Climate Change Report Series

Technical Report for PEI Pluvial Flood Mapping

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Executive Summary

The Government of Prince Edward Island (PEI) has launched the Coastal Hazards Information Platform (CHIP) in 2022, which provides coastal flooding maps under different storm surges and sea level rise scenarios. However, there are still no pluvial flooding maps (typically caused by heavy rainfall) available for PEI. The recent floods in Canada, China, US, and Europe have consistently suggested that global warming can intensify the hydrological cycle and lead to more frequent heavy rainfalls, thus more pluvial floods. This is also true for PEI as islanders have been seeing more intense and frequent heavy rainfalls in recent years. Therefore, the objective of this project is to fill the gap in pluvial flooding maps for PEI, by 1) carrying out pluvial flood modeling for PEI to help understand the potential pluvial flooding risks under current and future climate conditions, and 2) generating island-wide pluvial flooding maps for PEI so that islanders can use them to support their flood mitigation and adaptation plans.

In this project, the HEC-RAS 2D model is selected to conduct pluvial flood modeling for PEI after a preliminary and comparative assessment of three flood models (i.e., HEC-RAS 2D, PCSWMM, and FloodMapper). The model was validated with the flood event data for September 2, 2021 (for Charlottetown) and July 3-4, 2023 (for three counties across PEI). The rainfall Intensity-Duration-Frequency (IDF) curves with four return periods (10-yr, 25-yr, 50-yr, and 100-yr) under current and future climate condition developed by the Environment and Climate Change Canada (ECCC) are used to design rainfall events for pluvial flood mapping.

This report provides technical details about flood model selection, data collection, flood model setup, model calibration and validation, and quality assurance and control. The resulting pluvial flood maps for six municipalities (i.e., City of Charlottetown, City of Summerside, Town of Stratford, Town of Cornwall, Town of Three Rivers, and Town of Tignish), two Indigenous communities (Lennox Island First Nation and Abegweit First Nation, including Scotchfort, Morell Indian Reserve 2, and Rocky Point), and entire PEI are provided in the Annexes of this report. The flood maps are also made available for public viewing through the PEI Climate Hazard & Risk Information System (https://chris.peiclimate.ca). This report also summarizes the main assumptions and limitations introduced in this project and provides recommendations and potential improvements for future projects.

Acknowledgements

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Disclaimer

The pluvial flood maps generated from this project are developed with various tools and data from various sources. Although significant efforts have been made to ensure the accuracy, completeness, and timeliness of the hazard maps, it is important to acknowledge that the maps are not guaranteed to be correct or complete or current due to these factors: 1) the data collected from various sources may have different resolutions and levels of accuracy, 2) the modeling methods used always have their limitations in representing the real world, and 3) some data are being updated on a daily or weekly basis and any updates after the creation of the hazard maps are thus not reflected.

The pluvial flood maps in this project are produced to support high-level hazard screening, public awareness, preliminary planning, and preliminary risk assessments. Results are approximate and are not meant to support site-specific property or infrastructure assessments, which would require detailed engineering flood hazard mapping studies. For any site-specific questions or concerns, users are encouraged to consult with a competent professional.

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Table of Contents

List of Acronyms

2D	Two-Dimensional
AAFC	Agriculture and Agri-Food Canada
AMC	Antecedent Moisture Conditions
CGVD2013	Canadian Geodetic Vertical Datum of 2013
CN	Curve Number
CSC	Soil Conservation Services
DEM	Digital Elevation Model
ECCC	Environment and Climate Change Canada
ESA	European Space Agency
HEC-RAS	Hydrologic Engineering Center's River Analysis System
HRDEM	High-Resolution Digital Elevation Model
HSGs	Hydrologic Soil Groups
IDF	Intensity Duration Frequency
LULC	Land Use and Land Cover
NLCD	National Land Cover Database
NRCan	Natural Resources Canada
NRCS	Natural Resource Conservation Services
PCSWMM	Personal Computer Storm Water Management Model
PEI	Prince Edward Island
USDA	United States Department of Agriculture
USGS	United States Geological Survey

1. Introduction

The Government of Prince Edward Island (PEI) has launched the Coastal Hazards Information Platform (CHIP)[1,2], which provides coastal flooding maps under different storm surges and sea level rise scenarios. However, there are still no pluvial flooding maps (typically caused by heavy rainfall) available for PEI. The recent floods in Canada, China, US, and Europe have consistently suggested that global warming can intensify the hydrological cycle and lead to more frequency heavy rainfalls, thus more pluvial floods. This is also true for PEI as islanders have been seeing more intense and frequent heavy rainfalls in recent years, which always led to unexpected floods (see Figure 1).

Figure 1. A flooded street in the City of Charlottetown caused by an early morning thunderstorm[3].

Therefore, the objective of this project is to fill the gap in pluvial flooding maps for PEI, by 1) carrying out pluvial flood modeling for PEI to help understand the potential pluvial flooding risks under current and future climate conditions, and 2) generating island-wide pluvial flooding maps for PEI so that islanders can use them to support their flood mitigation and adaptation plans. This report aims to provide technical details about the flood model selection, data collection, flood model setup, model calibration and validation, and quality assurance and control. The resulting pluvial flood maps and recommendations for potential future improvements are also presented in this report.

2. Flood Model Selection

Selecting a flood model is the starting point for the generation of pluvial flood maps. In this section, the key challenges related to the pluvial flood modeling in the context of PEI are first described, followed by a preliminary and comparative assessment of three flood models (i.e., HEC-RAS 2D, PCSWMM, and FloodMapper) in terms of their capabilities in addressing these key challenges. Based on the initial assessment by the project team and discussions with the technical advisory committee, HEC-RAS 2D is selected for pluvial flood modeling in this project.

2.1 Challenges in Pluvial Flood Modeling for Coastal Communities

Below are some key challenges for modeling pluvial floods over a low-lying island like PEI:

(1) **Representation of stormwater systems in cities:** Stormwater systems in urban areas are designed to mitigate street flooding caused by heavy rainfall. It is no doubt that stormwater systems should be considered for pluvial flood modeling. However, a stormwater system usually consists of a very complicated network of street inlets and underground drainage pipes. Most of the existing flood models do not have the ability to reflect such a complex system. Even though some models have the ability, collecting data about urban stormwater systems can be a very challenging task in practice.

(2) **Representation of the impacts of ocean tides on the stormwater systems for coastal cities:** For coastal cities, the outlets of stormwater systems are connected to the ocean and can be easily affected by the changing tides. For example, the outlets can be submerged by ocean water during high tides, thus ocean water will flow back into the stormwater system and significantly reduce its capacity (see Figure 2). In addition, coastal cities are often located at an estuary where the flow direction in rivers can be easily reversed during high tides. This is especially true for the low-lying coastal communities in PEI. Therefore, any models selected for the pluvial flood modeling in PEI should at least be able to address the reversed-flow phenomenon.

(3) **Representation of hydraulic structures:** The main hydraulic structures in PEI are bridges and culverts. Bridges are typically over large river channels near estuaries or major roads, and they have already been removed from the existing DEM data. Therefore, the challenge here is mainly about the representation of culverts. Some flood models can model the water flow within culverts directly, while others typically use hydro-connected DEM to ensure the connection of rivers or streams at the locations of culverts.

(4) **Is the model good for island-wide pluvial flood modeling in PEI?** One of the objectives of this project is to produce island-wide pluvial flood maps for PEI. Therefore, it is also important to consider the feasibility of a flood model for regional-scale flood modeling.

Figure 2. A submerged outlet of Charlottetown's stormwater system during high tides.

2.2 Model Comparison & Selection

Based on the above-listed challenges, the project team initially narrows down the model options to three flood models, including HEC-RAS 2D, PCSWMM, and FloodMapper. Here it is worth noting that, due to the limited resources and the tight timeline of this project, the project team is unable to screen all available flood models on the market. The HEC-RAS 2D is developed by the Hydrologic Engineering Center of the US Army Corps of Engineers and it is a well-known and widely-used flood model[4]. The PCSWMM is developed by the Computational Hydraulics International (CHI) and it is widely used for stormwater and wastewater management modeling[5]. FloodMapper is developed by Dr. Wang in 2019 with the purpose of simulating urban flooding due to heavy rainfall and it is available as an open-source R package[6,7].

Table 1 shows a preliminary and comparative assessment of these three models in terms of their capabilities of addressing the above-listed challenges for pluvial flood modeling in PEI. Based on this assessment, PCSWMM is first removed from consideration for this project. This is because: (1) although PCSWMM is able to represent the complicated stormwater systems directly, the data for existing stormwater systems in the major cities in PEI are of poor quality and require considerable work for correction and improvement; and (2) it is primarily used for flood simulation over urban areas and might not be suitable for island-wide flood modeling in PEI. Following that, FloodMapper is further removed based on its comparison to HEC-RAS 2D. This is largely because: (1) HEC-RAS 2D can represent culverts directly while FloodMapper needs to use hydro-connected DEM; and (2) HEC-RAS 2D allows mesh refinements to increase model resolution at specific locations while FloodMapper only supports a consistent model resolution across the domain. Based on the initial assessment by the project team and discussions with the technical advisory committee, HEC-RAS 2D is finally selected for this project to produce both city-level and island-wide pluvial flood maps in PEI.

Table 1. A preliminary and comparative assessment of three flood models.

Challenges	HEC-RAS 2D	PCSWMM	FloodMapper
#1 **How to properly reflect stormwater systems in cities?**	This model is unable to represent urban stormwater systems directly. A practical resolution is to subtract a short return period rainfall intensity from the design flood rainfall intensity for urban areas. However, this is a very rough estimation and doesn't reflect the dynamic processes and constantly-changing capacity of stormwater systems during a rainfall storm. No data about stormwater systems are needed for this model.	This model is able to directly represent the detailed structures (i.e., both street inlets and underground drainage pipe networks) of urban stormwater systems. This model requires very detailed data and information about the existing stormwater systems. This can be a practical challenge as the data for stormwater systems (especially the underground pipe networks) are not publicly available.	This model considers the locations of street inlets for urban stormwater systems. The rainfall intensity used to design the stormwater system is considered by this model to properly reflect its designed capacity. This model might be used as a compromised solution between HEC-RAS 2D and PCSWMM.
#2 **How to properly reflect the impacts of ocean tides on the stormwater systems for coastal cities?**	This model allows users to set up ocean boundaries along with the simulation domain. Thus, it can reflect the reverse-flow phenomenon in the low-lying estuarial communities. However, since it doesn't consider the urban stormwater systems, the impacts of ocean tides on the outlets of urban stormwater systems cannot be reflected.	Since this model considers the detailed structures of the urban stormwater systems, it is certainly able to simulate the impacts of ocean tides on the outlets, reflecting the reduced flood drainage capacity while the outlets are submerged by ocean water.	This model can simulate reversed flows in rivers. However, the current version doesn't support the consideration of ocean tides. It is thus unable to reflect the direct impacts of ocean tides on the outlets of stormwater systems.

#3 **How to properly reflect the main hydraulic structures?**	This model can reflect all main hydraulic structures (e.g., bridges and culverts).	This model can reflect all main hydraulic structures (e.g., bridges and culverts).	The current version of this model does not represent hydraulic structures (e.g., bridges and culverts) directly. Instead, it requires hydro-connected DEM to reflect them.
#4 **Is the model good for island-wide pluvial flood modeling in PEI?**	This model can simulate multiple watersheds within one run, so it is good for island-wide pluvial flood modeling in PEI.	Although it has the capacity to be applied for non-urban areas, PCSWMM is primarily used for urban areas. Due to its considerable data requirements, it might not be suitable for island-wide flood modeling in PEI.	This model can simulate multiple watersheds within one run, so it is good for island-wide pluvial flood modeling in PEI.

3. Data Collection

This section describes the data used to run HEC-RAS 2D model. While the majority of the data used in the project can be obtained from existing sources, the project team has also conducted many field visits in order to collect detailed information about hydraulic structures in urban areas. In addition, flood event data are collected through archived news reports, social media, and field visits in order to support model calibration and validation.

3.1 DEM

The High-Resolution Digital Elevation Model (HRDEM) with a 1m x 1m resolution is obtained from Natural Resources Canada (NRCan) via the Open Government Portal[8]. The HRDEM is derived from airborne LiDAR data and refers to the Canadian Geodetic Vertical Datum of 2013 (CGVD2013), which is the reference standard for heights across Canada. The HRDEM for PEI is shown in Figure 3.

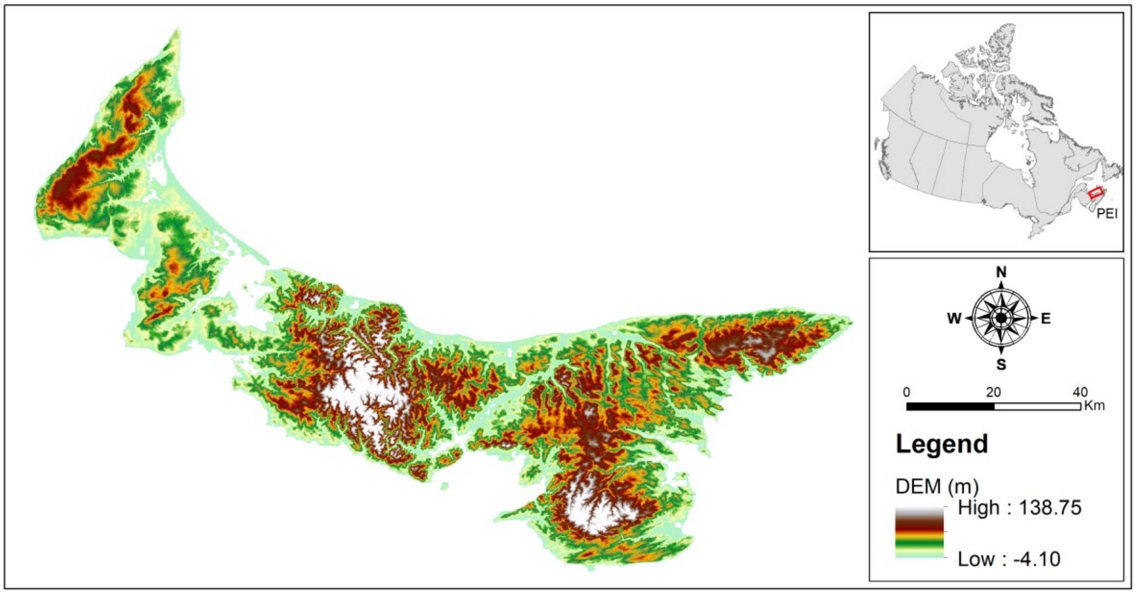


Figure 3. Map of HRDEM for PEI.

3.2 Land Use and Land Cover Data

The Land Use and Land Cover (LULC) data for PEI in 2020 with a 10m x 10m resolution is obtained from the ESRI[9].The ESRI LULC data is developed using Sentinel-2 satellite imagery from the European Space Agency (ESA) in collaboration with Microsoft and Impact Observatory partners. The LULC classes used for the HEC-RAS model are based on the United States Geological Survey (USGS) National Land Cover Database (NLCD). The conversions from the ESRI LULC classes to the NLCD classes are listed in Table 2. Figure 4 shows the 2020 LULC map for PEI.

Table 2. Conversion table from the ESRI LULC classes to the NLCD classes.

ESRI Class	NLCD Class	NLCD Code
Agriculture	Cultivated Crops	82
Commercial, Industrial, Transportation & Urban	Developed High Intensity (80-100% impervious)	24
Forestry	Mixed Forest	43
Institutional and Residential	Developed Medium Intensity (50-70% impervious)	23
Non-Evident	Barren Land	31
Recreation	Parks & Green Spaces	21
Wetland	Woody Wetlands	90

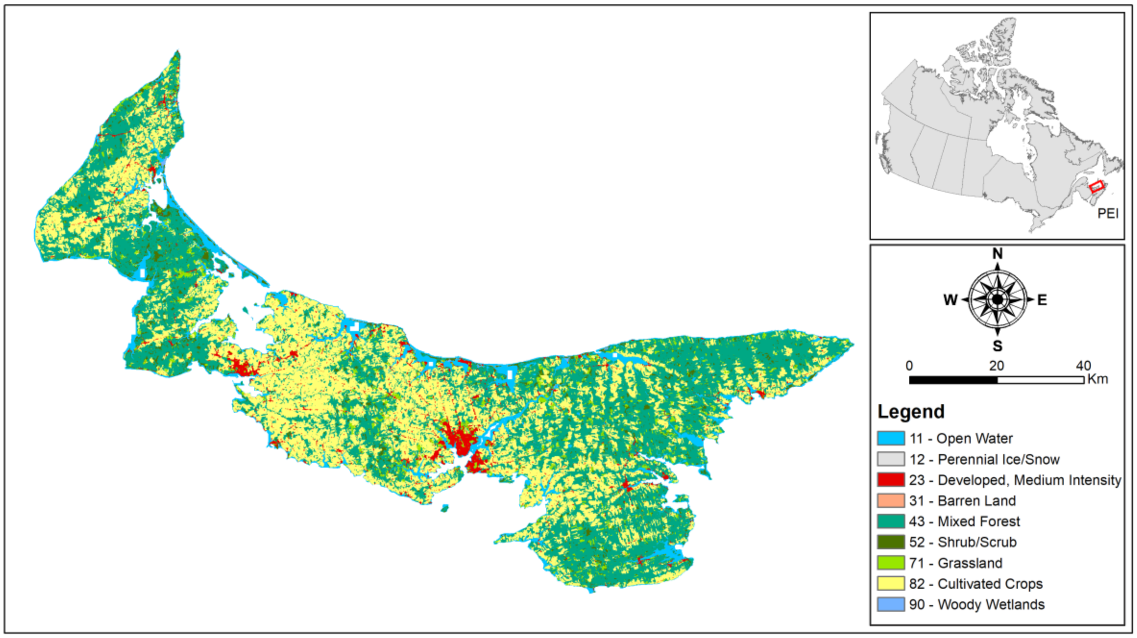


Figure 4. Map of LULC for PEI.

3.3 Soil Data

Soil data is required to estimate the infiltration and rainfall losses in HEC-RAS for rainfall-runoff modeling. The soil data for PEI is obtained from the Government of PEI which is based on survey data between 1970 and 1978[10]. To be used in the HEC-RAS model, the soil data is further reclassified into four Hydrologic Soil Groups (HSGs) based on the soil's runoff potential according to the Natural Resource Conservation Services (NRCS) guidelines. Table 3 shows the conversion table used here to convert the PEI soil classes to the NRCS's HSGs. This conversion table aligns with Agriculture and Agri-Food Canada (AAFC)'s guidelines on the conversion of Canadian soil classes to the NRCS's HSGs. The four HSGs include: Group A (sand, loamy sand or sandy loam types of soils), Group B (silt loam or loam), Group C (sandy clay loam) and Group D (clay loam, silty clay loam, sandy clay, silty clay or clay). Group A generally has the lowest runoff potential due to the highest infiltration capacity, and Group D has the highest runoff potential due to the lowest infiltration capacity. Although the soil classification represented by HSGs is coarse, it is suitable for the large-scale flood modeling analysis in this project. Figure 5 shows the soil type map for PEI.

Table 3. Conversion table from Canadian soil classes to NRCS's HSGs.

Canadian Soil Class	Canadian Soil Class Code	NRCS HSG
Very Rapidly	VR	A
Rapidly	R	A
Well	W	A
Moderately Well	MW	A
Imperfectly	I	B
Poorly	P	C
Very Poorly	VP	D
Not Available	NA (Rock, Snow or Missing)	B

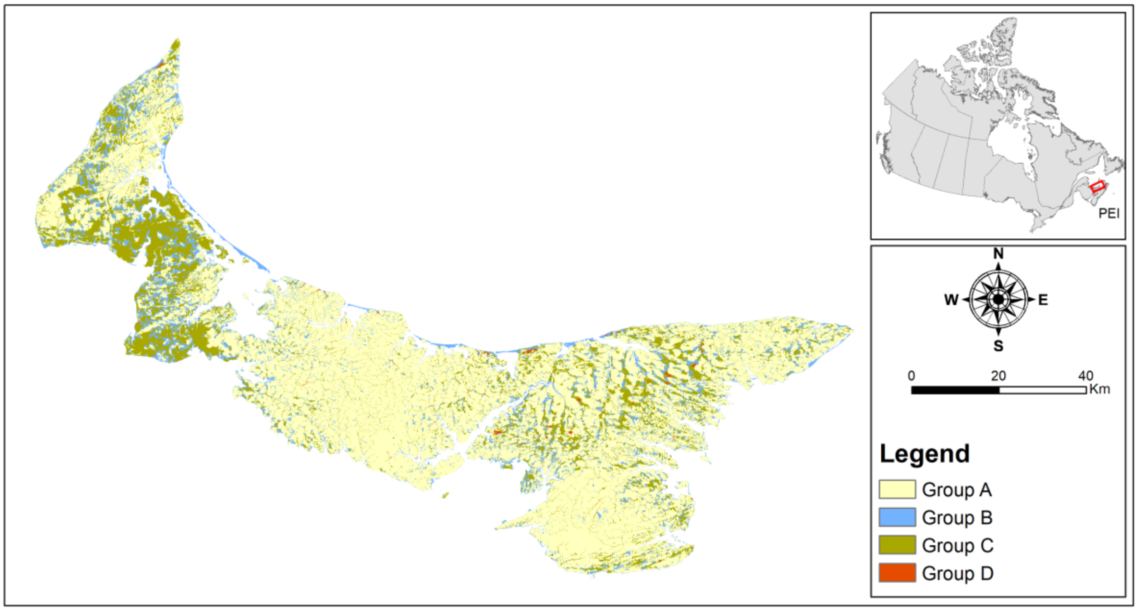


Figure 5. Map of soil type for PEI.

3.4 Roadway and Watercourse Network

The roadway and watercourse network are not direct inputs for HEC-RAS, but they are very important to guide model mesh refinement, culvert setup, field visits, and DEM breaching. The data for the roadway and watercourse network are collected from the Government of PEI's Open Data Portal[11].

3.5 Hydraulic Structures

Hydraulic structures such as culverts and drainage inlets are important infrastructure to mitigate pluvial flood risks and thus should be properly represented in the modeling process. The project team has requested data about culverts and bridges from the PEI Department of Transportation and Infrastructure[12]. However, the collected data only covers culverts with span width >= 1.2m and the key dimensional information for the included culverts is not complete. Therefore, the project team has conducted field visits to the major urbanized communities in Charlottetown, Summerside, Stratford, Cornwall, and Three Rivers (mainly Montague and Georgetown) in PEI to obtain field measurements of the key dimensional information about culverts. The information is then fed into HEC-RAS to ensure that all culverts are properly reflected for city-level pluvial flood modeling. Figure 6 shows photos about the filed surveys in Charlottetown and Summerside in 2023.

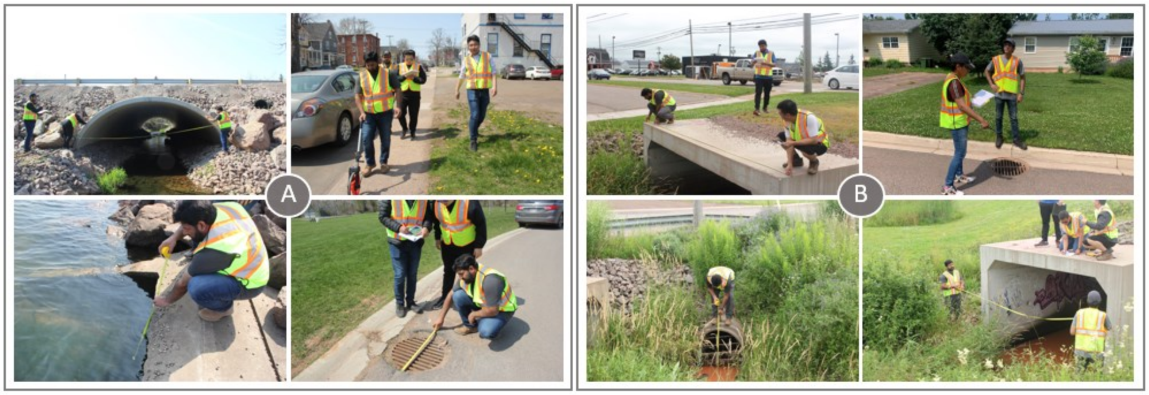


Figure 6. Field surveys for culverts and drainage inlets in (A) Charlottetown on May 12, 2023, and (B) Summerside on July 18, 2023.

3.6 Stormwater Systems

During the initial assessment, the project team has collected the data for the stormwater system in the City of Charlottetown in order to develop a preliminary PCSWMM model. The stormwater system data from the City of Charlottetown are available as shapefiles, mainly representing the pipe network and manholes. However, there are significant gaps and inaccuracies with the data, such as disconnected system components and missing key details about pipe invert levels and diameters as well as manhole rim elevations. The project team has also conducted field measurements about the stormwater system drainage inlets in Charlottetown for verification and testing purposes (see Figure 6). However, the field work for drainage inlet measurement is discontinued after the HEC-RAS 2D model is selected as the final model for this project. This is because the HEC-RAS 2D model is unable to directly represent urban stormwater systems.

3.7 Rainfall IDF Curves & Climate Change

Rainfall data is crucially important for pluvial flood modeling as it aims to simulate floods caused by extreme rainfall events. Here the project team uses the existing rainfall Intensity-Duration-Frequency (IDF) curves under both current climate and future climate conditions developed by the ECCC[13]. In particular, the project team considers two sets of IDF curves (i.e., current climate and future climate) to generate pluvial flood maps for PEI. In detail, current climate condition is based on the historical rainfall IDF curves, which are solely based on historical rainfall data from existing weather stations (i.e., future climate change is not considered). In comparison, future climate condition is based on the climate change-scaled IDF curves from ECCC which integrates different future climate change scenarios. Here in this project, the climate changes-scaled IDF curves under SSP5-8.5 (commonly known as a business-as-usual emission scenario) for the period of 2071-2100 are used.

3.8 Flood Event Data

Flood event data is collected to support model calibration and validation. Since this project will produce two levels of pluvial flood maps for PEI: 1) maps for major municipalities, and 2) island-wide maps for PEI, the project team has collected two sets of flood event data to facilitate the model calibration and validation at these two levels. In particular, for island-wide pluvial flood modeling for PEI, the measured flow rate and water level data for a heavy rainfall event on July 3-4, 2023 are collected from the hydrometric stations maintained by Environment and Climate Change Canada (ECCC)[14]. Figure 7 shows the available hydrometric stations for PEI. Three stations are finally selected in this project based on their data availability and spatial representation in three counties of PEI (i.e., Prince, Queens, and Kings).

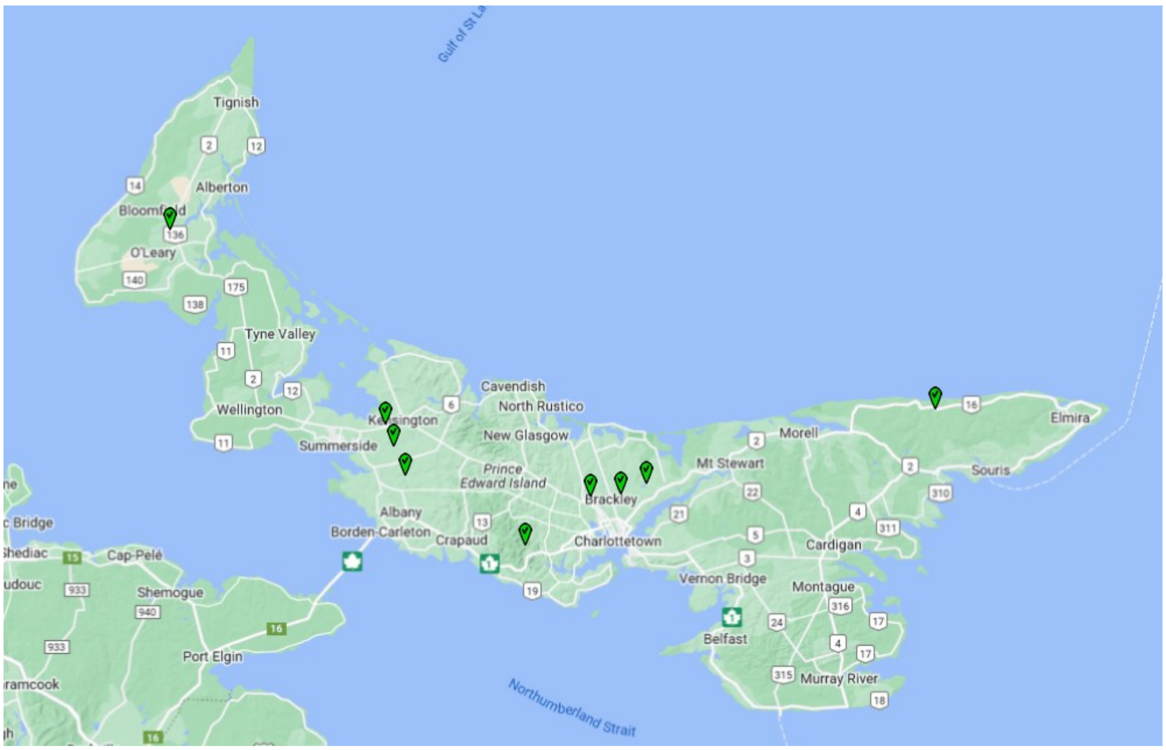


Figure 7. Map of the available hydrometric stations in PEI.

As for the flooding events in urban areas, the project team selects a flood event occurred in the City of Charlottetown on September 2, 2021 given that video footages about this flood event can be easily collected through public news reports or social media. In particular, the project team focuses on two locations in downtown Charlottetown: the parking lot of Holland College, and the junction of West Street and Richmond Street (see Figure 8). Note that the video footages for the parking lot of Holland College and the junction of West Street and Richmond Street are collected from social media[15,16].

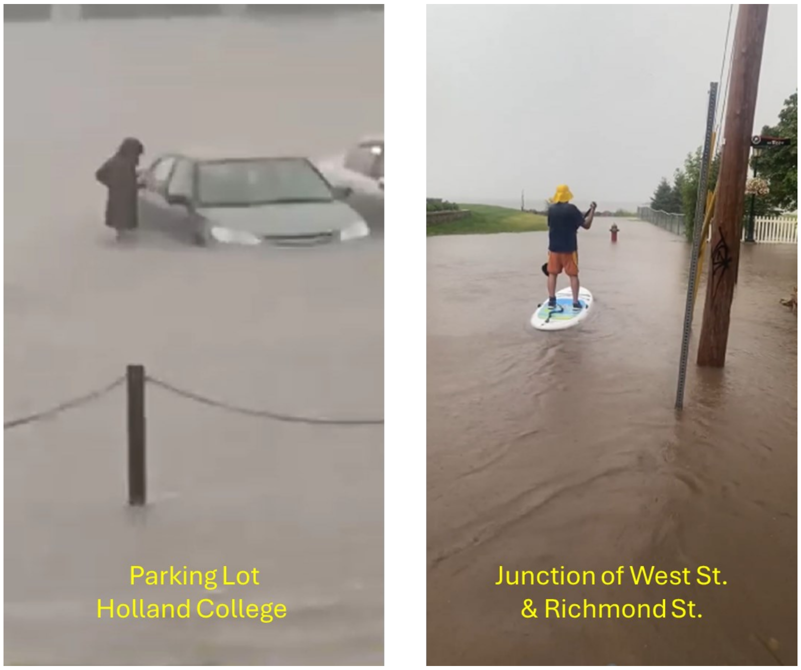


Figure 8. Video footage for the September 2, 2021 flood event in Charlottetown.

In order to estimate the flood depths within the available video footages, the project team performed various field trips at these two locations in the summer of 2023 (see Figure 9). This is to help determine the flood depths at the points of interest by cross-referencing existing inundated landmarks for the flood event on September 2, 2021.

Figure 9. Field visits at (A) the junction of the West Street and Richmond Street, and (B) the parking lot of Holland College in the summer of 2023.

4. Model Setup

This section describes the technical details about the model setup for HEC-RAS 2D, including its hydrological analysis, hydraulic analysis, and simulation setup. Note that the HEC-RAS 2D model is run at two levels (i.e., municipal and island-wide) in this project in order to generate detailed pluvial maps for major municipalities and high-level maps for the entire island of PEI. The technical settings for these two levels of model runs are different in several aspects and thus described separately whenever applicable.

4.1 Hydrological Analysis

4.1.1 Watershed Delineation

(1) Municipal Model

For municipalities, watersheds are delineated by using the 1m HRDEM data with a minimum area threshold of 5 hectares. This detailed delineation aims to accurately identify the full boundaries of contributing catchments while minimizing the HEC-RAS 2D model domain. This approach can help reduce the number of meshes and shorten the model computation time. Figure 10 illustrates an example of watershed delineation of the municipal model for the City of Charlottetown.

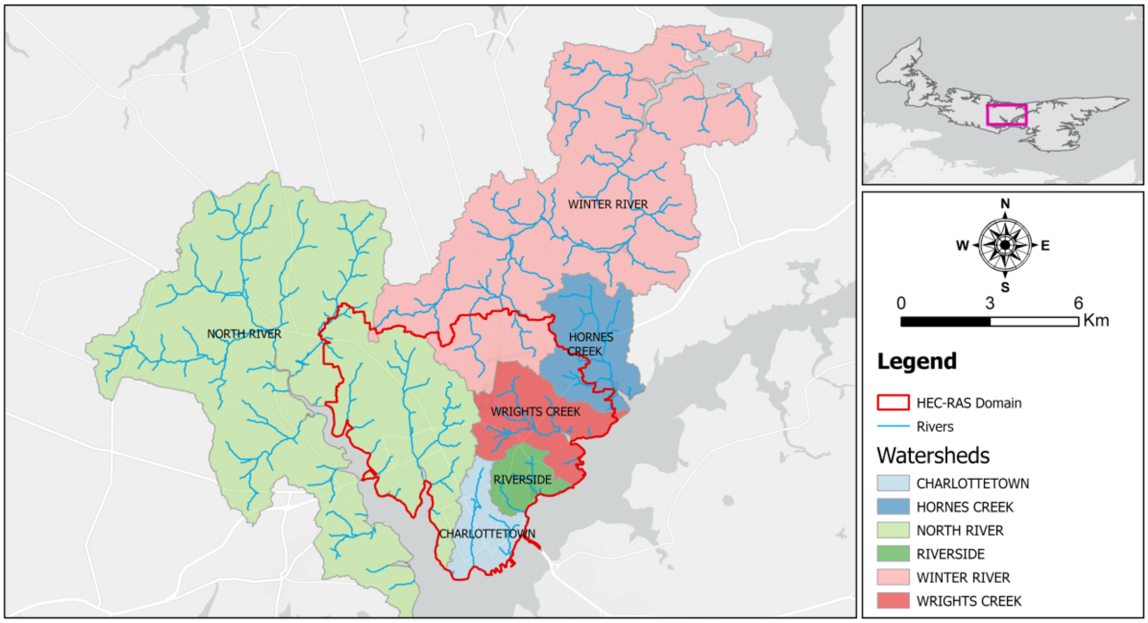


Figure 10. Watershed delineation for City of Charlottetown.

(2) Island-Wide Model

The county boundaries are not aligned with the natural watersheds. To ensure the HEC-RAS model includes all areas that contribute runoff, model domain was configured using the boundaries of provincial watersheds instead of county administrative limits (shown in Figure 11). This approach allows the model to accurately account for water flows from all contributing areas, without being limited to the administrative county areas.

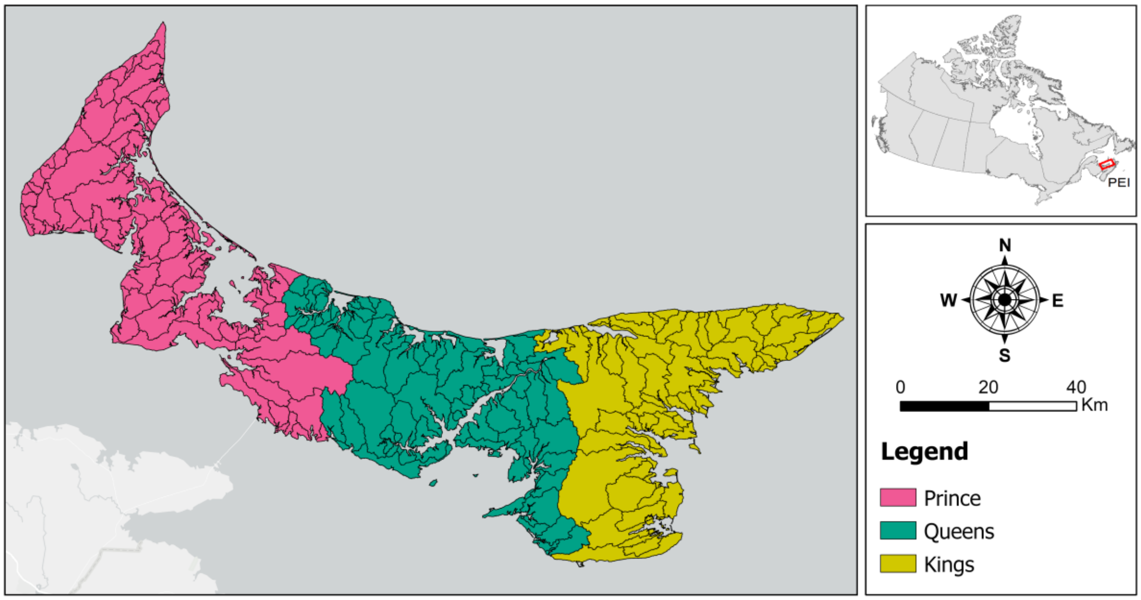


Figure 11. Watershed delineation for three counties in PEI.

4.1.2 Watershed Characteristics and Parameters

The province of PEI is situated within the Gulf of St. Lawrence along the eastern coast of Canada between latitudes 45°57′ and 47°04′ N and longitudes 61°55′ and 64°25′ W, stands as the smallest and most densely populated province in Canada. The province has an area of 5,620 km^2 and has a population of more than 154,000 as of 2021[17]. The highest point in the province is found on the southern coast and stands at 142 m above sea level. It is featured with characteristic red soil, red sand beaches, coastal sand dunes, and vast agricultural areas. As shown in Figure 11, watersheds in PEI vary erratically, with the smallest size being 0.023 km^2 (e.g., Cherry Island) and the biggest being 196.44 km^2 (e.g., Montague-Valleyfield). The LULC types in PEI are dominated by cropland and mixed forest, covering 45% and 39% of the total land area, respectively[18]. Wetlands, mainly salt marshes and bogs, account for about 2% of the total land area[19].

The climate in PEI is cool and humid during the winters (November – April), with temperatures ranging from -3 to -11°C, and moderately warm during the summers (June – August), with temperatures ranging from 20 to 34°C[20]. The annual average precipitation is estimated at about

1,100 mm, where 80% is attributed to rainfall and the remaining 20% to snowfall[21]. During the winter, the evapotranspiration rate accounts for 40% (440 mm) of PEI's annual precipitation, while the remaining 60% (660 mm) is distributed to streamflow, with 300 mm becoming surface runoff and 360 mm becoming groundwater. PEI streams are small, shallow, and short, with lengths of less than 16 km; therefore, the flows cannot accelerate rapidly but rather meander and spread out.

4.1.3 Design Rainfall Events

In this project, four design rainfall storms under two climate conditions are considered to generate eight scenarios for pluvial flood modeling. These eight scenarios are listed in Table 4.

Table 4. List of the eight scenarios for design rainfall events.

No.	Climate Condition	IDF Return Period
1	Current Climate	10-yr
2	Current Climate	25-yr
3	Current Climate	50-yr
4	Current Climate	100-yr
5	Future Climate (SSP5-8.5, 2071-2100)	10-yr
6	Future Climate (SSP5-8.5, 2071-2100)	25-yr
7	Future Climate (SSP5-8.5, 2071-2100)	50-yr
8	Future Climate (SSP5-8.5, 2071-2100)	100-yr

(1) IDF Curves

The IDF curves from the ECCC are used as inputs to generate the hyetographs for the design rainfall events with four commonly-used return periods including 10-yr, 25-yr, 50-yr, and 100-yr. Specifically, the Chicago method is used to generate the 24-hr hyetographs from the selected IDF curves in order to provide time series rainfall inputs for HEC-RAS model. The ECCC has IDF curves for seven stations in PEI and the details of these stations are described in Table 5.

Table 5. List of weather stations in PEI with IDF curves from the ECCC.

No.	Station Name	Station Code	Data Period
1	Charlottetown	8300301	1967 - 2016
2	Summerside	8300596	1964 - 2021
3	Harrington	830P001	2000 - 2021
4	Saint Peters	8300562	2004 - 2021
5	Maple Plains	8305500	2002 - 2018
6	East Point	8300418	2004 - 2021
7	North Cape	8300516	2004 - 2016

While analyzing the IDF curves, it is observed that the rainfall patterns at the North Cape and East Point stations demonstrated a significant lack of homogeneity when compared with other adjacent stations. This discrepancy primarily occurs due to the utilization of limited range data in the development of the IDF curves for these stations. The IDF constant values are also missing for these stations and the peak rainfall is very low based on nearest stations constant values. Therefore, to maintain the integrity and accuracy of the HEC-RAS model, it has been concluded that these two stations should be excluded. Thus, the five remaining stations are selected for inclusion in the island-wide pluvial flood modeling with the HEC-RAS model. This is to ensure that the pluvial flood modeling is based on more consistent and reliable rainfall data, enhancing the quality of the flood risk mapping results. The detailed IDF curves for these five selected stations under both current climate and future climate conditions are provided in Annex A.

(2) Chicago Design Storms

The Chicago method is one of the widely-used methods for generating design storm events. The synthetic hyetograph computed by the Chicago method is typically derived based on the intensity-duration-frequency (IDF) relationship for the rainfall in a particular area. The revised version of the original Kiefer and Chu[22] equation for the Chicago storm is used for this project:

$$i_{avg} = \frac{a}{(t_D + b)^c}$$

Where i_{avg} is the average rainfall intensity (mm/hr), t_D is the duration of rainfall event (min), and a, b, c are the IDF constants dependent on storm recurrence interval and time units. This equation can be used with or without the lag time b. The IDF constants provided by ECCC remove the lag time coefficient (i.e., b = 0). However, the urbanization level in PEI municipalities is very low compared to large cities, it is important to keep the lag time to reflect the delays in surface runoff generation after the rain falls onto the ground. Therefore, the IDF data tables provided by ECCC are used here to estimate the values for the three coefficients in the above equation. An additional parameter required for computation is r, which is the ratio of time to peak over the total storm duration (derived from the analysis of actual rainfall events, generally in the range 0.3-0.5). A value of 0.5 will set the peak rain intensity at the midpoint of the storm duration, a value < 0.5 will result in a hyetograph with the peak rainfall occurring before the midpoint, and a value > 0.5 will result in peak rainfall occurring after the midpoint. A value of 0.5 is used for current analysis to consider the peak rainfall at midpoint of the total storm duration. The Chicago rainfall time series is generated for the five selected weather stations in PEI. The stations in East Point and North Cape do not have proper a, b and c values to generate the Chicago rainfall hyetographs. Additional analyses indicate that the a, b and c values used from nearest stations cannot generate appropriate rainfall intensities. Hence, these two stations are excluded from the pluvial flood modeling in this project. The detailed a, b and c values for different stations and their resulting hyetographs are provided as follows. Note that since the HEC-RAS 2D model cannot represent the stormwater systems in urban areas, here the 2-yr return period storm event is subtracted from other longer return period storm events (i.e., 10-yr, 25-yr, 50-yr, and 100-yr) for those stations in urban areas (i.e., Charlottetown and Summerside only in this project) to approximately reflect the capacity of existing stormwater systems. Although the municipalities in PEI are now using the 10-yr storm to design the stormwater system for new divisions, it is worth noting that the majority of the existing stormwater systems in Charlottetown and Summerside have been in place many years ago with much smaller capacities. Therefore, the 2-yr return period storm is considered here to represent the overall capacity of urban stormwater systems in PEI.

(a) Chicago Design Storms for Current Climate

The a, b, and c constant values used to generate Chicago design storms for the various IDF return periods of those five selected stations in PEI under current climate conditions are presented in Table 6.

Table 6. IDF constant values for current climate.

Station Name	Return Period	a	b	c
Charlottetown	2-yr	257.074	5.794	0.622
	5-yr	320.039	3.751	0.613
	10-yr	361.930	2.985	0.609
	25-yr	418.641	2.437	0.607
	50-yr	459.362	2.034	0.605

	100-yr	502.539	1.822	0.605
Summerside	2-yr	384.776	7.211	0.714
	5-yr	537.948	5.546	0.723
	10-yr	634.889	4.994	0.725
	25-yr	770.131	4.668	0.73
	50-yr	872.703	4.441	0.734
	100-yr	972.494	4.418	0.735
Harrington	2-yr	347.985	5.768	0.672
	5-yr	619.689	7.861	0.718
	10-yr	818.287	8.722	0.738
	25-yr	1070.517	9.524	0.754
	50-yr	1276.098	10.167	0.764
	100-yr	1478.459	10.560	0.772
Maple Plains	2-yr	250.726	6.061	0.621
	5-yr	388.770	9.437	0.650
	10-yr	491.904	11.437	0.665
	25-yr	616.021	12.978	0.676
	50-yr	732.101	14.518	0.687
	100-yr	828.125	15.317	0.693
Saint Peters	2-yr	290.163	2.463	0.635
	5-yr	362.238	1.458	0.632
	10-yr	409.215	1.024	0.630
	25-yr	470.611	0.709	0.628
	50-yr	515.209	0.475	0.627
	100-yr	559.571	0.338	0.627

As mentioned above, to accommodate the existing stormwater and flood mitigation infrastructure in Charlottetown and Summerside, the 2-yr return period hyetograph is subtracted from the storm events to be considered in this project (i.e., 10-yr, 25-yr, 50-yr, and 100-yr). The resulting hyetographs for the five selected stations under current climate condition are provided in Annex A.

(b) Chicago Design Storms for Future Climate (SSP5-8.5, 2071-2100)

The a, b, and c constant values used to generate Chicago design storms for the various IDF return periods of those five selected stations in PEI under future climate conditions (SSP5-8.5, 2071-2100) are presented in Table 7.

Table 7. IDF constant values for future climate (SSP5-8.5, 2071-2100).

Station Name	Return Period	a	b	c
Charlottetown	2-yr	456.597	6.175	0.625
	5-yr	571.643	4.056	0.617
	10-yr	622.115	2.807	0.607
	25-yr	732.820	2.469	0.607
	50-yr	781.690	1.844	0.601
	100-yr	874.535	1.776	0.606
Summerside	2-yr	675.841	7.038	0.718
	5-yr	955.392	5.671	0.726
	10-yr	1103.560	4.833	0.725
	25-yr	1356.470	4.790	0.730
	50-yr	1510.021	4.430	0.730
	100-yr	1722.509	4.457	0.737
Harrington	2-yr	598.571	5.613	0.670
	5-yr	1072.805	7.886	0.716
	10-yr	1438.601	8.984	0.738
	25-yr	1864.655	9.624	0.752
	50-yr	2195.046	9.923	0.763
	100-yr	2561.104	10.438	0.772
Maple Plains	2-yr	456.597	6.175	0.625
	5-yr	571.643	4.056	0.617
	10-yr	622.115	2.807	0.607
	25-yr	732.820	2.469	0.607

	50-yr	781.690	1.844	0.601
	100-yr	874.535	1.776	0.606
Saint Peters	2-yr	507.185	2.562	0.638
	5-yr	632.470	1.513	0.636
	10-yr	715.244	1.148	0.631
	25-yr	822.351	0.801	0.630
	50-yr	881.577	0.468	0.624
	100-yr	976.868	0.426	0.628

Similarly, to accommodate the existing stormwater and flood mitigation infrastructure in urban areas (i.e., Charlottetown and Summerside in this project), the 2-yr return period hyetograph is subtracted from the storm events to be considered in this project (i.e., 10-yr, 25-yr, 50-yr, and 100-yr). The resulting hyetographs for the five selected stations under future climate condition are provided in Annex A.

4.2 Hydraulic Analysis

4.2.1 Mesh Development

Considering that the project will produce two levels of pluvial flood maps for PEI: 1) detailed flood maps for major municipalities, and 2) island-wide flood map for PEI, the project team uses different resolutions for the municipal model and the island-wide model. The project team also utilizes the mesh refinement function of HEC-RAS 2D to increase the spatial resolution at key infrastructure (e.g., roads, rivers, streams, and coastlines).

(1) Municipal Model

The models for 6 municipalities (i.e., Charlottetown, Summerside, Stratford, Cornwall, Three Rivers, and Tignish) and 2 Indigenous communities (i.e., Lennox Island First Nation and Abegweit First Nation) have an overall resolution of 10 m with a refined 2 m resolution along with the key infrastructure. The steps used for HEC-RAS domain setup and mesh refinement are described as follows:

Step 1. The HEC-RAS model domain is determined by merging all sub-watersheds within the administrative boundary of the selected municipality, as well as all sub-watersheds with water flowing into the administrative boundary of the municipality. For some inland sub-watersheds with water flowing out of the administrative boundary, model outlets are set up in HEC-RAS to allow water to flow out. The shoreline boundary of each municipality (if applicable) is represented as ocean boundary in HEC-RAS where the water can flow in or flow out depending on the ocean water level, the land elevation, and the overland water depth.

Step 2. Once the HEC-RAS model domain is determined, 10 m x 10 m grid cells are generated for the entire domain.

Step 3. The existing hydro network and road network are used to automatically generate breaklines in HEC-RAS in order to generate 2 m x 2 m refined meshes along with these breaklines. Since the hydro network also covers the shoreline boundary, this automatically includes the mesh refinements along with the ocean boundary. In addition, the density of road network reflects the population density and urban development, the refinements along with road network thus can automatically cover the mesh refinements for some populated areas. Figure 12 shows an example about the final mesh layout for one area in the City of Charlottetown.

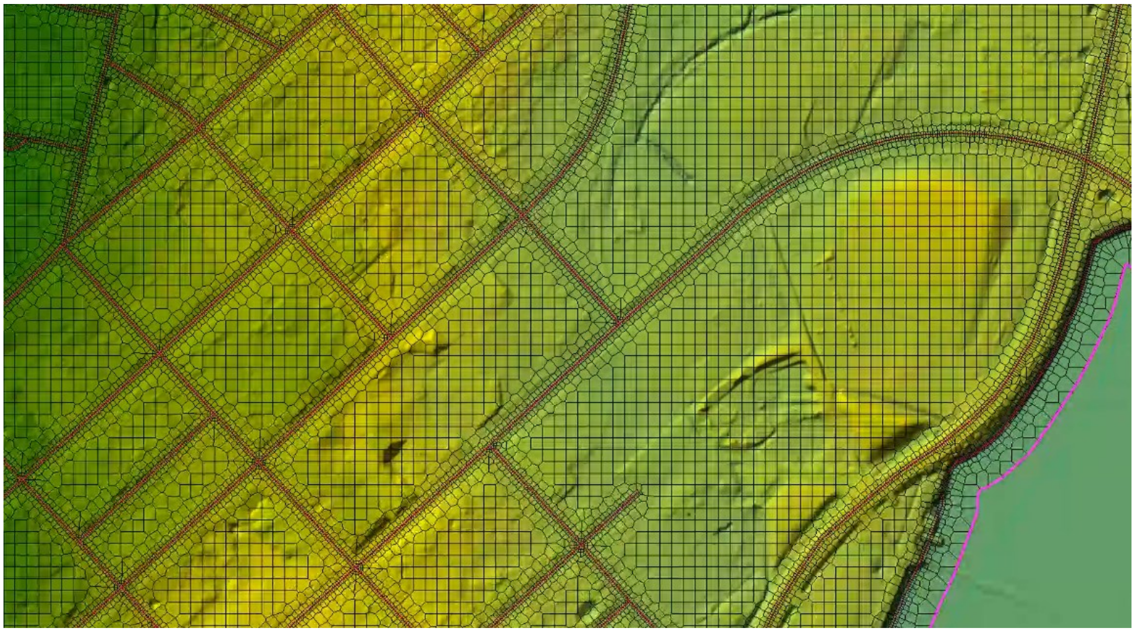


Figure 12. An example of mesh layout for one area in the City of Charlottetown.

(2) Island-Wide Model

In order to generate island-wide pluvial flood map, the entire island of PEI is divided into 3 regions by merging the related watersheds with reference to the administrative boundaries of three counties (i.e., Prince, Queens, and Kings), then the project team runs the HEC-RAS model for these three regions separately. The results for these three regions are finally merged together to generate island-wide flood maps. As for the mesh generation and refinement in HEC-RAS for each county, the project team first generates 100 m x 100 m grid cells for the model domain, and then apply 20 m x 20 m refinements along with hydro network (including ocean boundary) and road network.

The mesh resolutions and refinements for the municipal model and island-wide model are summarized in Table 8.

Table 8. Summary of mesh resolutions and refinements.

Model	Mesh Resolution	Mesh Refinement
Municipal model	10 m	2 m
Island-wide model	100 m	20 m

4.2.2 Hydraulic Structures

The project team uses two different approaches to represent hydraulic structures for municipal model and island-wide model. The primary hydraulic structures in PEI are bridges and culverts. For municipal models, individual structures with detailed dimensional information are explicitly reflected in the HEC-RAS 2D model. In comparison, culverts and bridges are breached for island-wide models. The detailed steps for hydraulic structure reflection in both municipal and island-wide models are described below.

(1) Municipal Model

Step 1. Generate all intersection points between the hydro network and the road network, denote all points as set A;

Step 2. Load all culvert/bridge points provided by the PEI Department of Transportation and Infrastructure, all points here are denoted as set B;

Step 3. All points in the two sets of A and B are considered to reflect the hydraulic structures at the city level. For any overlapping points between A and B, the dimensional information provided by PEI Department of Transportation and Infrastructure is used; for any points within B but not in A, the dimensional information provided by PEI Department of Transportation and Infrastructure is also used; for any points within A but not in B, the project team conducts field visits to measure the culverts. This is to ensure all the points in both A and B are properly represented in the HEC-RAS 2D model. Figures 13 and 14 show the locations of all hydraulic structures considered for two major cities (i.e., Charlottetown and Summerside).

Step 4. Bridges are represented as culverts in HEC-RAS due to the lack of information (e.g., height and piers). Since major bridges are already hydroconnected in the existing HRDEM data, there is no need to represent these bridges in HEC-RAS as the water flow at these bridges will not be affected in the model.

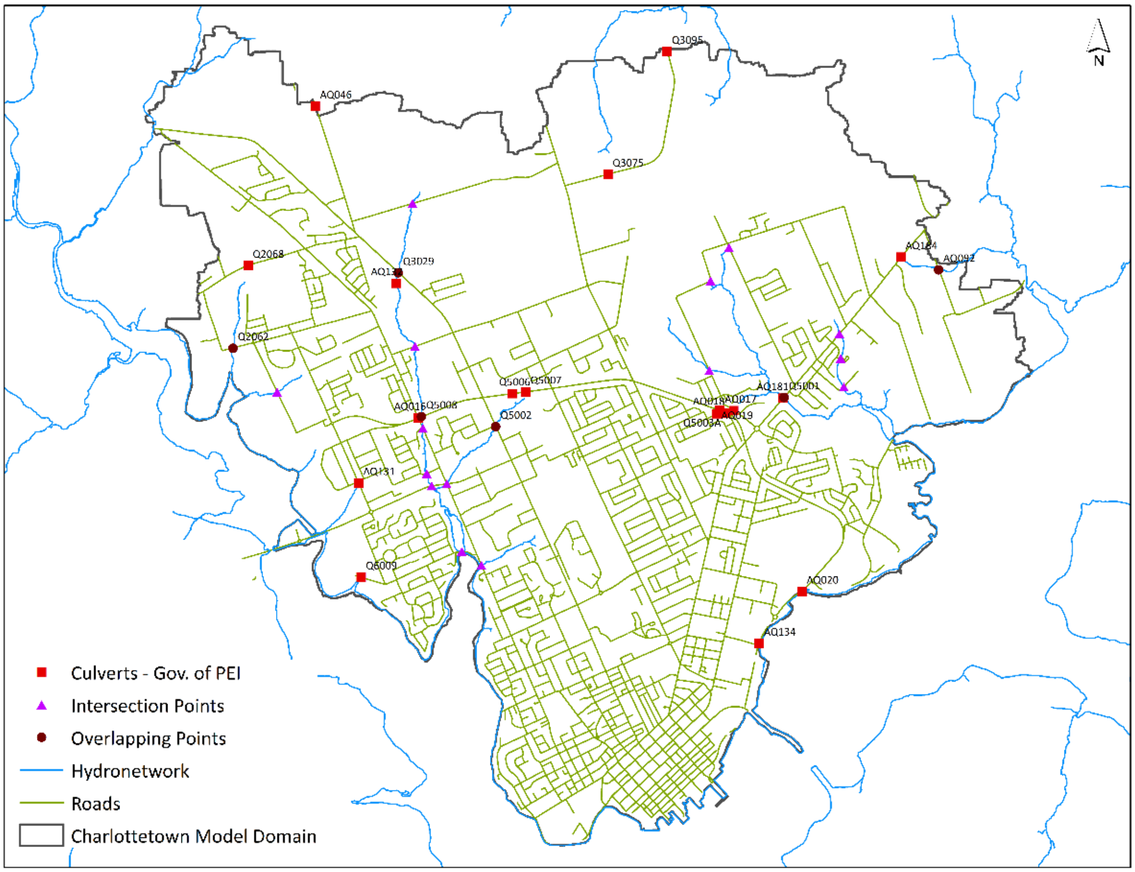


Figure 13. The location of the culverts represented in the municipal model for Charlottetown.

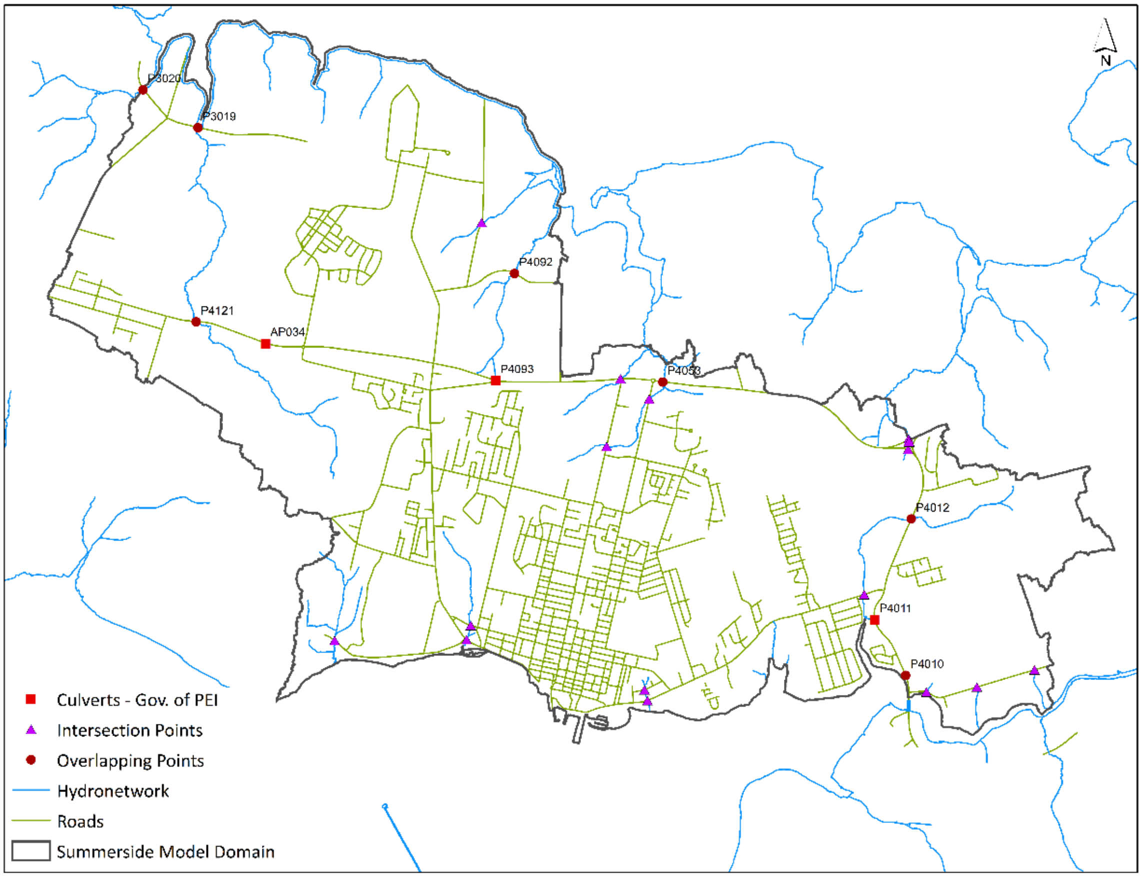


Figure 14. The location of the culverts represented in the municipal model for Summerside.

After all culverts are set up in the HEC-RAS model, the project team has conducted some test runs to ensure that these culverts are working properly by checking that if the water is flowing through a specific culvert at a reasonable rate. Figure 15 shows an example of 4 culverts in the City of Charlottetown and the testing results showing water passing through the culverts.

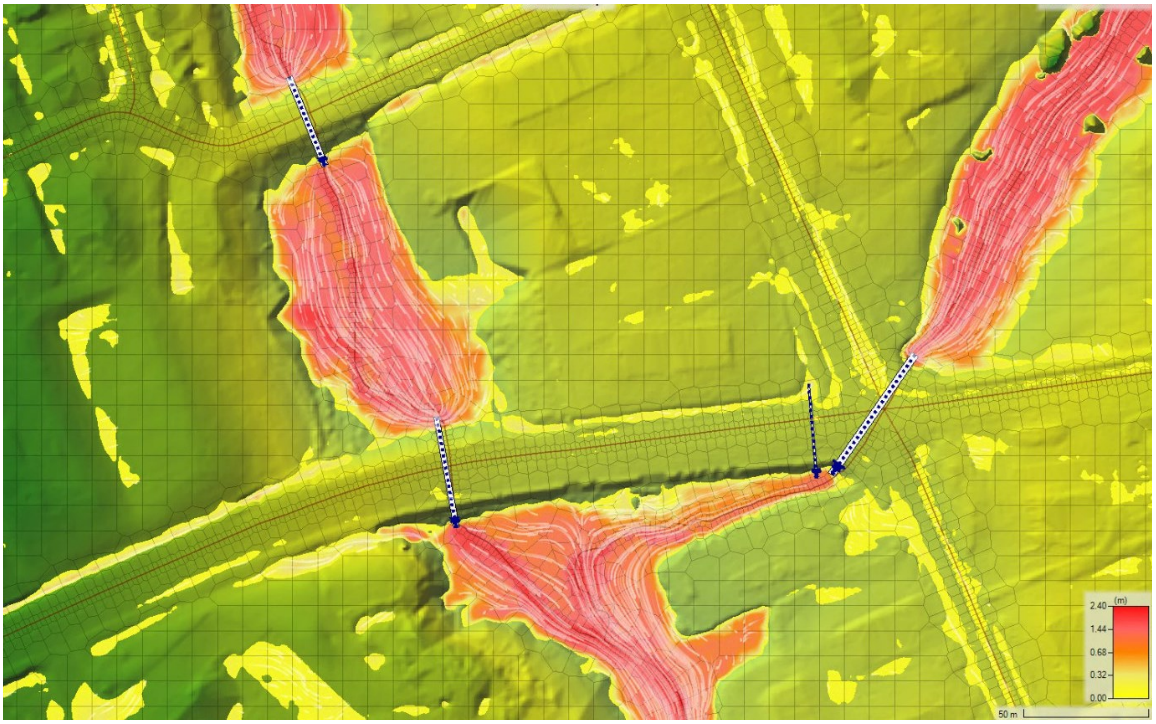
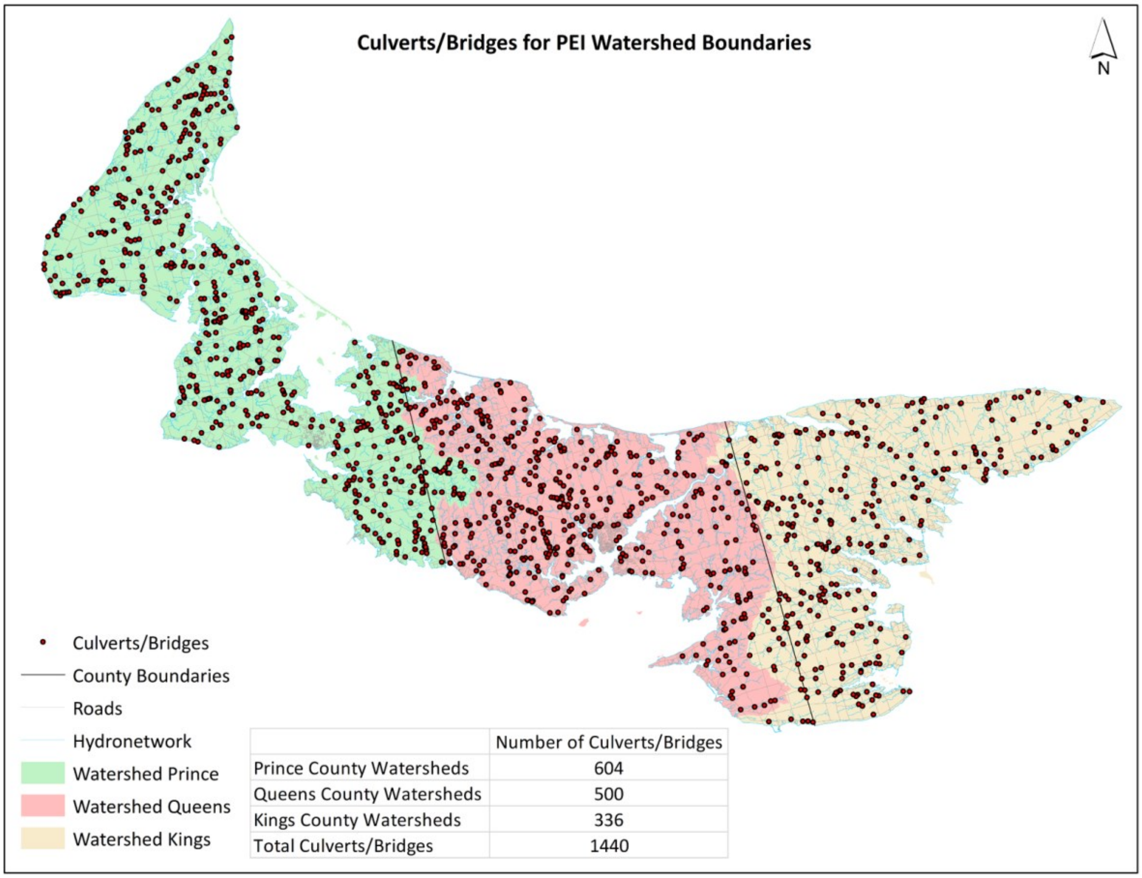


Figure 15. An example of 4 culverts in the City of Charlottetown and the testing results showing water passing through the culverts.

(2) Island-Wide Model

Since there is a large number of culverts/bridges (1,440 in total) in PEI according to the data provided by the PEI Department of Transportation and Infrastructure (see Figure 16), it is not realistic to represent all these hydraulic structures in HEC-RAS. First of all, since some major bridges are already breached (or hydroconnected) in the existing HRDEM data, there is no need to reflect these bridges in the HEC-RAS model. For the remaining bridges and all culverts, the project team introduces an automatic approach to breaching them in the existing HRDEM in order to connect the rivers and streams at road crossings. Based on field visits, the project team notices that the provincial database does not provide a full coverage of all culverts (particularly those with deck length < 1.2m). These small structures should also be reflected during the DEM breaching process.



	Number of Culverts/Bridges
Prince County Watersheds	604
Queens County Watersheds	500
Kings County Watersheds	336
Total Culverts/Bridges	1440

Figure 16. The location of all culverts and bridges across PEI.

The steps for the DEM breaching (or hydro-connection) process for island-wide models are described as follows. ArcGIS Pro is used to implement the DEM breaching process.

Step 1. Exclude those already hydroconnected bridges from the provincial database, denote this as set A;

Step 2. Generate intersection points between the hydro network and the road network, then remove those points which are already reflected in the provincial database, denote the remaining points as set B;

Step 3. For any points in set A, their deck length information is already available from the provincial database. The available deck length is used to determine the width of DEM breaching. As for the length of DEM breaching, a 75m buffer circle is generated along with the point (note that this 75m threshold is selected through many testing experiments). This buffer circle is then used to cut the hydro network in order to get a line segment with a length of 75m. The deck length for the hydraulic structure is used to generate a buffered area of this line segment (for example, if the deck length is 10m, then the buffer radius is 5m). As for the depth of DEM breaching, the project team uses the lowest elevation within this buffered area. Note that the provincial hydro network is not detailed enough in some areas (i.e., not extended into small streams where hydraulic structures may still exist), in this case the project team reproduces a detailed hydro network across PEI in order to minimize the likelihood of overlooking these hydraulic structures.

Step 4. For any points in set B, their deck length information is not readily available. Since the provincial database only includes hydraulic structures with a deck length >= 1.2m, here the project team applies a deck length of 1.2m for all points in set B in order to determine the width of DEM breaching. Although some culverts may have a smaller deck length than 1.2m, it still makes sense to use 1.2m. This is because the resolution of HRDEM is 1m, and any DEM breaching slimmer than 1m cannot be properly reflected. As for the length and depth of DEM breaching, the project team applies the same process described in Step 3.

Table 9 shows the total number of points (i.e., 2,895) for which the project team has applied the abovementioned DEM breaching process in order to generate the island-wide hydroconnected DEM for PEI. This new DEM dataset is then used for island-wide pluvial flood modeling. Note that the total number of points considered here is larger than the total number of culverts/bridges from the provincial dataset. This is because those intersection points between hydro network and road network listed in Table 9 are not included in the provincial dataset.

Table 9. Total number of points considered for DEM breaching.

Type of Structures	Number of Points
Culverts	1,183
Bridges	98
Intersection of hydro network and road network	1,614
Total	2,895

After applying the abovementioned automatic DEM breaching process, the project team has conducted some random visual checks to ensure that the hydraulic structures are properly breached. Figure 17 shows an example showing the difference before and after the automatic DEM breaching.

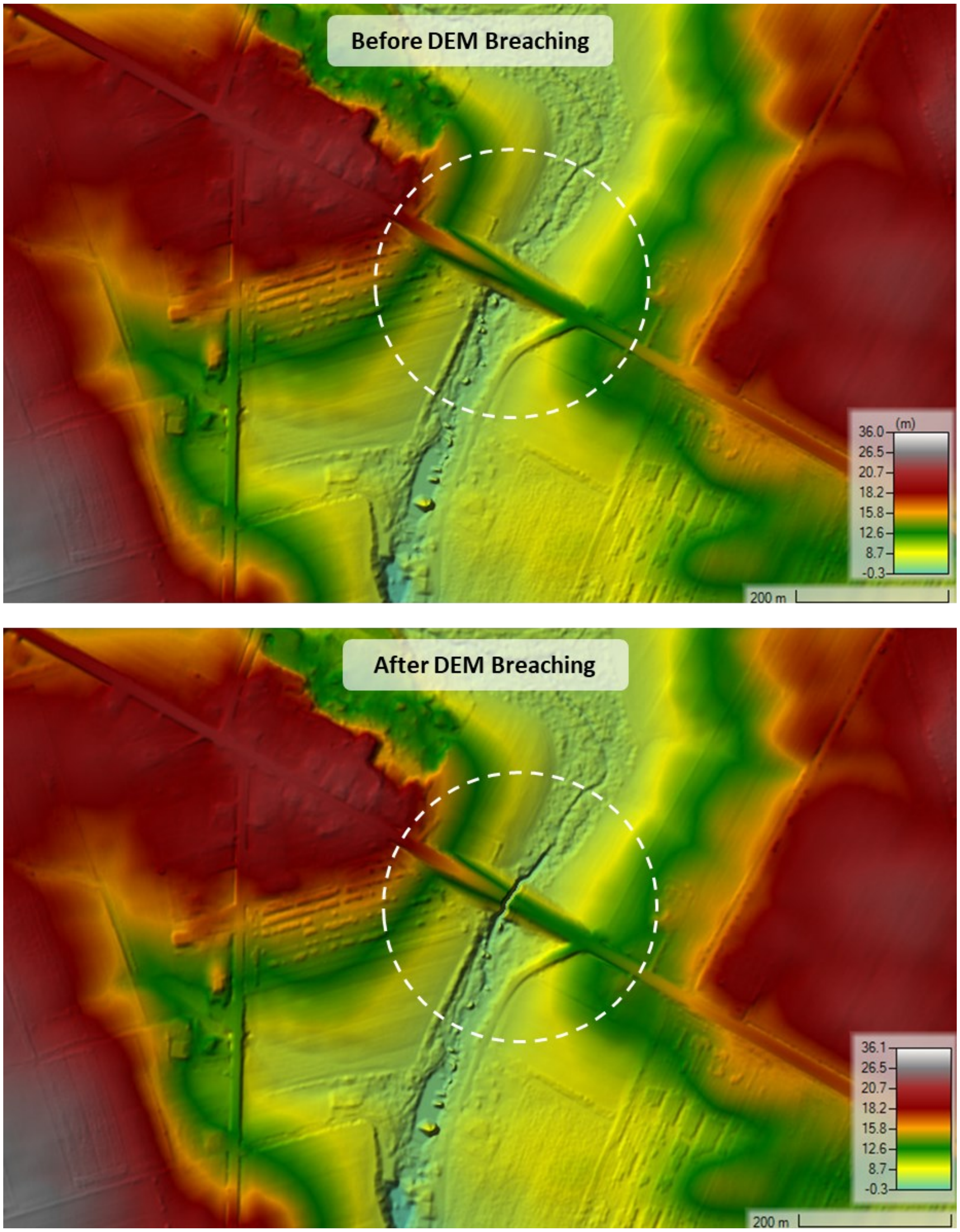


Figure 17. An example showing the difference before and after the automatic DEM breaching.

4.2.3 Coastal Boundary Conditions

The Government of PEI has conducted a previous study about coastal flooding in PEI[1,2] and the resulting coastal flood elevation are used here to provide ocean boundary conditions for the HEC-RAS flood simulations in this project. In particular, the 1.6-yr return period flood elevation under the 2020 High Flood Hazard scenario is used to drive the pluvial flood modeling under the current climate condition, while the 1.6-yr return period flood elevation under the 2100 Moderate-Low Flood Hazard scenario is used to drive the pluvial flood modeling under the future climate condition. Here it is worth noting that the islanders have seen the increasing risks of compound floods (i.e., coastal and pluvial floods) in PEI in recent years, especially during some extreme storm events (e.g., the post-tropical storm Fiona in 2022). This may suggest that the return periods of ocean boundary conditions should be adjusted properly to match the return periods of rainfall IDF curves. However, due to the lack of research in the compound flood risks in PEI, it is challenging to determine the appropriate return periods for coastal boundary conditions. After considerable discussions with the project technical advisory committee, the 1.6-yr return period ocean boundary conditions are tentatively selected for this project, with a caveat that this may not be capable of reflecting the increasing compound flooding risks in the context of climate change.

4.2.4 Downstream Boundary Conditions

On occasions when there is an open-end reach on the edge of the model domain towards the downstream that is not connected to the ocean, an outlet will be created with the Normal Depth method in HEC-RAS in order to allow the water to drain out of the model domain. This approach employs Manning's equation to determine the stage for each downstream reach. This requires a friction slope, which is called the energy grade line. The water surface slope is frequently an acceptable estimate of the friction slope, although it is challenging to establish ahead of time. The average bed slope at the boundary condition location is often used to determine the friction slope. The Normal Depth is typically useful when detailed stream downstream stage information is unavailable, which is the case in this study. The information about the Normal Depth boundary conditions for all HEC-RAS model runs in this project is presented in Table 12.

4.3 Simulation Setup

4.3.1 Model Parameters

Infiltration rates (measured in depth per unit of time, units: mm/hr) are used in the HEC-RAS model to quantify the amount of water infiltrating the soil surface. Infiltration rates are estimated in accordance with soil groups. Table 10 presents the minimum infiltration rates that are used in this project.

Table 10. Infiltration rates for different Hydrologic Soil Groups.

HSG	Minimum Infiltration Rate (units: mm/hr)
Group A	7.6
Group B	3.8
Group C	1.3
Group D	0.1

The Soil Conservation Services (SCS) Curve Number (CN) method is an empirical surface runoff method developed by the US Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) in 1985. Here the SCS CN is selected to estimate direct runoff resulting from rainfall. It estimates precipitation excess as a function of the cumulative precipitation, soil cover, land use, and antecedent soil moisture. The CN values typically range from approximately 30 (for permeable soils with high infiltration rates) to 100 (for water bodies, impervious surfaces, and soils with near-zero infiltration rates). As the antecedent moisture conditions (AMC) become wetter, the CN values increase, indicating reduced infiltration capacity and higher runoff potential. Detailed information on the CN is available in the USDA's Technical Release 55 - Urban Hydrology for Small Watersheds[23]. The province of PEI is known for its generally high moisture conditions due to its geographic location, abundant water sources and maritime climate, therefore, the AMC III, which represents wet soil conditions due to recent rainfall or saturation, is considered in this project. In SCS CN, initial abstraction is estimated as a function of the potential maximum retention, while maximum soil retention is computed from the runoff CN in inches. Table 3 summarizes the CNs and abstraction ratios used in this project. Note that the SCS method might not well correspond to the range of soils in PEI, but it is deemed acceptable for this high level of modeling in this project.

Manning's roughness coefficient represents the cumulative influence of channel roughness, vegetation, bends, and other elements that affect the flow resistance. Manning's roughness coefficients for various types of channels and riverbeds typically range from very low for smooth, man-made channels to higher for natural channels with dense vegetation, sediment deposition, or uneven bedforms. The Manning's roughness coefficients for different NLCD classes in this project are also listed in Table 11.

Table 11. List of CNs, abstraction ratios, and Manning's roughness coefficients used in this project.

NLCD Code	NCLD Class Name & HSG	Curve Number	Abstraction Ratio	Manning Coefficient
11	Open Water: Group B	100	0.00	0.025
	Open Water: Group A	100	0.00	
	Open Water: Group C	100	0.00	
	Open Water: Group D	100	0.00	
12	Perennial Ice-Snow: Group B	98	0.04	0.05
	Perennial Ice-Snow: Group A	98	0.04	
	Perennial Ice-Snow: Group C	98	0.04	
	Perennial Ice-Snow: Group D	98	0.04	
23	Developed, Medium Intensity: Group B	85	0.35	0.12
	Developed, Medium Intensity: Group A	82	0.44	
	Developed, Medium Intensity: Group C	90	0.22	
	Developed, Medium Intensity: Group D	92	0.17	
31	Barren Land (Rock-Sand-Clay): Group B	95	0.11	0.026
	Barren Land (Rock-Sand-Clay): Group A	90	0.21	
	Barren Land (Rock-Sand-Clay): Group C	94	0.12	
	Barren Land (Rock-Sand-Clay): Group D	97	0.06	
43	Mixed Forest: Group B	75	0.66	0.140
	Mixed Forest: Group A	57	1.51	
	Mixed Forest: Group C	86	0.33	
	Mixed Forest: Group D	93	0.16	
52	Shrub/Scrub: Group B	76	0.65	0.115
	Shrub/Scrub: Group A	55	1.61	
	Shrub/Scrub: Group C	82	0.43	
	Shrub/Scrub: Group D	90	0.21	
71	Grassland: Group B	87	0.31	0.025
	Grassland: Group A	71	0.82	
	Grassland: Group C	93	0.16	
	Grassland: Group D	93	0.16	
82	Cultivated Crops: Group B	87	0.31	0.025
	Cultivated Crops: Group A	71	0.82	
	Cultivated Crops: Group C	93	0.16	
	Cultivated Crops: Group D	93	0.16	
90	Woody Wetlands: Group B	98	0.04	0.097
	Woody Wetlands: Group A	98	0.04	
	Woody Wetlands: Group C	98	0.04	
	Woody Wetlands: Group D	98	0.04	

4.3.2 Warm-Up Period

In order to properly estimate the initial conditions for soil moisture and water filling up for rivers, streams, and ponds, a warm-up period needs to be added before the HEC-RAS pluvial modeling for the design rainfall storm. In this project, a 2-yr return period rainfall event is introduced into the warm-up period because it is often regarded as a common rainfall event. As for the position of the 2-yr rainfall event, the project team considers four options: 1) placing the peak of 2-yr rainfall event at 6-hr before the design rainfall storm; 2) 12-hr before; 3) 24-hr before; and 4) 36-hr before. Figure 18 illustrates these four options for the warm-up period.

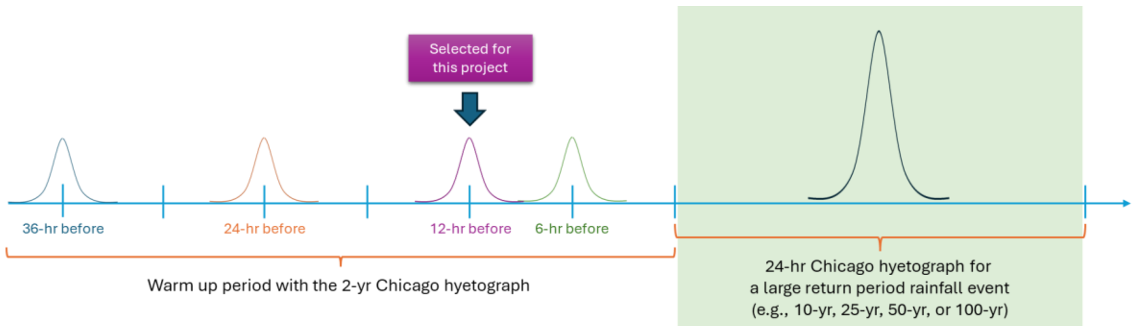


Figure 18. Illustration of the four options used for testing the warm-up period.

In order to test the performance of these four warm-up options, the project team uses the HEC-RAS model to simulate the July 3-4, 2023 heavy rainfall event for PEI. The observed flow rates from three ECCC hydrometric stations (i.e., #01CA003 in Prince County, #01CC010 in Queens County, and #01CD005 in Kings County) during this rainfall event are collected for evaluation purposes. Figure 19 shows the comparison results of four warm-up options and no warm-up in terms of their performance in capturing the observed flow rate at the station in Prince County.

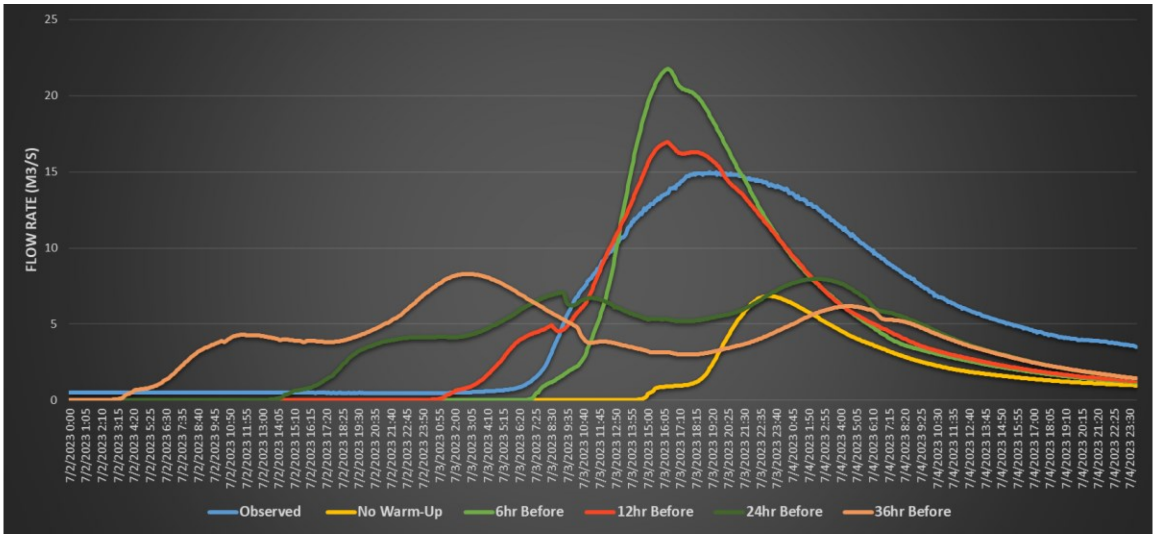


Figure 19. Testing results for warm-up options at the hydrometric station in Prince County.

The above testing results clearly suggest that a warm-up period is important to initiate the model simulation as the flow rates from the no warm-up run are significantly lower than the observed ones. As for the four warm-up options, the results suggest that placing the peak of 2-yr rainfall event at 12-hr before the storm event can produce the best simulation. Considering that the other two hydrometric stations in Queens County and Kings County represent much smaller watersheds compared to the one in Prince County, the testing results for Prince County here are deemed to be representative for other major watersheds in PEI. Therefore, the warm-up option of “12-hr before” is considered in this project for all pluvial flood model runs with HEC-RAS 2D.

4.3.3 Model Configurations

In this project, eight municipal models are set up for the City of Charlottetown, City of Summerside, Town of Stratford, Town of Cornwall, Town of Three Rivers, Town of Tignish, Lennox Island First Nation, and Abegweit First Nation in order to generate detailed pluvial flood maps. The island-wide pluvial flood modeling is implemented by combining the three model runs for Prince County, Queens County, and Kinds County. The detailed configurations for these model runs are provided in Table 12. Note that the approximate run times and the range of the resulting Courant Number for all model runs are also included in this table.

Table 12. Detailed configurations for all HEC-RAS model runs in this project.

Model Configuration	Municipal Model								Island-Wide Model		
	City of Charlottetown	City of Summerside	Town of Stratford	Town of Cornwall	Town of Three Rivers	Town of Tignish	Lennox Island First Nation	Abegweit First Nation	Prince County	Queens County	Kings County
Flow Simulation	Unsteady Flow Analysis										
Computation Interval	5 sec								10 sec		
Hydrograph Output Interval	5 min										
Mapping Output Interval	5 min										
Detailed Output Interval	5 min										
Equation Set	Diffusion Wave Equations										
No. of Ocean Boundaries	1	2	1	1	1	1	1	1	6	5	6
No. of Downstream Outlets	11	2	1	4	6	0	0	0	0	0	0
No. of Grid Cells	1,051,657	774,704	497,359	209,519	746,693	606,136	80,982	86,277	457, 061	404,570	367,876
Mesh Size & Refinement	10 & 2 m	10 & 2 m	10 & 2 m	10 & 2 m	10 & 2 m	10 & 2 m	10 & 2 m	10 & 2 m	100 & 20 m	100 & 20 m	100 & 20 m
Approximate Run Times	50 hr	18 hr	10 hr	3 hr	15 hr	8 hr	30 min	50 min	2 hr	2 hr	2 hr
Courant Number	0.6 - 1.0										

5. Model Calibration & Validation

5.1 Model Calibration

It is important to note that complete model calibration for this study area was not possible due to the lack of calibration data throughout the modeling domain and challenges associated with the domain size. Therefore, in lieu of complete model calibration, a preliminary sensitivity analysis was performed to identify an optimal combination of parameter values for AMC conditions, Manning's coefficient, and infiltration rates that yielded satisfactory results compared to observed events. Adjustments were also made to identify the ideal timing for the warm-up rainfall event (see Section 4.3.2); however, parameters were not further adjusted to account for specific local conditions in the catchments and sub-catchments, as would normally be the case.

To better understand how the model performance will react to different parameter settings and to determine a better combination of model parameter values, the project team conducted a set of sensitivity analyses of the HEC-RAS 2D model performance under seven scenarios. In particular, two options (II and III) for AMC are considered due to the high soil moisture nature in PEI; for Manning's coefficient and minimum infiltration rates, three options (i.e., min, mean, and max) are considered. Table 13 lists the information about seven scenarios included in the sensitivity analyses. It is important to note that this is not a systematic sensitivity analysis which typically considers all the combinations of parameter settings. The parameter settings in Scenario #7 are finally selected for this project because of its better performance in reproducing the observed peak flow for the July 3-4, 2024 heavy rainfall event in Prince County (shown in Figure 20).

Table 13. Information of the seven scenarios included in the sensitivity analyses.

Scenario No.	AMC	Manning's Coefficient	Minimum Infiltration Rate
1	II	min	min
2	II	mean	mean
3	II	max	max
4	III	min	min
5	III	mean	mean
6	III	max	max
7	III	mean	min

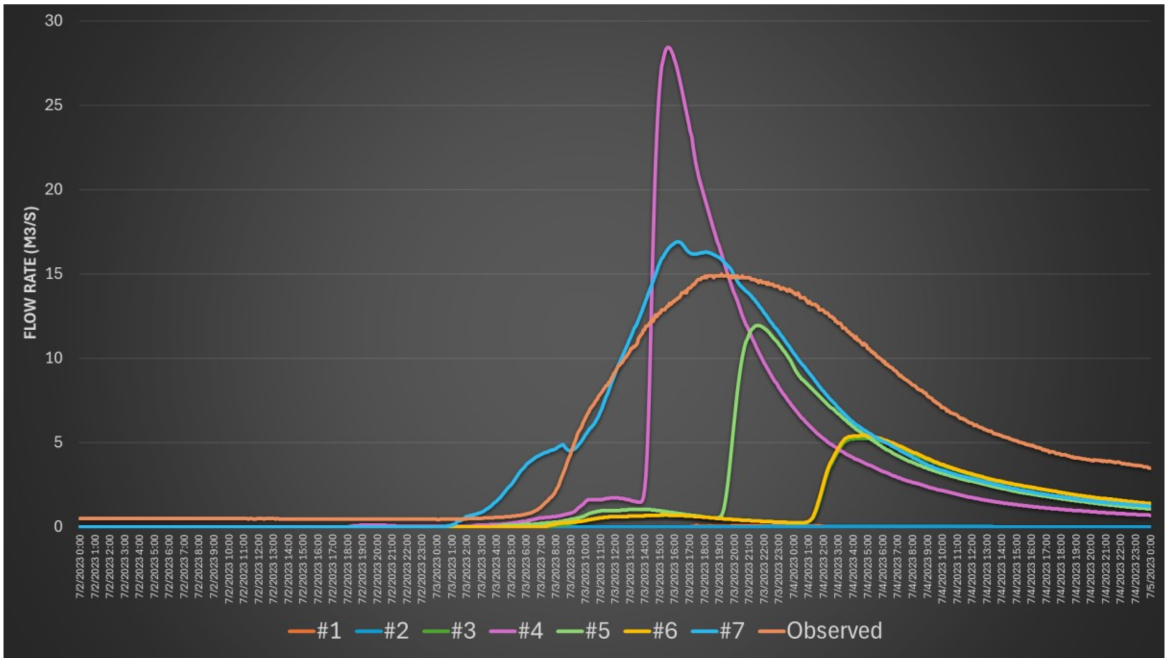


Figure 20. Comparison of the sensitivity analysis results for the July 3-4, 2024 heavy rainfall event in Prince County.

5.2 Model Validation

In light of the aforementioned constraints in hydrometric data, different flood data have been used for validating the flood models in this project. In particular, the flood event data for September 2, 2021 is used to validate the municipal model for the City of Charlottetown, while the flood event data for July 3-4, 2023, is used to validate the island-wide model.

Figure 21 shows the comparison of observed and simulated flood depths at two locations (the parking lot of Holland College and the junction of West Street and Richmond Street) in downtown Charlottetown. There is a good agreement in both flood depth and extent in the parking lot of Holland College between model simulation and observation. However, it seems that the model simulation tends to overestimate the observed flood depth (resulting in overestimation of flood extent too) near the junction of West Street and Richmond Street. After a thorough investigation of the potential causes, the main reason for flood overestimation at this location is because the HRDEM data used in this project was collected in 2020 and there were major developments (e.g., new residential properties and road repairs) in this area after the HRDEM data collection and before the September 2, 2021 rainfall event. Overall, the validation results in the City of Charlottetown demonstrate the good performance of the municipal model setup for HEC-RAS 2D.

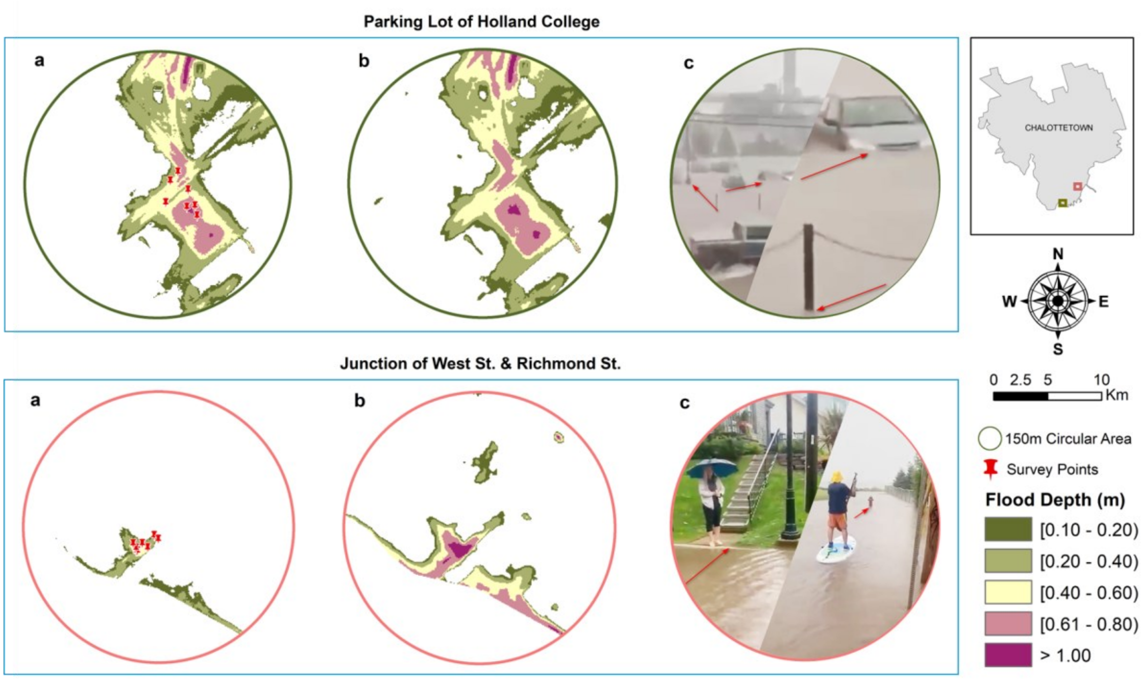


Figure 21. Comparison of observed and simulated flood depths for the September 2, 2021 flood event at two locations in the City of Charlottetown. (a) observed flood depth map based on the field measurements, (b) simulated flood depth map, and (c) screenshots of video footages.

Figures 22-24 present the validation results of flow rates for the July 3-4, 2023 rainfall event at three hydrometric stations for the island-wide model. The results show that the observed flow rates for the station in Prince County are significantly larger than the flow rates of two stations in Queens County and Kings County. This is because that these two stations only represent a small watershed, and their flow rates are very sensitive to the representation of local topography and landscapes. Since the island-wide model runs at a resolution of 20m along with the hydro network, it is not surprising to see that the observed flow rates for small rivers or streams are not accurately captured. However, it is worth noting that the pattern of observed flow rates for these two stations are well simulated by the model. As the station in Prince County receives water from a much larger watershed and is thus more representative of PEI's topography and landscape, the good agreement in simulated and observed flow rates at this station confirms the acceptable performance of the island-wide model setup for HEC-RAS 2D.

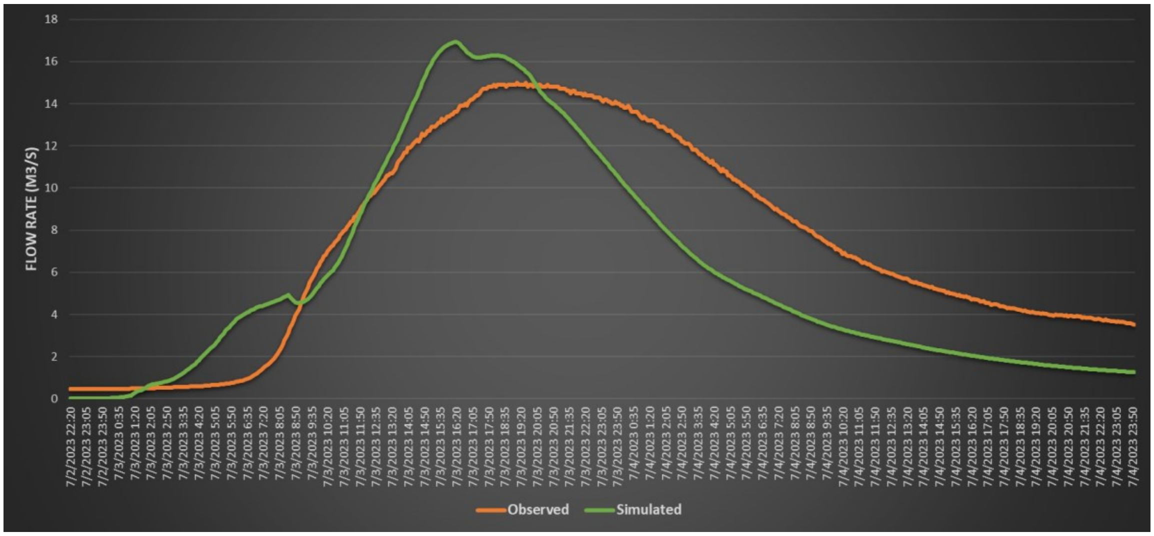


Figure 22. Flow rate comparison for the hydrometric station (#01CA003) in Prince County.

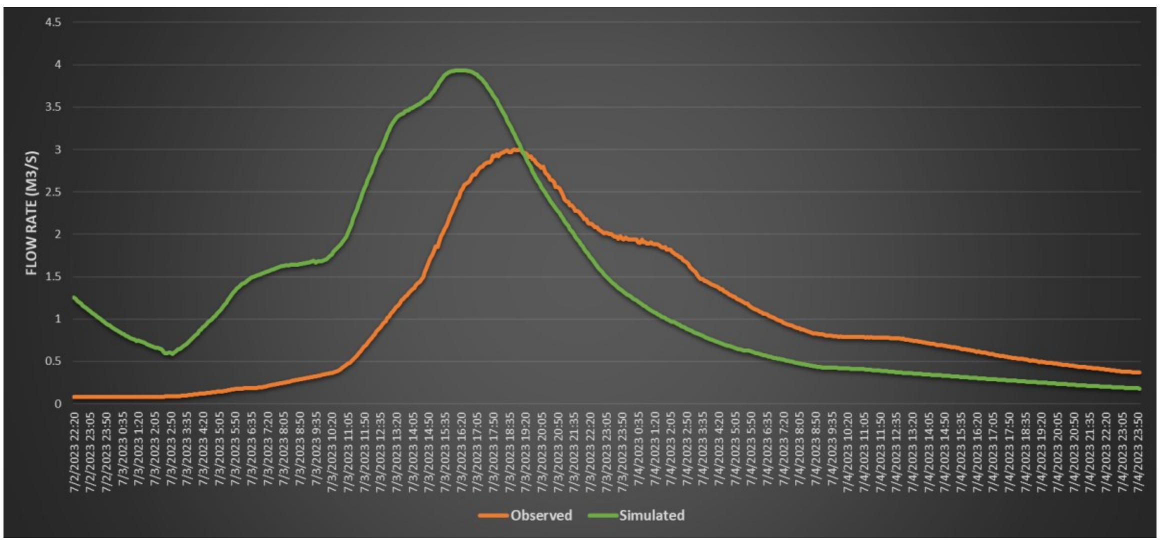


Figure 23. Flow rate comparison for the hydrometric station (#01CC010) in Queens County.

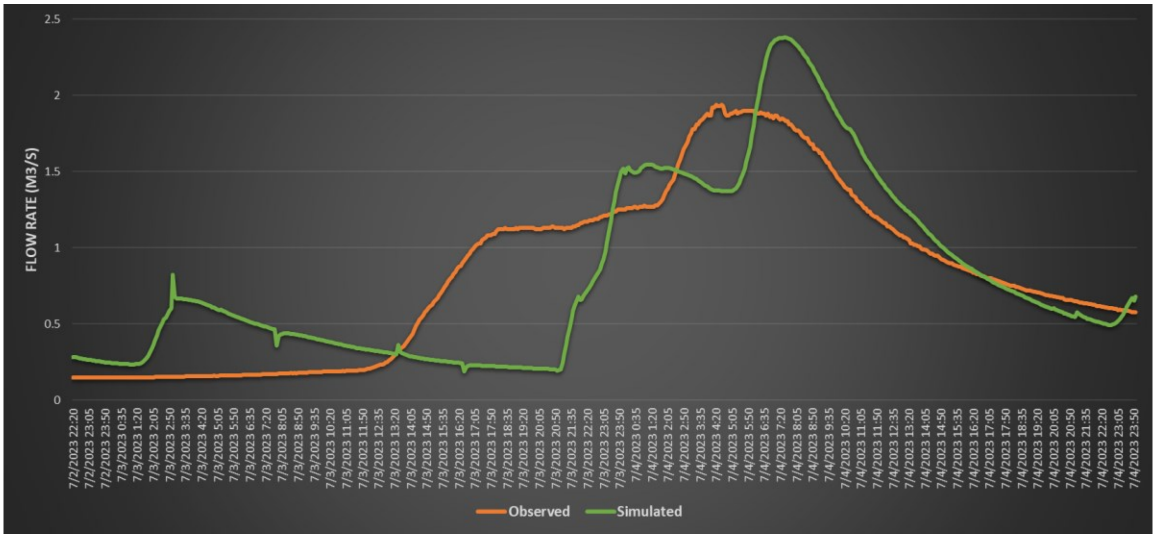


Figure 24. Flow rate comparison for the hydrometric station (#01CD005) in Kings County.

In addition to flow rates, the project team also attempted to collect the water level data at these three hydrometric stations to support further comparisons. However, most of the ECCC hydrometric stations in PEI do not provide necessary information regarding their references to the vertical datum of CGVD2013. In addition, due to the lack of bathymetry data for river floors in PEI, using the lidar-based HRDEM data will inevitably introduce some errors in water level simulation for rivers. Given these reasons, no water level comparison is presented for these three hydrometric stations.

Moreover, additional verification of model parameters was also considered by looking at the infiltration ratio patterns. Four test runs were then performed for two major cities (i.e., Charlottetown and Summerside) driven by the ECCC IDF curves under the current climate with consideration of four return periods: 10-yr, 25-yr, 50-yr, and 100-yr. The infiltration patterns for each test run are summarized by watersheds to help assess the appropriateness of model parameter settings. Figures 25 and 26 show the infiltration ratio (%) maps for the City of Charlottetown and the City of Summerside. The infiltration ratio here is calculated as: (cumulative infiltration depth / cumulative precipitation depth) x 100%. Overall, the maps of infiltration ratios match the spatial patterns of land cover, land use, and soil type very well. In particular, lower infiltration ratios are typically expected for urban areas with large impervious surfaces, while larger infiltration ratios are usually expected for rural areas. The high infiltration ratios in rural areas are well aligned with the fact that the PEI soils are very draining. This indicates the model parameter settings here are reasonable.

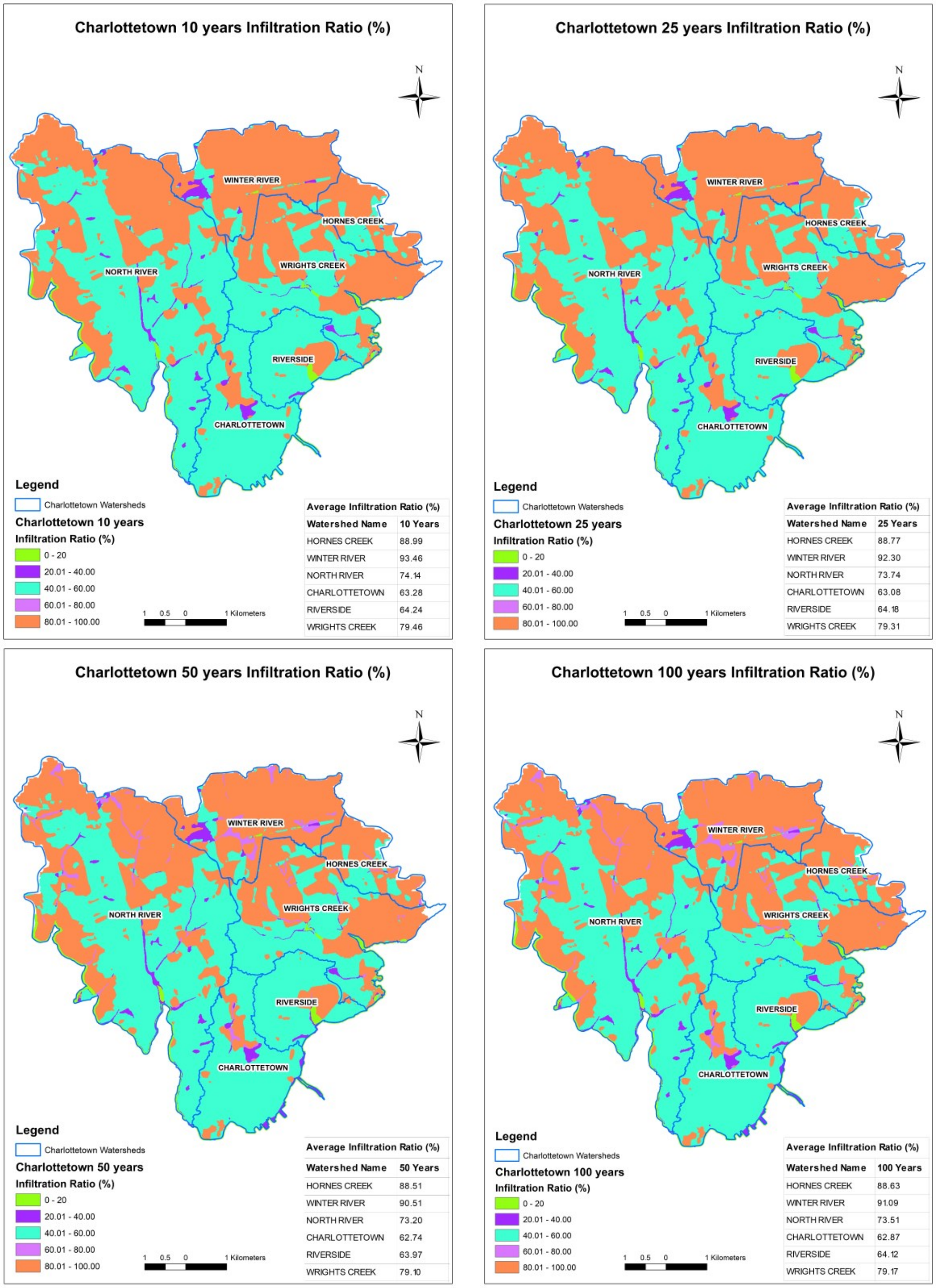


Figure 25. Maps of infiltration ratios for the City of Charlottetown.

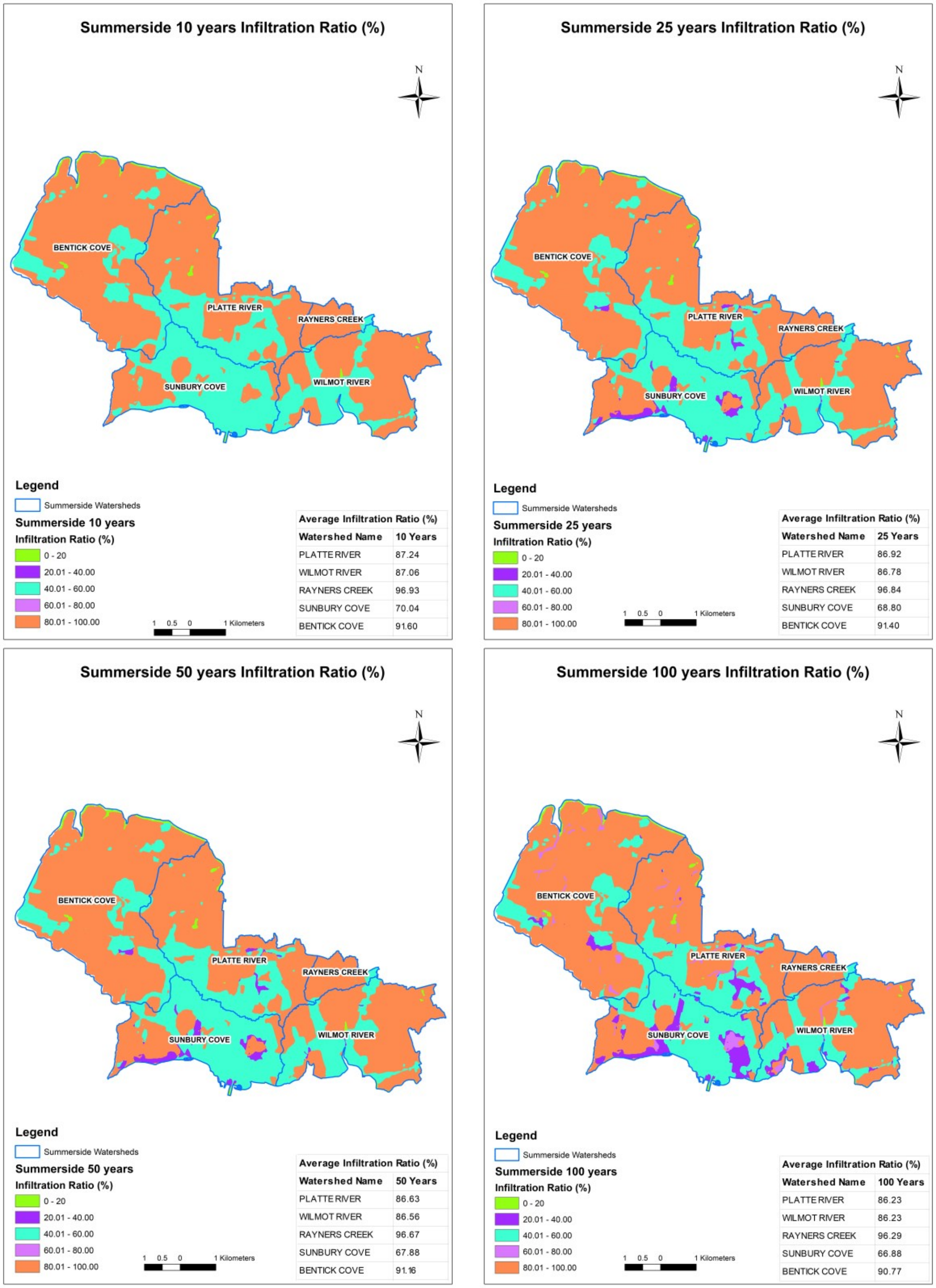


Figure 26. Maps of infiltration ratios for the City of Summerside.

In addition to the validation procedures, a cross-check of the differences between the island-wide model and the municipal model was adopted due to their different approaches of representing hydraulic structures (i.e., culverts and bridges). Due to the limitation of DEM breaching, which completely cuts the land and leads to no limits on the height of the channel (as illustrated in Figure 27), the major difference resulting from the different approaches for the reflection of hydraulic structures is that the island-wide model tends to generate lower flood depths and thus smaller flood extent in the upstream side at the crossing of hydro and road network (where a culvert typically exists). In other words, more water will flow from upstream to downstream in the hydro-connected DEM (used by the island-wide model) in comparison to the explicit representation of culverts in the municipal model. Figure 28 provides an example with a comparison of the 100-yr return period pluvial flood maps along with the highway in Summerside under the same current climate condition between the island-wide model and the municipal model.

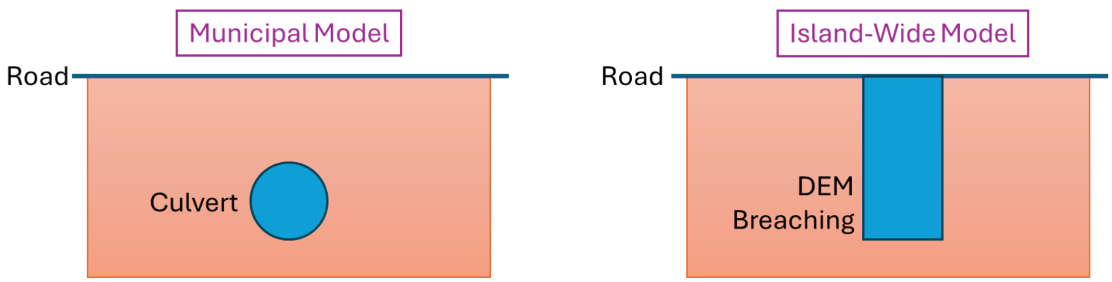


Figure 27. An illustration of the difference in culvert representation between municipal model and island-wide model.

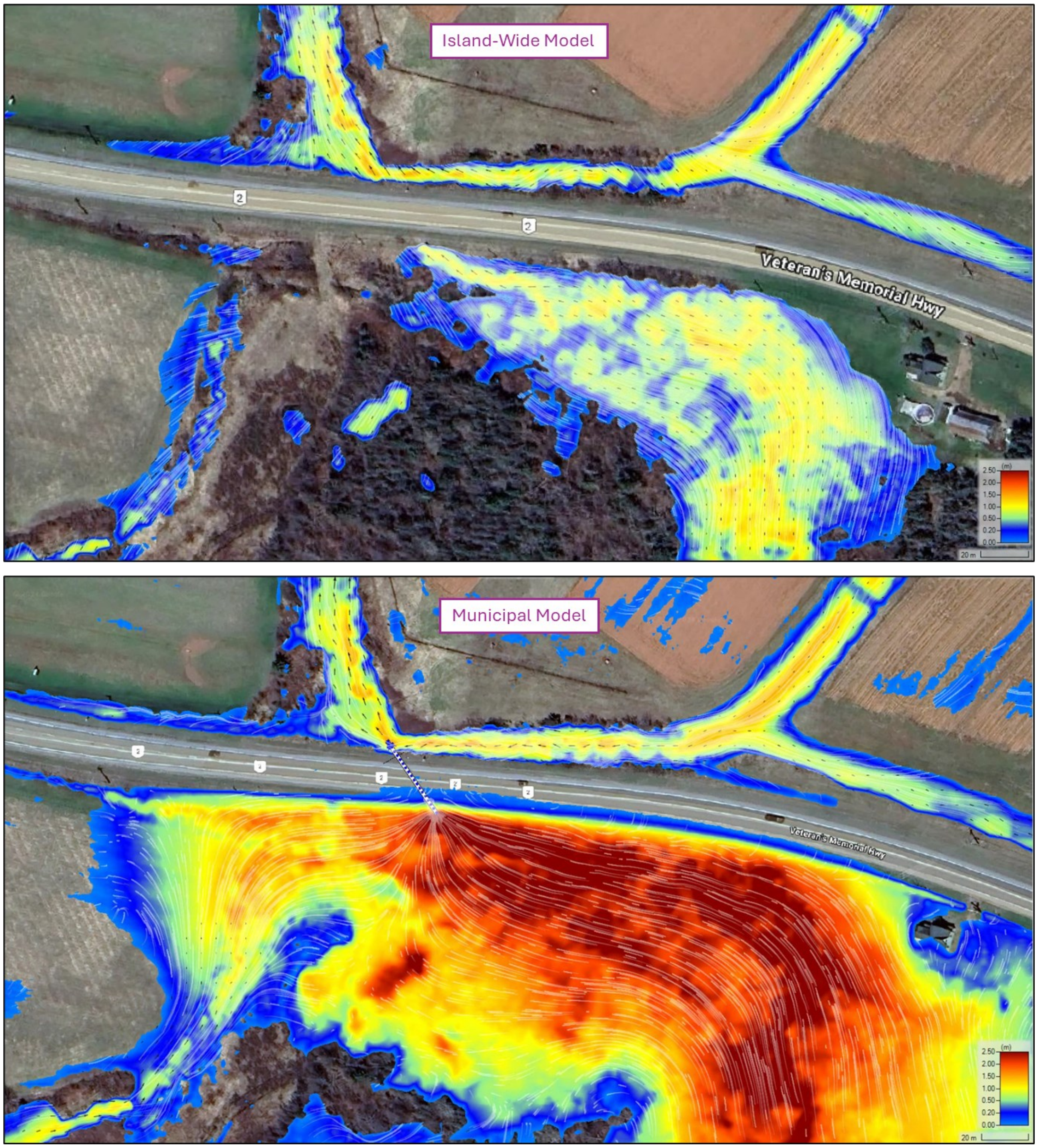


Figure 28. A comparison of the 100-yr return period pluvial flood maps along with the highway in Summerside under the same current climate condition between the island-wide model and the municipal model.

6. Quality Assurance & Control

In order to ensure the quality of the developed pluvial flood maps, the project team has taken a number of quality assurance and control measures throughout the HEC-RAS model runs and the post-processing of output maps. In particular, the percent error in water volume accounting is used as a criterion to check the validity of a model run; the output pluvial flood maps from the HEC-RAS are carefully inspected and post-processed to ensure a certain level of consistency for final map presentation. The detailed measures are described as follows.

6.1 Volume Accounting Error

The HEC-RAS 2D model produces a water volume accounting summary for each model run after it is completed (see the example shown in Figure 29). One of the key output information is the percent error which represents the overall water gain by the model (i.e., the computational error in water volume). Typically, this percent error should be very small in order for a model run to be treated as a stable simulation. Based on initial test runs, the project team notices that the HEC-RAS 2D model does not necessarily produce any error messages even if the percent error is very high (e.g., >20%). Therefore, here the project team uses a threshold of 5% for the percent error to help check whether each model run is a stable and valid simulation. If the output percent error is greater than 5%, the project team will adjust model tolerance settings to allow for more iterations to increase stability, and then rerun the model until a lower percent error (< 5%) is achieved. For the majority of model runs in this project, their percent errors are typically lower than 0.01% (or even lower than 0.001%), indicating high model stability in water volume accounting. The percent errors for model runs over major municipalities (e.g., Charlottetown and Summerside) are slightly higher because of their finer spatial resolution and large number of mesh cells. Nevertheless, the percent errors for the major municipal models are still ranging from 0.01% to 2%, which also confirms the validity of these model runs from the mass balance perspective.

```
        ***   Volume Accounting for 2D Flow Area in 1000 m^3   ***

     2D Area    Starting Vol      Ending Vol       Cum Inflow      Cum Outflow        Error   Percent Error   Precip Excess   Precip Excess
                                                (incl. precip)                                                        (m^3)            (mm)
     *******    ************      **********       **********      ***********        *****   *************   *************   *************

 Perimeter 1         117995.         131465.          298451.          284983.        1.266        0.000424          94359.     4504601120.


        ***  Total Volume Accounting (for the entire model) in 1000 m^3   ***

Total Boundary Flux of Water In         298451.
Total Boundary Flux of Water Out        284983.

Starting Volume                         117995.
Ending Volume                           131465.

Precipitation Excess (m^3)               94359.
Precipitation Excess (mm)           4504601120.

                        Error   Percent Error
                        *****   *************
                        1.266        0.000304
```

Figure 29. An example of the output summary for a HEC-RAS 2D model run.

6.2 Post-Processing of Flood Maps

In addition to the above-mentioned model validation towards specific flood events, the project team conducts further inspection for the output flood maps from the design storm events. Specifically, for each flood map, the project team identifies the areas with modeled flood depths over 1.5m for further inspection in terms of their validity and reasonableness. In most of the cases, these areas typically fall into three categories: 1) rivers or ponds filled with more water after heavy rainfall events, 2) low-lying coastal areas which are usually inundated by ocean water, and 3) the crossings of hydro and road networks which the culverts limit the volume of water flow and thus lead to high water depths in the upstream side of the watercourse. The experience and knowledge from local residents and field visits are also used to help inspect those commonly flooded areas. This is to ensure that the output flood maps are not dramatically different from what is expected.

Following the above validity and reasonableness inspection, the project team further compares the flood maps from municipal models with the maps from island-wide model to ensure consistency for urbanized areas. This is because there are two sets of flood maps available for the eight selected municipalities in this project: one is from their own municipal models, and one is from the island-wide model. Due to the obvious differences in model resolution and the representation of hydraulic structures, it is not surprising to see some differences in the output flood maps between municipal model and island-wide model. As shown in Figure 30, the major difference resulting from the difference in model resolution is that the municipal model can produce more detailed maps which are helpful for flood risk assessment for individual properties and key civil infrastructures (e.g., roads and highways), while this level of details is not attainable for the island-wide map.

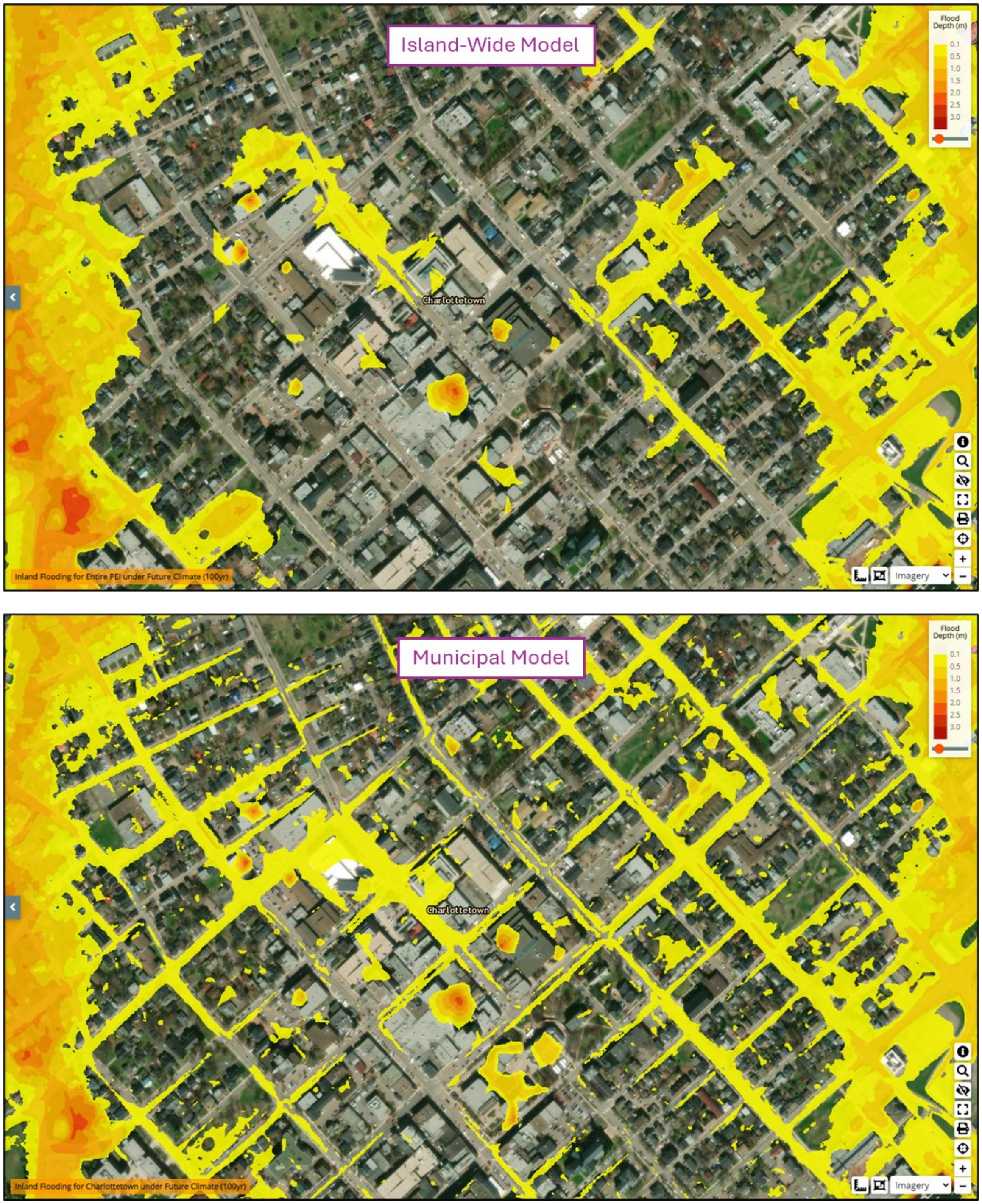


Figure 30. A comparison of the 100-yr return period pluvial flood maps for downtown Charlottetown under the same future climate condition between the island-wide model and the municipal model.

While the abovementioned differences in the pluvial flood maps for urbanized areas are understandable from the scientific perspective given the limitations in island-wide model, it might cause some potential confusions for the map users who do not necessarily understand the reasons. Since the detailed maps from municipal models can generate more reasonable results in urbanized areas, here the project team further updates the island-wide flood maps by replacing the maps for the selected municipalities and Indigenous communities with the detailed maps from their municipal models (see the illustration in Figure 31). Note that the detailed flood maps from municipal models are not clipped into the municipal boundary before the replacement. This is to avoid any potential mismatches between island-wide map and municipal maps along with the municipal boundary.

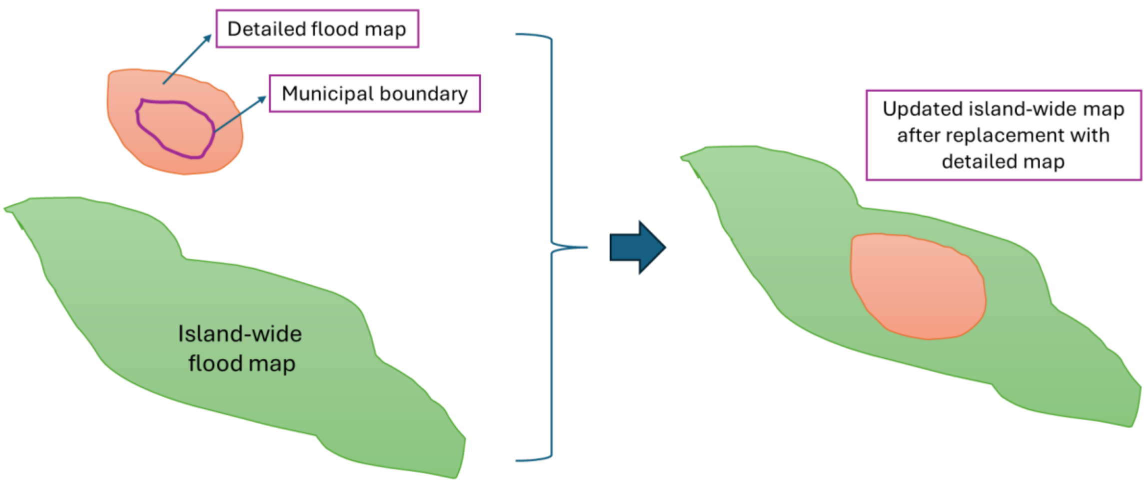


Figure 31. An illustration of the post-processing of island-wide flood maps.

During the flood map post-processing, the project team also notices that the provincial and municipal boundaries typically cover some areas above ocean water body because the original model domain is extended further into ocean. In order to avoid any flood depths above ocean water body, the project team has regenerated a new boundary mask with ArcGIS Pro to help extract the pluvial flood maps (see an illustration example in Figure 32). In addition, a 10 cm threshold of flood depth is used to extract the flood extent maps.

Figure 32. Comparison of the pluvial flood maps before and after applying the new boundary mask.

7. Summary & Recommendations

In this project, the project team has developed detailed pluvial flood maps for six municipalities (i.e., City of Charlottetown, City of Summerside, Town of Stratford, Town of Cornwall, Town of Three Rivers, and Town of Tignish), two Indigenous communities (Lennox Island First Nation and Abegweit First Nation), and the entire island of PEI. These flood maps are available for four return periods (including 10-yr, 25-yr, 50-yr, and 100-yr) and two climate conditions (i.e., current climate condition and future climate scenario for the period of 2071-2100 under SSP5-8.5). Throughout this project, the project team has encountered many challenges since this is the first attempt to generate island-wide pluvial flood maps for PEI. Given the limited scope and the tight timeline of this project, the project team has introduced a number of assumptions to ensure the successful delivery of the project.

The main assumptions and limitations for this project, as well as the recommendations for future research and improvements are summarized as follows:

- The HEC-RAS 2D model selected for this project is unable to represent the urban stormwater systems in urban areas. The 2-yr return period rainfall intensity under current climate condition is subtracted (only for urban areas) from the large return period rainfall intensity for the entire model domain in order to approximately represent the capacity of urban stormwater systems. However, it is worth noting that the capacity of urban stormwater systems can be affected by many factors (e.g., tidal changes from ocean water) and can also vary significantly by time and location. The current approach used in HEC-RAS 2D is certainly unable to reflect the spatiotemporal complexity of urban storm systems. Other flood models with the capacity of explicitly representing the capacity of urban stormwater systems (e.g., PCSWMM) should be used for further projects in order to generate more reliable pluvial flood maps in urban areas.
- Ocean boundary conditions are critically important for pluvial flood modeling over low-lying coastal areas likely PEI, where people have seen some unprecedented post-tropical storm events in recent years. These storm events are likely to bring extreme storm surges and heavy rainfall, plus if they take place during high tides, the resulting pluvial flood risk will increase significantly. Unfortunately, due to the lack of research on the compound flooding risk (i.e., coastal and overland) in PEI or in the region of Atlantic Canada, the project team uses the 1.6-yr return period ocean water levels under both the current and future climate conditions as the ocean boundary conditions to drive the pluvial models. As global warming continues, the compound flooding risk is very likely to increase. Therefore, it is important to investigate the compound flooding risk in the context of PEI in order to provide better scientific information to support the selection of ocean boundary conditions for pluvial flood modeling. Copula functions are commonly used by the scientific community for joint probability analysis and thus can be used for this purpose. After a systematic joint probability analysis, larger return

period ocean water levels (e.g., 25-yr, 50-yr, or 100-yr) might be needed to conduct additional pluvial model simulations.

- Although the island-wide pluvial flood maps generated from this project can provide useful information for decision-making, it is worth noting that there are certainly some limitations about the maps. For example, the island-wide model uses DEM breaching to burn in watercourses at road crossings, which tends to underestimate the water accumulation at the upstream side of culverts; the coarse resolution of the island-wide model can also lead to slight overestimation of the food depth and extent for those commonly flooded areas in comparison to detailed municipal models. Therefore, further efforts should be made to better represent the major hydraulic structures in island-wide pluvial modeling. How to better balance the considerable computational challenges from higher spatial resolution and the improved accuracy and details from the resulting flood maps is also a very important question to be addressed.
- The IDF curves developed by ECCC are based on a very limited number of weather stations in PEI which cannot fully represent the spatial variations of rainfall intensities. The Canadian Centre for Climate Change and Adaptation at UPEI has established a real-time weather monitoring network for PEI, named PEI Weather & Climate App[24]. This network covers over 100 weather stations across PEI and can potentially be used to capture the spatial variations of rainfall intensities. Another possible option is to use radar or satellite observations.
- Last but not least, the model calibration and validation in this project are limited due to the lack of high-quality data. Continuous efforts should be made in the coming years to build up a more comprehensive and reliable hydroclimatic database for PEI. This will eventually help develop more accurate flood models which are capable of reflecting the unique landscape of PEI and the increasing compound flood risk in the context of climate change.

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Annex A: IDF Curves & Chicago Storm Hyetographs

This annex includes all the IDF curves and Chicago storm hyetographs for five weather stations (Charlottetown, Summerside, Harrington, Saint Peters, and Maple Plains) under both current climate and future climate conditions.

Annex B: Pluvial Flood Maps

This annex includes all the pluvial flood maps generated for six municipalities (i.e., City of Charlottetown, City of Summerside, Town of Stratford, Town of Cornwall, Town of Three Rivers, and Town of Tignish), two Indigenous communities (Lennox Island First Nation and Abegweit First Nation), and the entire island of PEI. Each study area has a set of eight maps, including:

- 10-yr for current climate,
- 25-yr for current climate,
- 50-yr for current climate,
- 100-yr for current climate,
- 10-yr for future climate (SSP5-8.5, 2071-2100),
- 25-yr for future climate (SSP5-8.5, 2071-2100),
- 50-yr for future climate (SSP5-8.5, 2071-2100),
- 100-yr for future climate (SSP5-8.5, 2071-2100).

For a better exploration experience, the project team has incorporated these pluvial flood maps into the PEI Climate Hazard & Risk Information System (CHRIS, https://chris.peiclimate.ca). CHRIS is a GIS- and web-based platform which provides free and easy access to all the pluvial flood maps generated from this project.

CLIMATE CHANGE REPORT SERIES

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