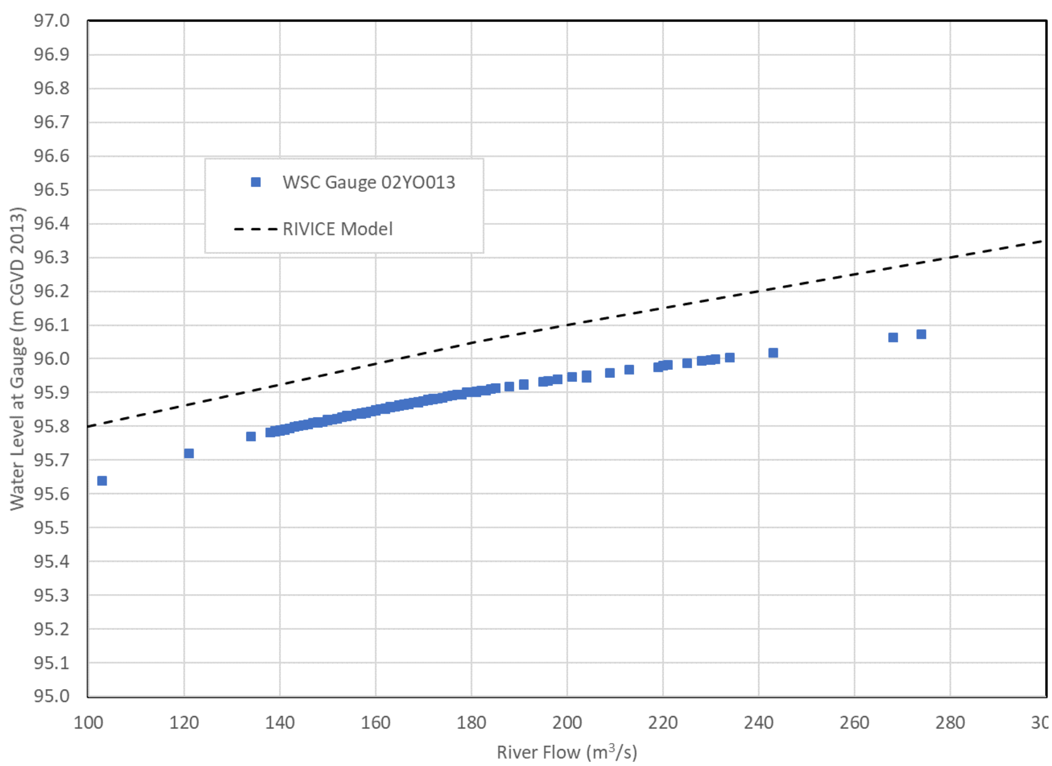

Figure 6-51: Model Comparison With Badger Gauge 02YO013

6.6.4.2 Selection of Events

A number of well-documented historical ice jam events have been experienced on the Exploits River. These events have been summarized in various documents, and detailed and comprehensive observations have been compiled for a number of these events. The strategy followed for calibration of the model was to select (i) events for which relatively detailed hydrometric data (meteorological data, flow data, and water level data) exists, (ii) events that represent the full range of conditions that can occur, and (iii) events that were in place long enough to represent a quasi-steady state condition in the reach. It should be noted that identical ice parameter sets (ice specific gravity, porosity, internal friction angle and stress ratio) were used for all years in all calibration runs. The 2013/14, 2002/2003, and 2009/10 events were selected for calibration of the model.

Each event is briefly described below, along with its rationale for selection as a calibration case. It should be noted that the descriptions of the events use WSC gauge observations, which are in CGVD28. RIVICE model results are in CGVD2013. To be properly compared with RIVICE results, WSC gauge readings shown in the figures in this section have been shifted downwards by 0.2 m to be adjusted to the CGVD2013 datum.

2013/14 Ice Formation:

The 2013/14 winter was colder than normal, with an average river flow during the ice formation period of approximately 220 m^3/s. The ice cover began advancing from the Rushy Pond area in mid December, and eventually progressed through the community of Badger in late January. A peak ice level of 99.2 m was recorded in the community on January 28th.The cover continued to advance past the community of Badger, eventually stalling below Red Indian Falls.

The peak elevation reached is one of the highest experienced in the community since the record event of 2003. This makes this year an excellent candidate for calibration.

2002/2003 Ice Formation:

Winter ice formation in 2002/03 resulted in the highest water level in recorded history in the Community of Badger. The winter itself began early, and a cover was initiated upstream of Goodyear's Dam by December 5th. The ice cover first arrived at Badger by January 24th, and the water level rose to approximately el. 98 m. The cover then briefly retreated, but re-advanced by mid-February and water levels rose again to approximately el. 98 m. However, on February 15th, portions of the ice cover upstream of the town suddenly released, causing the level within the community to shoot up to el. 100.3 m. The event is documented in a detailed situation report prepared by WRMD (WRMD, 2003). The release of the upstream cover led to an influx of water and ice upstream of and through Badger, resulting in an unprecedented rate of rise and ultimate level. Following the mid-February event, the cover continued to advance upstream, eventually stalling below Red Indian Falls.

The peak elevation reached is the highest experienced in the community since records have been kept. This makes this year an excellent candidate for calibration.

2009/10 Ice Formation:

The 2009/10 ice formation event was selected as a third event for calibration. The 2009/10 winter was one of the warmer winters on record, with an average river flow of approximately 180 m^3/s during the ice formation period. The ice cover closed and began advancing from the

Rushy Pond area on January 10th, and eventually progressed to approximately the Badger Chute location. Since the cover did not progress past Badger, the peak level reached during the winter was only 96.2 m, which is essentially an open water level. This year was selected for calibration to evaluate the model's ability to simulate ice conditions during a warmer than normal year. Climate change projections suggest that winter temperatures will increase in the future, and therefore this year is an excellent candidate to test the performance of the model when simulating future (warmer) climate scenarios. This event represents the lower end of the range for calibration.

6.6.4.3 *Calibration Approach and Selection of Ice Jam Parameters*

Calibration of the RIVICE model requires the selection of a number of ice related parameters. During this process, various sets of parameters were tested until a single set of parameters was able to consistently achieve the best match between measured and calculated ice cover elevation within Badger, as well as the timing of the ice cover progression from the downstream reach up through the community.

The ice cover roughness is likely variable from year to year, but a single value has been used to achieve a best fit in each year. Past experience on other river systems indicates that the covers that may form through Badger are likely composed of relatively similar floe thicknesses and floe sizes, and the resulting covers may be of similar thickness for a fully developed cover. Therefore, it is expected that the configuration of the underside of the jams also would be more or less similar from year to year. Notwithstanding second order effects that might be attributed to the effects of flow depth (hence discharge), it would be expected that the year to year variability in ice cover roughness would be quite low.

Considering the above, the calibration proceeded as follows:

- The recorded field data was reviewed and the initiation point for the cover was identified, along with the time at which ice cover advancement began. Since 2004, C-CORE has supplied WRMD with regular satellite images of the ice cover location on the Exploits River. The chainage of the initiation point was translated into relative model coordinates (model boundaries) and applied to the appropriate reach segment.
- The water level at the downstream end of the reach was set equal to the expected level upstream of the Goodyear Dam, given the estimated formation discharge and the structure rating curve. Ice formation discharges were set equal to the discharges recorded by area WSC stations, and estimates provided in earlier study reports.
- The hydro-meteorological data for the given calibration year was then entered into the model.
- The model was then run to simulate ice processes on the river for the given calibration year. The ice generation in the reach was based on the simplified heat transfer option. Physical ice cover properties such as ice specific gravity, ice jam internal strength, ice jam porosity, and deposition and erosion velocities were initially set to typical values

found in the literature for wide ice jams (Beltaos, 1996). The ice erosion velocity was set to 1.8 m/s (Michel, 1971).

- The roughness of the ice cover was set and left as a fixed variable for all simulations. The KGS option was used to define ice cover roughness, with a thin cover roughness set equal to 0.027, and the roughness for a 5 m thick cover set to 0.10. Composite roughness values are then calculated within RIVICE using the bed roughness, and the well known Belokon-Sabaneev method. These values are certainly within the range of values suggested by other researchers and practitioners for mechanically thickened ice covers (Nezhikhovskiy, 1964).

The final adopted ice related calibration parameters are as follows:

- Manning's n (0.1 m thickness) - 0.027
- Manning's n (5 m thickness) - 0.100
- Ice jam specific gravity - 0.92
- K1tan(phi) - 0.17
- K2 - 8.7
- Porosity of ice cover - 0.70
- Porosity of slush ice/frazil - 0.50
- Deposition velocity - 1.2 m/s
- Erosion velocity - 1.8 m/s
- Ice cohesion - 0 Pascals
- Border ice coefficient - 0.1
- Border ice exponent - 1.5
- Heat Loss Coefficient - 11 W/m^2

6.6.4.4 *Calibration Results*

6.6.4.4.1 2013/2014

Model calibration results are presented below for the 2013/14 simulation.

Figure 6-52 shows a comparison of simulated and computed ice advancement rates in the reach, with the time scale on the x axis, and the location of ice front shown on the y axis. This provides a good overall summary of how well the model is doing in terms of replicating ice generation in the reach and storage of this generated ice in the developing cover. Observed data is represented by blue dots, whereas the green line represents the location of the computed ice front with time. As shown, the overall match between the simulated and observed ice advancement rate is reasonably good, with deviations of only a few days for areas that are at or downstream of the community of Badger.

Figure 6-53 shows the estimated ice profile in the reach for a time in which the maximum stage had been reached in Badger, and ice front had advanced approximately 10 km upstream of the townsite. The red markers shown in this figure represent the observed water levels taken from WSC gauges in area at Badger and Charlie Edwards Point, and the dashed grey line represents the calculated top and bottom of the ice cover. The overall match between observed and simulated levels is very good, with maximum differences of only 0.2 m. The model is suggesting that the ice cover must consolidate and thicken while progressing upstream, and develops thicknesses of between 1 and 2 m over much of the reach. The reach becomes steeper and requires some additional thickening in the areas just downstream of Badger, including Badger Chute and Badger Rough Waters. This can also be seen in the processed satellite image provided by C-CORE for this winter, shown in **Figure 6-54**. Areas of consolidation are shown with some red infill and extend throughout this reach, and this is consistent with the calculated profile.

Finally, **Figure 6-55** shows the computed and historical water level traces within the town of Badger for this event. Historical traces were taken from WSC gauge 02YO013 located at the downstream end of the community. The overall match on the timing of ice front arrival, and magnitude of stage increase is good. The only deficiency in the model is the fact that it cannot account for the subsequent smoothing of the cover after first formation. This smoothing of the cover leads to an immediate drop in water level, as shown in the historical trace. This capability has not yet been built in to the current RIVICE model, but consideration should be given to adding it in the future.

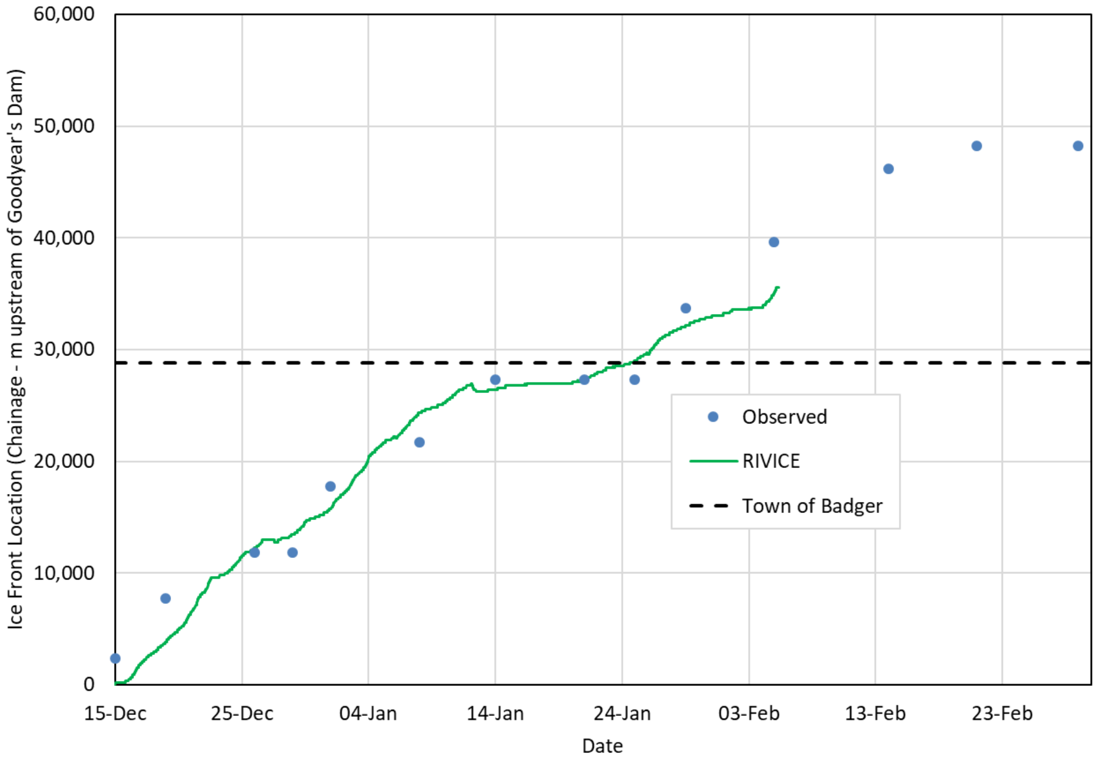

Figure 6-52: Simulated and Observed Ice Advancement for 2014 Ice Cover Formation

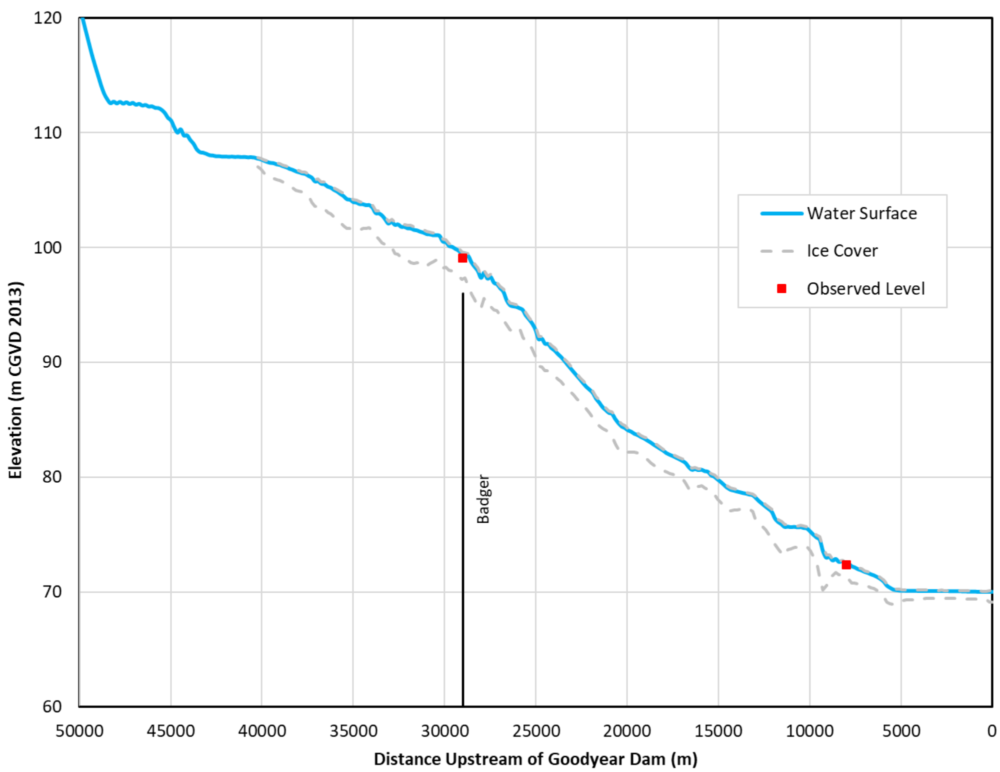

Figure 6-53: Ice Cover Profile for 2014 Ice Cover Formation (February 5th)

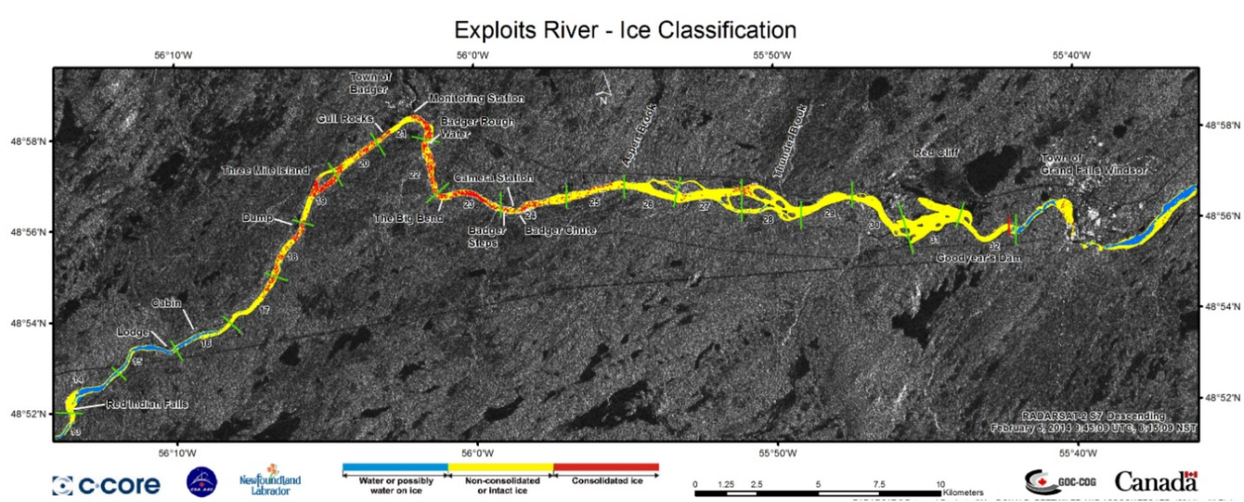

Figure 6-54: Historical Ice Cover Classification for February 5th, 2014

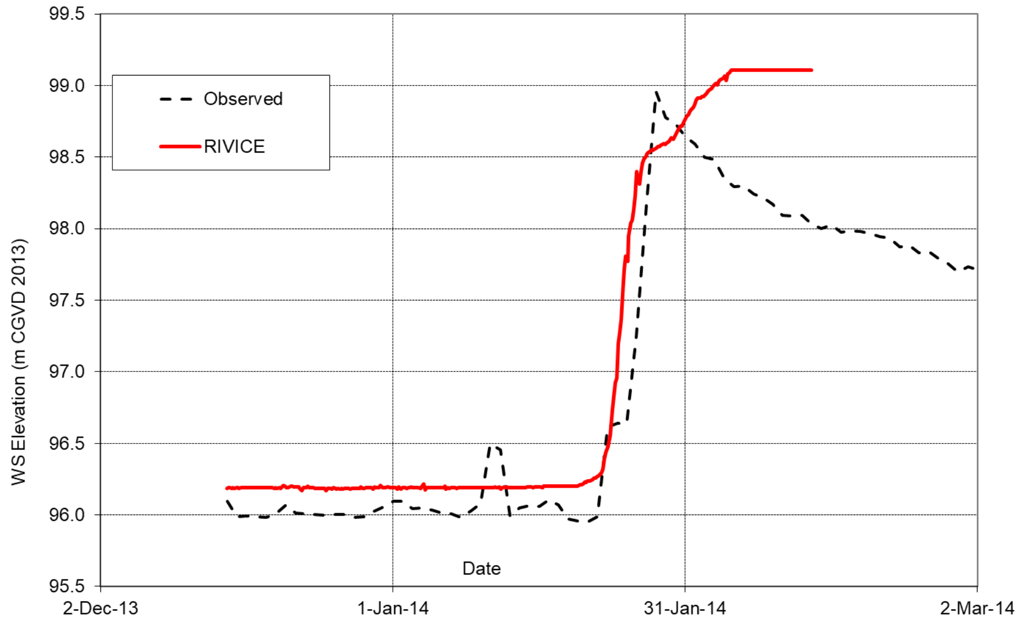

Figure 6-55: Simulated and Observed Water Level Trace in Badger for 2014 Ice Cover Formation

6.6.4.4.2 2002/2003

The next calibration year involved simulation of the 2002/2003 winter period, which represents the largest ice induced water level in the community since records were kept. Model calibration results are presented below for this simulation.

Figure 6-56 shows a comparison of simulated and computed ice advancement rates in the reach. The time scale is shown on the x axis, and the location of the ice front is shown on the y axis. This provides a good overall summary of how well the model is doing in terms of replicating ice generation in the reach and storage of this generated ice in the developing cover. The observed data is represented by blue dots, whereas the green line represents the location of the ice front with time. As shown, the overall match between the simulated and observed ice advancement rate is reasonably good, with deviations of only a few days for areas that are at or downstream of the community of Badger.

Figure 6-57 and **Figure 6-58** shows the estimated ice profile in the reach for both maximum peaks in which maximum stage was reached in Badger, and the ice front had advanced upstream of the townsite. The red markers shown in this figure represent the observed water levels taken from WSC gauges in the area at Badger and Charlie Edwards Point. The bottom red marker represents the cover on February 10th and the top red marker represents the cover on February 17th. The dashed grey line represents the calculated top and bottom of the ice cover. The overall match between observed and simulated levels is very good, with a difference on February 17th of only 0.1 m. The model is suggesting that the ice cover must consolidate and thicken while progressing upstream, and develops thicknesses of between 1 and 2 m over much of the reach. The reach becomes steeper and requires some additional thickening in the areas just downstream of Badger, including Badger Chute and Badger Rough Waters. C-CORE imagery was not gathered before 2004, so it is not available for comparison with this event.

Finally, **Figure 6-59** shows the computed and historical water level traces within the town of Badger for this event. Historical traces were taken from WSC gauge 02YO013, located at the downstream end of the community. As shown, timing of the initial stage increase was captured reasonably well by the model, but it was not able to simulate the subsequent retreat and re-advancement of the cover through Badger. As well, the model overpredicts the initial stage increase in the community, but the second larger peak was captured. Another deficiency in the model is that fact that it cannot account for the subsequent smoothing of the cover after first formation. This smoothing of the cover leads to an immediate drop in water level, as shown in the historical trace. This capability has not yet been built in to the current RIVICE model.

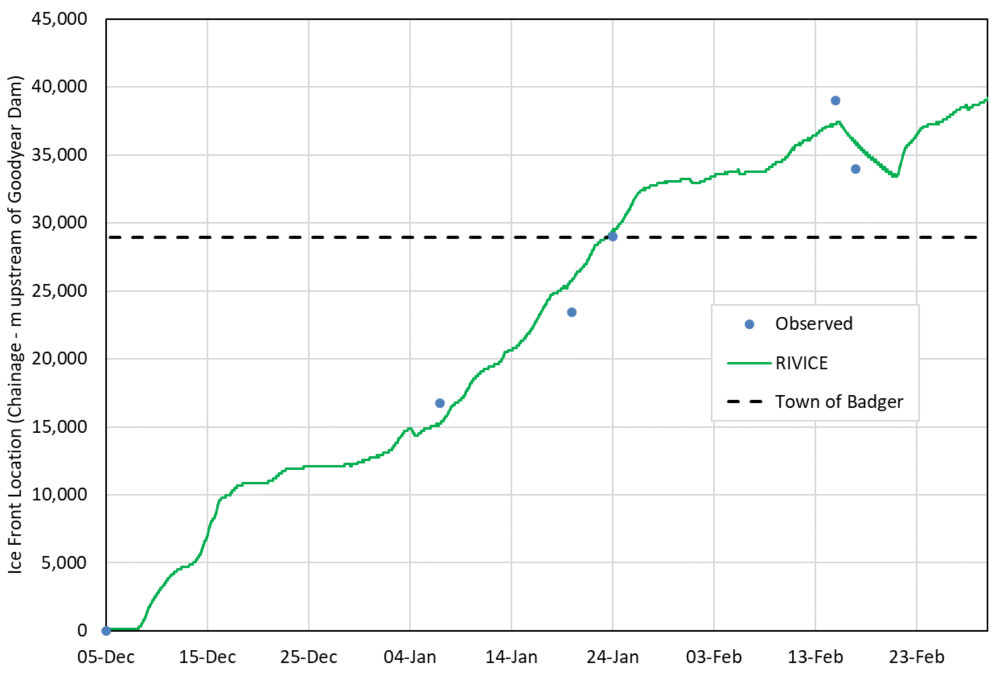

Figure 6-56: Simulated and Observed Ice Advancement for 2002/2003 Ice Cover Formation

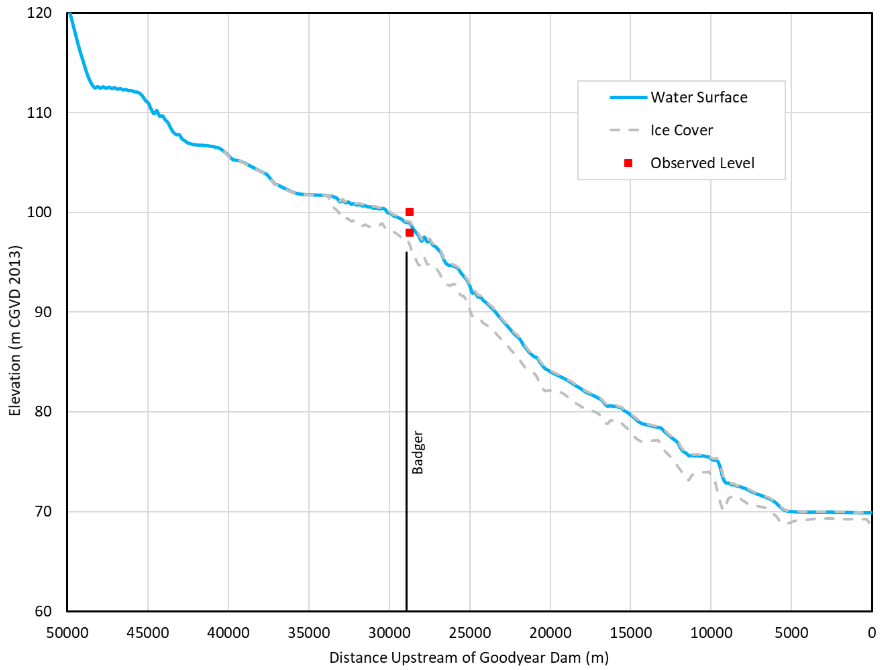

Figure 6-57: Ice Cover Profile for 2002/2003 Ice Cover Formation (February 10th)

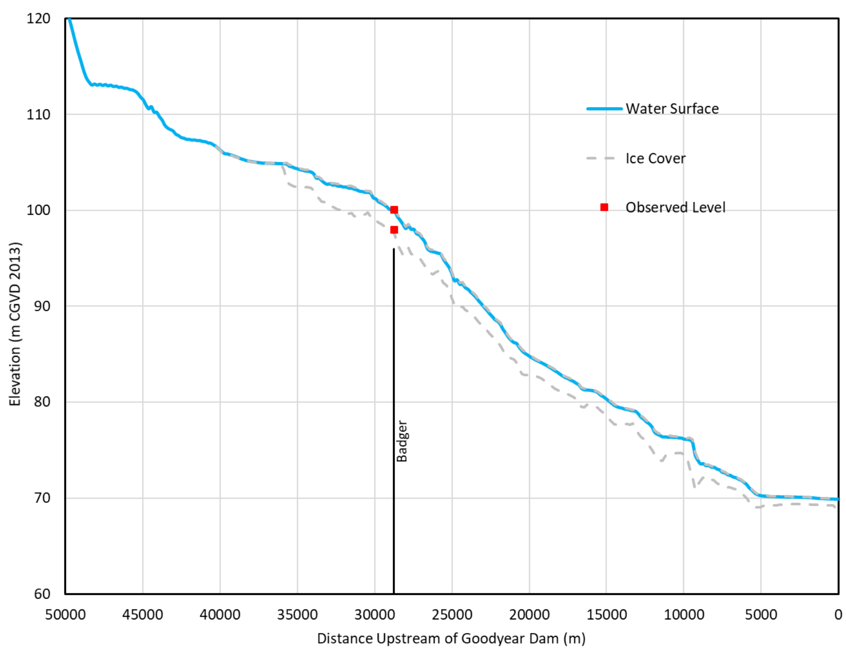

Figure 6-58: Ice Cover Profile for 2002/2003 Ice Cover Formation (February 17th)

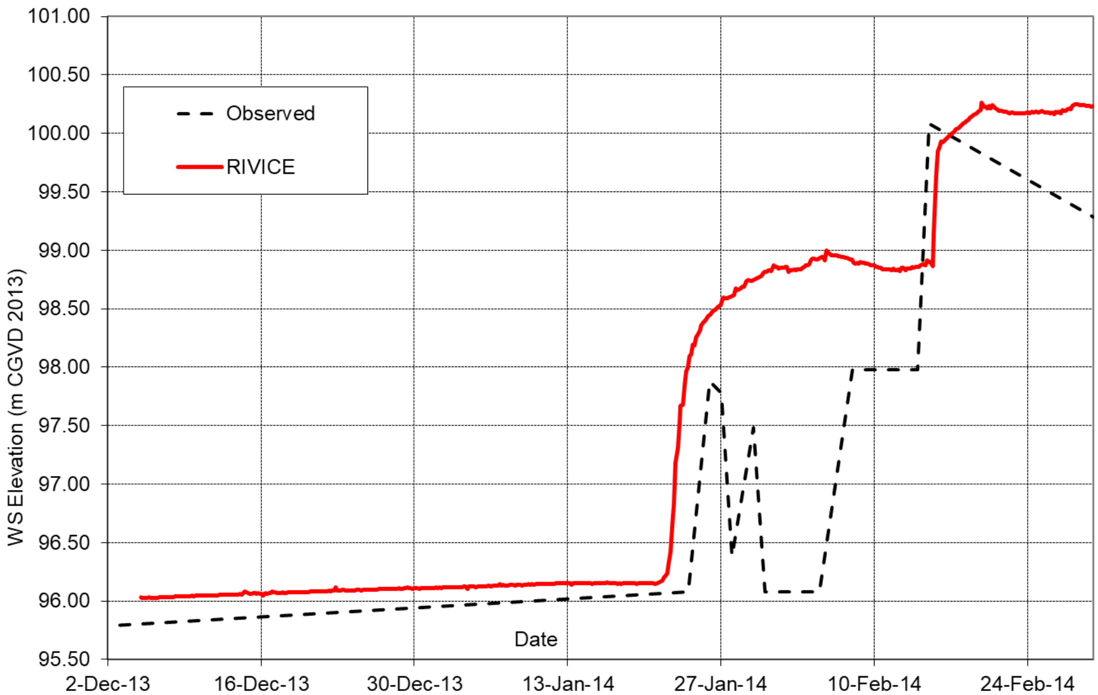

Figure 6-59: Simulated and Observed Water Level Trace in Badger for 2002/2003 Ice Cover Formation

6.6.4.4.3 2009/2010 Winter

The 2009/10 ice formation event was selected as the third event for calibration. As noted earlier, the 2009/10 winter was one of the warmer winters on record, with an average river flow of approximately 180 m^3/s during the ice formation period. This year was selected for calibration to evaluate the model's ability to simulate ice conditions during a warmer than normal year and represents the lower end of the range for calibration.

For this year, the model was setup with all hydro-meteorological data from the 2009/2010 winter. The cover was initiated historically in the Rushy Pond area on January 6th, and the model was set up to replicate this start date and location. Model parameters (density, porosity, erosion velocity, friction strength, etc.) remained identical to those in the calibration simulations.

Figure 6-60 shows a comparison of simulated and computed ice advancement rates in the reach, with the time scale on the x axis, and the location of ice front shown on the y axis. This provides a good overall summary of how well the model is doing in terms of replicating ice generation in the reach and storage of this generated ice in the developing cover. Observed data is represented by blue dots, whereas the green line represents the location of the ice front with time. As shown, the overall match between the simulated and observed ice advancement rate is reasonably good, with deviations of only a few days.

Figure 6-61 shows the estimated ice profile in the reach for a time when the ice front had reached its point of maximum ice progression. The red markers shown in this figure represent the observed water levels taken from WSC gauge at Badger, and the dashed grey line represents the calculated top and bottom of the ice cover. The overall match between observed and simulated levels is very good, with maximum differences of only 0.2 m. The model is suggesting that the ice cover must consolidate and thicken while progressing upstream, and develops thicknesses of between 1 and 2 m over much of the reach. The cover advancement ends at Badger Chute, since the warm temperatures associated with this winter did not generate sufficient ice to allow further progression to occur. This can also be seen in the processed satellite image provided by C-CORE for this winter, shown in **Figure 6-62**. The good match obtained in ice generation and accumulation for this run provides confidence that the model can be used moving forward in what is likely to be a warmer winter climate.

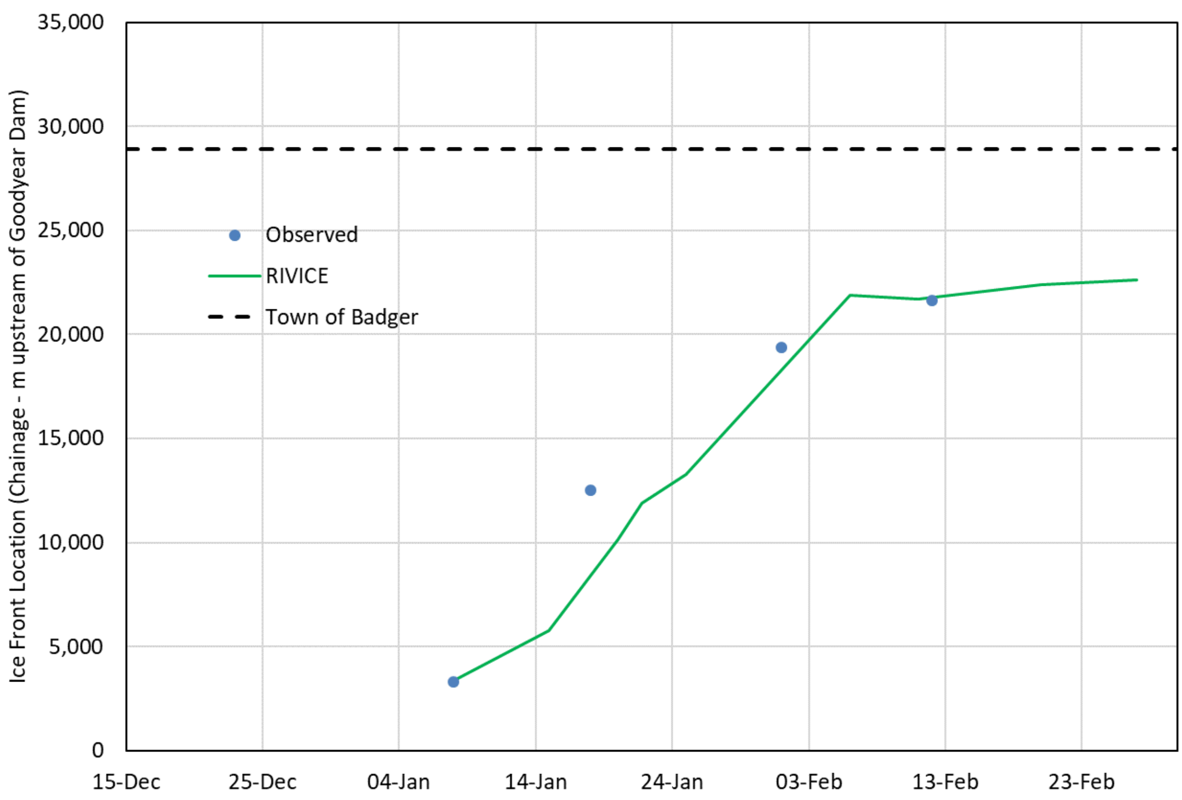

Figure 6-60: Simulated and Observed Ice Advancement for 2009/2010 Ice Cover Formation

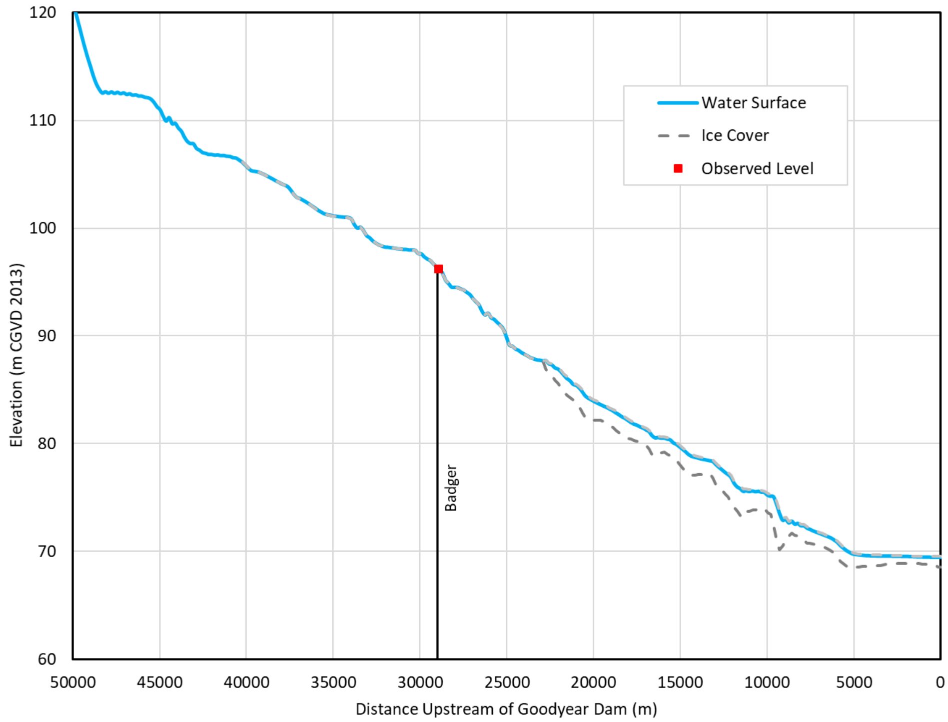

Figure 6-61: Ice Cover Profile for 2009/2010 Ice Cover Formation

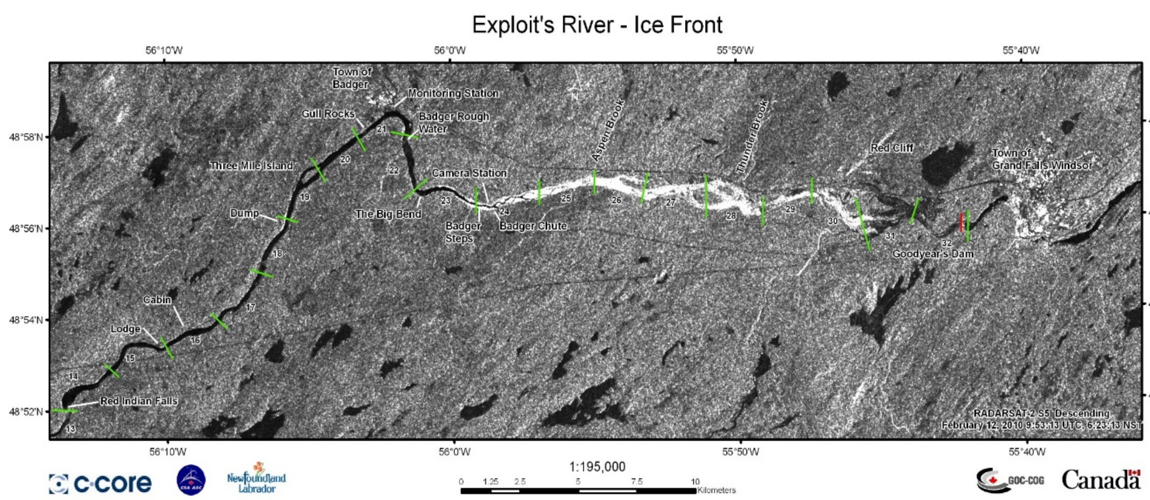

Figure 6-62: Historical Ice Front Image for February 12th, 2010

6.6.5 Climate Change

River ice processes can be affected by changes in the local climate. It is expected, for example, that average winter temperatures on the Exploits basin will rise in the future, leading to a reduction in the accumulated degree days of freezing along the river, and this can greatly affect ice generation potential. In tandem with this, warmer fall temperatures will lead to a delay in the freezeup date, and warmer spring temperatures will likely lead to earlier breakup dates, and shorter winter seasons. These changes will affect the nature and character of the ice cover that forms on the river, and the processes that drive its formation.

To explore these potential changes, the calibrated RIVICE model was set up to simulate ice cover formation on the Exploits River under future climate scenarios involving modified river flow and air temperature sequences.

It was first necessary to estimate potential impacts to these two important model inputs. Air temperature records were reviewed for the Environment Canada climate station at Badger, and two winter seasons were identified that represent i) an average winter temperature sequence, and ii) a more severe winter temperature sequence with a 1:100 AEP. Frequency assessments were carried out on the accumulated average degree days of freezing (AADF) for each winter over the formation period (assumed to be December to February) in order to rank winter seasons from the coldest to the warmest. The 2015/2016 winter was identified as a winter with an average number of AADF, while the 2013/14 winter was identified as a winter with approximately a 1:100 AEP temperature severity.

For each scenario, it was then assumed that the temperature profiles for these events would be increased by the temperature differential that was estimated by Finnis and Daraio (Finnis, 2018) in their study of projected impacts of climate change for the Province of Newfoundland and Labrador. These studies indicate that on the Exploits basin, mean daily temperatures will vary as noted below.

Table 6-11: Average Daily Temperature

Station	Period	Current Avg (°C)	2041 - 2070		2071 - 2100	
			Ensemble Avg (°C)	Increase (°C)	Ensemble Avg (°C)	Increase (°C)
Exploits Dam	December-January-February	-7.1	-2.6	+4.5	-0.2	+6.9
Grand Falls	December-January-February	-6.4	-1.7	+4.7	0.7	+7.1

Notes:
1. Taken from Finnis and Daraio (Finnis, 2018) - Projected Impacts of Climate Change for the Province of Newfoundland and Labrador

In tandem with these temperature increases, the average and 1:100 AEP estimates of formation flow were assumed to increase marginally by approximately 6 percent as shown in **Table 5-29**. Separate scenarios were considered for the periods from 2041 – 2070, and 2071 - 2100.

Various combinations of temperature and flow were tested; the most severe scenario tested involved the occurrence of a 1:100 AEP combination of flow and temperature. This combination assumed an average formation flow combined with a “2041-71” period 1:100 AEP air temperature sequence. The results showed very convincingly that there will be a significantly decreased risk of flood by ice jam formation in the future; there is simply not enough ice being generated upstream to allow full advancement of the cover under the simulated future temperature/flow combinations, including the 1:100 AEP temperature sequence. This is not an unexpected result, as the accumulated degree days of freezing in future years are expected to drop by over 60 percent. This will limit ice jam potential within Badger as it will lead to:

- A delay in the typical date at which a cover may initiate upstream of Goodyear’s Dam. Therefore the ice formation season will become considerably shorter.
- Considerably reduced volumes of ice being produced in upstream reaches. This ice will pass through Badger and begin to collect locally in the downstream areas once the cover has bridged, but the volume isn’t sufficient to allow it to advance up to and through Badger.
- The reduced severity of the winters will also lead to a much reduced chance that the migrating ice floes would temporarily stall at Badger Chute or Badger Rough Waters. This can only happen if the concentration of ice floes is large enough to temporarily overwhelm the conveyance capacity of the stream at this location. The dramatic increase in winter temperatures predicted for even the 2041-70 period makes this very unlikely.

As a result, it is Hatch’s conclusion that future flood hazard will very likely be governed by open water flood flows, and therefore the climate change scenario will not require ice jam as part of flood risk mapping for the community of Badger.

6.6.6 1:20 and 1:100 AEP Simulation

As noted earlier, maximum winter staging in the town of Badger tends to occur soon after the an ice front has staged through the community, and additional staging can occur if it leads to some secondary consolidation of the cover in this area. This can occur if the cover advances rapidly and collapses, and/or if flows begin to rise after the cover has formed. In addition, past experience had shown that if river flows rise by too much, the cover will release and actually flush past the community to accumulate in the downstream reaches. Taking into consideration these complexities, it was necessary to test a variety of cases to identify a scenario resulting in maximum winter water levels for the 1:20 and 1:100 AEP events. Initially, two basic families of scenarios were tested:

- Formation Events: For this series of events, formation of the cover was simulated under various combinations of flow and temperature. It was assumed that the flow distributions and temperature distributions were statistically independent, and therefore combinations tested for the 1:100 AEP event included 1:100 AEP flow with average temperature, 1:50 AEP flow with 1:2 AEP temperature, 1:20 AEP flow with 1:5 AEP temperature, and the average flow with the 1:100 AEP temperature sequence. Similar combinations were tested for the 1:20 AEP events.

- Mid-Winter Flood Event: This event tested the impact of a possible mid-winter flood event that could cause a sudden breakup of the cover. It was assumed that the cover would initially form under average flow and temperature conditions, but that the basin would experience either a 1:20 or 1:100 AEP mid-winter flood event. For these events the 1:20 AEP mid-February event was assumed to be 432 m^3/s based on a frequency assessment of February flows, and the 1:100 AEP mid-February event was estimated to be 800 m^3/s.

Initial testing of these scenarios showed that the governing flood levels would be developed by the formation types of events. Exposure of the developed cover to the 1:20 or 1:100 AEP mid-February flood events causes the full cover to collapse and retreat past the community, whereas for the formation events tested, the cover remained firmly in place.

Flows and air temperatures for formation events were developed based on a frequency assessment of historical flow and temperature records on the basin. Temperature records at the Badger MSC station were reviewed, and the AADF for the primary formation months of December through to February were summed. A frequency analysis was conducted on the annual record, the results of which are summarized in **Figure 6-63**. Based on this analysis, the average AADF was estimated to be -570 deg-days and the 100 year AADF was estimated to be -930 deg-days.

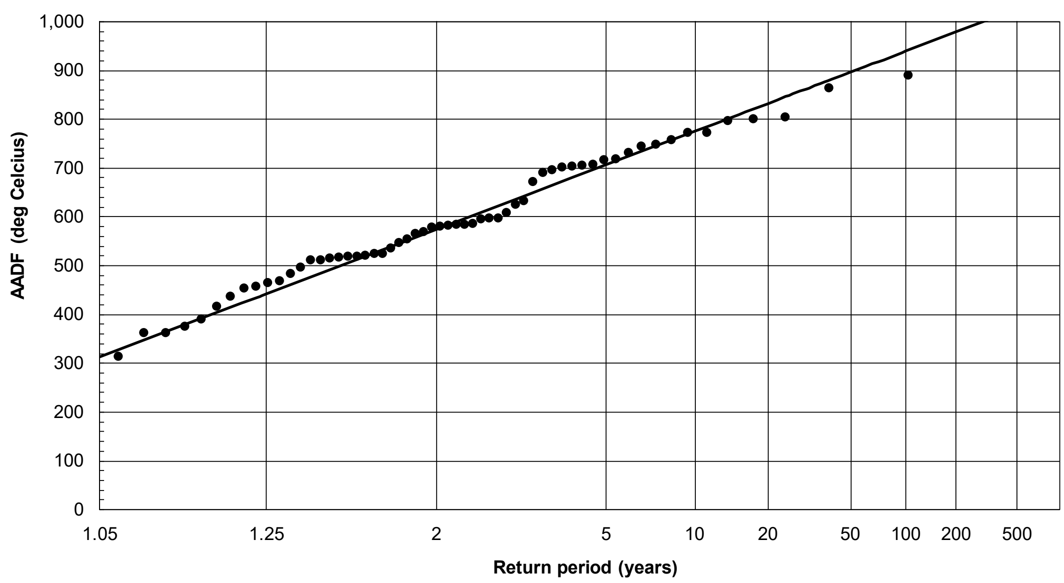

Figure 6-63: Frequency Assessment of Accumulated Annual Degree Days of Freezing (Badger)

For formation flow, a similar frequency assessment was performed on the average Badger flows recorded over the Dec-Feb formation period as discussed in **Section 5.3.1.1**. The analysis indicated the average formation flow to be 195 m^3/s, the 20 year formation flow to be 278 m^3/s, and the 100 year formation flow to be 312 m^3/s.

To estimate the 1:20 and 1:100 year ice profiles, the RIVICE model was then setup to simulate various combinations of flow and meteorological conditions. In the end, the 1:20 and 1:100 AEP flows described above were used in the RIVICE model with an average temperature sequence to provide the final 1:20 and 1:100 AEP water levels. These levels are provided in the tables in **Appendix A**.

Final modeled water levels are compared with historical 1:20 and 1:100 AEP water levels at Badger arena in **Table 6-12.** The modeled water levels are within 0.5 m of the historical levels.

Table 6-12: Water Level Comparison at Badger Arena

	Historical Water Levels (m - Fenco 1985)		Hatch Modeled Water Levels (m)	Difference [Hatch – Historical] (m)
	CGVD 1928	CGVD 2013	CGVD 2013	
1:20 AEP	99.48	99.26	99.73	0.47
1:100 AEP	100.36	100.14	100.3	0.16

6.7 1:20 and 1:100 AEP Results

Results from the steady state and ice model 1:20 and 1:100 AEP runs were compared, with the higher elevation governing. In general, for the current climate, ice conditions governed the peak water level elevations in the Badger area and for the upstream portion of the Rushy Pond area. Ice formation did not occur during the climate change condition.

Peak ice and open water levels at each cross-section for the 1:20 and 1:100 AEP current climate and climate change events are provided in **Appendix A.** Water levels at bridges and culverts in the community areas are shown in **Table 6-13** and **Table 6-14.** Red bold text indicates that the structure is overtopped.

Table 6-13: Peak 1:20 and 1:100 AEP Water Levels for Bridges in Community Areas

River	River Station	Bridge ID	Bridge Name	Northing (UTM Zone 21)	Easting (UTM Zone 21)	Deck Elevation (m)	Span (m)	Peak Water Levels (m)			
								1:20 CC	1:100 CC	1:20 CLC	1:100 CLC
Badger Brook	0.383	BB-CR-1	Badger Brook T'Railway Bridge	5,425,280	570,735	100.3	58	99.2	100.1	98.4	98.7
Badger Brook	0.793	BB-CR-2	Badger Brook TCH Bridge	5,425,648	570,771	100.9	68.9	99.2	100.1	98.9	99.3
Badger Brook	0.937	BB-CR-3	Badger Brook Footbridge	5,425,773	570,821	99.8	48.5	99.2	**100.1**	99.1	99.5
Unnamed Stream BF-3	0.692	BF3-CR-3	Beaumont Heights 2 Bridge	5,429,495	609,311	27.1	9.1	25.8	26.0	25.9	26.1
Unnamed Stream BF-3	0.736	BF3-CR-4	Dominic Street 1 Bridge	5,429,525	609,281	29.8	6.2	28.7	28.9	28.8	28.9
Unnamed Stream BF-3	0.771	BF3-CR-5	Dominic Street 2 Bridge	5,429,558	609,268	32.6	9.2	31.7	31.9	31.8	32.0
Unnamed Stream BF-3	0.817	BF3-CR-6	Dominic Street 3 Bridge	5,429,591	609,243	34.8	7	33.7	33.9	33.8	33.9
Corduroy Brook	0.616	CB-CR-3	Corduroy Brook Nature Trail 1 Bridge	5,421,513	597,853	68.2	8	67.7	67.7	67.7	67.8
Corduroy Brook	0.774	CB-CR-4	Corduroy Brook Nature Trail 2 Bridge	5,421,651	597,923	70.2	10.8	69.4	69.5	69.4	69.5
Corduroy Brook	0.933	CB-CR-5	Squires Lane 1 Bridge	5,421,804	597,885	70.9	15.3	70.3	70.4	70.3	70.5
Corduroy Brook	1	CB-CR-6	Squires Lane 2 Bridge	5,421,863	597,854	71.5	11.2	70.6	70.7	70.7	70.7
Corduroy Brook	1.561	CB-CR-9	Duggan Street 1 Bridge	5,422,314	597,881	73.6	8.4	**74.9**	**75.0**	**74.9**	**75.1**
Exploits River	21.69	E-CR-1	Sir Robert Bond Bridge	5,431,142	613,498	9.8	218	4.2	4.9	4.5	5.1
Exploits River	25.262	E-CR-2	Bishop's Falls Trestle	5,429,456	610,431	20.2	295	13.4	14.2	13.7	14.4
Little Red Indian Brook	0.679	LRI-CR-1	Route 370 Buchans Hwy Bridge	5,425,340	569,949	101.3	28.2	99.8	100.8	98.8	99.1
Rushy Pond Brook	1.18	RP-CR-1	Golf Course Bridge	5,421,500	593,878	73.8	45.8	71.3	71.6	71.4	71.7
Rushy Pond Brook	1.483	RP-CR-2	Rushy Pond Brook TCH Bridge	5,421,748	594,035	72.6	47.5	71.3	71.6	71.4	71.7
Rushy Pond Brook	1.529	RP-CR-3	Rushy Pond Brook T'Railway Bridge	5,421,800	594,038	72	24.6	71.3	71.6	71.4	71.7
Wigwam Brook	2.898	WB-CR-2	Wigwam Brook Newfoundland T'Railway Bridge	5,422,457	590,332	73.2	4.5	72.7	73.0	72.8	**73.3**
Wigwam Brook	2.928	WB-CR-3	Red Cliff Road Bridge	5,422,488	590,331	73.1	8.6	73.0	**73.4**	**73.1**	**73.6**

Table 6-14: Peak 1:20 and 1:100 AEP Water Levels for Culverts in Community Areas

River	River Station	Culvert ID	Culvert Name	Northing (UTM Zone 21)	Easting (UTM Zone 21)	Lowest Road El. around Culvert (m)	Number of Barrels	US Invert Elevation (m)	Diameter or Dimensions (m)	Peak Water Levels (m)			
										1:20 CC	1:100 CC	1:20 CLC	1:100 CLC
Unnamed Stream B-1	0.562	B1-CR-1	Stream B1 Newfoundland T'Railway Culvert	5,425,731	569,491	100.2	1	99.5	1.1	**100.4**	**100.8**	**100.5**	**100.5**
Unnamed Stream BF-1	0.173	BF1-CR-1	Sunset Drive Culvert 1	5,431,928	614,461	9	1	7.6[1]	1.2	8.4	8.4	8.4	8.4
Unnamed Stream BF-2	0.235	BF1-CR-2	Sunset Drive Culvert 2	5,431,961	614,410	11.7	1	9.85[1]	1.05	10.3	10.3	10.3	10.3
Unnamed Stream BF-2	0.28	BF2-CR-1	Culvert Under Private Home	5,430,650	611,802	15	1	13.7	1.4 h, 1.8 w	**15.2**	**15.3**	**15.3**	**15.4**
Unnamed Stream BF-2	0.364	BF2-CR-2	BF2 Stream Main Street Culvert	5,430,702	611,754	15.7	1	14.6	1.6	**16.5**	**16.4**	**16.4**	**16.4**
Unnamed Stream BF-2	0.42	BF2-CR-3	BF 2 Stream Exploits Valley and Beothuk Trail Culvert	5,430,740	611,716	17	2	15.6 / 15.7	2 – 0.9	**17.6**	**17.6**	**17.6**	**17.7**
Unnamed Stream BF-2	0.54	BF2-CR-4	Kings Road Culvert	5,430,835	611,755	17.9	3	16.5[1]	1 – 1.1 / 1 – 1.1 / 1 – 0.8	**18.1**	**18.2**	**18.2**	**18.3**
Unnamed Stream BF-3	0.29	BF3-CR-1	BF3 Stream Main St Culvert	5,429,256	609,306	17.8	1	16.4	1.9	**18.6**	**18.9**	**18.8**	**18.9**
Unnamed Stream BF-3	0.637	BF3-CR-2	Beaumont Heights 1 Culvert	5,429,440	609,315	24.2	2	22.8 / 22.9	2 – 1.4	**24.6**	**24.8**	**24.7**	**24.9**
Unnamed Stream BF-3	0.948	BF3-CR-7	BF3 Stream TCH Culvert	5,429,694	609,229	41.4	1	36.8	2.5 (US) – 1.7 h, 2.6 w (DS)	39.0	39.4	39.1	39.5
Unnamed Stream BF-4	0.345	BF4-CR-1	BF4 Stream Main Street Culvert	5,427,220	607,143	18.5	1	15.8	0.8 h, 1.2 w	16.3	16.4	16.4	16.5
Unnamed Stream BF-4	0.494	BF4-CR-2	BF4 Stream Exploits Valley and Beothuk Trail Culvert	5,427,330	607,045	18.5	2	17.4 / 17.5	2 – 0.9	18.3	18.4	18.4	**18.5**
Unnamed Stream BF-4	0.608	BF4-CR-3	BF4 Stream Newfoundland T'Railway Culvert	5,427,358	606,938	18.6	2	17.5 / 17.6	2 – 0.8	18.5	**18.7**	**18.6**	**18.7**
Corduroy Brook	0.29	CB-CR-1	Corduroy Brook Unnamed Road Culvert	5,421,303	597,639	63.8	2	61.1 / 61.2	2 – 1.0	63.8	63.8	63.8	63.8
Corduroy Brook	0.51	CB-CR-2	Lincoln Road Culvert	5,421,433	597,823	67.1	2	64.8 / 65.8	1 – 0.8 / 1 – 1.8 h, 2.1 w	66.5	66.7	66.6	66.8
Corduroy Brook	1.11	CB-CR-7	Corduroy Brook Lane Culvert	5,421,965	597,808	73.3	1	70.5	1.7	**73.3**	**73.4**	**73.4**	**73.4**
Corduroy Brook	1.375	CB-CR-8	Corduroy Brook TCH Culvert with Pedestrian Underpass	5,422,195	597,742	75.7	2	71.8 / 74.6[1]	1 – 1.7 / 1 – 2.4 h, 2.4 w[2]	74.8	75.0	74.9	75.1
Corduroy Brook	1.798	CB-CR-10	Duggan Street 2 Culvert	5,422,460	598,002	75.5	1	73.8	1.8	75.3	**75.5**	75.4	**75.6**
Corduroy Brook	2.41	CB-CR-11	Cromer Avenue Culvert	5,422,527	598,535	81.1	1	78.4	1.5	81.0	**81.2**	**81.2**	**81.2**

River	River Station	Culvert ID	Culvert Name	Northing (UTM Zone 21)	Easting (UTM Zone 21)	Lowest Road El. around Culvert (m)	Number of Barrels	US Invert Elevation (m)	Diameter or Dimensions (m)	Peak Water Levels (m)			
										1:20 CC	1:100 CC	1:20 CLC	1:100 CLC
Corduroy Brook	2.675	CB-CR-12	Harris Ave Culvert	5,422,742	598,704	82.2	1	79.3	1.8	81.8	82.0	82.0	82.1
Corduroy Brook	3.252	CB-CR-13	Princess Drive Culvert	5,423,087	599,021	82.7	1	80.2	1.7	82.4	**82.8**	82.6	**82.8**
Corduroy Brook	3.306	CB-CR-14	Corduroy Brook Newfoundland T'Railway Culvert	5,423,136	599,029	81.7	1	79.9	1.5	**82.4**	**82.8**	**82.6**	**82.8**
GF1 Stream	0.048	GF-CR-1	GF1 Stream Newfoundland T'Railway Bridge	5,425,713	602,793	70.3	2	69.3	2 – 1.2 h, 1.2 w	**70.8**	**70.8**	**70.8**	**70.8**
GF1 Stream	3.999	GF-CR-2	Hardy Avenue Culvert	5,423,105	600,998	103.2	2	101.55	1 – 0.4, 1 – 0.9	101.7	101.9	101.8	102.0
Little Rushy Pond Brook	0.05	LRP-CR-1	Little Rushy Pond Stream Unnamed Road Culvert	5,422,449	594,826	70.5	1	69.7	0.7	**71.3**	**71.6**	**71.4**	**71.7**
Mullen's Pond	0.003	MP-CR-1	Second Avenue Culvert	5,423,039	597,254	73.8	1	72.7	0.8	**74.0**	**74.1**	**74.0**	**74.1**
Wigwam Brook	1.424	WB-CR-1	Trans Canada Highway at North Angle	5,421,787	591,439	72.6	1	68.6	1.6 h, 1.6 w	72.6	72.6	72.6	72.6
Wigwam Brook	3.72	WB-CR-4	Wigwam Brook Unnamed Road 1 Culvert	5,422,741	590,951	73.4	2	71.6 / 71.8	2 – 1.4	**73.6**	**73.6**	**73.6**	**73.7**
Wigwam Brook	4.408	WB-CR-5	Wigwam Brook Unnamed Road 2 Culvert	5,422,819	591,455	73.6	3	72.2 / 72.3 / 72.7	1 – 1.1 h, 1.5 w / 2 – 1.1 h, 1.2 w	73.6	**73.8**	73.5	**73.8**

Notes:
1. Based on channel elevations as measured from LiDAR.
2. Estimated from orthophotos.

6.8 Sensitivity Analysis

The peak flow and Manning's roughness coefficient in HEC-RAS were varied by ±10%, ±20% and ±30%. The 1:100 AEP current climate scenario was used to assess the effect that these changes have on the water levels in the study areas. Key sensitivity results are summarized in **Table 6-15** and cross-section results are tabulated in **Appendix A**. Water levels were more sensitive to the peak flows in the reach than to Manning's n.

Table 6-15: Sensitivity Analysis Results

	Parameter Increase			Parameter Decrease		
	10%	20%	30%	-10%	-20%	-30%
Mean Change in Water Level (m) - Sensitivity to Peak Flow						
Exploits River	0.2	0.5	0.7	-0.3	-0.5	-0.8
Badger Brook	0.2	0.4	0.5	-0.2	-0.4	-0.6
Corduroy Brook	0.1	0.2	0.2	-0.1	-0.3	-0.5
Mean Change in Water Level (m) - Sensitivity to Manning's n						
Exploits River	0.2	0.4	0.6	-0.2	-0.4	-0.6
Badger Brook	0.1	0.3	0.4	-0.1	-0.2	-0.3
Corduroy Brook	0.0	0.0	0.0	0.0	0.0	0.0

6.9 Badger Ice Progression Model Review

The Badger Ice Progression Model was developed to simulate ice cover advancement and formation in the Exploits River between Millertown and Goodyear's Dam. The model was originally developed in the mid-1980s, and has since then undergone periodic updates to ensure it remains compatible with current operating platforms. The model was most recently converted to a C++ platform.

Hatch was able to review a copy of the original FORTRAN source code for the model. The model is relatively simple in nature, and seeks to simulate the progression of an ice cover on the Exploits River given key meteorological and flow data. The model includes detailed ice generation algorithms, but adopts a more simplified approach to accumulate this ice in the downstream cover. To do so, the model divides the river reach into 32 segments as shown in **Figure 6-64**.

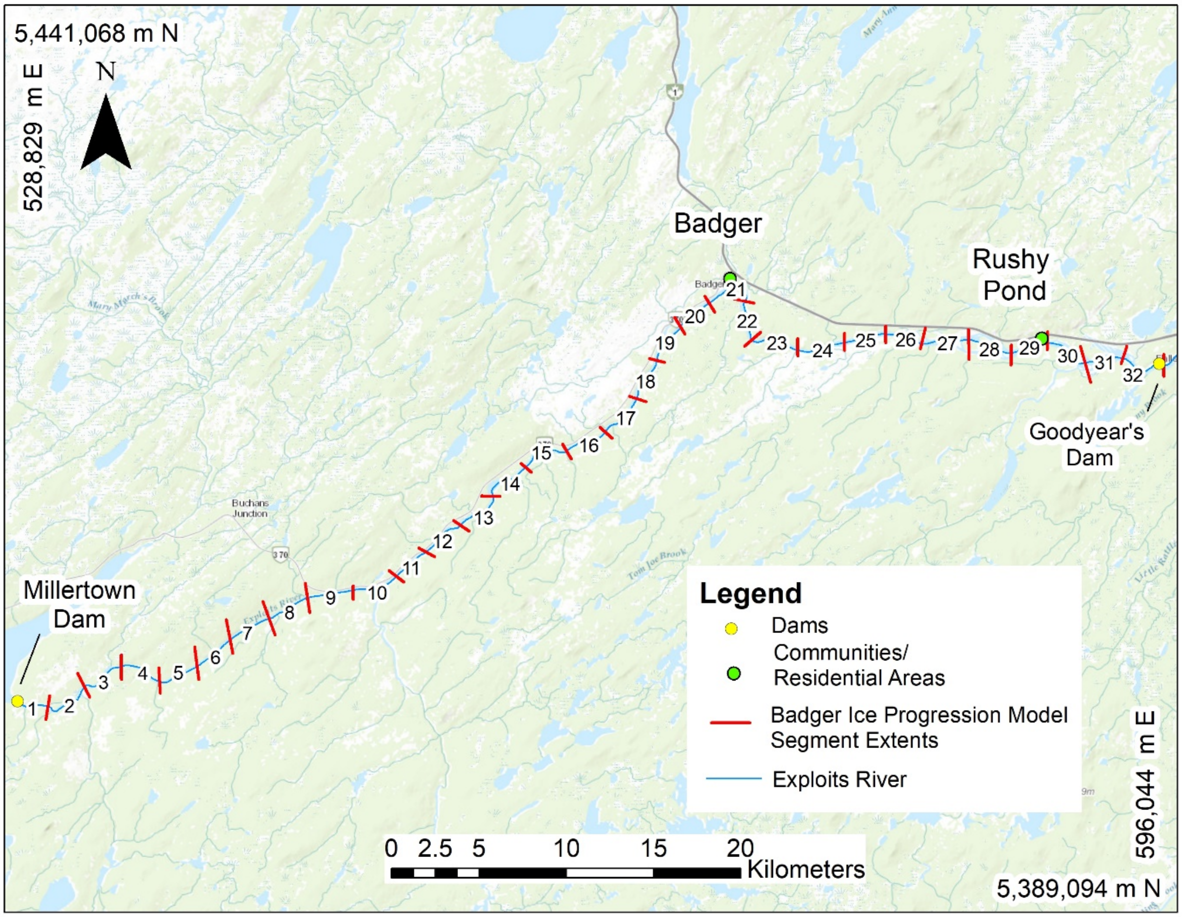

Figure 6-64: Badger Ice Progression Model Extents

It is Hatch's understanding that the hydraulic character of each segment (depth, area, and ice storage volume) is based on an estimate of the reach average value for each segment. Working in a downstream to upstream direction, generated ice is stored in each segment sequentially. The ice front advances as downstream segments reach their specified ice storage volume. Unlike modern ice models like RIVICE, the Badger ice model does not include logic to account for consolidation, or mechanical thickening of the cover when subjected to higher flow events. There will naturally be some variation in the volume of ice stored in each river reach, depending on the formation flow. It is understood that at present this variation is indirectly accounted for by adjusting key input parameters, like the ice cover porosity or the exit temperature of the Millertown Dam releases. Adjustments are made manually to these parameters to match observed ice front locations in the field.

It should be noted that storage volumes can vary in the reach from winter to winter based on the nature of the cover and the flow. In years with low flows, the ice may form based on a juxtaposed single ice floe and might have a thickness of 10 or 20 cm, and a relatively smooth roughness. In other years, it could be much thicker and most of the storage in the reach could be mobilized. There are a number of factors contributing to the ice thickness which are not currently accounted for in the model.

After reviewing the model code, Hatch concluded that any updates to the code would not significantly improve the functionality of the model. The same calibration features would still be required to fit modeled conditions to observed conditions.

It is Hatch's understanding that the model currently works quite well. Hatch would certainly recommend that the model continue to be used as a supplementary forecasting tool. The RIVICE model will directly account for a wider range of parameters and should give a better match of modeled conditions to observed conditions, but the Badger model is faster to run, and will continue to provide good insight into predicted advancement rates.

Two suggestions are put forward to perhaps improve overall performance of tool and to make it more consistent with the RIVICE model:

- Review and update of section characteristics
- Development of autocalibration routine

6.9.1 Volume Comparison

Hatch used the HEC-RAS model to check the ice storage volumes currently specified for each of the 32 segments. The comparison was conducted using a flow of 150 m^3/s, which was the average flow at the Millertown (Exploits) Dam during flood events (Fenco MacLaren, 1995). It was found that significant discrepancies exist in some areas between the original ice storage volumes and the volumes developed from the HEC-RAS model cross-sectional data. As it is not known how the original volumes were developed, it is not possible to state a precise reason for the discrepancy. It was noted during the checking process that for the upstream portion of the reach, the original volumes were generated by multiplying the average depth of the segment by the surface area of the segment. However, for the downstream end of the reach, the volumes were not generated by this multiplication; it is likely that limited cross-section data was used to provide a better estimate of the volumes. Some irregularities were noted in the original volumes. For example, the area covered by segment 24 is approximately 730,000 m^2. The average depth of flow in the Hatch HEC-RAS model segments was 0.9 m. However, the original volumes in this area were 2,236,000 m^3, which implies an average depth of flow of 3 m. The area covered by Segment 31 is approximately 1.7 km^2 and the average depth of flow in the Hatch HEC-RAS model segments was approximately 2.6 m. However, the original volume in this area was 1,050,000 m^3, which implies an average depth of flow of 0.6 m. WRMD may wish to review how these volumes were developed; information on the volume development was not provided in the documentation reviewed by Hatch.

The comparison between original and the HEC-RAS model volumes is shown in **Table 6-16.**

Table 6-16: Ice Storage Volume Comparison

Model Segment	Original Volumes (m^3)	HEC-RAS Volumes (m^3)	Percent Difference (relative to HEC-RAS)
1	735,000	212,254	71%
2	465,000	498,091	-7%
3	350,000	542,403	-55%
4	525,000	307,339	41%
5	812,500	340,893	58%
6	812,500	675,959	17%
7	837,500	580,994	31%
8	837,500	292,665	65%
9	1,030,000	619,679	40%
10	772,500	726,409	6%
11	735,000	642,055	13%
12	735,000	627,916	15%
13	620,000	334,882	46%
14	620,000	649,122	-5%
15	500,000	518,423	-4%
16	500,000	673,083	-35%
17	515,500	565,658	-10%
18	1,160,000	464,578	60%
19	1,045,000	589,861	44%
20	1,610,000	575,978	64%
21	773,000	681,345	12%
22	1,456,000	290,614	80%
23	2,400,000	598,515	75%
24	2,236,000	488,520	78%
25	1,965,000	534,053	73%
26	2,020,000	397,990	80%
27	1,623,000	777,881	52%
28	1,918,000	672,168	65%
29	1,773,000	608,661	66%
30	1,871,000	1,212,432	35%
31	1,050,000	5,529,771	-427%
32	515,000	1,539,744	-199%
Total	**34,818,000**	**23,769,935**	**32%**

The volume of storage calculated using the HEC-RAS model is significantly lower than the original model segments. Hatch recommends that the ice progression model be updated with the storage volumes calculated by Hatch. Results from this model should be compared with the original volume results to see whether a better fit to observed conditions is obtained.

6.9.2 *Model Update*

At present, an iterative approach is taken to calibrate the model to match an observed ice front location. It is understood that the modeller must manually test various combinations of ice cover porosity and release temperature until a match is obtained between the computed and the observed ice front location.

To assist in this, Hatch has developed and provided to WRMD an autocalibration routine for the model's temperature and porosity adjustment factors. This involves an automatic iterative application of the model with sequential adjustment of the porosity and outlet temperature until the model matches the observed ice front location.

6.10 Hydraulics Conclusions and Recommendations

An unsteady state HEC-RAS hydraulic model was developed and calibrated for use in the flood forecasting system. A steady state HEC-RAS hydraulic model was developed and calibrated to provide water levels, velocities and depths for flood maps. A RIVICE model of the ice conditions on the Exploits River was developed and calibrated.

The potential impact of climate change on water levels was modeled. Hatch's ice modeling indicates that future flood hazard will be governed by open water flood flows, and therefore the climate change scenario will not require ice jam as part of flood risk mapping.

The Badger Ice Progression Model was reviewed.

Hatch recommends the following:

1. The Badger River Ice Progression Model should be updated with the storage volumes calculated by Hatch. Results from this model should be compared with the original volume results to see whether a better fit to observed conditions is obtained, The autocalibration routine developed by Hatch should also be implemented.
2. The hydraulic model results for bridges and culverts may be used for preliminary screening of structures that may have inadequate capacity, for the purpose of capital works planning. Design of individual structures should be made on the basis of more detailed site-specific analyses.
3. It is noted that the program does not have a "hot start" capability which would allow it to save the results of a previous run and begin part of the way through a winter season. Instead, the program must start from the beginning of the winter season each time a simulation is run to advance the cover and estimate it's downstream thickness. This significantly increases the run time. Addition of a "hot start" capability is recommended to facilitate adjustment of parameters in the model from a given point in the winter season.
4. It is noted that the RIVICE model does not have a routine to simulate the natural smoothing of the underside of an ice cover that will occur after initial cover formation. This will result in a slow drop in water levels as the cover becomes more smooth with time. It is recommended that an algorithm such as that proposed by Nezhikhovskiy (1964) be implemented to the code to augment it's ability to simulate this effect.

7. Flood Mapping

7.1 Introduction

The water levels and velocities from the hydraulic steady state model and RIVICE model were used to create flood maps showing the flooded areas in the Exploits River communities, as well as the water depths, water velocities and flood hazard areas. The contours derived from LiDAR were used in the maps as well as the aerial photographs taken during the field program.

Figure 7-1 provides an overview of this section.

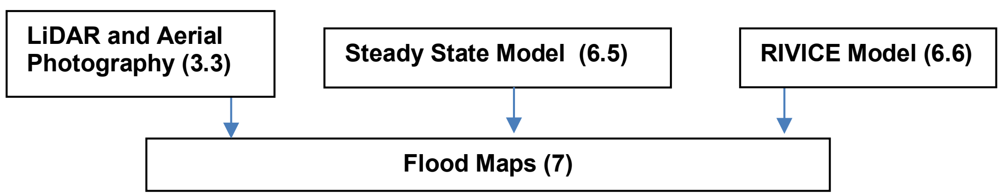

Figure 7-1: Flood Mapping Section Overview

7.2 Mapping Sets

Using the outputs from the steady state and ice models, flood mapping was completed to show the flood extents, depths, velocities and flood hazard associated with the various events.

1:25,000 scale overview maps were prepared to cover the entire study area from Badger to the outlet of the Exploits River. 1:2,500 scale detail maps were prepared in community and residential areas. 13 map sets were prepared as summarized in **Table 7-1** and provided in **Appendix F.**

Table 7-1: Mapping Sets

Map Type	1:20 AEP	1:100 AEP
Current Climate And Current Development Condition (CC-CD)		
Flood Extent – Composite Ice and Open Water	Map Set 1	Map Set 1
Flood Extent – Ice (Badger Area Only)	Map Set 2	Map Set 2
Flood Extent – Open Water (Badger Area Only)	Map Set 3	Map Set 3
Comparison of Flood Extent – Composite Ice and Open Water with Historical Flood Extents	Map Set 4	Map Set 4
Flood Inundation	Map Set 5	Map Set 6

Map Type	1:20 AEP	1:100 AEP
Flood Velocity	Map Set 7	Map Set 8
Flood Hazard	Map Set 9	Map Set 10
Climate Change And Current Development Condition (CLC-CD)		
Comparison of Flood Extents – CC-CD with CLC-CD	Map Set 11	Map Set 12
Flood Extent	Map Set 13	Map Set 13

1:25,000 overview maps are provided on base imagery provided by ESRI. 1:2,500 detail maps include orthophotographs and 1 m elevation contours from LEG.

7.3 Ice Jam Flood and Open Water Flood Extents

Ice jam flood and open water flood extents were mapped for the Badger area, as the ice jam flood levels are greater than the open water flood levels for much of the reach in that area. This will allow the town to discern where the risks are between ice and non-ice flood events. Hatch also provided a composite flood extent that combines both ice and open water profiles to facilitate an understanding of flood risk for the entire community. The historical extents are compared with the composite flood extents, as the historical extents are also a composite product.

The open water profile is the dominant one for most of the Rushy Pond area apart from a few sections at the upstream end where the ice levels are marginally higher than the open water ones. Given these minor differences and the small number of residences and low risk to the population in this area, only a composite flood extent has been shown for the Rushy Pond area.

The ice model extends only to Goodyear’s Dam. Ice conditions have not been a historically significant factor in flooding downstream of Goodyear’s Dam.

Velocity, depth and hazard maps were prepared based on the composite flood extents only.

7.4 Community Development

Flows associated with current and future community development were assessed in the hydrologic model as discussed in **Section 5.5.2.**

Model results indicated that the “fully developed” case had a negligible impact on the water levels and flows (0-1% increase over current development conditions) as the fully developed areas are too small to make a significant contribution to the runoff hydrograph peaks of the stream systems in this study. As such, the “fully developed” case was not modeled in the hydraulic model, nor were maps prepared.

7.5 Flooded Area Comparison

A comparison of flooded areas between the current and climate change condition is shown in **Table 7-2.** The climate change condition represents a 0.1% increase in flooded area from the current condition for the 1:20 AEP scenario, and a 2% decrease in flooded area for the 1:100 AEP scenario. The small increase for the 1:20 AEP scenario and the decrease in the 1:100 AEP scenario is due to the lack of ice in the climate change scenarios. In the town of Badger, the flooding due to ice represents a significantly larger flooded area than the open water conditions. The reduction in flooded area due to the lack of ice flooding in the climate change scenario offsets the increase in flooded area due to higher climate change flows.

The historical flood areas for the Badger, Rushy Pond and Bishop's Falls areas shown in the Canada-Newfoundland Flood Damage Reduction Program Flood Information Maps (n.d. and 1990) were digitized and compared with current climate flood extents modeled in this study. The current climate flood extents are between 20% and 25% greater than the Badger historical flood areas, despite the water surface elevation of the current flood estimate being only slightly higher than that of the historical estimate. This is due to the LiDAR data providing a more detailed and accurate representation of the topography that would be flooded.

In the Rushy Pond and Bishop's Falls areas, the current climate flood extents are between 8% and 13% smaller than the historical flood areas. During the Bishop's Falls flood of 1983, significant flooding took place in the Bishop's Falls Dam headpond area. Since 1983, Bishop's Falls Dam has been rebuilt with enhanced flood discharge capability which will result in a lower headpond level during extreme floods. Comparisons are shown in **Table 7-2.**

Table 7-2: Flooded Area Comparison

Flood Type	Flood Extent	Current Condition (km^2)	Climate Change (km^2)	Historical Record (km^2)	% Increase
Entire Study Area – Composite Ice and Open Water	1:20 AEP	31.98	32.02	-	0.1%
	1:100 AEP	34.10	33.39	-	-2%
Badger – Composite Ice and Open Water	1:20 AEP	0.63	-	0.50	20%
	1:100 AEP	1.10	-	0.84	25%
Rushy Pond – Composite Ice and Open Water	1:20 AEP	4.69	-	5.12	-9%
	1:100 AEP	4.95	-	5.57	-13%
Bishop's Falls – Composite Ice and Open Water	1:20 AEP	3.57	-	3.87	-8%
	1:100 AEP	3.82	-	4.15	-9%

7.6 Flood Mapping Conclusions and Recommendations

Hatch prepared flood maps showing flooded areas, inundation (depth), velocity and flood hazard. Flooded areas were compared with historical flood mapping.

Hatch recommends the following:

1. WRMD and the Exploits River communities should adopt the flood extents developed in the current study for regulation of floodplain development and for municipal planning, as applicable. The inundation, flood velocity and flood hazard maps should be used for emergency preparedness planning.

8. Flood Forecasting Service

The deterministic hydrologic model (**Section 5.4**), unsteady flood forecasting hydraulic model (**Section 6.4**) and RIVICE model (**Section 6.6)** were used by WEST Consultants to develop a flood forecasting service on the HEC-RTS software platform.

The deterministic hydrologic model simulates how rainfall and snowmelt on the Exploits River basin is converted to flows in the Exploits River and the streams in the community areas. The hydrologic model results are used in the unsteady state flood forecasting model and the ice model.

The unsteady state flood forecasting hydraulic model shows water levels on the Exploits River, Badger Brook, Little Red Indian Brook, North Angle/Wigwam Brook and Rushy Pond Brook when there is no ice on the Exploits River. When there is no ice on the river, the river is said to be in "open-water conditions". The ice model is used in the flood forecasting system to show water levels on the Exploits River during the winter when there is ice on the Exploits River.

The flood forecasting system helps to predict floods up to 48 hours in advance. The system collects observed and forecasted information about rain, snow, and temperature and converts them into flows in the rivers and streams using the deterministic hydrologic model. It then estimates how high the water levels will be in those rivers and streams using the unsteady state flood forecasting hydraulic model and ice model. The flood forecasting system helps communities plan what flood protection or emergency measures should be carried out, if any. Details of the flood forecasting service development are provided in a separate report.

Figure 8-1 provides an overview of this section.

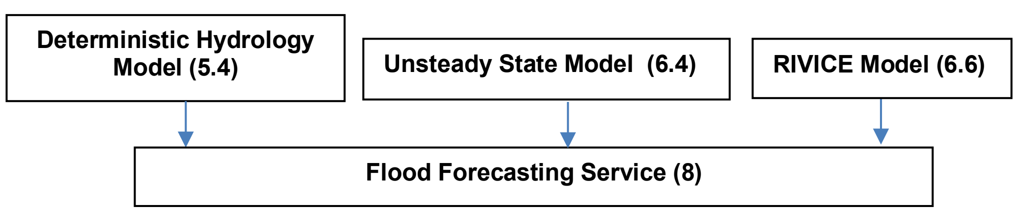

Figure 8-1: Flood Forecasting System Section Overview

9. Conclusions and Recommendations

Hatch carried out a climate change flood risk mapping study and developed a flood forecasting service for the communities along the Exploits River.

Historical flooding was reviewed and a field program was conducted which collected survey data as well as LiDAR and aerial photography. A land classification exercise was conducted with a good success rate suitable for the purposes of this study.

The hydrology of the basin was assessed through stochastic analyses and construction of a deterministic model in HEC-HMS. Flows from the stochastic analyses and deterministic model were used to develop flood maps. The potential impact of climate change on flows was assessed. The deterministic model was used in the HEC-RTS flood forecasting system to provide the flows in the watercourses arising from the precipitation in the study area.

An unsteady state HEC-RAS hydraulic model was developed and calibrated for use in the flood forecasting system. A steady state HEC-RAS hydraulic model was developed and calibrated to provide water levels, velocities and depths for flood maps. A RIVICE model of the ice conditions on the Exploits River was developed and calibrated for use in the flood maps and flood forecasting system.

The potential impact of climate change on water levels was modeled. Hatch’s ice modeling indicates that future flood hazard will be governed by open water flood flows, and therefore the climate change scenario does not require ice jam as part of flood risk mapping. The Badger Ice Progression Model was reviewed.

Flood maps were prepared showing the flooded areas in the Exploits River communities, as well as the water depths, water velocities and flood hazard areas. The historical flood extents were compared with the current flood extents.

A flood forecasting service for the Exploits River communities was developed using HEC-RTS software.

The recommendations of the study are as follows:

1. Installing additional precipitation gauges would help reduce uncertainty in the spatial distribution of precipitation, and could improve hydrological model calibration. It is recommended that additional stations be installed in southern part of the watershed where coverage by the existing observation network is sparse (e.g., Noel Pauls and Great Rattling sub-basins).
2. It is recommended that a means of continuous flow measurement be implemented at Bishop’s Falls as there is currently no active long term record of flow at that location. One alternative may be for Nalcor to implement discharge calculations based on hydro generation and spill at the Bishop’s Falls Generating Station or calibration of the Bishop’s Falls tailwater curve via field measurement of flow and level. Another alternative may be

for WRMD to establish an independent gauge at a suitable location. A continuous record of flow at Bishop’s Falls would provide the following benefits:

- Additional years of record in the flood series would improve the confidence of statistically-based flood estimates for future updates to this study.
- Information from future floods in the basin could be used to improve the calibration of the hydrological model developed in the current study.

3. In addition to the use of climate change rainfall IDF projections, WRMD should consider using the calibrated deterministic hydrologic model in a continuous precipitation-runoff simulation approach, using downscaled temperature and precipitation projections from climate models. Such an approach would provide a way of making climate change flood estimates that quantitatively consider the effects of future changes in snowpack, snowmelt, and soil moisture, which are important contributors to annual flood peaks in large river basins such as the Exploits River.
4. The Badger River Ice Progression Model should be updated in the 2020-2021 ice season with the storage volumes calculated by Hatch. Results from this model should be compared with the original volume results to see whether a better fit to observed conditions is obtained, The autocalibration routine developed by Hatch should also be implemented.
5. It is noted that the program does not have a “hot start” capability which would allow it to save the results of a previous run and begin part of the way through a winter season. Instead, the program must start from the beginning of the winter season each time a simulation is run to advance the cover and estimate it’s downstream thickness. This significantly increases the run time. Addition of a “hot start” capability is recommended to facilitate adjustment of parameters in the model from a given point in the winter season.
6. It is noted that the RIVICE model does not have a routine to simulate the natural smoothing of the underside of an ice cover that will occur after initial cover formation. This will result in a slow drop in water levels as the cover becomes more smooth with time. It is recommended that an algorithm such as that proposed by Nezhikhovskiy (1964) be implemented to the code to augment it’s ability to simulate this effect.
7. The hydraulic model results for bridges and culverts may be used for preliminary screening of structures that may have inadequate capacity, for the purpose of capital works planning. Design of individual structures should be made on the basis of more detailed site-specific analyses.
8. WRMD and the Exploits River communities should adopt the flood extents developed in the current study for regulation of floodplain development and for municipal planning, as applicable. The inundation, flood velocity and flood hazard maps should be used for emergency preparedness planning.

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