Assessment of Flooding Hazard along the Highway 101 corridor near Windsor, NS using LIDAR

Final Report submitted to the
Nova Scotia Department of Transportation and Infrastructure Renewal (NSTIR)

Prepared by
Dr. Danika van Proosdij
Department of Geography

October 22, 2009

TABLE of CONTENTS

EXECUTIVE SUMMARY

The purpose of this project was to assess the impacts of 'natural' processes (e.g. storm surge, freshwater flooding and coastal erosion) on highway infrastructure in the region. The section of the Highway 101 twinning project that will run along the Windsor Causeway and across the Avon River will be highly vulnerable to both coastal and overland (freshwater) flooding. Flood risk was assessed using ArcGIS 9.3 and a high resolution LIDAR elevation survey of the area conducted in April 2007. The LIDAR was flown by the Advanced Geomatics Research Group at the Centre of Geographical Sciences (COGS) as part of a collaborative research exercise with Saint Mary's University, NS Department of Agriculture (Land Protection Section) and NS Department of Transportation and Infrastructure Renewal. In addition, the IKONOS satellite was tasked by the Maritime Provinces Spatial Analysis Research Centre (MP_SpARC) at Saint Mary's University to capture a high resolution image of the area in October 2007 as part of a research project studying the intertidal morphodynamics of the Southern Bight.

Normal and flood water levels were chosen based on Canadian Hydrographic Service data, information from NS Agricultural personnel at the Windsor tide gate and existing tide gauge records at that location as well as published rates of sea level rise. Flood levels were modeled for four tide scenarios which included a 1 in 20 year storm surge above higher high water large tides (HHWLT) of 0.6 m, a storm tide (8.6 m CGVD28) which occurred in January 10, 1997 (van Proosdij & Baker, 2007), a 1 in 100 year surge event (1.2. m) (8.77 m CGVD28) and then the 1 in 100 year event coupled with a rise in sea level by 0.7 m (total 9.4 m CGVD28) (IPCC, 2008; Parkes et al., 2006; Bindoff et al., 2007; Vasseur & Catto, 2008). Additional analyses were performed to simulate freshwater flooding events based on critical overtopping at the Falls Lake and Forks Dams. In all cases care was taken to ensure connectivity to either a coastal or riverine source of water similar to other coastal flooding studies (e.g. Webster et al., 2004).

Seven areas of concern were identified and in most cases the areas along the 101 highway corridor will only be at risk during large precipitation events at high tide when the aboiteau cannot adequately discharge water or during storm conditions in the future. Specific areas of concern include highway conditions at Exit 6 (tidal) and Exits 5 (freshwater) & 8 (tidal and freshwater). The area adjacent to the St. Croix coastal restoration project near Exit 4 may be at risk of bank failure during storm conditions due to the proximity of the highway to flooding

waters. The flooding situation at Exit 8 may be able to be mitigated in part by repairing or replacing the existing broken aboiteau structure at the mouth of Halfway River. The eastern and western sections of the causeway, particularly the eastern on ramp near Exit 6 are at risk of storm surge overtopping within the next decade given current rates of sea level rise. It is advised to consider increasing the elevation of these sections during the twinning process. In addition, the western section will be highly vulnerable to the impacts of sea level rise and storm surge given the orientation of the main tide gate channel with the dominant fetch. Both sections should be raised to minimum of 9.75 m. Careful attention will need to be focused during the bridge construction process on the placement of the bridge abutments as the area around the tide gate channel is highly susceptible to erosion and at a high risk of flooding. The entire area surrounding the proposed location of the bridge is in a flood hazard zone therefore additional fill and shore armouring will be required.

Removing the tide gate will cause significant flooding to occur within the town of Windsor, even during 'normal' spring tide conditions. The majority of the original protective dyke works have been removed over time as they were no longer maintained after the causeway was built in 1971. As a result, all of the original marshland areas would flood as well as a considerable section of the downtown Windsor waterfront area. Water Street and the old rail bed would provide a partial restriction during normal spring tides however during storm conditions, once breached, would permit almost continuous flow of water into the low lying regions behind the rail bed. Floodwaters would cross King St. and join the NS68 Tregothic marshbody. These low lying areas are also at risk from flooding from freshwater flooding events when prolonged precipitation events exceed the capacity of the tide gate to discharge adequate amounts of water to lower the lake and river levels to a safe level (e.g. timing at high tide). As a result, further development should be restricted in low lying areas and any roads crossing these areas should be raised where possible.

ACKNOWLEDGEMENTS

This research would not have been possible without the continued support of the Nova Scotia Department of Agriculture, Resource Stewardship Division, Land Protection Section personnel, specifically Ken Carroll, Darrel Hingley and Hank Kolstee.

Special thanks is extended to Greg Baker, research instrument technician at the Maritime Provinces Spatial Analysis Research Centre (MP_SpARC), at Saint Mary's University for coordinating the IKONOS satellite image capture. In addition this project would not have been possible without the geomatics infrastructure available through MP_SpARC. This centre was funded by the Canada Foundation for Innovation, Nova Innovation Trust Fund and various industrial partnerships.

The LIDAR data acquisition could not have been possible without the assistance of Tim Webster and Chris Hopkinson of the Advanced Geomatics Research Group at COGS who collected and post processed the data. The LIDAR acquisition was a joint research funding endeavor between AGRG (in-kind), Saint Mary's University, NS Department of Transportation and Infrastructure Renewal and NS Department of Agriculture, Resource Stewardship, Land Protection Section.

LIST of FIGURES


ROAD CLOSED
DO NOT ENTER

Assessment of Flooding Hazard along the Highway 101 corridor near Windsor, NS using LIDAR

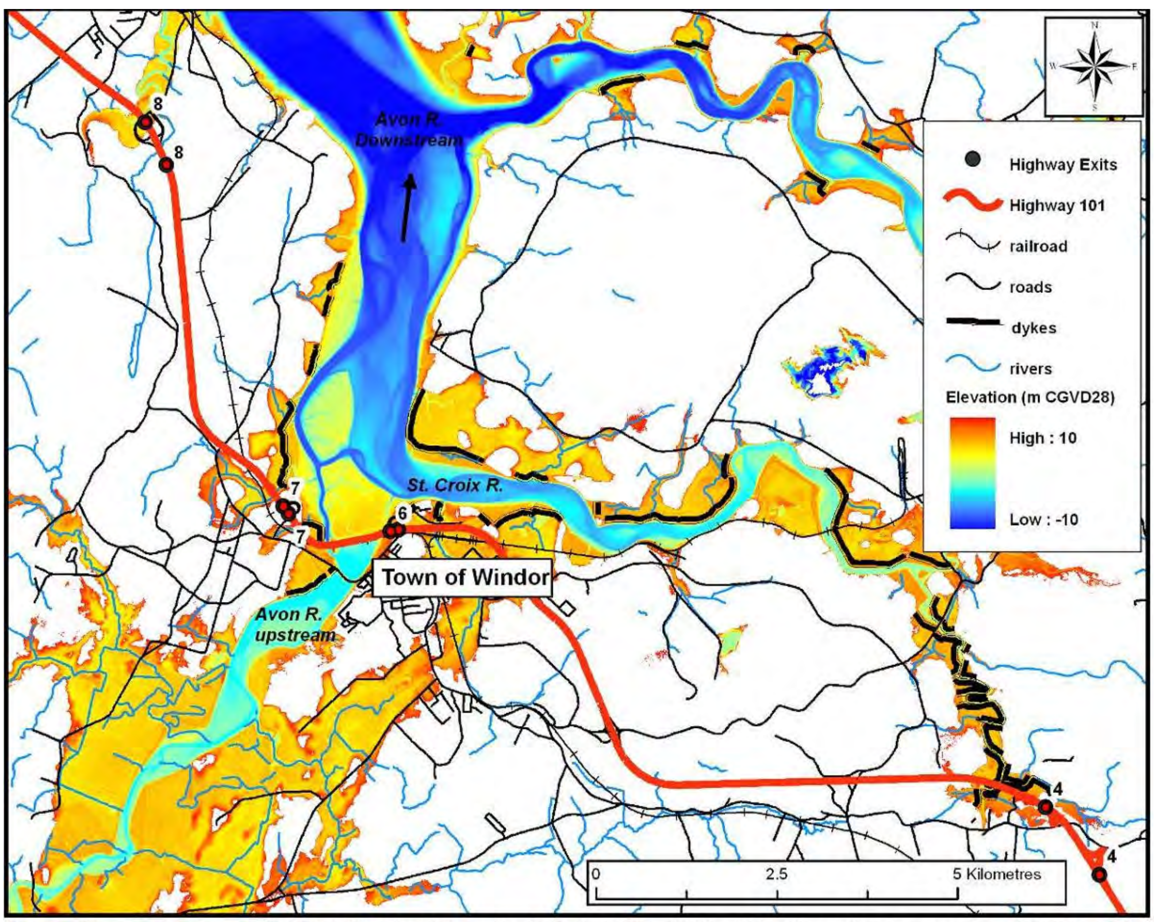
Introduction

To date, a number of reports have been published that focused primary on the direct and indirect impacts of the Highway 101 twinning project on the intertidal ecosystem both up and downstream of the Windsor Causeway (e.g. Daborn et al., 2003; van Proosdij et al. 2004; 2006; 2007). The purpose of this project was to assess the impacts of 'natural' processes (e.g. storm surge, freshwater flooding and coastal erosion) on highway infrastructure in the region. The section of the Highway 101 twinning project that will run along the Windsor Causeway and across the Avon River will be highly vulnerable to both coastal and overland (freshwater) flooding. In addition, the proposed bridge across the Avon River will be at risk from coastal erosion and this process will need to be considered during both design and construction phases in order to ensure the long term sustainability of the structure. Furthermore, some sections of the highway through the study area will be at risk of freshwater flooding due to inadequate drainage through standard culverts.

Figure 1: Bankfull conditions along the St. Croix river near Wentworth Rd.

This issue will be particularly compounded in areas near dykelands where freshwater drainage is dependant on existing aboiteau structures. These structures can only drain during low tides since they are designed to prevent salt water intrusion. Therefore, a high rainfall event that takes place during a high spring tide can cause areas behind the dyke to flood considerably. Moreover, despite the fact that the sections of the highway that cross low lying topographic areas are for the most part protected by dykes, there is a real risk of flooding when these dykes are overtopped.

This project focused on assessing the risk to infrastructure within the study area (Figure 2) from marine and freshwater flooding as well as from coastal erosion. The study focused primarily on the section within and surrounding the town of Windsor, however also identified vulnerable areas along the Highway 101 transportation corridor between Exits 4 and 8 and will provide recommended elevations to minimize the risk of flooding. Effective assessment of this vulnerability is dependent on the accuracy of the digital terrain model employed.



Created by D. van Proosdij, Saint Mary's University, MP_SpARC, 2008. Lidar flown & processed by AGRG at COGS.

Figure 2: Study area with digital elevation model depicted up to 10m elevation contour.

In order to fully appreciate the potential risk to the region, it is important to have a basic understanding of the mechanics of tidal processes, historical storm activity and climate change.

Tides

The Bay of Fundy is renowned for its large tidal range, which reaches a maximum of 16.3 m at Burntcoat Head in the Minas Basin. Tidal range in the Avon River estuary varies from 8.2 m Chart Datum at neap tide and 15.6 m CD at lunar perigee spring tide (CHS 1976, predictions for Hantsport). Tides are strongly semidiurnal (twice a day) with a diurnal inequality that is almost always less than 0.6 m (Lambiase, 1980).

Tides produce strong currents which are the main agents of transportation and deposition of sedimentary material in the Bay, effectively transporting, creating, and remolding surface and geological features. A recent publication by Desplanque and Mossman (2004) provides a comprehensive overview of the mechanics and impacts of Fundy tidal processes on the geology of the region. Due to the relatively shallow nature of the Avon River Estuary, the rising limb of the tide will be compacted within a shorter period, whereas the period of the falling tide will increase (Carter 1998). However, this process will vary depending on the lunar cycle. At neap tide, the tidal curve is generally symmetrical with both the ebb and the flood flow lasting around 6.5 hours. In contrast, the tidal curve for spring tides is slightly asymmetric at the mouth of the estuary with ebb flows lasting 0.5 hours longer than flood. This asymmetry increases as one travels up the estuary, where there can be as much as 8.5 h of ebb flow with only 4 h of flood flow (Lambiase, 1980). As mentioned previously, the tidal prism is the volume of water flowing in and out of the estuary with the rise and fall of the tide. Because tides are variable in strength, the tidal volume and tidal prism are variable, as is the wetted cross sectional area. In addition, during low water, sections of the estuary south of Hantsport are completely drained since bottom elevations are higher than the lower tidal limit.

Cycle	Period	~ Tidal range
Diurnal cycle due to relation of moon to earth	0.517 days (12 hr 25 min)	11.0 m
Spring/neap cycle	14.77 days	13.5 m
Perigee (high) / apogee (low)	27.55 days	14.5 m
206 day cycle due to spring/neap and perigee/apogee cycles	206 days	15.5 m
Saros cycle (last peaked in 1994-95 predicted peak in 2012-2013 AD)	18.03 years	16.0 m

Table 1: Summary of characteristics of major constituents of tidal cycles in upper sections of the Bay of Fundy (Desplanque & Mossman, 2004).

In general, higher water levels are recorded during spring tides and lower water levels are recorded during neap tides although, due to the tidal asymmetry in the Bay of Fundy, this is not always the case. In addition, the absolute elevation of the tide will vary depending on the relative position of the sun and the moon and orbital cycles (Table 1). The most favorable combination of factors to produce strong tides in the Bay of Fundy occurs when the perigee coincides with a spring tide and other cycles to produce Saros tides every 18.03 years (Desplanque & Mossman, 2004). Based on Desplanque & Mossman's (2004) calculations, the peaks of the Saros cycles within the last century occurred in 1904-1905, 1922-1923, 1940-1941, 1958-1959, 1976-1977, 1994-1995, and the next will occur in 2012-2013. In addition, detailed tidal records over several decades show that there will be slightly higher maximum monthly high water marks in a 4.5 cycle year, examples being the peaks in 1998 and 2002 (Desplanque & Mossman, 2004).

The only permanent tide gauge operated by CHS is located in St. John, New Brunswick, therefore one must depend on predicted tides at Hantsport for most historical calculations. Data were located for both Windor and Hantsport stations for limited two month time periods. However, detailed tide records have been maintained by Maritime Marshland Rehabilitation Administration (MMRA) and Department of Agriculture personnel at the Windsor Tide gate from the mid 1980s. In addition, MMRA and NSDA personnel routinely recorded tides at select marsh bodies throughout the region for short time periods. These data provide an idea of the difference in water level elevations between different marsh bodies. For example, a large tide on April 4, 1958 was recorded as 8.23 m CGVD28 (26.96 ft) at the Windsor bridge and 8.18 m at Burlington marsh (across from Hantsport), but 8.23 m at Herbert River and Chambers. Fortunately, the MMRA had recently increased the height of dykes in the region but this had not received extensive support at the time.

> "*The highest tide recorded by the MMRA at the Windsor Bridge was 26.96 geodetic on April 4^th^, 1958, when the tide height predicted (tide table) for Saint John, New Brunswick was 29.1 low water datum. Note that this was the highest predicted tide for the region at least since 1932. The actual height reached at Saint John on this occasion was 29.0. The tide in the upper end of the Falmouth Great Dyke, above the Windsor Bridge, reached 26.85 geodetic, approximately one-tenth of a foot lower than the Windsor bridge peak.*
>
> *Many of the dykes constructed by this Administration around the inner perimeter of the Bay of Fundy were overtopped in sections by this tide which was*

sufficiently above our predictions to puzzle us. There were meteorological conditions favouring this particular occurrence and subsequent tides of the same predicted magnitude verified this as having been unusually severe.

These tides, of 1958 and 1959, as peaks of the very definite cycle of approximately 18 years proved to us the adequacy of our dyke construction grades. It may be of interest to note that marshland owners at Falmouth were of the opinion dyke grades were too high when construction was in progress. It is believed that this 18 year cycle is not generally realized and that past occurrences are attributed to other factors or are forgotten."

Portion of letter from J.D. Conlon, Chief Engineer, Dept of Agriculture, MMRA to
Mr. J.A. Brown, District Engineer, Habours & Rivers Engineering Branch,
Department of Public Works on Oct 12, 1961in response to file No. 1411-11
re Windsor Tidal Flooding.

To date, the highest tides recorded at the causeway tide gate were 8.87 m (29.1 ft) (date unknown) (pers com. K. Carroll, 2007) and 8.6 m CGVD28 (28.2 ft) on January 10, 1997. These tide levels reflect the Saros cycle or the 4.5 yr cycle mentioned previously. Examining the digital record between April 2002 and September. 2006, a total of 121 tides exceeded the HHWLT elevation (7.57 m CGVD28). Eleven of these dates were greater than 8.0 m (Table 2) with the highest recorded tide on February 1, 2006 (8.2 m) which overtopped dykes in many areas (Figure 3).

Date	Recorded Tide Height (m CGVD28)
Feb 1, 2006	8.211
Nov 25, 2003	8.206
Feb 09. 2005	8.170
Feb 10, 2005	8.129
Feb 11, 2005	8.129
Dec 25, 2003	8.082
Dec 13, 2004	8.046
Dec 24, 2003	8.040
Dec 12, 2002	8.004
Aug 21, 2005	8.004
Feb 28, 2006	8.004

Table 2: Record of tides greater than 8 m geodetic at the Windsor tide gate between April 2002 and Sept. 2006.

Figure 3: Storm impacts on Feb 1, 2006 at the Avonport Dyke. a) storm waves battering marsh; b) storm surge reached upper limits of dyke and dyke overtopped. Photo by T. Hamilton, 2006.

Waves & Storms

Due to the large tidal range, the time period during which waves can exert a significant influence is limited. Lambiase (1980) reports that waves are not an important hydraulic process on intertidal sand bodies in the Avon River estuary since waves tend to be small due to the limited fetch. These waves are believed to be the cause of small-scale slumps observed on sand bodies in the Avon and Cobequid bay (Darlrymple, 1979). Observed wave heights did not exceed 1.3 m in Lambiase's (1980) study and most ranged between 0.3 and 0.6 m. However, during high water the foreshore is covered with a significant amount of water, and a much larger percentage of wave energy reaches the shoreline than when the tide is at low water. Waves can exert a significant influence in exposed areas on the edges of marsh cliffs and foreshore, causing erosion and local re-suspension of sedimentary material. In addition, it can cause considerable damage to dykes in exposed areas that are not protected by a vegetated foreshore. This was evidenced on August 23, 2009 when Hurricane Bill passed offshore Nova Scotia. Waves caused significant damage to the dyke at Noel despite the presence of shoreline armouring (Figure 4a). Some of this rock material was transported over the top of the dyke into the low lying region behind (Figure 4b). It is likely that another storm would have completely breached the dyke at the eroded location if it had not been rapidly repaired. The section of dyke protected by a section of marsh received minimal damage since once waves travelled over the marsh surface their energy was rapidly dissipated (e.g. Möller & Spencer, 2002). Therefore marshes can serve as natural forms of coastal defense. The extensive marsh which has developed downstream of the Windsor causeway offers a natural form of shore protection for the causeway, although limited protection is provided in the tide gate channel itself. In other areas such as along the outer bend of river channels, strong tidal currents will be the primary forces causing foreshore and marsh erosion.

Storm surges are a large rise in water level which can accompany a coastal storm, and are caused by strong winds and low atmospheric pressure. Conversely, a negative storm tide can result from higher atmospheric pressure producing lower water levels than predicted. Compared to the Atlantic coast, storm surges exert less of an influence on the intertidal zone in the Upper Bay of Fundy due to the large tidal range. For example, a hurricane in July 1975 (recorded speeds of 130 km/h) only generated waves around 1.25 m in height and caused minimal changes to the morphology of sand waves in the Avon River Estuary (Lambiase, 1980). However, when a storm tide coincides with an exceptionally high astronomical (e.g. perigeen or Saros tide) tide the results can be significant, causing extensive coastal flooding and damage to infrastructure.

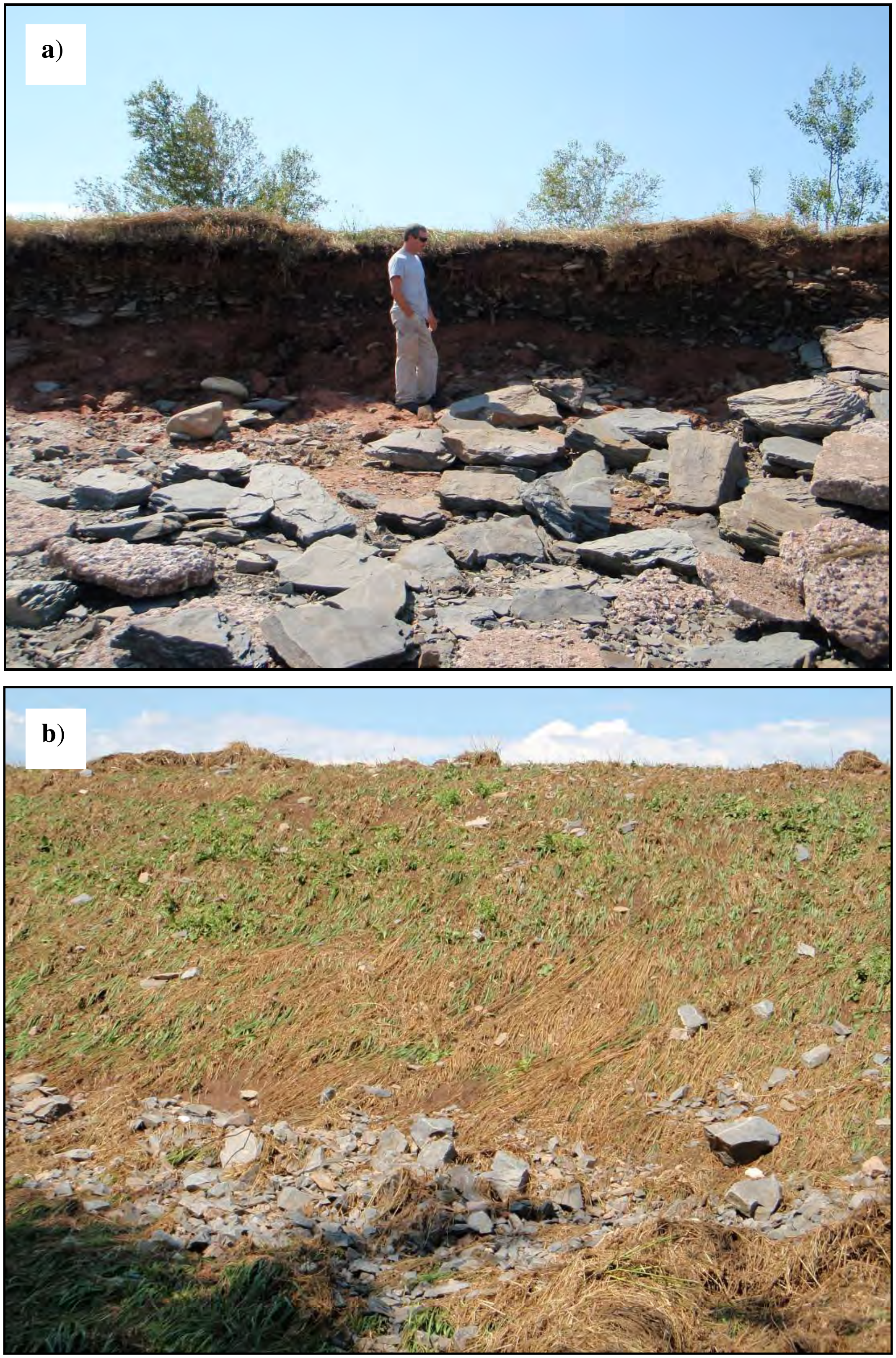


Figure 4: Impacts of Hurricane Bill on dyke at Noel in August 2009. a) erosion and undercutting of earthen dyke structure and removal of shoreline armouring, b) armouring rocks transported to the landward side of the dyke by wave action and overtopping. Photo by K. Carroll, 2009.

The heavy rainfall accompanying such an event can also cause extensive overland, freshwater flooding since the numerous aboiteaux and tide gates cannot discharge water at high tide. This has been seen in Truro, Nova Scotia on a number of occasions.

Historically, a number of significant storm events have occurred in the Bay of Fundy. Desplanque and Mossman (2004) provide a detailed account of the events surrounding them. One of the most notable storms was the Saxby Gale (or "Saxby Tide") which occurred on October 4th, 1869. Severe coastal flooding and wind damage occurred all along the North American seaboard. By 1:00 am on October 5th, the Saxby tide overtopped dykes by at least 0.9 m. In the Cumberland Basin, the tides were such that two fishing vessels were lifted over the dykes bordering the Tantramar marshes and deposited 5 km from the shoreline. At Moncton, the water level rose about 2 m higher than the next highest tide on record (Desplanque & Mossman, 2004). While damage in the Minas Basin was less severe, dykes were breached throughout the region, cattle and sheep drowned, and in many areas travel become impossible since the transportation lines (e.g. rail and road) were washed away. Desplanque and Mossman (2004) estimate that the Saxby Tide was at least 1.5 m higher than astronomically caused high tides.

The 'Groundhog's Day' storm (February 2nd, 1976) is a classic example of the difference in impact due to timing with tide levels. Significant damage and coastal flooding were reported in Maine where water levels rose more than 2.5 m above the predicted level, heavily eroding the shoreline (Desplanque & Mossman, 2004). The strong SSE winds which had been blowing for five to six hours over the open water resulted in a storm surge up Penobscott Bay, and much of Bangor, Maine was flooded. Water levels rose to 3.2 m above predicted tides in fifteen minutes (Desplanque & Mossman, 2004). Fortunately for those in the Bay of Fundy, the tide was an apogean (e.g. lower) spring tide, therefore, although there was a recorded surge of 1.46 m, the damage was limited. If the storm had occurred during the perigean spring (sixteen days later on February 18th), the damage would have been significant (Desplanque & Mossman, 2004). It is estimated that if the Goundhog's Day storm had occurred on April 16th, 1976 it would have had the potential of "c*ausing calamity on the scale of the Saxby Tide*" (Desplanque & Mossman, 2004 p. 102).

If such an event were to occur in the present day it would result in billions of dollars of damaged infrastructure and potentially loss of life, given the amount of development which has occurred behind the dykes (Shaw et al., 1994). Desplanque & Mossman (2004) suggest that the probability that a 'Saros' tide would coincide with an astronomically high spring tide is about 3%. However, postglacial sea-level rise significantly influences this probability. With every repeat of the 'Saros', an increase of the high tide mark of at least 3.6 cm (2 mm/yr for 18 yrs) can be expected (Desplanque & Mossman, 2004).

> *"Since the Saxby Tide more than seven 'Saros' ago, sea level has risen eustatically nearly 25 cm. Added to the minimum 1.5 m by which the Saxby Tide exceeded high astronomical tides, a height is calculated that that is more than sufficient to overtop the present dyke system"*
>
> (Desplanque & Mossman, 2004)

Methods

This study used topographic data from a LIDAR survey flown in early April 2007 (Figure 5) by the Advanced Geomatics Research Goup (AGRG) using an ALTM3100 with a vertical precision of 15 cm. A detailed overview of LIDAR technology and use for coastal flood mapping can be found in Webster et al. 2004 and will not be repeated here. Data were verified and processed at AGRG and the resultant digital elevation and digital surface models provided at a 1m ground resolution. These data were complimented by a IKONOS Satellite image (1 m pixel panchromatic) acquired in October 2007 through the Maritime Provinces Spatial Analysis Research Center at Saint Mary's University. These data were collected as part of a larger on-going research project examining the ecomorphodynamics and historical evolution of the Avon River estuary. This project compliments on-going research investigating the spatial and temporal variations in the intertidal geomorphology of the Avon River Estuary (van Proosdij and Baker, 2007) and the impacts of engineering structures on these processes. Data collected and analyzed within this project are shared by Saint Mary's University, NS Department of Transportation and Infrastructure Renewal, NS Department of Agriculture (Land Protection) and the Advanced Geomatics Research Group at COGS.

The risk of flooding from both overland (e.g. riverine source) and tidal sources was analyzed using the 3D analyst extension within ArcGIS 9.3^{tm} (ESRI, Redlands, CA) at the Maritime Provinces Spatial Analysis Research Centre (MP_SpARC) at Saint Mary's University. This study is also concerned with low lying areas that will not drain as a result of heavy rainfall coinciding with high tide which prevents the one way aboiteau from properly draining.

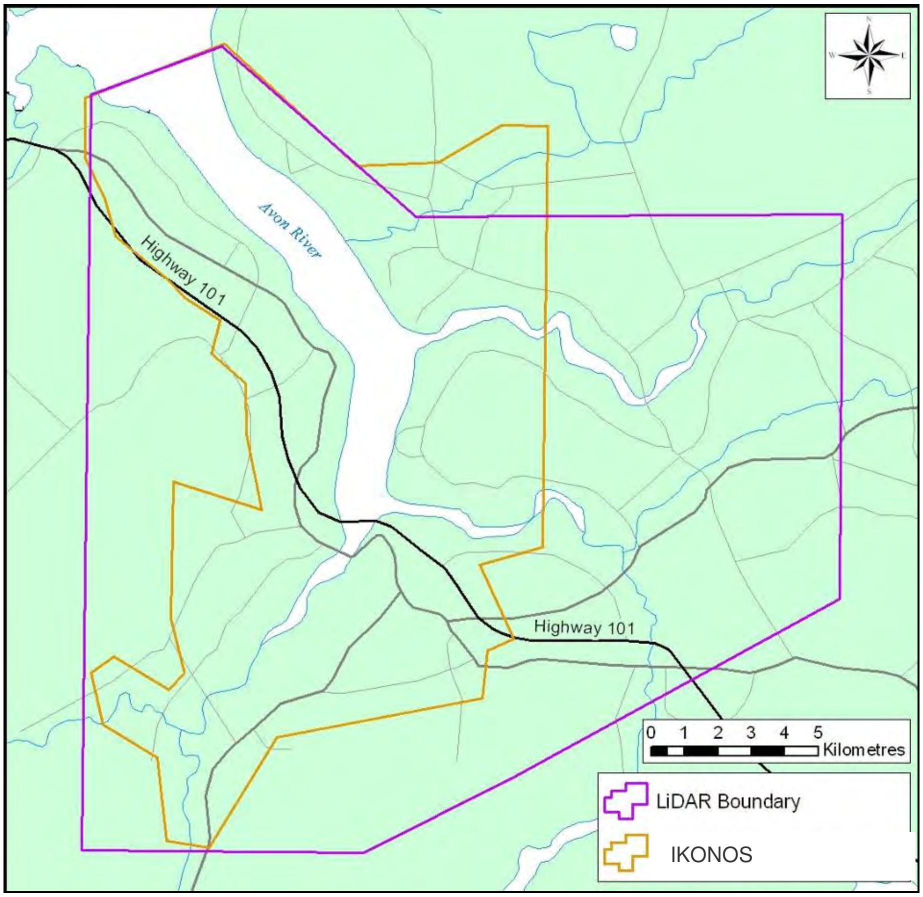


Figure 5: Map depicting the boundaries of the LIDAR survey and IKONOS image new data collect. Note the IKONOS image boundary was restricted by the maximum swath width of the satellite.

The flood levels chosen for this analysis are based on a combination of information gathered from the Canadian Hydrographic Service, NS Department of Agriculture Windsor tide gate personnel and scientific literature regarding sea level rise for the region. Nova Scotia, as with much of the land in Atlantic Canada, is currently undergoing tectonic subsidence (lowering), as a response to the post-glacial uplift that took place for much of the last 10 000 years. This translates to a relative sea level rise of 20-30 cm per century. Using current climate models, scientists predict an additional global increase of approximately 50 cm due to human-induced climate change. This results in a situation where the coastline of Atlantic Canada could be inundated with 70-80 cm of higher sea-level by the end of the 21st century (Parkes et al., 2006; Bindoff et al., 2007; Vasseur & Catto, 2008). Coastal flood levels were modeled for four different water levels (at a common vertical datum CGVD28): higher high water large tides (HHWLT) (7.57m CGVD28) with a 1 in 20 yr storm surge of 0.6 m (Webster et al., 2004); a storm tide (8.6 m CGVD28) which occurred in January 10, 1997 (van Proosdij & Baker, 2007);

HHWLT with a 1 in 100 yr storm surge (1.2 m) for a probable maximum flood level of 8.77 m CGVD28 and the 1 in 100 year storm with sea level rise (SLR) of 0.7 m (9.47 m CGVD28). It is also anticipated that there will be an increased frequency of high intensity (> 80 mm) rainfall events and storm surges. It is possible that a significant rainfall event coupled with high lake levels and high tide (which would prevent freshwater from draining at the tide gate) can create a scenario where the capacity of the hydro dams upstream (Forks and Fall Lake Dams) would be exceeded. Two probable maximum freshwater flood scenarios were chosen based on the Emergency Preparedness Plan for the Avon Hydro System (Oct 1998). The Falls lake dam would flood up to the 7.1 m contour (CGVD28) whereas a Forks Dam flood would exert a more significant impact at 8.4 m.

The extent of flooding was determined using standard methods of analysis for coastal flooding using the ground LIDAR digital elevation model (e.g. Webster et al. 2004; Webster and Forbes, 2005). The flood limit for each water level was converted to a vector polygon and used to select sections that were contiguous with and open to flooding from either the river or coastal waters. Culverts were assumed to exist in areas that contained a defined stream network passing under Highway 101. Smaller culverts that may exist along smaller roads were not included in this analysis due to lack of field validation. Most of the dykes contain aboiteaux with gates to allow for freshwater drainage but prevent tidal waters from entering therefore these locations did not allow coastal flooding. The only exception to this rule were aboiteaux that were known to be missing a gate or in disrepair based on consultation with Department of Agriculture personnel. Most of these were located under CN rail lines. In addition to the extent of inundation for each flood level there are also concerns regarding the depth of water that would result over the surface which influence the level of damage to infrastructure in the region. To determine this, the flood layer raster was assigned a geodetic flood elevation and the ground DEM was subtracted by this layer using map algebra to produce a map of water depth. This raster was reclassified to exclude negative values and show only depth at 0.5 m intervals for coastal flooding. In the case of freshwater flooding, water depth was expressed at 0.2 m intervals relative to the high lake level of 2.9 m CGVD28 (pers comm. Ken Carroll August 2009). It should be noted that this analysis does not take into account the residence time, or time for floodwaters to drain nor does it take into account friction effects or length of time of flooding in the case of dyke overtopping.

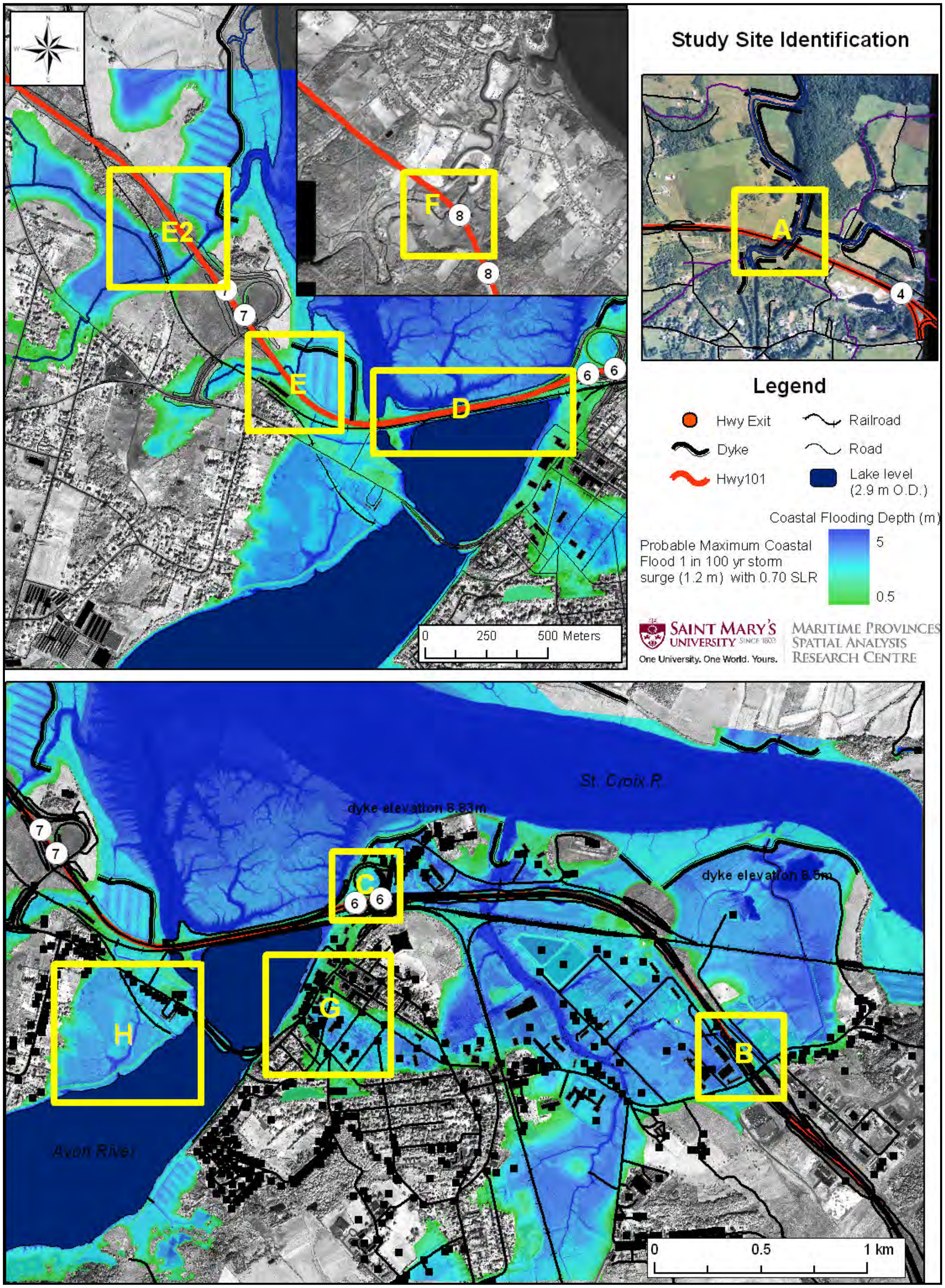


Figure 6: Location of study sites to be used in the analysis.

The purpose of this project was to assess the risk to department of transportation infrastructure from flooding therefore most of the analysis focused along the 101 highway corridor. Specific areas of concern are indicated on Figure 6. Site A near St. Croix and exit 4, Site B near Exit 5, Site C at the on ramp near Exit 6 at Windsor, Site D along the causeway, Site E immediately west of the Windsor tide gate and near NS3 Elderkin Marsh, Site E2 west of Exit 7, Site F at Exit 8, Site G downtown Windsor and Site H along the western side of Lake Pisiquid. In addition, since there are questions regarding the feasibility of modifying or removing the tide gate during the twinning process, a brief assessment of the resultant flooding was performed. These results are preliminary and qualitative in nature. A more in-depth analysis of the flood risk to specific infrastructure (e.g. schools, hospitals) in the town of Windsor both from freshwater and hypothetical tidal sources is beyond the mandate of this contract and should be performed in the future.

Results & Discussion

In order to get an overview of the spatial extent and connectivity of both coastal and freshwater flooding, a series of maps were derived to illustrate these effects. The initial analysis of the impacts from a 1 in 20 year surge on HHWLT (8.1 m CGVD28) showed that these impacts were limited to coastal erosion along dykes not protected by a marsh foreshore and situated in areas exposed to wave action rather than coastal flooding. The 8.1 m event would not overtop any dykes in the region. Most of the damage from the 8.6 m storm event from 1997 was limited to the boundaries of marshland boundaries and did not have a significant impact on infrastructure in most areas with the exception of some minor roads. The main marshbodies affected were NS14 Elderkin and the eastern tract of NS68 Tregothic (Figure 7).

The Probable Maximum Flood taking into account climate change is a different scenario. A Probable Maximum Flood is defined as the flood expected from the most severe combination of critical meteorological and hydrologic conditions that are reasonable in a particular drainage area. From the coastal flooding perspective, a 1 in 100 yr storm surge (1.2 m) coupled with a minimum 0.7 m sea level rise (= 9.4 m CGVD28) would have the potential to cause significant damage to infrastructure. This level is sufficient to overtop all of the dykes in the region by 0.8m on average (Figure 8). Most of the floodwaters would then be able to travel through existing culverts to flood into surrounding areas. The area most impacted would be those areas adjacent to the NS68 Tregothic marshbody. This marsh historically was part of a larger tract of marshland that extended into what is now the downtown core of Windsor (Figure 8). The impacts of this coastal flood would be exacerbated by precipitation which would most likely co-occur with the surge event, further confounding the situation. Sections of Highway 101 would be flooded as would large tracts of the rail line. Details will be provided in subsequent sections.

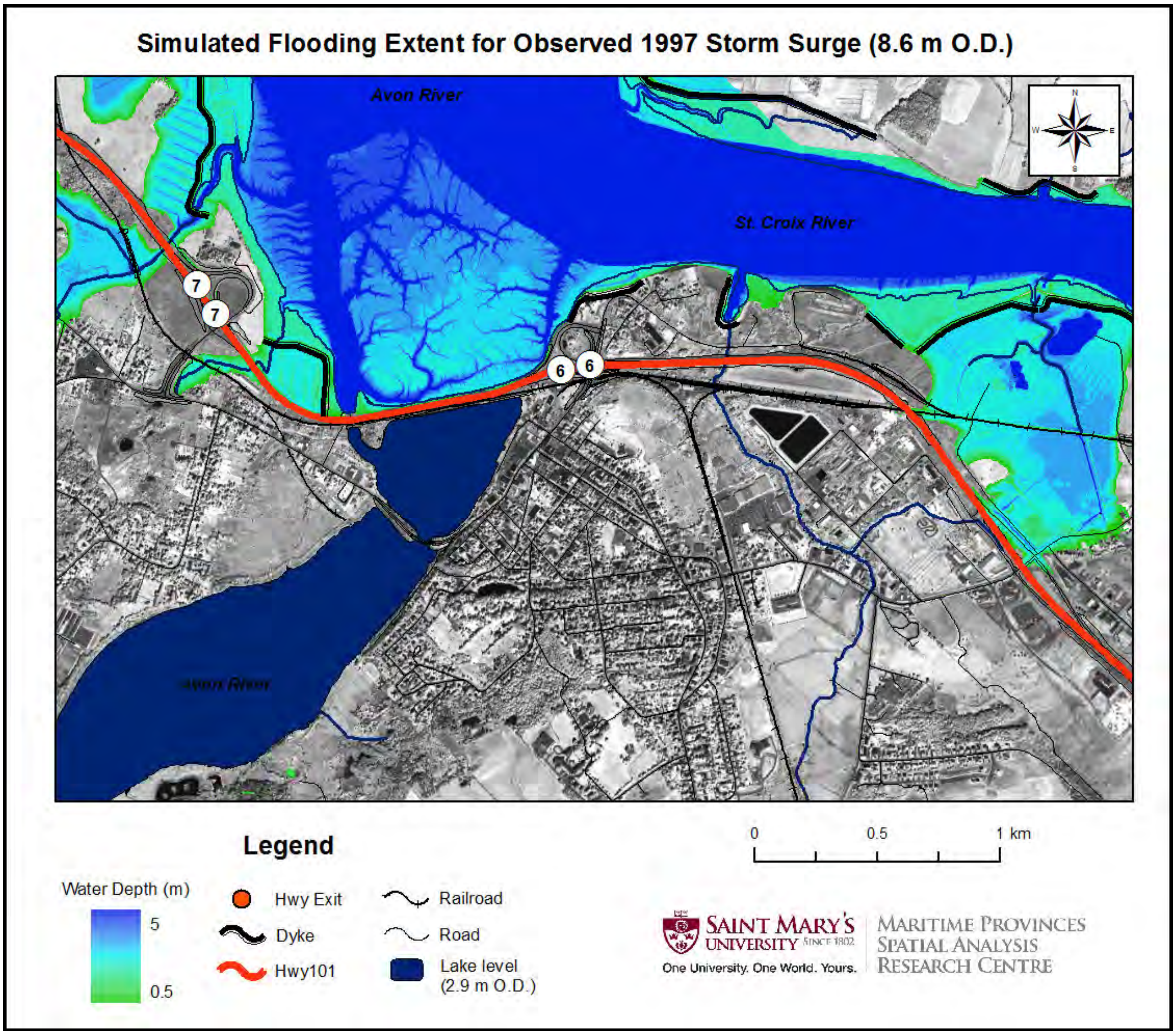


Figure 7: Overview of the extent of flooding derived from the 8.6 m storm event from 1997. Basemap IKONOS 2007 panchromatic satellite image.

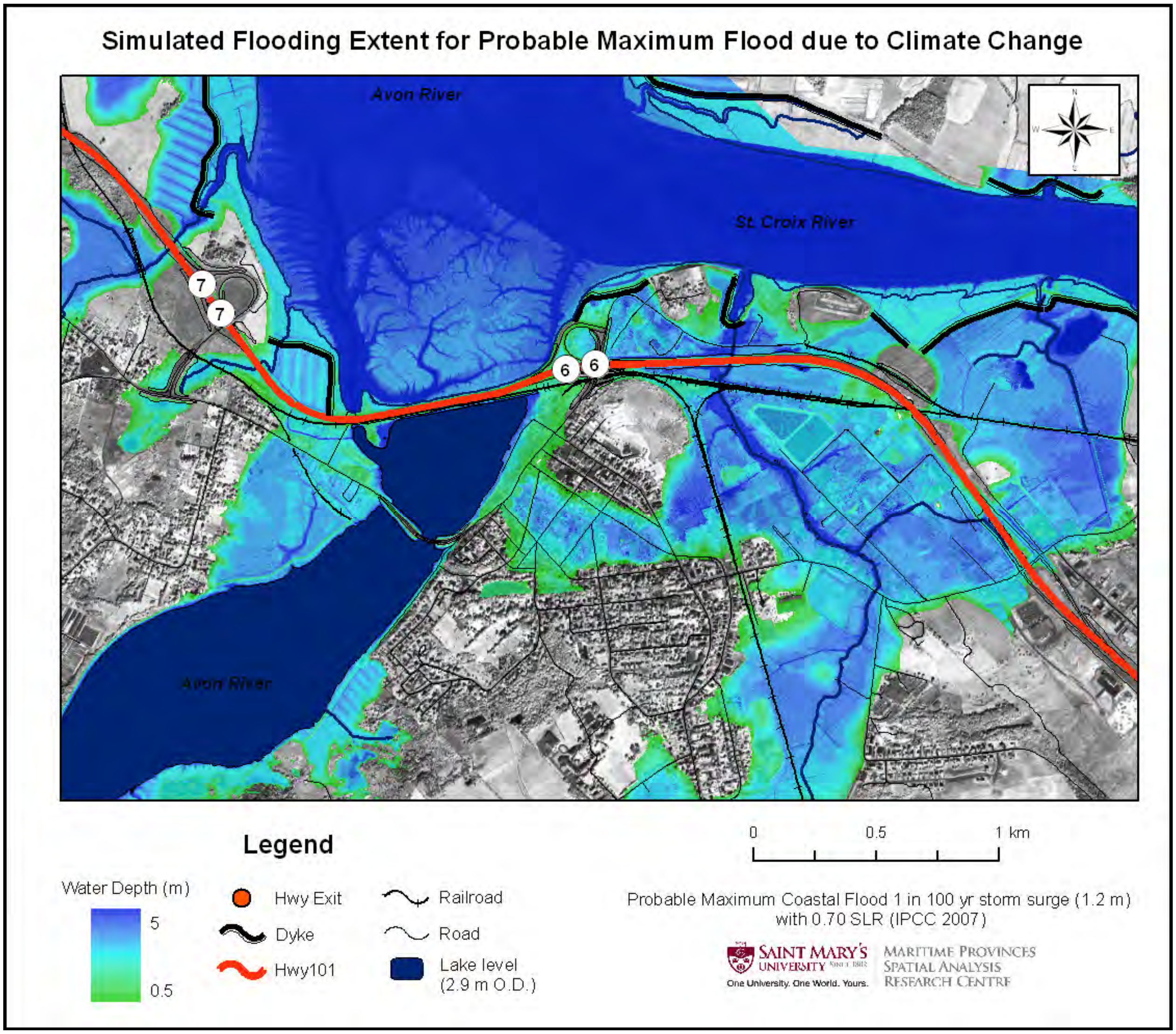


Figure 8: Simulated flooding extent and water depths for a 1 in 100 year storm surge (1.2 m) with a SLR of 0.7m.

Figures 9 and 10 illustrate the flooding extent and depth associated with probable maximum floods at the Falls Lake and Forks Dams. In both cases, the majority of marsh bodies upstream of the causeway would be flooded, including NS3 Falmouth, NS69 Martock, NS104 Sunny Slope and NS75 Armstrong. Most of this is due to the fact that dykes within these areas have long been removed after the causeway was constructed or not maintained. In the case of the Falls lake flood, the levels of Pisiquid lake would rise less than 0.5 m above base level (2.9 m CGVD28) and cause only minor localized flooding along the waterfront. A Forks Dam flood however has the potential to cause significant damage as the elevation of neither Water St. nor Turner Lane are sufficiently high to block the flow of water (Figure 10). Water would flow past King St. and join the larger Tregothic marshbody behind.

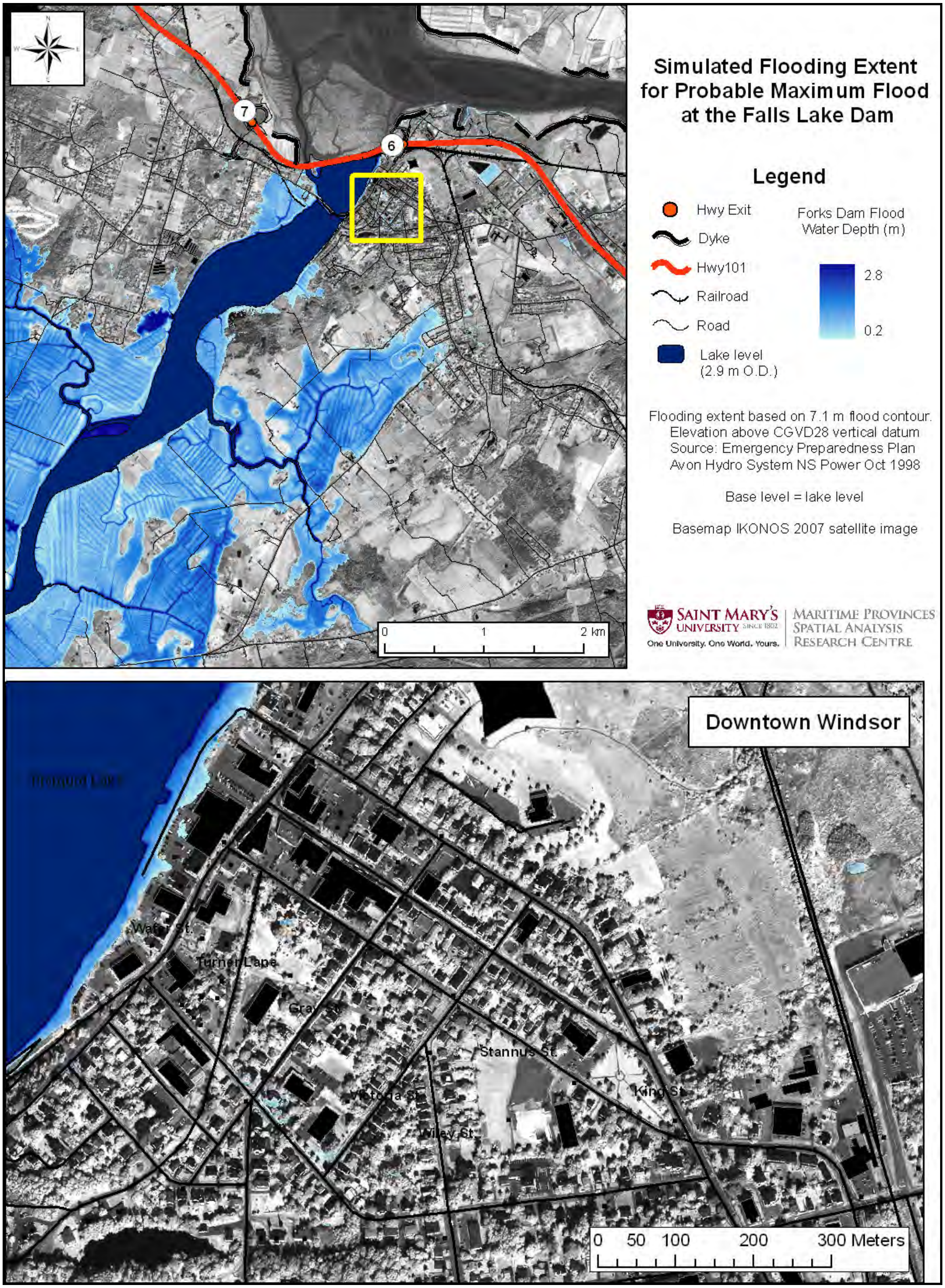


Figure 9: Predicted impact a Falls Lake Dam flood event based on a 7.1 m flood elevation (CGVD28).

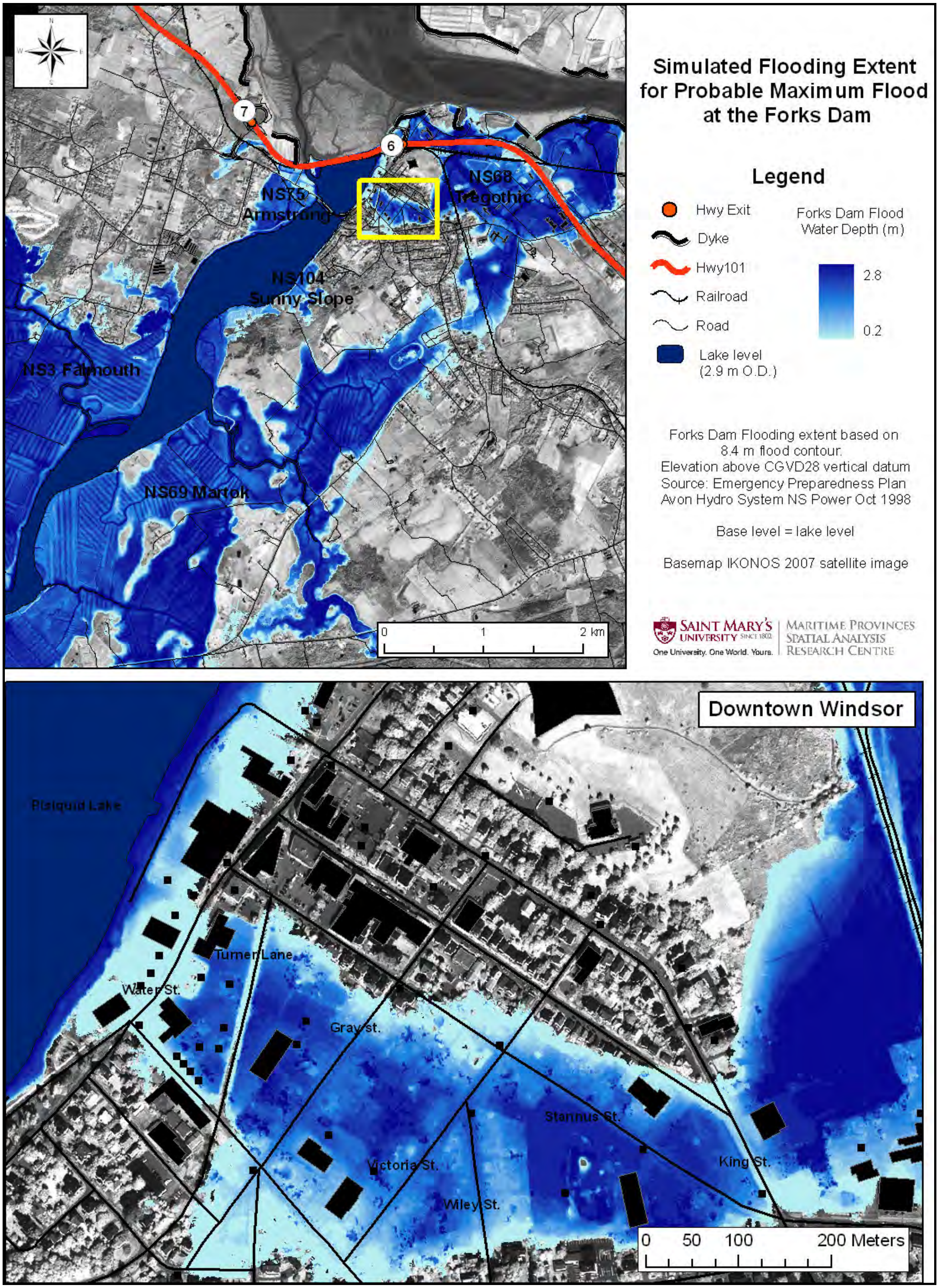


Figure 10: Simulated flood event for a probable maximum flood at the Forks Dam depicted damage to the Town of Windsor.

Site A is located approximately 1 km west of Exit 4 where the St. Croix River passes under Highway 101. The site is bordered on the northern edge by the MMRA marsh body NS38 St. Croix with a mean dyke elevation of 8.38m. NSTIR has currently breached sections of the dyke in order to restore high salt marsh and coastal flood marsh habitat. During storm conditions flooding will occur on the service road to the north of the highway; however there is minimal risk of flooding to the highway itself due to its elevation greater than 10 m (Figures 11 & 12). There is risk however of undercutting the seaward side of the road and subsequently slumping of fill during a storm event despite its relatively sheltered location.

At Site B, north of Exit 5 (Figures 13 & 14), there is a risk of flooding both from freshwater sources and tidal sources given the right conditions. A low zone (elevation 8.02 m) was identified along Highway 101 (Figure 13, 14a). If the Tregothic dyke were to breach during a storm tide (dyke elevation 8.53 m) and the duration of the tide was long enough to allow enough water to pool behind the dyke there could be some flooding issues. The rail bed will provide protection up to 8.2 m. However, the likelihood of tidal waters reaching this location given the distance from the St. Croix river is minimal. The greatest risk is from flooding from the combined influence of a tidal breach and freshwater flooding from the small stream draining at the southern edge of the study site (Figure 13).

Site C is located at Exit 6 near the Tourist bureau and has the potential to be highly impacted by marine processes due to its proximity to the Fundy coast. High water levels associated with storm waves will have the potential to erode the banks of the causeway but the causeway itself it not in imminent risk from flooding. However, the model suggests that it is at risk of overtopping given the current rates of sea level rise (SLR) during storm conditions (Figure 15). Given a maximum road elevation of 9.48 m from cross sectional profile 1 (Figure 16) and current rates of SLR, it is feasible that the on ramp section of the causeway could flood within this decade, particularly due to wave overtopping. The salt marsh will offer some protection however will not completely decrease all risk. Risk from freshwater flooding is minimal except in low lying areas where water will pool during high precipitation events. A Forks Dam flood would not significantly affect transportation infrastructure within the section.

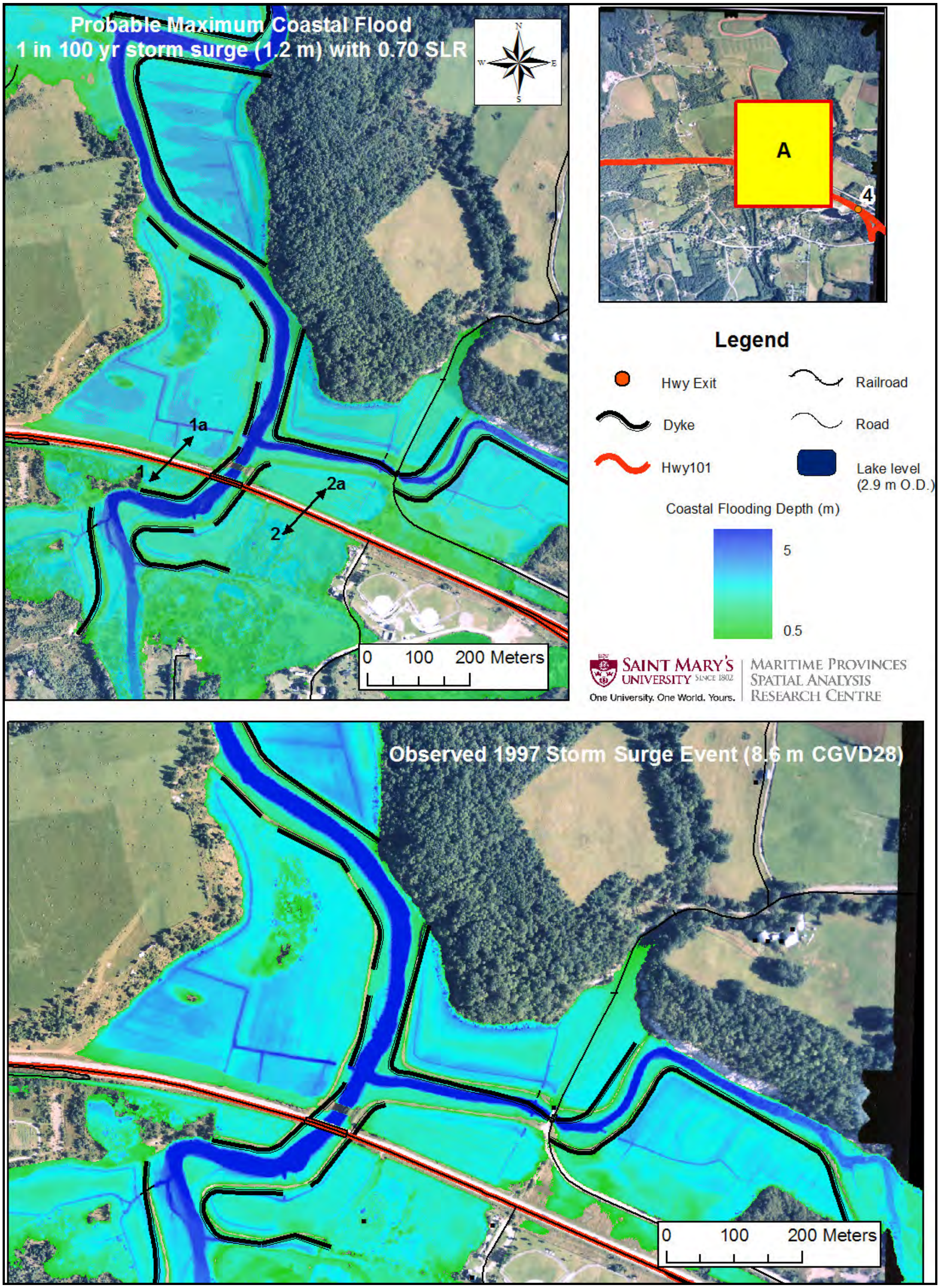


Figure 11: Exit 4 Study Site A impacts of flooding from a 1 in 100 yr storm with SLR and the 1997 observed storm level. Note breached dyke areas for coastal habitat restoration.

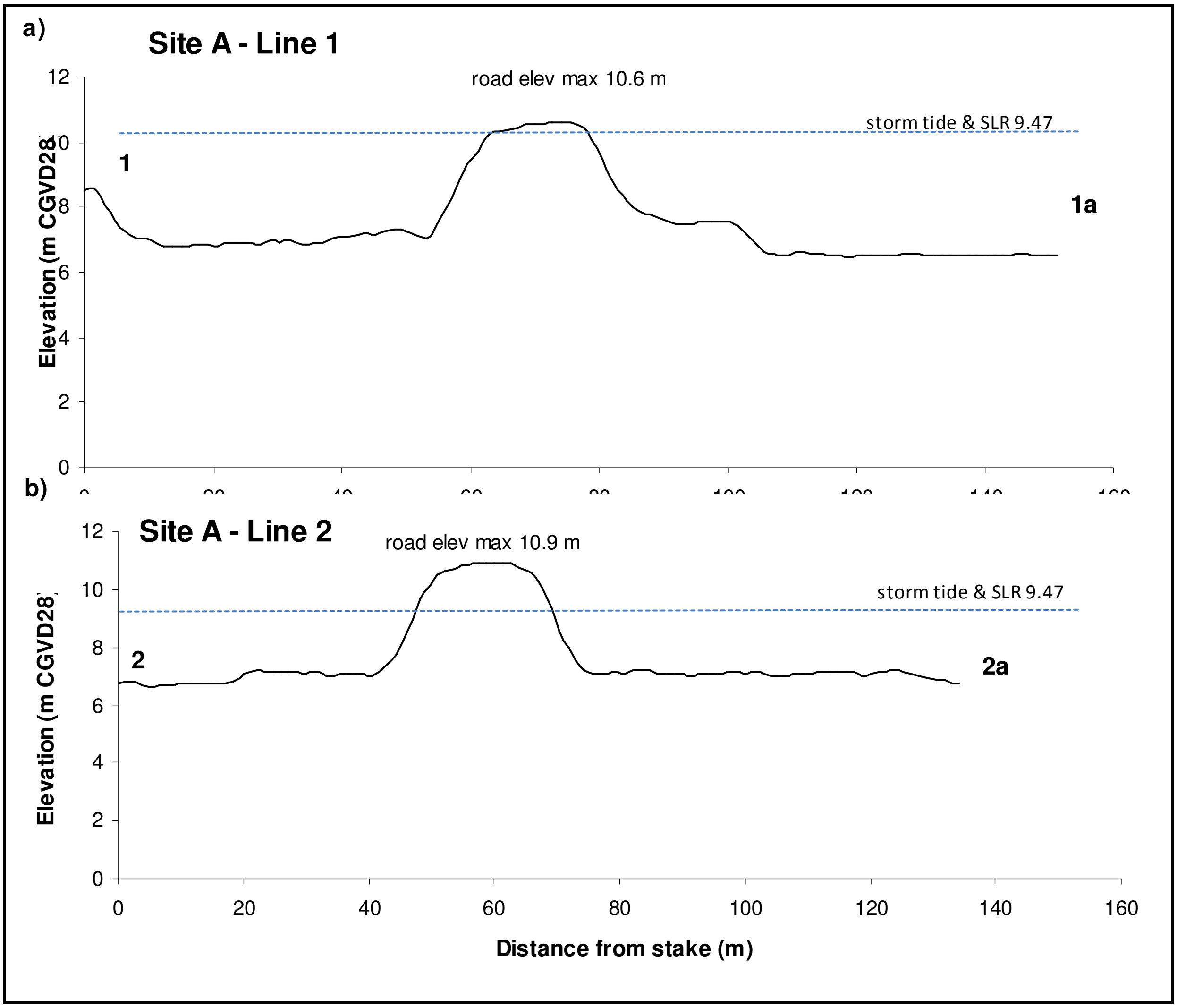


Figure 12: Cross sectional profiles perpendicular to Highway 101. Location of profiles indicated on Figure 11.

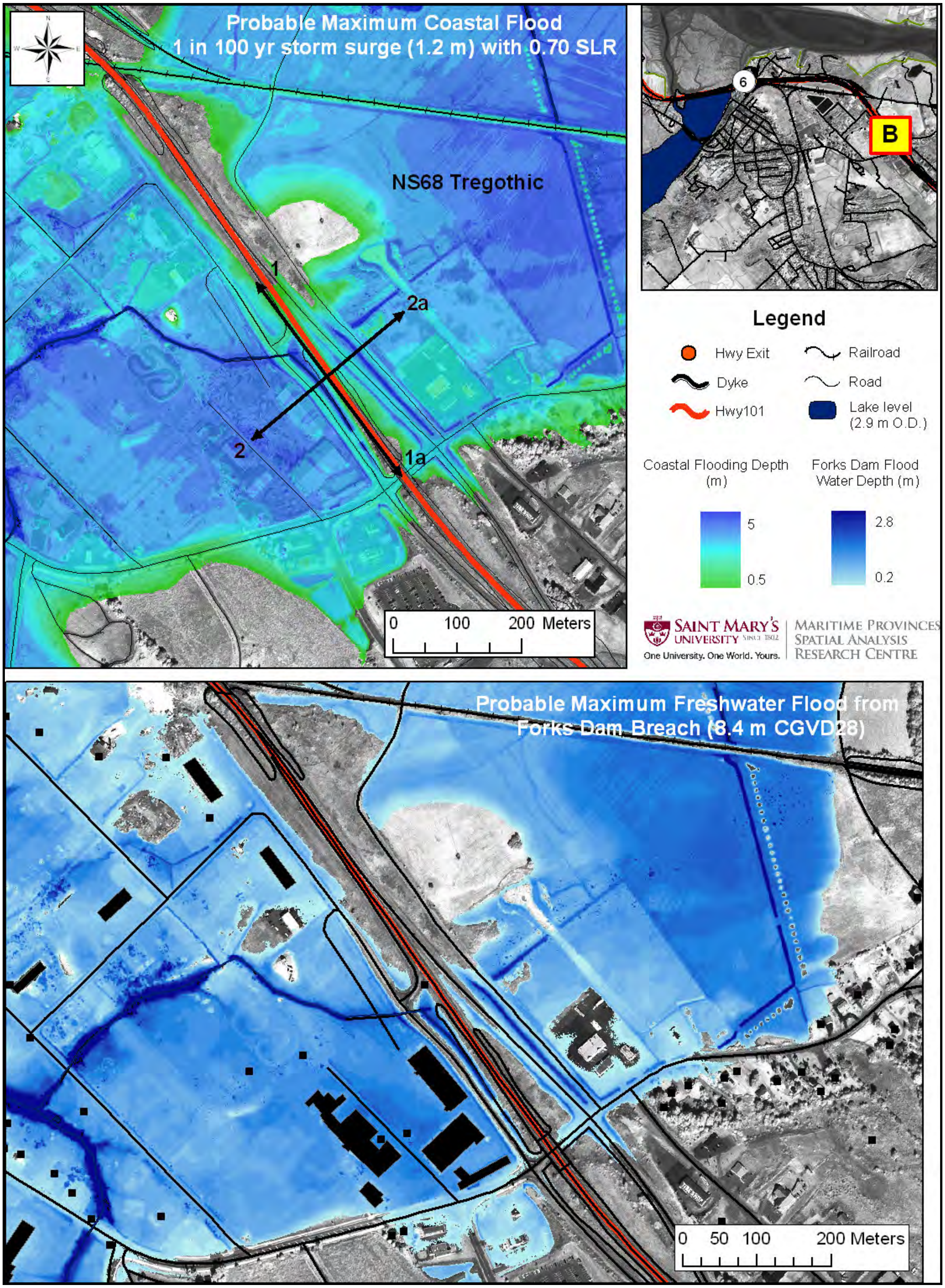


Figure 13: Exit 5 Study Site B with Maximum probable flood due to climate change from coastal and freshwater sources.

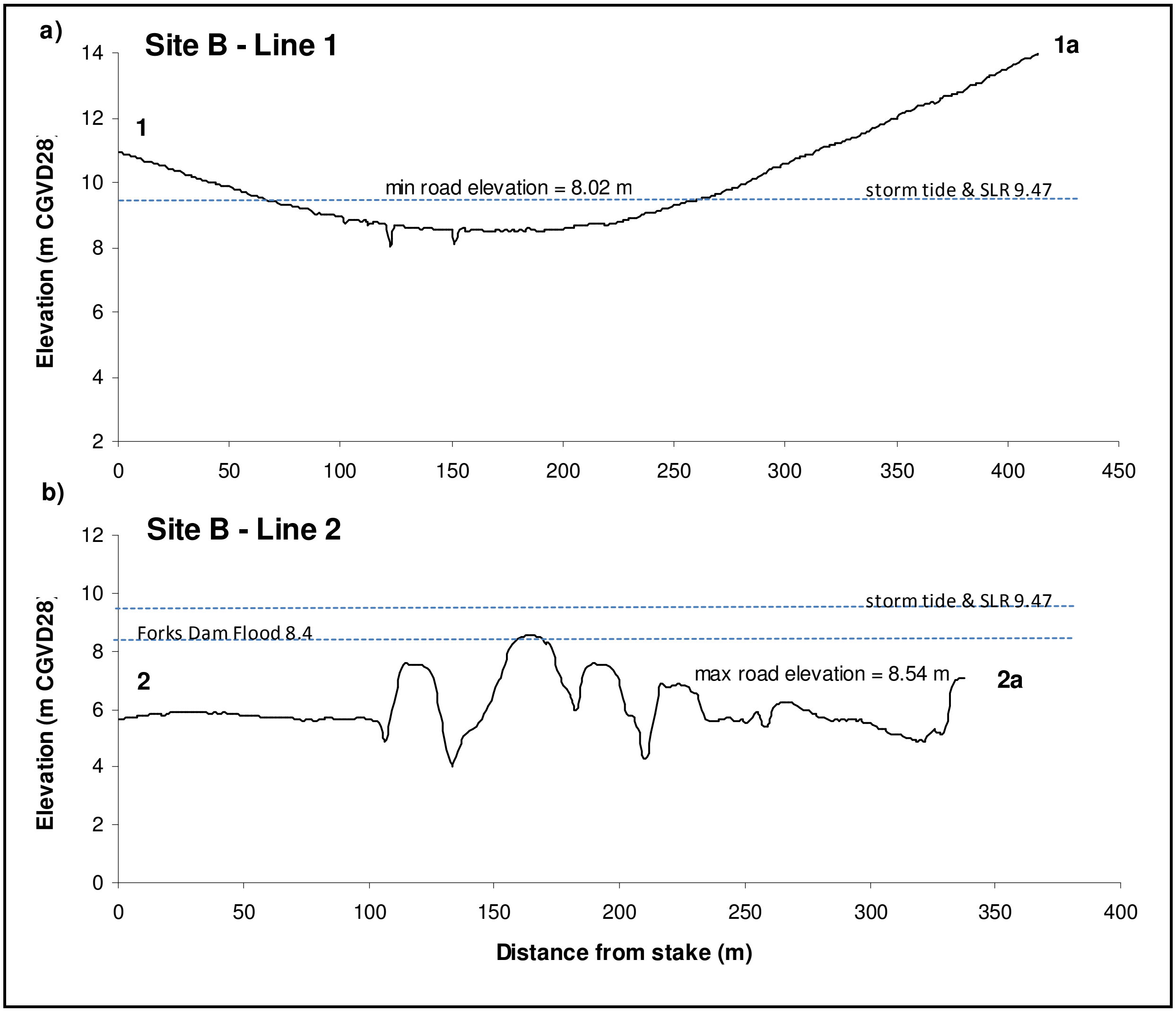


Figure 14: Exit 5 Study Site B with Maximum probable flood due to climate change from coastal and freshwater sources.

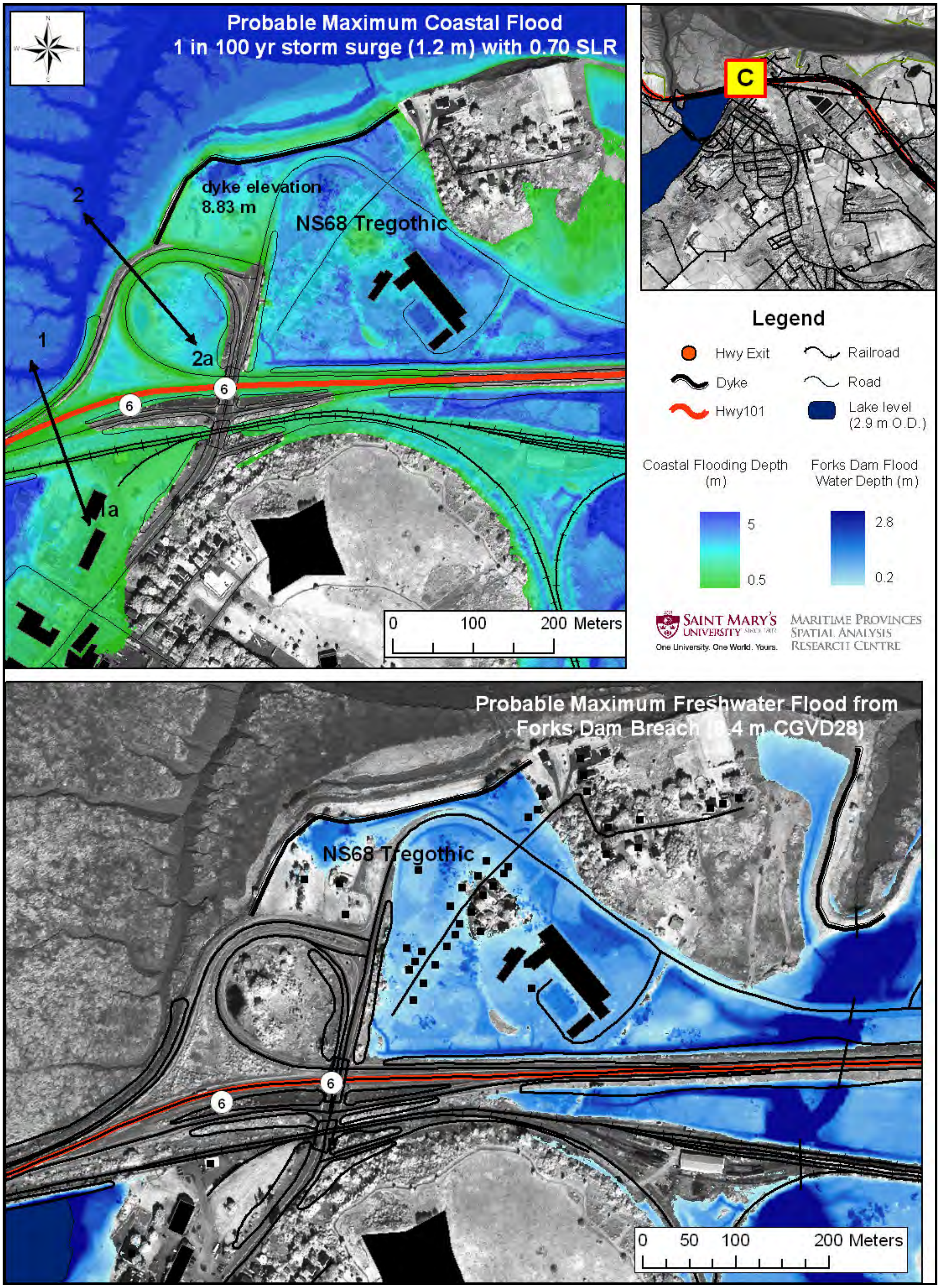


Figure 15: Exit 6 Study Site C illustrating depth of flooding from the 1 in 100 yr storm with SLR and freshwater flooding from the Forks Dam.

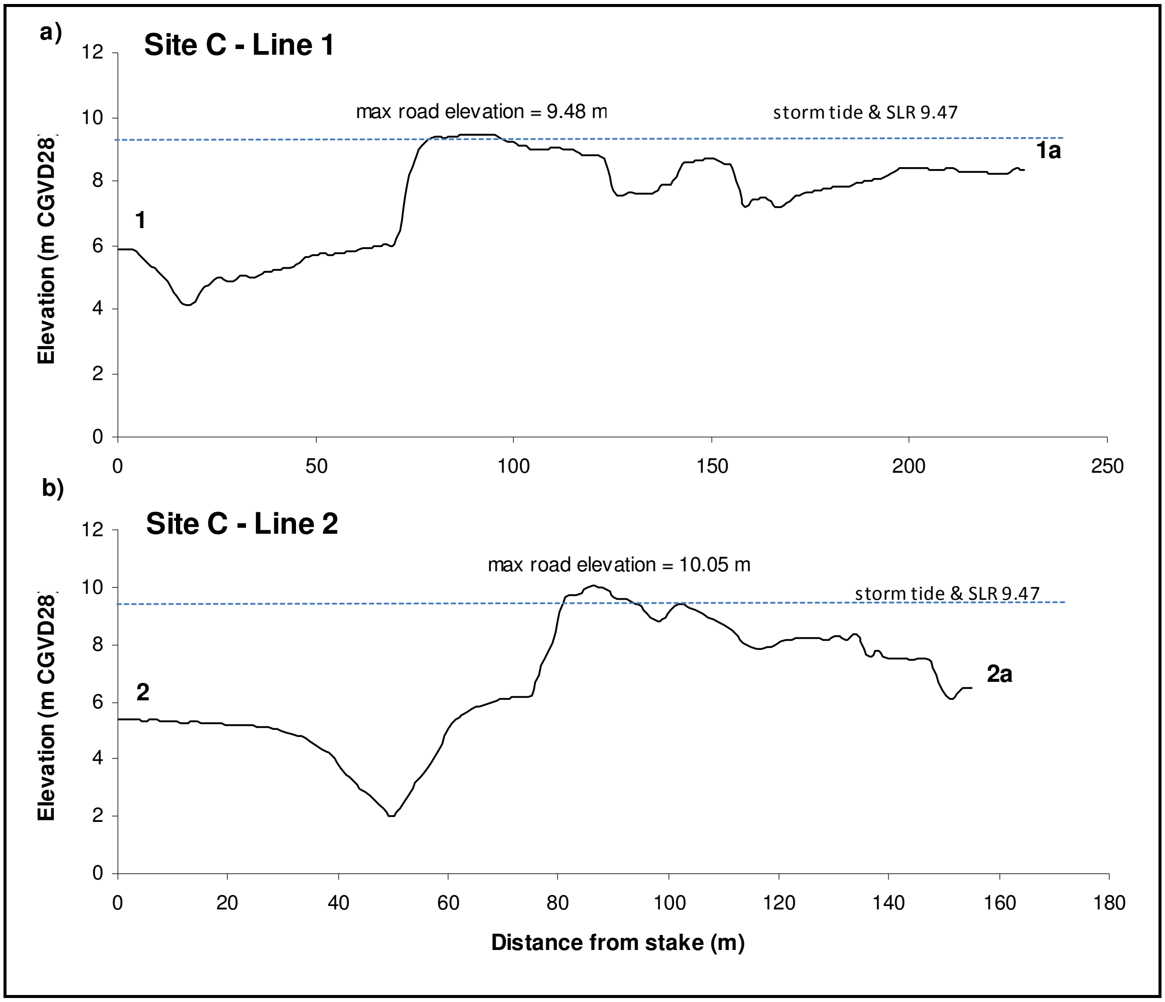


Figure 16: Cross sectional profiles at Site C perpendicular to the a) causeway on ramp at Exit 6 and b) edge of the causeway. Location of profiles are indicated on Figure 15.

The main area of vulnerability through this section of the highway 101 transportation corridor is the Windsor causeway. The central portion of the causeway is not the main concern as the mean elevation is approximately 10.4 m (Figure 17). Based on cross section and GIS analysis, the areas at the western and eastern edges of the causeway are lower in elevation and are at risk of flooding in the future (Figures 17 & 19). This includes the current tide gate infrastructure. The eastern edge is fronted by at least 1 km of salt marsh and would be protected from the majority of the storm wave's energy. The western portion however, is vulnerable since the orientation of the main tidal channel is also oriented in the direction of the longest fetch and hence has the potential to receive more of a storm's impact. The impacts from a freshwater flooding event are likely to be minimal.

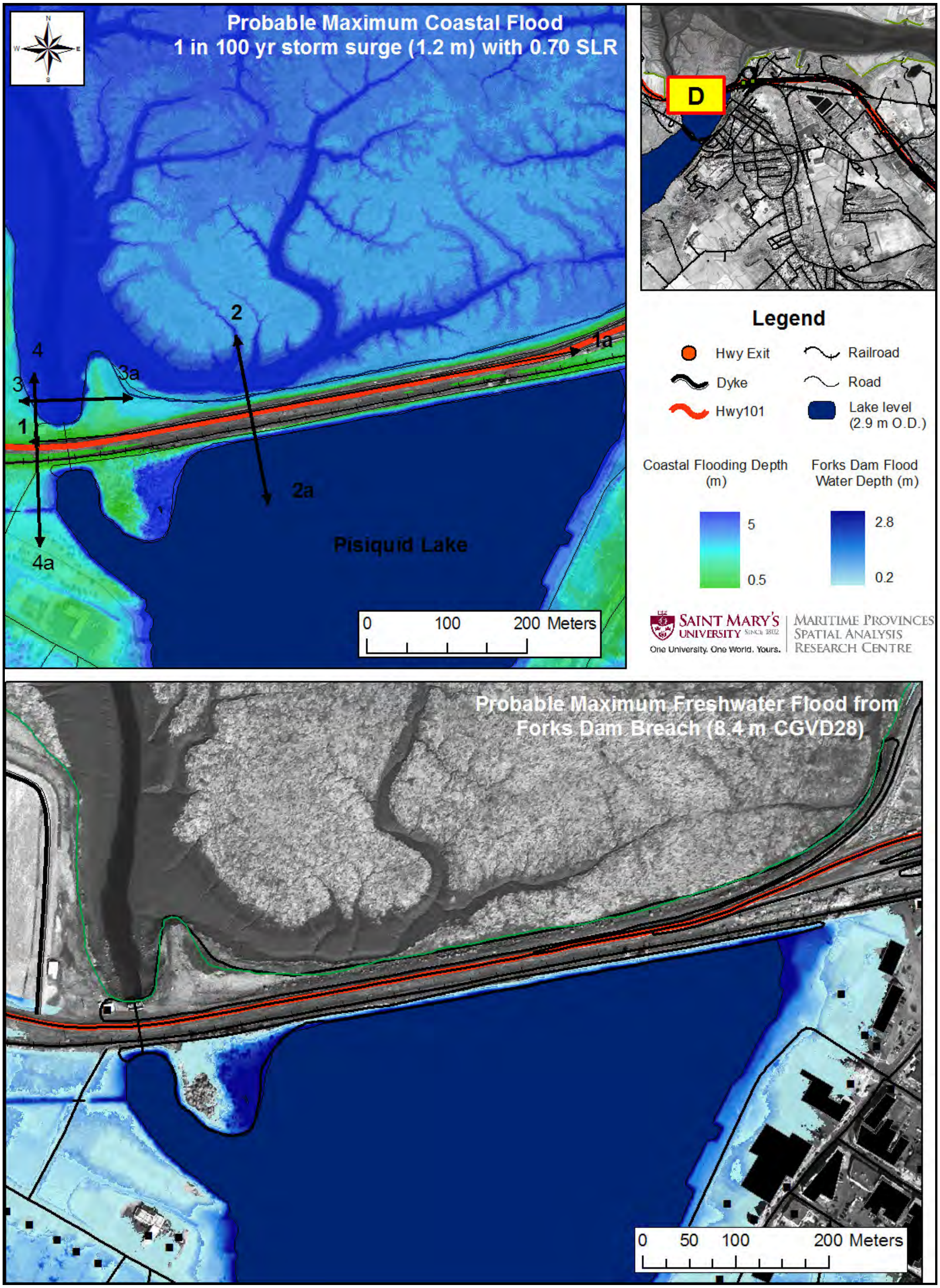


Figure 17: Causeway Study Site D impacted by coastal due to SLR and storm surge and freshwater flooding.

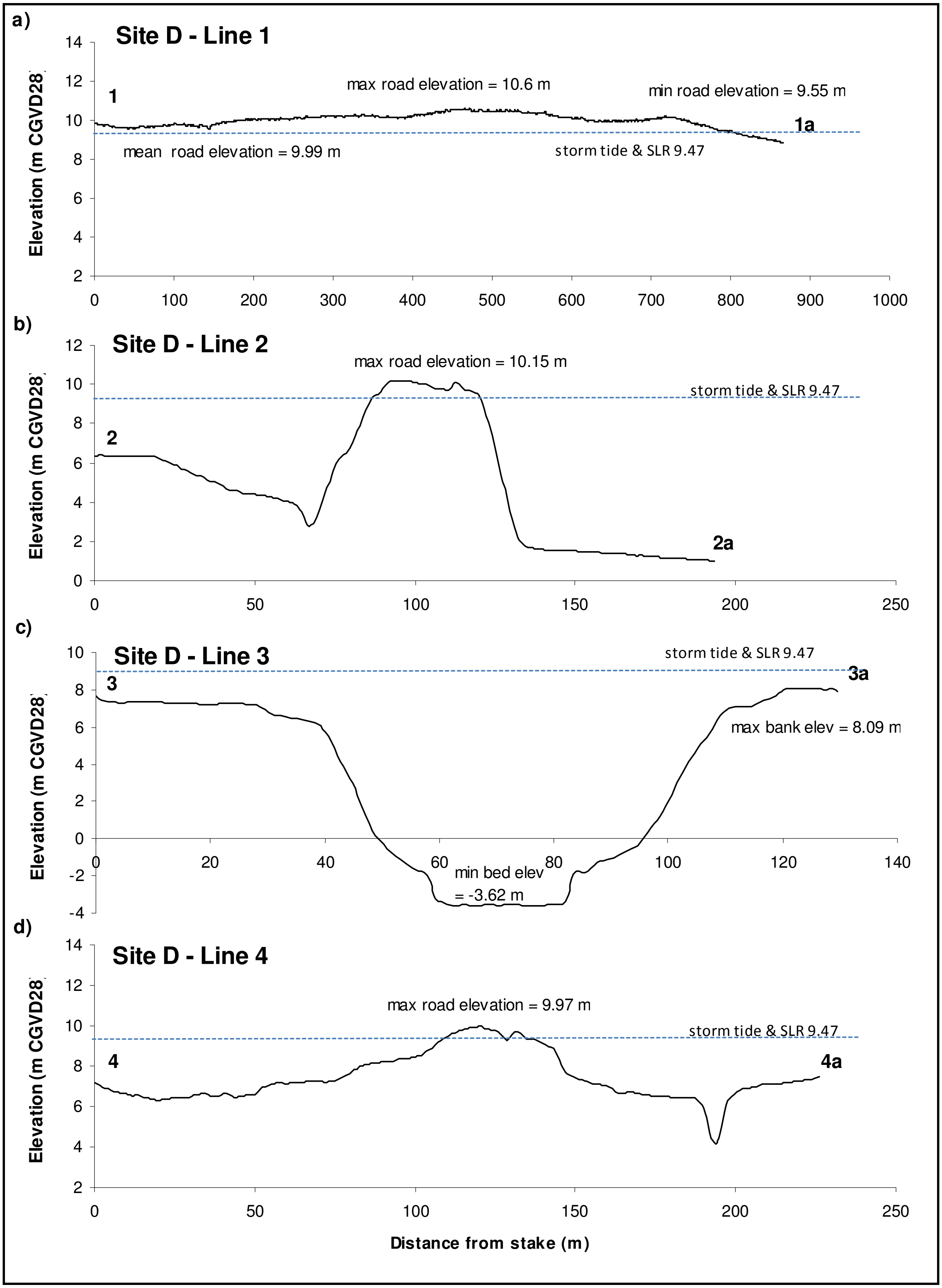


Figure 18: Causeway cross sectional profiles at Site D a) along Highway 101 on the causeway; b) perpendicular to the causeway; c) across the tide gate channel and d) far western edge of the causeway. Location of profiles indicated on Figure 17.

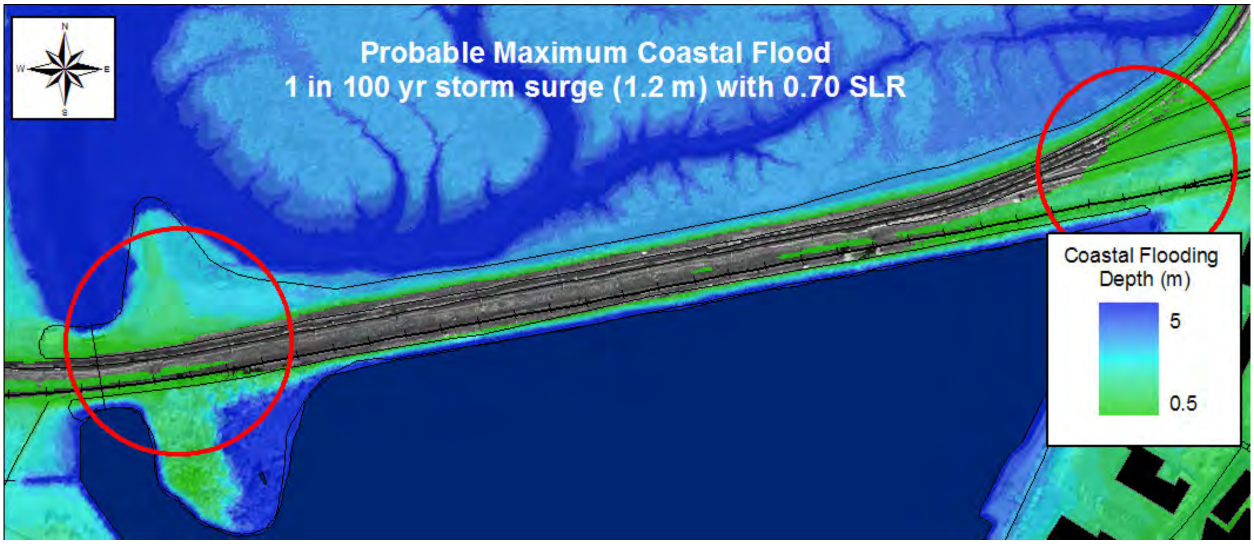


Figure 19: Impact of a 1 in 100 year storm surge with SLR on the Windsor Causeway. Red circles depict areas at greatest risk of flooding or coastal erosion.

Site E is located to the west of the causeway, adjacent to the MMRA marsh body NS14 Elderkin Marsh (Figure 20). This dyke has overtopped in the past (e.g. 1997) and will likely overtop in the future. Depending on the length of time that floodwaters exceeded the level of the dyke, the primary impacts on transportation infrastructure would be mostly associated with bank erosion along the edge of the highway and potential slumping of adjacent fill. The cross sectional profiles indicate that the road has a maximum and minimum elevation of 9.76 and 9.44 m respectively (Figure 21). A greater risk arises however if storm tides coincide with heavy rainfall and high tides and the aboiteau on NS14 is not able to drain (Figure 20). This has occurred in the past in the Truro region causing significant amounts of damage.

Site E2 is located near Exit 7, and although there are numerous low lying regions surrounding it, the highway itself and surrounding roads are at minimum risk (Figures 22 & 23). The road elevation exceeds 13 meters in the majority of this section (Figure 23). Some flooding could arise from high precipitation events if the capacity of the existing culvert structures are exceeded however the likelihood of this is minimal. The area at greatest risk in this section is the rail line and Water St. (Highway 1) near Falmouth.

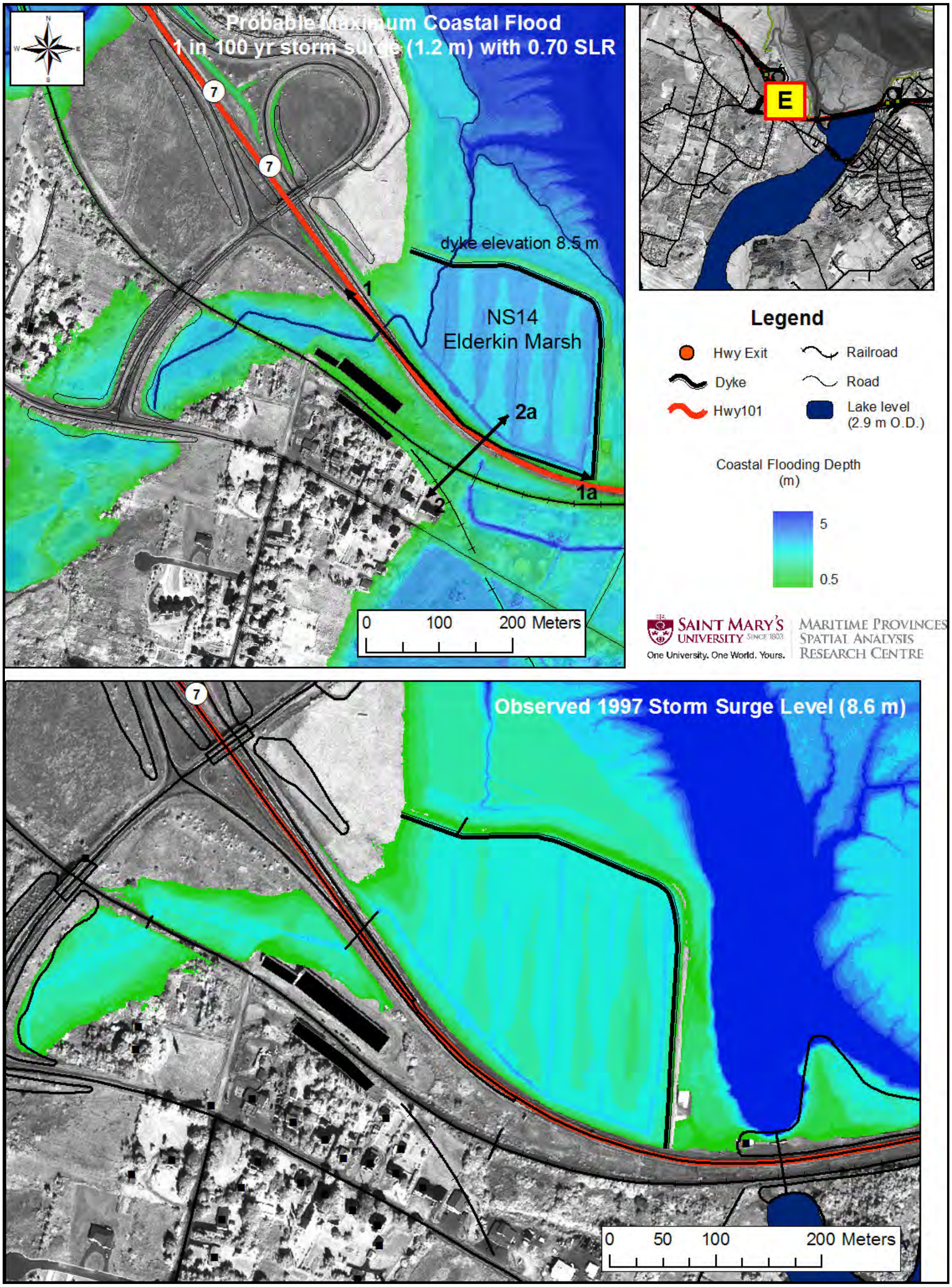


Figure 20: Elderkin Marsh Site E illustrating extent and depth of coastal flooding due to the combined effects of storm surge and sea level rise and the 8.6 m observed storm event in 1997.

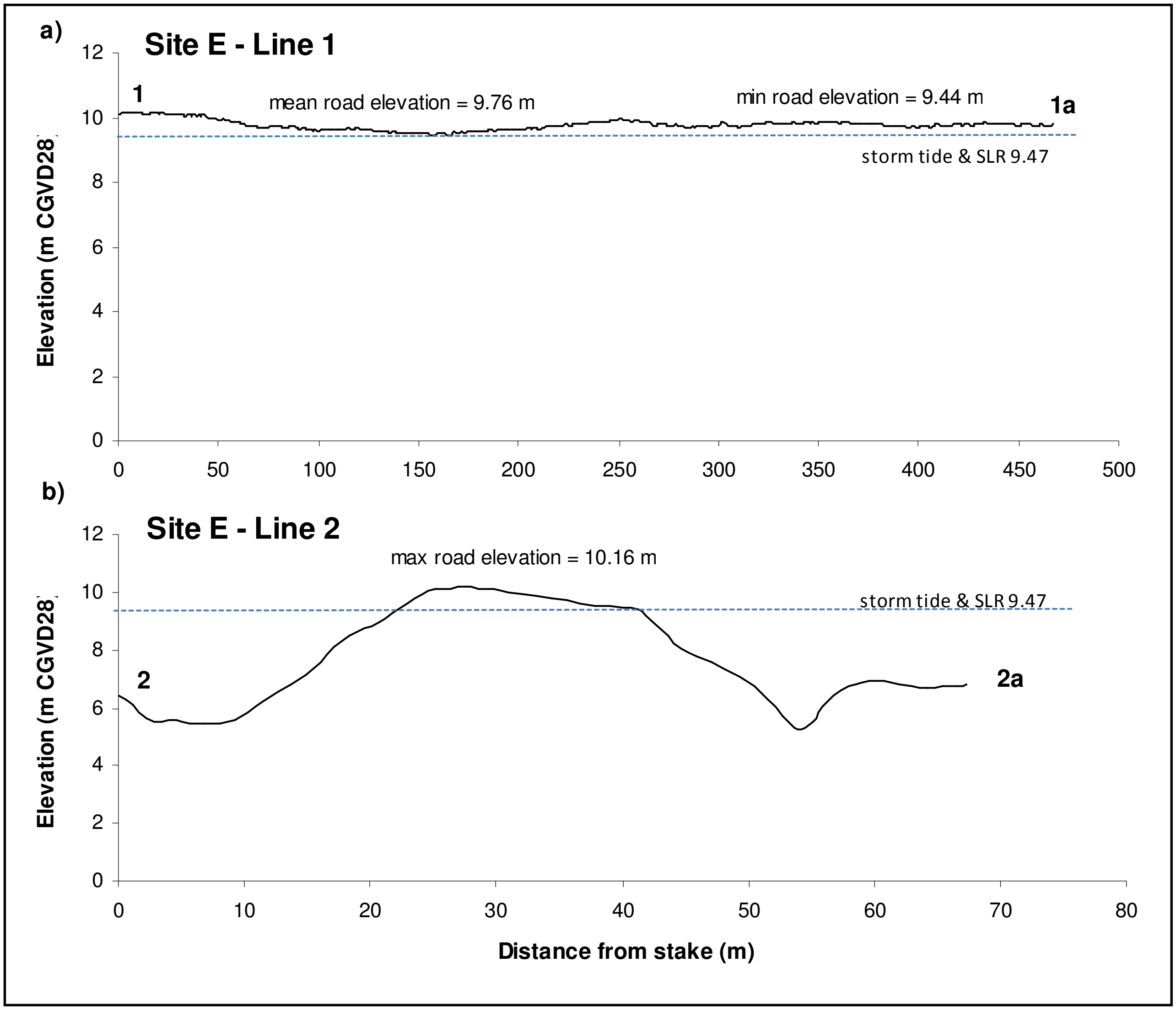


Figure 21: Cross sectional profiles at Site E on the western edge of the causeway a) along highway 101 and b) perpendicular to the highway. The location of profiles are indicated on Figure 20.

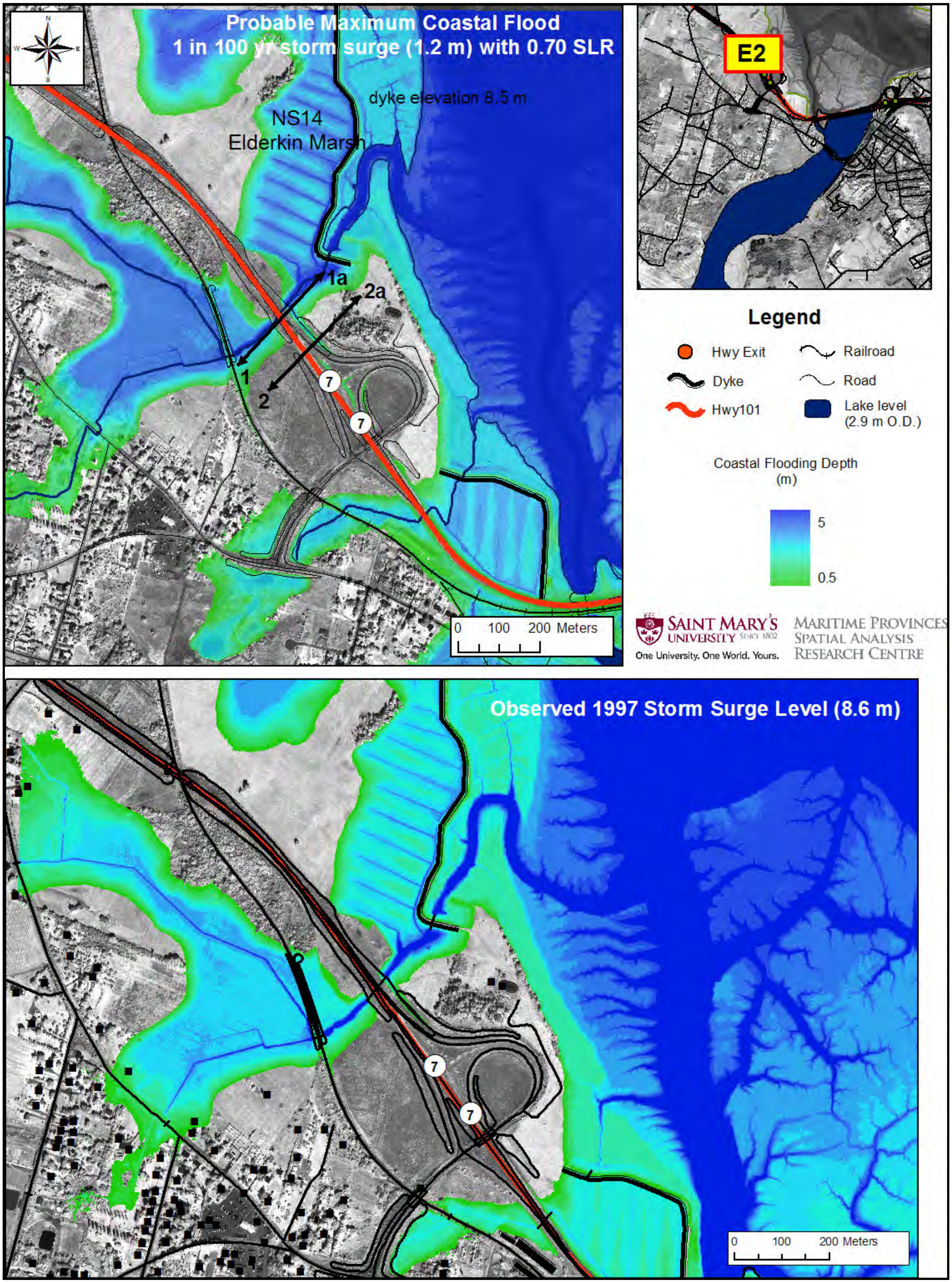


Figure 22: Exit 7 Study Site E2 extent and depth of flooding due to the combined effect of storm surge and SLR as well as the observed 8.6 m storm surge level of 1997.

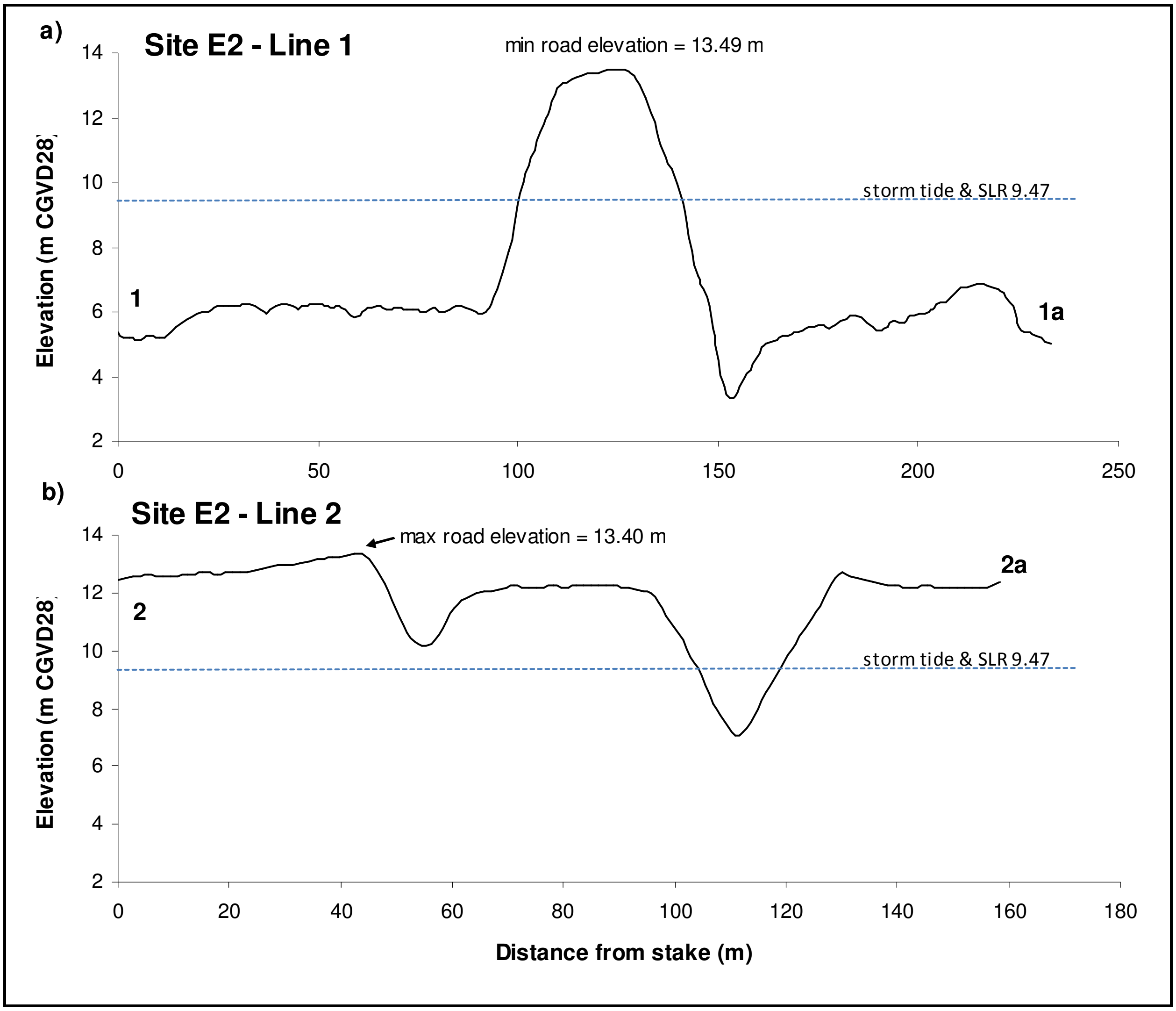


Figure 23: Cross sectional profiles at Site E2 near Exit 7 perpendicular to Highway 101. The location of profiles are indicated on Figure 22.

Site F is located near Exit 8 – Hantsport and although the highway itself is sufficiently high (17 m), the on and off ramps are vulnerable from flooding from the adjacent Halfway River (Figures 24 & 25). The approximate maximum elevation of this section of road is 8.95 m and the elevation of the river ranges from 1.8 to 2.6 m based on the LIDAR data. The risk of flooding in this area is significant since the existing aboiteau beneath the rail line at the mouth of the Halfway River is in disrepair and is missing a gate allowing partially restricted tidal flow (pers comm. Ken Carroll, Oct 19, 2009). The road leading into the town of Hantsport is at risk of flooding during a storm event.

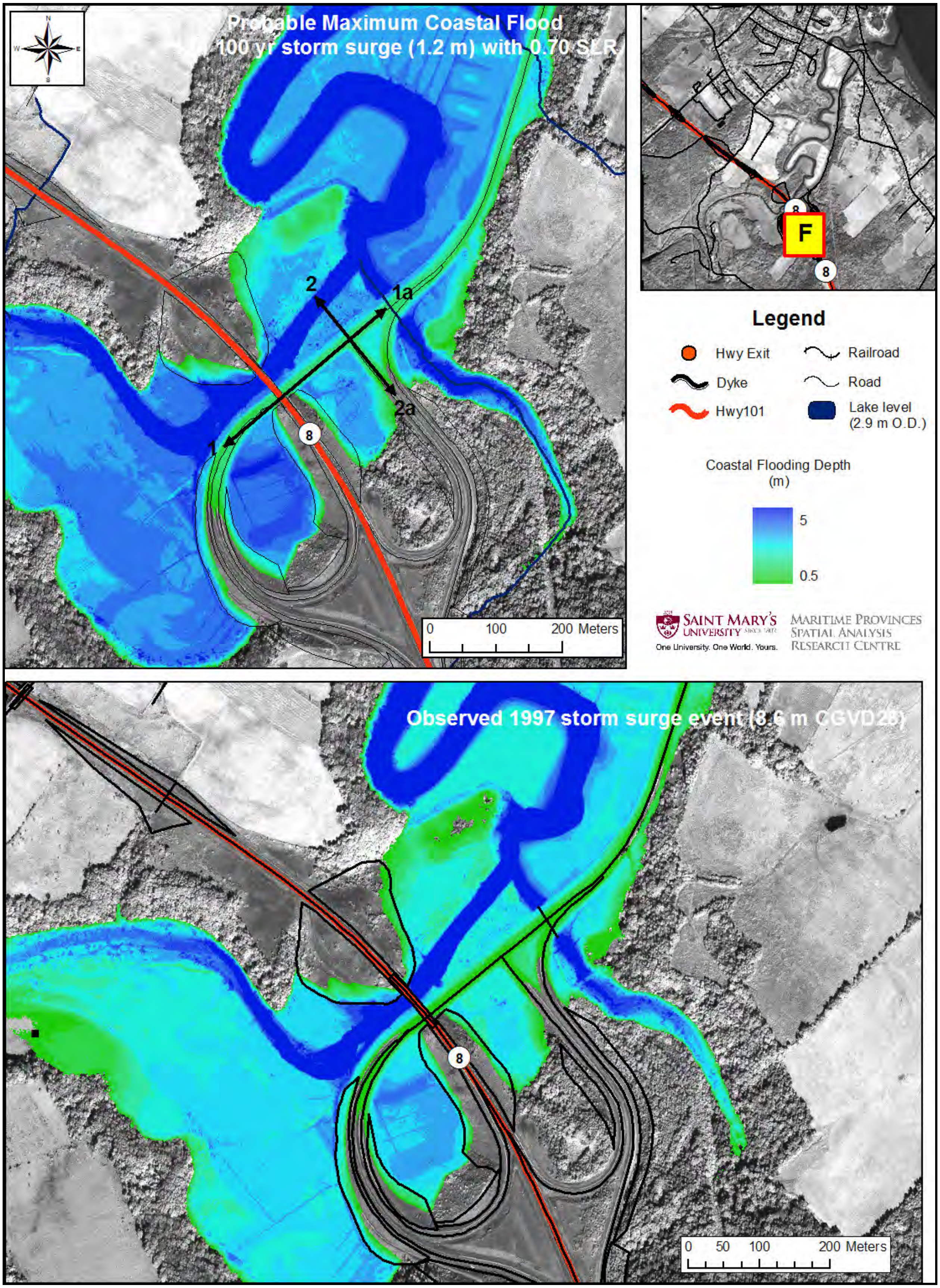


Figure 24: Extent and depth of flooding at Site F due to combined effects of storm surge and SLR as well as the observed 8.6 m storm surge event in 1997.

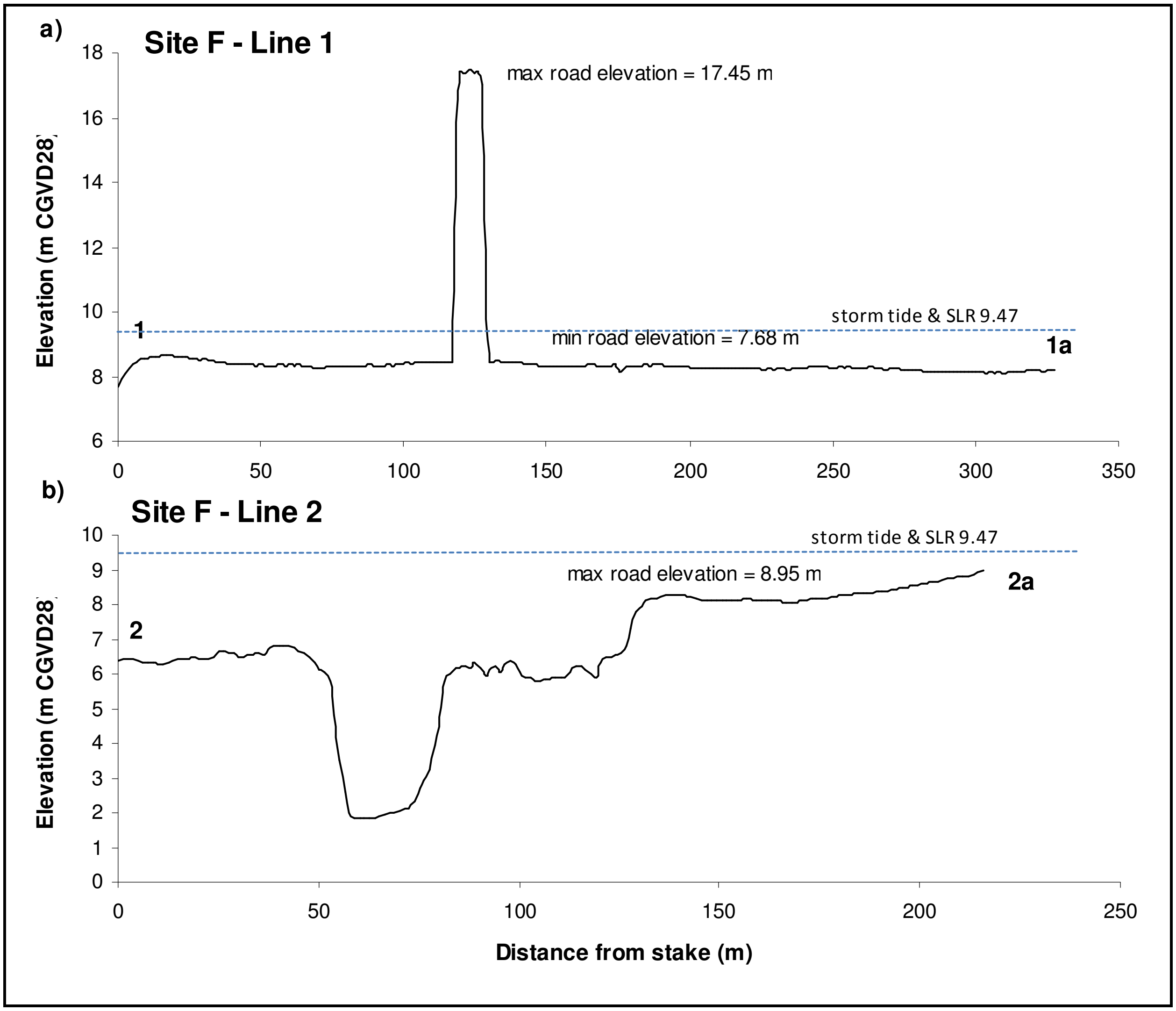


Figure 25: Cross sectional profiles at Site F near Exit 8 a) along the on ramp and b) perpendicular to the highway on ramp. Location of profiles indicated on Figure 18.

Figure 26 reflects the risk at Site G to the town of Windsor from both freshwater flooding, a significant storm event with SLR or if the tide gate were removed and full tidal exchange were restored to the Avon River. Since this area has been isolated from the tides since 1970, new development has taken place in areas that were once marshland and original protective dykes removed in many areas. Although the water levels in the Avon River are regulated to some degree by the hydro corporation and the tide gate, there are still situations that arise such as a prolonged period of heavy rainfall coinciding with sequence of high tides where flooding is a real threat. If full tidal flow were restored or during a significant storm event with SLR, the Town of Windsor would be at significant risk from flooding. Examination of Figure 26 clearly shows that the downtown core adjacent to Pisiquid Lake will flood under both coastal and Forks Dam failure scenarios. Although the water would be initially restricted somewhat by the old rail bed (~7.6 m) depicted in Figures 25 and Water Street at line 1 (Figure 27) (elevation 8.17 m), once this was exceeded, there are minimal restrictions that remain. It will be crucial to groundtruth the elevation of these roads in the future.

A similar situation arises at Site H on the western shore of Pisiquid lake and the Avon River. The LIDAR information indicates that the Armstrong marsh dyke (NS75) is no longer completely continuous and would be easily breached near the bridge (Figures 28). The elevation in this area is around 7.36 m. The road elevation derived from the cross sectional profile is 8.16 m (Figure 29). Both indicate that during storm conditions, this area would be easily flooded.

Much of the flooding hazard upstream of the causeway originates from building on or near former agricultural marshland. Figure 10 depicts the marsh bodies and flood zones upstream of the causeway. The area of flooding is extensive and surrounds the town of Windsor. If the causeway were to be removed, there would be significant risk to the town and associated infrastructure and considerable cost in rebuilding and/or repairing the dykes. One of the original reasons for constructing the causeway in the first place was to decrease the amount of area that needed to be protected by dykes that require regular, costly maintenance. It should be noted that this assessment of flood hazard to the town of Windsor is preliminary and further in depth studies are required regarding the economic implications and site specific impacts (e.g. built infrastructure and property level) as well as groundtruthing.

The proposed new twinned section of highway will cross the Avon River at the tide gate via a bridge. The positioning of the bridge abutments will need to be carefully considered since the area around the banks of the tide gate channel are both at a high risk of erosion and of flooding (Figure 30). Even if additional fill is placed on the sea ward edge of the existing dyke, this area is susceptible to erosion and currently is within the flood zone for normal spring tides. This risk will continue to increase with increasing water levels which will accelerate any bank scour in the area. Addition rock armouring will also be required. In addition, significant discharge events from the tide gate will continue to erode the banks adjacent to the sluice gate. The eastern edge of the causeway will likely flood with storm tides within the next decade given current rates of sea level rise. In both cases additional fill will be required as well as bank armouring.

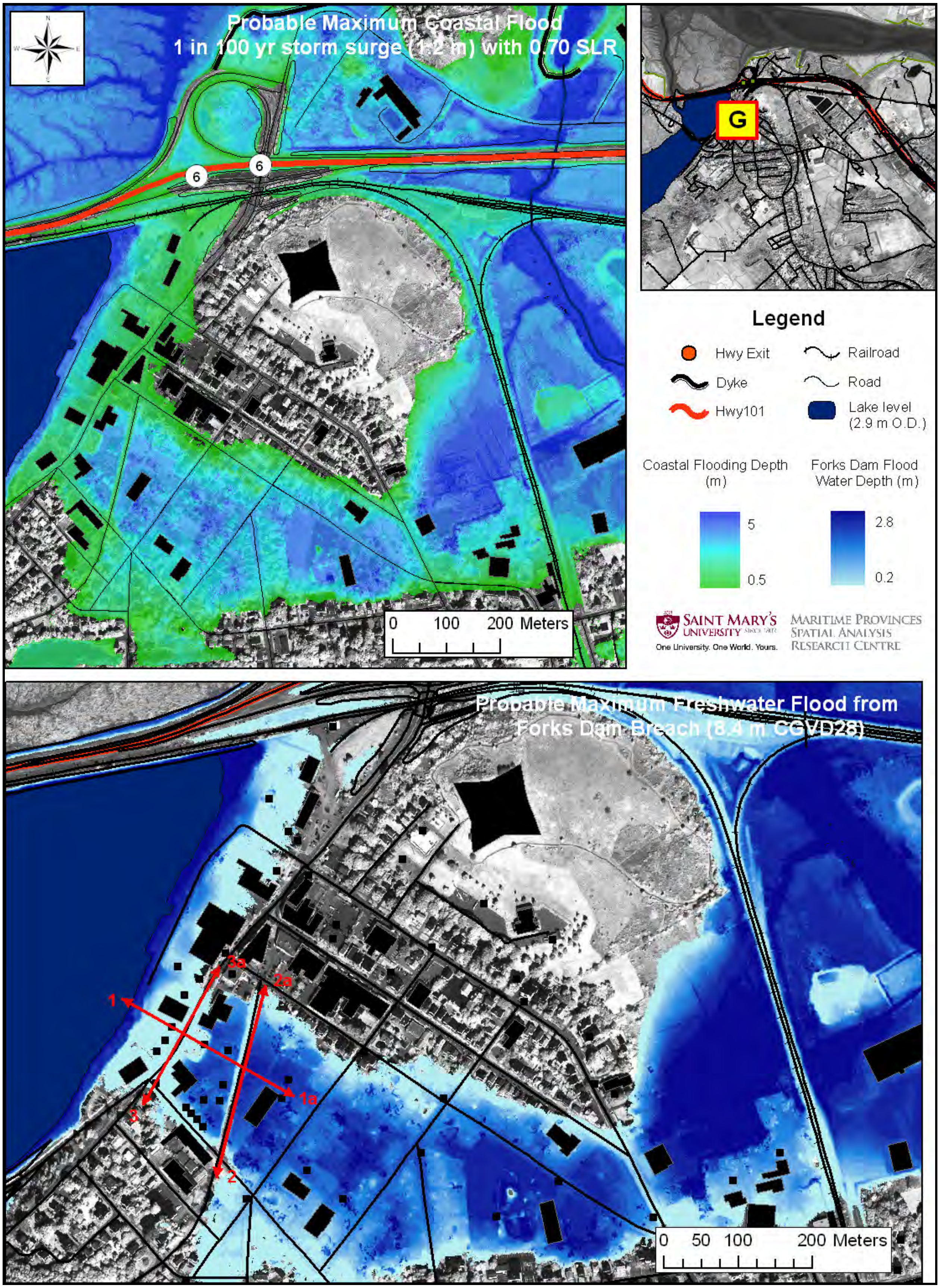


Figure 26: Impacts of coastal flooding and freshwater flooding due to failure of the Forks Dam through downtown Windsor at Site G.

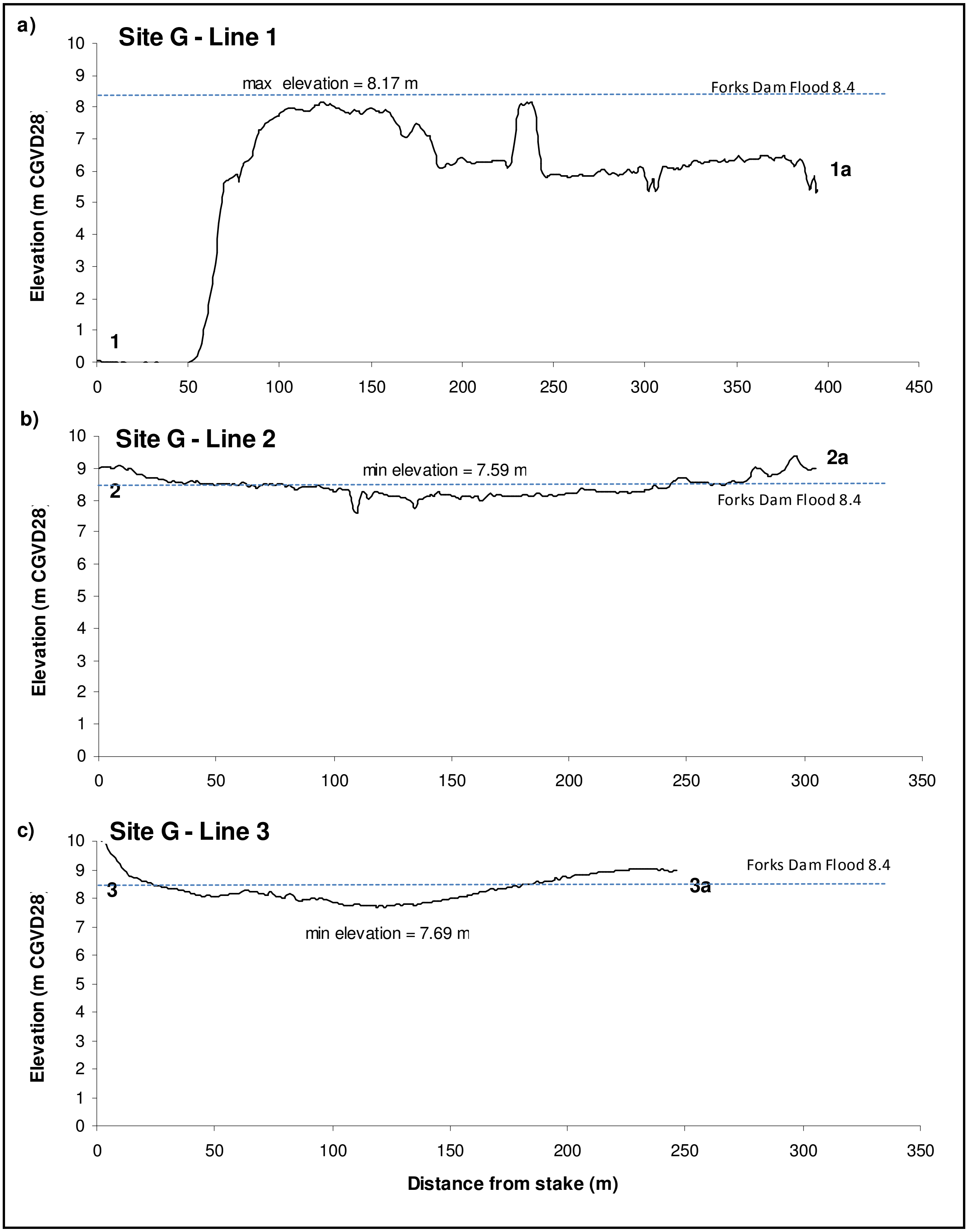


Figure 27: Cross sectional profiles at Site G adjacent to the Windsor waterfront downtown. Location of profiles indicated on Figure 26.

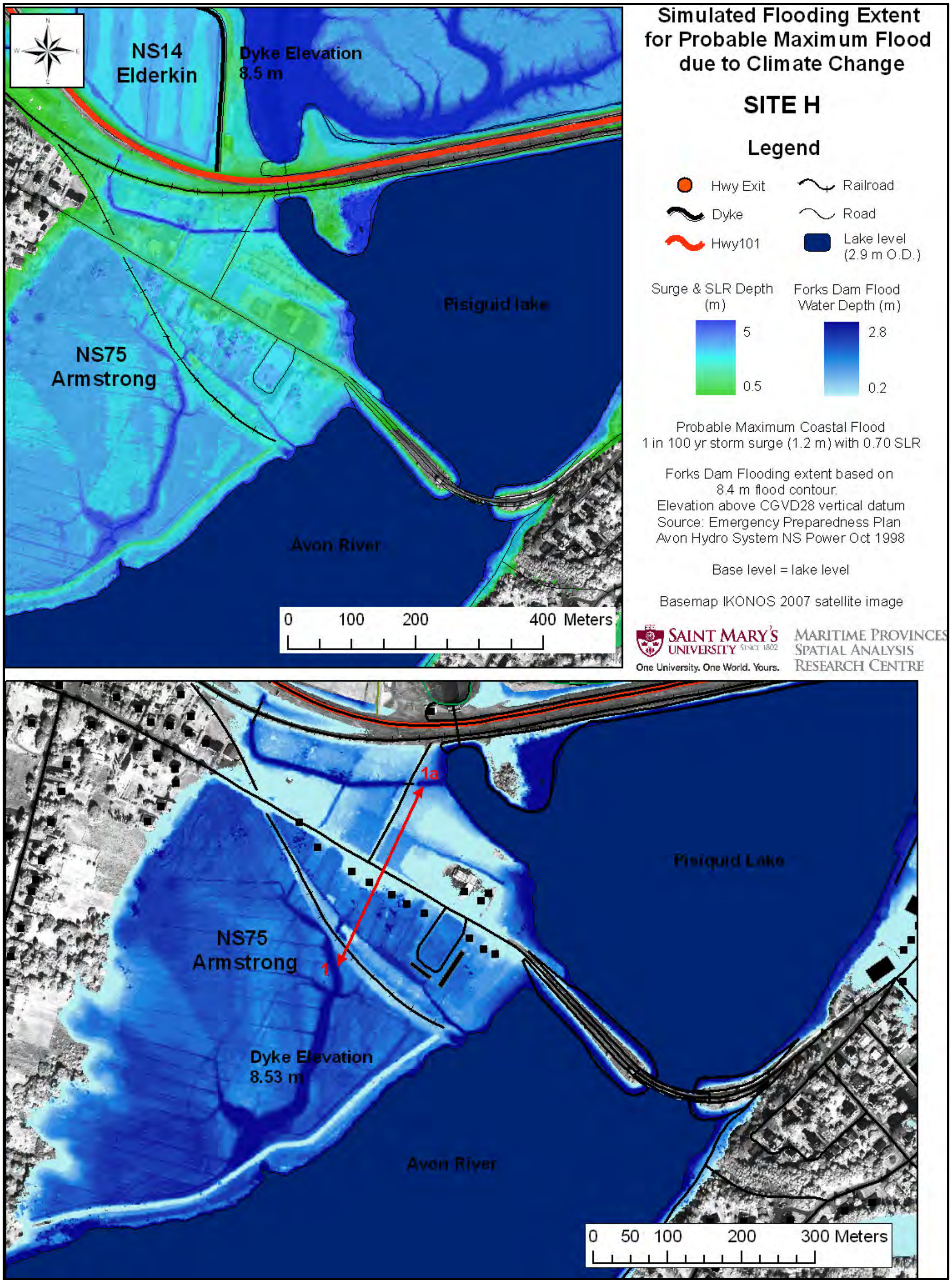


Figure 28: Extent and depth of flooding at Site H due to both coastal storm surge with SLR and failure of the Forks Dam.

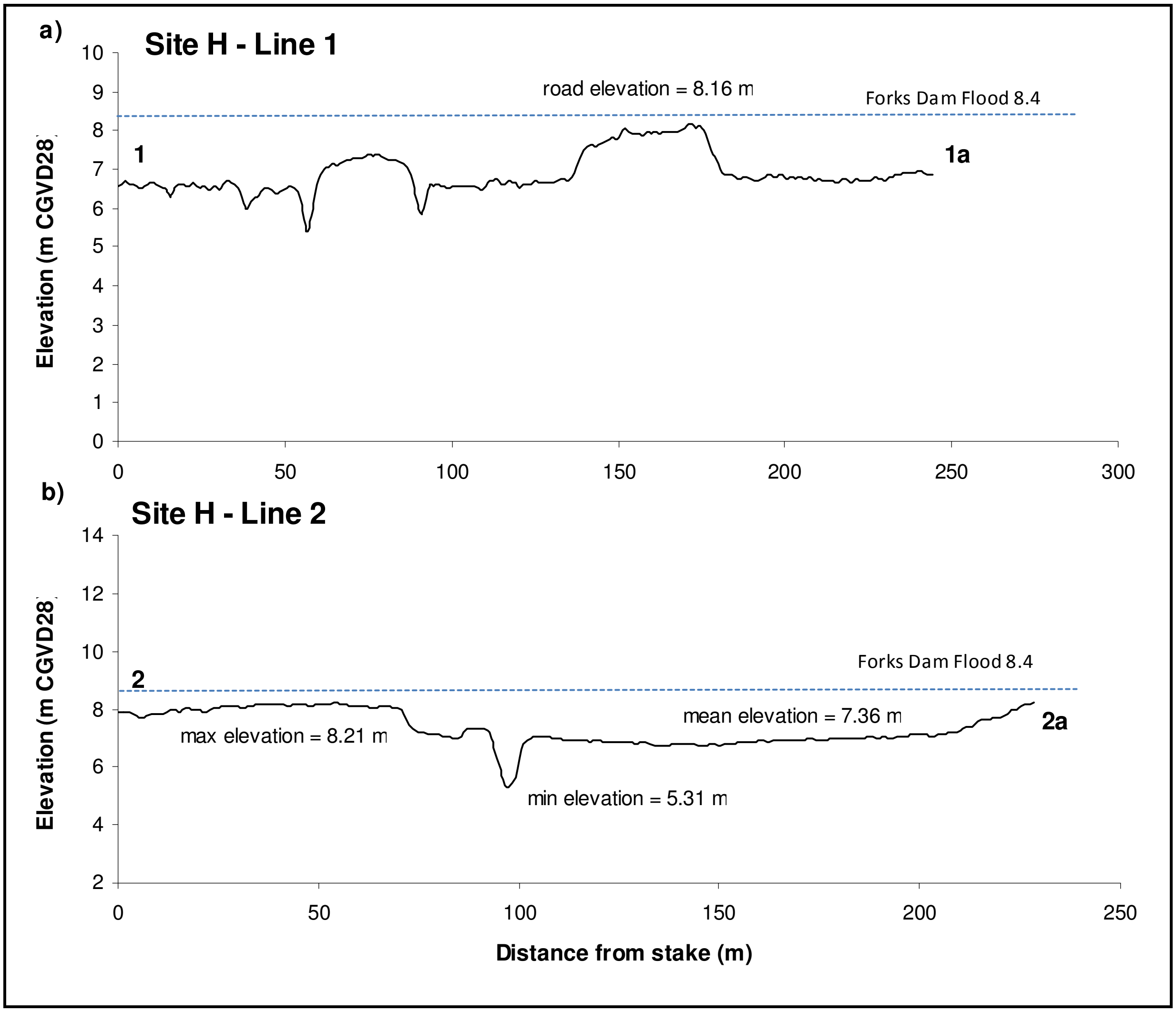


Figure 29: Cross sectional profiles at Site H on the western shore of Pisiquid Lake. Location of profiles indicated on Figure 28.

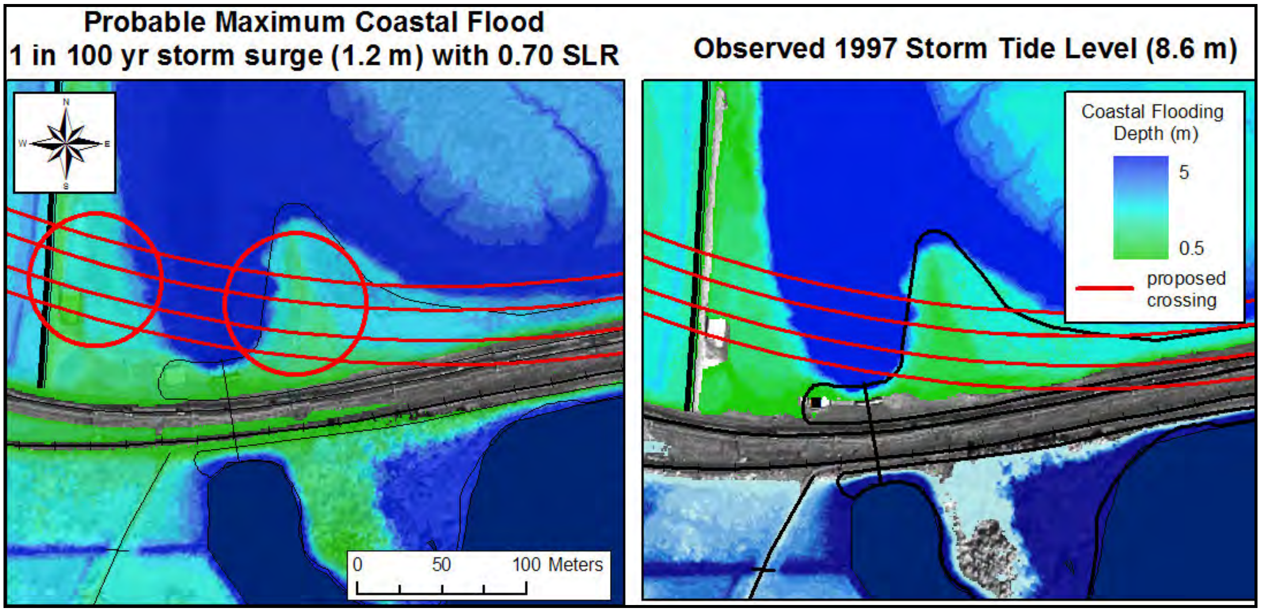


Figure 30: Potential area of concern for the proposed new twinned Highway 101 crossing near the Windsor Tide Gate.

Conclusions

Within the majority of the study area, the elevation of the 101 Highway is sufficient to keep it from being flooded in all but high storm conditions. There are however small pockets of vulnerability, most notably at the on ramp at Exit 6 (tidal) and Exits 5 & 8 (freshwater). The tidal impacts however are time limited and restricted to the period at high tide initially which limits the amount of water that can fill the 'basin'. This water can then become trapped behind the dyke and remain for a period of time. Additional research will be needed to determine basin fill times and develop an emergency evacuation plan avoiding roads that will flood. Alternatively, freshwater flooding can result from prolonged rainfall which is not able to drain through aboiteau that are held shut by concurring high tides. This can result in very rapidly rising water levels. The causeway itself is at an adequate elevation in the central portion to withstand rising sea levels, however it is recommended to increase the elevation of both western and eastern ends to exceed approximately 9.75 m. Some areas of concern such as those at site F near Exit 8 can be mitigated in part by replacing the old aboiteau structure with a new one.

One of the questions to the addressed within this study what the flooding impacts would be on the Town of Windsor if the tide gate were removed. A preliminary, primarily qualitative analysis was performed, which depicts a significant impact on the downtown core even during normal spring tide conditions. The majority of the impacts surround Pisiquid lake however there is a large central corridor radiating out from the lake which is completely inundated, flooding numerous homes and businesses. This same area would be flooded based on the flood elevation (8.4 m CGVD28) provided by the Emergency Preparedness Plan for the Avon Hydro System (Oct 1998) for failure of the Forks Dam. Additional in-depth site specific analyses on the flood hazards within the town are recommended.

References

- Daborn, G.R.; van Proosdij, D. and M. Brylinsky. 2003. Environmental Implications of Expanding the Windsor Causeway (Part One). Report prepared for Nova Scotia Department of Transportation Contract # 02-00026. Acadia Centre for Estuarine Research Publication No. 72. 15 pp.

- Daborn, G.R.; Brylinsky, M. and D. van Proosdij. 2003. Ecological Studies of the Windsor Causeway and Pesaquid Lake, 2002. Final report prepared for Nova Scotia Department of Transportation Contract # 02-00026. Acadia Centre for Estuarine Research Publication No. 69. 111 pp.

- Desplanque, C. and D, Mossman. 2004. Tides and their seminal impact on the geology, geography, history and socio-economics of the Bay of Fundy, eastern Canada. *Atlantic Geology* 40(1):1-30.

- Bindoff, N.L., J. Willebrand, V. Artale, A, Cazenave, J. Gregory, S. Gulev, K. Hanawa, C. Le Quéré, S. Levitus, Y. Nojiri, C.K. Shum, L.D.Talley and A. Unnikrishnan, 2007: Observations: Oceanic Climate Change and Sea Level. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S.,D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

- Parkes, GS.; Forbes, D.L. and Ketch, L.A. 2006. Sea-level rise and regional subsidence in southeastern New Brunswick. *In* Impacts of Sea Level Rise and Climate Change on the Coastal Zone of Southeastern New Brunswick (ed) R. Daigle, D. Forbes, G. Parkes, H. Richie, T. Webster, D. Berube, A. Hanson, L Debaie, S. Nichols and L. Vasseur: Environment Canada 613 p.

- van Proosdij, D. and G. Baker. 2007. Intertidal Morphodynamics of the Avon River Estuary. Final report prepared for the Nova Scotia Department of Transportation 186 pp.

- van Proosdij, D; Bambrick, J. and G. Baker. 2006. Spatial and Temporal Variations in the Intertidal Geomorphology of the Avon River Estuary. Final report prepared for the Nova Scotia Department of Transportation 82 pp.

- van Proosdij, D. 2005. Monitoring Seasonal Changes in Surface Elevation in Intertidal Environments near the Windsor Causeway. Final report prepared for the Nova Scotia Department of Transportation 22 pp.

- van Proosdij, D., Daborn., G.R. and M. Brylinsky. 2004. Environmental Implications of Expanding the Windsor Causeway (Part Two): Comparison of 4 and 6 Lane Options. Report prepared for Nova Scotia Department of Transportation Contract # 02-00026. Acadia Centre for Estuarine Research Publication No. 75. 17 pp.

- Vasseur, L. and N. Catto. 2008. Atlantic Canada; *in* From Impacts to Adaptation: Canada in a Changing Climate 2007, *(ed)* D.S. Leman, F.J. Warren, J. Lacroix and E. Bush; Government of Canada, Ottawa, ON p. 119-170.

- Webster, T., Dickie, S., O'Reilley, C., Forbes, D., Parkes, G., Poole, D. And R. Quinn. 2003. Mapping storm surge flood risk using a Lidar- derived DEM. Geospatial Solutions May, 5 pp.

- Webster, T., Forbes, D., Dickie, S. and R. Shreenan. 2004. Using topographic Lidar to map flood risk from storm-surge events for Charlottetown, Prince Edward Island, Canada. Canadian Journal of Remote Sensing 30(1): 64-76.