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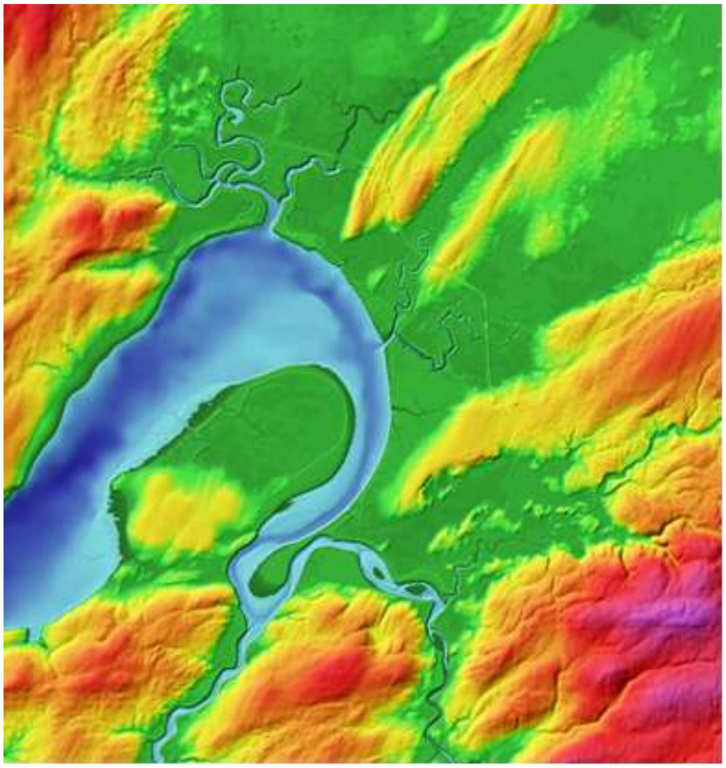

An Evaluation of Flood Risk to Infrastructure Across the Chignecto Isthmus

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Executive Summary

With sea-level rise (SLR) estimates of 1 to 5 m predicted for the Chignecto Isthmus by 2100, and more intense storms another likely consequence of climate change, Nova Scotia Transportation and Infrastructure Renewal (NSTIR) has real concerns for protecting the significant public infrastructure that it has to manage. At present, a system of agricultural dykes and the Canadian National Railway (CNR) in Nova Scotia and New Brunswick hold back the sea and protect the Trans-Canada Highway (TCH), many secondary roads and residents of Amherst, NS, and Sackville, NB, and thousands of hectares of dykeland with public and private assets exceeding $100 million (more than $70 million in NS). The area has flooded many times over the past 300+ years including major flooding events in 1758, 1869 (the Saxby Gale), 1887, 1958, and 1976 (the Groundhog Day Storm). These flooding events led to considerable property damage and loss of lives, and all were associated with storm surges that coincided with very high tides.

Flood modeling using a new high-resolution digital elevation model (Lidar-DEM) of the Isthmus terrain between the upper Bay of Fundy (Cumberland Basin) and the Northumberland Strait (Baie Verte) clearly shows (1) critically-low segments within agricultural dykes in NS and NB that would flood during storm surges that coincide with high tides, (2) dyke overtopping at these low areas and flooding of portions of the CNR and TCH (delays in inter-provincial and international trade with a value of $50 million per day, based on annual trade volumes on the order of $20 billion), (3) extensive flooding of local roads and protected dykelands (~2,200 ha in NS), and (4) salt water damage to agricultural lands and the many non-agricultural, public and private assets (with more than ten times the value of agricultural assets according to recent estimates from NS Agriculture).

In the longer term, sea levels will be considerably higher in the Isthmus than global averages given its position at the head of the Bay of Fundy, continued crustal subsidence of the Maritimes, and dynamic oceanographic processes associated with ocean currents, ice melt and variations in temperature and salinity. With extreme predictions of SLR, up 4-5 m by 2100, Nova Scotia could become an island, particularly during storm surges, unless the dyke system is considerably upgraded or other adaptation options implemented. While this event is likely a long time off, or a rare occurrence, it is prudent that NSTIR, other NS Government Departments and CNR start planning for the long-term sustainability of the Atlantic Gateway, a more robust dyke system, EMO actions, and collaborative adaptation actions.

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1 Introduction

Nova Scotia's road and rail gateways to Canada are situated within the Chignecto Isthmus – a low-lying area that is vulnerable to rising sea levels and storm surges from both the Bay of Fundy and the Northumberland Strait. Currently, a system of agricultural dykes, the Canadian National Railway (CNR) and the Trans-Canada Highway (Hwy 104) protect this area (2,200 ha), its vital transportation links, and more than $70 million of public and private assets. However, the area has historically flooded during large storm events and climate change will increase flooding frequency, duration and intensity. The NS Department of Transportation and Infrastructure Renewal (NSTIR) and CNR will continue to maintain their systems in face of environmental hazards but practical adaptation options must also be developed as part of integrated provincial and corporate approaches to climate change.

In partnership with the Natural Resources Canada (NRCAN), Nova Scotia's Climate Change Directorate and other ACASA members, NSTIR set out to investigate the short and long-term risks of flooding of the Isthmus and initiate an adaptation program to respond to climate change. As a first step, NSTIR commissioned Dr. Tim Webster and associates of the Applied Geomatics Research Group (AGRG) of the Nova Scotia Community College (NSCC) to conduct a research project to develop flood risk maps right across the Isthmus (NS Frontier). This work was achieved by carrying-out eight key tasks:

i. acquire and process additional lidar (Light detection and ranging) data in a narrow band near Route 366 to Tidnish Head and Baie Verte, and integrate this information with the newly-completed Lidar coverage in the Amherst, NS, and Sackville, NB areas;
ii. gather the necessary existing information to conduct flood risk modeling and mapping across the rest of the NS frontier (to the Tidnish-Baie Verte area);
iii. conduct additional field surveys to ground-truth the digital elevation model (DEM) and the flood modeling predictions;
iv. prepare an integrated set of flood risk maps of the Isthmus area;
v. identify areas and transportation infrastructure at risk on the Isthmus;
vi. identify potential alternative routes for sustainable transportation;

vii. present summaries of the research project at the ACAS conference in March 2012 (http://atlanticadaptation.ca/ACAS-Conference); and

viii. prepare a Final Report for NSTIR and ACASA.

1.1 Study Area

This project focused on the area of the Chignecto Isthmus that connects Nova Scotia to New Brunswick and the rest of the continent. It has two distinct coasts: the Northumberland Strait on the northeast and the Bay of Fundy on the southwest (Figure 1). The Isthmus is Canada's "Atlantic Gateway" with two critical transportation systems - the Trans-Canada Highway (TCH) and the CNR (http://www.atlanticgateway.gc.ca/index2.html). Spooner (2009) examined the economic impact of climate change on Nova Scotia's highways and highlighted the extreme value of goods that pass through the Isthmus. Even temporary flooding of the highway and the CNR line could delay inter-provincial and international trade of more than $50 million per day based on annual trade of ~$20 billion (Spooner 2009; Atlantic Gateway 2011).

The Isthmus area, like many other low-lying coastal areas in Nova Scotia, has been dyked in order to use the highly productive soils landward of the dykes for agricultural purposes. The dykes serve us well for routine tides but are less dependable during periods of anomalously high water of storm surge events. Storm surges are caused by winds and low atmospheric pressures. Tide levels can be increased by centimetres to metres above their predicted values. Depending upon when a surge arrives at the coast, tide waters can overtop dykes that are typically constructed to 30 cm (one foot) above the highest [predicted] high tide levels. The dykes in the Isthmus have failed many times over the past 300 years (see next section), resulting in extensive flooding and the loss of property and life. Surges have over-topped or breached dykes all around the Bay of Fundy with considerable damages recorded from to Yarmouth to Amherst.

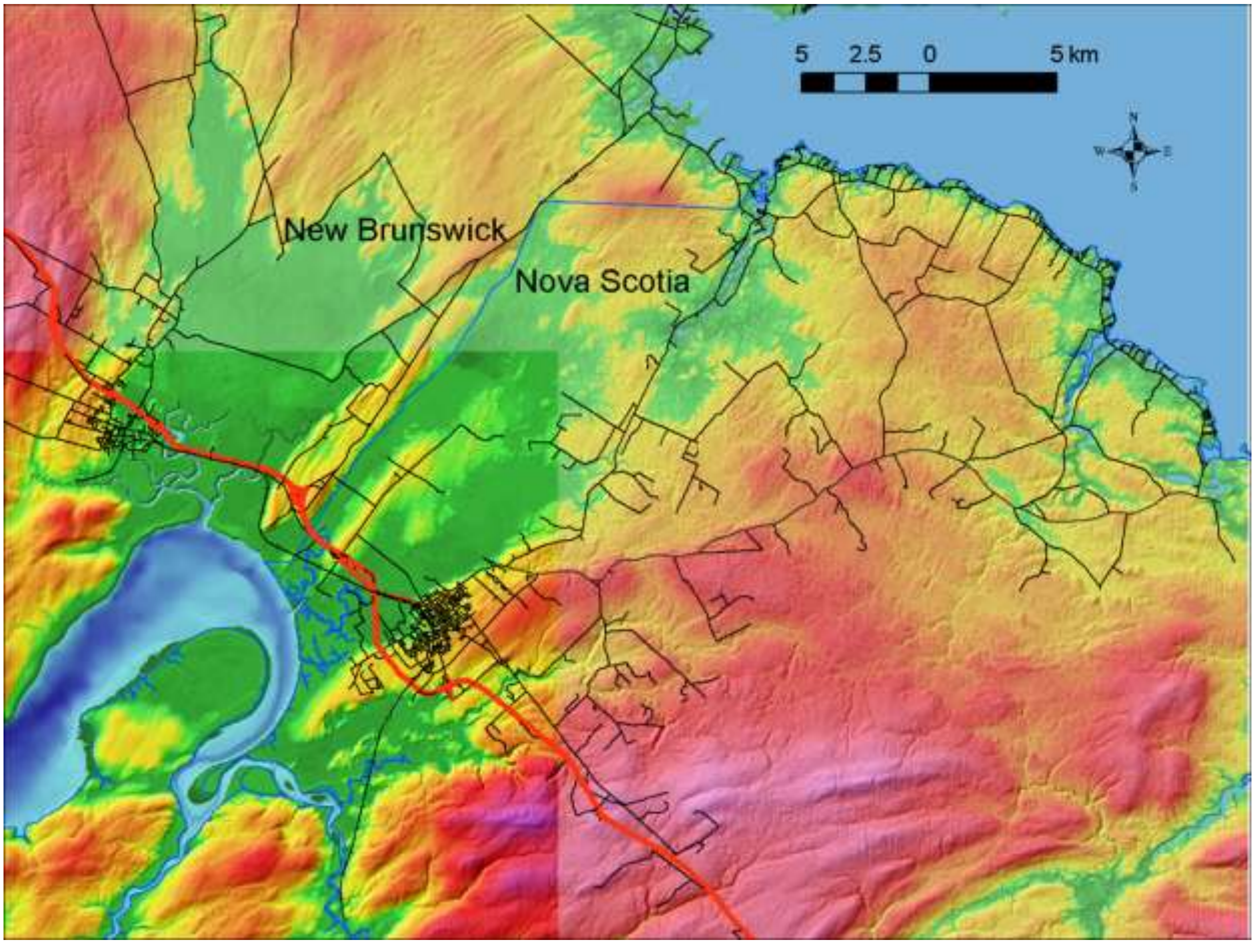

Figure 1 Chignecto Isthmus at the New Brunswick-Nova Scotia border with colour shaded relief DEM. The land separates the Bay of Fundy to the southwest from the Northumberland Strait to the northeast. The darker colours of the elevation model depict the focus of the study area.

1.2 Saxby Gale and Tidal Cycles

The most famous storm to affect this area is known as the Saxby Gale which occurred on October 4-5, 1869. The tide level was at least 1.5 m higher than the predicted high tides which were naturally very high because of astronomical conditions. The Saxby Gale inundated the low lying areas and overtopped the dykes by about 0.9 m (Desplanque and Mossman, 2004). The water level was reported to be 2 m higher than the predicted tide in Moncton, NB (Parkes et al. 1997). The Saxby Gale was named after Lieutenant Saxby, a civilian instructor of Naval Engineers of the British Royal Navy. He predicted a year earlier that there would be very high tides in the North Atlantic Ocean on October 5, 1869 and warned the public to be prepared in case of a coincident hurricane. His prediction based on the astronomical conditions of the sun, earth and moon, indicated that at this time period, the sun and the moon would line up on the earth's equator when the moon was closest to the earth (in perigee).

The timing of higher than normal high tides is very predictable and result from coincidences of tide generating forces associated with the elliptical orbits of the moon and sun. Besides the typical spring tides that occur every 14 days (new and full moons), perigean spring tides occur three or four times per year, in the spring and fall, when a new or full moon coincides with the perigee of the moon. Other important long-term tidal cycles that generate high astronomic tides occur with frequencies of 18.61, 9.305, 8.85 and 4.425 years (all related to precessions of the moon – rotation periods of two planes of the moon's orbit; Haigh et al., 2011), The 18.61 year nodal cycle and 4.425 year cycle are the most important in generating the higher high tides. The next peak of the 18.61 year nodal cycle will be in 2015 (water levels will be more than 30 cm higher than those of 2012 in the upper Bay of Fundy; see Section 2.2.5).

Other notable storms such as a Groundhog Day Storm of February 1976 and those in 1958, 1887, and 1758 also caused dyke breaches and extensive flooding around the perimeter of the Bay of Fundy but not to the same level as the Saxby Gale (see Figure 2; Desplanque and Mossman, 1999; Bleakney 2004). Sea-level has been rising at an average rate of 22 cm per century in the Bay of Fundy based on the tide gauge record at Saint John, NB. Thus, mean sea-level has risen by approximately 32 cm since the time of the Saxby Gale. Dykes today have been built and maintained using modern construction equipment and are currently at an average elevation of 8.5 m above the Canadian Geodetic Vertical Datum of 1928 (CGVD28), the datum used for land topographic maps. However, there are low spots in places and hence vulnerable to storm surges. Dykes are basically earthen dam structures with a grass cover. They are susceptible to settling and compaction and require constant inspection and maintenance. Sections of dykes that bear the brunt of storm waves can also be quickly eroded and then breached by incoming tides.

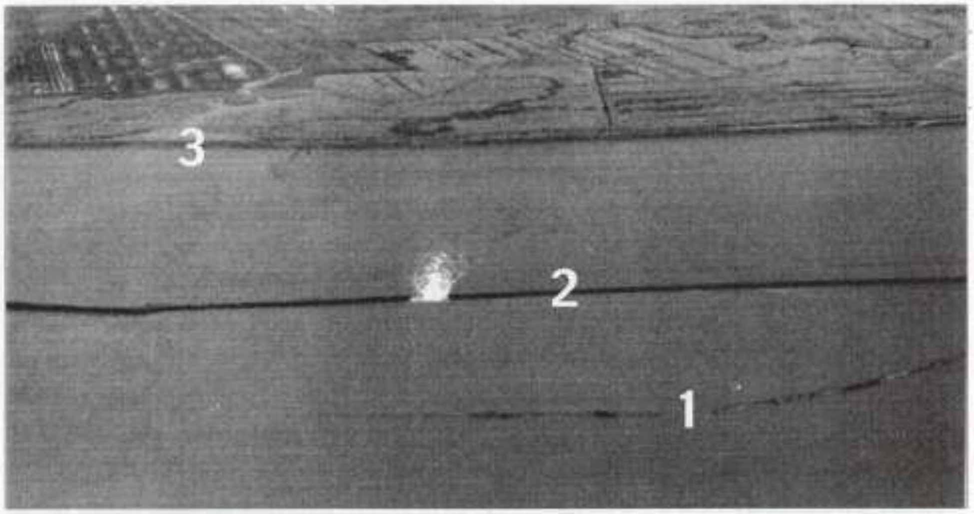

Figure 9.2.4 Aerial view from above the Guzzle channel looking west on 6 April 1958. Dyke 1 is a Planter dyke from 1760–70; the breached Dyke 2, where water is foaming through the gap, was built by Robert Palmeter in 1939–40; and Dyke 3 was the new, larger one constructed in 1950. The entire Grand Pré farmland was threatened by the Seros Cycle extreme tide in 1958. (Nova Scotia Department of Agriculture and Marketing, MMRA photo no. 16-028)

Figure 2 Example of a breached dyke at Grand Pre, NS, during the 1958 storm surge (from Bleakney, 2004).

1.3 Estimation of Risk – High-Water Level Return Periods

There is no long-term tide gauge record for the upper Bay of Fundy from the Canadian Hydrographic Service (CHS) of Department of Fisheries and Oceans (DFO), so calculating the probability of high-water level return periods is difficult. The actual water level of the Saxby Gale is not accurately known, so we have used the predicted tide plus storm surge, based on the Joggins Wharf station (~20 km away). This is the nearest port with details available on tidal water levels and the relationship between chart datum (CD) and the Canadian Geodetic Vertical Datum of 1928 (CGVD28). To determine the risk or return period of high water events we have utilized a tool developed at AGRG, “Time Series Modeller” (Webster et al., 2008). This tool utilizes the closest historical water level records, usually derived from a tide gauge operated by the CHS. Unfortunately the closest tide gauge is at Saint John, New Brunswick, and has a very different tidal range than basins in the upper Bay of Fundy.

Daigle (2011) produced a report for ACASA for estimating sea-level rise for six municipalities including Sackville, NB. However, neither the AGRG nor Daigle methods takes into account the historic Saxby Gale or other rare extreme events. Thus the return periods for this region should be used with extreme caution. Daigle (2011) estimated water levels for Sackville, NB, with return periods of 1, 2, 5, 10, 25, 50 and 100 years. Lieske and Borrnemann (2011) used the water level elevations and constructed flood inundation maps based on the NB lidar coverage. Yevdokimov (2011) then used these maps to estimate the length of the highway system that would be inundated and the associated annual probability (reciprocal of the return period) to calculate the risk of inundation. He obtained estimates to repair the highway ranging from minor damage simply requiring asphalt resurfacing to more severe damage requiring modification and grading of the road base and resurfacing. Yevdokimov (2011) also estimated the impact of the closure of the Trans-Canada Highway (TCH) and the CNR and the disruption of the traffic. Along a similar line he also calculated the potential impact on travel time and increased accident rate resulting from possible closures of Highway 104. As Yevdokimov (2011) states in his report, the monetary values he calculates are based on very strong assumptions. One of the main ones is based on the return period water levels and associated risk proposed by (Daigle, 2011). Daigle’s (2011) 1 year return period surge in the year 2000 (present-day conditions) is estimated to be 8.07 m with a margin of error of 0.7 m and rises to 8.22 m with a margin of error of 0.73 m in 2025. Based on our analysis of the dyke elevations, this water level would overtop low spots in the dyke system and inundate sections of the TCH and CNR. Given there have not been frequent dyke overtopping events or TCH/CNR flooding, we think these predicted water levels are too high. The fact there is no long-term time series of water level measurements in the upper Bay of Fundy makes it very challenging to establish reliable water level values and associated return periods or probability of occurrence estimates. Rather than apply monetary values based on risk assessments that have very high uncertainties, we have opted to simply calculate the length of road sections that would be overtopped from different water levels for the Nova Scotia section of the TCH (Highway 104) at the Isthmus.

1.4 Sea-Level Rise

Global sea-level rise, as predicted by climate change models, will increase making more coastal areas vulnerable to flooding and coastal erosion (Church et al., 2001; Meehl et al., 2007). Our coasts are presently at risk to the occurrence of storm surges during high tides which result in flooding and erosion. For future planning we need to identify the current areas, then look to future sea-level predictions and determine the areas at long term risk. The latest Intergovernmental Panel on Climate Change (IPCC) Assessment Report 4 (AR4) has projected global mean seal-level to rise between 0.18 and 0.59 m from 1990 to 2095 (Meehl et al. 2007). However as Forbes et al. (2009) point out, these projections do not account for the large ice sheets melting and that measurements of actual global sea-level rise (SLR) are higher than the previous predictions of the third assessment report (AR3). Rhamstorf (2007) compared observed SLR to future projections and found SLR exceeded the IPCC AR3 projections; he suggested a rise between 0.5 and 1.4 m from 1990 to 2100. Forbes et al. (2009) used an upper limit of 1.3 m of SLR over 100 years as a precautionary approach to SLR projections in the Halifax region. Recent extreme predictions by Hansen and Sato (2011) suggest SLR may go up by 2-5m by 2100 because of non-linear glacier disintegration. The selection of an upper limit of flooding is dependent on realistic projections of SLR – clearly a difficult decision.

Another factor affecting sea-level rise is associated with local crustal subsidence or uplift. Researchers use SLR projections based on relative sea-level (RSL) whenever possible to account for the net change in sea level (up or down) for specific geographic areas. The major influence on crustal motion for the Maritimes is related to the last glaciation that ended ~10,000 years ago (Shaw et al., 1994; McCullough et al. 2002; Peltier, 2004). The areas where the ice was thickest were depressed the most, while peripheral regions were uplifted and are termed the "peripheral bulge". The ice was thickest over Hudson Bay in central Canada and the crust was most depressed. Today this area is still rebounding from the removal of the ice load and continues to uplift (including the shores of Hudson Bay). The Maritimes are within the peripheral bulge and southern New Brunswick and Nova Scotia are subsiding (Peltier, 2004). Subsidence rates vary across the region with Nova Scotia having a rate of ~15 cm per century (Forbes et al., 2009). The subsidence of the crust is important for coastal communities in that it compounds the problem of local sea-level rise and must be considered when projecting future flood risk. For the Chignecto Isthmus, Greenburg et al. (2012) estimate relative sea level (RSL) to increase between 0.79 m – 1.40 m by 2100 with a central value of 1.12 m with a margin of error of approximately 0.25 m. The contribution from the mean global sea-level for these predictions was ~0.40 m which appears to be a lower estimate than used by Forbes et al. (2009) who used a range of 0.57 to 1.30 m (Halifax study) and Daigle (2011) who used 0.85 m for Sackville, NB.

Other local factors also need to be considered for estimating RSL – basin shape, bottom topography, and oceanographic circulation patterns. As noted in the last section, tidal ranges for the lower (St. John, NB) and upper Bay of Fundy are quite different. The upper basins, Cumberland and Minas Basins, have a larger tidal range than the lower bay as a result of the size (length) of the bay that is close to matching the natural gravitation cycle of the moon that dominates the tide. The resonance effect increases the tidal range at the end of the bay and in the upper reaches of the Cumberland and Minas Basins. Webster et al. (2011) estimates RSL for communities in the upper Bay of Fundy (i.e., Chignecto Bay, Cumberland and Minas Basins) to increase between 1.20 and 1.93 m by 2100. On average, the Bay of Fundy tidal range is expected to increase by another 10-30 cm in the future with an increase in sea-level and cause even stronger resonance of seiches with the bay and tidal forcing (Godin, 1992; Greenberg et al., 2012). Sallenger et al (2012) recently identified the eastern North American coastline, especially north of Cape Hatteras to Newfoundland, as a “hotspot” of recently accelerated SLR. Dynamic oceanographic processes associated with ocean currents, ice melt and variations in temperature and salinity are believed to generate the Northeast Hotspot (NEH) with SLR rate increases of ~3-4 times higher than the global average. For the Isthmus area, we must combine global sea-level rise (SLR), local estimates of crustal subsidence and tidal amplitude, and dynamic oceanographic processes to produce a realistic estimate of relative sea-level (RSL) in the future. Remember that RSL estimates do not include the expected impacts of increased storm intensity, duration and frequency. Storm surges ride on top of sea level and coincidence of surges and high tides, especially during spring tides (every two weeks) and peaks of the long-term tidal cycles (18.6 and 4.4 year periods), can lead to catastrophic flooding and erosion (Oost et al., 1993; Gratiot et al., 2008; Haigh et al., 2011; Baart et al., 2012).

1.5 Flood Mapping and Lidar

As a result of the uncertainties associated with SLR projections and storm surges, we have generated flood risk maps to a maximum level of 12 m CGVD28 at 10 cm increments (see Section 2.2). The number of flood level GIS layers ensures that the flood extent information is available whatever the water level used in the projections in the future. For much of the Nova Scotia coast, the best generally available terrain information is based on the Nova Scotia Topographic Database (NSTDB) at a scale of 1:10,000 map series. Importantly, for predicting the above mentioned impacts of climate change and storm surge, the maps define the 5 or 10 m contour as their lowest elevation information inland from the shoreline with a vertical accuracy of 2.5 m. Our typical maximum storm surges we experience today are 1.5 m (with a frequency on the order of 100 years; Webster et al., 2008), so to accurately map this elevation, we need information more accurate than 1.5 m. Lidar offers an elevation accuracy of 15 cm or better in open areas, thus is an excellent mapping tool for flood risk studies.

Recently collected lidar data (2009-2011) was used to construct high-resolution digital elevation models (DEM) of the entire Isthmus in order to build flood inundation maps from storm surges and longer-term SLR for the Upper Bay coastline and a small strip along Highway 366 connecting the Northumberland Strait (see Section 2.1). Lidar is a remote sensing technique that involves an aircraft equipped with a laser rangefinder that shoots pulses of light towards the earth, and by measuring the two-way travel time, determines the distance or range from the aircraft to the earth's surface very accurately. By knowing the precise location of the aircraft by GPS and the distance to the earth's surface, land elevations can be determined. The lidar measures the earth's surface every 1-2 m on the ground with vertical accuracies within 15 cm.

2 Methods

2.1 Lidar and DEMs

The first phase of airborne lidar was flown on October 29, 2009, utilizing an Optech ALTM 3100 sensor with a ground point spacing of 0.5-1 m for the NS coast of the upper Bay of Fundy (see Webster et al., 2011 and Figure 3). An additional strip of lidar data was acquired by NSTIR along Highway 366 connecting the Fundy lidar to the Northumberland Strait - a possible alternate route if Highway 104 was ever compromised. This corridor was acquired by Leading Edge Geomatics (LEG) on June 16, 2011. A lidar DEM was obtained from New Brunswick Environment for the NB coast of the upper Bay of Fundy; this data was acquired by LEG in 2010 and 2011. The lidar data for each flight line were adjusted for any offsets to ensure a consistent data set. The lidar point cloud was classified into ‘ground’ and ‘non-ground’ targets. Extra care was taken to ensure that elevated land features such as dykes were correctly classified as land. These types of abrupt features are problematic and are often areas of misclassification and not included as ‘ground’. The lidar ‘ground’ points were used to construct a DEM, and ‘ground’ and ‘non-ground’ points were used to construct a Digital Surface Model (DSM) of the study area. The original elevations of the lidar surface models are referenced to the GRS80 ellipsoid and an HT2 geoid-ellipsoid undulation model was used to convert the ellipsoidal height models to orthometric heights referenced to CGVD28 (see Webster et al., 2011 for further description).

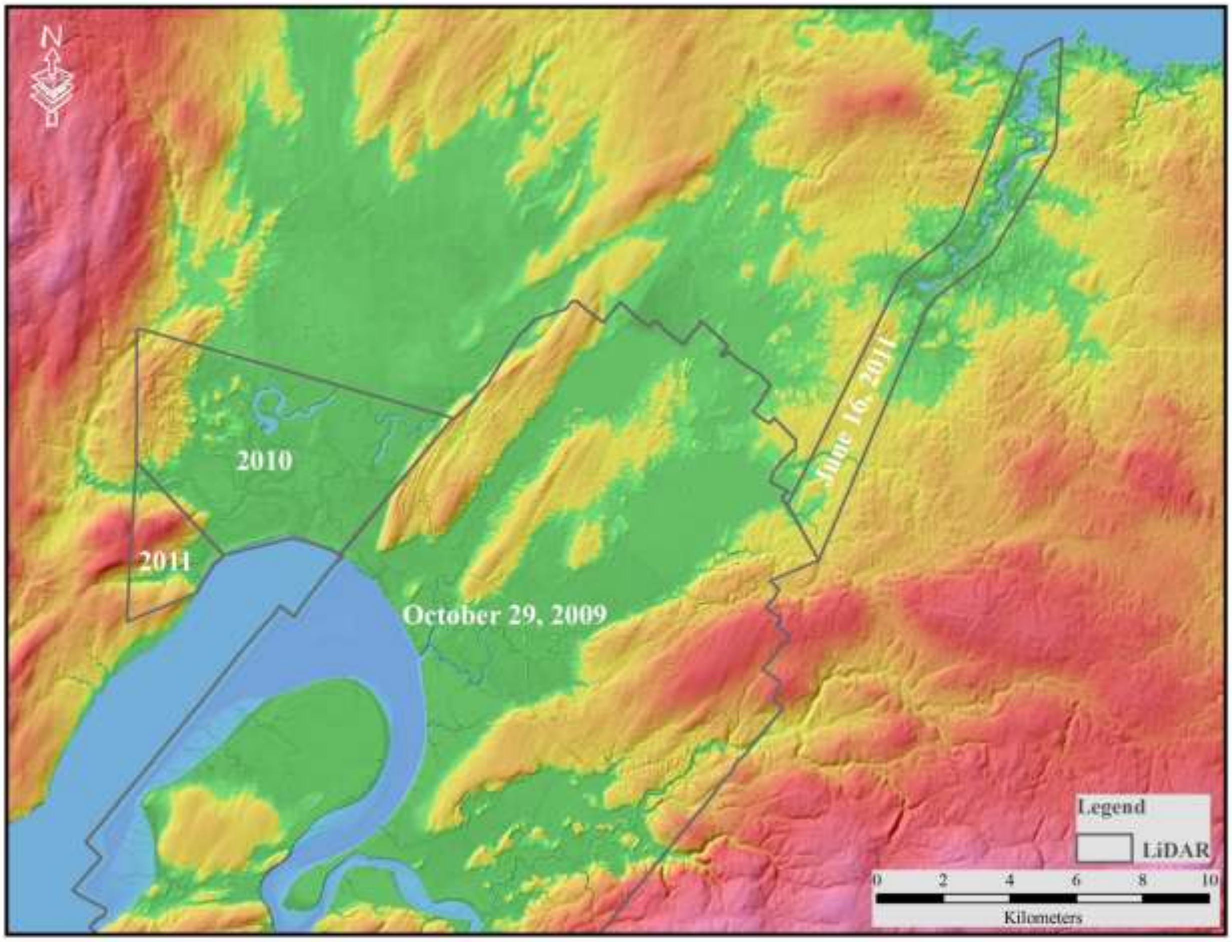

Figure 3 Lidar coverage areas. Background image is a 5 colour shaded relief elevation model of the Isthmus.

In addition to a GPS base station and a high precision network monument to control the aerial lidar survey, ground-based checkpoints were obtained using survey-grade GPS equipment throughout the study area. These field data were used to validate the lidar derived DEM following the methods described by Webster (2005). The accuracy of the 1 m resolution (1 m by 1 m grid cell) DEM in open cleared areas on hard surfaces (e.g., roads) was analyzed and compared to a specification of a vertical accuracy better than an average of 15 cm.

The lidar DEM was used to map the flood inundation areas utilizing GIS from storm surge events. The method raises the water level as a flat plane, known as “still-water” and inundates low lying areas with free connection to the coast as described in Webster et al. (2006, 2008, 2010). The culvert locations were obtained from the NS topographic database GIS layer for the main roads and only contain culverts that cross a stream on the map. The lidar DEM was used to generate profiles along the TCH and the CNR in NS and NB. Transverse profiles crossing the dykes, rail line and highway were also extracted from the lidar DEM across the Isthmus.

In addition to analyzing the coast on the Fundy side, the lidar was merged with data from the 1:10,000 NS and NB DEMs (70 m point spacing elevations derived from photogrammetry) that were available from GeoNova and Service New Brunswick. The DEMs covered the entire area of the Chignecto Isthmus and its coastal areas of the Bay of Fundy and Northumberland Strait. The spot elevations were interpolated using a Triangulated Irregular Network (TIN) method to a 5 m DEM. In addition, the road system and other topographic information for the Isthmus were incorporated into the map (Figure 4). The Trans-Canada Highway crossing the Chignecto Isthmus is composed of Highway 104 in Nova Scotia and Highway 2 in New Brunswick. Highway 104 was downloaded from GeoNova and the Highway 2 was downloaded from NB’s GeoBase. These highways were also converted into points to be able to extract the elevation from the DEM. GPS information about the dyke elevation from surveys across and along the top of the dykes was provided by Saint Mary’s University (Figure 4). A seamless elevation model was constructed from the 5 m lidar DEM flown at low tide, and soundings from a CHS chart.

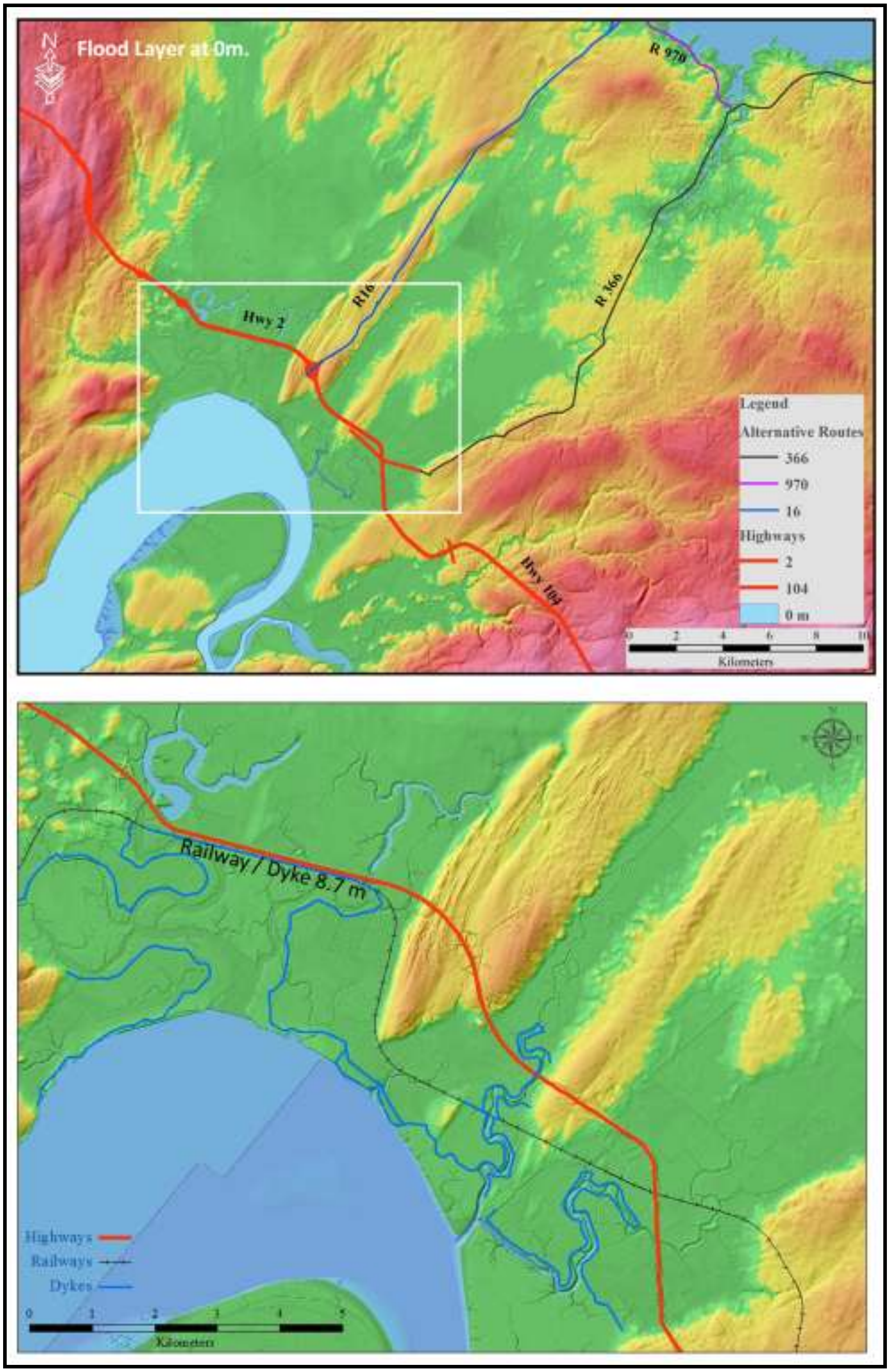

Figure 4 The top map is the 5 m DEM with the road network labelled (white box denotes the lower map location). The bottom map is the 1 m lidar DEM with the Hwy 104 (red), CNR (dashed black), and agricultural dykes (blue).

2.2 Flood Risk Mapping

Flood inundation maps were constructed for the Bay of Fundy side of the Isthmus at 10 cm water level increments from 5-10 m above CGVD28. We use then used these detailed inundation layers to highlight the most vulnerable sections of the dyke to overtopping. These flood layers were also used to construct perspective views with flood inundation animations. A Landsat satellite image or colour-shaded relief DEM is draped over the DSM and the water level is increased in the animations. We also use these overtopping layers to estimate the length of the highway that would be affected at different water levels and calculate the potential repair costs. The integrated 5 m DEM of the entire isthmus connecting the coasts was used to increase the water level at 1 m increments from 0 m to 12 m. These flood layers were used to assess possible alternative routes if the highway and dyked marsh areas were compromised.

2.2.1 Hydrodynamic Model

A high resolution hydrodynamic model was developed using the DHI Mike21 software module (DHI, 2012) in order to simulate inland 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 within the Cumberland Basin, Nova Scotia.

2.2.2 Bathymetry

Model bathymetry roughly covered the extent of the Cumberland Basin. Bathymetric data were composed of coarse resolution CHS digitized nautical chart soundings (circa 1974) around the basin and deep river systems. The bathymetric data were supplemented with high resolution lidar elevations flown in the town of Amherst. Standard lidar does not penetrate water, so additional field surveys were conducted at low tide. As a result, several intertidal mud flats and coastal features within the study area were clearly defined within the dataset. CHS soundings were converted from chart datum to CGVD28 in order to establish a common vertical datum between all datasets. An interpolation algorithm was used to fill the gaps between coarse CHS soundings in order to create a continuous raster of surface elevations suitable for hydrodynamic modeling. A spline with boundary interpolation was decided to be the most suitable based on the available data. The boundary of the spline corresponded to the extent of 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 un-interpolated. The final product was a seamless transition between interpolated bathymetry and terrestrial lidar. The surface was gridded at a 5 m cell resolution and was suitable for hydrodynamic modeling.

2.2.3 Boundary Condition

The boundary condition was developed using deep ocean tidal predictions obtained from the Department of Fisheries and Oceans (DFO) WebTide Tidal Prediction Model (v0.7.1; Dupont et al., 2005). The WebTide application was used to predict ocean elevation within the Upper Bay of Fundy using ten tidal constituents. Predictions were made at three points along the west boundary of the study area which was coincident with the top, middle and bottom of the Mike21 hydrodynamic model boundary. Predictions were made at 5 minute intervals for 25 years between the dates of January 1st, 1990 and December 31st, 2014 (predictions for 2010 to 2014 are shown in Figure 5). 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 25 year prediction period.

2.2.4 Model

Once the bathymetry and boundary condition were completed, a long term Mike21 hydrodynamic simulation was created and executed for calibration and validation purposes between the dates of April 1st and September 30th of 2011. Model results were extracted at the location of an established tide gauge installed along the armour stone protecting the outer dyke at Fort Beauséjour in Aulac, NB, courtesy of Dr. Jeff Ollerhead, Mount Allison University. 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, simulations were created for a variety of periods of time including the perigean spring tides occurring in mid-November of 2012.

To simulate another possible Saxby Gale, we added a 2 m storm surge to our tide model boundary condition (Figure 6). Although sea levels during the Saxby Gale were reported to be up 1.5 m (Parkes et al., 1997), sea level has risen by 32 cm since 1869; so we selected a surge of 2 m. The dykes and lidar were used to ensure the coarse resolution models used for the hydrodynamic models were accurate for the dykes, since coarse models have a tendency to lower elevations of small features such as dykes.

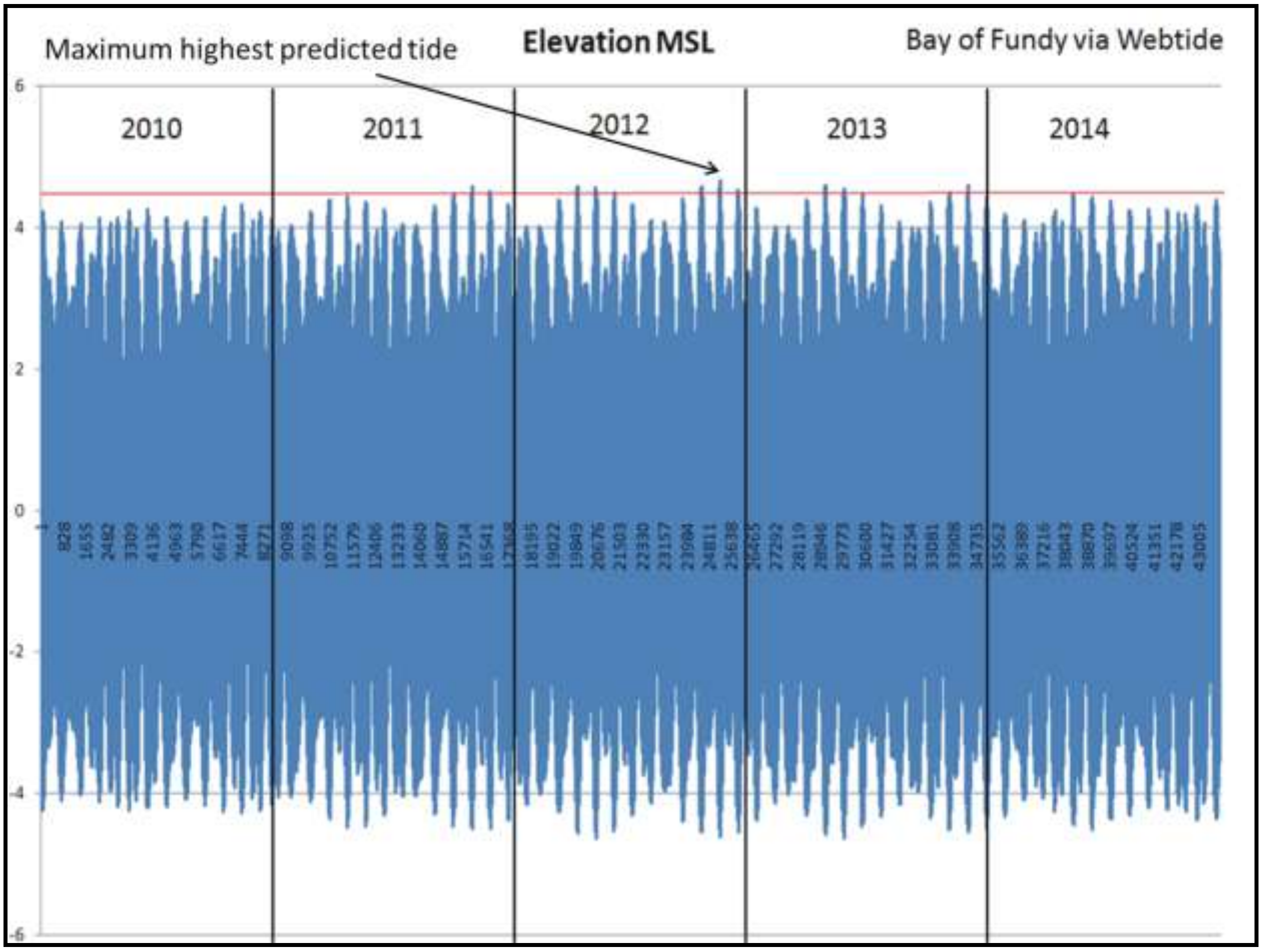

Figure 5 Predicted tide for the centre of the upper Bay of Fundy (not a harbor or port) from WebTide. Maximum tides from 2010 to 2014 occur on November 16, 2012.

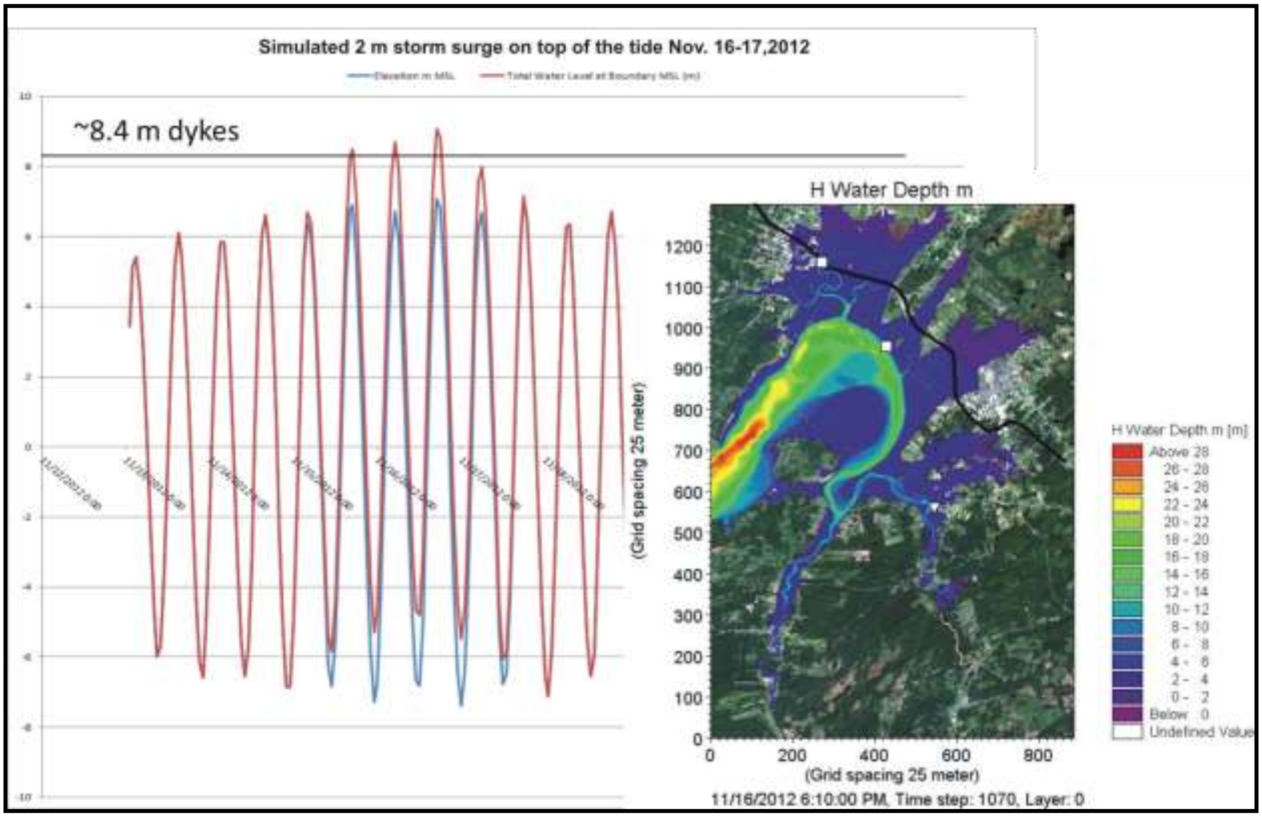

Figure 6 Highest predicted tide during November 16, 2012 (blue line) with a 2 m storm surge (red line). The tide model domain, with the depth of water flooding results overlaid on a satellite image with the Trans-Canada Highway (black).

2.2.5 Additional Tidal Predictions

WebTide predictions, which are based on a model produced by DFO (Dupont et al. 2005), were used in the previous example to generate a tidal boundary across the upper Bay of Fundy in order to construct a hydrodynamic model for the area and add an additional 2 m storm surge to the tide. The water level generated from WebTide is referenced to mean sea-level.

Additional tidal predictions can be obtained for select harbors and ports in the upper bay and provide the tide elevations related to that specific site for the local conditions referenced to chart datum, typically defined as the lowest possible water level to occur during large tides. We extracted the predicted tide for Joggins, approximately 25 km south of the Isthmus, hourly for the year 2012 to the end of 2015 (http://tbone.biol.sc.edu/tide/). The peak tide level is predicted to be 12.98 m above chart datum on October 28, 2015 (Figure 7). This water level is approximately 36 cm higher than the highest tide predicted for November 2012.

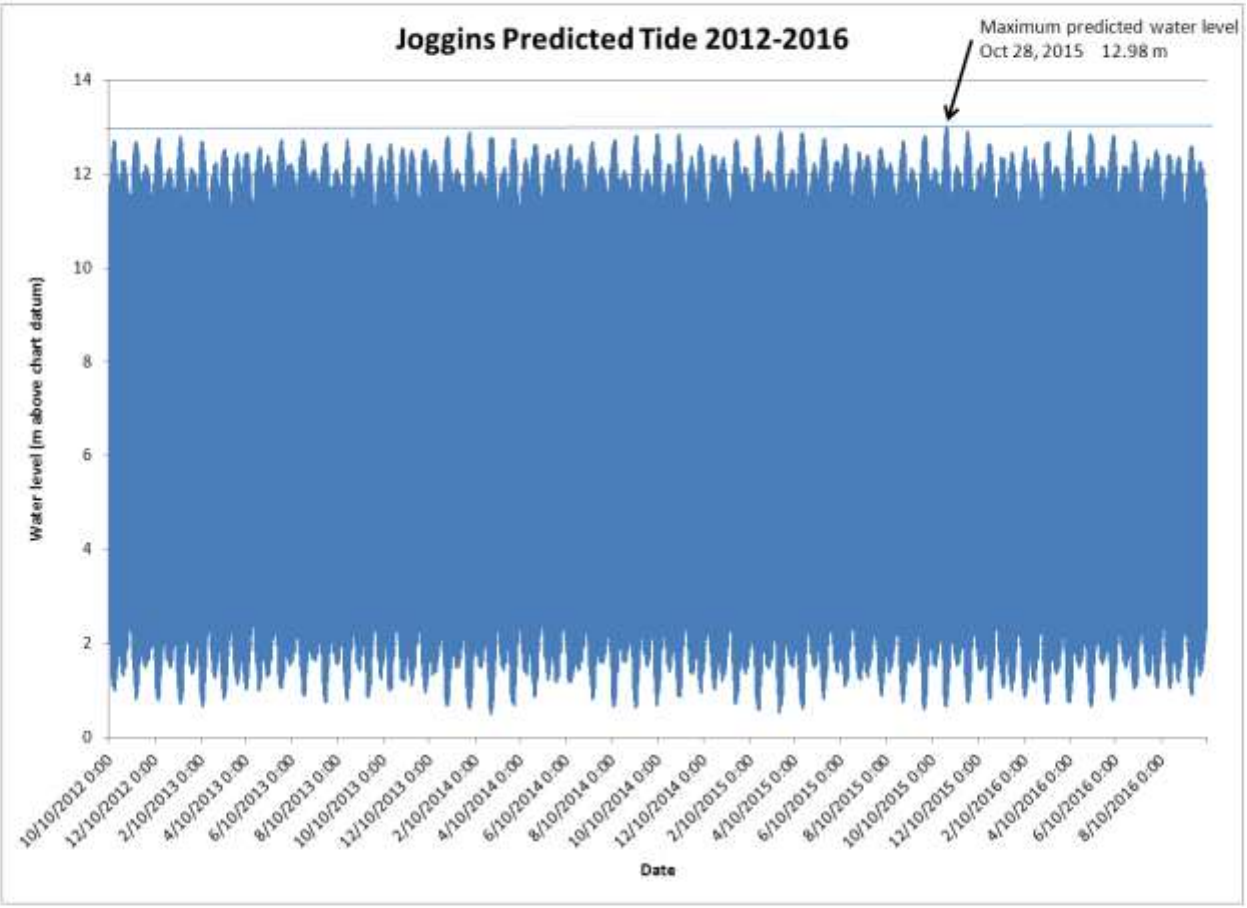

Figure 7 Predicted tide water level for Joggins, NS, between October 2012 and October 2016.

3 Results

3.1 Profiles

Critical elevations of the key infrastructure, the TCH and CNR, linking NS to NB were extracted in the form of longitudinal profiles along the length of the structures (Figure 8) and as transverse profiles across the structures out to the outer dyke features (Figures 9-13). The lowest section of the TCH occurs in New Brunswick where the elevation is 7.8 m CGVD28. The dykes that protect the low-lying marsh land are around 8.5 m in this area. The TCH is the lowest along a 4 km stretch across the Tantramar Marsh area in NB, and again for a small stretch on the NB side of the border (Figure 78 upper). The lowest section of the CNR is also in NB at an elevation of 6.8 m (Figure 8, lower). The narrow drops in the profiles correspond where the road or rail line crosses a river or stream – bridges have not been included in the bare-earth DEM.

The four transverse profiles were constructed from the outer protective dyke landward to connect to the critical infrastructure (Figure 9). In Profile 1, the outer protective dyke is 8.45 m and the rail line is 9.74 m and acts like a dyke in this area (Figure 10). The next section of dykes that are crossed range in elevation from 8.45 to 8.69 m along the Missaguash River which forms the border between NB and NS (Figure 10). The elevation of the lanes of the TCH along this profile are 8.79 and 8.9 m. Dyke elevations on the other side of the TCH protected from high water in the Missaguash River are 8.57 and 8.61 m (Figure 10). Similar details can be extracted from Profiles 2-4 (Figures11-13).

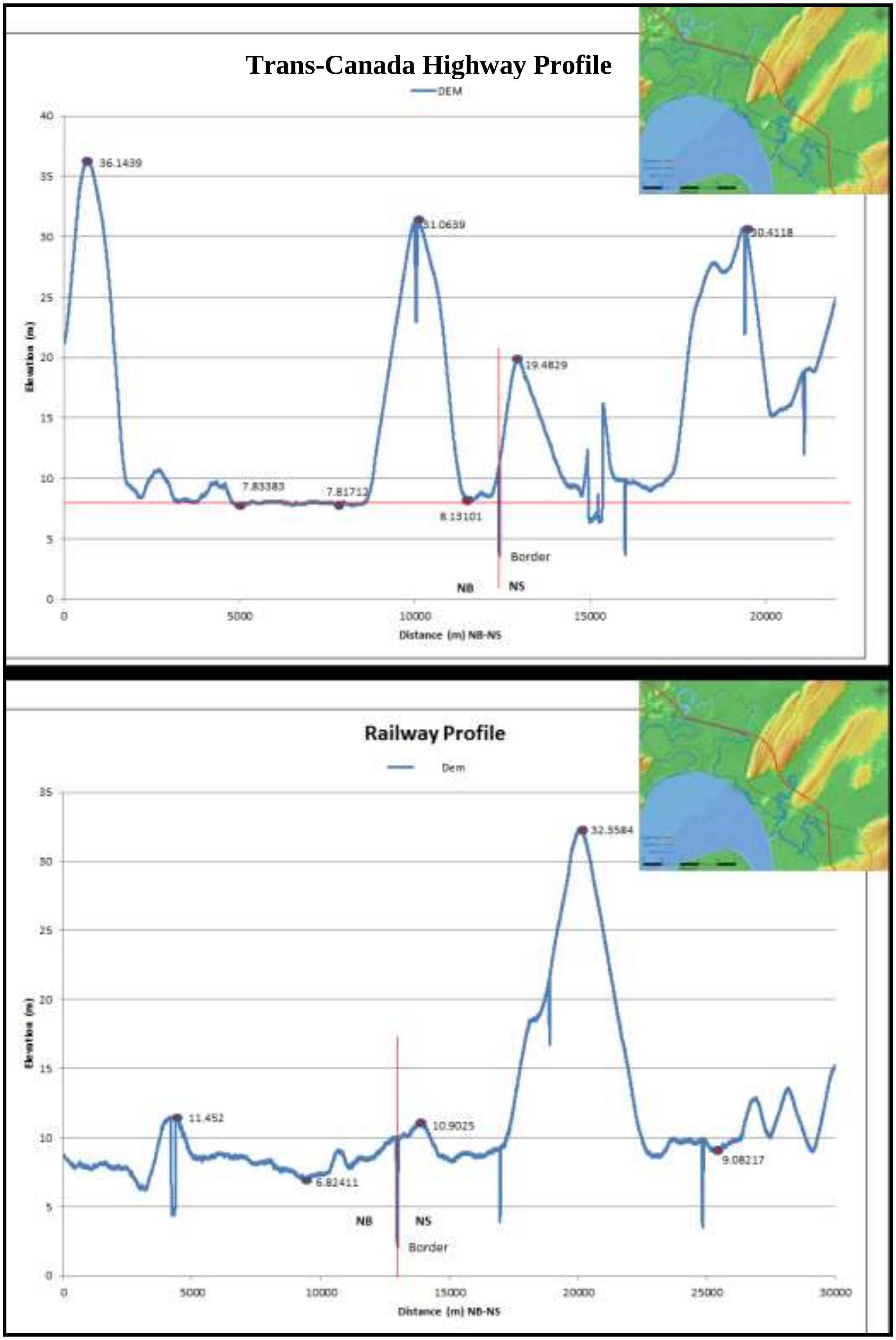

Figure 8 Longitudinal profiles of the critical transportation infrastructure. Top profile is along the Trans-Canada Highway from NB to NS. Lower profile is along the CNR from NB to NS.

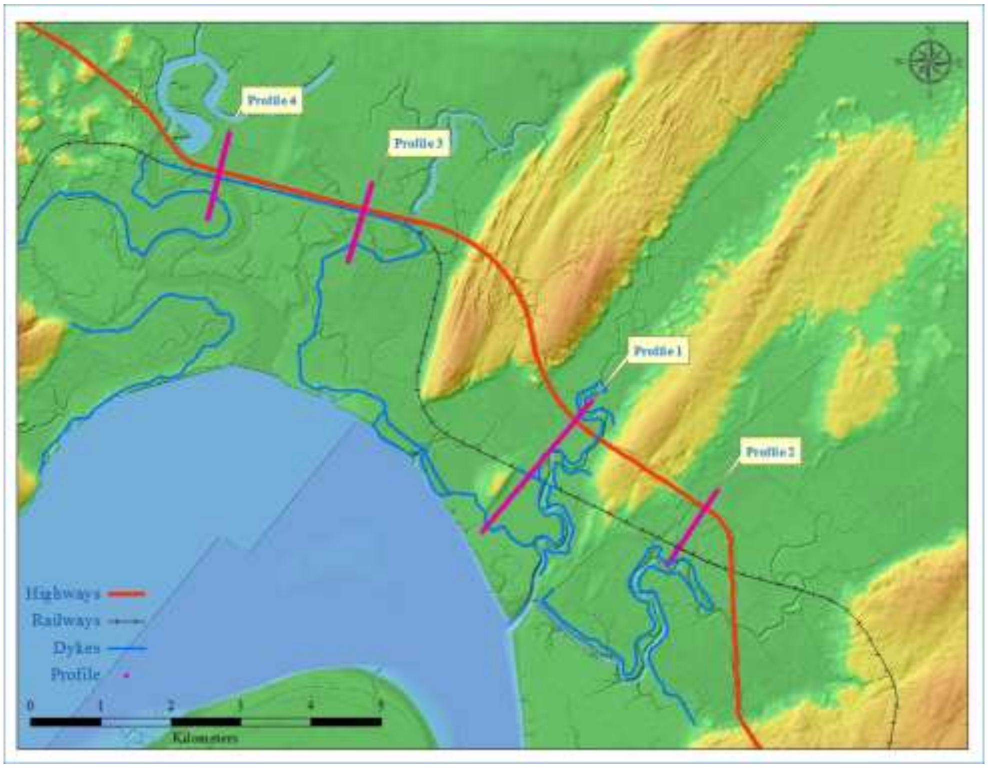

Figure 9 Profile locations which include the critical infrastructure and the agricultural dykes.

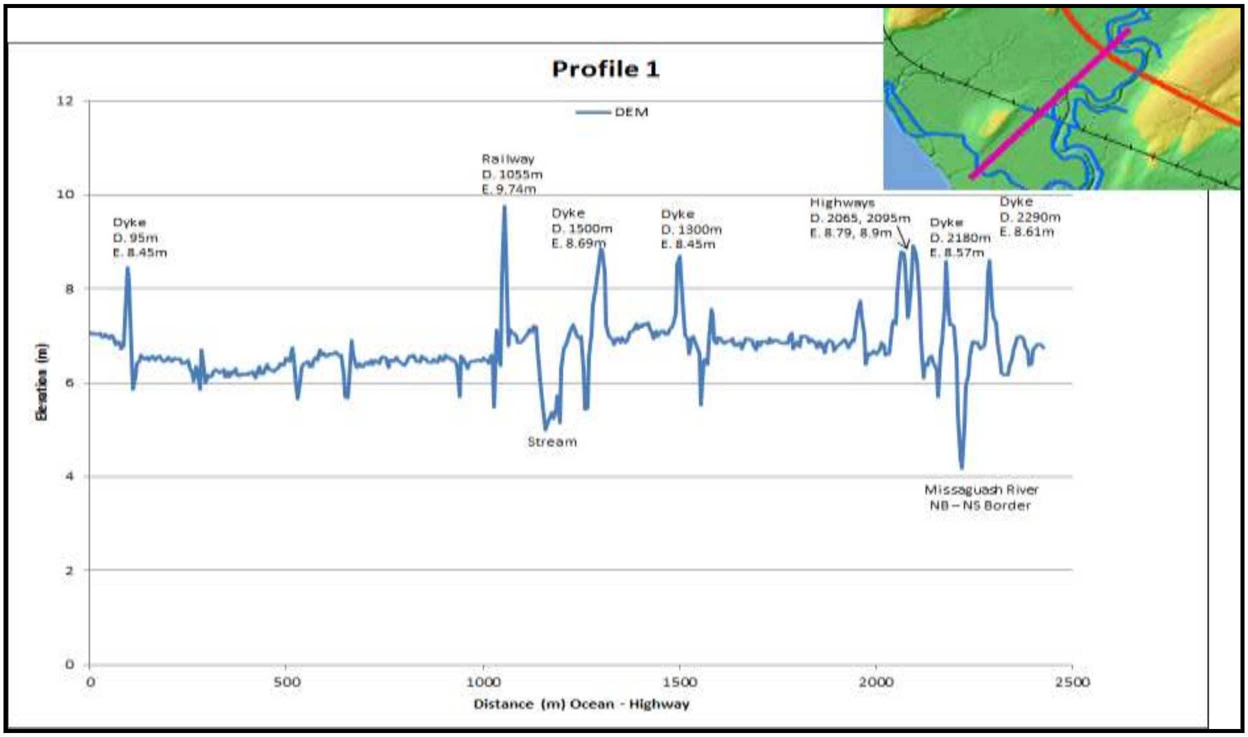

Figure 10 Profile 1, traversed from the southwest to the northeast – the NB dykes in this area are at 8.45, 8.69, 8.57, and 8.61 m. The rail line elevation is 9.74 and the TCH lanes are 8.8 and 8.9 m.

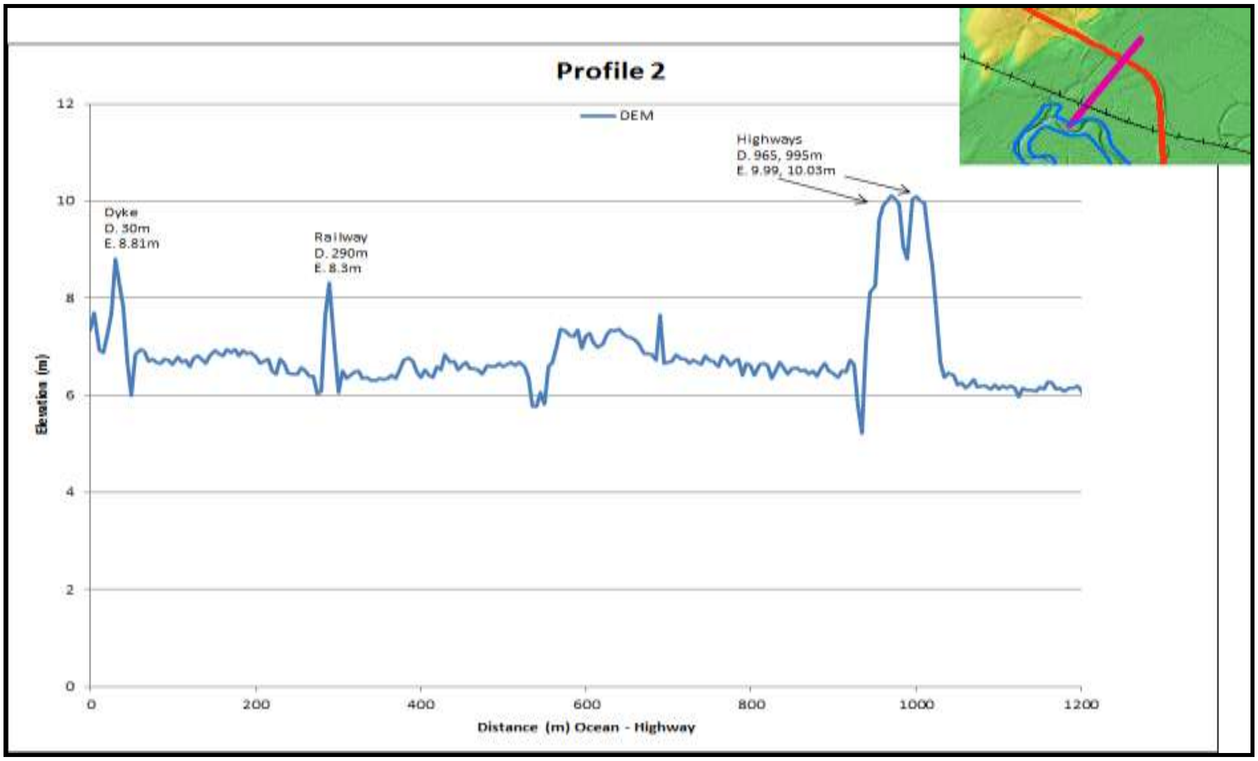

Figure 11 **Profile 2, traversed from the southwest to the northeast – the NS dykes in this area are at 8.81 m. The rail line elevation is 8.3 and the TCH (Highway 104) lanes are at 10 m.**

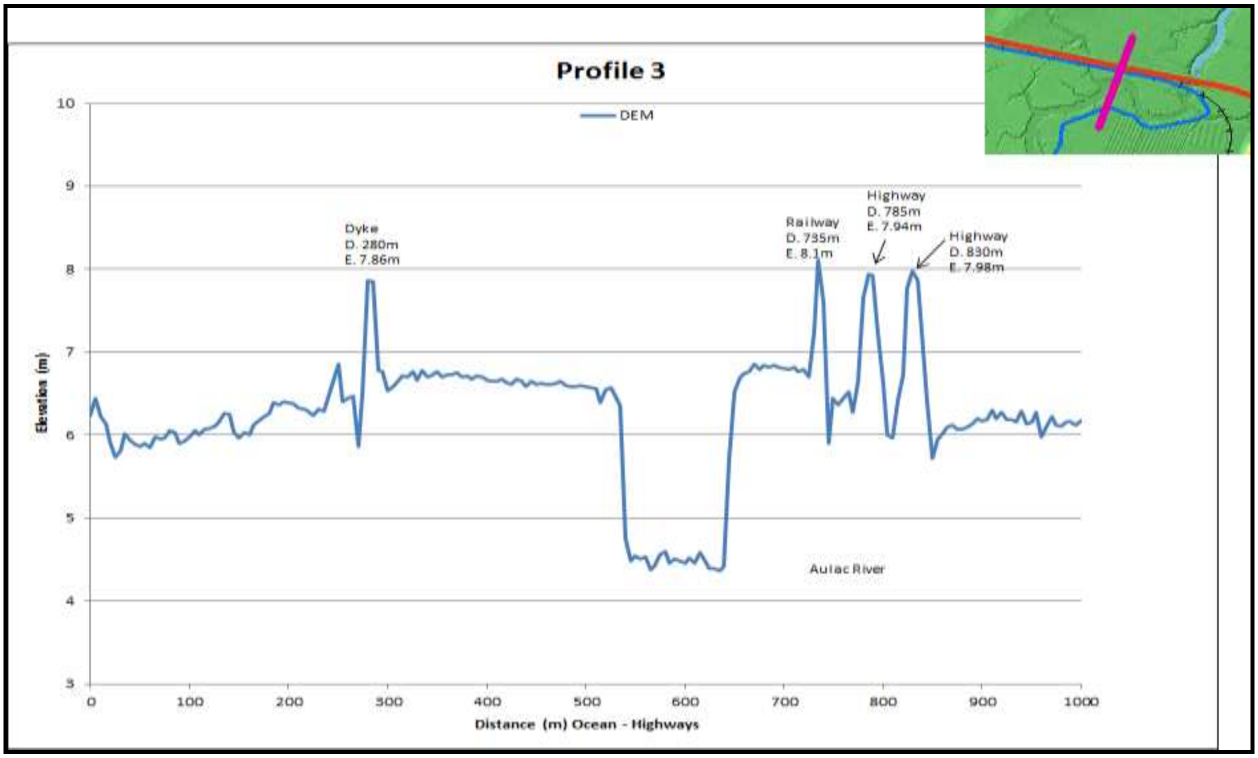

Figure 12 Profile 3, traversed from the southwest to the northeast – the NB dykes in this area are at 7.86 m. The rail line elevation is 8.1 m and the lanes for the TCH are at 7.9 and 8 m.

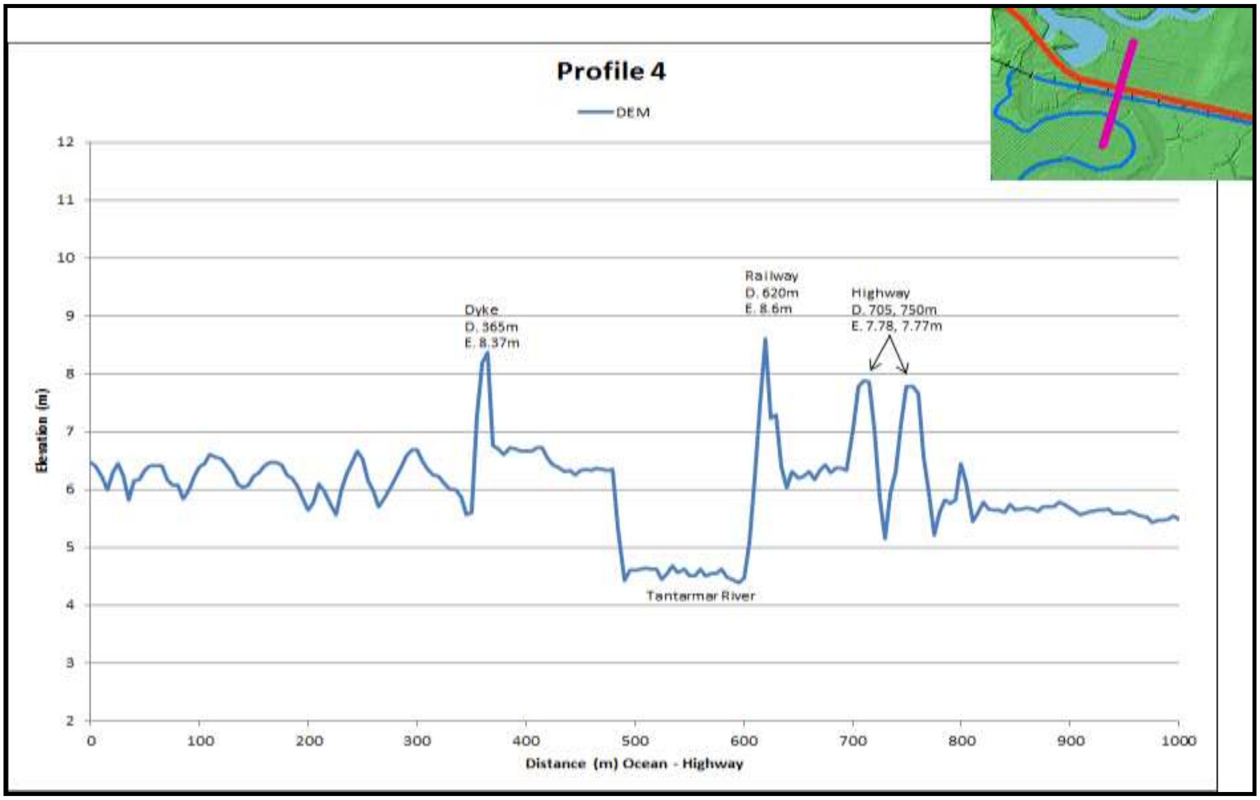

Figure 13 Profile 4, traversed from the southwest to the northeast – the NB dykes in this area are at 8.37 m. The rail line elevation is 8.6 m and the TCH lanes are at 7.8 m.

3.2 Flood Inundation Maps

Flood layers were generated connecting the Bay of Fundy to low-lying land from 5 m to 10 m at 10 cm increments. A system of agricultural dykes, the CNR and the TCH collectively protect the low-lying land behind it but once any portion of the system is overtopped, a large area of land is vulnerable to flooding because of its low elevation. In addition to the low elevation, much of the land north of the TCH and CNR consists of wetlands and lakes indicating that the land is already saturated and the water table is very high in this area. If portions of the dykes were to be overtopped by a storm surge, the land would not be able to absorb much of the water and thus increase the residence time of the flood water behind the dykes. The dyke system holds back the ocean at 7.7 m (Figure 14). The rail line at 8.7 m acts as the main dyke protecting the TCH along the Tantramar Marsh at this water level. However at 7.8 m, portions of the adjacent agricultural dykes in New Brunswick begin to overtop and flood the highway, a low section of the CNR (at 6.8 m), and agricultural land near the NS-NB border. Note that the straight line representing the flood limit north of NB Highway 2 (TCH) is a result of the limited extent of the lidar 1 m DEM; the water would extend much farther inland than depicted on the map (Figure 14). When the water reaches 8.0 m, the dyke system is compromised and many local roads and properties would be inundated (Figure 14). Highway 104 in NS is still not overtopped although it is surrounded by water since it is above 8 m. By comparison in New Brunswick, the TCH would have ~20 cm of salt water covering it (Figure 14). The full extent of the inundation area if an 8 m water level was sustained for a period of time is depicted on Figure 15. One must consider that the tide would soon drop and depending on the damage to the dykes and transportation infrastructure (in turn a function of the severity and duration of the storm), emergency repairs could be made to limit the impact of the next high tide (assuming staff and equipment can be effectively mobilized). Of greater concern though is the likely slow drainage of water from the flooded areas (several days). The presence of the TCH and CNR (as barriers) would slow down the drainage back to the aboiteau in the agricultural dykes which in turn can only release water during low tide periods. This event would still be a disaster for many people in the Amherst and Sackville areas. As noted above, many local roads and properties would be flooded and there would be considerable damage to assets and properties by salt water exposure.

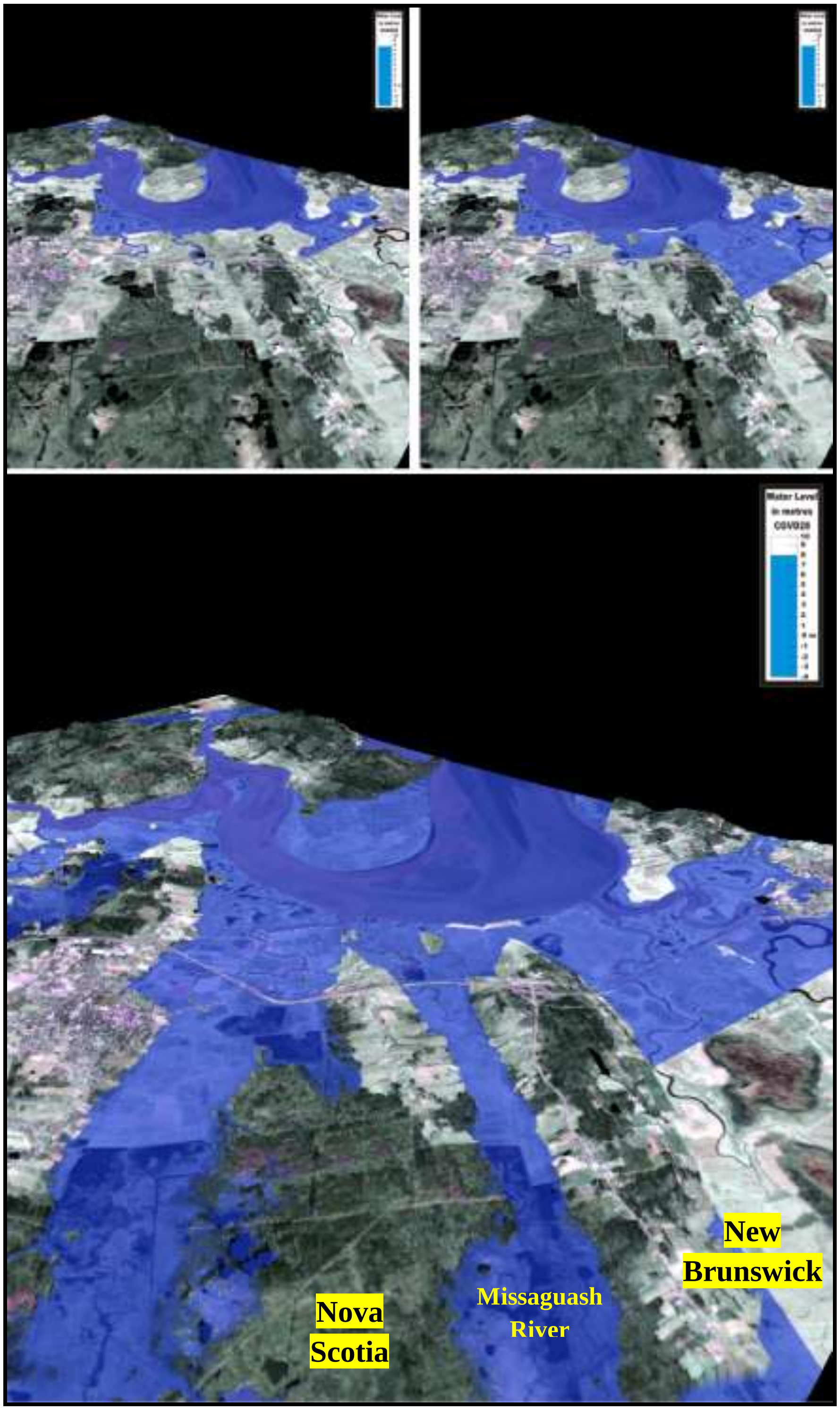

Figure 14 Perspective views looking south of the Isthmus at different water levels. Upper left image shows the water level at 7.7 m – dykes holding. Top right image shows water level at 7.8 m and some dykes have overtopped in NB. Lower image is the water level at 8.0 m overtopping all of the dykes, although the TCH (Hwy 104) is still above water in NS.

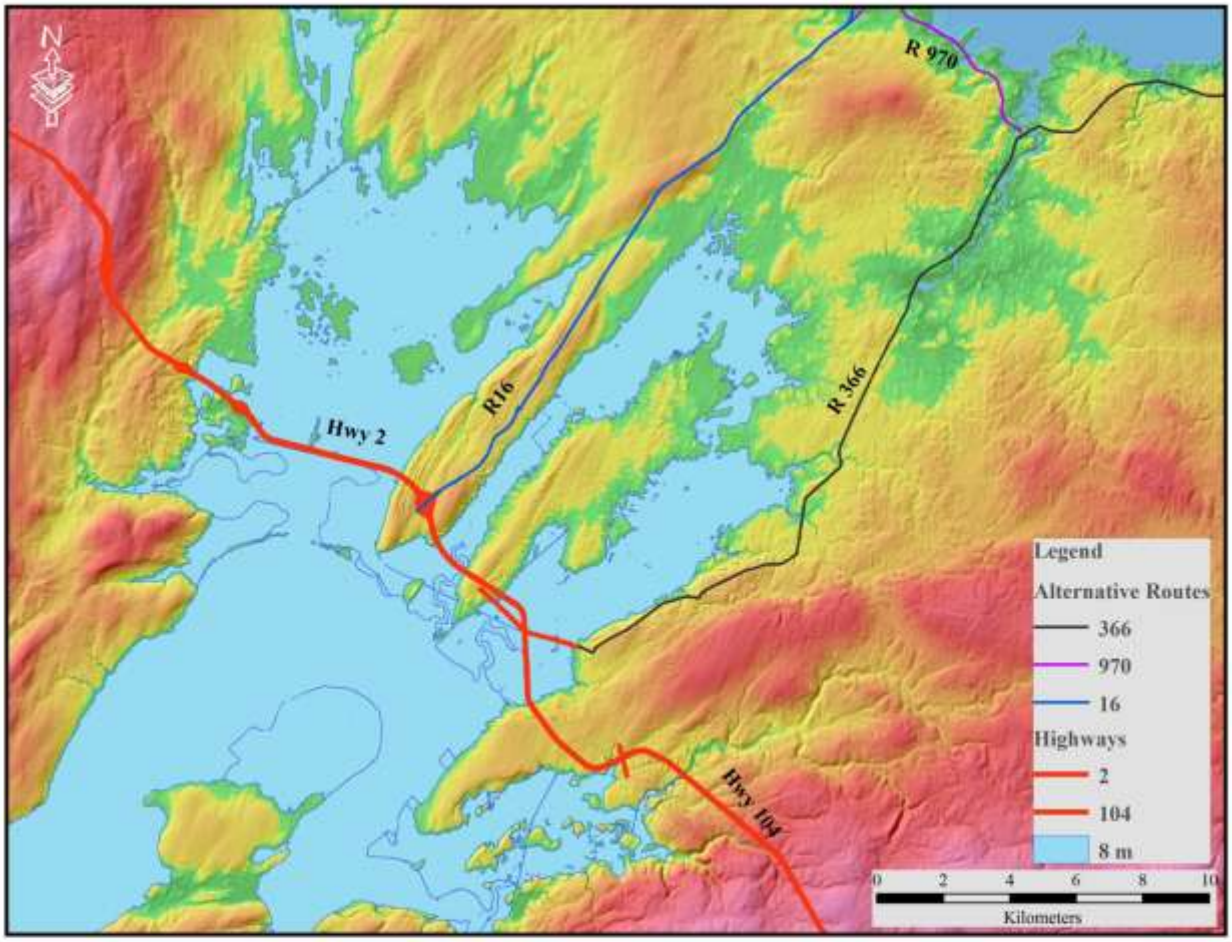

Figure 15 Maximum extent of a water level of 8.0 m which overtops at sections of all the dykes. Highway routes are labelled since the TCH and CNR would not be passible at this level.

If a 2 m storm surge occurs on a perigean spring high tide as was the case with the Saxby Gale, the water level would be close to 10 m. Both the CNR and TCH would not be passible and trade would be halted, likely for days. Community and private assets would be severely damaged and farm productivity lowered for years because of saltwater inundation.

Nova Scotia becomes an island when the water level reaches 12 m CGVD28 which allows the Bay of Fundy to connect to the Northumberland Strait (Figure 16). With future predictions for SLR going as high as 5 m by 2100, a water level of 12 m (~4 m above current higher high tides) is not beyond the realm of possibilities for long-term planning of significant infrastructure such as the Atlantic Gateway. Highway 104 at its current elevation will be long gone and under ~4 m of water at this time. Portions of NS Route 366 and NB Route 970 along the northern coast of NS and NB will not be accessible at this level either. The white line on Figure 16 marks the highest terrain in this area and thus provides the safest environment for the longest period of time to the threat of sea-level rise and storm surges.

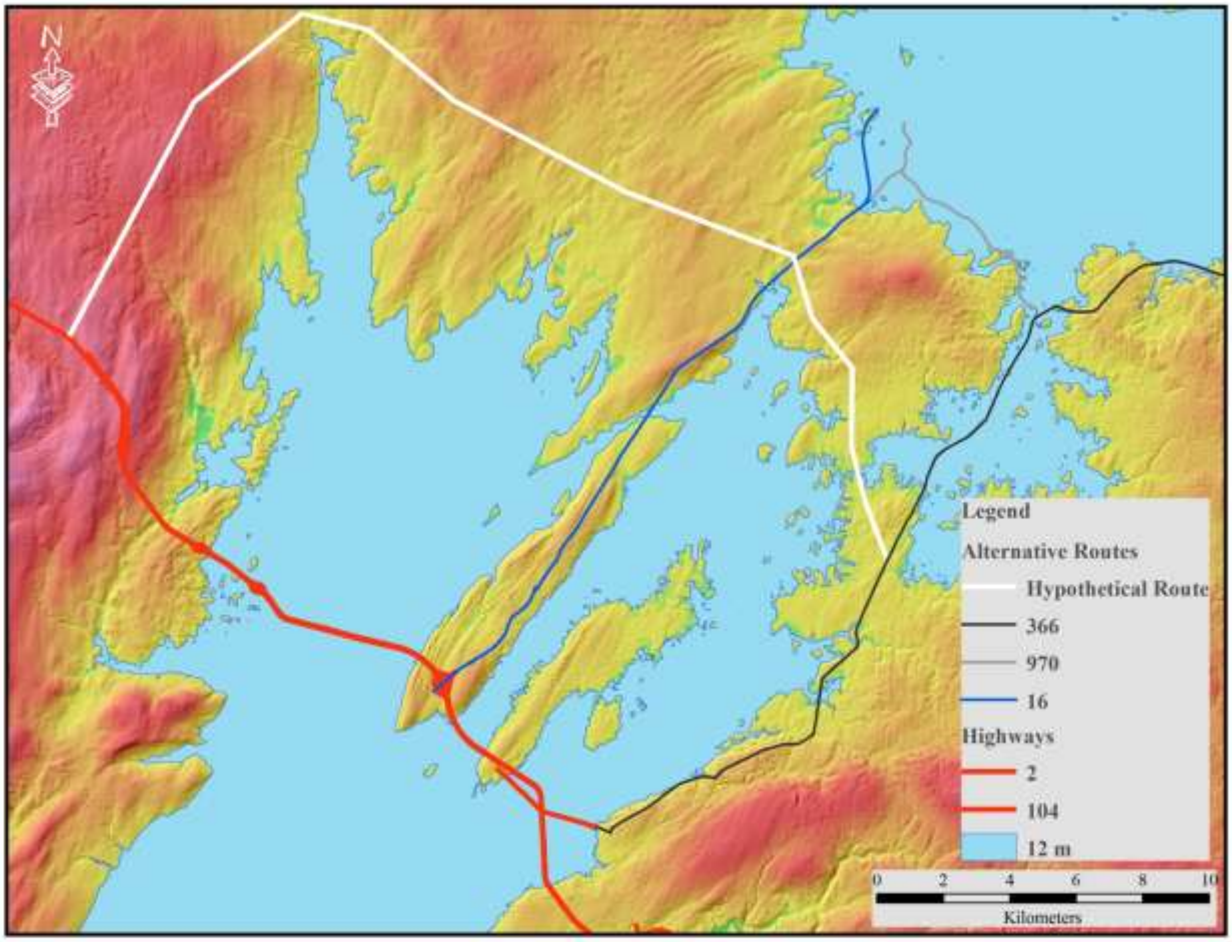

Figure 16 Nova Scotia becomes an island when sea level reaches 12 m. The existing highway routes are mapped along with a hypothetical connector route along the highest terrain (white line).

In order to better determine where the exact overtopping of the dykes occurs and at what critical water level, the flood inundation layers were closely examined in relation to the dyke elevations. In general, the dykes are around 8.45 m CGVD28, however there are lower sections in the dykes making them more vulnerable to overtopping. These areas should be an early target for adaptation efforts to raise the level and strengthen the dykes. Other low sections will also be vulnerable because of erosive effects of storm-driven waves. Further evaluations are required to document the extent of this problem and best solutions to armour the dyke tops with more than just grass. In the longer term, higher dykes of the future will need to be more robust to prevent erosion and geotechnically stable on the relatively poor foundation of the former marsh soils.

Thirteen locations were identified where sections of the dyke elevation is low enough to allow overtopping at critical water level elevations (Figure 17). The lowest critical elevations occur along the dykes in New Brunswick where they begin to overtop at water level 7.8 m near Aulac at the east side of the Tantramar Marsh (Figure 17). This low section occurs south of the bend in the CNR line which is at one of its lowest elevations in this area at less than 7 m. Another low elevation of 7.8 m occurs along the dyke on the west side of the Missaguash River south of the rail line on the NB side.

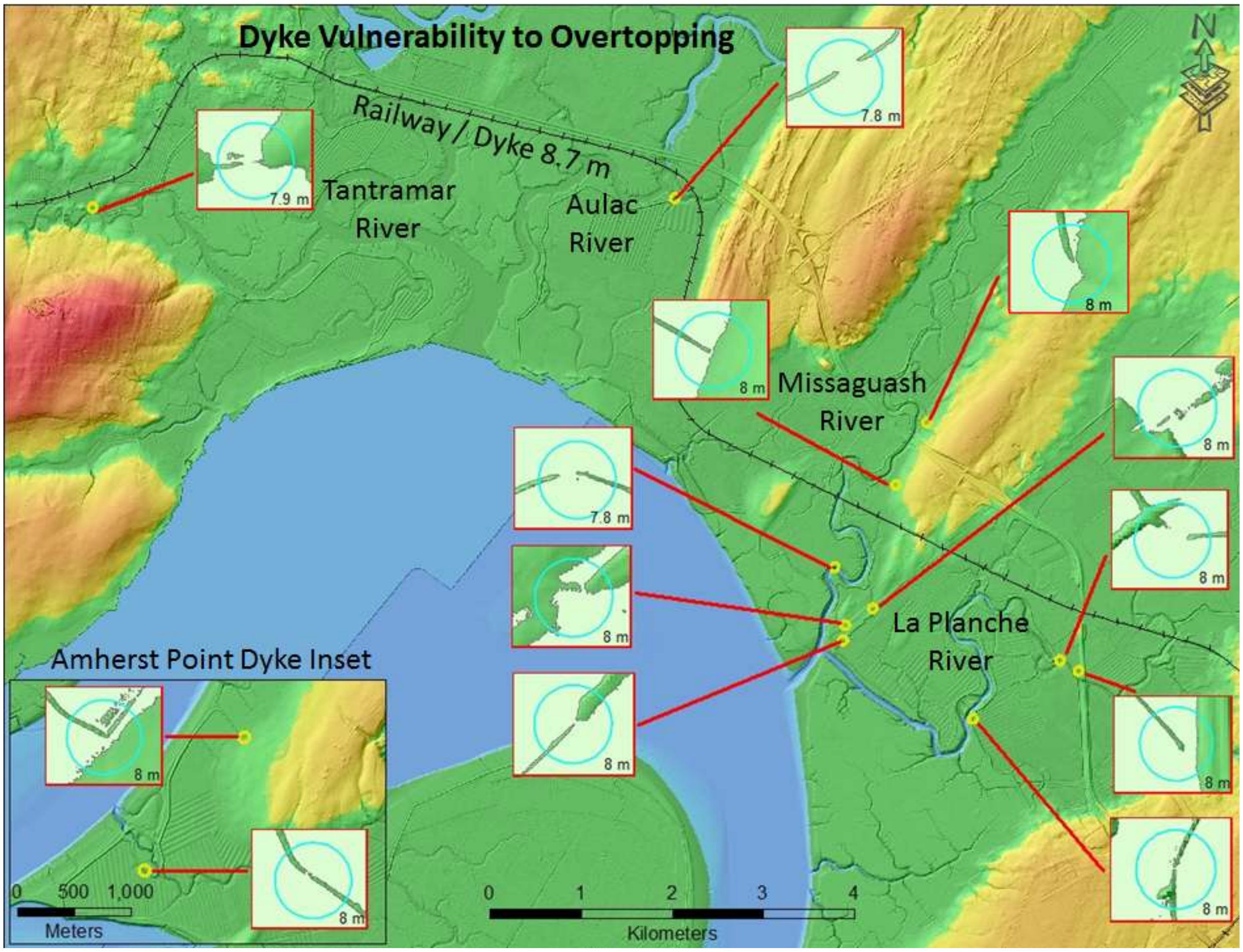

Figure 17 Critical dyke overtopping locations and water levels.

The next critical dyke elevation for overtopping occurs at water level 7.9 m. This occurs at a dyke on the north side of the west branch of the Tantramar River south of Sackville, NB, near Highway 106 at West Sackville (Figure 17). At a water level of 8.0 m, several dykes have locations where overtopping can begin in Nova Scotia. The NS dykes on the east side of the Missaguash River have two locations south of the CNR line (Figure 17), and one location between the CNR and Highway 104 where the dyke abuts the topographic high associated with the Amherst on-ramp system to Highway 104. A water level of 8.0 m also overtops the dyke on the east side of the Missaguash River north of Highway 104 (Figure 17). Other areas where the 8.0 m water level overtops the dykes include two locations on the southern dykes along the LaPlanche River near the main aboiteau (Figure 17). The dyke on the north side of the LaPlanche River also overtops where it abuts to Highway 104. The inset map on Figure 17 highlights dykes at Amherst Point that would be overtopped by a water level of 8.0 m. These types of maps provide NSTIR and NS Department of Agriculture officials with information on the critical locations where the dykes are most vulnerable to overtopping and should be raised as part of the adaptation solutions.

The results of the hydrodynamic modelling during perigean spring tides in November 2012 are shown in Figure 18. The extent of this storm surge flooding is similar to that produced by Leiske and Borrnemann (2011) for the 1 in 10 year return period based on water levels by Daigle (2011). We rarely experience 2 m storm surges, however surges of 0.5 to 1 m are not uncommon (expected frequencies from 7 to 55 years; Webster et al., 2008). The probability of an event overtopping the dykes is increased significantly with the occurrence of the seasonal and long-term astronomic high tides. The duration of time the flood waters would reside behind the dykes was beyond the scope of this project and was not calculated. Figure 18 was produced for illustration purposes only to show that during very large tides, as was the case for the Saxby Gale and Groundhog Day Storm, the dyke system and a very large “land” area are vulnerable to overtopping if the tides are associated with a storm surge (as noted earlier, a large portion of the flooded area is already classified as wetlands).

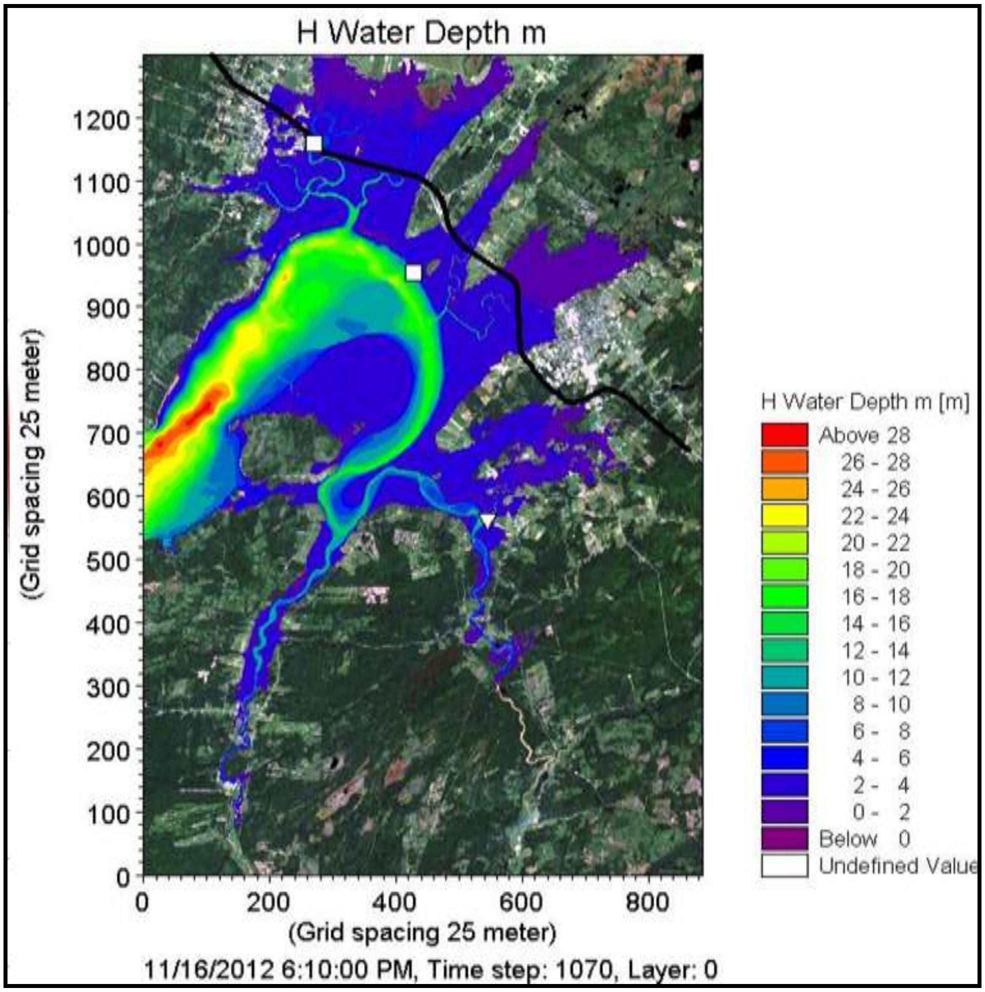

Figure 18 Results of inundation from Mike 21 simulation of the water depth of flooding associated with high tides predicted for November 16, 2012 with a 2 m storm surge. TCH depicted as a black line.

The still-water flood levels and critical dyke elevations (Figure 17) were used to assess the potential impacts to repairs of Highway 104. We have calculated the precise length of the road segments covered at certain critical water levels and report the length of road affected at each water level (Figures 19-21). Note that the lidar DEM does not include the elevated section of the highway where it passes over the rail line or the bridge over the LaPlanche River. A water level of 9 m begins to inundate small sections of the highway and the on-ramp near Amherst for example (Figure 19). Our model increments the water level at 10 cm steps and we are able to measure the length of road overtopped (see Table 1). A water level of 9.5 m begins to overtop the highway north of Amherst (Figure 20).

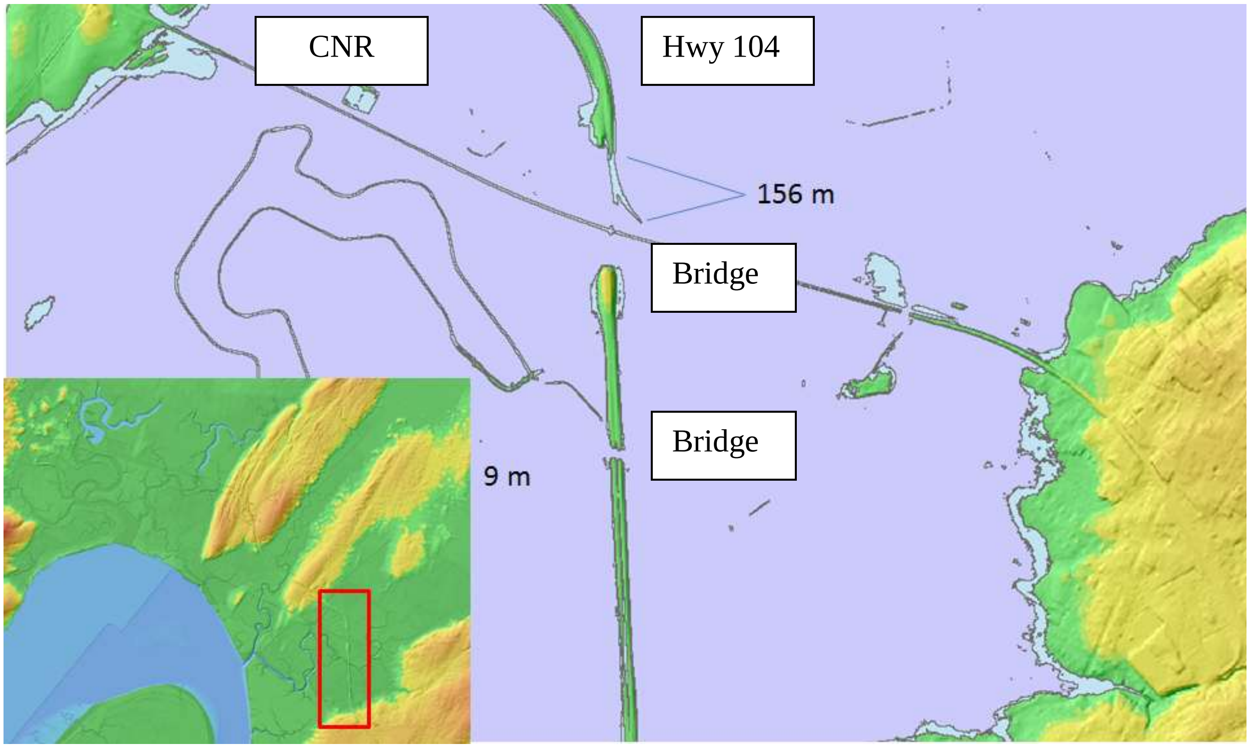

Figure 19 Impact of water level of 9 m on Highway 104 north of Amherst. A 156 m-long section of highway would be flooded.

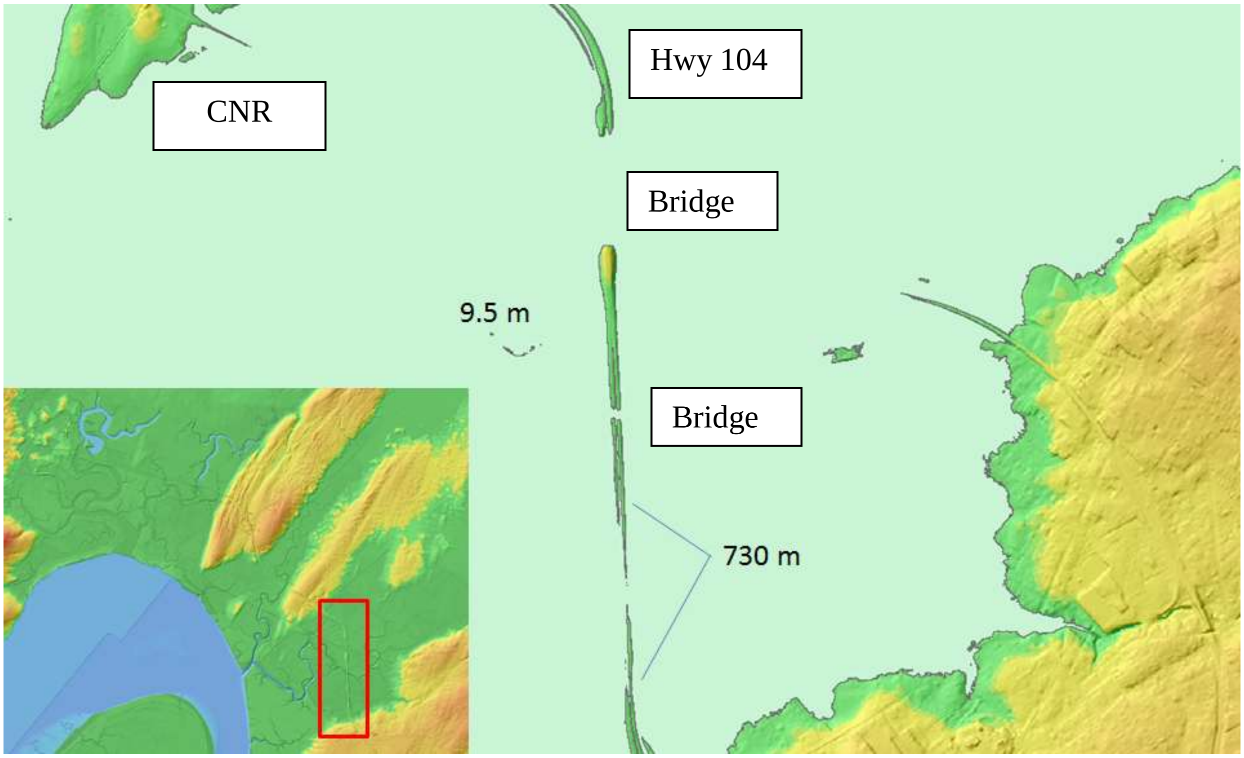

Figure 20 Impact of water level of 9.5 m on Highway 104 north of Amherst. A 730 m-long section of highway would be flooded.

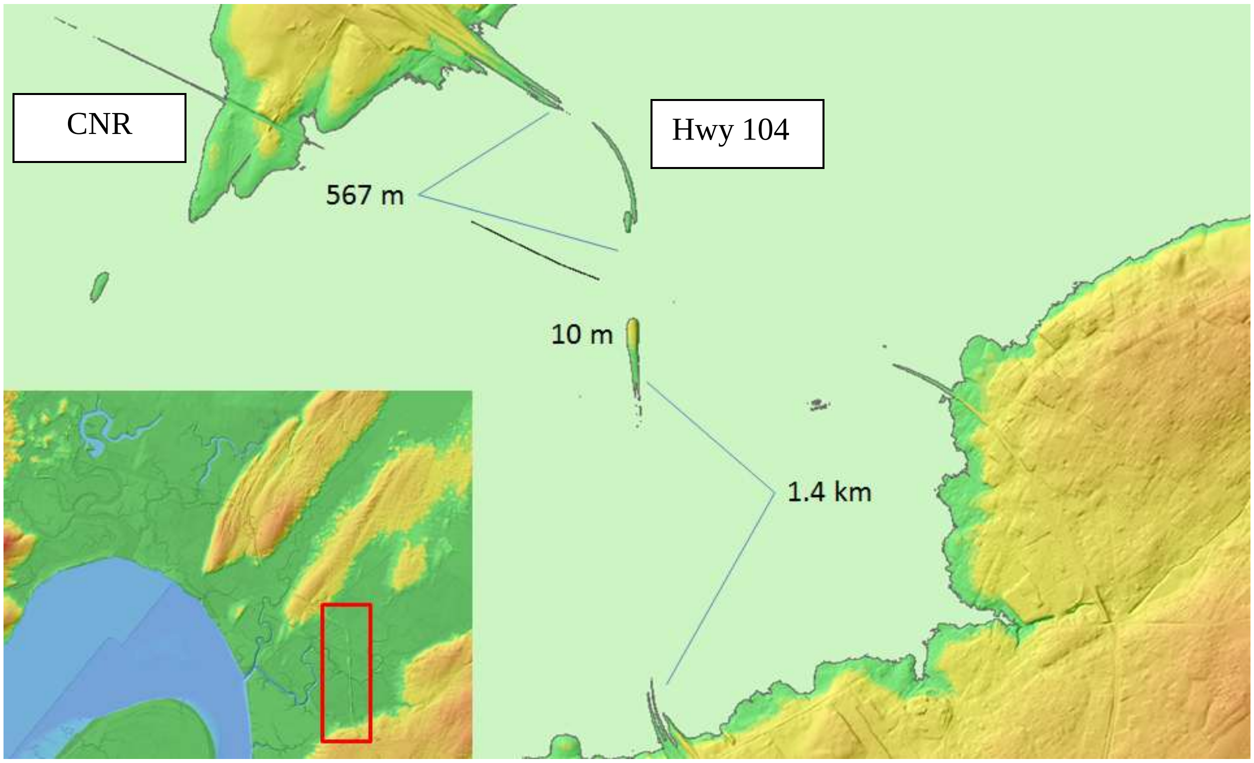

Figure 21 Impact of water level of 10 m on Highway 104 north of Amherst. Two sections of the highway are overtopped; one that is 1400 m long and another that is 567 m.

Table 1 Summary of water levels and length of Highway 104 that is inundated.

Water Level (m)	Highway Length (m)
9.1	100
9.2	195
9.3	496
9.4	606
9.5	810
9.6	961
9.7	1260
9.8	1745
9.9	1997
10	2137

4 Conclusions and Recommendations

This study has demonstrated that the critical transportation corridor that crosses the Chignecto Isthmus is vulnerable to coastal flooding from storm surges as well as long-term sea-level rise. We have demonstrated that there are low sections of agricultural dykes at present that are vulnerable to overtopping during storm surge events (>7.8 m). NSTIR and NS Agriculture could collaborate to strengthen the NS dykes and avoid costly delays to trade flow at the Atlantic Gateway, flooded local roads, damage to public and private assets, and lower farm production. The dyke vulnerability maps can serve as a guide to where adaptation efforts should be focused in the near term. Note also that a short section of the CNR west of Aulac, at 6.8 m, would be covered by a metre of water if the total sea-level reaches 7.8 m.

A significant storm with an associated strong Southwest wind during spring tide periods over the next few years, and especially during the spring and fall tidal maxima, could be catastrophic. Coincidence of the storm and high tides could generate a 1.5 to 2 m surge that would cause extensive flooding, possible loss of life, a temporary halt in traffic through the Atlantic Gateway (both TCH and CNR with projected trade loss of $50 million per day), and severe damage to a wide variety of public and private assets in the Amherst and Sackville areas. NSTIR and the NS EMO should consider advanced preparations for this possibility.

In the longer term, Nova Scotia will become an island when sea-level rises to 12 m CGVD28, following a storm surge or during a higher RSL period. The Bay of Fundy will join with the Northumberland Strait. Considering the critical importance of the Atlantic Gateway, the Federal Government, the provincial governments of Nova Scotia and New Brunswick, CNR and the municipalities and towns affected will have to consider if a dyke system can be maintained and defended or if other alternatives should be built. Although this decision is likely still a long time off, when considering adaptation solutions and the large risks associated with sea-level rise and increased storm intensity, duration and frequency, it is prudent for NSTIR and other departments to start the planning and perhaps “protect” the areas of most risk for the longest period of time. In the case of the Chignecto Isthmus, we have shown an alternative route on higher ground that could maintain a land connection between NS and NB in the face of rising sea-level.

One final recommendation is directed at a variety of federal and provincial government departments. The probability of storm surge and high tidewater events occurring in the upper Bay of Fundy is low and has a high degree of uncertainty but very high costs if/when it happens. These extreme events have occurred several times in the last few hundred years and this behooves us to at least consider implementing “no or low risk” adaptation actions. Records of water levels in this region were never collected in large part because of the lack of commercial ship traffic and major harbours. However, now that sea-level rise has been recognized as a major threat to land-based infrastructure, trade and human safety, and SLR is expected to significantly increase in the future, at least two permanent tide gauges should be established in the upper Bay of Fundy, one in the Cumberland Basin and another in the Minas Basin, in order to begin to establish long-term records of storm surge events. A 30 year record would allow for calculations of return periods of extreme water levels with a much higher degree of certainty than the estimates we currently are using. This is a trivial cost compared to the likely damage of a major surge on infrastructure and communities near Amherst, Windsor, Wolfville, Kentville, and Truro, NS, and Sackville, NB.

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