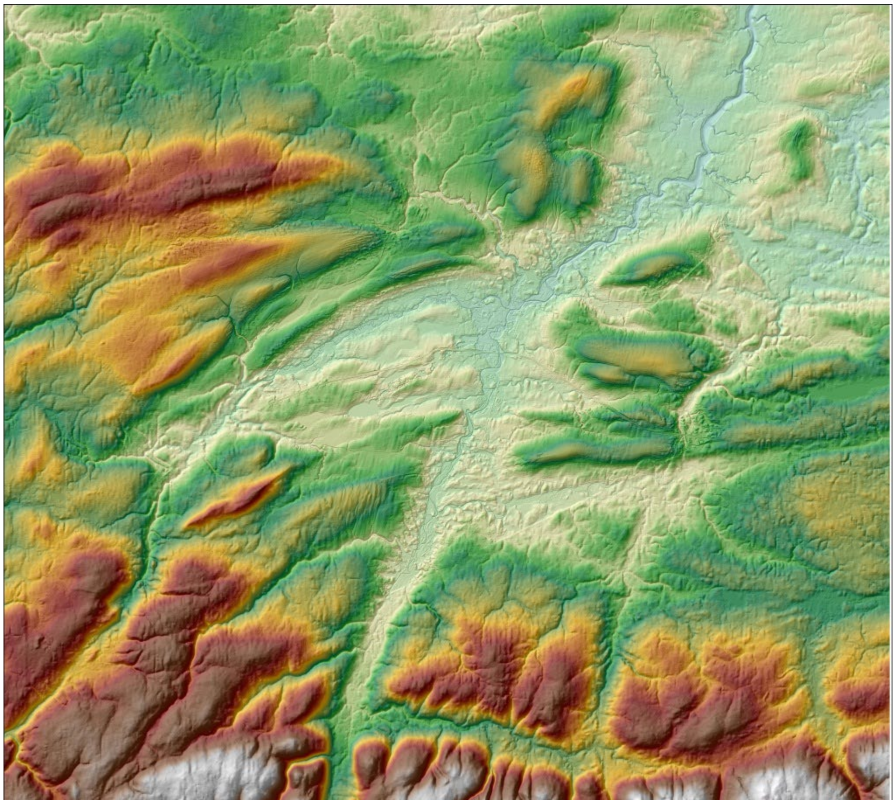
Near Shore and Estuary Bathymetric Mapping to Support Integrated River and Coastal Hydrodynamic Flood Risk Mapping



Tim Webster, PhD
Nathan Crowell, Kevin McGuigan, Kate Collins
Applied Geomatics Research Group
Centre of Geographic Sciences
NSCC, Middleton
Tel. 902 825 5475
email: timothy.webster@nscc.ca

Submitted to

Climate Change Directorate
Will Green
Climate Change Adaptation Specialist
Nova Scotia, Department of the Environment
March, 2012

Executive Summary

This project has demonstrated the need to integrate costal tidal-surge models with watershed river run-off models in order to accurately model flood risk for communities located along estuaries. The discharge of rivers during rainfall run-off flooding events is often influenced by the tide in the downstream estuary. Thus, in order to accurately model the flooding upstream, one must take into account the interaction of the river discharge and the water level conditions in the estuary. In order to use hydrodynamic models, weather two-dimensional coastal circulation or one-dimensional river hydraulic, one must have adequate information about the topography. In the case of floodplains and terrestrial areas, laser altimetry, or lidar, provides the detail to generate high-resolution elevation models representing the bare-earth, or surface models representing the objects on the earth. However, bathymetric information is severely lacking for estuaries and river beds. Limited bathymetric data exists for the off shore areas in the form of nautical charts, however these do not approach shore, are of limited resolution and are typically dated. We have used a low cost depth sounder coupled with survey grade GPS to track the variations in water levels in tidal environments during surveys. The GPS data has been used to constrain the elevation of the boat and combined with the soundings to produce depths that have been processed to a common vertical datum, in this case the Canadian Geodetic Vertical Datum of 1928 (CGVD28).

We have collected bathymetric data in the LaHave and River Phillip estuaries. Only River Phillip has lidar coverage along the floodplain upstream to Oxford, which is prone to flooding and local officials have indicated that the tide influences the stage of the river there. As a result we have only applied our couple river runoff watershed model with the coastal two-dimensional model in this area. We have simulated a river flooding event for Oxford from Sept. 1999. As a result of the limited number of tide gauges in the region and specifically along this coast of the Northumberland Strait, we have used a coastal boundary condition that mimics the Dec. 21, 2010 storm conditions in the Strait since we have a record of the 1.5 m surge at that time. We have combined these two events to demonstrate that the tide has an influence on the river stage 18 km upstream in Oxford. We have had to use limited daily rainfall and temperature data to model the 1999 event and expect our results could be improved with better temporal environmental data. However our results indicate this type of coupled river runoff and coastal model should be employed at other coastal communities in Nova Scotia to assess flood risk.

Contents

Figures

1. Introduction

In the current ACAS project, flood inundation maps were constructed in a GIS using still water levels of past events and possible future levels from sea-level rise and climate change (see Webster *et al.*, 2012 for details). In order to advance the use of coupled river (one-dimensional model) and coastal (two-dimensional model) hydrodynamic models, bathymetric information is critical. For most areas around Nova Scotia, the only available bathymetric information is in the form of charts which consist of sparse dated point soundings. The near shore coastal areas have not been mapped and there is no bathymetry information for the estuaries and rivers. This lack of information severely limits the application of these types of sophisticated hydrodynamic models (such as Mike 21 and Mike 11 from DHI) in this environment. The high resolution lidar only covers the land to the low tide mark, after that the data are very sparse or nonexistent.

In this project we conducted bathymetric surveys of River Phillip and the LaHave River, which are both important estuaries that are part of the ACAS study. AGRG researchers used their boat and depth sounder equipped with GPS that is capable of collecting these data. We then used these bathymetric data to generate a continuous seamless DEM incorporating the lidar and chart information.

River Phillip had lidar high-resolution elevation data collected along the coast and either side of the estuary up to the town of Oxford, however the critical bathymetric and river cross-section information was missing. This seamless DEM allowed for the construction of river cross-sections (used to model river stage and flow momentum) and the two-dimensional bathymetry near shore that is critically required for these integrated one and two-dimensional hydrodynamic models. The watershed draining into River Phillip extends landward for several kilometres where the land cover is dominantly forest covered (Figure 1). The degree of clear cutting and regeneration of the forest was qualitatively evaluated by examining historical Landsat satellite images for the watershed (Figure 1).

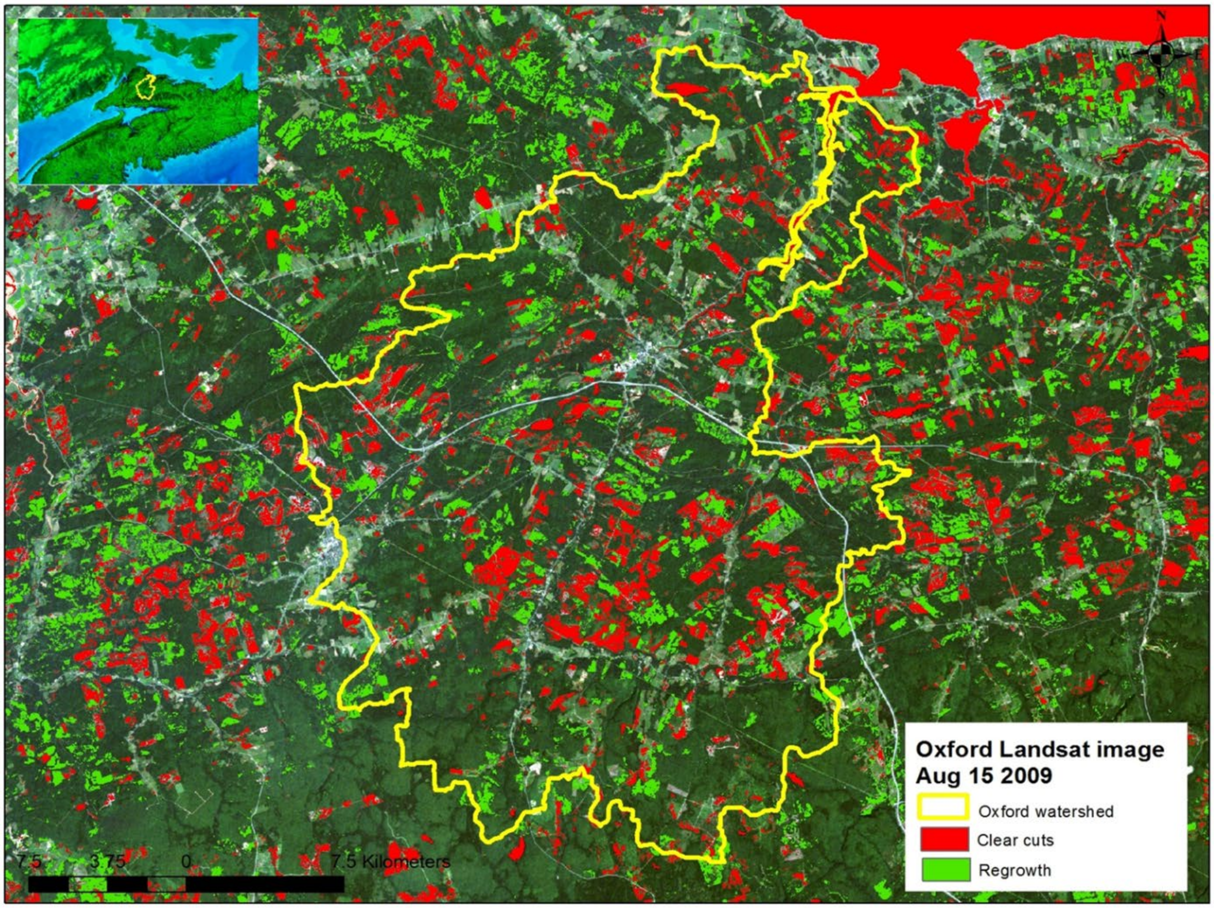


Figure 1. Watershed of River Phillip (yellow outline) with Landsat image backdrop, top left corner show inset location map. The red patches represent clear cuts between 2009 and 1999 and the green patches represent regrowth between 2009 and 1999.

The coastal areas of the District of Lunenburg have been covered by airborne lidar (see Webster *et al.* 2012). However, no lidar data exists for the banks and floodplain of the LaHave River and the watershed extends over half way across the province (Figure 2). Depth sounding measurements were acquired that overlapped the CHS chart information up to the town of Bridgewater (Figure 3). Upstream of Bridgewater, the river is too shallow to safety acquire bathymetric data. Surveys were conducted to capture cross-sections of the river as well as the channel (Figure 3). However, since lidar does not exist along the floodplain of the LaHave River and the size of the watershed, it appears the existing data is not sufficient to warrant modeling efforts. The reminder of the report concentrates on our efforts in the River Phillip estuary where sufficient data exist to allow for detailed modeling to test the interaction between river discharge and tidal water level conditions.

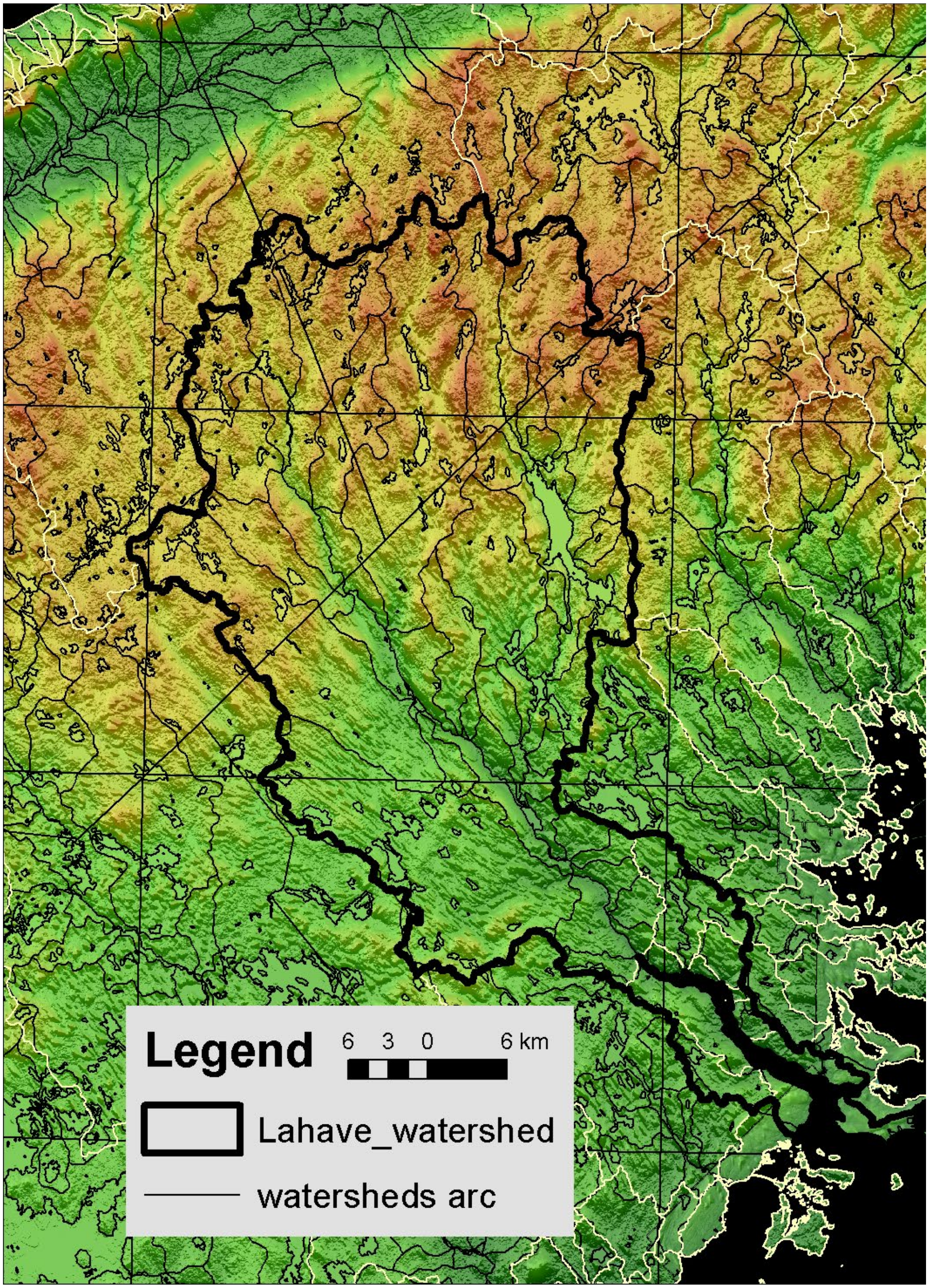


Figure 2 LaHave River watershed (thick black line) with secondary watersheds (thin black line) over a 20 m colour shaded relief DEM. Lidar coverage exists for the coastal areas only.

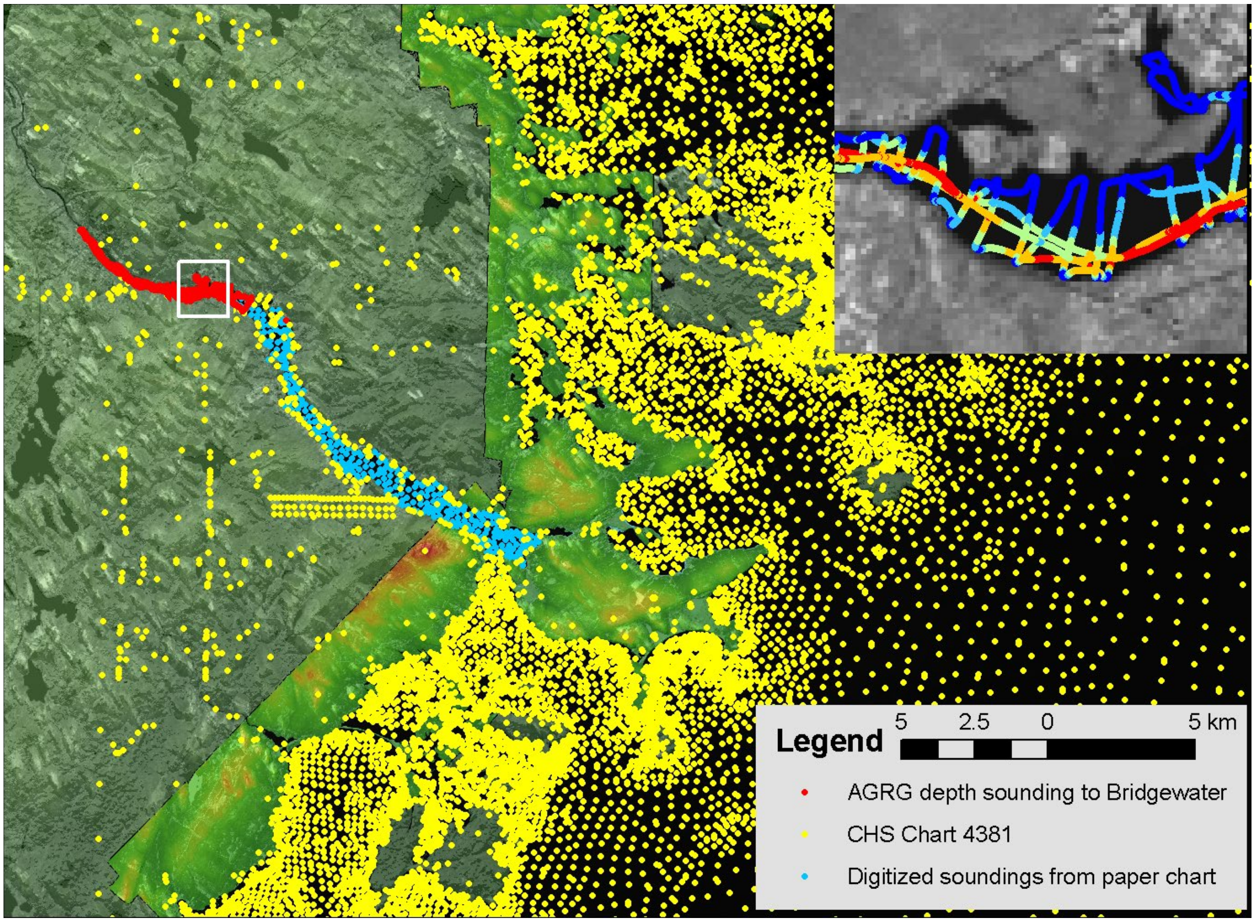


Figure 3 Sounding information available in digital format (yellow points), digitized from paper chart (blue points), and our survey (red points) up to Bridgewater, white box denotes detailed inset map of depths (upper right). The background map is the 20 m DEM except along the coast where lidar exists.

2. Methods

2.1 Topographic Data Collection and Integration

One of the most crucial aspects of hydrodynamic modeling is the accurate definition of geomorphology within the area of study. In this study, terrestrial and bathymetric geomorphologies were surveyed and interpolated using the techniques described in detail below.

2.1.1 Bathymetric Elevation Data

Model bathymetry roughly covered the extent of Pugwash Harbour, Pugwash Basin, and the northern extent of River Phillip. Bathymetric data were composed of coarse resolution Canadian Hydrographic Services (CHS) digitized nautical chart soundings (Chart 4023) localized around Pugwash Harbour and the Northumberland Strait. CHS soundings were converted from chart datum to CGVD28 in order to establish a common vertical datum between all datasets. Due to the sparse point density of the CHS soundings, supplemental data were collected using a small boat equipped with a Huminbird 957c sonar transducer to measure depth (precise to 10 cm vertically). Sonar surveys were conducted in tandem with a real-time kinematic (RTK) differential global positioning system (GPS) surveys in order to precisely attribute geographic coordinates to surveyed depths (accurate to 2.5 cm in three dimensions) (Figure 4). Sonar surveys were concentrated in areas that lacked sufficient data for hydrodynamic modeling such as river branches and shallow water bodies. In areas where soundings were acquired, a cross-sectional approach was adopted where transects were surveyed in straight lines between river banks where possible.

Figure 4. Low-cost bathymetric survey setup. The Huminbird depth sounder was mounted at the stern of the boat under the code GPS antenna (A). An RTK GPS survey was conducted in unison with the sonar survey in order to attribute geographic coordinates to sounding elevations (B).

2.1.2 Terrestrial Elevation Data

Bathymetric data were supplemented with high resolution light detection and ranging (lidar) elevation data surveyed May 12th of 2006 around the town of Oxford, Port Howe, and River Phillip Estuary on October 28th and 29th of 2009 for surrounding coastal areas (see Webster *et al.* 2012 for details). Lidar surveys were conducted using an Optech Airborne Laser Terrain Mapper (ALTM) 3100 at an altitude of 1600 m above ground level with a pulse frequency of 70 kHz and a scan angle of 20° at a frequency of 30 Hz. LiDAR elevation data were geometrically corrected and classified into ground and non-ground returns. The ground points from the corrected data were rasterized into a digital elevation model (DEM) with a cell resolution of 1 m using a linear triangulated irregular network (TIN) interpolation technique. The high resolution lidar grid was validated against an RTK GPS survey of roadway elevations within the study area. Standard lidar does not penetrate water, so it was insured that surveys were conducted at low tide. As a result, several coastal features within the study area were clearly defined within the dataset. Inland terrestrial elevations which fell outside the lidar survey extent were obtained from the Nova Scotia Topographic Database (NSTDB) 20 m resolution Nova Scotia DEM. Elevation values in the database had a 2.5 m vertical resolution and were derived using stereo aerial photography.

2.1.3 Interpolated Data

An interpolation algorithm was required to fill gaps in the bathymetric data to create a continuous surface elevation raster suitable for hydrodynamic modeling. Gaps in the data occurred between CHS soundings and between sonar survey transects in River Phillip (Figure 5).

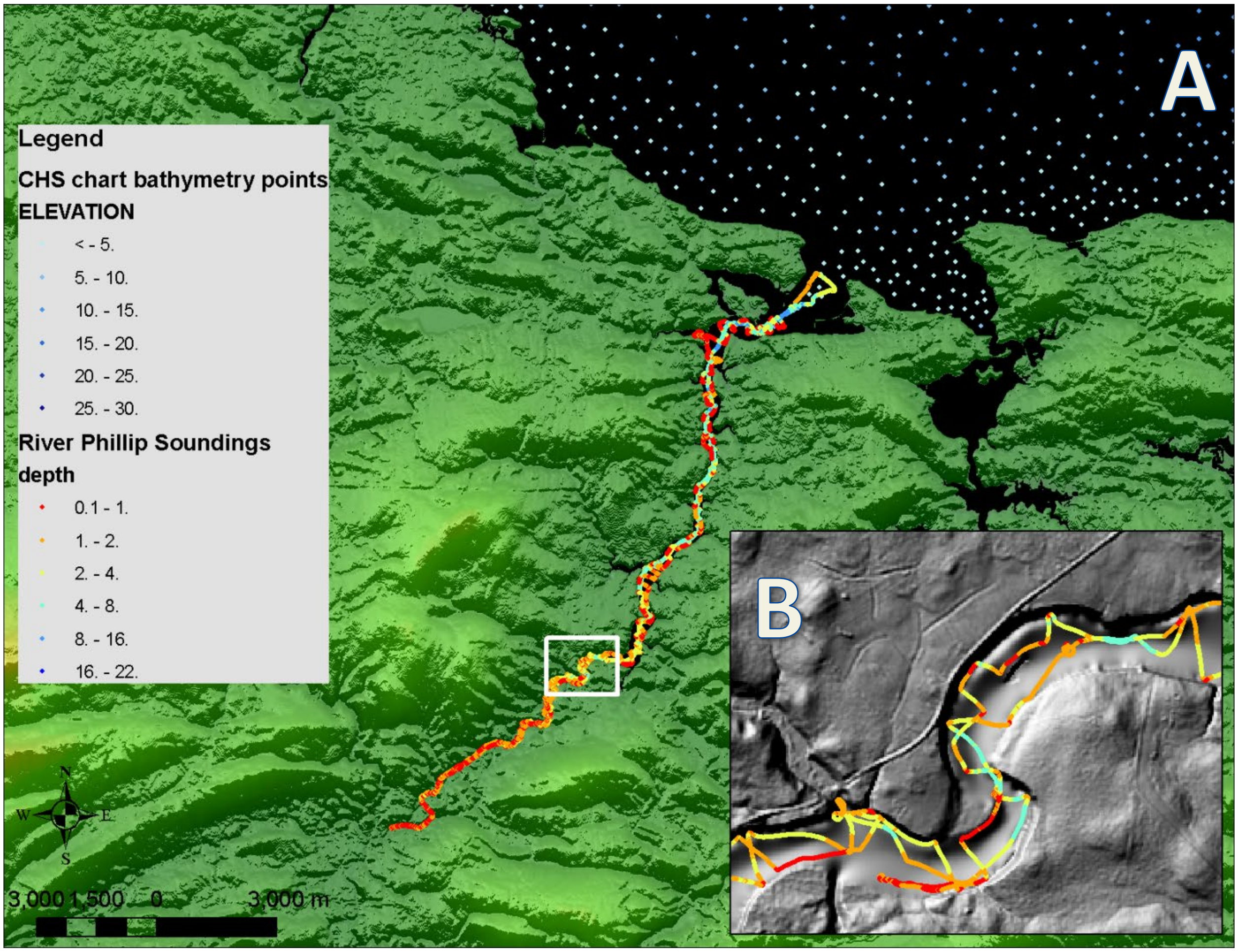


Figure 5. Sources of bathymetric data around the River Phillip modeling domain. Sparsely spaced CHS soundings were concentrated in Pugwash Harbour and Northumberland Strait boundary (A). Sonar survey points were more densely concentrated along survey tracks, but large gaps were present between survey lines (B). Gaps between measured points were interpolated to ensure a smooth bathymetric surface.

A novel approach was used to interpolate the River Phillip system which ensured that flow characteristics could be properly modeled within the intertidal system. The method relied heavily on river transects surveyed using the Huminbird sonar system. Each transect along River Phillip was converted into a two dimensional cross section. The lowest point within each cross section was defined as the river thalweg. Between transects, the thalweg position was digitized as a line using the observed fluvial geomorphology. A linear interpolation was used to estimate the elevation of the digitized thalweg line between the extracted transect points at a 5 m sampling interval. Dense sampling of the thalweg ensured that the critical hydrological morphology of River Phillip would be maintained after interpolation was performed. Once the River Phillip data were prepared, a spline with boundary interpolation was used to fill the remaining gaps in the bathymetric data. The boundary of the spline corresponded to the extent of low elevation non-water lidar returns. The spline technique ensured a smooth bathymetric surface which extended to the intertidal lidar extent despite the coarse and irregular point spacing of CHS soundings while the boundary ensured that lidar data were left unaffected. The final product was a seamless transition between interpolated bathymetric elevations and terrestrial elevations. The surface was gridded at a 54 m cell resolution for the purpose of two-dimensional hydrodynamic modeling, and a 5 m cell resolution for watershed and one-dimensional hydrodynamic modeling.

2.2 Mike21 Two-Dimensional Hydrodynamic Model

A high resolution hydrodynamic model was developed using the DHI Mike21 software module in order to simulate tidal events. This two dimensional hydrodynamic model provided the linkage between deep ocean tidal predictions and inland tidal events by simulating water level variations and flows over modeled bathymetry in response to a forcing tidal boundary condition at the northern extent of Pugwash Harbour, Nova Scotia (Figure 6).

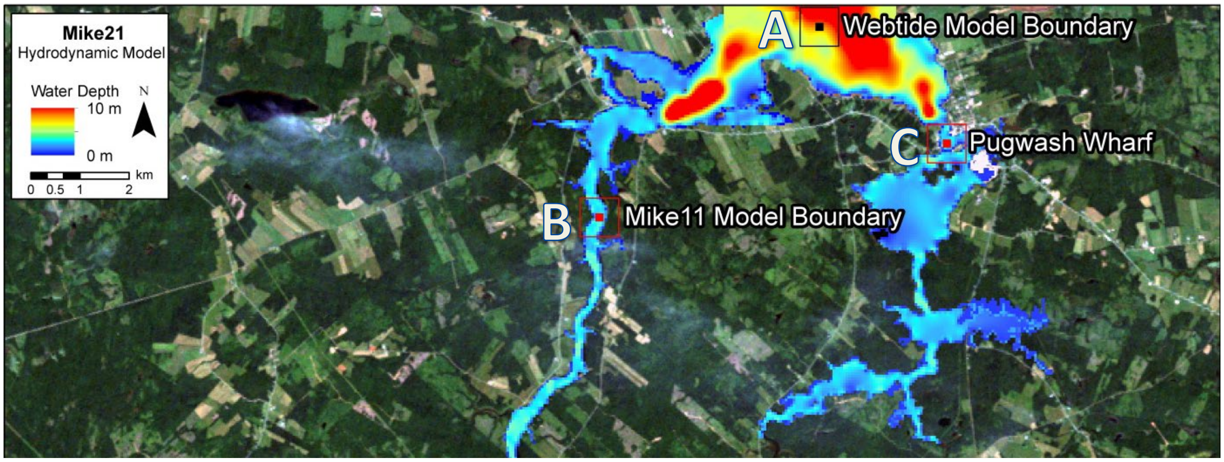


Figure 6.Overview of the Mike21 modeling domain. Flooding was simulated on a coarse resolution grid with a cell resolution of 2916 m^2. Simulations recorded water depth, shown above, surface elevation and current magnitude at a 5 minute time-step interval. The model was driven by WebTide sea-surface elevation predictions at the northern boundary (A). Surface elevations were extracted over two points of interest: (B) The Mike11 Model Boundary point for integration with Mike11 simulations, (C) The Pugwash Wharf for validation purposes.

2.2.1 Bathymetry

The bathymetry used for Mike 21 hydrodynamic simulations was the 2916 m^2 cell surface discussed within the *Interpolated Data* section. The coarse resolution aided in model stability and system performance during simulation periods.

2.2.2 Boundary Condition

The boundary condition was developed using deep ocean tidal predictions obtained from the Department of Fisheries and Oceans WebTide Tidal Prediction Model (v0.7.1). The WebTide application was used to predict ocean elevation within the Northumberland Strait using five tidal constituents. Predictions were made at latitude 45.872, longitude -63.702. This coordinate was coincident with the central portion of the open ocean boundary of the Mike21 hydrodynamic model (Figure 6). Predictions were made at 5 minute intervals for the duration of 20 years between the dates of January 1st 1995 December 31st 2015. The gaps between points along the boundary were filled using a linear interpolation for each of the 5 minute predictions. The end result was a predicted ocean elevation boundary which was suitable for forcing the simulation of high resolution hydrodynamics within the study area over the 20 year prediction period.

2.2.3 Two-Dimensional Hydrodynamic Model

Once the bathymetry and boundary condition were developed, a Mike21 hydrodynamic simulation was created and executed for calibration and validation purposes between the dates of July 14th and July 30th of 2010. Model results were extracted at the location of a tide gauge installed under Fisherman's Wharf on Brickyard Road in Pugwash (Figure 6). Comparisons were made between model predictions and gauge observations in order to establish proximal tide phase differences and elevation residuals caused by environmental factors. Once the model parameters were validated, a simulation was created for the period between December 10th of 2010 and January 6th of 2011 during which time a significant storm surge was recorded within the Northumberland Strait. To model this event, the predicted tidal boundary was modified to add a 1.5 m storm surge as observed elsewhere for this event. Mike21 model results were extracted at an inland portion of River Phillip which was coincident with a Mike11 Watershed / One-Dimensional Hydrodynamic Model boundary (Figure 6). Tidal elevations extracted at the Mike11 boundary were used to investigate the influence of tide on the magnitude of flooding within the town of Oxford.

2.3 Mike11 Watershed Model

A watershed model was developed in order to simulate the hydrological cycle within the area of study. The watershed phase of the hydrological cycle was modeled using a mathematical model while evapotranspiration and precipitation were integrated using environmental observations. Watershed model development and integration of environmental input factors are described in detail below.

2.3.1 Model Hydrology

A watershed model was developed using the DHI Mike11 rainfall-runoff software module in order to simulate the rainfall-runoff processes at a catchment scale. Within the rainfall-runoff modeling framework, a rainfall dependent inflow and infiltration (RDII) model was used to represent catchments that generate lateral inflows to river networks. The RDII model accounted for the water content in three different and mutually interrelated storages (surface storage, lower zone storage, and ground water storage) which represented different physical elements of each catchment. Specific model parameters which managed the routing characteristics between stores were adjusted based a record of observed discharge in response to environmental events. A full list of model parameters can be viewed within the Appendix of this report. Observed discharge was calculated for a gauged portion of the watershed, and is explained in detail within the *Rating Curve* section below. In addition to the conceptual RDII parameters, the rainfall-runoff model required a set of physical and environmental inputs to execute a successful simulation. These inputs consisted of the meteorologically controlled aspects hydrological cycle such as evapotranspiration and precipitation, detailed in the *Environmental Input Data* section below, and the physical drainage areas covered by each of the model catchments, detailed in the *Input Catchments* section below.

2.3.2 Environmental Input Data

Environmental data were required as inputs to the Mike11 rainfall-runoff module. Hourly Temperature (°C) and precipitation (mm) observations were retrieved from the Weather Underground Inc. website for an Environment Canada meteorological station in Nappan for the period from June 20th 2004 to December 31st 2011. Daily precipitation and minimum/maximum temperature values were retrieved for the same observation station from the Environment Canada website for the period from January 1st of 1998 to December 4st of 2003 because these historical observations were unavailable from Weather Underground Inc. These data were supplemented with observations from AGRG weather stations located at Oxford and Collingwood (Figure 7) for the period of November 9th to 19th of 2011.

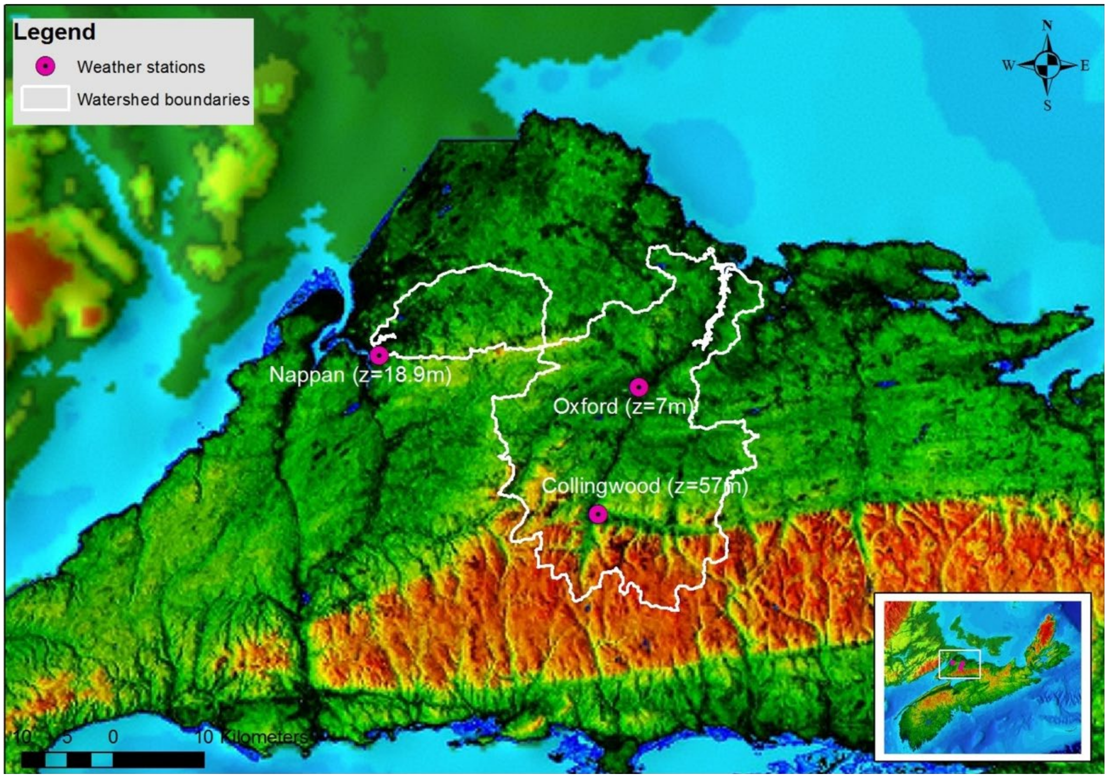


Figure 7. Environment Canada meteorological station within the Nappan watershed to the west and AGRG weather station locations established November 9th of 2011 within the Oxford watershed to the east. Z indicates weather station elevation.

AGRG weather station data were compared against the Environment Canada meteorological station observations during a period of overlap from November 9th to 19th of 2011 to ensure consistency between sources. Precipitation data were used as a Mike11 rainfall-runoff model input, and temperature data were used to calculate evapotranspiration for catchments within the study area. Evapotranspiration was calculated using a lengthy set of equations which can be viewed within the Appendix of this report. Evapotranspiration was recorded at a daily interval using Environment Canada temperature data recorded before 2004, and hourly interval using Weather Underground temperature data recorded after 2004. Once complete, the evapotranspiration data were used as a Mike11 rainfall-runoff model input.

2.3.3 Input Catchments

The River Phillip watershed extent was calculated using a suite of hydro tools within the ESRI ArcMap 10 software package which relied heavily on elevation data obtained from the constructed 5 m DEM discussed in the *Topographic Data Collection and Integration* section above. The tools were used to simulate theoretical drainage between adjacent cells based on elevation to form watershed boundaries and river networks based on accumulated flow calculation. The DEM was appropriately prepared by lowering elevation values where culverts or bridges existed to ensure proper drainage characteristics between adjacent cells. In the correction process, each structure was removed from the DEM and the lowest surrounding elevation value was used to fill the gap. The River Phillip watershed was delineated as the extent of cells which drained into River Phillip. This extent was calculated to be an area of 681.59 km^2. River branches and contributing catchments were delineated when accumulated flow areas surpassed 150 000 m^2 (Figure 8). Catchment areas were used as an input parameter within the Mike11 Rainfall-Runoff model.

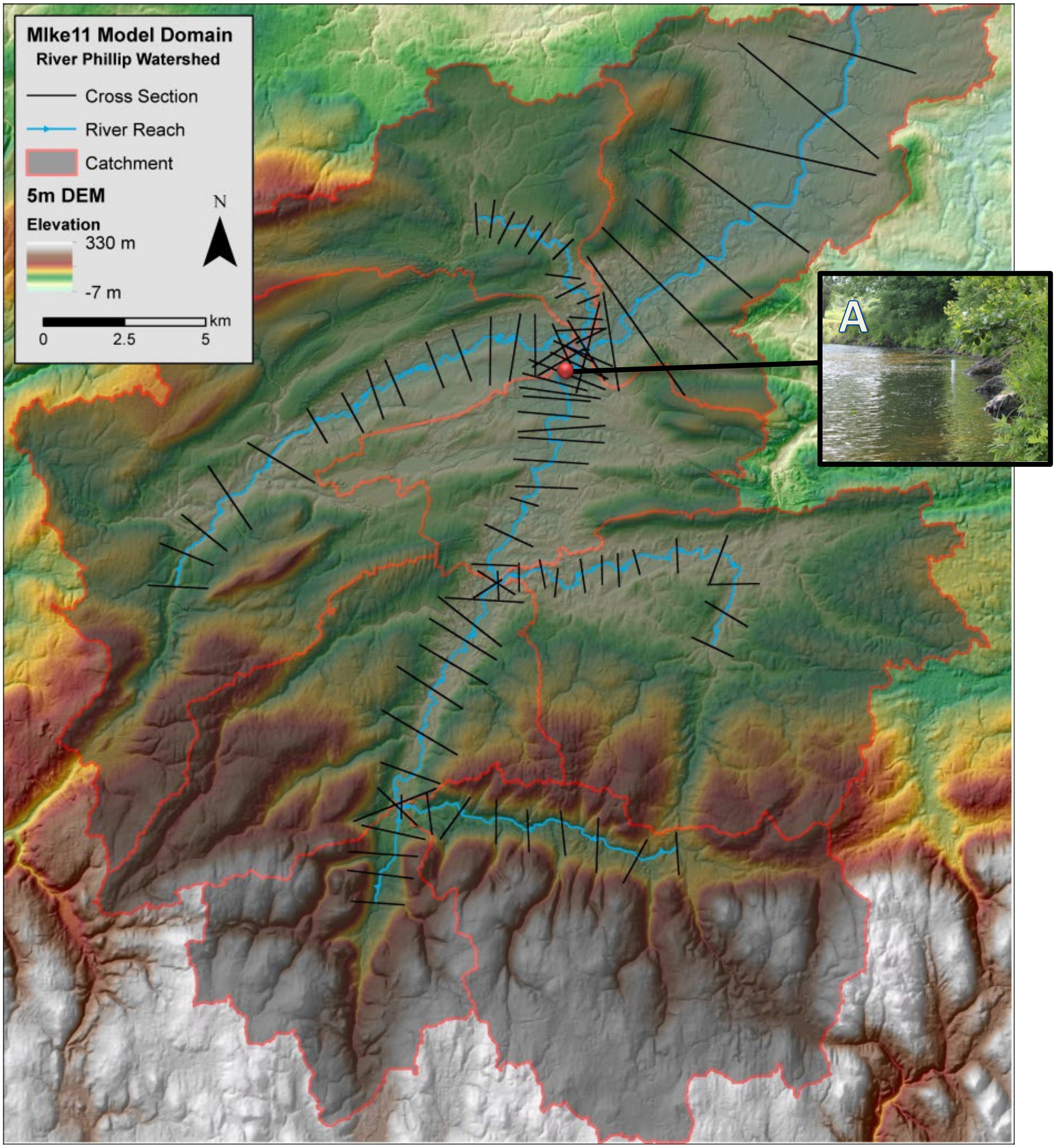


Figure 8. Overview of the Mike11 modeling domain with critical model components such as watershed catchments, river reaches, and cross-sections delineated over the 25m^2 DEM used to create them. A pressure transducer was used to gauge river stage at an upstream portion of the River Phillip watershed (A).

2.3.4 Rating Curve

A Solnist pressure transducer was installed in close proximity to the Water Street Bridge to record water depth at a 15 minute interval for the period between June 8th and September 14th of 2011. The sensor location was recorded using an RTK GPS survey, accurate to within 3 cm vertically. Sensor depth observations were converted to stage elevations by measuring the offset between the sensor position and the recorded depth. Variance in barometric pressure was compensated for using readings from a second pressure transducer which was installed above the floodplain. Discharge values were calculated from gauged elevation data using the rating curve methodology discussed below. The data were used to calibrate and validate both the Mike11 Rainfall-Runoff and Hydrodynamic models.

A rating curve was calculated for the River Phillip watershed in order to establish the relationship between discharge and river stage. Once established, the rating curve would allow discharge to be calculated based only on river stage data. In situ discharge measurements were taken using a Valeport electromagnetic (EM) flow meter or a Valeport suspended impeller flow meter depending on safety requirements related to river stage. The method of flow calculation was the same for both units; flows were recorded under a bridge on Water Street perpendicular to the river orientation at a 2 m sampling interval. Velocity was measured for each of the 2 m columns using the average of 30 second sampling intervals which recorded 1 sample per second. For depths less than 50 cm water velocity was measured at the 60% depth (in a water depth of 10 cm, a velocity measurement was recorded at 6 cm). For depths greater than 50 cm, water velocity was calculated using the average of a 20% depth measurement and 80% depth measurement. Velocity was averaged over each of the 2 m columns to produce an average flow measurement. Total discharge was calculated by summing flows from each of the 2 m columns. Discharge surveys were conducted on May 5th, June 8th, July 6th, and October 26th of 2011. The coordinates of the Water Street Bridge deck and rail were surveyed using a differential RTK GPS setup to within 3cm of vertical accuracy. River stage elevations were calculated by measuring the offset between the bridge rail and the water surface during each of the flow measurements. Equation 1 was used to calculate the relationship between stage and discharge for the catchment area upstream of the Water Street Bridge:

Equation 1:

$$Q = 22(G - a)^{1.5}$$

Where Q = discharge (m^3/s), G = the river stage (m), and a = the river thalweg (m).

2.4 Mike11 One-Dimensional Hydrodynamic Model

The Mike11 Hydrodynamic Model (Mike11HD) was used to simulate the flow of water through a network of river reaches. For a successful simulation, the model required a network, cross-section, and boundary input in addition to specific HD parameters. Model input components and parameters are discussed in greater detail below.

2.4.1 River Network and Cross-sections

The Mike11HD model required accurate stream and floodplain topography in order to simulate the flow of water through the system. The MikeGIS software suite was used to incorporate topographical data into the Mike11HD model setup. River network extents and catchments were imported from the accumulated threshold process described within the *Input Catchments* section above. The MikeGIS software was used to section the river network into unique reaches with length (chainage) measured in meters. Each reach was then linked with its appropriate catchment in order to create a stable network input for simulations.

The Mike11HD model did not continuously calculate flow along river branches; potential flows were calculated at defined cross-sections in order to transfer conveyance between cross-sectional distances. Cross-sections were manually digitized across river branches and flood plains perpendicular to the direction of flow. Cross-sections were roughly spaced at 100 m intervals along river branches while ensuring that a cross-section was drawn at the start and end chainage of each river branch. Cross-section width was dependent on topography and was ensured to capture potential flood plains during significant flooding events. The MikeGIS software was used to apply elevation data, extracted from the 25 m^2 DEM, to each cross-section (Figure 9). Conveyance was calculated for each of the two-dimensional cross-sections based on theoretical water elevation within the cross-section at 1 cm increments. Cross-section topography and conveyance potentials were stored within the final cross-section input file for HD simulations.

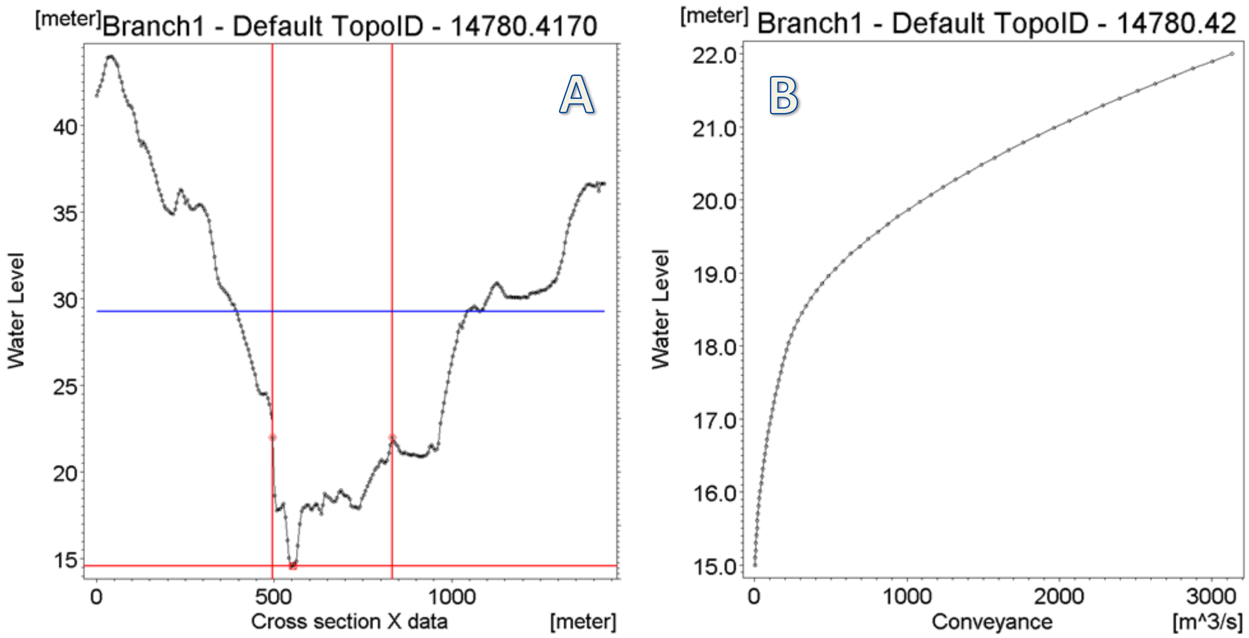


Figure 9. River branch 1 cross-section oriented perpendicular to flow (A). Elevation data along the length of the cross-section were extracted from the 25m^2 DEM. The minimum possible water level corresponded to the minimum elevation within the cross-section (horizontal red bar) and the maximum flood banks of the cross-section were drawn at the 22 m mark (vertical red bars). (B) Potential conveyance was calculated based on water level increments within the possible flood area (B).

2.4.2 Boundary Conditions

Precipitation events, captured in rainfall-runoff calculations, were transferred to the Mike11HD model though a series of boundary conditions. These boundary conditions linked lateral inflow calculated within the rainfall-runoff module for each catchment to its respective river reach using the river network file. The model was configured to account for tidal influence based on a water level boundary condition fed by the Mike21HD extraction point discussed in the *Two-Dimensional Hydrodynamic Model* section above.

2.4.3 One-Dimensional Hydrodynamic Model Parameters

Model parameters were used to specify the initial water level and discharge conditions. These values were adjusted based on environmental observations at the simulation start date. Mapping outputs and time-series were also specified within the parameter file. Flood maps were produced by transferring water elevations simulated at cross-sections to the 5 m DEM. A complete list of Mike11HD model parameters can be viewed within the Appendix of this report.

2.5 Integrated Model Simulations

An integrated model was developed by linking the Mike11 rainfall-runoff and one-dimensional hydrodynamic models to the Mike21 shallow water two-dimensional hydrodynamic model using a coincident boundary. This linkage provided the ability to simulate flood events which were driven by precipitation events or tidal influence.

2.5.1 Calibration and Validation

A long term simulation was developed to run from June 1st to September 30th of 2011 in order to calibrate, validate, and test the stability of model components. During the simulation period, discharge was observed for the gauged portion of River Phillip. Results of the simulation were used in an iterative process to adjust problematic bathymetry, calibrate rainfall-runoff module parameters, and validate the one-dimensional hydrodynamics.

2.5.2 Event Simulations

Integrated model event simulations were developed to measure the flood boundaries over significant weather events. A rainfall-based flood simulation was developed to model major flooding within the town of Oxford caused by the remnants of Hurricane Harvey which deposited over 300 mm of rainfall between the dates of September 21st and 23rd of 1999. The simulation was run for the period of September 1st to September 30th of 1999. Flood results from the simulation were compared against previous modeling performed by Doug Stiff (Stiff, 2008), observational data obtained from press documents (The Oxford Journal, 1999). A storm surge based flood simulation was developed to model a major storm event observed along the Northumberland Strait on December 21st of 2010 during which time tidal elevations were 1.5 m above predicted levels (Figure 10).

Figure 10. A photo from the Amherst Daily News which depicts waves impacting a portion of coastline west of River Phillip along the Northumberland Strait on December 21st of 2010.

The simulation was run for the period of December 10th of 2010 to January 6th of 2011. A combined events simulation was created by artificially merging the rainfall observations from the September 1999 flood simulation with tidal observations from the December 2011 flood simulation. This methodology effectively simulated flooding extents caused by the hypothetical scenario of a major rainfall event occurring during a significant storm surge. Summary statistics were calculated for each of the event simulations are comparisons were performed.

3. Results

3.1 Lidar

An RTK GPS survey of roadways within the collected lidar extent was conducted by AGRG to validate the final high resolution lidar grid for the area of Oxford and Port Howe. GPS points were collected on Oct. 28th and 29th of 2009 (Figure 11). Validation results showed a mean difference of -0.10 m and a standard deviation of 0.13 m between the lidar DEM and GPS survey. These results were found to be suspect, due to a potential error in the RTK configuration. As a result, GPS data were recollected on July 30th of 2010. Validation results from the second survey showed a mean difference of 0.00 m with a standard deviation of 0.13 m.

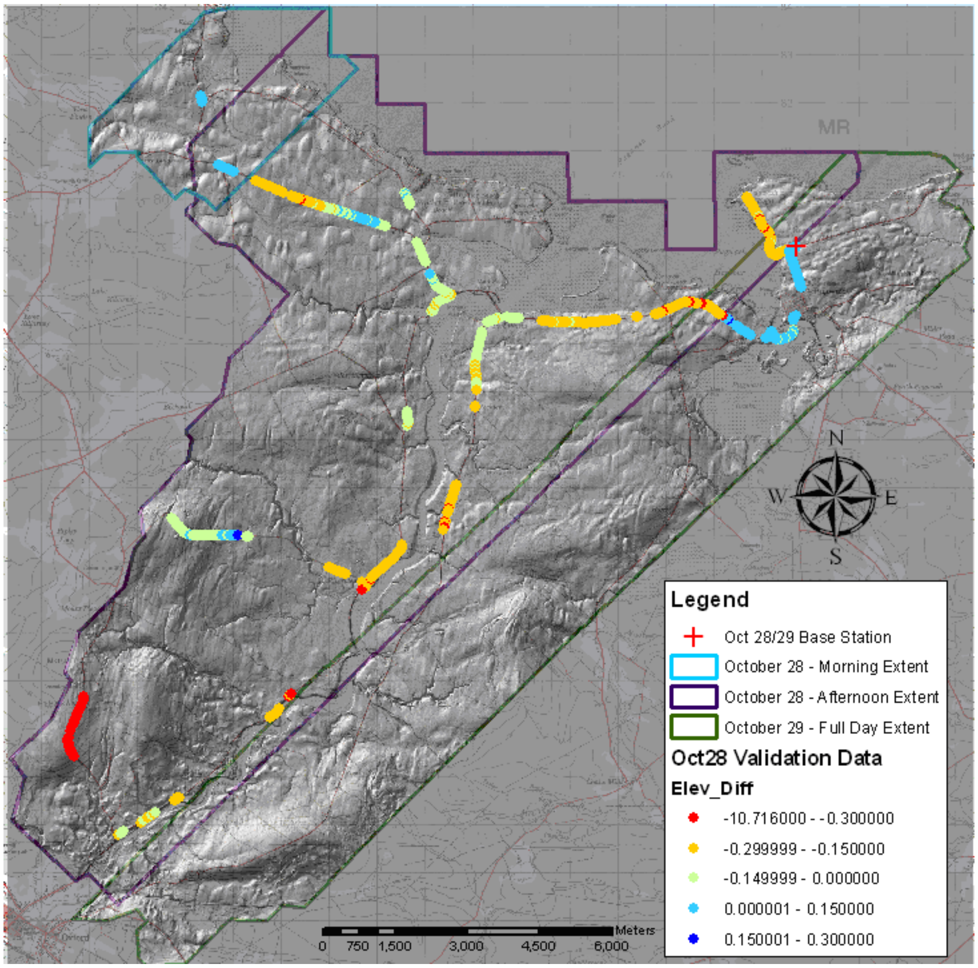


Figure 11. Survey extent and elevation differences between an RTK GPS survey and the high resolution lidar DEM for the Oxford-Port Howe area.

3.2 Mike21 HD Model

Comparison between Mike21 hydrodynamic results and the established tide gauge located in Pugwash showed a good overall agreement between simulated and observed tides (Figure 12).The Mike21 model was under estimating water elevation by -0.08 m, however a large amount of variance was observed around that average (SD 0.285).

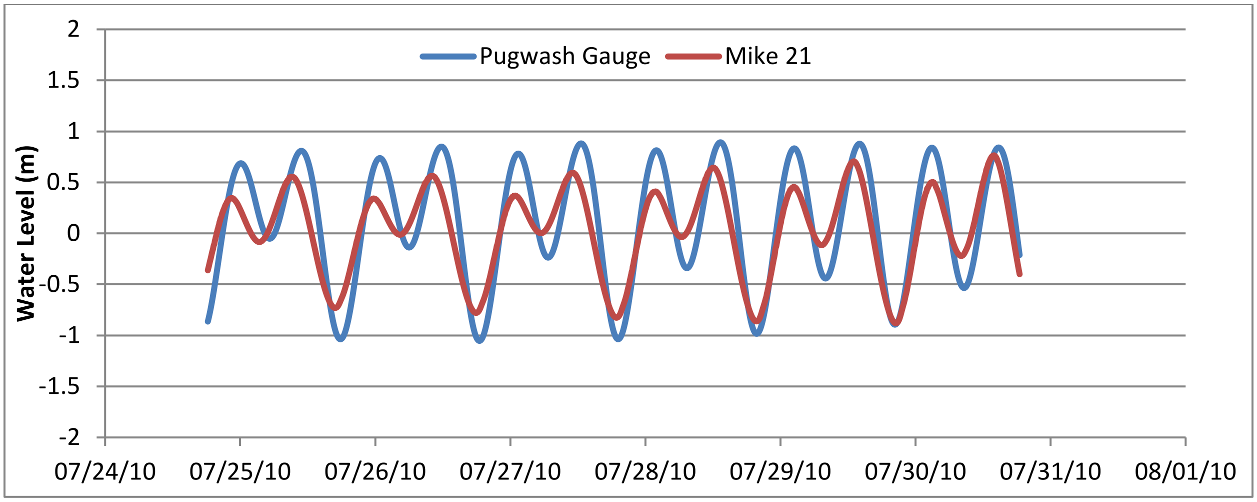


Figure 12. Mike21 hydrodynamic water levels extracted over an established tide gauge located at Fisherman's Wharf in Pugwash.

3.3 Mike11 Model Components

Several components of the Mike11 rainfall-runoff one one-dimensional models required calibration or validation. Mike11 component results are discussed in detail below.

3.3.1 Environmental Data

Weather Underground Inc. observations from an Environment Canada weather station in Nappan were validated against weather stations established by AGRG in Collingwood and Oxford (Figure 13). Comparison between data sources revealed little variability in temperature and pressure variables and high level of variability in precipitation and wind variables.

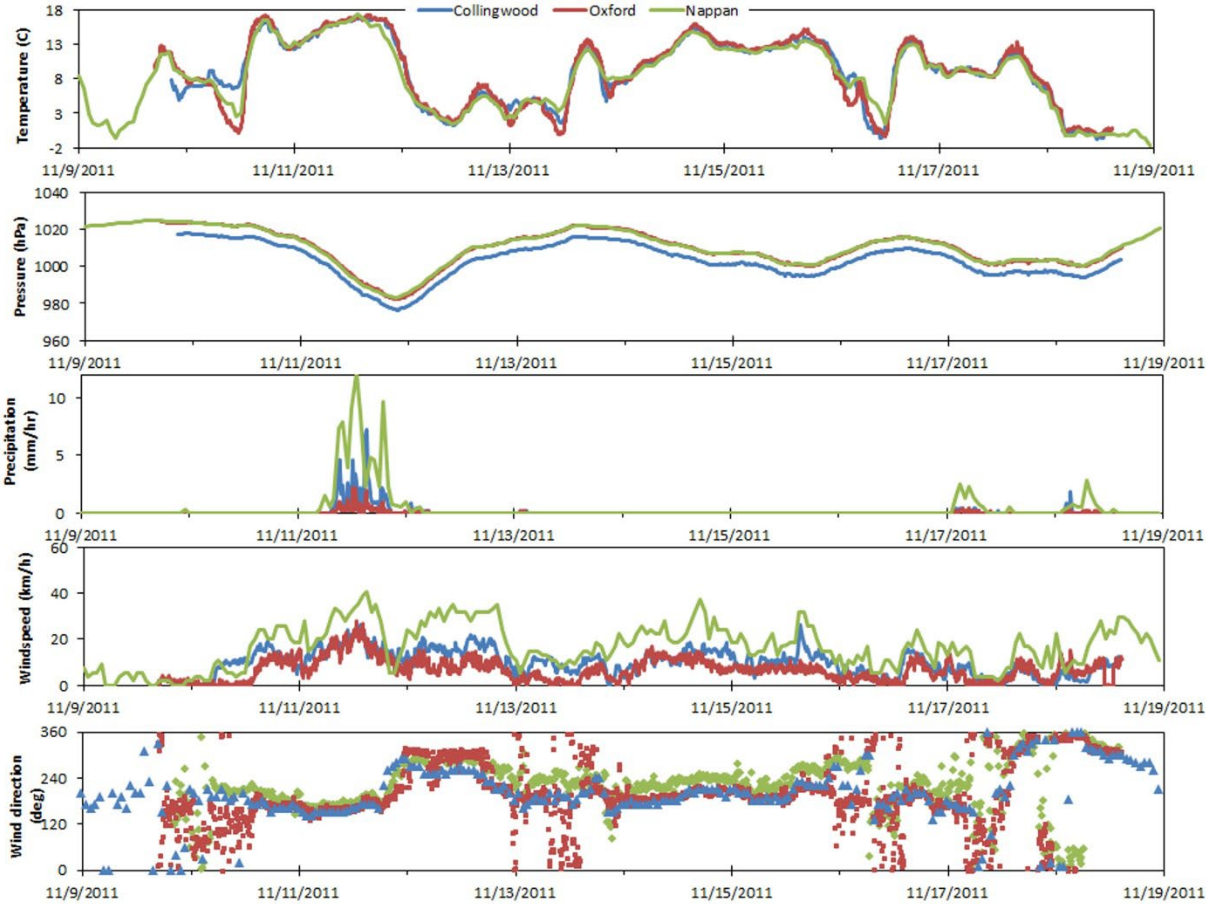


Figure 13. AGRG weather station observations from Collingwood and Oxford compared to Environment Canada observations from Nappan for the period from November 11th to November 19th of 2011.

3.3.2 Rating Curve Calculation

The rating curve was formed by calculating the relationship between *in-situ* flow observations and river stage and accounted for 98% of the variability within the data (R^2 = 0.98). The rating curve was found to be suitable for relating stage measurements recorded by a pressure transducer to discharge at the gauged portion of River Phillip (Figure 14).

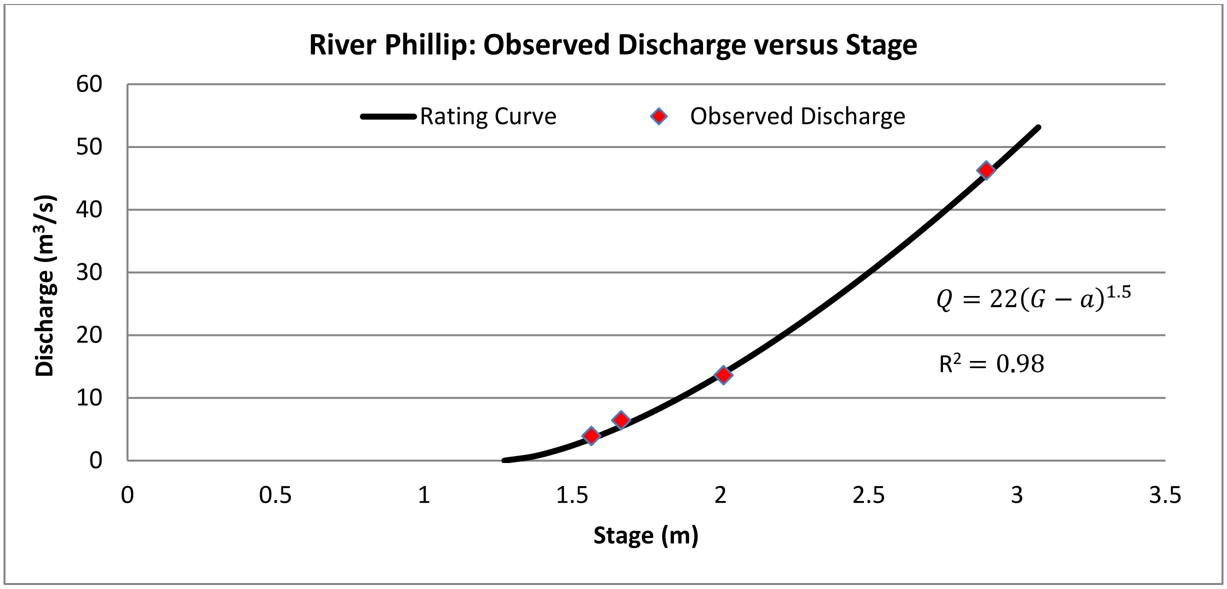


Figure 14. Rating curve for the gauged portion of River Phillip which related stage measurements to discharge observations using the data from four surveys conducted in 2011 by AGRG.

3.3.3 Rainfall-runoff Hydrograph

Mike11 rainfall-runoff model results were extracted over the location of the established pressure transducer and compared against calculated discharge values and rainfall observations for the model calibration period (Figure 15). Hydrograph results show the rainfall-runoff was able to represent periods of peak discharge most accurately.

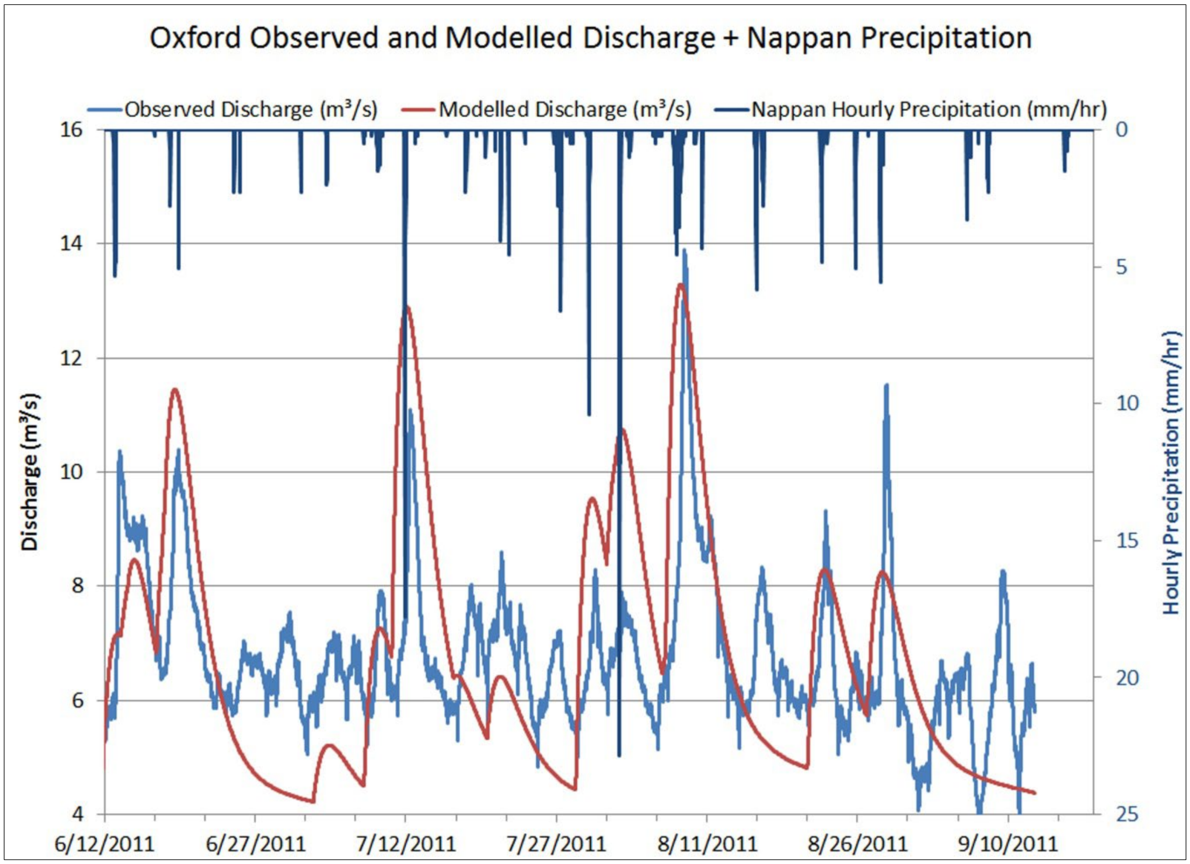


Figure 15. Hydrograph displaying Mike11 rainfall-runoff modeled discharge against observed discharge of the left axis and Nappan precipitation observations on the right axis.

3.4 Integrated Model Results

The surface DEMs were found to be suitable for both shallow water Mike21 hydrodynamic simulations and Mike11 rainfall-runoff and one-dimensional hydrodynamic modeling. The integrated model simulations were found to be computationally stable under strenuous high-flow situations and successfully simulated the September 1999 rainfall event, the December 2011 storm surge event, and the combined event model. The results of each simulation are described in detail below.

3.4.1 September 1999 Rainfall Event

Model results showed a significant flooding within the town of Oxford in response to high levels of rainfall between September 21st and September 23rd of 1999 (Figure 16). At the maximum extent 2.06 km^2 of land were flooded with an average depth of 1.85 m and a maximum overland flood depth of 6 m (SD = 1.47 m).

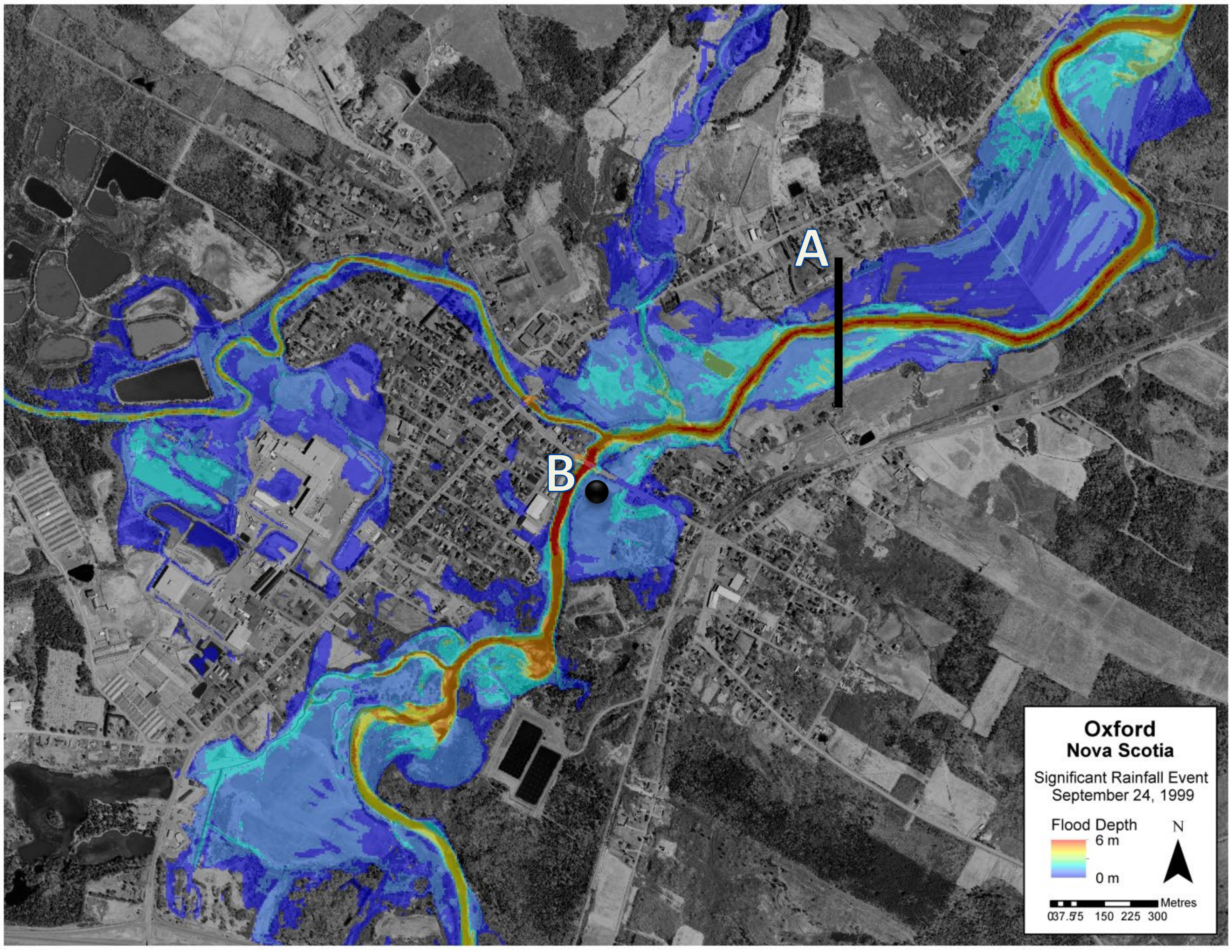


Figure 16. Integrated model results showing the peak flood level extent around the town of Oxford in response to over 300 mm of rainfall between the dates of September 21st and 23rd of 1999. Simulation results were extracted over a model cross-section for further analysis (A). Model results showed 1.6 m of flooding at a baseball field located along Water Street (B).

Model results were extracted along the length of a Mike11 cross-section displayed in Figure 16 over the simulation period. Extracted results showed a maximum discharge of 610 m^3/s when the river stage reached 5.8 m (Figure 17).

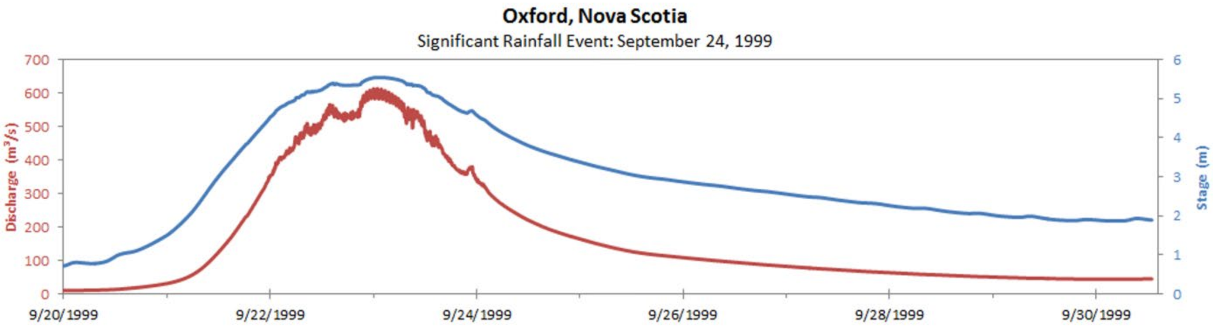


Figure 17. River Phillip stage (blue) and discharge (red) values extracted from the integrated model for the September 1999 rainfall event.

Results were enforced by observations made during the flood event at a baseball field to the south of Water Street where 1.5 m of flooding was observed compared to 1.6 m within the simulation (Figure 18).

Figure 18. Before and after photos showing a baseball dugout constructed within a floodplain to the south of Water Street in the town of Oxford. The structure was approximately 1.8 m in height (a), during the flood event about 1.5 m of the structure were submerged (b).

3.4.2 December 2010 Storm Surge Event

The storm surge simulation results showed far less flooding than rainfall event results. Flooding associated with the surge was concentrated in tidal floodplains (Figure 19). At the maximum extent 0.36 km^2 of land were flooded with an average depth of 0.63 m and a maximum overland flood depth of 4 m (SD = 0.77 m).

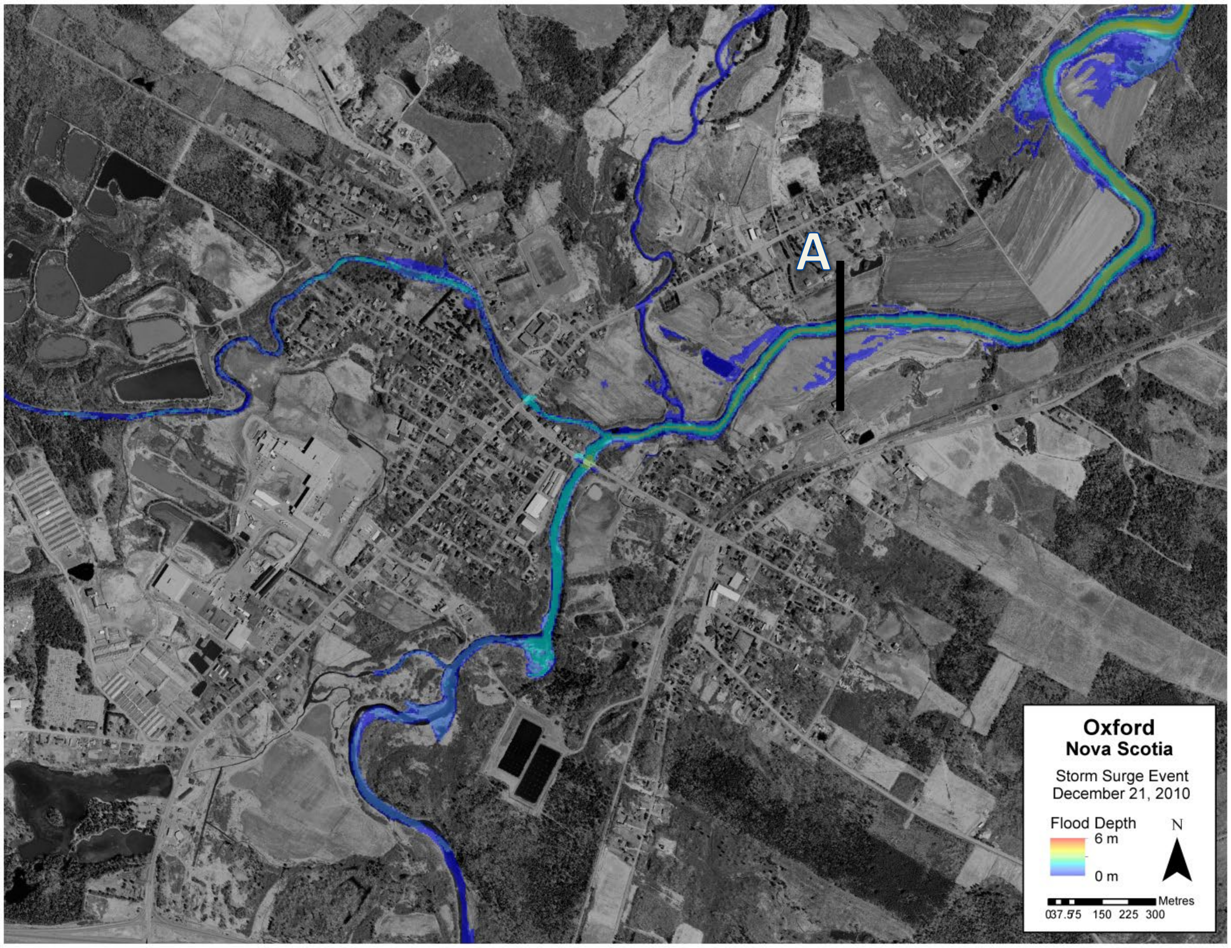


Figure 19. Integrated model results showing the maximum flood extent after the December 21st of 2010 storm surge event during which time a 1.5 m tidal surge was recorded within the Northumberland Strait. Simulation results were extracted over a model cross-section for further analysis (A).

Model results were extracted from the Mike11 cross-section and showed a maximum discharge of 22 m^3/s when the river stage reached 2.8 m (Figure 20).

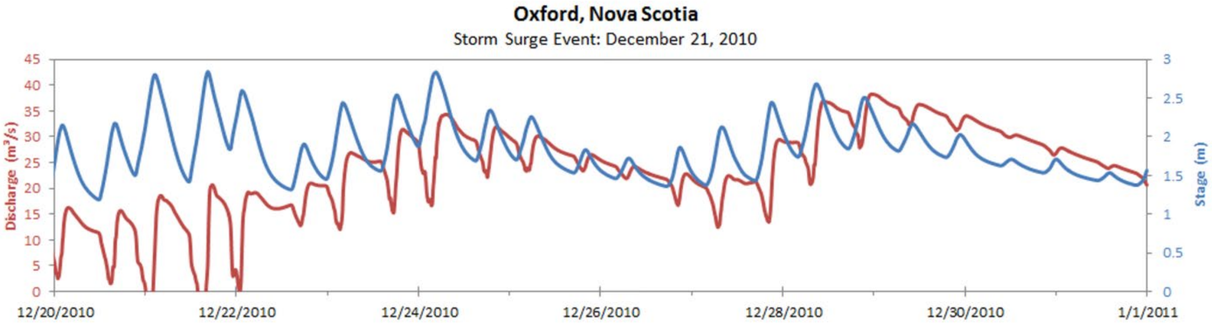


Figure 20. River Phillip stage (blue) and discharge (red) values extracted from the integrated model for the December 2010 storm surge event.

3.4.3 Combined Events Simulation

The combined events simulation was successful in producing a theoretical situation which introduced a 1.5 storm surge to the September 1999 rainfall event. Flood levels were greater in magnitude than the rainfall event alone (Figure 21). At the maximum flood extent, 2.44 km^2 of land were flooded with an average depth of 2.16 m and a maximum overland flood depth of 7 m (SD = 1.62 m).

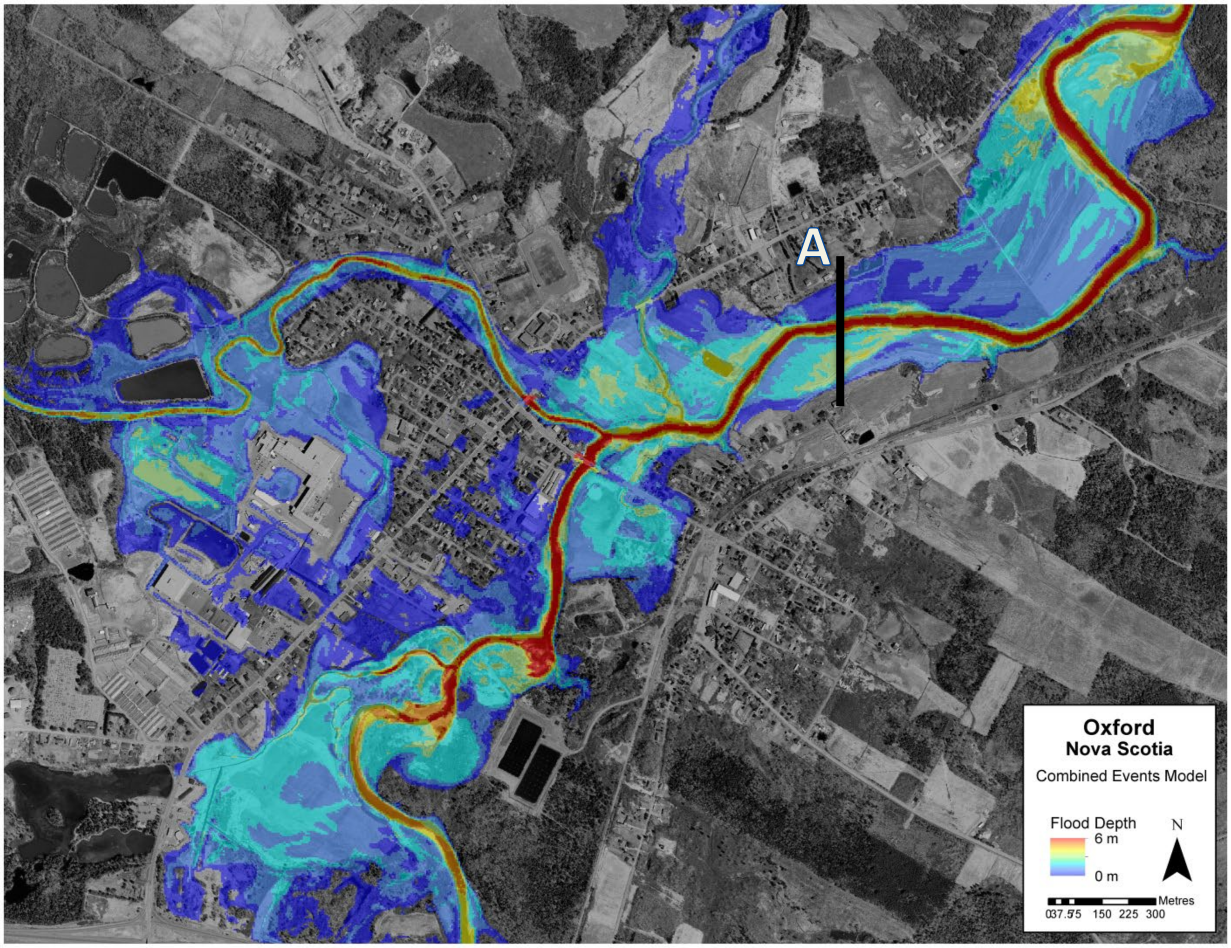


Figure 21. Integrated model results showing the maximum flood extent during a simulation which combined 300 mm of rainfall associated with the September 1999 flood event with a 1.5 m tidal surge recorded during the December 21st storm surge event. Simulation results were extracted over a model cross-section for further analysis (A).

Model results were extracted from the Mike11 cross-section and showed a maximum discharge of 825 m^3/s when the river stage reached 6.3 m (Figure 22).

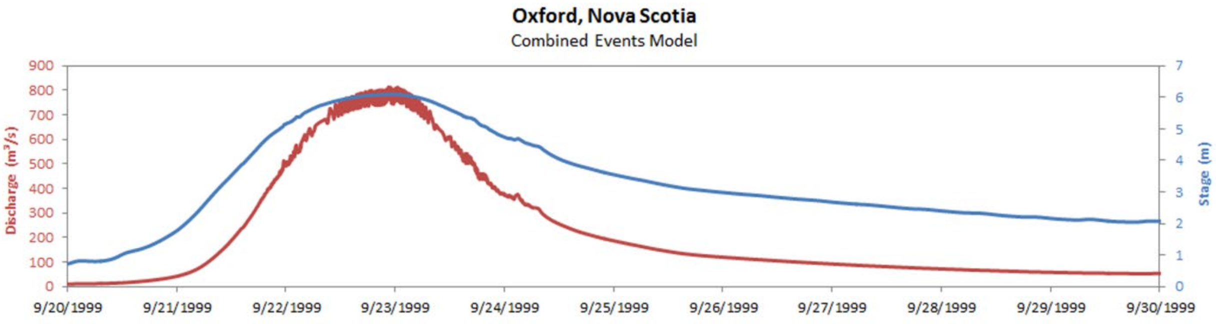


Figure 22. River Phillip stage (blue) and discharge (red) values extracted from the integrated model for a combined events model which combined the September 1999 rainfall event with the December 2010 storm surge event.

4. Discussion

4.1 Lidar Validation

Lidar data were used to form the 5 m grid which served as the basis for delineating river reaches, catchments, and cross-sections used within the Mike11 HD and RR models. The 5 m grid was successful in modeling lateral flooding which occurred between cross-section extents. Accurate lidar data was also found to be useful as a boundary condition for interpolating bathymetric data.

4.2 Mike21 HD Model

The Mike21 model successfully simulated the hydrodynamics of Pugwash Harbour in response to tidal influence. The influence of tide on the River Phillip system was transferred to the Mike11 one-dimensional hydrodynamic model using level extractions at coincident boundary between the two models. This model linkage was able to successfully simulate significant tidal surge within River Phillip and surrounding floodplains. Model validation results at Fisherman's Wharf in Pugwash showed a high level of variability between modeled and observed water levels. The bathymetry of Pugwash Basin was a major source of the observed error. The large intertidal basin was unrepresented in CHS sounding data and was not part of the low cost bathymetric survey performed by AGRG. As a result, water retention and flow within the basin were absent from the model elevation results extracted at the proximal tide gauge. A second and less critical source of error was the absence of environmental parameters such as barometric pressure and wind speed within the Mike21 HD model. Significant events would have been captured by the tide gauge and absent from model results. It is recommended that in future work any tide gauge used for validation purposes is installed within an area of known bathymetry and in close proximity to the model linkage boundary.

4.3 Mike11 HD Model

The one-dimensional HD model was able to accurately simulate flood events which occurred around the town of Oxford using simple cross-sectional flood extents. A potential drawback to this method of flooding is the absence of hydraulic connectivity checks along flooded cross-sections. This was not seen as a concern for the Oxford area due to the magnitude of modeled flooding and the flat topography. A more robust linkage between the Mike11 HD model and DEM could be established using the Mike Flood software suite. Unless required, it is suggested that Mike Flood simulations are avoided as they require substantially more processing time and space than Mike11 HD simulations.

4.4 Mike11 Rainfall-Runoff Model

Mike11 rainfall-runoff components and parameters are discussed in detail below.

4.4.1 Environmental Data

Sources of environmental data were able to supplying the Mike11 rainfall-runoff model with adequate input parameters to perform simulations. Possible inaccuracy within model results may have been generated by daily precipitation and temperature values retrieved previous to 2004. Daily values were interpolated to match the model time-step. Interpolation reduced the temporal accuracy of flood events and may have reduced severity of short-term rainfall events. A second possible source of error was the location of the Environment Canada weather station used to collect environmental data. The station, located within the Nappan watershed, was used to model events within the River Phillip watershed. The spatial offset may have generated errors of timing and magnitude for rainfall and, to a lesser extent, temperature. In future work, model accuracy may be increased by collecting environmental data on at least an hourly timescale from stations located within the watershed of interest if possible.

4.4.2 Rating Curve Calculation

The rating curve was extremely useful for monitoring river discharge when coupled with long-term stage measurements (June 8th to September 14th of 2011). Simultaneous discharge and weather records allowed for immediate comparison between simulated and observed discharge when adjusting rainfall-runoff parameters. This allowed for parameters to be adjusted in an iterative process rather than calculated based on theorized catchment hydrology.

4.4.3 Rainfall-runoff Parameters

The rainfall-runoff model parameters were configured uniformly for all catchments to simulate major rainfall events such as those which contributed to flooding during the September of 1999 event. As a result, the rainfall-runoff model was not able to perform as well during less severe weather events. This result was acceptable given the scope of the project and time constraints. The drawback could be corrected in future studies by configuring rainfall runoff parameters for individual catchments within the study area. This process would be expedited by gauging each of the parameterized catchments.

4.5 Integrated Model

The integrated models successfully simulated flood events based on heavy rainfall and storm surge events as well as a combined model which incorporated both events. The models are discussed in detail below.

4.5.1 September 1999 Rainfall Event

Widespread flooding was observed over the period of the simulation. Analysis of cross-section conveyance potential identified three major bottlenecks caused by bridges within the study area. These bottlenecks were determined to be the major causes of flooding within the town of Oxford. The Water Street Bridge over River Phillip was a bottleneck for an upstream catchment with an area of 390 km^2 which received over 300 mm of rainfall between the dates of September 21st and 23rd of 1999. The structure was unable to route the overland flow portion of the 1.17×10^8 m^3 of water dumped into the system over the three day period. The inevitable backup of this system led to significant flooding at the baseball field and Irving station to the south of Water Street and southern portion of Main Street. A second bridge over Black River on Main Street was bottleneck for an upstream catchment with an area of 137 km^2 and was responsible for routing the overland flow portion of 4.11×10^7 m^3 of water over the three day period. The backup of this system caused flooding at the soccer field behind the elementary school, Home Hardware, and over a portion of Lower Main Street over which flow was routed. Finally, a third bridge on Lower Main Street over Little River was the bottleneck for an upstream catchment with an area of 57.5 km^2 and was responsible for routing the overland flow portion of 1.725×10^7 m^3 of water over the three day period. Backup within this system overtopped Lower Main Street.

4.5.2 December 2010 Storm Surge Event

The storm surge event resulted in flow levels of inland flooding around the town of Oxford. During the simulation period, three weather events resulted in higher than average tidal events. The largest surge occurred during the December 21st storm event and lesser surges occurred during an event on December 24th and December 28th of 2010. Only the largest residual surge (1.5 m) was used for the combined events model, and was applied to the high tide which occurred during peak rainfall discharge.

4.5.3 Combined Events Simulation

The unison of the September 1999 rainfall event and the December 21st storm surge events in the combined events simulation produced results which were unique to the theoretical situation. The increase in the magnitude and extent of flooding was not simply caused by the summed levels of the respective constituents. Greater flooding was caused by the reduced rate of discharge within the intertidal zone in response to the decrease in water velocity experienced with an incoming tide. This logic is supported by the fact that peak flood elevations during the rainfall event alone were above the tidal range.

5. Conclusions

This study demonstrated the need to integrate costal tidal-surge models with watershed river run-off models in order to accurately model flood risk for communities such as Oxford which are located along estuaries. The results of this study confirm that discharges of rivers during significant rainfall-runoff flooding events are influenced by the tide in the downstream estuary. In order to accurately model the flooding, the interaction between river discharge and the water level within the estuary must be taken into account. Models that simulate this interaction require accurate terrestrial and bathometric topography. Lidar was found to provide sufficient detail to generate high-resolution surface models representing floodplains and terrestrial areas. Low cost sonar surveys conducted for this study were found to be extremely useful for providing bathymetric data in shallow areas which fell outside CHS nautical chart soundings. The integration of these data sources provided sufficient topographic information to interpolate a seamless surface DEM which could be used for accurate rainfall-runoff and hydrodynamic modeling. This study has shown that these integrated models produce accurate flood simulation results.

6 Acknowledgements

We would like to thank Steve Ferguson, Director of Policy and Research for the Municipality of Cumberland for the letter and in-kind support for the project. We would also like to thank Jim Hannon, EMO Cumberland County, Mike MacDonald of the Oxford DNR Regional office for his assistance. We thank Jeff Merrill, Acting Director of Planning for the District of the Municipality of Lunenburg for the letter and in-kind support for the project. We would also like to thank from AGRG-NSCC Peter

MacDermott, Candace MacDonald, Chris Webster and Lyly Ngo for various field and data processing assistance to the project.

6. References

Oxford Journal, 1999. Oxford Journal".

Stiff, D. 2008. Investigating Flood risk in an Ungauged Watershed Using Lidar, GIS, and HEC Tools. Acadia University MSc. Thesis.

Webster, T.L., McGuigan, K., MacDonald, C. 2012. Lidar processing and Flood Risk Mapping for the Communities of the District of Lunenburg, Oxford-Port Howe, Town and District of Yarmouth, Chignecto Isthmus and Minas Basin. Atlantic Climate Adaptations Solutions Association unpublished report.

7. APPENDIX

Evapotranspiration Calculation

Described below is the procedure for calculating evapotranspiration (ET_o) using FAO Penman-Monteith with only minimum and maximum temperature

Required data:

Elevation, metres [m]
Latitude, degrees [°]
Minimum Temperature, degree Celsius [°C]
Maximum Temperature, degree Celsius [°C]
Classification as Coastal or Interior
Classification as Arid or Humid
Julian day

Assumed data or constants:

Wind speed	2 m/s
Albedo or canopy reflection coefficient, α	0.23
Solar constant, G_{sc}	0.082 $MJ^{-2}min^{-1}$
Interior and Coastal coefficients, K_{Rs}	0.16 for interior locations
0.19 for coastal locations	
Humid and arid region coefficients, K_o	0 °C for humid / sub-humid climates
2 °C for arid / semi-arid climates	

Procedure:

Calculate mean air temperature, T [°C]

$$T = \left(\frac{T_{\min} + T_{\max}}{2} \right)$$

Calculate actual vapour pressure, e_a [kPa]
Use minimum temperature and adjustment factor depending on climate classification humid or semi-arid.

$$e_a = 0.6108 \ \exp\left[\frac{17.27\ (T_{\min} - K_o)}{(T_{\min} - K_o) + 237.3} \right]$$

where:
K_o = 0 °C for humid and sub-humid climates
K_o = 2 °C for arid and semi-arid climates

Stations are classified as coastal and interior, interior stations are considered semi-arid, while coastal stations are considered to be humid.

Calculate saturated vapour pressure for T_{max}, $e_{(T_{max})}$ [kPa]

$$e_{(T_{\max})} = 0.6108 \ \exp\left[\frac{17.27\ T_{\max}}{T_{\max} + 237.3} \right]$$

Calculate saturated vapour pressure for T_{min}, $e_{(T_{min})}$ [kPa]

$$e_{(T_{\min})} = 0.6108 \ \exp\left[\frac{17.27\, T_{\min}}{T_{\min} + 237.3}\right]$$

Calculate saturated vapour pressure, e_s [kPa]

$$e_s = \left(\frac{e_{(T_{\min})} + e_{(T_{\max})}}{2}\right)$$

where:
$e_{(T_{max})}$ = Step 3
$e_{(T_{min})}$ = Step 4

Calculate inverse relative distance Earth-Sun, d_r [rad]

$$d_r = 1 + 0.033 \ \cos\left(\frac{2\,\pi}{365}\, J\right)$$

where:
J = Julian day

Convert latitude to radians, φ [rad]

$$\varphi(rad) = \frac{\pi}{180}\, lat(^\circ)$$

where:
lat = latitude of station in degrees

Calculate solar declination, δ [rad]

$$\delta = 0.409 \sin\left(\frac{2\,\pi}{365}\, J - 1.39\right)$$

where:
J = Julian day

Calculate sunset hour angle, ω_s [rad]

$$\omega_s = \arccos\left[-\tan(\varphi)\,\tan(\delta)\right]$$

where:
δ = Step 7
φ = Step 8

Calculate extraterrestrial radiation, R_a [$MJm^{-2}\ day^{-1}$]

$$R_a = \frac{24 \times 60}{\pi} G_{sc}\ d_r\ \left[\omega_s\ \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)\right]$$

where:
G_{sc} = solar constant = 0.082 $MJm^{-2}\ min^{-1}$
d_r = Step 6
δ = Step 7
φ = Step 8
ω_s = Step 9

Calculate clear sky solar radiation, R_{so} [$MJm^{-2}\ day^{-1}$]

$$R_{so} = \left(0.75 + 2 \times 10^{-5} z\right) R_a$$

where:
Z = elevation of climate station above sea level [m]
R_a = Step 10

Calculate solar radiation, R_s [MJm^{-2} day^{-1}]

Use adjustment factor K_{Rs} depending on station location, coastal or interior

$$R_s = K_{Rs}\sqrt{(T_{\max} - T_{\min})}\, R_a$$

where:

K_{Rs} = 0.16 for interior locations

K_{Rs} = 0.19 for coastal locations

Calculate net longwave radiation, R_{nl} [MJm^{-2} day^{-1}]

$$R_{nl} = \sigma\ \frac{(T_{\max} + 237.15)^4 + (T_{\min} + 237.16)^4}{2}\ \left(0.34 - 0.14\sqrt{e_a}\right)\left(1.35\frac{R_s}{R_{so}} - 0.35\right)$$

where:

e_a = Step 2

R_s = Step 12

R_{so}= Step 11

σ = 4.903 x 10^{-9} MJK^{-4}m^{-2}day^{-1}

Calculate net solar radiation, R_{ns} [MJm^{-2} day^{-1}]

$$R_{ns} = (1-\alpha)\ R_s$$

where:

R_s = Step 12

α = 0.23

Calculate net radiation, R_n [MJm^{-2} day^{-1}]

$$R_n = R_{ns} - R_{nl}$$

where:

R_{ns} = Step 14

R_{nl} = Step 13

Calculate slope vapour pressure, Δ [kPa °C^{-1}]

$$\Delta = \frac{2504\ \exp\left(\dfrac{17.27\,T}{T + 237.3}\right)}{(T + 237.3)^2}$$

Calculate atmospheric pressure, P [kPa]

$$P = 101.3\ \left(\frac{293 - 0.0065\,z}{293}\right)^{5.26}$$

where:

z = elevation above sea level [m]

Calculate psychometric constant, γ [kPa °C^{-1}]

$$\gamma = 0.665\times10^{-3}\,P$$

where:

P = Step 17

Calculate evapotranspiration, ET_o

$$ET_o = \left[\frac{0.408\,\Delta\,R_n + \gamma\,\left(\frac{900}{T+273}\right)\,u_2\,(e_s - e_a)}{\Delta + \gamma\,\,(1 + 0.34\,u_2)} \right]$$

ET_o reference evapotranspiration [mm day^{-1}],
R_n net radiation at the crop surface [MJ m^{-2} day^{-1}],
G soil heat flux density [MJ m^{-2} day^{-1}],
T mean daily air temperature at 2 m height [°C],
u_2 wind speed at 2 m height [m s^{-1}],
e_s saturation vapour pressure [kPa],
e_a actual vapour pressure [kPa],
e_s - e_a saturation vapour pressure deficit [kPa],
Δ slope vapour pressure curve [kPa $°C^{-1}$],
γ psychrometric constant [kPa $°C^{-1}$].

Mike11 Model Parameters

Rainfall-runoff Model

RR Simulation time-step:	300 sec
Result storing frequency:	300 sec

Catchment Overview:

Name	**Model**	**Area (km^2)**
CATCHMENT1	NAM	94.1135
CATCHMENT2	NAM	0.04245
CATCHMENT3	NAM	56.368
CATCHMENT4	NAM	50.9885
CATCHMENT5	NAM	137.839
CATCHMENT6	NAM	79.0145
CATCHMENT7	NAM	106.547
CATCHMENT8	NAM	49.8099
CATCHMENT9	NAM	106.864

NAM:

- Surface-rootzone:
  - Storage:
    - Umax: 8
    - Lmax: 300
  - Runoff Parameters:
    - CQOF: 0.35
    - CKIF: 600
    - CK 1, 2: 39
    - TOF: 0
    - TIF: 0.5
- Ground Water:
  - TG: 0
  - CKBF: 2800

Hydrodynamic Model

HD Simulation time-step: 10 sec
Result storing frequency: 300 sec

Initial Conditions:
    Water Level: 0.5 m
    Discharge: 0.8 m^3/s

Bed resistance: Uniform 0.05 Manning (n)

Wave Approximation: Fully Dynamic

Default Values:
    Computation Scheme:
        Delta: 0.5
        Delhs: 0.01
        Delh: 0.1
        Alpha: 1
        Theta: 1
        Eps: 0.0001
        Dh Node: 0.01
        Zeta Min: 0.1
        Struc Fac: 0
        Inter1Max: 10
        NoIter: 1
        MaxIterSteady: 100
        FroudeMax: -1
        FroudeExp: -1

    Switches:
        Node Compatibility: Water level

Flood Plain Resistance:
    Global Value: -99

Encroachment:
    Iteration: Max no. of iterations 20

Stratification:
    No. of layers: 10

    Turbulence model:
        Viscosity: 0.003
        Turbulence model in fluid: k-eps model
        Turbulence model at bed: drag coefficient
        Richards numbers correction: true

Corrections:
- Baroclinic pressure
  - Factor: 1
  - Local bed slope: 0

- Convection / Advection
  - Factor horizontal momentum: 1
  - Factor vertical momentum: 1
  - Factor Advection: 1

- Dispersion:
  - Factor horizontal viscosity: 1
  - Factor vertical viscosity: 1

Mike21 HD Model Parameters

Basic Parameters:
- Module Selection: Hydrodynamic model only

- Bathymetry:
  - Type: Cold Start
  - Apply Coriolis forcing: True
  - Number of areas: 1

- Simpulation time-step: 15 sec

- Flood and Dry:
  - Drying Depth: 0.1 m
  - Flooding Depth: 0.5 m

Hydrodynamic Parameters:
- Initial surface elevation: equal to webtide prediction

- Boundary:
  - FAB Type: 12
  - No tilting: True
  - User defined flow direction: False

- Eddy Viscosity:
  - Velocity Based: 9

- Resistance:
  - Constant: 25 (manning)