Atlantic Climate Adaptation Solutions Association

Solutions d'adaptation aux changements climatiques pour l'Atlantique

Coastal Dykelands in the Tantramar Area : Impacts of Climate Change on Dyke Erosion and Flood Risk

By

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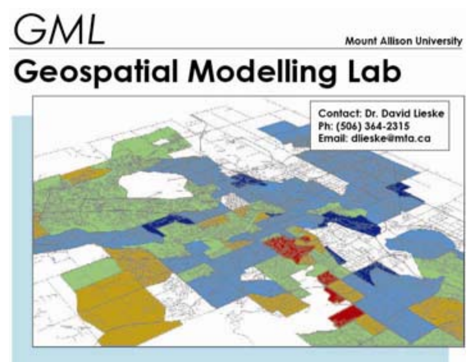

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Abstract

Climate-change related sea level rise, accompanied by increasing storm frequency and intensity, are raising flood risks in many low lying coastal areas around the world. To address the potential flood risk facing the Tantramar dykelands of NB, Canada, flood high-water marks were mapped using recent estimates calculated as part of a regional climate-change adaptation initiative. Based on extreme sea level (m) from 2000 and projections for 2025, 2055 and 2085, sea levels during 10, 25, 50 and 100-year storm events were predicted and mapped for the Tantramar region, including the town of Sackville, NB and surrounding rural/agricultural areas. We found that the average height of the dykes in the Tantramar region is 8.6 m, which is lower than even the least severe prediction based on the current 1:10-year sea level estimate of 8.9 $\pm$ 0.1 m. Clearly, the Tantramar region is at immediate risk of a major flood event. Based on a logistic regression model, we also identified sections of dyke exhibiting

unusually high levels of erosion, and present maps and empirical evidence confirming that vegetated sections further from the Bay of Fundy (and its tidal water courses) are less vulnerable. The results of this analysis can be used to identify the sections which will require the greatest long-term financial investment to maintain.

Given the topography of the Tantramar flood plain, compromises of the dyke system under increasing sea level rise scenarios make relatively little impact on the horizontal area affected. For the Town of Sackville, comparison of the flooded extents at baseline and largest 1:10 year storm surge area reveals a marginal change from 20.6 to 21.9%. However, we expect that increased water depth will intensify the damage to assets within the flood zone. At current estimates for a 1:10 year flood cycle, a substantial amount of the community will be potentially affected: 1049 parcels and 156 buildings. As well, flooding of major and secondary highways will be render them impassable, the sewage lagoon will be flooded, agricultural lands will be inundated, and even some non-flooded residential areas within the Town of Sackville will remain as isolated “islands” surrounded by flood water.

Based on the results of this analysis, we recommend some future steps for planners and government decision makers towards developing regionally-appropriate policy and emergency planning responses.

1. Introduction

Two main components of regional flood vulnerability are exposure and susceptibility. Exposure is the probability and extent of a flood whereas susceptibility is the damage occurred. Exposure is a concern in the Tantramar because of the close proximity to the ocean, and a dyke system that is currently inadequate for climate induced increases in sea level and storm surge intensity and frequency. Agricultural, municipal and transportation assets are susceptible to a flood. Susceptibility increases as flood characteristics such as duration, frequency, velocity, extent and depth also increase.

Communities can manage exposure and susceptibility to risk by increasing both response and adaptive capacity. The response capacity is the ability to “bounce back” from a flood event and restore itself to pre-flood conditions. Adaptive capacity is the ability to reduce the susceptibility of flooding in the first place (such as increasing the height of dykes, flood-proofing structures, moving out of the flood zone etc).

The goal of this report is to assess the exposure and vulnerability of the Tantramar region to coastal flooding to help inform decision makers on ways to improve the response and adaptive capacity. There are two specific objectives:

1) To model vulnerable sections of the Tantramar dykes using information obtained by remote sensing and ground survey.

2) To assess the infrastructure at risk in the Tantramar region under climate-induced sea level rise for four time periods: 2000 (baseline), 2025, 2050 and 2085.

The remaining part of the introduction consists of a description of the Tantramar region with a focus on the dyke history and management as well as a summary of the susceptible assets. The exposure of the region to past and predicted storm events is then presented.

The following sections present the methods followed by the results, discussion and conclusions/recommendations. A GIS methodology is taken in this study. The flood extent for the current and estimated sea levels is generated from high precision LiDAR elevation data. The calculated flood extent assumes that the water is free flowing and reaches the contour line of the each sea level scenario. The flood extents do not consider freshwater flooding.

1.1 Study area

The study area is defined by the lands that are protected by a system of dykes in the Tantramar region of New Brunswick, Canada (Figure 1). The Tantramar dykelands are located at the upper part of the Bay of Fundy, and are exposed to the highest tides in the world. As a result, tides rather than waves are the dominant coastal force (Trenhaile, 1998), and have lead to considerable coastal erosion in recent years (Personal communication, 2010).

A profile of the Tantramar dykelands starting from the coast can be generalized: salt-marshes or landmasses that buffer the dykes from coast; the dykes, approximately 10 m width; agricultural lands adjacent to dykes; part of the Town of Sackville; major transportation corridor across Canada that consists of the TransCanada Highway and railway; followed by the low lying Tantramar River basin extending to the North that consists primarily of agriculture and wetlands (Figure 2).

The adaptive capacity of the region is partially limited by the historic management of the dykes. The area was settled by the Acadians in the 17^{th} Century, who created agricultural lands from exisiting salt marshes by building a system of dykes called aboiteaus. Aboiteaus have a valve that allows water to drain at low tide and close to prevent salt water from entering during high tide. Since the dykes would be periodically overtopped, the aboiteaus allowed for the salt water to drain. The dykes have been maintained by the Province of New Brunswick to protect agricultural activity, and while part of the Town of Sackville occurs on dykelands, it is not a partner in the funding of dyke management. The dykes have been gradually improved over time through such measures as raising dyke heights, reinforcing high exposure areas with armour stone, and vegetating dykes to prevent erosion. Such improvements are currently limited by environmental regulation as well as available funding.

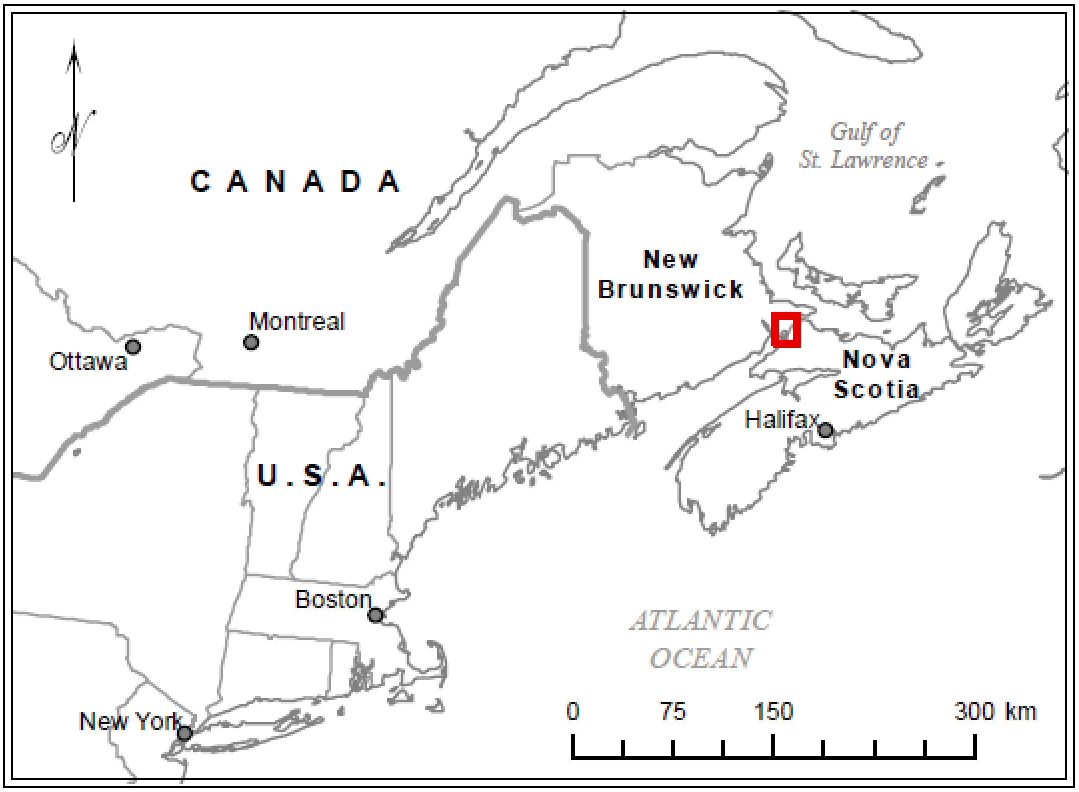

Figure 1. Tantramar area of south-east New Brunswick.

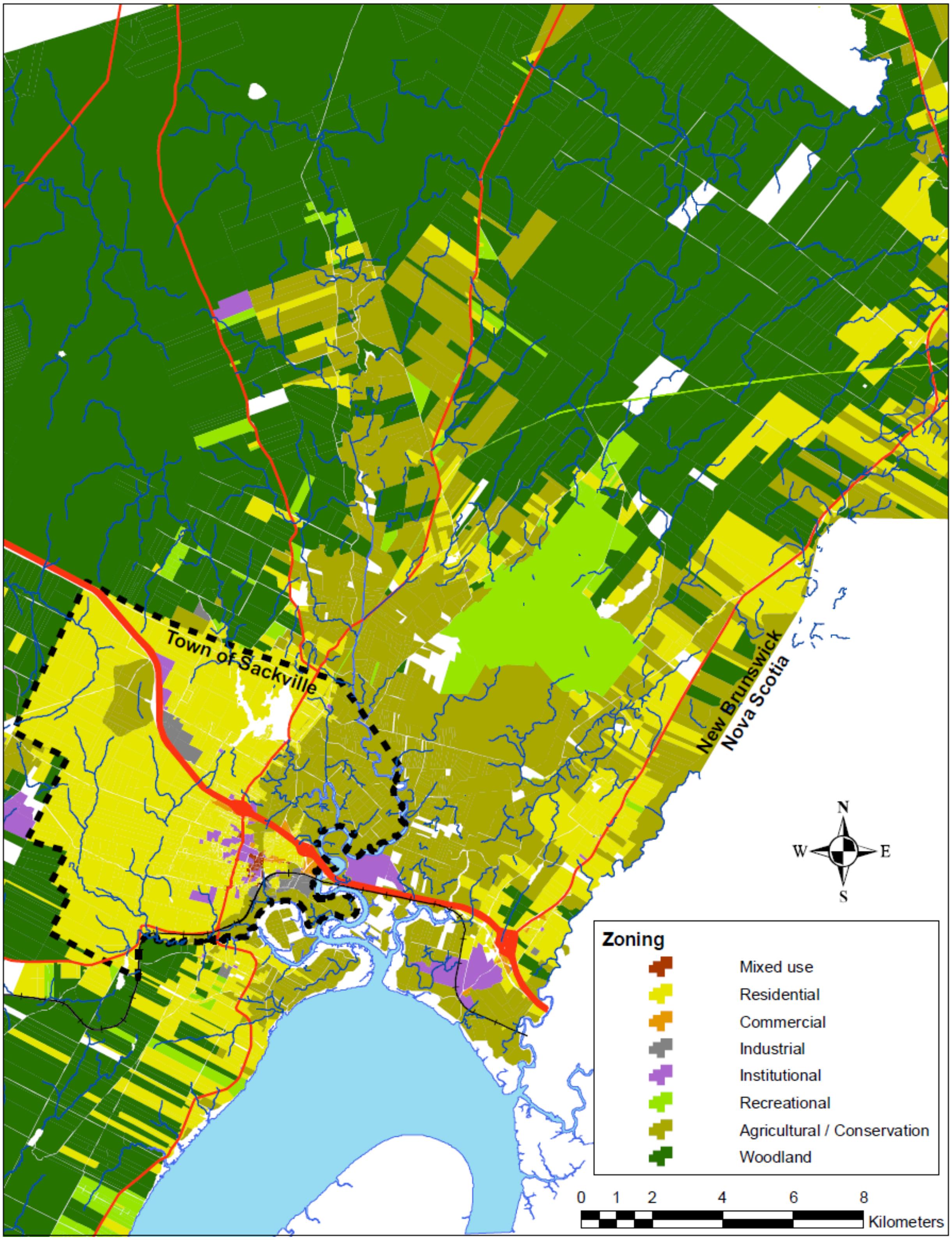

Figure 2. Zoning map.

1.2 Exposure to storm events

The greatest risk of coastal flooding occurs during storm surges, which are unpredictable (stochastic) events. A storm surge is created by a low pressure system, such as a hurricane, which reduces atmospheric pressure on the ocean. Strong winds associated with these events further increase sea level, the effects of which are intensified during spring/high tides.

Since the Tantramar dykes were never meant to prevent against all flood events, there is a history of the dykes overtopping. The most notable was the Saxby Gale in 1869. This resulting storm surge reached a sea level of approximately 10.1 metres. Large sea levels since then have been considerably smaller in magnitude. In recent history the majority of flooding in the Tantramar is primarily due to freshwater storms where the dykes acted as barriers to keep the water from draining. The aboiteau dykes permit slow drainage and only at low tide (which occurs twice daily). An example storm occurred in 1961, when freshwater flooding reached an elevation of 8.7 m. In recent years the frequency of the dykes being overtopped has increased (personal communication, Claude Robichaud). The extent of this flooding is limited to the adjacent agricultural lands. This observed increase in frequency of high sea level illustrates the growing risk of sea flooding.

Increases in both storm surge frequency and sea level rise have been measured in the region. Records of hurricane and tropical storms that have passed through the study area show that the frequency of storms has more than tripled in the past 25 years compared to records over the past century (derived from data from Knapp et al, 2010). Thirteen storms have occurred since 1985 and fourteen during the period of 1900-1985 (Figure 2). Sea level records from the nearest Canadian Hydrographic Service long term tidal gauge in St. John, NB (station 65), located approximately 150 km down the Bay of Fundy, also show an increase in sea level over time (Figure 3).

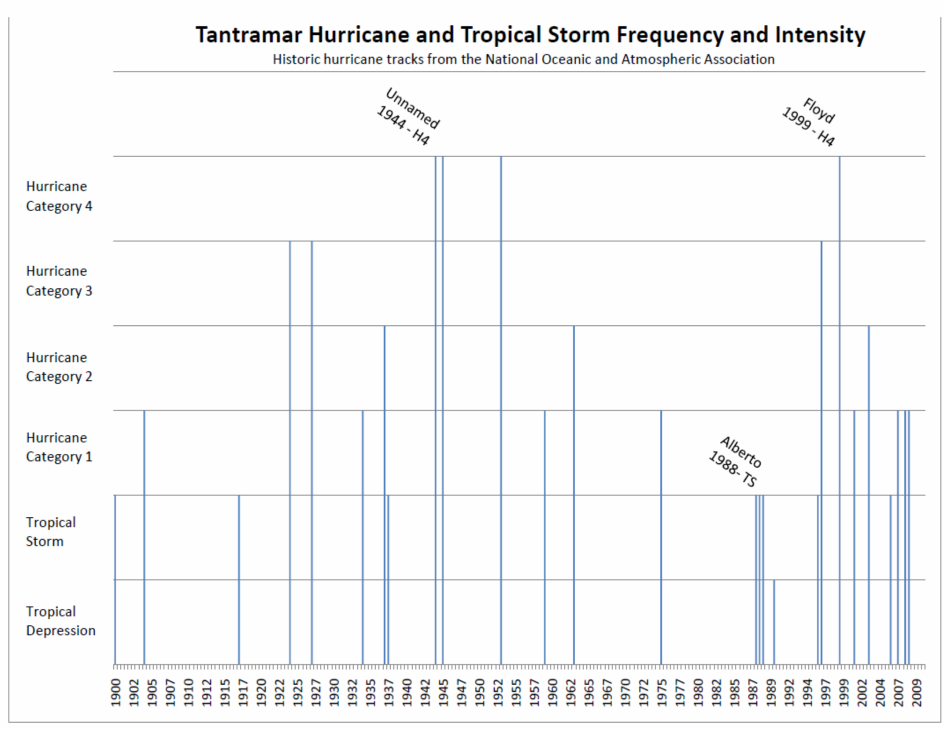

Figure 2. Hurricane and tropical storms that have passed through the Tantramar region. The maximum storm strength is given rather than strength when the system reached the region. There have been three direct hits in 1944, 1988 and 1999.

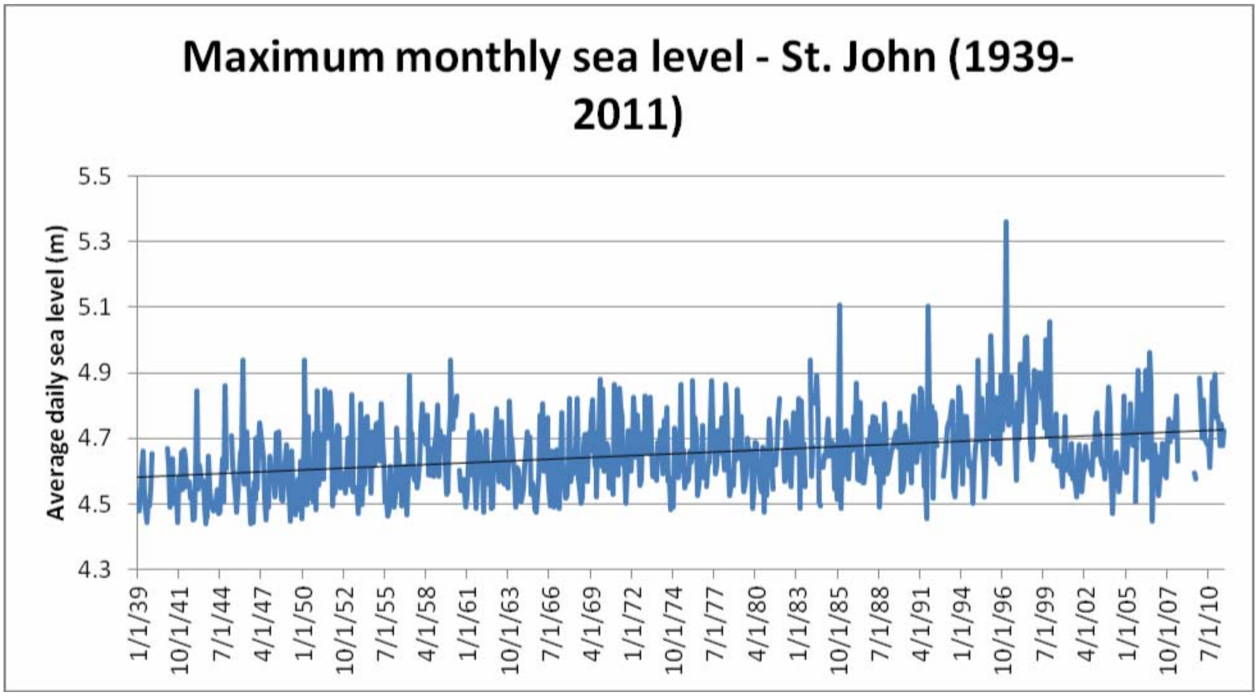

Figure 3. Maximum monthly sea levels (based on daily averages) for St. John, New Brunswick between 1939 and 2011.

A recent report by R.J. Daigle Enviro (2011) provided sea level estimates of the Tantramar region due to the effects of climate change. Sea levels were estimated for 1:10, 1:25, 1:50 and 1:100 year events for baseline (2000) and projected years of 2025, 2050, 2085 and 2100 (Table 1), based on a combination of predicted storm surge potentials, Higher High Water Large Tide (HHWLT, based on tide gauge measures for 8 April 2009 to 31 December 2010), thermal expansion, and crustal subsidence. The results in this report will be given for the 1:10 year sea levels as they are the most frequent and are characteristic of the range of flood events.

Table 1. Climate induced sea level estimates (From R.J. Daigle Enviro, 2011)

Return period	Sea level (m) (2000 estimate)	Sea level (m) (2025 estimate)	Sea level (m) (2050 estimate)	Sea level (m) (2085 estimate)
1:10 year	8.9 ± 0.1 m	9.0 ± 0.1 m	9.3 ± 0.2 m	9.7 ± 0.4 m
1:25	9.0 ± 0.1 m	9.1 ± 0.1 m	9.4 ± 0.2 m	9.8 ± 0.4 m
1:50	9.0 ± 0.1 m	9.2 ± 0.1 m	9.5 ± 0.2 m	9.8 ± 0.4 m
1:100	9.1 ± 0.1 m	9.3 ± 0.1 m	9.6 ± 0.2 m	9.9 ± 0.4 m

2. Methods

A Geographic Information System (GIS) was used to assess regional flood vulnerability as it allowed for the input, management, analysis and output of relevant spatial information. ESRI ArcGIS 10.1 software was used to manage the spatial data and conduct the analyses. Two aspects of susceptibility to flood were analyzed: (1) the state of the dykes protecting the low-lying lands from coastal flooding, and (2) the terrestrial assets at risk under different flood scenarios.

A number of spatial data sources were obtained for and are summarized in Table 2. The analysis relied on high resolution elevation data to determine the extent of each sea level scenario. High-precision LiDAR (Light Detecting and Ranging) elevation data was obtained to construct a Digital Elevation Model (DEM) of the area. LiDAR data is collected by measuring the time it takes for an emitted pulse of light to reflect off of a surface and return to the aircraft. By capturing subsequent returns of the pulse, multiple elevations can be recorded along the above ground elevation profile (such as the height of: tree top, tree canopy, herbaceous undergrowth and ground). The LiDAR data obtained for this study was flown at two times by Leading Edge Geomatics with an estimated vertical precision of 15 cm and spacing of 0.3 metres. The ground elevations were used to construct the DEM by calculating the average of all LiDAR spot heights that fall within each 1 m^2 pixel. Where gaps in the LiDAR data exist (such as waterbodies) the gaps are filled with the average of surrounding pixel elevations (ESRI, 2010). For the portion of the study area that was not covered by LiDAR data, lower resolution (1.5 m vertical precision, 30 m horizontal spacing) data was used.

The elevation of the LiDAR DEM was compared to higher precision Kinematic GPS ground surveys (sub-cm precision) for quality control of the elevation accuracy. Standard deviation and Root Mean Squared Error are used to assess the accuracy. The ground accuracy is also examined under different land cover using Analysis of Variance Analysis. This is to determine if high or dense vegetation cover, such as trees and brush, cause an error in the LiDAR data.

Table 2. Summary of datasets used in this study.

Dataset	Source	Date	Description of data	Derived product(s)
LiDAR	Leading Edge Geomatics, GNB, RAC	November 9, 2009 and December 18, 2010	High resolution elevation data (15 cm vertical precision, 30 cm spacing)	-Sea level flood extents -Building heights -Dyke centerline elevation
Property mapping	SNB, TDPC	April 2011	Location of property parcels, zoning and land use	-Identify property at risk
High resolution orthometric imagery	Leading Edge Geomatics, GNB, RAC	November 13, 2009	10 cm ortho-imagery	-Building footprints
Multispectral satellite imagery		September 16, 2010	Worldview-02, panchromatic 0.5 m, multispectral 2 m, RGB+NIR bands	-Dyke vegetation cover
Ground K-GPS survey	NB Dept Agriculture	Dixon Island: December 2006; Fort B: December 2003; Aulac: December 2005	Transects of dyke elevation; cm precision	-Used in combination with LiDAR to determine change in dyke height
Topographic	Service New Brunswick	1996	Transportation, hydrographic and elevation (1.5 m vertical precision, 30 m spacing) data	-Identify assets at risk -Elevation used to construct a DEM for

Environmental and cultural areas	Parks Canada	2011	National historic sites and conservation areas	-Identify assets at risk

While not the focus of this report, a focus group was conducted on April 19, 2011 with findings that are relevant for this study. Two outcomes presented here include a prioritization of vulnerable locations as well candidate adaptation strategies (which are reviewed in Section 4).

2.1 Dyke vulnerability

We identified three factors that could potentially increase the vulnerability of the dyke system to coastal flooding: low elevation, lack of vegetation cover and distance to open water. Low elevation obviously renders a given dyke section vulnerable to being overtopped, but we hypothesized that exposed, non-vegetated sections of dyke closest to potential flood water would also be subjected to the greatest energy during high tides and storm surges, and would exhibit the highest rates of erosion.

The LiDAR-derived DEM was used to identify the highest points along the length of the dykes. To achieve this, the dyke centerline was digitized and a 3x3 maximum neighbourhood filter was used to ensure that the highest elevation was returned in the case where the pixel of highest elevation is adjacent to the centerline. This line was mapped to identify low sections along the dyke. Dyke elevation was compared to predicted sea levels to determine which sections of dyke would be over topped.

Vegetation cover was measured by applying a Normalized Differentiation Vegetation Index (NDVI, Jensen 1996) to the sensor values collected by the multispectral satellite imagery (see Table 2):

$$NDVI = \frac{(NIR - VIS)}{(NIR + VIS)} * 100 \qquad (1)$$

Where plants absorb visible light (*VIS*) and reflect near infra-red radiation (*NIR*), the resulting ratio provides a good approximation of the density of vegetation cover: values close to 100 indicate a pixel saturated with vegetation, whereas values approaching 0 indicate little to no healthy vegetation.

The distance to open water was measured by the Euclidean distance (metres) from the coastline to dyke centerline.

Dyke erosion rate (per annum), for n = 916 survey points, randomly selected, was calculated as:

$$Erosion = \frac{Elev_{LiDAR} - Elev_{Survey}}{Years} \qquad (2)$$

A preliminary inspection of erosion rates revealed that the distribution of values were highly skewed and non-normal. For this reason, erosion rates which met or exceeded -0.20 m were categorized as “highly eroded”, otherwise classed as “non eroded”.

Logistic regression modelling was then performed using NDVI and distance to coastline (DIST) as independent/explanatory variables in order to measure the influence of these factors on the likelihood of a dyke section being “highly eroded”:

$$\log it(Y) = \log\left(\frac{P(Y)}{1-P(Y)}\right) = \beta_0 + \beta_1 NDVI + \beta_2 DIST \quad (3)$$

The logistic regression model was calculated using the *R* Statistical Package (Ihaka and Gentleman 1996). Classification accuracy was assessed using the area under the receiver operating characteristic curve (ROC) using the package Epi (Carstensen et al. 2011).

2.2 Assets at risk

An asset was defined “at risk” if it occurred at or below the potential high water mark indicated for each of the sea level rise scenarios. A GIS was then used to store community assets, including such features as: road, rail, hydrography, property zoning, buildings, and conservation areas.

In order to determine which assets are impacted by different flood scenarios “flat water” models were generated for each of the estimated 1:10 year sea level. Since the elevation data originated in three datasets (from two separate LiDAR scenes and lower resolution spot heights) polygons were created for elevations in each scene that fell under a given water level. The three shapefiles were merged and island polygons were removed (ie those that would not result from coastal flooding). Tables and maps were then produced summarizing the features damaged in each sea level.

3. Results

3.1 LiDAR ground truth

One hundred and seventeen on the ground points were calculated using Leica GPS 1200 sub-cm GPS base station and rover units. The mean difference between the LiDAR DEM and ground survey for the November 2009 and December 2010 data are 0 and +8 cm respectively. For the 2009 LiDAR, the standard deviation and RMSE are both 0.13 cm. For the 2010 LiDAR, the standard deviation is 0.11 cm and RMSE is 0.14 cm. Results from the Analysis of Variance show that there appears to be a systematic bias of LiDAR data in strub and tree land cover. Barren ground (N=34) and grass (N=72) had means of 3.9 and -0.3 cm respectively. Based on Tukey’s test both shrub (N=6) and tree (N=6) were significantly different from grass with means of 16.1 and 15.5 cm respectively.

3.2 Dyke vulnerability

The average dyke height was found to be 8.6 metres (Figure 4). The vast majority of the dykes are overtopped in all scenarios. At the current baseline 1:10 year sea level of 8.9 metres 89% of the dykes would be overtopped. Figure 5 shows the distribution of dyke elevation. The dykes are 27.6 km in length and the minimum dyke height is 7.7 m, and a maximum of 10.6 m. The higher sections of dykes are located around roads and bridges. The other measures of dyke vulnerability distance to coast and vegetation are shown in Figures 6 and 7 respectively.

Figure 6 shows how far dykes are from open water. Twenty two percent of the dykes are within close proximity (25 m) of the dyke centreline.

It was found that 63% of the dykes are vegetated (Figure 7). Based on a combination of aerial photograph interpretation and ground survey, pixels with a NDVI value greater than ~36 has a majority of vegetation. The ground surveys found that there is considerable mixing of land cover within pixels. For example, many sections of the dykes have dirt roads with foot wide tire tracks straddled by vegetation. As a result a continuous measure for vegetation is more appropriate for the resolution than a binary one.

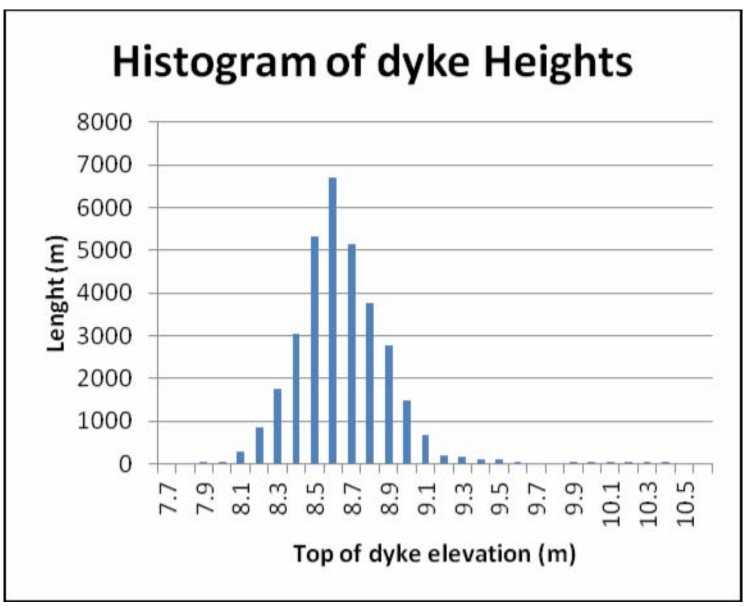

Figure 4. Histogram of dyke elevation (mean = 8.6m).

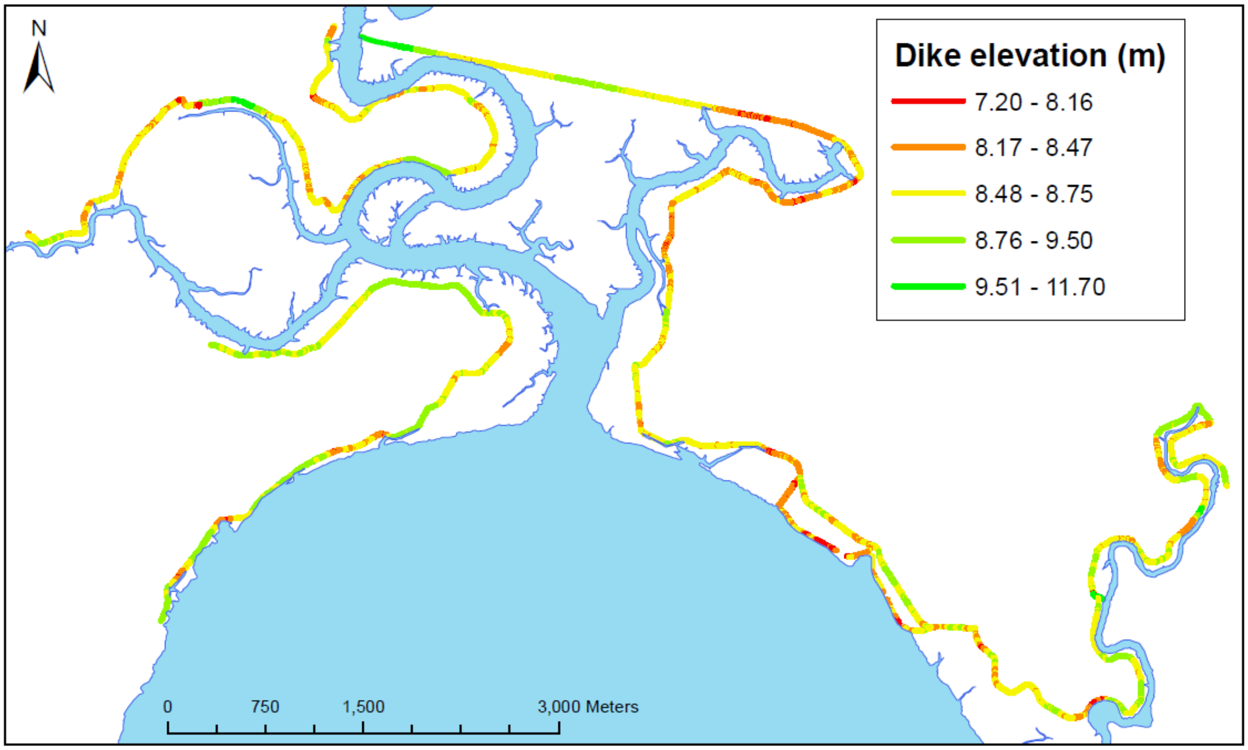

Figure 5. Dyke centreline elevation

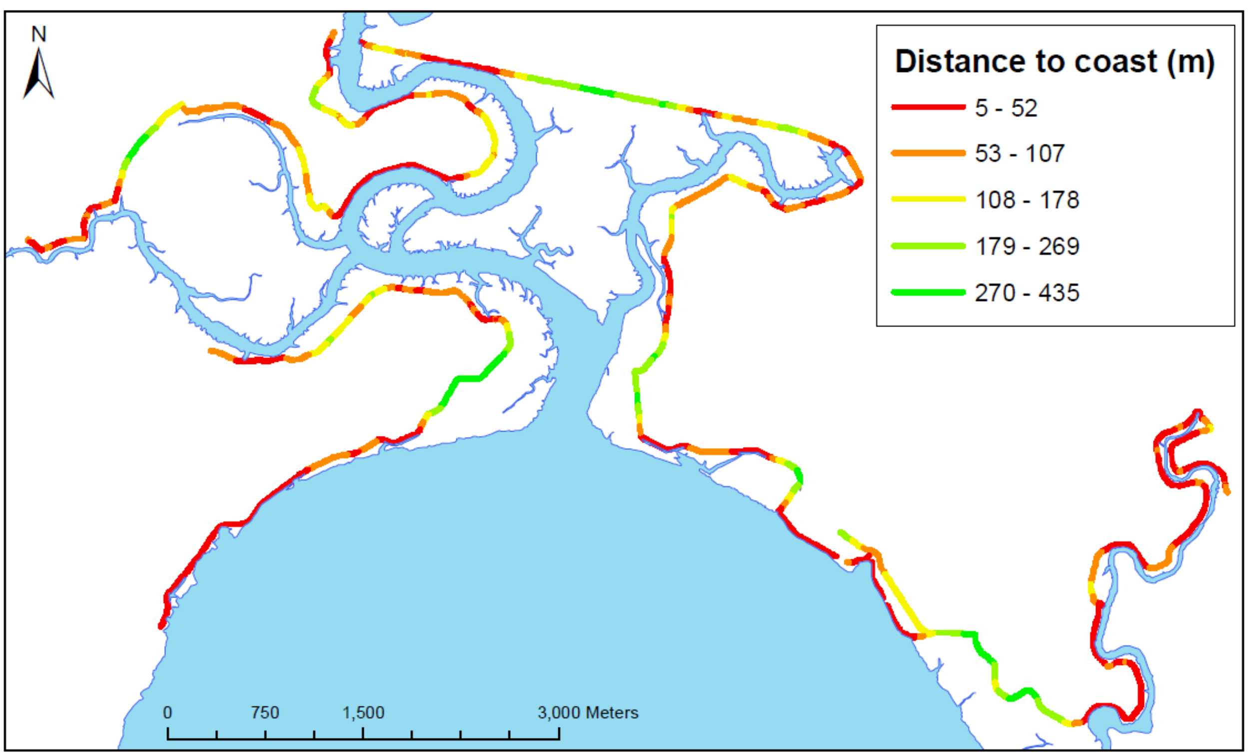

Figure 6. Euclidean distance to coast.

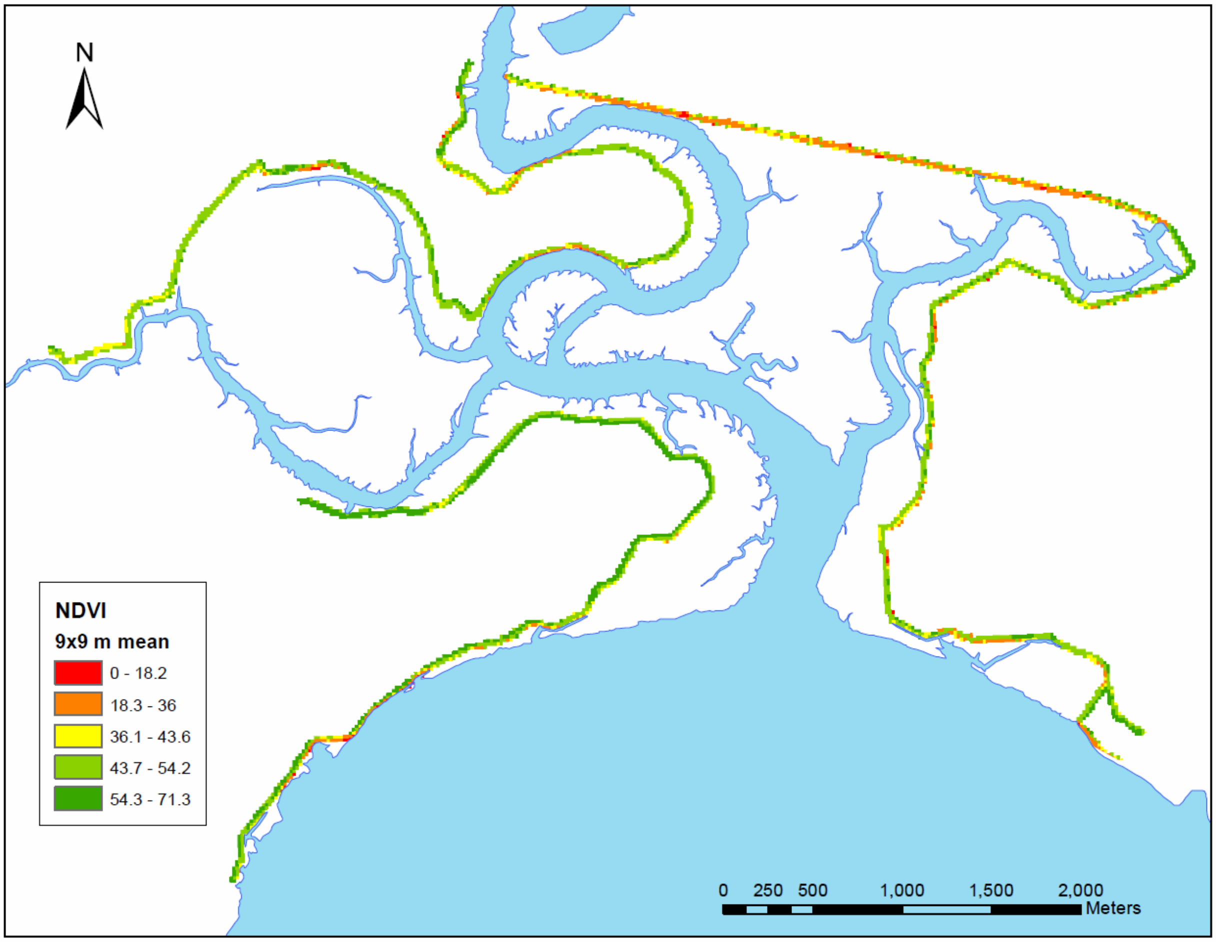

Figure 7. Normalized Differentiation Vegetation Index. Values greater than 36 are areas with a majority of vegetation.

3.3 Factors contributing to dyke erosion

Inspection of the centile distribution of dyke erosion rates (Fig.8) revealed that approximately 2% of the randomly selected survey locations could be defined as “highly eroded”.

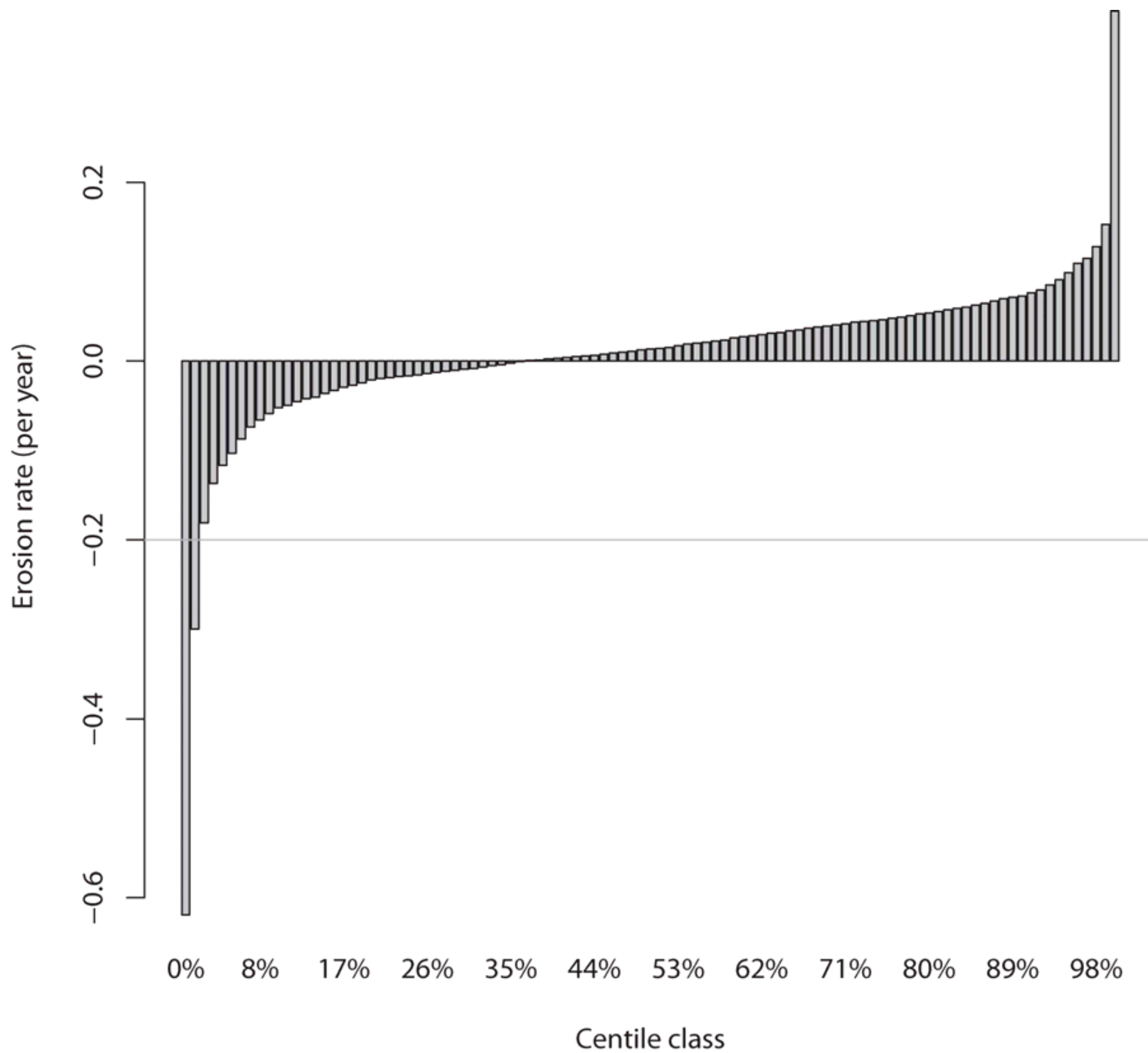

Figure 8. Centile distribution of dyke erosion rates with the -0.20m rate indicated as a horizontal line.

On this basis, a logistic regression was calculated and the results reported in Table 3:

Table 3. Logistic regression analysis of 916 surveyed locations, randomly selected.

Predictor	β	SE β	df	Wald Statistic (χ^2)	*P*	e^{β} (odds ratio)
Intercept	-0.6749	0.5677	1			
NDVI	-0.0560	0.0172	1	10.5733	**0.0011**	0.9456
DIST	-0.0020	0.0081	1	5.9811	**0.0145**	0.9803

Based on these results it can be concluded that increasing vegetation cover (as indexed by increasing NDVI values), and increasing distance from potential floodwater, decreased the probability of a dyke section falling into the "highly eroded" class.

The discriminatory power of the logistic regression, based on the area under the receiver operating characteristic curve, was 0.813 (Fig. 9).

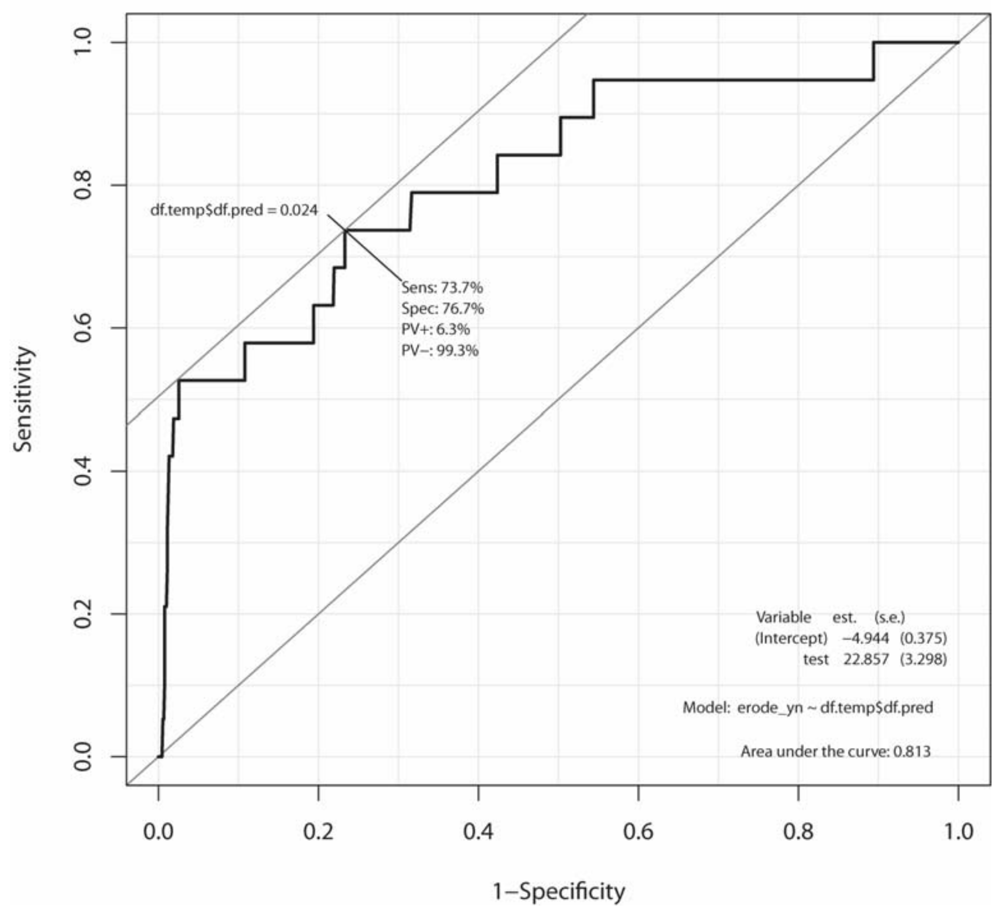

Figure 9. Classification accuracy of the logistic regression, based on the area under the receiver operating characteristic curve.

Based on these results, a dyke vulnerability map was produced to identify sections of dyke under greatest threat to erosion (Fig. 10).

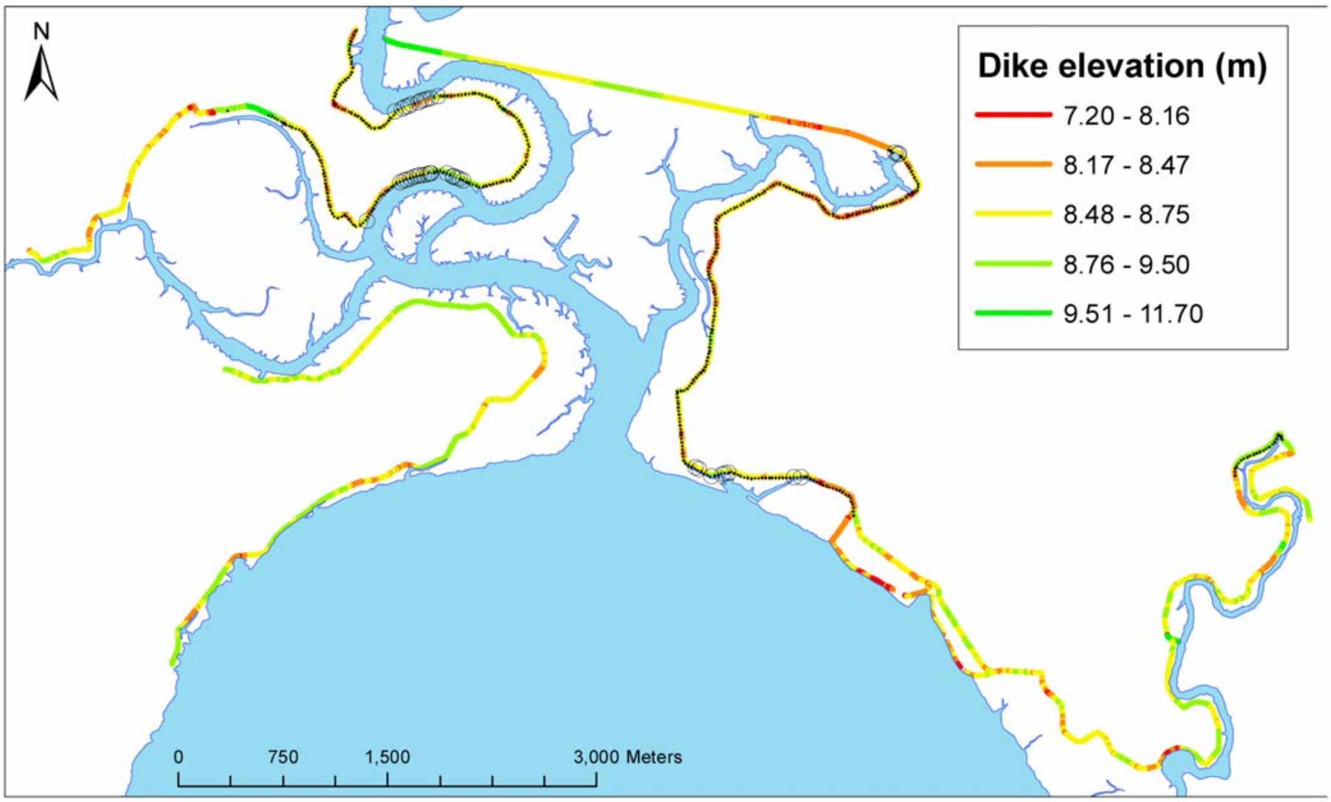

Figure 10. Vulnerable dyke sections (as indicated by large circles) as a function of vegetation cover (indexed by NDVI) and distance to water (DIST, in metres). Small, filled circles indicate sections of the dyke that were included in the model training and which yielded probabilities of high erosion ≤ 0.132. Please note that model predictions were not applied to all sections of the dyke system.

3.4 Assets at risk

The land area flooded under each of the 1:10 sea levels in considerable. At the 2000 level, 115 square km of land is flooded. This corresponds to 20.6% of Sackville and 9.2% of the Tantramar Planning District. At the largest sea level examined 2085, 123 square km of land is flooded. This corresponds to 21.9% of Sackville and 9.9% of the Tantramar Planning District. The flood extent statistics for each of the flood scenarios is summarized in table 4.

Table 4. Percent Sackville and Tantramar Planning District flooded under estimated 1:10 year scenarios

Estimated Sea Level	**Total area flooded (square km)**	**Percent Town of Sackville flooded**	**Percent Tantramar Planning District flooded**
8.9 m (2000)	114.6129	20.60%	9.19%
9.0 m (2025)	115.4125	20.78%	9.25%
9.3 m (2050)	120.4428	21.23%	9.66%
9.7 m (2085)	123.2636	21.87%	9.88%

Figure 11 shows the flood extent for the 2000 and 2085 1:10 year sea level scenarios. At this small scale, there is little visual perception in the difference of flood extent. Due to the increased slope at the edge of the flood plain, the horizontal change in flood extent between these two scenarios generally does not exceed 30 meters in inhabited areas. The largest change in horizontal extent in inhabited locations is the residential area bounded by Tantramar Place, Churchill Avenue and Bridge Street where there is a horizontal area flooded extends over 100 m between the two scenarios (Figure 12).

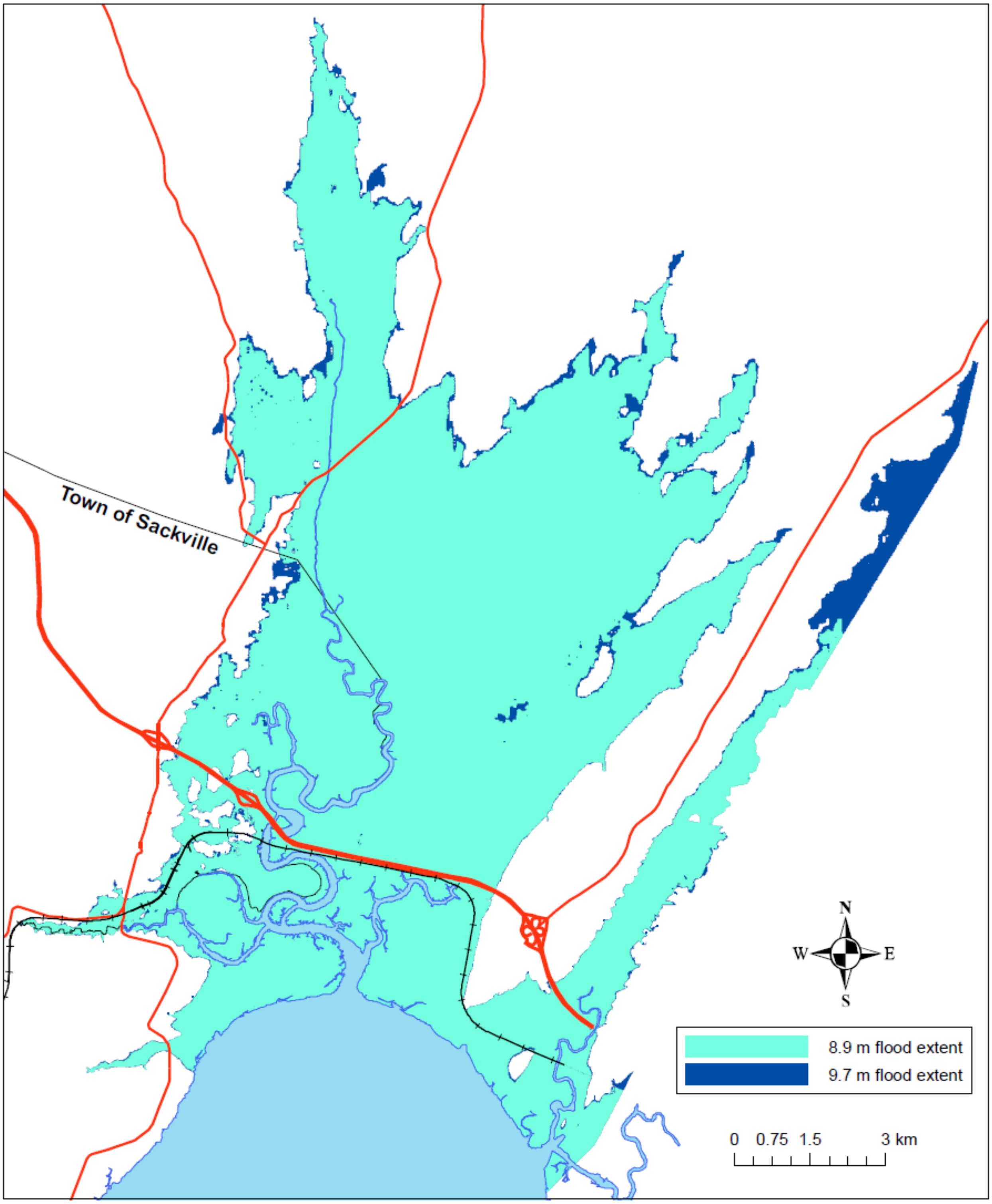

Figure 11. Map showing the flood extent of the 1:10 year flood extent for 2000 (8.9 m) and 2085 (9.7 m)

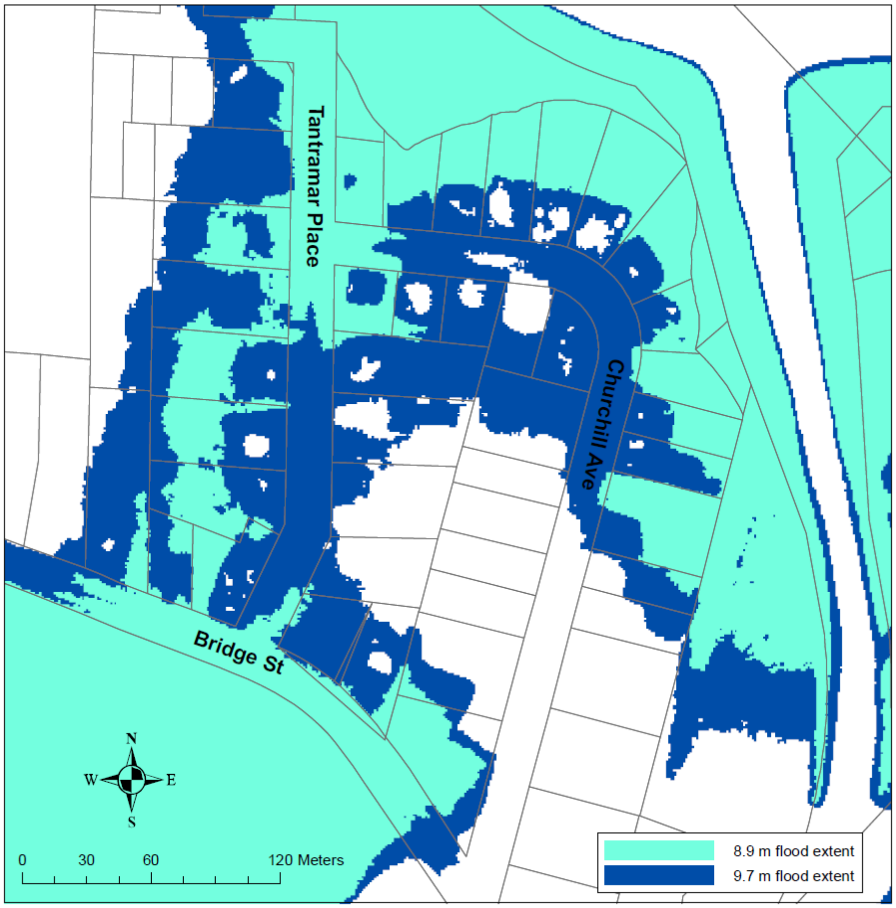

Figure 12. Large scale map showing the in 1:10 year flood extent scenarios

Property parcels and buildings provide an estimate on the impact of a flood. Table 5 summarizes the number of parcels affected by zone classification under each 1:10 year sea level. While there are a large number of parcels initially affected (1049), there is only a 11% increase in parcels affected under the 2085 scenario. The most impacted property types are residential and agricultural and conservation.

Changes in impacted buildings show a different trend (Table 6). At the 2000 level, only 15 percent of parcels have a building affected (156). However, at the 2085 level there is a 70% increase in buildings affected (266) over the 2000 level. The majority of buildings affected at all scenarios is residential. Some non-residential affected at the 2000 level include: 15 institutional (including public works, train station and a church), 9 commercial (including 2 garages) and 4 industrial buildings.

The results of the focus group identified the perception of features most at risk. The assets with the most response include: TransCanada highway, CN railway, sewage lagoon and water treatment plant, property along Lorne St, Sackville waterfowl park, and Radio Canada International. The graduated circles in Figures 13 (Sackville) and 14 (Tantramar) show the number of groups (out of a total of 5) who identified the particular asset at risk.

In addition to the horizontal change in flood extent, there is also the vertical component as the sea level increases. Figure 15 shows an example of how the flood level changes for a person standing at Lorne and Main St in the Sackville Town centre. The water level increases from chest to shoulder to head to well overhead for a 6 foot person. Figure 16 shows how the depth changes in the Sackville Town center between the 2000 and 2085 flood scenarios. This map shows that not only will more buildings (shown in red) be impacted by the larger flood extent but the depth of those areas flooded in (a) will be covered by an additional 80 cm under the 2085 scenario.

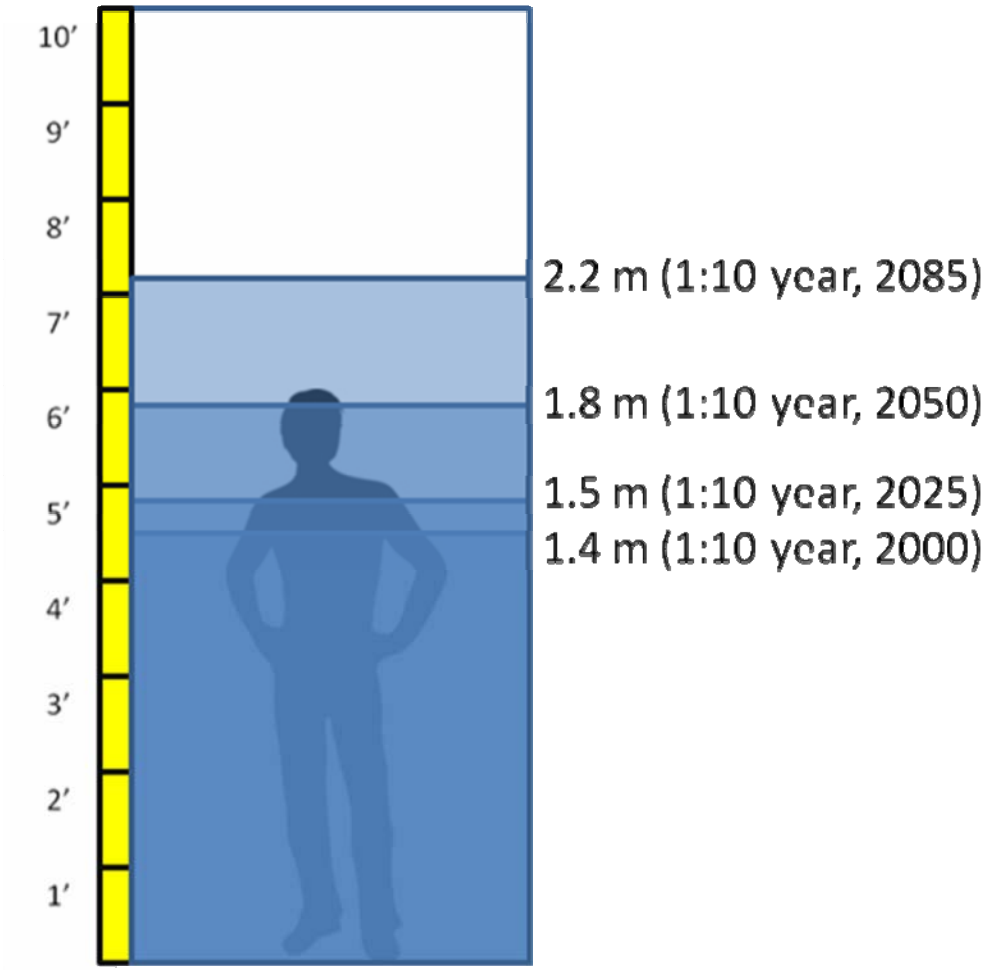

Figure 15. Visualization of water levels at the intersection of Lorne and Main Streets.

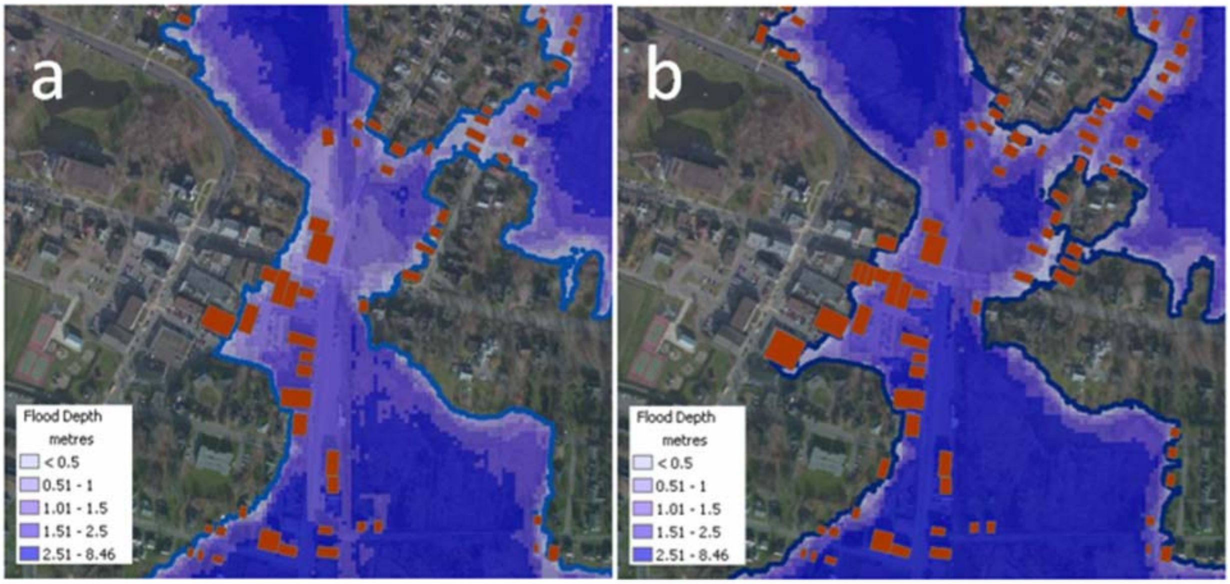

Figure 16. Comparison of water depth and extent under the 2000 (a) and 2085 (b) 1:10 year sea levels. Buildings affected are highlighted in red.

Table 5: Parcels of Land Affected by Various Flood Levels in Sackville

Zoning Category	8.9 m sea level 1:10 - 2000	9.0 m sea level 1:10 - 2025	9.3 m sea level 1:10 - 2050	9.7 m sea level 1:10 - 2085
Other	393	395	401	418
Agricultural & Conservation	218	218	219	223
Highway commercial	22	22	23	24
Institutional	15	15	16	17
Industrial	29	29	29	32
Mixed use	61	63	65	72
Residential (low-density)	259	267	284	309
Residential (mid-density)	13	13	14	14
R3 (highest-density)	5	6	8	8
Residential Historic Commercial	16	16	18	22
Rural	18	21	24	30
Total	**1049**	**1065**	**1101**	**1169**

Table 6: Buildings Affected by Various Flood Levels

Zoning Category	8.9 m sea level 1:10 - 2000	9.0 m sea level 1:10 - 2025	9.3 m sea level 1:10 - 2050	9.7 m sea level 1:10 - 2085
Other	30	33	34	38
Highway commercial	1	1	5	5
Institutional	4	4	5	6
Industrial	10	11	15	16
Mixed use	19	19	20	23
Residential (low density)	*69*	*77*	*110*	*142*
Residential (medium density)	5	5	6	8
Residential (high density)	2	2	3	5
Residential Historic Commercial	4	5	6	7
Rural	12	12	13	16
Total	**156**	**169**	**217**	**266**

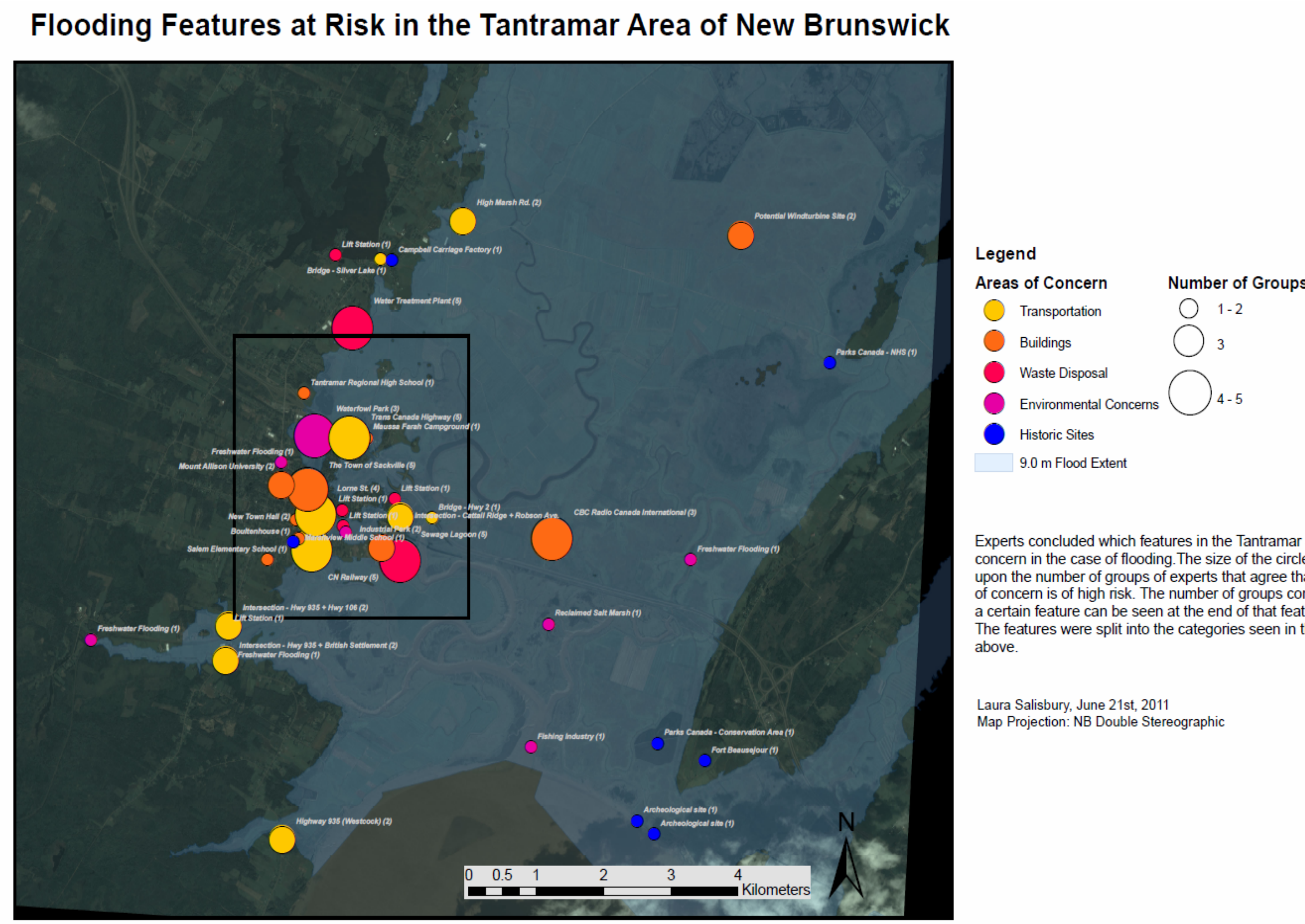

Figure 17a. Features identified as particularly at risk by the April 19, 2011 focus group (Tantramar-wide).

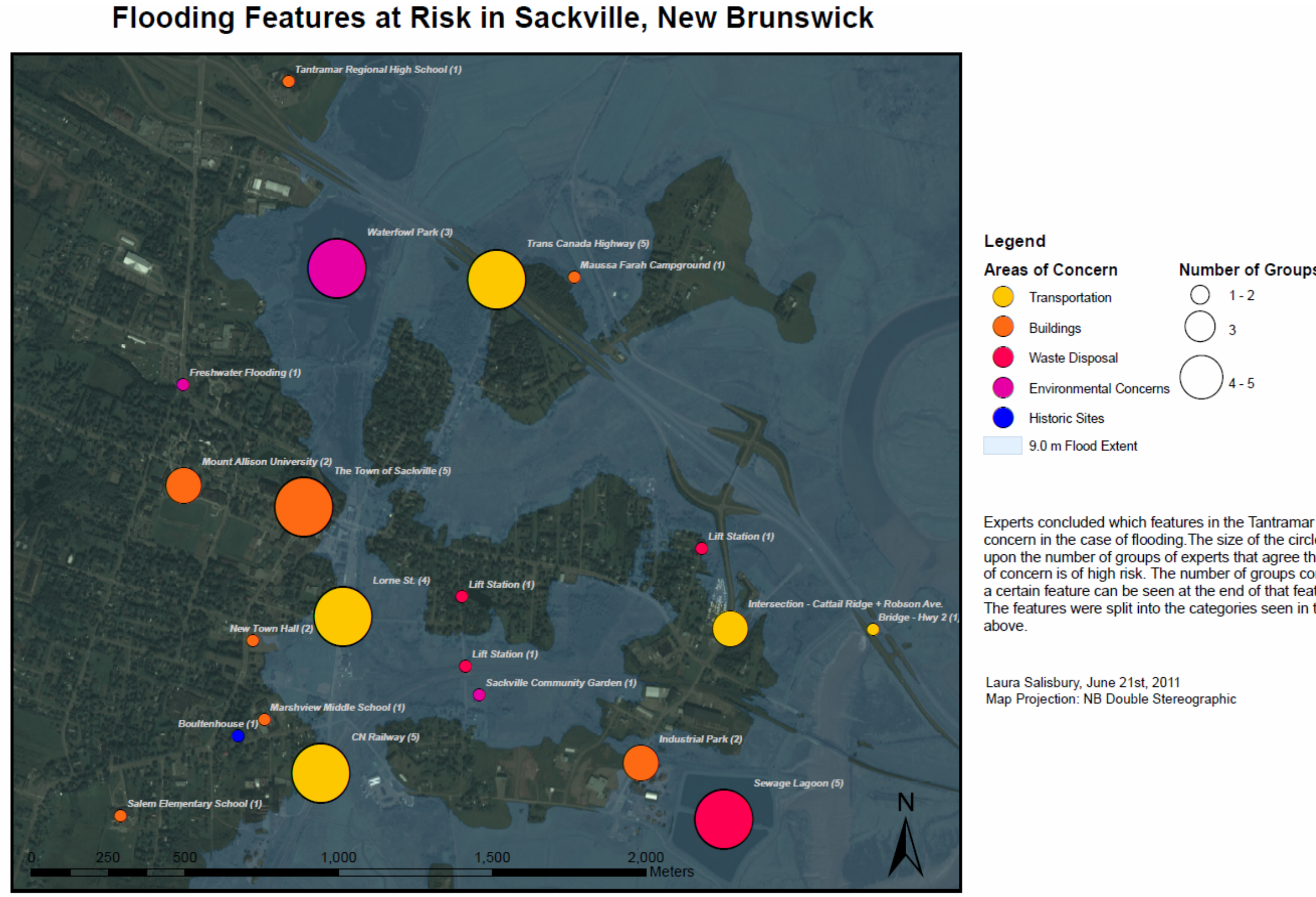

Figure 17b. Features identified as particularly at risk by the April 19, 2011 focus group (Sackville focus).

4. Discussion and recommendations

4.1 Dyke vulnerability

- The dykes are at immediate risk (as of 2000) of 8.9m coastal flooding, a scenario which would overtop 89% of our dyke system and potentially flood 20.6% of Sackville (9.19% of the entire Tantramar Planning District). The dykes were built to limit exposure from increases in sea level, but are not high enough to floodproof the region from current 1:10 year sea levels storm surges.

- Areas in need of dyke improvement can be identified by the dyke vulnerability maps (particularly Figure 10). They show where low elevations need to be built up, where vegetation could be planted to reduce erosion or actions taken to reduce immediate exposure to open water. Entire dykes need to be raised evenly over entire length to reduce overall exposure from estimated sea levels.

- Prioritization of dyke maintenance should be addressed. At a community-level, what are the most valuable assets in need of protection by the dyke system? This type of analysis was initiated in the April 19, 2011 focus group where particularly vulnerable/critical locations were identified (Figures 17a,b).

- It is unclear how to predict whether storm severity will actually overtop dykes and spread through the flood plain or be deflected and dissipated by the dykes. How long and how intense does a storm have to be to force water to the maximum extent indicated by the flat water model presented here (Figure 11)?

4.2 Assets at risk

- Key transportation corridors are impacted under all 1:10 year sea level scenarios, both within and outside of Sackville. Within Sackville, even non-flooded areas may be isolated as “islands” during a flood event. This could trap residents and pose a concern for emergency responders. With the exception of the westward portion of the TransCanada highway all major roadways exiting Sackville are cut off. It will be important that alternate routes are created to ensure that safe passage is available in and out of Sackville during a flood.

- Determining the susceptibility of property to flood damage depends on whether the focus is on parcels or buildings. Buildings appear to provide a better estimate of damage in urban areas as more capital is tied up in structures, and damage to landscaping is proportionally less important. For this reason, the number of parcels impacted by flooding can be misleading when trying to assess potential damage. In agricultural areas without built up infrastructure, permanent damage could still occur if formed lands or ditches were damaged.

- Both the vertical and horizontal extent of flooding needs to be considered in flood susceptability. While there are additional buildings and properties affected in larger floods, it must also be considered that areas in the previous flood are further under water. For example, if a 2000 flood reaches the doorstep of a house, a 2085 1:10 year flood would be 80 cm higher putting the living quarters at risk of flooding. Susceptibility can be reduced by raising the dyke system or by limiting the assets in the flood zone that could be damaged by flood.

- There appears to be systematic errors for all of the 2010 LiDAR data as well as shrub and tree land covers. The magnitude of these errors (8 cm and 15 cm, respectively) are within the expected LiDAR precision, and given the small horizontal changes in flood footprint under different flood scenarios, these errors can be considered inconsequential.

4.3 Recommendations

Due to the escalating nature of the flood risk facing the Tantramar region, both short- and long-term strategies need to be adopted. In the short term, it must be recognized that there is an immediate threat of dyke compromise and a strategy (or combination of strategies) needs to be developed that can be quickly implemented to cope with this reality. Ideally, these same strategies could also be adapted to meet longer term risk. Short-term strategies identified by the April 19, 2011 focus group include:

- Developing an emergency response plan (to improve response capacity).

- Improving the dyke system to protect against the chance of a breach, e.g., increasing the height of the dykes, vegetating exposed sections of dyke.

- Educating the public about the emergency response plan, and communicating steps they can take to protect their own property (thereby lowering risk and potential impact, and possibly improve response capacity).

Long-term strategies are also required to counter the escalating threat. Strategies identified by the focus group include:

- Building the dykes higher

- Prioritizing particular sections of dyke to protect critical assets.

- Relocating residents, businesses and infrastructure (such as the sewage treatment plant)

- Restoring salt marshes which may offer a buffering capacity against storm surges. Fully implemented this could lead to the formation of a “green corridor” and enhance regional biodiversity.

- Creating stringent regulations for buildings in vulnerable areas (e.g., such as all living quarters must be above a certain elevation) or restricting new construction outside the most vulnerable areas

In deciding which adaptation strategies to adopt, we suggest the following risk management principles: (1) define the most critical infrastructure in order to focus the development of adaptation strategies, and (2) conduct a cost benefit analysis to help determine which strategies provide the most economic, social and environmental benefits. For example, elevating the dykes to a height that would provide 100% protection against a 2085, 1:100 year sea level may be economically prohibitive given the economic assets they protect. Quickly relocating inhabitants outside of flood prone area may have immediate and significant social and cultural costs. Table 7 provides a compilation of key report findings and/or recommendations relevant to different community stakeholders.

Table 7. Summary of key report findings/recommendations relevant to different community stakeholders.

Emergency response planners	- Low lying roads will be flooded, and even when not flooded, some areas will remain as isolated "islands". - Emergency headquarters, shelters, goods and equipment should be located in areas that are accessible to as many locations as possible in the event of a flood. - Many secondary highways in Sackville will be flooded, leading to a disruption in the transportation of goods and the free movement of emergency vehicles. - There is a need for strong coordination between RCMP, CN rail, Department of Transportation, and Utilities.
Dyke managers	- Dyke system is differentially vulnerable to a combination of low elevation and erosion rates (Figure 10). - Figure 10 suggests areas in need of improvement, i.e., which are either too low, or experience an elevated erosion rate. Maps show where these factors coincide. - Protection of municipality needs to be incorporated within the broader mandate to protect agriculture and highways/railway. - Improve the aboiteaux to improve drainage during flood events.
Municipality and planning community	- Identify what the acceptable risks are. What assets should be protected at all costs? Which ones can tolerate occasional flooding? - Evaluate adaptation strategies (aided by cost benefit analysis). - Inform the public of the flood risks and candidate adaptation strategies. - Define regionally relevant best practices -- targeted at residents and agricultural producers -- to reduce the flood risk and impact.
Environmental planners	- Assess potential impact on natural areas. For example, the Tantramar Wildlife Area. How does a saline intrusion affect freshwater wetlands and impact biodiversity? - Assess potential for salt marsh restoration as a candidate adaptive strategy to buffer against the affect of storm surges.
General public	- Adopt recommended best practices to reduce the risk and impact of flooding.

5.1 Literature Cited

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