One Dimensional, Two Dimensional and Three Dimensional Hydrodynamic Modeling of a Dyked Coastal River in the Bay of Fundy

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Abstract

The urban development in Truro, Nova Scotia is situated on the floodplain of the Salmon River near its outlet to the Cobequid Bay. Extreme water levels in the Salmon River estuary and its tributaries overtop the dyke system that protects the area from high tides, resulting in widespread flooding of roads, residences, schools, senior homes, offices, commercial areas, industrial facilities and agricultural land. These high water levels are a result of the complex interactions between large river flows, the highest tides in the world, mudflat sedimentation and ice jamming. This paper presents the details of the extensive hydrodynamic modeling that was carried out for the Salmon River estuary and its tributaries as part of a comprehensive flood risk study using the latest in 1D, 2D and 3D modeling software. An integrated 1D–2D PCSWMM model was used to simulate the hydrology and the dynamic interaction between river and tidal flows, dyke breaching and urban floodplain hydraulics; MIKE21 and MIKE3 models were used to simulate the tidal ingress and amplification between the Bay of Fundy and Salmon River estuary as well as sedimentation rates in the estuary; and a HEC–RAS model was used to simulate ice jamming. Together these models were used to quantify the flood extents of the Salmon River estuary and its tributaries and to evaluate the impacts of over 40 potential flood mitigation solutions.

1 Introduction

The Truro area consists of a low lying urban development located along the floodplain of the Salmon River estuary in Nova Scotia (Figure 1). The Salmon River estuary outlets to Cobequid Bay, which is an inlet of the Bay of Fundy located in the Minas Basin and is therefore home to some of the highest tides in the world (Desplanque and Mossman 2004). The urban area in Truro is protected from these extraordinary high tides by a large network of dykes that were originally constructed by the French Acadians in the 1600s to acquire fertile land from the saltwater marshes (Robinson et al. 2004). The Acadians also built culvert and sluice gate systems called *aboiteaux* that open during low tide to discharge freshwater flows from the river tributaries and close during high tide and to prevent tidal flooding of the acquired farmland. Since 1948, the dykes and *aboiteaux* have been maintained by governmental bodies and are currently the responsibility of the Nova Scotia Department of Agriculture and Fisheries Resource Stewardship Division, Land Protection Section.

Figure 1 Map of study area and Bay of Fundy.

As the dyke system that protects the Truro area was only originally intended to hold back the saltwater high tides to protect farmland, the dykes become overtopped during significant rainfall events. Furthermore, since portions of the land protected by the dykes have now been urbanized, dyke overtopping in the region causes widespread flooding of roads, residences, schools, senior homes, offices, commercial areas and industrial facilities in

addition to the flooding of agricultural land. According to a previous study of the Salmon River floodplain by Environment Canada and the Government of Nova Scotia (Belore 1988), these flood events are not only caused by large rainfall events, but are a result of the complex interactions between high river flows, the high Bay of Fundy tides, tidal mudflat sedimentation and morphology, ice jamming, dyke constrictions, bridge constrictions and floodplain infilling. The study also presents an inventory of all flood events that have been documented since 1792, which suggested that flood events occur almost every year.

One of the primary objectives of the previous floodplain study (Belore 1988) was to estimate the 1 in 20 y and 1 in 100 y flood extents based on a 1D hydrodynamic model. The 1D model used for the study consisted of floodplain cross sections approximately every 1 km and all major hydraulic structures including bridges, culverts, aboiteaux and dykes. A later study of the floodplain completed by Environment Design & Management Limited (EDM 1997) made minor geometric improvements to the model to update the 1 in 20 y and 1 in 100 y floodplain extents. However, since neither of these studies used the 1D model to evaluate the impacts of flood mitigation solutions, no supporting calculations have been provided to support and therefore implement the numerous recommendations for alleviating flood risks that have historically been put forward by various studies (Belore 1988). Furthermore, knowledge about climate change and improvements in modeling software, computing power and topographic mapping have significantly improved since the time of the EDM study.

The Joint Flood Advisory Committee (consisting of representatives from the County of Colchester, the Town of Truro and Millbrook First Nation) therefore decided in 2014 to commission one of the most comprehensive flood risk studies ever undertaken in Atlantic Canada entitled the *Truro Flood Risk Study*, which would be supported by lidar topographic mapping and modern modeling software, including 1D, 2D and 3D hydrodynamic models of the Bay of Fundy, the Salmon River estuary and the full length of four of its major tributaries (Salmon River, North River, McClures Brook and Farnham Brook). The models would then be used as tools to update the floodplain mapping for the Truro area as well as to evaluate all potential flood mitigation options that have been discussed in previous studies and to support further recommendations. Different types of models were needed for this study because no single modeling platform was found to be adequate for simulating all of the processes that occur along the Salmon River estuary and its tributaries. Additionally, since the primary purpose of the models was to develop tools for producing floodplain mapping and for flood mitigation engineering analysis, hundreds of simulations involving various modifications to model inputs and physical parameters were needed for the study. Model stability and simulation time were therefore considered when selecting the modeling software and developing the models. Ultimately, the following models described in Table 1 were developed for the study.

Table 1 Hydrologic and hydraulic models used for study.

Model Description	Software
Hydrologic & 1D–2D Hydrodynamic Model	PCSWMM
Bay of Fundy 2D Hydrodynamic Model	MIKE21
Salmon River Estuary 3D Hydrodynamic & Sediment Model	MIKE3
1D Ice Jam Model	HEC–RAS

PCSWMM by Computational Hydraulics International (CHI) was used to develop the primary model used for the study. The PCSWMM model consisted of a hydrologic model and an integrated 1D–2D hydrodynamic model of the Salmon River, North River, McClures Brook and Farnham Brook from their upper tributaries to ~7 km downstream of Truro where the Salmon River estuary expands and is no longer influenced by freshwater hydrodynamics. MIKE21 and MIKE3 by Danish Hydraulic Institute (DHI) were then used to model the Bay of Fundy and the tidally influenced zone of the Salmon River. The purpose of the MIKE models was to develop tidal boundary inputs for the PCSWMM model and to assess sedimentation rates in the mudflats of the river. Finally, HEC–RAS by the United States Army Corps of Engineers (USACE) was used to develop an ice jam model of the Salmon River and to assess the impacts of ice jam reduction measures.

This paper therefore presents a case study of how PCSWMM, MIKE21, MIKE3, and HEC–RAS were used to model the complex flood conditions experienced in the Truro area that are unique to the Bay of Fundy in Atlantic Canada. Background information on the various processes that occur in the Bay of Fundy, the Salmon River estuary and its tributaries are described along with how these processes were modeled for the purposes of the floodplain mapping and flood mitigation analysis objectives of this study.

2 MIKE Modeling

2.1 Overview of Bay of Fundy Processes

The modeling exercise for this study begins in the Bay of Fundy where various tidal processes needed to be accounted for to estimate tide level boundary conditions for the PCSWMM model and to estimate sedimentation rates in the Salmon River estuary. Water levels and sediment levels in the Salmon River estuary and the lower reaches of its tributaries are greatly influenced by the semidiurnal tides that travel from the Bay of Fundy to the Minas Basin, and then through the Cobequid Bay to the estuary.

Bay of Fundy Tides

The Minas Basin is arguably home to the highest tides in the world with an astronomical tidal range that can approach 16 m before accounting for meteorological disturbances (Desplanque and Mossman 2004). These exceptionally high semidiurnal tides are attributed to the oscillation in the Bay of Fundy and Gulf of Maine system having a natural period of 13.3 h, which results in near resonance with the most common astronomical tide period of 12.42 h (Garrett 1972). Furthermore, according to Greenberg et al (2012), tidal expansion in the Bay of Fundy caused by future sea

level rise could increase the wave propagation speed of the Bay, bringing its natural oscillation period closer to resonance with the tide period. This decreased wave frequency could cause the amplitude of the tides to increase by 7% to 17% of sea level rise per century.

The tidal dynamics in the Bay of Fundy are also highly influenced by the Coriolis effect. According to Desplanque and Mossman (2004), Coriolis forces in the Bay of Fundy can cause its water levels to be ~0.52 m higher on the Nova Scotia side than on the New Brunswick side, depending on the velocities in the Bay. This contributes to the counter clockwise gyre observed in the Bay of Fundy, which was able to be produced by a 3D model of the Bay by Sankaranarayanan and McCay (2003). According to further 3D modeling of the Bay of Fundy by Aretxabaleta et al. (2008), the primary controlling mechanisms of the observed counterclockwise gyre are tidal rectification and density driven circulation, whereas river discharge and wind have limited impacts on the depth averaged flows that drive the currents.

Tidal Amplification in the Minas Basin and Salmon River Estuary

The high tides of the Bay of Fundy that enter into the Minas Basin are then further amplified due to the narrow and shallow bathymetry of the Minas Passage and its location at the north-east end of the Bay of Fundy (Desplanque and Mossman 2004). Further amplification then occurs along the Salmon River estuary where the tides in the Cobequid Bay form a tidal bore and travel up the estuary to just past Truro, depending on astronomical conditions (Belore 1988).

While no long term tide gauging has been carried out for the Salmon River estuary or the Cobequid Bay, short term tide gauging data collected from 1971 to 1972 at the former Board Landing Bridge location near Truro have historically been used to develop tide level relationships between Truro and the permanent tide gauge operated by Fisheries and Oceans Canada (DFO) at Saint John, New Brunswick. However, these three relationships were found to produce differences in water levels between those observed and those predicted in the order of 0.8 m to >1 m (Belore 1988). Thus, more data would need to be collected and the additional processes that occur in the Bay of Fundy and Salmon River estuary would need to be accounted for to improve the relationship. For this study, additional tide gauging data was collected in the Salmon River estuary near Truro and hydrodynamic modeling using 2D and 3D models was performed to relate tide levels between Saint John and Truro.

Sedimentation

The mudflats of the Salmon River estuary are constantly morphing due to the significant amount of sediment deposited by the Bay of Fundy tides and due to erosion from river flows (Belore 1988). This impacts water levels in the estuary and is therefore a factor that contributes to flooding. While minimal data is available on sedimentation rates in the Salmon River estuary, observations were performed for this study throughout 2014 to analyse the

mudflat morphology. Based on the 2014 observations, it was estimated that ~2 m sediment accumulated in the estuary on average during the summer of 2014, which was a particularly dry summer in which only 93.4 mm of total rainfall was recorded at the Environment Canada Debert climate station for July and August. Since freshwater flows in the river are a driving force for mudflat erosion, the sediment deposited in 2014 was therefore likely higher than average. However, Belore (1988) also observed river channel bottom elevation differences in the order of 2.5 m at the former Board Landing Bridge location and in the order of 1.5 m at Park Street Bridge. The 2014 observations therefore generally agreed with previous observations, indicating that significant sedimentation and morphology occurs in the Salmon River estuary each year.

Furthermore, anecdotal information from retired Nova Scotia Environment staff noted that large sediment bars can form at some locations along the estuary and maintain water levels at approximately high tide elevation. This was witnessed to occur twice in the last 50 y. Based on these observations, it was therefore estimated that the sediment accumulation in the estuary is capable of reaching high tide levels in extreme circumstances.

2.2 MIKE21 Bay of Fundy 2D Model

To simulate tide levels in the Bay of Fundy for this study, a 2D modeling platform was needed that takes into account the bathymetry and all relevant forcing functions contributing to the natural oscillations and current circulations in the Bay. MIKE21 was therefore selected for this study to produce a 2D model of the entire Bay of Fundy that included the Minas Basin and the Salmon River estuary. The MIKE21 Bay of Fundy model consisted of a variable resolution mesh with triangular and rectangular cells that ranged in length from ~25 m to 2 000 m, as shown in Figure 2. The model was calibrated to observed water levels at Saint John, predicted water levels at Five Islands, and water levels measured in the Salmon River estuary as part of this study. Following calibration, the model was used to estimate tide levels in the Cobequid Bay for inputs into the more refined 3D model of the Salmon River estuary.

Figure 2 Mesh of MIKE21 Bay of Fundy 2D model.

2.3 MIKE3 Salmon River Estuary 3D Model

The tidal amplification that occurs along the Salmon River estuary is a result of complex hydrodynamics related to the bathymetry and friction of the estuary. Thus, a 3D modeling platform was selected for this study to simulate how the Bay of Fundy tides become amplified as they travel up the Salmon River estuary and interact with freshwater river flows. MIKE3 was therefore used for this study to develop a more refined 3D model of the Salmon River estuary from the Cobequid Bay to just upstream of Truro along the Salmon River and North River. The MIKE3 model consisted of a variable resolution mesh with triangular and rectangular cells that ranged in length from ~20 m to 50 m in the river, up to 300 m in the floodplain and up to 1 300 m in the estuary, as shown in Figure 3. Tide gauging data collected in the Salmon River estuary in 2014 was used to calibrate the hydrodynamics of the MIKE3 model.

Figure 3 Mesh of MIKE3 Salmon River estuary 3D model.

2.4 MIKE3 Sedimentation Model

A 3D model was also needed for this study to simulate vertical variations in currents and sediment concentrations to evaluate sedimentation rates in the estuary. Thus, the MIKE3 model of the Salmon River estuary was expanded to include MIKE3's Mud Transport module. One reason why MIKE3 was specifically selected for the sedimentation model was because the model updates the bathymetry of the river for each time step based on the amount of sedimentation and erosion from the previous time step at each cell. This modeling feature was applicable for the Salmon River since the river can receive >2 m of sediment during the summer period. The MIKE3 sedimentation model was calibrated to field data collected in 2014 including acoustic Doppler current profiler (ADCP) velocity and backscatter data, pressure sensor data, turbidity sensor data, rising stage bottle data, total suspended solids (TSS) data and sediment samples taken along five transects during different seasons.

3 PCSWMM Modeling

3.1 PCSWMM Model Approach

The PCSWMM model of the Salmon River estuary and its tributaries was the primary model used for this study to estimate flood extents and evaluate flood mitigation options. The model consisted of the following three submodels that were developed independently and then combined into a single model:

1. Hydrologic model of the Salmon River estuary watershed;
2. 1D model of the upper reaches; and
3. Integrated 1D–2D model of the Salmon River estuary.

3.2 PCWMM Hydrologic Model

The hydrologic model of the Salmon River estuary watershed was developed in PCSWMM based on hydrological inputs estimated using ArcGIS, a Geographic Information System (GIS) program developed by the Environmental Systems Research Institute (Esri). ArcGIS was used in conjunction with a 1 m resolution lidar DEM, land classification mapping and soil mapping, to automatically delineate 137 subwatersheds and estimate their watershed characteristics including average surface slope, surface roughness, imperviousness and soil infiltration properties. A map of the Salmon River estuary watershed and sub-watersheds delineated for this study is presented in Figure 4.

Figure 4 Salmon River estuary watershed delineation and hydrometric station locations.

As shown in Figure 4, five former Environment Canada hydrometric stations are located within the watershed. However, prior to calibrating the hydrologic model to the flow data available at these stations, a hydraulic model of the upper reaches first needed to be developed to route the flows from each sub-watershed into the main river channels where the stations were located.

3.3 1D Model of Upper Reaches

The floodplain characteristics of the upper reaches vary significantly upstream of the tidally influenced zone, as the floodplain becomes narrower, the floodplain fringes become steeper, and the river slope increases. These floodplain characteristics result in the floodplain flows of the upper reaches to have well defined and unidirectional flow paths, indicating that a 1D modeling platform would be suitable for simulating their river hydraulics. A 1D hydrodynamic model of the upstream reaches was therefore developed for this study using PCSWMM.

1D Model Development

The PCSWMM model of the upper reaches consisted of >70 hydraulic structures and a network of 1D conduits containing floodplain cross sections at a 20 m spacing with cross section widths that ranged from 800 m to 1 500 m. The floodplain cross sections were produced automatically using the Transect Creator tool in PCSWMM. Since 1 m resolution lidar data was available, a high resolution station spacing of 1 m was able to be applied for each cross section. However, since SWMM is unable to process >1 000 stations per cross section, an averaging routine was applied to produce a 1.5 m station spacing, which was instead used for when the floodplain width was >1 000 m. The resultant 1D model of the upstream reaches therefore consisted of >3 400 cross sections that included >3 000 000 elevation data points.

Despite the large amount of geometrical data included in the model, it was found that the simulation times for the model remained short due to the manner in which SWMM processes its transect data. Since SWMM converts each cross section into a simplified table of area, top width and hydraulic radius for each depth (Rossman 2015), the complexities of the cross sections become ignored during the simulation. This approximation allows for short simulation times and stable model results for highly detailed floodplain cross sections, which would likely result in impractically long simulation times if modeled at the same resolution using a 2D model.

Flow Calibration

The completed 1D PCSWMM model of the upper reaches was then integrated with the hydrologic model and the combined model was calibrated to flow data collected at the former Environment Canada owned hydrometric stations (see Figure 4). The following three hydrometric stations were selected based on the availability of both rainfall and flow data and the data coverage of significant historical storm events:

- Salmon River at Murray Siding (station 01DH002);
- Fraser Brook near Archibald (station 01DH003); and
- North River at North River (station 01DH004).

Two of the largest historical rainfall events that occurred during the historical flow data collection period were used to calibrate the model, the 1971-08-16 event and the 1978-01-15 event. Two rainfall events were needed since the North River at North River station was installed after the Salmon River at Murray Siding

station was decommissioned. Rainfall data for the two events was obtained from Environment Canada for the former Truro climate station.

Model calibration was carried out by modifying the watershed characteristics until the peak flows and runoff volumes simulated in the model were optimized to represent the observed values. Calibration results for the model are presented in Table 2. It is noted that the measured flow data only included estimated peak flow measurements and daily averages, which prevented a precise model calibration. Furthermore, model calibration could only be completed for flow rates since historical water level data could not be obtained for these stations to calibrate the hydraulic model for water levels. However, accurate estimation of water levels upstream of the urban area was not a priority for the study, as these areas are not prone to flooding.

Table 2 Flow calibration results for PCWMM model.

Station	Event	Parameter	Recorded	Modeled	Error
01DH002	1971-08-16	Peak Flow (m ³ /s)	254	227	-10.8%
		Volume (10 ⁶ m ³)	34.5	33.7	-3.0%
01DH003	1971-08-16	Peak Flow (m ³ /s)	6.5	6.8	5.5%
		Volume (10 ⁶ m ³)	0.82	0.92	12.3%
01DH004	1978-01-15	Peak Flow (m ³ /s)	170	146	-14.2%
		Volume (10 ⁶ m ³)	24.7	26.1	5.3%

3.4 PCSWMM 1D–2D Model

After the upstream branches enter into the tidally influenced zone where they then become dyked, the floodplain becomes significantly flatter, wider and more developed. This location is also where both the Salmon River and the North River discharge to the Salmon River estuary and therefore substantially increase freshwater flows in the channel. The river channel in the Salmon River estuary continues to have a well defined flow path between the dykes, where flows are typically either travelling parallel to the dykes in the downstream direction during low tide or in the upstream direction during high tide. However, once the water levels in the river channel become high enough to overtop the dykes, the river flows then enter the urbanized floodplain area. Since the floodplain area is wide and flat, flows that overtop the dykes travel through the floodplain and back into the river along unpredictable flow paths that could only be well represented by a 2D model. Thus, an integrated 1D–2D model was developed for the Salmon River estuary using PCSWMM, where the river channel was modeled in 1D and the floodplain was modeled in 2D, as depicted in Figure 5. The dykes therefore acted as the boundary between the 1D and 2D modeling zones. After the integrated 1D–2D PCSWMM model of the tidally influenced zone was complete, the model was then joined with the hydrologic model and the 1D model of the upstream reaches.

Figure 5 1D–2D PCWMM model.

1D Model Component

The 1D component of the 1D–2D PCSWMM model consisted of 1D conduits containing cross sections of the river channel every 20 m with 1 m station spacing. Bathymetry data used to produce the river channel cross sections consisted of data collected from a single beam echo sounder boat survey and a topographic survey. Since the width of the river from dyke to dyke was typically between 100 m and 600 m, selecting a 1D model allowed for a high level of detail in the transverse direction. If a 2D model was instead used for the river channel, the 1 m cross section station spacing resolution would have needed to be sacrificed to reduce model simulation times.

The 1D component of the model also contained the dyke system, which was included in the model to simulate both dyke overtopping and dyke breaching. It is noted that the previous model developed for the Environment Canada and Government of Nova Scotia study (Belore 1988) used a dyke overtopping subroutine to simulate overtopping at eleven locations, which also allowed for the floodplain flows to overtop the dykes when returning to the river channel further downstream. The dyke breaching routine was then improved for the EDM study (1997). These previous studies therefore exemplified the concerns of needing to accurately model the dyke overtopping to predict representative flood levels in the Truro area.

For this study, the dyke system was modeled in PCWMM by inputting both a dyke overtopping conduit and a dyke breaching conduit at every river channel junction (20 m spacing). These conduits were connected to junctions on the floodplain side of the dykes within the 2D modeling zone. The dyke overtopping conduits were offset to the local top of dyke elevations to allow for high river flows to locally overtop into the floodplain. However, when water levels exceed the local top of dyke elevation by 0.3 m from either side of the dykes in the model, control rules were used to open the dyke breaching conduits that were set to lower elevations. This allowed for local dyke breaching to occur throughout the model simulations at any 20 m span along the

approximately 27 km dyke network. Additionally, having the dykes fail from either side allowed for the model to simulate how the overtopped flows accumulate behind the dykes further downstream and then overtop and breach the dykes again on their way back into the river channel.

2D Model Component

The 2D modeling zone consisted of the floodplain area beyond the dykes. Since the floodplain area that needed to be modeled for this study was large (17 km²), the resolution of the 2D mesh had to be relatively coarse such that model simulation times would be reasonable. A 40 m resolution hexagonal mesh was therefore selected for locations in the floodplain that were flat and had very little change in elevation over a 40 m distance. Since the floodplain area consists primarily of flat or gently sloped agricultural land, the 40 m resolution was able to be applied to most of the floodplain without sacrificing topographic detail that would impact the model results. The 40 m resolution was also able to be applied for most of the urban area of the floodplain, as most of the low lying properties were constructed at higher but common fill elevations. However, to increase the model accuracy for the urban area, break lines were inserted into the model where there were significant changes in elevation over short distances. Furthermore, roadways were modeled using directional meshes bound by break lines to prevent the floodplain flows in the coarse mesh from passing through the roadway embankments until the water levels reach the centreline elevations of the respective roads. Finally, an Elevation layer was used in the PCSWMM model to allow the elevation assigned to each cell to be based on the average elevation contained within the cell.

One issue that can arise with using a coarser 2D mesh is that the flood extent presented by the model results will also be coarse due to the extent following the shape of the cells. A significant amount of horizontal accuracy can therefore be lost for floodplain mapping studies when using the cells of a 2D mesh to delineate flood lines. However, GIS tools can instead be used to interpret the coarse model results and produce more accurate flood lines. For this study, the maximum water levels estimated by the model for each cell were extracted and an interpolation was performed with ArcGIS using the 1 m resolution lidar DEM. The use of GIS tools therefore indicated that the coarser level of detail used for the 2D mesh at the floodplain extents would not impact the resulting flood lines.

The floodplain area also contains numerous brooks and streams that drain toward the dykes and into the Salmon River estuary. Since the widths of these watercourses are within the 5 m to 30 m range, the watercourses would therefore not be included within the 40 m resolution 2D mesh. Thus, these additional brooks and streams were modeled using 1D conduits containing the geometry of the channels below the elevation of the 2D mesh. The 1D conduits were then connected to the 2D mesh every 20 m along their alignments to allow for flows to interact between the channels and the floodplain. Finally, all bridges,

culverts and aboiteaux that convey these watercourses in the 2D zone were modeled using 1D conduits.

Water Level Calibration

While most of the model was already calibrated to the historical flow gauging data further upstream, water level calibration was needed to verify that the model output represented actual water level responses to rainfall and tidal inputs. However, minimal historical flow and water level gauging data was available for the Salmon River estuary. Furthermore, according to the EDM study (1997), some members of the public disagreed with the previous flood line delineations of the Truro area. Thus, it was important for this study to involve the public in the water level calibration phase, which meant that a flood event of recent memory should be selected for calibration.

Ultimately, a large flood event that occurred on 2012-09-10 was selected since it was the most recent major flood event at the time of the study that caused widespread flooding throughout the Truro area. The 2012-09-10 flood event therefore had the most extensive coverage of photos and videos, and the details of flood levels were well recalled by the public. The event was simulated in the PCSWMM model by modifying the dyke infrastructure to its 2012-09 configuration, estimating and inputting sediment levels in the river at the time of the event, inputting tide levels estimated from the MIKE21 and MIKE3 models based on the predicted tide levels at Saint John, and then inputting rainfall data.

The available rainfall data for the 2012-09-10 flood event was limited to data from the Debert climate station and from a private rain gauge located within Truro. However, historical radar data for the 2012-09-10 rainfall event showed a significant spatial variation of rainfall throughout the watershed, indicating that the data collected from the two rain gauges would not have been representative of the rainfall that fell over the entire watershed. Thus, a radar rainfall model was developed using the Radar Acquisition and Processing (RAP) project tools in PCSWMM to estimate the historical rainfall hyetographs for each of the 137 subwatersheds based on a simulation of historical radar data, as shown in Figure 6. The radar time step presented in Figure 6 of the rainfall event illustrates this spatial distribution of rainfall amongst the watershed. It is noted that no historical radar data was available for the 1971-08-16 and 1978-01-15 flow calibration events, indicating that the spatial distribution of rainfall during these events could not be predicted and the rainfall data from the former Truro climate station had to be assumed for the entire watershed.

Figure 6 Radar rainfall PCWMM model of 2012-09-10 rainfall event.

The radar rainfall model of the 2012-09-10 event used radar data provided by Environment Canada at a 1 km² resolution grid, where each grid cell contained a rainfall intensity time series estimated by the radar data at a 10 min time step. These rainfall intensities were then calibrated using the radar processing tools in PCSWMM by comparing the average rainfall amounts for each grid cell to the average rainfall amounts measured at the two rain gauges. Finally, the calibrated rainfall intensities were averaged across each subwatershed in the model to produce a unique rainfall time series for each subwatershed. According to the radar rainfall model results, the total rainfall amounts for the 2012-09-10 event varied between the sub-watersheds from 70 mm to 135 mm, which illustrates a significant spatial distribution in rainfall. Furthermore, the Debert rain gauge measured 70 mm and the private rain gauge in Truro measured 80 mm, indicating that the use of these rain gauges for the entire watershed would have substantially underestimated the rainfall amounts.

Thus, water level calibration for the PCSWMM model was carried out by simulating the 2012-09-10 flood event and modifying the floodplain and channel roughness until the flood extents were consistent with historical photos, videos and anecdotal information collected from the public. Floodplain mapping was then produced from the model results and presented to the JFAC, who provided feedback on where the model was producing flood extents or water levels that were not consistent with historical observations. Multiple iterations of producing floodplain mapping and receiving feedback from the JFAC occurred before the model was considered to be adequately calibrated.

3.5 PCSWMM Model Sensitivity Analysis

After calibrating the PCWMM model, a sensitivity analysis was then carried out to understand which model parameters have the greatest influence on flooding under various rainfall, tide and sediment conditions based on 1 in 100 y return period events (as defined in Section 5). The model parameters that were evaluated and their impacts on flood extents are presented in Table 3.

Table 3 PCWMM model sensitivity results.

Flood Event	Parameter	Modification	Impact on Flood Extents
1 in 100 y Rainfall	1 in 100 y Rainfall	+/-25%	+6.7%, -2.9%
	1 in 2 y Tide	+/-25%	+0.8%, -0.1%
	1 in 2 y Sediment	+/-1 m	+1.7%, -1.9%
	Channel Roughness	+/-50%	+5.1%, -7.7%
	Soil Hydraulic Conductivity	+/-50%	-1.4%, +1.7%
	Structure Losses	+/-25%	+0.1%, -0.8%
	Development	+/-50%	+2.4%, -5.2%
	Clear Cut	+/-50%	-1.5%, +1.2%
	Bridge Scour	+/-1 m	-0.1%, +0.2%
	Watershed Roughness	+/-50%	-2.9%, +3.2%
1 in 100 y Tide	Partial Dyke Breach	-1 m	-0.4%
	Full Dyke Breach	Full Breach	-0.3%
	1 in 2 y Rainfall	+/-25%	+7.2%, -12%
1 in 100 y Sediment	1 in 2 y Sediment	+/-1 m	+3.0%, -17%
	1 in 2 y Rainfall	+/-25%	+8.7%, -11%
	1 in 2 y Tide	+/-1 m	+2.4%, 0%
	1 in 100 y Sediment	+/-1 m	+2.5%, -2.3%

As a result of the findings from the sensitivity analysis, the watershed surface roughness was increased by 25% and both the channel surface roughness and soil hydraulic conductivity were decreased by 25% for the floodplain mapping scenarios. The results of the sensitivity analysis also provided vital information on what would be expected from implementing different types of flood mitigation options prior to carrying out the flood mitigation modeling exercise.

4 HEC-RAS Ice Jam Modeling

4.1 Ice Jam Processes in the Salmon River

Ice build-up along the Salmon River estuary and its tributaries is another major concern for the Truro area. While most of the largest documented flood events in the area were not related to ice, ~40% of all floods have been attributed to ice jamming in the river (Belore 1988). Thus, while historical major rainfall events have typically not occurred in combination with ice jamming, ice jam flood events that cause minor to moderate flood damages are frequent occurrences in the area. It is also noted that a statistical analysis carried out by Carson (1978) of flood levels in the Truro area with and without ice jams found no significant difference between the two conditions.

The ice accumulation in the Salmon River estuary and its tributaries is caused by a combination of both river and tidal ice formations, although flooding issues in the Truro area related to ice jamming are likely more attributed to river ice (Belore 1988). In general, river ice typically begins to form on the river surface beginning at the banks. According to the USACE (2006), ice crystals will then join and accumulate, sometimes attaching to the underside of the ice cover or to the river bed as anchor ice. Frazil pans and floes are also major components in the formation of the initial ice cover in the river. Ice jams then typically form when floating ice, slush or blocks encounter a stable ice cover, which

often occurs during spring or midwinter thaws. In the Salmon River and North River, the rivers become constricted and flattened near the extent of the tidally influenced zone, reducing the capacity of the river to transport ice and resulting in frequent ice jamming (Belore 1988).

Tidal ice that forms along coastal rivers in the Bay of Fundy is typically defined by one of four major ice types: drift ice, shorefast ice, frozen crust and sheet ice (Gordon and Desplanque 1983). Drift ice forms on the seawater surface of the Bay of Fundy as ice chunks that are in the order of a few metres or less in diameter. These ice chunks have a high sediment content and are often carried up and deposited on tidal rivers during high tide. Shorefast ice forms along the mudflats between neap and spring tides, and can result in thick accumulations of >5 m that attach to the steep walls of the tidal rivers in the Bay of Fundy. Frozen crust is ice that forms on the intertidal sediment deposits with thicknesses up to ~0.5 m. Finally, sheet ice is a continuous layer on ice with low sediment content that forms in tidal rivers at locations with low salinity and tidal velocities. Together, these tidal ice formations contribute to the hydrodynamics of the Salmon River estuary during the winter season. Ice formations in the Salmon River estuary at times can even completely block the high tides of the Bay of Fundy from entering into the estuary (Belore 1988). Furthermore, the formation of tidal ice along coastal rivers in the Bay of Fundy is also influenced by the mudflats being exposed for longer periods of time during winter nights, which is a result of the lower high water (LHW) occurring between 18:00 and 06:00 in the fall and winter seasons (Desplanque and Mossman 2004).

The previous floodplain study of the Truro area (Belore 1988) attempted to quantify the impact of ice jamming by calibrating the hydraulic model to water levels recorded during the 1971-02-14 ice jam event. The event was then simulated with the calibrated model and with the non-calibrated model to compare the differences in water levels for the event with and without ice jamming. The study found that while they were not able to simulate ice jamming, significantly increased flood levels were observed in the model as a result of ice.

Thus to achieve a better understanding of how the ice accumulates in the Salmon River estuary and its tributaries for this study, field observations were carried out in 2014-03. During these field observations, the mudflats along the tidally influenced zone of the river were found to be frozen into thick chunks of fractured ice with thicknesses sometimes >4 m. Some locations along the river were also found to have a layer of ice covering the entire river surface <1 m thick with flow occurring below the ice sheet. Since the river widens near Truro to a few hundred metres, a significant volume of frozen mud, freshwater and saltwater was found to be accumulated on the banks of the river in addition to fractured ice sheets covering the river channel. The ice formations showed signs of the ice frequently being fractured, displaced and deposited by the tidal flows. This movement of ice chunks was found to result in stacks of ice that partially obstruct the hydraulic openings for the bridge structures.

4.2 Ice Jam Model Development

To simulate the ice jamming in the Salmon River and its associated flooding experienced in the Truro area, an ice jam model was developed for this study using HEC–RAS, as depicted in Figure 7. The PCSWMM model was therefore converted into a simplified 1D HEC–RAS model, which was performed by first removing the 2D elements of the PCSWMM model and then extending its 1D cross sections of the river channel into the floodplain. Next, the cross sections were converted from SWMM format into HEC–RAS format using customized algorithms and were input into the HEC–RAS model. Finally, HEC–RAS simulation results were compared with PCSWMM simulation results to ensure that the simplified HEC–RAS model was able to produce similar flood water levels before including ice inputs.

Figure 7 HEC–RAS ice jam model cross sections.

Ice jam simulations performed by the HEC–RAS model used the wide river ice jam option, which estimates ice jam thicknesses using an ice jam force balance equation based on stresses acting on the ice jam and the channel banks (USACE 2006). The inputs into the model therefore consist of the initial ice cover thicknesses, ice surface roughness, internal friction angle, porosity, cohesion and maximum average velocity under the ice cover. Thus, the different types of ice observed in the area needed to be approximated in the model by ice sheets that are uniform along the river cross section.

4.3 Ice Jam Model Sensitivity Analysis

Minimal data was available to compare model results with ice jam thicknesses in the Salmon River estuary during rainfall events. Thus, prior to using the model to estimate extreme ice jam floods levels, a sensitivity analysis was first carried out to assess the impact of the initial ice cover thickness parameter and to evaluate the likelihood of ice jam formation throughout the river. This was performed by modifying the initial ice cover thickness in the model and by simulating the average annual maximum (1 in 2 y) rainfall event. The results of the sensitivity analysis found that the largest ice jam thickness that could be accumulated in the Salmon River estuary during a 1 in 2 y rainfall event before breaking up was ~1 m. Further upstream, ice jamming was able to accumulate to thicknesses in the order of several metres. The analysis therefore

showed little sensitivity in inputting initial ice cover thicknesses >1 m.

5 Floodplain Mapping

Following the completion of the MIKE21, MIKE3, PCSWMM and HEC–RAS models, the models were then used to simulate extreme flood event scenarios to develop the following flood lines:

- 1 in 2 y, 1 in 10 y, 1 in 20 y, 1 in 50 y and 1 in 100 y flood lines;
- 1 in 20 y and 1 in 100 y flood lines with climate change impacts for the year 2100; and
- probable maximum precipitation (PMP) flood lines.

Since multiple processes in the Salmon River estuary contribute to flooding, the definition of these flood lines first needed to be established. For example, while a 1 in 100 y flood line is often approximated for rivers by the flood extent that occurs during the 1 in 100 y rainfall event, this approximation cannot be applied to the Salmon River estuary since extreme tides, sedimentation and ice jam also contribute to flooding. Moreover, it would be statistically incorrect to define a 1 in 100 y flood as the 1 in 100 y rainfall event occurring at the same time as the 1 in 100 y tide level during a 1 in 100 y sediment accumulation and a 1 in 100 y ice accumulation. Thus, the 1 in 100 y flood line was instead developed for this study by first defining and simulating the 1 in 100 y rainfall, tide, sediment accumulation and ice jam events separately. The maximum water level elevation at every location in the floodplain between the multiple scenarios was then calculated and interpreted into a flood line using GIS tools. The resultant 1 in 100 y flood line was therefore defined as the maximum 1 in 100 y flood extent of multiple 1 in 100 y flood event scenarios involving different processes. This procedure was then repeated for all flood line scenarios. With the exception of ice jam flood events, all flood events were simulated using PCSWMM.

5.1 Extreme Rainfall Floods

Extreme rainfall flood events were defined for this study by the respective extreme rainfall event occurring at the same time as the average annual maximum (1 in 2 y) tide level and sediment level. The 1 in 2 y, 1 in 10 y, 1 in 20 y, 1 in 50 y and 1 in 100 y design rainfall hyetographs used in the PCWMM model for existing climate conditions were developed following a 24 h duration Chicago distribution based on the upper bound 95% confidence limit intensity–duration–frequency (IDF) curves for the former Truro climate station. The PMP for Truro was estimated to be 327 mm using the statistical estimation method by Hershfield (1965), and was then used to form a 24 h duration Chicago distribution.

The impact of climate change on extreme rainfall amounts in the watershed was analysed to develop design rainfall hyetographs for future climate change conditions. While limited research has been published on future increases in extreme rainfall amounts, two publications available at the time of this study were evaluated to estimate the future rainfall amounts. The first study by Kharin et al. (2007) used a multi-model approach of combining

fourteen climate change models to predict increases in 1 in 20 y rainfall amounts for the 1981 to 2100 horizon. However, the study arbitrarily selected climate emission A1B and A2 for its analysis from the *Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios* (IPCC SRES, IPCC 2000), and the model results were applied to all of North America. Another study by Lines et al. (2009) predicted future 24 h duration 1 in 10 y, 1 in 50 y and 1 in 100 y rainfall amounts at the Greenwood Airport climate station in Nova Scotia for the 2071 to 2099 horizon using statistical downscaling of global climate change models. However, the Lines et al. (2009) study only compared two climate change models and also arbitrarily selected emission scenario B2 from the IPCC SRES (IPCC 2000). Furthermore, the SRES scenarios used in these two studies have since been superseded by the representative concentration pathways (RCPs) adopted by the IPCC for its *Fifth Assessment Report* (IPCC 2013).

While climate change research has been updated since the time of these two studies, the estimation of future extreme rainfall amounts inherently presents high uncertainties. However, since the scope of this study did not include an evaluation of global climate change models using statistical downscaling, the results from Lines et al. (2009) were selected for the purposes of this study because of their local applicability. The extreme rainfall amounts predicted for the Greenwood area were then considered to be similar to those in the Truro area based on the 24 h mean annual extreme rainfall amounts mapped by Environment Canada (Hogg and Carr 1985). An increase in extreme rainfall amounts of 29% was therefore estimated for the this study and was applied to the 1 in 20 y and 1 in 100 y design rainfall hyetographs to simulate climate change conditions in the PCSWMM model for 2100.

5.2 Extreme Tidal Floods

Extreme tidal floods were defined for this study by the respective extreme tide event occurring at the same time as the average annual maximum (1 in 2 y) rainfall event and sediment level. The 1 in 2 y, 1 in 10 y, 1 in 20 y, 1 in 50 y and 1 in 100 y design total sea levels under existing climate and future climate change conditions were estimated based on an analysis of astronomical tides, storm surges and sea level rise. The results from this analysis are presented in Table 4 using Canadian Geodetic Vertical Datum 1928 (CGVD28).

Table 4 Extreme sea levels estimated for 2015 and 2100.

Return Period	Tide	Storm Surge	Sea Level Rise	Design Sea Level
1 in 2 y (2015)	9.0 m	+0.87 m	+0.11 m	9.98 m
1 in 10 y (2015)	9.0 m	+1.09 m	+0.11 m	10.20 m
1 in 20 y (2015)	9.0 m	+1.17 m	+0.11 m	10.28 m
1 in 50 y (2015)	9.0 m	+1.30 m	+0.11 m	10.41 m
1 in 100 y (2015)	9.0 m	+1.40 m	+0.11 m	10.51 m
1 in 20 y (2100)	9.0 m	+1.17 m	+1.11 m	11.28 m
1 in 100 y (2100)	9.0 m	+1.40 m	+1.11 m	11.51 m

Extreme astronomical tides were estimated based on the higher high water large tide (HHWLT), which is the average of

the highest high waters, one from each of 19 y of predictions. According to tide predictions from the Upper Fundy WebTide model of the Cobequid Bay (Dupont et al. 2005), the maximum tide elevation occurring in mid-June of 2014 corresponded well to the HHWLT observed in the predictions. Thus, the spring tide measurement collected in mid-June of 2014 in the Salmon River estuary near Truro of 9.0 m CGVD28 was assumed to represent the HHWLT. A time series peaking at 9.0 m elevation was then developed for the downstream boundary of the PCSWMM model based on WebTide predictions in the Cobequid Bay.

Storm surge residuals, which are differences between predicted astronomical tide levels and the actual water levels, were then estimated for 1 y, 1 in 2 y, 1 in 10 y, 1 in 20 y, 1 in 50 y and 1 in 100 y return period occurrences. Estimated storm surge residuals for Burntcoat Head in the Minas Basin were published by Richards and Daigle (2011) based on a previous study carried out on storm surges in Atlantic Canada by Bernier (2005). The upper 95% confidence limit storm surge residual values for Burntcoat Head were therefore used for this study and were added to the peak of the HHWLT tide time series used for the downstream boundary in the PCSWMM model.

Sea level rise for the Bay of Fundy was estimated using values published by DFO (Zhai et al. 2014), which are based on predictions from the *IPCC Fifth Assessment Report* (IPCC 2013) and local crustal subsidence estimations from James et al. (2014). According to DFO (Zhai et al. 2014), sea level rise was projected to increase by 1.11 m (95th percentile) from 2000 to 2100 for the high emissions scenario RCP 8.5. This increase in sea level at Saint John was therefore assumed to be the same as at Truro, and was added to the HHWLT and storm surge time series to produce tide boundary conditions for the PCSWMM model under climate change conditions. To represent sea level rise conditions for 2015, an interpolated sea level rise value of 0.11 m was added to the HHWLT and storm surge.

It is noted that the increase in tidal amplitude of 7% to 17% of sea level rise estimated by Greenberg (2012) was not included in this study, as this increase would have minimal impact on flooding, and tidal expansion in the Bay of Fundy remains a topic of ongoing research. Furthermore, the impacts of wind driven waves in the Minas Basin was also not accounted for, as Desplan-que (1977) estimates that these large waves are likely to be significantly reduced as they enter into the Salmon River estuary.

5.3 Extreme Sediment Accumulation Floods

Extreme sediment-accumulation-related floods were defined for this study by the respective sediment level occurring at the same time as the average annual maximum (1 in 2 y) rainfall event and tide level. However, no long term records of sediment accumulation were available in the Salmon River estuary to estimate the 1 in 2 y, 1 in 10 y, 1 in 20 y, 1 in 50 y and 1 in 100 y sediment levels. Thus, a 1 in 2 y sediment level of 2 m with a relative depth distribution was selected for flood mapping purposes, as this level seemed to roughly represent observed annual maxima based on

the Belore (1988) and 2014 observations. As previously mentioned, anecdotal observations indicated that sediment accumulation may be capable of reaching high tide levels in extreme circumstances. Thus, the higher high water mean tide (HHWMT), which is the average of the higher high waters from 19 y of predictions, was estimated to be the most extreme sediment level that could occur in the estuary, and was therefore selected to represent the 1 in 100 y sediment level. The HHWMT for Truro was estimated by correlating WebTide model predictions to the 2014 observations and was found to be 6.4 m CVGD28. The 1 in 10 y, 1 in 20 y and 1 in 50 y sediment levels were then estimated by interpolating between the 1 in 2 y and 1 in 100 y levels.

Riverbed elevations in the PCSWMM model were modified to the respective sediment levels using a natural logarithm function that reduces the sedimentation as the end of the tidally influenced zone is approached. Thus, while the estimated extreme sediment levels used for this study are not supported by long term records and are not based on statistical analyses, they generally represented the observed and possible sediment conditions in the river well enough based on the information that was available to perform the floodplain mapping objectives of this study. Furthermore, the impacts of climate change on extreme sediment levels were not investigated for this study, as no information was available to support these impacts, resulting in a significant amount of uncertainty with any estimation. It is also noted that while a MIKE3 sediment model of the Salmon River estuary was developed for this study, the long term continuous simulations needed to estimate extreme sediment levels could not be carried out for the study due to impractical simulation times. Furthermore, a large uncertainty would have been associated with the model results since the model was not calibrated in detail to extreme conditions.

5.4 Extreme Ice Jam Floods

Extreme ice jam floods were defined for this study by the respective extreme ice cover thickness occurring at the same time as the average annual maximum (1 in 2 y) rainfall event, tide level and sediment level. However, no quantifiable long term data was available to estimate extreme ice conditions in the Salmon River estuary watershed. Ice cover thicknesses used as inputs for the HEC-RAS model were therefore estimated using a method published by the USACE (2006) with long term historical temperature data for the former Truro climate station. Based on a statistical analysis of maximum annual ice thicknesses estimated using the USACE method, the 1 in 100 y ice accumulation was found to reach a thickness of 0.82 m.

Unfortunately, since the HEC-RAS model was a simplified version of the PCWMM model that did not include 2D hydrodynamics, the model results of the HEC-RAS model were coarser and could not be directly compared to the PCWMM results. Furthermore, a much larger uncertainty was associated with the ice jam flood results due to the lack of data to support some of the large ice jams that formed in the model at select locations.

Thus, the ice jam flood extent could not be included in the compiled flood line delineations for this study, and was instead presented separately.

6 Flood Mitigation Modeling

After completing the floodplain mapping objectives for this study, the models were then used to evaluate >40 potential flood mitigation solutions grouped into the following approaches:

- constructing aboiteaux to contain extreme tide levels;
- raising the existing dykes to contain river floods;
- widening the existing dykes to restore some of the natural river floodplain and increasing the drainage capacity of the river within the dykes;
- dredging or improving the river cross section to increase its drainage capacity;
- widening or straightening the river to increase its drainage capacity;
- constructing a floodway bypass to double the drainage capacity of the river;
- reducing upstream flows through storage or infiltration;
- protecting specific areas at risk using localized dykes;
- protecting specific services at risk by raising roads;
- protecting specific areas at risk at the lot scale;
- constructing ice control structures; and
- modifying the dykes to reduce ice jamming.

Each flood mitigation option was evaluated by performing model simulations of the 1 in 100 y rainfall, tide, sediment accumulation and ice jam flood events, as applicable. Flood lines were then produced for each simulation such that the impacts of each flood mitigation option on flood extents and flood depths could be compared to those of existing conditions, resulting in >100 simulations and corresponding flood line delineations. The model results were then used for this study to rank the various flood mitigation options and develop recommendations based on their impacts on flooding as well as cost, environment impacts, the value of land at risk, and the impacts to vital infrastructure. Further considerations included stakeholder values, social justice, availability of budgets, timing considerations and the long term effectiveness and sustainability of the various options. Thus recommendations from this study provided the County of Colchester, the Town of Truro, and Millbrook First Nation with guidance that, for the first time, is backed by defensible model calculations as well as stakeholder and sustainability considerations.

7 Conclusions

The hydrologic and hydrodynamic modeling carried out for the Truro Flood Risk Study demonstrated how the complex interaction between the various processes occurring in the Salmon River estuary and its tributaries could be quantified using modern

modeling and GIS tools for the purposes of estimating extreme flood scenarios and evaluating a wide variety of flood alleviation solutions. Furthermore, the models developed for this study could be used in the future for engineering design of flood mitigation solutions. The following conclusions were drawn from the model assessment performed for this study:

1. Tide levels in the Bay of Fundy could be representatively simulated using a 2D model whereas a 3D model was more suitable for simulating the tidal amplification between Burntcoat Head and Truro as well as mudflat sedimentation in the Salmon River estuary;
2. 2D modeling as opposed to 1D modeling was found to be necessary only when the flow paths were not well defined, as 1D modeling presented major advantages in providing stable, quick and representative results for flow paths that are unidirectional;
3. A relatively coarse 2D mesh could be applied for the river floodplain model without noticeably impacting water level results due to a combination of the flat floodplain terrain, detailed break lines and a GIS interpretation of the model results;
4. The significant amount of model simulations needed for this study demonstrated the need for a careful balance between model detail and the practicality of developing models that have reasonable simulation times and that remain stable when modified;
5. The large variation found between radar-rainfall model estimations and single point rainfall data sources for this study indicated the importance of using radar-rainfall modeling for model calibration; and
6. Ice jam modeling of the Salmon River estuary was found to remain a highly uncertain practice due the lack of measurable and quantifiable data and the lack of advanced modeling software that can accurately simulate ice jamming processes and complex 2D hydrodynamics.

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