Assessing Relative Coastal Vulnerability in a Macrotidal Environment to the Increased Risk of Storm Surges due to Climate Change

By Jeremy R. Tibbetts

A Thesis Submitted to
Saint Mary's University, Halifax, Nova Scotia
in Partial Fulfillment of the Requirements for
the Degree of Master of Science in Applied Science.

April 24th, 2012, Halifax, Nova Scotia

Approved:	Dr. Danika van Proosdij, Supervisor Department of Geography
Approved:	Dominique Bérubé External Examiner NB Department of Natural Resources Geological Surveys Branch
Approved:	Dr. Don Forbes Supervisory Committee Geological Survey of Canada
Approved:	Dr. Philip Giles Supervisory Committee Department of Geography
Approved:	Dr. Jeremy Lundholm Graduate Studies Representative
Date:	April 24th, 2012

Your file Votre référence
ISBN: 978-0-494-91627-8

Our file Notre référence
ISBN: 978-0-494-91627-8

Assessing Relative Coastal Vulnerability in a Macrotidal Environment

to the Increased Risk of Storm Surges due to Climate Change

By: Jeremy R. Tibbetts

Abstract

Historically, there has always been a close relationship between Atlantic Canadians and the ocean; however, under climate change this relationship is evolving. In collaboration with the Atlantic Climate Adaptation Solutions (ACASA) project, the overall purpose of this research was to develop a tool which determines the vulnerability of a macrotidal coastal environment, such as those found in the Bay of Fundy, to the increased risk of storm surges associated with climate change, based on several physical and anthropogenic parameters.

In order to achieve the goal of developing a vulnerability assessment tool, two main objectives were defined. First, a conceptual framework was designed which outlined the variables to be used in the analysis and to illustrate the relationship among them. The variables used in this analysis are: freeboard, observed erodibility, coastal slope, width of foreshore, the presence of anthropogenic or natural protection, the presence of vegetation and coastline exposure (fetch length, dominant wind direction, and significant wave height) and morphological resilience.

Second, the guidelines set out in the framework were used to develop a custom Python programming script, within a geographic information system (GIS), in order to calculate coastal vulnerability. The analysis was performed for four coastlines, backshore, upper foreshore, middle foreshore and lower foreshore. The results of the analysis, which highlight areas of concern in regards to the risk of storm surge, allow for coastal managers and other stake holders, to make informed decisions for adaptation solutions.

April 24th, 201

Acknowledgements

I need to first thank my project supervisor, Dr. Danika van Proosdij, for providing me the opportunity to work on this project and contributing valuable ideas and insights throughout. Without her guidance, patience and expertise I would still be in the Department of Geography at Saint Mary's University growing ever more frustrated with ArcGIS. I also need to thank my committee members, Dr. Philip Giles and Dr. Don Forbes, for providing different perspectives and sources of expertise and ensuring scientific integrity. Greg Baker, from the Maritime Provinces Spatial Analysis Research Centre (MP_SpARC) located at Saint Mary's University, was instrumental in assisting with GIS analysis and programming issues. Much of this research could not have been completed without the effort of Barbara Pietersma-Perrott, who collected field data along the Cornwallis River Estuary, in the Bay of Fundy, Nova Scotia. I also need to thank Devon Olivola Eulie from the Department of Geological Sciences at East Carolina University, in North Carolina, USA, who guided me through the aches and pains of AMBUR. I would also like to thank Darrel Hingley, Ken Carroll, and members of the Applied Geomatics Research Group (AGRG) for providing data necessary to this project. I must thank Mr. Dominique Bérubé for being the external examiner of this thesis and providing his expertise and insights. Lastly, I need to thank the Atlantic Climate Adaptation Solutions Association (ACASA), and the project partners for providing this research opportunity and the necessary funding to complete it.

Table of Contents

List of Tables

Chapter 2

Chapter 3

Chapter 4

List of Figures

Chapter 1:

Chapter 2:

Chapter 3:

Chapter 1

Coastal Vulnerability Assessment in a Macrotidal Environment: An Introduction

1.0 Introduction

Communities throughout Atlantic Canada, and all over the world, are experiencing the effects of climate change, and it is assumed that these effects will increase. In Atlantic Canada, most of the human population, infrastructure and resources are found at or near the coast. In order to limit the negative effects of climate change, policy makers and managers need to understand the processes happening at the coast (Vasseur et al., 2008). The physical, economic and social relationship Atlantic Canada has with the ocean is evolving under climate change. In order to develop a foundation of information to assist community members, decision-makers, managers and all other stakeholders, throughout this evolution, the Atlantic Canadian Adaptation Solutions (ACASA) project was formed in 2009 (Atlantic Canadian Adaptation Solutions Association, 2012)

In collaboration with the ACASA project, the overall purpose of the research presented in this thesis is to develop a globally applicable tool that determines the vulnerability of a macrotidal coastal environment, to the increased risk of storm surges associated with climate change, based on several physical and anthropogenic parameters. This project aims to give communities in Atlantic Canada the necessary information to make informed decisions and policies concerning coastal management. The ACASA has four main outcomes (Atlantic Canadian Adaptation Solutions Association, 2012):

- Improve the resilience and adaptive capacity of vulnerable Atlantic coastal and inland communities.
- Build on existing knowledge and modify tools to better meet community needs.
- Mainstream climate change adaptation considerations into provincial and municipal land-use planning and development.
- Promote meaningful regional collaboration, coordination and sharing of good practices on integrating climate change into policy planning.

There have been several methods developed for assessing vulnerability to climate change-related risks (Aboudha and Woodroffe, 2010; Boruff, Emrich and Cutter, 2005; Dolan and Walker, 2003; Garmendia et al., 2010; Gornitz et al., 1994; Klein and Nicholls, 1999; McLaughlin, McKenna and Cooper, 2002; Ozyurt and Ergin, 2010; Pendleton, Thieler and Williams, 2010; Theiler and Hammar-Klose, 1999) However, none have been developed specifically for coastal environments with an extreme tide range. The need to have an assessment method which emphasizes tide elevation is due to its influence on storm surge potential. Having an assessment tool for a macrotidal environment is important to the ACASA project because many coastal communities, especially in the New Brunswick and Nova Scotia portions of the Upper Bay of Fundy, are subject to the effects of very large tides, which range up to up to 16 m in that region.

This thesis is divided into four chapters; this chapter outlines the rationale and purpose behind this research before going on to define key terminology and the objectives of this study. It is important to understand and define these concepts in order to accurately illustrate the type of vulnerability being assessed. Chapter 2 outlines the development of a conceptual model intended to illustrate the interactions of physical characteristics and processes within a macrotidal environment, and how these interactions can be used to determine coastal vulnerability. Chapter 3 details the application of the globally applicable vulnerability tool, developed within a Geographic Information System (GIS), as tested within the Cornwallis River Estuary in the Bay of Fundy, Nova Scotia, Canada. The final chapter integrates results of chapters 2 and 3, with a goal to develop recommendations for integrated coastal zone management within the study area. Chapters 2 and 3 have been written as stand-alone manuscripts formatted for publication in specific journals. Chapter 2 is to be submitted for publication to Sustainability Science while chapter 3 is to be submitted for publication to the Journal of Coastal Research.

1.1 Rationale

This study aimed to produce a globally applicable tool that determines coastal vulnerability of a macrotidal environment. Due to the objectives of the ACASA project, and the influences of climate change in this region, the Bay of Fundy is the area of interest throughout this research. Even without the influences of climate change in the Bay of Fundy, intense storm surge events have occurred and will continue to occur over time. A study by Desplanque and Mossman (1999) investigated extreme storm surges that coincided with high tides in the Bay of Fundy; these events are known as storm tides. The strongest Fundy storm tides occur every 18 years (due to the Saros cycle), when anomalistic, synodical and tropical monthly cycles align. When storms occur during this peak, significant surges can occur. Three such storms were described by Desplanque and Mossman, the most destructive being the Saxby Gale in 1869. The Saxby Gale resulted in significant flooding in the upper Bay where all the dykes were exceeded, resulting in extensive damage to infrastructure, resources, livestock and human life.

Due to the fact that storm surge threats exist, and will only continue to increase in the future with climate change, a procedure needs to be put in place that will limit these negative impacts; this is the overall goal of ACASA. However, before climate change adaptation planning can begin, analyses such as coastal vulnerability assessment must be performed. Understanding the needs of each coastal zone will allow for decision and policy makers to discuss options for the best solution.

As described previously, there have been many coastal vulnerability methods developed; however, none were designed specifically for a macrotidal environment. The important concept when developing a method for assessing macrotidal environments is the current tide elevation. Previous studies did not include tide elevation as a variable within their assessment, nor was it the most influential variable. As shown in Greenberg et al. (in press) and Desplanque and Mossman (2004), if a storm surge occurs at high tide, there is potential for a greater amount of impact on both the physical and socio-economic characteristic of the coast, than if the same surge occurs at low tide. The development of a vulnerability assessment method that not only includes current tide elevation as a variable, but emphasizes its influence on storm surge potential, is important to the ACASA project, because many communities found along the Bay of Fundy are subject to macro level tides.

1.2 Key Terminology in Coastal Vulnerability Research

1.2.1 Coastal Vulnerability

It is important to understand the types and magnitudes of potential changes that could occur within a coastal zone due to climate change. For this research, there are two main target coastal zones: backshore and foreshore. The nearshore zone has not been included in this research. The definition of these zones is found in Table 1 of chapter 3 of this thesis. In order to identify the options available to limit the impact of climate change, a coastal vulnerability assessment is conducted. However, assessing coastal vulnerability is not an easy endeavor. In combination with data collection, processing, and validation, the assessment is compounded by the confusion surrounding the multiple definitions and applications of the term 'vulnerability'. Vulnerability is specific to a given location, at a given time, to a certain group or sector (Hinkel and Klien, 2006). As the conditions change within the coastal zone, the level of vulnerability will also change. Therefore, there is no single or all-inclusive method for determining or understanding vulnerability.

This study does not assume that there is an over-arching, all-inclusive, 'correct' or 'best' definition of vulnerability that will describe all situations equally. There are many conceptualizations and definitions of vulnerability because there are many disciplines, hazards and contextual situations in climate change research (Fussel, 2007; Kasperson et al., 2005). In order to develop efficient and accurate solutions to climate change and its impacts, several disciplines need to work within a cohesive environment. Climate change researchers, planners, engineers, economists, biologist, geologists, and geographers must work together to create meaningful adaptive solutions for climate change. However, conflicting or confusing terminology within these different disciplines will cause problems and slow down the process. The initial step when assessing vulnerability in climate change research is to define vulnerability within the context of the research, along with the goals and the necessary objectives to obtain them. In the field of coastal management, this is called a 'terms of reference'.

As defined by Cutter (1996, p. 532)

> "Vulnerability is the likelihood that an individual or group will be exposed to and adversely affected by a hazard."

As defined by Turner et al. (2003, p. 8074)

> "Vulnerability is the degree to which a system, subsystem, or system component is likely to experience harm due to exposure to a hazard."

As defined in Downing and Patwardhan (2004, p. 78)

> "The degree to which a system is susceptible to, or unable to cope with, adverse effects from climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity and its adaptive capacity."

As defined by Adger (2006, p. 268)

> "Vulnerability is the state of susceptibility to harm from exposure to stresses associated with environmental and social change and from the absence of capacity to adapt."

The core concept developed from analyzing these definitions is that vulnerability is the current state of the coastline, and that state will determine the level of harm the coastline will experience from exposure to a hazard. This state or level of vulnerability does not remain constant, but will change over time. An important factor in this change of vulnerability state is the ability of the coastline to cope with the exposure to a hazard. As defined for this research, *vulnerability is the degree to which a coastline will be adversely affected by (e.g. erosion and inundation) and be unable to cope with exposure to a hazard, due to an increase in climate change events such as coastal storms*.

1.2.2 Hazard

Vulnerability can only be meaningfully understood when discussed as the 'vulnerability of a specified system to a specified hazard' (Brooks, 2003). In other words, in order to have an accurate account of vulnerability, the target coastline needs to be specified (backshore, upper, middle or lower foreshore) and a hazard or range of hazard needs to be determined. A coastal zone could be highly vulnerable to storm surge, but the same location might not be vulnerable to increased precipitation.

As defined by Brooks (2003, p.3)

> A hazard is… "A physical manifestation of climatic variability or change, such as droughts, floods, storms, episodes of heavy rainfall, long-term changes in the mean values of climatic variables, potential future shift in climatic regimes and so on."

As defined by Cardona, found in Birkman (2006, p. 462)

> "The probability of occurrence, within a specific period of time, in a given area, of a potentially damaging natural phenomenon."

As defined by the European Spatial Planning Observation Network, found in Birkman (2006, p.462).

> "A hazard is a potentially damaging physical event, phenomenon or human activity, which may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation. Hazards can be single, sequential or combined in their origin and effects. Each hazard is characterized by its location, intensity and probability."

As defined by Fussel (2006, p.6)

> "A hazard is understood as some influence that may adversely affect a valued attribute of a system. A hazard is generally but not always external to the system under consideration."

Consistent throughout the literature is that a coastal hazard is a physical event or series of events which could negatively affect the coastal zone, within a specified time period. Therefore, as defined for this research *hazard is a physical event; or series of events, such as storm surge or flooding, induced by climate change, which causes damage to a specified coastline, during a specified temporal range.* The temporal range of analysis will differ depending on the frame of reference established in the research. The main effort of this research is determining coastal vulnerability based on change in tide elevation; therefore, the temporal range is restricted to one tidal cycle and does not include synergistic effects.

1.2.3 Exposure

A coastline's vulnerability is directly related to its exposure to a hazard. The coastline's exposure to a hazard will determine the level and type of stress it receives. In other words, if the exposure to the hazard is low, the vulnerability of the coastline to that specific hazard will be low as well. For instance, a coastline characterized with protection, shallow water depth and short fetch lengths will have a less of an exposure than one with no protection, deep water depth and long fetch lengths.

As defined by Turner et al. (2003, p. 8075)

> "Exposure… the manner in which the coupled system experiences hazards."

As defined by Luers (2005, p. 217)

> "The characteristics of forces that could stress the system, (e.g. storm waves) such as magnitude and frequency."

As defined by Nicholls and Klein (2005, p. 206)

> "Exposure defines the nature and amount to which a system is exposed to climate change."

As defined by Adger (2006, p. 270)

> "Exposure is the nature and degree to which a system experiences environmental or socio-political stress. The characteristics of these stresses include their magnitude, frequency, duration and areal extent of the hazard."

In this research, *exposure* is defined as *the level of potential stress a coastline could experience from a storm surge event.* The level of exposure is related to the magnitude of the hazard (e.g., storm surge height), physical characteristics of the coastline, and most importantly, tide elevation. If the tide level is below the elevation of the coastline, exposure will be greatly reduced.

1.2.4 Risk

If a coastal zone has the potential to be exposed to a hazard or a range of hazards, the coastal zone is at risk. The following definitions were used to determine the definition of risk for this research.

As defined by Hori et al. (2002, p. 1)

> "The risk associated with flood disaster for any region is a product of both the regions exposure to a hazard (natural event) and the vulnerability of objects (system). It suggests three main contributions to a region's risk: hazard, exposure and vulnerability."

As defined by Crichton, in Brooks (2003, p. 7)

> "Risk is the probability of a loss, and this depends on a hazard, vulnerability and exposure."

As defined by Cardona, found in Birkman (2006, p. 470)

> "Risk is the potential loss to the exposed subject or system, resulting from the 'convolution' of a hazard and vulnerability".

As defined by Rashed and Weeks (2003, p.550)

> "Risk indicates the degree of potential losses … due to … exposure to hazards and can be thought of as the product of vulnerability of hazard occurrence and the degree of vulnerability."

As defined for this research, *risk is the degree of potential loss a coastal zone may experience from exposure to a hazard.* The assessment tool designed for this research illustrates the vulnerable locations, but are there sections of the coast that are more at risk than others? For example, a coastline that has valuable infrastructure and high human population will be more at risk than a coastline with no infrastructure and minimal population.

1.2.5 Resilience

As discussed previously, vulnerability reflects the degree to which a coastal zone can be negatively affected by a hazard. Resilience describes the coastline's stability and ability to return to an equilibrium state following exposure from a hazardous event. Throughout the literature, terms such as response capacity, coping capacity and resistance have been used as synonyms for resilience.

As defined by Klein and Nicholls (1999, p. 184)

> "Analysis of coastal vulnerability always starts with the notion of the natural system's susceptibility to the biogeophysical effects of sea level rise [or some other hazard event] and its natural capacity to cope with these effects."

As defined by Holling (1973) in Klein (2002, p. 16)

"A measure of the ability of [a] system to absorb changes and still persist." Pg. 16

As defined by Pimm (1984) in Klein (2002, p.16)

"The speed with which a system returns to its original state following a perturbation."

As defined by Adger (2006, p. 268)

"Resilience refers to the magnitude of a disturbance that can be absorbed before a system changes to a radically different state as well as the capacity to self-organize and the capacity for adaptation."

Resilience, for this research, is used in the sense of morphological resilience. *Morphological resilience is the ability of a coastline to return to a state of equilibrium or original form following a hazardous event.* As described by Klein et al. (1998), this type of resilience can be thought of as a measure of the ability to withstand a high degree 'potential coastal dynamics'. The ability to withstand a high degree of potential coastal dynamics would mean that the coastline would have a high morphological resiliency. For example, a gentle sloping ramped coastal feature can be subjected to large scale morphological changes, and return to an equilibrium or original state. If a cliffed feature is subjected to large morphological changes, it cannot return to an original state in its original position and therefore has a lower morphological resiliency.

1.2.6 Adaptive Capacity

The vulnerability state for a coastal zone, whether high or low, is dynamic. Adaptation measures, solutions and strategies can be put in place in order to limit the exposure a coastline could face from a hazard. Instituting such measures, reduces the risk associated with climate change hazard, and therefore reduces the system's overall vulnerability. The ability to put in place adjustments to limit the impact of climate change hazards is known as adaptive capacity.

As defined by the International Panel on Climate Change, found in Birkman (2006, p. 454)

> "The potential or ability of a system, region or community to adapt to the effects or impacts of climate change, enhancement of adaptive capacity represents a practical means of coping with changes and uncertainties in climate.
>
> The degree to which adjustments in practices, processes or structures can moderate or offset the potential for damage or take advantage of opportunities created by a given change in climate."

As defined by Fussel (2006, p. 10)

> "Ability [of a system] to adapt to long term climate change" pg. 10

As defined by Smit and Wandel (2006, p.287)

> "Adaptive capacity is similar to or closely related to a host of other commonly used concepts including adaptability, coping ability, management capacity, stability, robustness, flexibility and resilience. The forces that influence the ability of the system to adapt are the drivers or determinants of adaptive capacity."

For this research, *adaptive capacity is defined as the potential or ability a coastal zone has to adapt to climate change and its impacts.* The ability to adapt to climate change has many potential influences, including political and socio-economic conditions. Although the assessment tool designed for this research is bio-physical in focus, the socio-economic influences are not ignored. Spatial analysis within the GIS, allows for the socio-economic data (infrastructure, census information) to be compared with vulnerable locations. Assessing vulnerable populations or valuable infrastructure, located at these vulnerable locations, allows for more precise prioritization when installing climate change adaptation solutions.

1.3 Climate change within the Bay of Fundy

As described previously, this research aimed to produce a globally applicable vulnerability assessment method for macrotidal environments. Due to the objectives of the ACASA project and the influences of climate change in this region, the Bay of Fundy is the macrotidal environment of interest throughout this research. The following section aims to describe the conditions of climate change within this region, and the expected level of influence of climate change on an increase in storm surge potential. This is to further emphasize the necessity for an assessment tool, specifically designed for a macrotidal environment.

Tides in all oceans are the result of astronomical effects, such as the distance between the Moon and Earth, and influenced by non-astronomical effects, such as continental shelf width, water depth and the shape of the coastline (Desplanque and Mossman, 2001). In general, the defined limit of 'macrotidal' is when the tide range exceeds 4 m (Davies, 1980; Masselink and Short, 1993). This is best illustrated by the tides found within the Bay of Fundy, between New Brunswick and Nova Scotia. The tidal range in the head of the Bay of Fundy reaches 16 m (Desplanque and Mossman, 2001) and is therefore classified as a high or hyper-macrotidal environment (Desplanque and Mossman, 2004).

Research by Shaw et al. (1998) suggests that 67% of Canada's coastline has a low sensitivity to sea level rise. However, Atlantic Canada is a region which is susceptible to the adverse effects of sea level rise, more specifically, the upper Bay of Fundy; due to the extensive dykelands found throughout this region, characterized by significant low lying environments. A study by Greenberg et al. (in press) aimed to illustrate the change in sea and tide level in the Bay of Fundy. The analysis of long term sea level records shows that the sea and tide levels in the Bay of Fundy are rising due to a combination of climate change factors, tidal range expansion and isostatic rebound. High water in the Bay of Fundy is projected to rise to 1 m above current levels by 2100 (Greenberg et al., in press, Richards and Diagle, 2011).

As well, many studies have attributed the change in sea level to non-anthropogenic causes. Past research has shown that sea levels along the shores of Atlantic Canada have been rising throughout the late Holocene in response to isostatic crustal movements. Studies by Gehrels et al. (2004) and Donnelly (1998) indicate the depression of the lithosphere and displacement of the mantle by the Laurentide ice sheet (ice loading) in the late Pleistocene is thought to have created a peripheral forebulge. Glaciers centered in Hudson Bay caused the middle of the continent to depress, tilting up the margins out to the edge of the continental shelf (Gehrels et al., 2004 and Donnelly, 1998). The migration and collapse of the bulge following deglaciation, has resulted in uplift in regions depressed by the ice sheet and subsidence in regions near the extent of the ice sheet. The upper Bay of Fundy is one such region now experiencing subsidence.

Other studies such as Shaw, Gareau and Courtney (2002), Liverman (1994) and Grant (1970), all suggest similar reasons for submergence of Atlantic Canada and resulting sea level rise. Prior to the industrial revolution, postglacial isostatic adjustment was the main contributor to sea level rise within this region. However, since the industrial revolution, climate change and corresponding sea level rise have been accelerated due to increased greenhouse gas concentrations in the atmosphere attributed to the burning of fossil fuels and other human induced emissions; not only within in this region, but on a global scale (IPCC, 2007; van Aalst, 2006; Milly et al., 2002). Whether the climate change is attributed to natural causes, or human induced global warming, the end result is the same and adaptation strategies need to be put in place in order to help resolve any potential issues.

A storm surge is an observed rise in sea level, differing from predicted (astronomical) tide elevation, associated with a coastal storm event. A direct result of sea level rise is more frequent coastal flooding events, in relation to existing coastal features and structures. Sea level rise increases the risks associated with storm surges because, over time, current adaptation measure, such as dykes, will become ineffective in protecting the coast. From the Canadian perspective, storm surges occur primarily on the Atlantic coast, but have occurred on all three. In many cases, it is the storm surge that causes the greatest amount of destruction, rather than winds and precipitation from a coastal storm event (Danard, Munro and Murty, 2003).

The majority of storm surges occur in association with high winds and waves and the surges raise the level of wave attack against the shore. Although risks and magnitude of a storm surge is dependent on the characteristics of the storm, generally tropical storms tend to have larger storm surges than extra-tropical (von Scortch and Woth, 2008). The impact of storm surges is highly dependent on the current tidal state. Tides are the driving force of many coastal processes and are therefore important when attempting to analyze vulnerability in the coastal zone. The tidal state, whether the water level is high or low tide, will have an impact on the effect of a storm surge. A storm surge that occurs at high tide, will be a much more severe event than a storm surge that occurs when the tide low (Greenberg et al., in press; Hinton, 2000). As shown in Greenberg et al. (in press), and Desplanque and Mossman (2004) the risk of flooding, along the Bay of Fundy, increases when storm surges occur within 1 to 2 hours of a high tide. In the upper Bay of Fundy, the difference in height between a storm surge that coincides with a high tide instead of a mean tide is 2.1 m (Greenberg et al., in press). Having a solid understanding of this is important for this research. The level of coastal vulnerability, especially to storm surges, will decrease when the tide level is low, and increase when the tide level is high. Therefore, this variable must not only be included when designing a coastal vulnerability tool for a macrotidal environment, but also be the most heavily weighted. Coastal vulnerability assessment strategies, prior to this research, have not included the current tidal level when determining vulnerability for a coastal area.

1.4 Purpose and Objectives

The level of vulnerability to storm surge, will decrease and increase with changing tidal state. This tidal influence on vulnerability is enhanced with the unique tidal range of the Bay of Fundy. Due to this tidal range, along with other macrotidal environments, a coastal vulnerability assessment tool needs to be designed specifically for the Bay of Fundy. In order to achieve this, the following objectives must be met.

1) Construct a conceptual model to show relationships between variables and processes that help determine coastal vulnerability in the Bay of Fundy. Developing a conceptual model will help determine the variables which are most useful for calculating coastal vulnerability and the relationship between these variables.
2) Design a digital assessment tool, within a GIS platform, which determines coastal vulnerability within a macrotidal environment based on the analysis and framework developed through the conceptual model.
3) Validate the model by using coastal erosion analysis determined by Analysis Moving Boundaries Using R (AMBUR) software package, along with locations of known flooding.
4) Develop recommendations for integrated coastal zone management within the study area, based on the results from the previous objectives.

1.5 Study Area

The tool developed in this research has been designed to assess vulnerability within any macrotidal environment. The ACASA project has selected several coastal communities around the Bay of Fundy, for which adaptation solutions will be developed. One such location is the main focus point of this research, the Cornwallis River Estuary (Figure 1.1), situated between the communities of Wolfville and Kingsport, which will be used to test the applicability of the assessment tool.

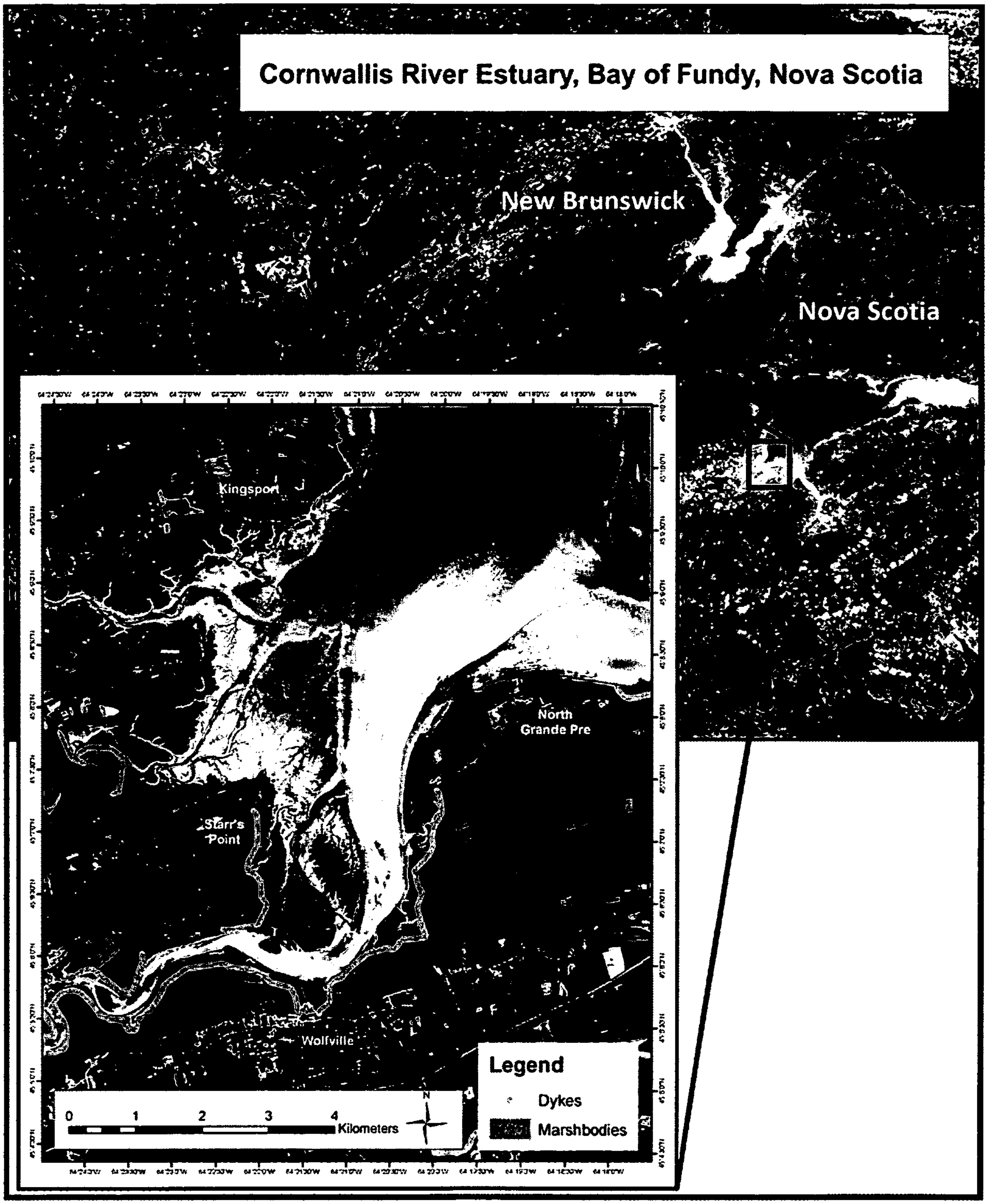


Figure 1.1 - The Cornwallis River Estuary, in the Bay of Fundy, Nova Scotia, Canada. Satellite imagery, taken in 2008 with Quick bird, was processed and ortho-rectified by the Maritime Provinces Spatial Analysis Centre, Saint Mary's University, Halifax, Nova Scotia.

1.6 Methodological Overview

In order to successfully complete the objectives set out for this research, the following methodologies were adopted.

1.6.1 Objective 1 – Chapter 2

Through the process of a literature review, a conceptual model will be designed to show relationships between variables and processes that help determine coastal vulnerability in a macrotidal environment. Developing a conceptual model will help determine the variables which are most useful for calculating coastal vulnerability and the relationship between these variables.

1) Determine which variables or parameters to use in the coastal vulnerability analysis.
2) Design a conceptual framework, illustrating the relationships and interactions of variables used to determine coastal vulnerability in a macrotidal environment.

1.6.2 Objective 2 – Chapter 3

Design a digital assessment tool using a GIS (ArcGIS 9.3) which determines coastal vulnerability within a macrotidal environment based on the analysis and framework developed through the conceptual model.

1) Collect data for each variable and design a coastal vulnerability matrix for the study area.
2) Apply an appropriate weighting scheme to ensure a more accurate evaluation of coastal vulnerability.

3) Design a digital tool, using python scripting and the ArcGIS 9.3 tool set, which determines vulnerability.

1.6.3 Objective 3 – Chapter 3

Validate the assessment tool by comparing the results with observed locations of concern and historical erosion analysis.

1) Observations in the field have shown that locations of the backshore coastline are prone to both flooding and erosion. A comparison will be made between the results of the assessment tool and these locations of concern.
2) In order to assess the results within the foreshore, coastal erosion rates for the study area, calculated using the Analysis Moving Boundaries Using R (AMBUR) software package, will be compared to the results of the tool.
3) If locations are similar between known and predicted locations, the model will be determined as valid.

1.6.4 Objective 4 – Chapter 4

The results of objective 1 and 2 will be integrated and used to develop recommendations for integrated coastal zone management within the Cornwallis River Estuary, Nova Scotia, Canada. The following section describes two international examples of measurements taken to develop climate change adaptation solutions. The experiences and recommendations illustrated in these examples will be incorporated into the climate change adaptation recommendations for this research.

United Kingdom – England

Due to the increasing influences of climate change, the geology, wave action and the number of industrial, commercial and socio-economic activities along England's coast, the government has put forth guidelines for coastal development. During the 1990s, shoreline management plans (SMPs) were produced for England and Wales. Almost 40 SMPs were designed and these documents divided coastal management into units based on geomorphological, sedimentological and land-use criteria. Within these divisions, one of four strategic plans would be implemented (Bray, Hooke and Carter, 1996; De La Vega-Leinert and Nicholls, 2008):

1. Do nothing - Let current defences stay, and eventually fail.
2. Retreat the line - Build new defences further inland.
3. Hold the line - Maintain current defences
4. Advance the line - Construct new defences seaward of current structures.

Other programs, such as the Estuary Management Plan (EMPs) and the Coastal Zone Management Plan (CZMPs) are documents that act as guidelines for coastal management. However, in the past decade, the Department for Environment, Food and Rural Affairs, (DEFRA), has produced several documents that suggest, if economically viable and strategically correct, the policy of managed realignment should be adopted (DEFRA, 2009; DEFRA, 2005; DEFRA 2003; De La Vega-Leinert and Nicholls, 2008).

Managed realignment is the readjustment of existing coastal defences to a new defence line, often set back from the existing position (DEFRA, 2005; De La Vega-Leinert and Nicholls, 2008). As well, managed realignment encourages a shift from the use of 'hard' structural defences (sea wall, gryone), to 'soft' engineering practices (beach nourishment). This shift was due to the realization that natural processes play a fundamental role in coastal defence. Managed realignment allows for these natural processes to occur (erosion/accretion, wetland maintenance/restoration) and provides a level of certainty in regards to control and establishing long term sustainability. Long term sustainability is established and maintained by having the new defence 'set back' from the previous, allowing for a buffer. The setback distance would depend on a number of factors, including erosion rates, rate of sea level rise, storm surge and flooding prediction.

United States – Louisiana

Within continental US, one major examples of coastal management, comes in the wake of one of the worst disasters in recent history. In August of 2005, hurricane Katrina hit the shores of Louisiana, causing storm surge and large volumes of water to crash against the levees, eventually leading to their failure (Knabb, Rhome and Brown, 2005; Lopez, 2006). What has been titled, Integrated Ecosystem Restoration and Hurricane Protection: Louisiana's comprehensive Master Plan for a Sustainable Coast, Baton Rouge, is a coordinating effort of local, state and federal agencies aimed at long term and comprehensive coastal protection based on the most accurate and reliable science and engineering. The Coastal Protection and Restoration Authority (CPRA), aimed to integrate activities, organizations and disciplines in order for long term success to be attainable (CPRA, Executive Summary, 2007).

In an effort to limit the impact of climate change, CPRA has outlined two broad initiatives. Traditional land-use patterns in Louisiana have disrupted natural processes occurring at the coast. The community has built levees and canals to re-direct water flows and has drained the wetlands. The main purpose behind these practices was to increase the land available for development. However, the outcome is a coastal area that is highly unstable with a large population at risk. CPRA recognizes this is a major issue and controlling land use development in areas at risk is the most appropriate solution. Along with implementing meaningful zoning regulations, the CPRA has called for improvements in building codes for new construction and retrofitting older buildings, in order to withstand hurricane force winds (CPRA, Chapter 3, 2007).

The second broad initiative has suggested implementing several lines of defence for protection against hurricanes and flooding. There is an emphasis on using natural features, such as marshlands and barrier islands, to complement manmade structures, such as levees and flood gates (CPRA, Chapter 3, 2007; Lopez 2006). Recent studies have shown that natural features at the coast are able to dissipate wave energy and could limit the impact of climate change, sea level rise and storm surges (Morton, 2003). The understanding has led to the resurgence of wetland restoration along Louisiana's coast and incorporation of natural features into the CPRA coastal protection policy. The use of multiple protection measures allows the most vulnerable areas to be secure and protected even in the worst predictable conditions. Protection and restoration methods must work together in combination with land use and zoning regulations for the management policy to be effective.

1.7 Limitations

The level of vulnerability calculated through the assessment method generated by this research is for ice-free conditions. Historically, the Bay of Fundy is has been prone to ice conditions for several months during the year. The decision to exclude ice within the analysis was made early in the research and for three main reasons. First, coastal storm events and storm surges occur most frequently in the late summer and early fall when water temperatures are highest in this region. Second, the assumption was made that the presence of ice would only dampen energy (e.g. limiting wind fetch or absorbing wave energy) and therefore would lower vulnerability. Lastly, although the Bay of Fundy has been prone to ice conditions in the past, there has been a lack of significant ice coverage in recent years, and it is likely that this will continue with increasing ocean temperatures.

As well, there is a temporal limitation accuracy of the data collected for this research. The physical characteristics of each coastline will change over time (for example, a stable coastline could become unstable) therefore the database used to design the assessment tool will need to be updated periodically to ensure accuracy. Along with periodically updating the database which contains the physical characteristics of each coastline, the changes would need to be applied to the Python code of the assessment tool; however, these changes would be minor.

1.8 Literature Cited

Abuodha, P.A.O. and Woodroffe, C.D., 2010. Assessing vulnerability to sea level rise using a coastal sensitivity index: A case study from Southeast Australia. *Journal of Coastal Conservation*, 14, 189-205.

Atlantic Canadian Adaptation Solutions Association, 2012. Nova Scotia Protjects. URL: http://atlanticadaptation.ca/acasa/ns_projects; accessed on March 20, 2012.

Adger, W.N., 2006. Vulnerability. *Global Environmental Change*, 16(3), 268-281.

Birkmann, J., 2006. Measuring vulnerability to promote disaster-resilient societies: Conceptual frameworks and definitions, *In*: Birkmann, J. (ed.), Measuring Vulnerability to Natural Hazards: towards disaster resilient societies. United Nations University Press, Tokyo, 9-54.

Boruff, B.J.; Emrich, C, and Cutter, S,L., 2005. Erosion hazard vulnerability of US coastal counties. *Journal of Coastal Research,* 21(5), 932-94.

Bray, M. J.; Hooke, J. M., and Carter, D., 1997. Planning for sea-level rise on the South Coast of England: Advising the decision-makers. *Transactions of the Institute of British Geographers*. New Series, 22(1), pp. 13-30.

Brooks, N., 2003.Vulnerability, risk and adaptation: A conceptual framework. Working Paper 38. Tyndall Centre for Climate Change Research, Norwich, UK. URL: http://tyndall.ac.uk/sites/default/files/wp38.pdf; accessed on July 26, 2011

Coastal Protection and Restoration Authority (CPRA), 2007. Integrated ecosystem restoration and hurricane protection: Louisiana's comprehensive master plan for a sustainable coast, Baton Rouge. URL: http://coastal.louisiana.gov/index.cfm?md=pagebuilder&tmp=home&nid=24&pnid=0&pid=28&fmid=0&catid=0&elid=0; accessed on January 15, 2011.

Cutter, S.L., 1996. Vulnerability to environmental hazards. *Progress in Human Geography*, *20*(4), 529-539.

Danard, M.; Munro, A., and Murty, T., 2003. Storm surge hazard in Canada. *Natural Hazards*, 28, 407-431.

Davies, J.L., 1980. *Geographical variation in coastal development.* 2nd Edition. London: Longmans. pp.212

De La Vega-Leinert, A.C. and Nicholls, R.J., 2008. Potential implications of sea level rise for Great Britain. *Journal of Coastal Research*, 24(2), 342 – 357.

Department for Environment, Food and Rural Affairs, (DEFRA), 2009. Flood and water management act. URL: http://www.defra.gov.uk/environment/flooding/policy/fwmb/; accessed on January 15, 2011.

Department for Environment, Food and Rural Affairs, (2005) Making space for water. Taking forward a new government strategy for flood and coastal erosion risk management in England. URL: http://www.defra.gov.uk/environment/flooding/policy/strategy/; accessed on January 15, 2011.

Department for Environment, Food and Rural Affairs, 2003. Managed realignment: Land purchase compensation and payment for alternative beneficial land use. URL: http://www.defra.gov.uk/environment/flooding/policy/guidance/realign.htm; assessed on January 15, 2011.

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

Desplanque, C. and Mossman, D., 2001. Bay of Fundy tides. *Geoscience Canada.* 25(1), 1-11.

Desplanque, C. and Mossman, D., 1999. Storm tides of the Fundy. *The Geographical Review*, 89(1), 23-33.

Dolan, A.H., and Walker, I.J., 2003. Understanding vulnerability of coastal communities to climate change related risks. Journal of Coastal Research, SI 39 (Proceedings of the 8th International Coastal Symposium), Itajaí, SC – Brazil, ISSN 0749-0208

Donnelly, J.P., 1998. Evidence of late Holocene post-glacial isostatic adjustment in coastal wetland deposits of Eastern North America. *GeoResearch Forum*, 3-4, 393-400.

Downing, T. E. and Patwardhan, A., 2004. Assessing vulnerability for climate adaptation. *In*: Lim, B., and Spanger-Siegfried, E. (eds.), *Adaptation Policy Frameworks for Climate Change: Developing Strategies, Policies, and Measures.* Cambridge: Cambridge University Press,, 67-90.

Fussel, H.M., and Klein, R.J.T., 2006. Climate change vulnerability assessments: an evolution of conceptual thinking. *Climatic Change*, 75, 301-329.

Fussel, H.M., (2007). Vulnerability: A generally applicable conceptual framework for climate change research. *Global Environmental Change*, 17, 155 – 167.

Garmendia, E.; Gamboa, G.; Franco, J.; Garmendia, J.; Liria, P., and Olazabal, M., 2010. Social multi-criteria evaluation as a decision support tool for integrated coastal zone management. *Ocean & Coastal Management*, 53, 385-403.

Gehrels, R.W.; Milne, G.A.; Kirby, J.R.; Patterson, R.T., and Belknap, D.R., 2004. Late Holocene sea-level changes and isostatic crustal movements in Atlantic Canada. *Quaternary International*, 120, 79-89.

Gornitz, V.M.; Daniels, R.C.; White, T.W., and Birdwell, K.R., 1994. The development of a coastal risk Assessment database: Vulnerability to sea-level rise in the U.S. Southeast. *Journal of Coastal Research*, 12, 327-338.

Grant, D.R., 1970. Recent coastal submergence of the Maritime Provinces, Canada. *Canadian Journal of Earth Sciences*, 7, 676-689.

Greenberg, D.A.; Blanchard, W.; Smith, B., and Barrow, E., in press. Climate change, mean sea level and high tides in the Bay of Fundy. Bedford Institute of Oceanography.

Hinkel, J. and Klein, R.J.T., 2006. Integrating knowledge for assessing coastal vulnerability to climate change. *In:* McFadden, L., Nicholls, R.J. and Penning-Rowsell, E.C. (eds.) *Managing coastal vulnerability: An integrated approach* Elservier Science, Amsterdam, The Netherlands. URL: http://www.pik-potsdam.de/research/transdisciplinary-concepts-and-methods/projects/project-archive/favaia/pubs/hinkel_klein_2006.pdf; accessed on March 21, 2012.

Hinton, A.C., 2000. Tidal changes and coastal hazards: Past, present and future. *Natural Hazards*, 21, 173-184.

Hori, T.; Zhang, J.; Tatano, H.; Okada, N., and Likebuchi, S., 2002. Micro-zonation-based flood risk assessment in urbanized floodplain. Second Annual IIASA-DPRI Meeting Integrated Disaster Risk Management Megacity Vulnerability and Resilience. Laxenburg, Austria, 29-31 July, 2002. URL: http://www.iiasa.ac.at/Research/RMS/dpri2002/Papers/hori.pdf; accessed on March, 18 2012.

Intergovernmental Panel on climate Change, 2007. Climate Change 2007: Synthesis Report, Summary for Policy Makers. URL: http://www.ipcc.ch/publications_and_data/ar4/syr/en/spm.html; accessed on January 20, 2011.

Kasperson, J.X., Kasperson, R.E., Turner II, B.L., Schiller, A., Wen-hua, H., (2005). Vulnerability to global environmental change. *In:* Kasperson, J.X., Kasperson, R.E. (Eds.), *Social Contours of Risk.* Earthscan, London, 245–285.

Klein, R.J.T., 2002. Coastal vulnerability, resilience and adaptation to climate change: An Interdisciplinary Perspective. Germany: Christian-Albrechts-Universität zu Kiel, Ph.D. thesis, 133p. URL: http://www.oceandocs.net/bitstream/1834/789/1/Klein.pdf ; accessed on, March 21, 2012.

Klein, R.J.T, and Nicholls, R.J., 1999. Assessment of coastal vulnerability to climate change. . *Ambio*, 28(2), 182-187.

Klein, R.J.T.; Smit, M.J.; Goosen, H. and Hulsbergen, C.H., 1998. Resilience and Vulnerability: Coastal Dynamics or Dutch Dikes? *The Geographical Journal*, 164(3), 259-268.

Knabb, R.D.; Rhome, J.R., and Brown, D.P., 2005. Tropical cyclone report: Hurricane Katrina, 23 – 30, August 2005. *Rep. of the National Oceanic and Atmospheric Administration* National *Hurricane Center*. URL: http://www.nhc.noaa.gov/pdf/TCR-AL122005_Katrina.pdf; accessed January 25, 2011.

Liverman, D.G.E., 1994. Relative sea level rise and isostatic rebound in Newfoundland, Canada. *Boreas*, 33, 217-230.

Lopez, J., 2006. The multiple lines of defence strategy to sustain coastal Louisiana. New Orleans, LA: Lake Pontchartrain Basin Foundation.

Luers, A.L., 2005. The surface of vulnerability: An analytical framework for examining environmental change. *Global Environmental Change*, 15, 214-223.

Masselink, G. and Short, A.D., 1993. The effect of tide range on beach morphodynamics and morphology: A conceptual beach model. *Journal of Coastal Research,* 9(3), 785-800.

McLaughlin, S., McKenna, J., Cooper, J.A.G., 2002. Socio-economic data in coastal vulnerability indices: Constraints and opportunities. *Journal of Coastal Research*, 36, 487 – 497.

Milly, P.C.D.; Wetherald, R.T.; Dunne, K.A., and Delworth, T.L., 2002. Increasing risk of great floods in a changing climate. *Nature*, 415, 514-517.

Morton, R.A., 2003. Factors controlling storm impacts on coastal barriers and beaches: A preliminary basis for near real-time forecasting. *Journal of Coastal Research,* 18 (3), 486-50.

Nicholls, R.J, and Klein, R.J.T., 2005. Climate change and coastal management on Europe's coast. *In:* Vermaat, J.E., Bouwer, L., Turner, K., Salomons, W., (eds.). *Managing European Coasts: Past, Present, and Future*, Springer: 1 edition pp.199 -225.

Ozyurt, G. and Ergin, A., 2010. Improving coastal vulnerability assessments to sea-level rise: A new indicator based methodology for decision makers. *Journal of Coastal Research,* 26(2), 265-273.

Pendleton, E.A.; Thieler, E.R., and Williams, S.J., 2010. Importance of coastal change variables in determining vulnerability to sea- and lake-level change. *Journal of Coastal Research,* 26(1), 176-183.

Rashed, T. and Weeks, J., 2003. Assessing social vulnerability to earthquake hazards through spatial multicriteria analysis of urban areas. *International Journal of Geographic Information Science*, 17(6), 549-576.

Richards, W. and Daigle, R., 2011. Scenarios and Guidance for Adaptation to Climate Change and Sea Level Rise – NS and PEI Municipalities. URL: www.atlanticadapation.ca; assessed on April, 27, 2011.

Shaw , J.; Gareau, P. and Courtney, R. C., 2002. Paleogeography of Atlantic Canada 13–0 kyr. *Quaternary Science Review,* 21, 1861-1878.

Shaw, J.; Taylor, R.B.; Solomon, S., and Christian, H.A., 1998. Potential impacts of global sea level rise on Canadian coasts. *The Canadian Geographer*, 42(4), 365-379.

Smit, B. and Wandel, J., 2006. Adaptation, adaptive capacity and vulnerability. *Global Environmental Change*, 16, 282-292.

Thieler, E.R., and Hammar-Klose, E.S., 1999, National assessment of coastal vulnerability to future sea-level rise: Preliminary results for the U.S. Atlantic Coast: U.S. Geological Survey, Open-File Report 99-593. URL: http://woodshole.er.usgs.gov/project-pages/cvi/; accessed on March 20, 2011.

Turner, B.L.; Kasperson, R.E.; Matson, P.A.; McCarthy, J.J.; Corell, R.W.; Christensen, L., Eckley, N.; Kasperson, J.X.; Luers, A.; Martello, M.L.; Polsky, C.; Pulsipher, A., and Schiller,A., 2003. A framework for vulnerability analysis in sustainability science. Proceedings of the National Academy of Sciences 100, 8074-8079. URL: http://www.pnas.org/content/100/14/8074.full.pdf; accessed March 20, 2012

Van Aalst, M.K., 2006. The impacts of climate change on the risk of natural disasters. *Disasters*, 30, 5-18.

Vasseur, L.; Catto, N.; Burton, D.; Chouinard, O.; Davies, J.; DeBaie, L.; Duclos, G.; Duinker, P.; Forbes, D.; Hermanutz, L.; Jacobs, J.; Leger, L.; McKenzie, K.; Parlee, K., and Straatman, J., 2008. "Atlantic Canada" *In:* Lemmen, D.S., Warren, F.J., Lacroix, J. and Bush, E. (eds.), *From impacts to adaptation: Canada in a changing climate 2007*, Government of Canada, pp. 119-170.

Von Scortch, H., and Woth, K., 2008. Storm Surges: Perspectives and Options. *Sustainability Science*, 3, 33-43.

Chapter 2

Conceptual Framework for Assessing Vulnerability in a Macrotidal Environment

Paper to be submitted to Sustainability Science

2.0 Introduction

Most coastal environments around the world are experiencing the relative effects of climate change. Coastal communities throughout Atlantic Canada are also feeling the impact of climate change and it is believed that these effects will increase. In order to limit the negative effects of climate change, policy makers and mangers need to understand the process happening at the coast (Vasseur et al., 2008). Determining vulnerable locations, allows for proper implementation of long term policy, such as restriction of construction in vulnerable areas, and short term policy, such as the dissemination of resources during an emergency. The Atlantic Climate Adaptation Solutions Association (ACASA) project was formed in 2009 to develop a foundation of information to assist policy makers and managers in adapting to climate change (Atlantic Canadian Adaptation Solutions Association, 2012).

In coordination with the goals outlined by the ACASA project, the overall purpose of this research is to develop a globally applicable tool, within a geographic information system (GIS) that determines the vulnerability of a macrotidal coastal environment to the increased risk of storm surges associated with climate change, based on several physical and anthropogenic parameters. There have been several methods for assessing vulnerability developed (Aboudha and Woodroffe, 2010; Boruff, Emrich, and Cutter, 2005; Dolan and Walker, 2003; Garmendia et al., 2010; Gornitz et al., 1994; Klein and Nicholls, 1999; Ozyurt and Ergin, 2010; Pendleton, Thieler, and Williams, 2010; McLaughlin, McKenna and Cooper 2002; Theiler and Hammar-Klose, 1999); however, none have been developed specifically for coastal environments with an extreme tide range. The ACASA project provides an opportunity to test the tool within the Bay of Fundy, which has one of the highest tides in the world.

Tides in all oceans are generated by astronomical effects, such as the distance between the moon and Earth, and non-astronomical effects, such as continental shelf width, water depth and the shape of the coastline (Desplanque and Mossman, 2001). This is best illustrated by the tides found within the Bay of Fundy, between New Brunswick and Nova Scotia. The tidal range in the head of the Bay of Fundy reaches 16 m, even without extreme atmospheric influences (Desplanque and Mossman, 2001).

Even without the influences of climate change in the Bay of Fundy, intense storm surge events have and will continue to occur over time. A study by Desplanque and Mossman (1999) investigated extreme storm surges that coincided with high tides in the Bay of Fundy. The strongest Fundy storm tides occur every 18 years (due to the Saros cycle), when lunar, anomalistic, synodical and tropical monthly cycles align. When storms occur during this peak, significant storm surges can occur. Three such storms were described by Desplanque and Mossman, the most destructive being the Saxby Gale in 1869. The Saxby Gale resulted in significant flooding in the upper Bay where all the dykes were exceeded, resulting in extensive damage to infrastructure, resources, livestock and human life.

The purpose of this paper is to develop a conceptual framework in order to show the relationships between the variables and processes which help determine coastal vulnerability in a macrotidal environment, such as the Bay of Fundy. Prior to developing the tool to calculate coastal vulnerability, there needs to be firm understanding on which variables to use and how these variables work together. This paper first considers the various types of vulnerability assessments, in order to determine which method is best for a macrotidal environment. After outlining the variables used within the conceptual framework, the framework itself is introduced and discussed.

2.1 Types of Vulnerability Assessments

There are a variety of variables that can be used to predict vulnerability of a coastline. It is assumed by some that with a greater number of variables, the accuracy of prediction will increase. However, as more variables are included in the model, the complexity and possibly the source of error increases (Capobianco et al., 1999; Cooper and McLaughlin, 1998); therefore, it is more advantageous to choose a smaller number of more influential determinants. A review of the literature has shown three different methods or schools of thought for determining which variables to use when assessing coastal vulnerability.

The earliest studies to evaluate coastal vulnerability used a biophysical assessment method to uncover their conclusions. Assessments that have a biophysical focus define vulnerability in terms of exposure to a hazardous event, regardless of social conditions within the coastal zone. Furthermore, how this exposure affects the coastal zone is based on its physical attributes or characteristics (Dolan and Walker, 2006). Gornitz et al.

(1994) published one of the earliest studies and used only physical/marine and climatological variables to uncover coastal vulnerability. Other early studies such as Shaw (1998) and Thieler and Hammar-Klose (1999) also used physical variables to evaluate coastal vulnerability. Some more recent studies have also used primarily physical variables in their assessments. Studies by Ozyurt and Ergin (2010) and Pendleton, Jeffress and Theiler (2004) are examples of this. However, physical assessments do not address possible socio-economic conditions that would affect the overall vulnerability.

There have been other studies that suggest vulnerability is a social construct and is not related to exposure from a physical hazard or event (Dolan and Walker, 2006). Studies by Boruff, Emrish and Cutter (2005), Cutter (1996), Garmendia et al. (2010), Kelly and Adger (2000) and McLaughlin, McKenna and Cooper (2002) investigated coastal vulnerability based on socio-economic variables. This type of vulnerability assessment is influenced by social conditions that put communities at risk to climate change related events (Dolan and Walker, 2006; Wu, Yarnai and Fisher. 2002). Therefore the cause of social vulnerability (e.g.. poverty), is the focus within those studies and not the hazard itself.

The final method for determining vulnerability attempts to marry both the physical event with the causes of social vulnerability. For example, Wu, Yarnai and Fisher (2002) used a GIS-based assessment method to address physical vulnerability to flood hazards under sea level rise and increased storm intensities. The study also assessed social vulnerability at the community scale based on attributes such as age, gender, race and income. Integrated assessments combine physical and social vulnerabilities to create an overall vulnerability for the study area. Studies by Dolan and Walker (2003), Sterr, Klein and Reese (2000) and Wu, Yarnai and Fisher (2002) and others use an integrated assessment method that includes both physical and socio-economic variables.

This research is primarily biophysical in focus but does not ignore the social aspect of vulnerability within the coastal zone. However, this is not a truly integrated assessment, and could potentially be interpreted as a 'modified integrated assessment' method. Instead of designing a vulnerability assessment tool that integrates physical and social aspects, potentially increasing complexity and increases in data compatibility issues, this research evaluates coastal vulnerability purely based on physical attributes of the coastline and then uses GIS-based analysis to infer adaptation response for the community based on that vulnerability. As the conceptual model described in this paper illustrates, the response to vulnerability (i.e. adaptation solutions such as dykes or barriers to inundation) will influence the overall vulnerability via feedback loops, but it is not included in the initial vulnerability assessment method.

2.2 Vulnerability Assessment Variables

The following section outlines the qualitative selection of the variables used to calculate coastal vulnerability within a macrotidal environment for this research. The idea here is to not only describe each variable, but understand why it was chosen for this analysis. A summary of the variables chosen for this research is found in Table 1.

2.2.1 Freeboard

Within a macrotidal environment, one of the most influential characteristics, when determining coastal vulnerability, is tide elevation. Tide elevation will impact the severity of a storm surge on the backshore coastline; a storm surge is a sudden rise in sea level, associated with a coastal storm event. Due to an increase in wind speeds provided by the storm, waves are able to become much larger and have more energy associated with them than normal. If a storm surge hits at high tide, a surge could cause a dramatic negative impact on the coastline; however, the same storm surge at low tide could be harmless. A simple simulation of this is found in Figure 2.1.

Storm surge at high verses low tide

Figure 2.1 – A simple diagram to show the impact of storm surge is dependent on the level of the tide. A storm surge that occurs at high tide has a greater chance of causing inundation and damage, while the same storm surge at low tide could cause very little impact.

Therefore it is essential to include the tide elevation when trying to measure the vulnerability to storm surges in a macrotidal environment. The importance of tide elevation is addressed by the variable freeboard. Freeboard is the height of the coastline (either backshore, upper, middle or lower foreshore) above the total water level (tide elevation plus storm surge). This elevation relates to the top of dyke, top of cliff, top of slope or some other coastline feature. If the coastline elevation is above the total water level, then there is limited vulnerability because the storm surge will not be overtopping the coastline; alternatively, if the coastline elevation is below the total water level there will be overtopping.

It is interesting to note that a macrotidal environment has been determined as being less vulnerable than a microtidal environment (Aboudha and Woodroffe, 2010; Pendleton, Jeffress and Theiler, 2004; Theiler and Hammar-Klose, 1999). This is because on a macrotidal coastline, there is only a small chance of the storm surge occurring at high tide. For a microtidal coastline, the range is significantly less, and the effect of high and low tide would remain similar. However, as explained by Desplanque and Mossman (2001), although the probability of a storm surge coinciding with a high tide within a macrotidal environment is low, severe consequences can ensure if and when such a coincides occurs.

2.2.2 Coastline Exposure

Coastline exposure is concerned with how the shore is exposed to wave energy; exposure to less or more energy will influence the overall vulnerability. If the shore is highly exposed to waves, it is considered more vulnerable than one that is less exposed. Exposure is determined by measuring water depth, fetch lengths and local wind speed for the region. How a particular shore is orientation relative to the dominant wave direction will influence how much energy it receives, thus making some coastline segments more vulnerable others.

For this research, coastline exposure was calculated using the wave exposure model (WEMo) version 4.0, developed by Fonseca and Malhotra, (2010). WEMo was developed in order to predict and represent the effect of exposure to wind waves. WEMo is a one-dimensional numerical model based on linear wave theory and ray tracing techniques (Fonseca and Malhotra, 2010). WEMo estimates wave energy, using local wind information and bathymetry data. It represents the total wave energy in one wavelength per unit wave crest width and the relative wave exposure (RWE) units are in $J \cdot m^{-1}$.

2.2.3 Width of Foreshore

The foreshore is the gradually sloping, lower portion of a shore, vegetated marsh platform or beach, which is regularly covered and uncovered by the rise and fall of the tide (van Proosdij and Pietersma-Perrott, 2012). The presence and overall width of this zone will influence the coastline's vulnerability. The vulnerability is considered lower along coastlines with a wide foreshore, because there is a higher likelihood that wave energy will be dissipated along these features (Moller, 2003; Moller and Spencer, 2002).

On vegetated coasts, such as salt water marshes, plants may help shield the coastlines from the forces of coastal hazards. In this way, the presence of a wide foreshore will cause a coastline to be less vulnerable than an environment that lacks these features. Also, with greater width more water volume is needed in order for inundation to occur. This means that a storm surge will have to be greater in order to affect these areas.

2.2.4 Presence of Vegetation

In conjunction with foreshore width, vegetation type plays an important role in dissipating wave energy (Moller, 2003). The presence of vegetation, regardless of the type, will significantly reduce the movement of waves over the foreshore (Leonard and Reed, 2002). This concept is called 'bioshielding' by Nobi et al. (2010). The two main genera of plant found in marshes along the Bay of Fundy are *Juncus* and *Spartina*. The type of vegetation that forms is dependent on climatic factors, such as the latitude of the coastal zone, and elevation within the intertidal zone.

However, elevation is most important because it determines the duration of tidal submergence. The low marsh area, which is inundated most frequently and for the longest time span, is dominated by *Spartina* plants. In North America, the most common type is *Spartina alterniflora*. The plants which occupy the highest zone, and are inundated less frequently are *Juncus sp.* and *Spartina patens*. *Juncus gerardii* is most common in northern North America (Davidson-Arnott, 2010; Davis Jr. and Fitzgerald, 2004; Bird, 2000). As described by Moller and Spencer (2002), most of the most rapid reduction in wave energy and height occurs within the low salt marsh area, where *Spartina alterniflora* dominates.

Although width of foreshore and presence of vegetation seem similar, it must be emphasized that width of foreshore is the physical width from the coastline (e.g. backshore) to the furthest extent of marsh vegetation; while in this study, vegetation refers to the type of vegetation found directly at the coastline and does not incorporate the vegetation which precedes it.

2.2.5 Coastal Slope

Coastal slope is used to describe the measure of steepness or gradient of a coastline (Aboudha and Woodroffe 2010). The slope of the coast is an important factor in determining coastal vulnerability because slope is linked to the susceptibility of a coastline to erosion during a storm surge event; where steep slopes are more vulnerable than gentle slopes (Bryan et al., 2001; Kosloski, 2008). Steep slopes increase vulnerability because the stability of the coastline is decreased when flooded or is affected by intense wave action of a storm surge. Waves that strike a coastline with steep slope will cause an increase in erosion, decrease in coastline stability and therefore increases the overall vulnerability (Maryland Department of Natural Resources, 2006). Coastal slope analysis has been included many coastal vulnerability assessments including: Aboudha and Woodroffe (2010); Boruff, Emrich and Cutter (2005); McLaughin, McKenna and Cooper (2002); Nicholls and Klein (1999); Ozyurt and Ergin (2010); Pendleton, Theiler and Williams (2010) and Theiler and Hammar-Klose (1999).

2.2.6 Observed Erodibility

This variable reflects the observed ability of a coastal feature to resist erosion. Highly stabilized features are able to withstand the impacts of sea level rise and storm surges more effectively than partially stabilized or un-stabilized features. The variable stability was used in several studies including: Aboudha and Woodroffe, (2010); Boruff, Emrish and Cutter (2005); McLaughin, McKenna and Cooper (2002); Klein and Nicholls (1999); Ozyurt and Ergin (2010); Pendleton, Theiler and Williams (2010) and Theiler and Hammar-Klose (1999). However, these studies determined stability based on the geology of the coastline, and not observed signs of erosion. The level of stability used in this study consists of the following terms, definitions and direct field observations (van Proosdij and Pietersma-Perrott, 2012):

- **Highly stabilized:** No visible signs of erosion.
- **Partially stabilized:** Visible signs of erosion including cliffing, however very little to no vegetation is slumping away from the coastline.
- **Un-stabilized:** Significant visible signs of erosion including cliffing, with vegetation slumping away from the coastline.

2.2.7 Anthropogenic or Natural Protection

Many studies have omitted the presence of possible barriers or protection against wave propagation; however, this research has included barriers, such as groins, dykes or breakwaters because they will influence wave propagation. Also, there are natural features which provide protection to wave propagation found within the Bay of Fundy. Features such as rock outcrops will also act as protection. Therefore, if these structures are present, a coastline will be less vulnerable than one without.

2.2.8 Morphological Resilience

The resilience is the ability of a coastline to cope with and recover from exposure to a short-term coastal event (storm and storm surge). There are many ways to address resiliency, and for this research it is thought of in the sense of morphological resilience. Morphological resilience is the ability of a coastline to return to a state of equilibrium or original form following a hazard event. Most other assessment methods have not included the resilience of the coastline when determining coastal vulnerability. However, this research believes that the ability to recover from a coastal event is influential in determining coastal vulnerability.

[redacted]	Remarks
	Freeboard is the height of the coastline (either backshore, upper, middle or lower foreshore) above the total water level (tide elevation plus storm surge).
	Coastline exposure is concerned with how the coastline is exposed to wave energy; exposure to less or more energy will influence the coastal environment's vulnerability. Exposure is determined through dominant wind direction, fetch length and water depth.
	A coastline with a wide foreshore is considered to be less vulnerable than one with a narrow foreshore because the features within these systems act as a method to dissipate wave energy.
	Naturally occurring vegetation, such as plants and shrubs can shield the coastline from the forces of waves. This has been called 'Bio-shielding'. The presence of vegetation will result in a coastline being less vulnerable than a location that lacks these features.
	Coastal slope is linked to the susceptibility of a coastal segment to erosion during a storm surge event; where steep slopes are more vulnerable than gentle slopes
	Erodibility reflects the observed ability of a coastal feature to resist erosion. Highly stabilized features are able to withstand the impacts of sea level rise and storm surges more efficiently than partially stabilized or un-stabilized features.
	The presence of groins, dykes, breakwaters, outcrops and cliffs will influence wave propagation. If these structures are present, a coastline will be less vulnerable than one without.
	Resilience reflects the ability of a coastline to cope with and recover from exposure to a short term hazardous event.

Table 2.1 – This table outlines the variables chosen for this research, and briefly explains the rationale for their inclusion in the research.

2.3 Previous Conceptual Models

The different views and definitions surrounding the concepts of vulnerability, hazard, exposure, risk, resilience and adaptive capacity have led to the development of various conceptual models in order to demonstrate the interaction of these conditions in vulnerability research. Several vulnerability frameworks were reviewed for this research and several vulnerability factors or dimensions to vulnerability were uncovered.

2.3.1 The BBC Framework

The term 'BBC' framework comes from the work on previous conceptual models by Bogardi and Birkman (2004) and Cardona (1999 and 2001). This framework was developed around three main components.

1. Linking vulnerability to human security and sustainable development.
2. A holistic approach to disaster risk assessment.
3. Measuring environmental degradation in the context of sustainable development.

The BBC framework views vulnerability as a process, which is dynamic and changes with time. The framework consists of several feedback loops which emphasize current vulnerability status, adaptive capacity of the coastal zone, and the ability to reduce the current vulnerability status. Essential to this model, which supports the idea of vulnerability being dynamic, is the concept that there are two opportunities to reduce vulnerability of a system. Vulnerability reduction prior to exposure from a hazard (t=0) and vulnerability reduction after an event has occurred (t=1). The first option, preparedness, emphasizes introducing adaptation measures prior to an event occurring in order to reduce the vulnerability of the system. The second option, disaster/emergency management, aims to reduce the vulnerability after an event has occurred. This portion of the model emphasizes, along with determining vulnerability from the characteristics of the system, the importance of including actions that may reduce potential vulnerability (Post et al. 2007; Birkman, 2006).

2.3.2 The Turner II et al. Framework

The model put forth by Turner et al., (2003) is considered to be a representation of the global environment and determines vulnerability beyond basic risk-hazard (RH) and pressure-and-release (PAR) models. The core concept for this model is that vulnerability is not purely determined by exposure of the system to a hazard, but also resides in the resilience and adaptive capacity of the system (Turner et al., 2003). Other key elements of this model include:

1. The interaction of multiple stressors.
2. Multiple scales (world, region and place) and the interaction of elements in the model across these scales).
3. Detailed account of exposure (going beyond the presence of a stressor; and analyzes the characteristics of the exposure).
4. Restructuring of the system (re-adjustment/adaptation) to reduce vulnerability.

As Turner et al., (2003) suggest the human and biophysical environments are linked and a coupled-human environment system of analysis is preferred. Although the conceptual model detailed later in this paper is purely biophysical in nature, the use of GIS technology allows for an assessment of possible socio-economic vulnerabilities. Such possibilities include infrastructure (buildings, roads) as well as human populations (elderly, low income families). Vulnerability analysis is not one-dimensional and should include multiple spatial-temporal scales.

2.3.3 The Kasperson et al. Framework

The conceptual model presented in Kasperson et al. (2009) framework is similar to Turner et al. (2003). As Kasperson et al. (2009) state, this framework seeks to include all elements that determine vulnerability and illustrate their complex linkages across multiple scales. Key concepts such as multiple stressors (hazards), exposures, resilience and adaptation are found in this model. When compared to the conceptual model by Tuner et al. (2003), the Kasperson et al. framework includes the influence of pre-emptive measures on the reduction of the level of exposure. Installing measures to reduce the exposure would lead to a reduction in overall vulnerability for the system.

2.4 Proposed Conceptual Model

2.4.1 Introduction

Fussel (2005, 2006) states that climate change related vulnerability assessments should be based on the characteristics of the system, the type and number of stressors (hazards), their root causes, their effects on the system and the time horizon of the assessment. Downing and Patwardhan (2004) suggest the vulnerability of a system needs to be determined through assessing the threat, the region, the sector, the population group, the consequence and the time period. Lastly, Metzger, Leemans and Schroter (2005) conclude a vulnerability assessment must include the ecosystem, location, scenario of stressors and time. The above frameworks, and several others, have the following three characteristics in common:

- Specified system – the coastal zone of analysis will vary depending on the focus of the research.
- Hazard – an event or series of events that could potentially cause damage to the specified system. Could be outside the system or within the system itself.
- Temporal reference – a time frame for the vulnerability assessment. (Short term or long term).

Defining these attributes prior to analysis allows for more accurate and appropriate assessment. The conflicting terminology across disciplines will find common ground when these attributes are defined. Fussel (2006, 2007) also concludes that the research context must also be defined prior to any vulnerability investigation. Called the 'discipline domain' in 2005 and 'knowledge domain' in 2006, Fussel suggests that determining the research focus in the initial phases of the assessment will eliminate confusion. When performing a vulnerability assessment, there are two basic research areas or knowledge domains. The assessment could be from a socio-economic focus (related to the population, cultural practices, economy etc.) or a biophysical focus (physical characteristics of the system, such as topology, environmental conditions, climate change etc.). For this research, the vulnerability assessment will have the following characteristics and focus:

- Specified system – The Bay of Fundy, a macrotidal coastal environment, subject to extreme variation in tide levels, currently experiencing an increase in sea level rise and more intense coastal storm events and storm surges.

- Hazard – The climate change related events discussed for this research are coastal storms and storm surges.
- Temporal reference – The time frame for this analysis is short term. Although an increase in coastal storms frequency and intensity is due to long term climate change, the storms and storm surges occur in a short time frame.
- Knowledge domain – This vulnerability research is biophysical in focus. The socio-economic conditions and characteristics can be used for further analysis once the assessment has been performed using the physical variables.

2.4.2 Model description

The conceptual model developed for this research, which assesses coastal vulnerability in a macrotidal environment is found in Figures 2.2 and 2.3. Through the relationships illustrated in this conceptual model, the following equation will be used to determine coastal vulnerability in the Bay of Fundy. Each condition is composed of the sum of corresponding variables. Each condition is then multiplied by a weight, according to its importance in calculating the coastal vulnerability index, as determined for this research. As shown in the equation below, the Exposure Condition, calculated by freeboard and coastal exposure is deemed the most influential variable and is therefore given the highest weighted value.

Equation 1

RVCI =

(Exposure Condition*0.50) + (Physical Condition*0.33) + (Resilience Condition*0.17)

Where:

RCVI = Relative Coastal Vulnerability Index

Exposure Condition = Freeboard + Coastal Exposure

Physical Condition = Width of Foreshore + Presence of Vegetation + Coastal Slope + Observed Erodibility + Anthropogenic or Natural Protection

Resilience Condition = Morphological Resilience

Conceptual Model – Framework for Assessing Vulnerability in a Macrotidal Environment.

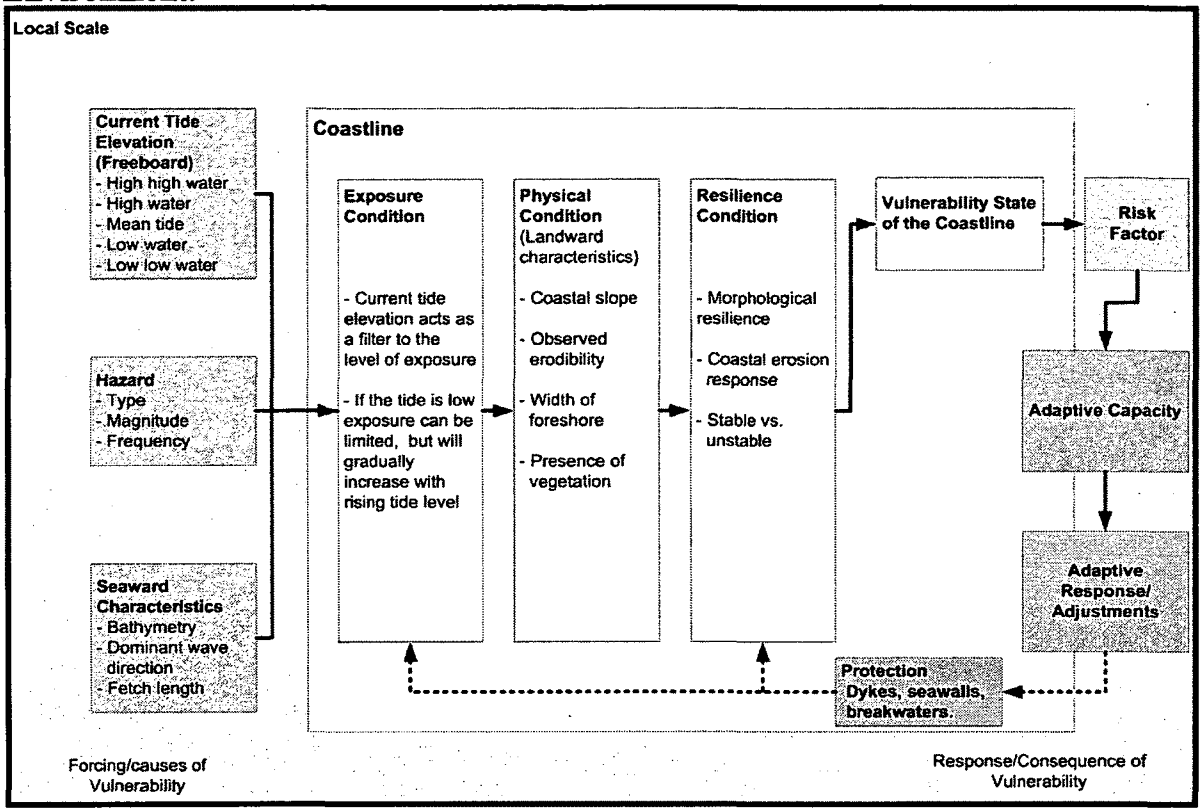


Figure 2.2 - Conceptual model developed for this research, illustrates the interaction of variables and processes within a macrotidal environment. Portions of the model are broken down and explained in the following sections.

2.4.3 Forcing Variables

As Figure 2.2 shows, the model consists of the local scale and the coastline. Within the local scale, the components of 'current tide state', 'hazard' and 'seaward characteristics' are labeled as the forcing variables or causes of vulnerability. As discussed previously, the tide elevation will greatly affect the impact of hazard events, such as storm surges, and is the focus of this research. Fundamentally, in order for the coastal system to be in a state of vulnerability, a hazard needs to occur. More important than the occurrence of a hazard are the characteristics of type, magnitude and frequency.

Every coastline will not be vulnerable to all hazard types or all magnitudes all the time. Therefore it is crucial to define hazard type and magnitude of hazard in order to accurately assess the vulnerability of the target coastal system.

1. Type – A coastal system will be more adversely affected by one type of hazard than another. For example, a system could be more susceptible to storm surges than to an increase in precipitation.
2. Magnitude – A hazard even could be severe enough to push a system past a threshold value, causing the characteristics of the system to permanently change.

Conceptual Model – Exposure, Physical and Resilience Conditions

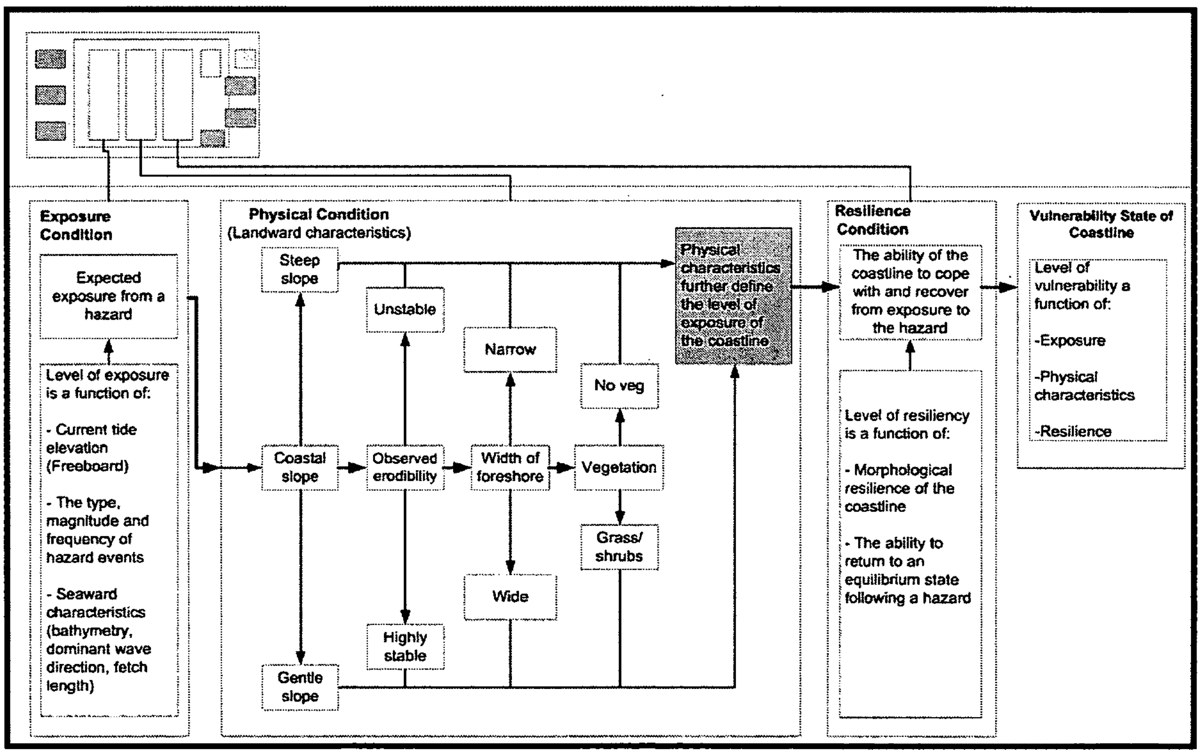


Figure 2.3 - This figure illustrates the interaction of variables within the three conditions (exposure, physical, resilience) used to calculate vulnerability in this research.

2.4.4 Exposure Condition

As well, the characteristics of the waves coming into the system must be included when determining the system's vulnerability. Characteristics such as water depth, fetch length (which is influenced by the presence of both natural and anthropological protection), and wind speed define the 'type' of wave interaction with the coastline. The combination of these three components is used to calculate the coastline's exposure condition. As defined previously in this thesis, exposure is the level of potential stress a coastline could experience from a storm surge event. In other words, for a given tide level, with a given hazard type and magnitude, and wave characteristics, the expected level of exposure can be determined.

2.4.5 Physical Condition

This level of exposure can be further defined by the physical characteristics, or physical vulnerability of the coastline. As seen in the zoom in view of the conceptual model in Figure 2.3, physical characteristics such as coastal slope, observed erodibility, width of foreshore and the presence of vegetation will impact the exposure of a coastline to a hazard. The understanding is that a coastline with a steep slope, signs of active erosion, a narrow foreshore and lacks vegetation, it will be more vulnerable to a storm surge than a coastline with a gentle slope that is highly stable with a wide foreshore and vegetation.

2.4.6 Resilience Condition

As outlined previously, resilience is the ability of a coastline to cope with and recover from a coastal storm event, as defined by its morphological resilience. As described by Klein et al. (1998), this type of resilience can be thought of as a measure of 'potential coastal dynamics'. The ability to withstand a high degree of modification during a storm event would mean that the coastline would have a high morphological resiliency. A gentle sloping ramped coastal feature can be subjected to large scale morphological changes, and return to an equilibrium or original state. If a cliffed feature is subjected to large morphological changes, and passes a threshold, it cannot return to an original state, and therefore has a lower morphological resiliency.

2.4.7 Current Vulnerability State and Risk Factor

Under the response/consequences of vulnerability portion the conceptual model, the previously defined vulnerability conditions (exposure, physical, resilience) within the coastal zone are used to calculate the current vulnerability index of the coastline. The coastal vulnerability index is calculated based on the equation mentioned previously, which includes the vulnerability conditions with appropriate weighting. The vulnerability assessment tool, outlined in Tibbetts et al. (submitted), is what calculates the vulnerability value for this research. The adaptive capacity and adaptation solutions available in the coastal zone are not included within this calculation.

The current vulnerability state of the coastline is referred to as the 'risk factor' within this conceptual model. There is a difference distinguished between the 'Vulnerability State of the Coastline' and the 'risk factor' because the vulnerability state is seen as dynamic and changing. For instance, the level of vulnerability for the coastline will change with increasing or decreasing water level. The risk factor is essentially a static vulnerability value based on certain hazard, exposure, physical characteristic and resilience conditions. The risk factor, in other words, the distribution of vulnerable locations for certain conditions, is used by coastal managers and planners to install measurements to lower the overall vulnerability. For example, a coastal planner could recommend increasing dyke elevations at locations of potential inundation in order to reduce vulnerability.

2.4.8 Response Variables

Adaptive capacity within the coastal zone is the potential or ability to adapt to climate change and its impacts. As described in the previous section, adaptive capacity and adjustments made to reduce vulnerability are not included in the initial calculation of vulnerability. But rather, after coastal managers and planners have installed adjustments, feedback loops illustrate a potential for such adjustments to influence and reduce vulnerability.

2.5 Discussion

There are three main types of vulnerability assessments, biophysical, socio-economic and integrated, each with advantages and disadvantages. However, including both the physical and social aspect within the assessment is critical because the level of physical vulnerability will influence the adaptation response and the type of adaptation response will alter the physical vulnerability (Dolan and Walker, 2003). The physical and social aspects are not independent, but are influenced by one another.

This vulnerability framework is considered a modified integrated assessment method. It is primarily biophysical in focus but does not ignore the social aspect of vulnerability within the coastal zone. Although this assessment tool is based primarily on bio-physical characteristics, the efficiency of a GIS allows for simple assessment of socio-economic vulnerability. Once the user of the assessment tool, a coastal manager or planner, has determined vulnerable locations, a GIS query can select possible roads, buildings and populations adjacent to the location, and assign these features as 'at risk'. Understanding that there are possible infrastructure and populations at risk near a vulnerable feature, allows for more comprehensive prioritization in adaptation solutions.

The variables chosen for this research include tide elevation, coastline exposure, coastal slope, observed erodibility, width of foreshore, presence of vegetation, presence of natural or anthropogenic protection, and morphological resilience. The variables coastal slope and observed erodibility were used in most studies including Aboudha and Woodroffe, (2010); Boruff, Emrich, and Cutter, (2005); Dolan and Walker, (2003); Garmendia et al., (2010); Gornitz et al., (1994); Kumar et al. (2010); Ozyurt and Ergin, (2010); Pendleton, Thieler, and Williams, (2010); McLaughlin, McKenna and Cooper, (2002) Rao Nageswara et al., (2008) and Thieler and Hammar-Klose, (1999). The remaining variables chosen for this research, have either never been included in a vulnerability assessment, or were included in very few. However, these variables are crucial in vulnerability classification due to their prevalence within a macrotidal environment and are included in this research.

Within this framework, the combination of current tide elevation, hazard and the seaward characteristics are used to understand the expected level of exposure (exposure condition). Current tide elevation has been deemed the most influential when determining coastal vulnerability within a macrotidal environment. Essentially, tide elevation acts as a filter for the risk of storm surges associated with climate change. If the storm surge occurs at low tide, there could be little to no vulnerability throughout the coastline, however; if the same storm surge occurs at high tide, there will be an increase in coastal vulnerability (Desplanque and Mossman, 2004; Greenberg et al., in press).

This exposure level can be further increased or decreased when analyzing the physical characteristics of the coastline (physical condition). Variables such as coastal slope, coastal erodibility, width of foreshore, the presence of vegetation and the presence of natural or anthropogenic protection will further influence the exposure level of the coastline. The morphological resilience of the system is also included when determining the vulnerability of a coastline (resilience condition). The ability of the coastline to cope with and recover from an event is influential in this calculation.

This conceptual model illustrates how the variables and processes interact within a macrotidal environment and how these interactions are used to calculate coastal vulnerability for this research. The coastal vulnerability calculation is intended to highlight areas of concern for coastal managers and planners. As found in previous vulnerability frameworks, such as the BBC framework or Kasperson et al. (2009), once areas of concern have been highlighted, and adaptation solutions are adopted, the influence of these adaptations must be evaluated. This conceptual framework evaluates coastal vulnerability purely based on physical attributes of the coastline; however, as indicated by the feedback loop within the model, adaptation solutions and adjustments within the coastal zone are also considered. For example, if the elevation of a dyke is increased to reduce vulnerability within the backshore, the model addresses these changes and allows for re-evaluation of coastal vulnerability.

2.6 Conclusion

Prior to developing a tool which determines coastal vulnerability within a macrotidal environment, there needs to be a firm understanding of the processes and interactions which define such environments. The framework outlined in this paper defines the variables considered most relevant for this research and method of analysis used to calculate coastal vulnerability within a macrotidal environment. The overall aim is to highlight areas of concern, in order to efficiently integrate adaptation solutions for climate change within a macrotidal environment.

2.7 Literature Cited

Abuodha PAO, Woodroffe CD (2010) Assessing vulnerability to sea level rise using a coastal sensitivity index: A case study from Southeast Australia. Journal of Coast Conservation 14: 189-205

Atlantic Canadian Adaptation Solutions Association, URL: http://atlanticadaptation.ca; accessed on March 20, 2012.

Bird ECF (2000) Coastal geomorphology: an Introduction. Chichester Wiley

Birkmann J (2006) Measuring vulnerability to promote disaster-resilient societies: Conceptual frameworks and definitions. In: Birkmann, J., (ed) Measuring vulnerability to natural hazards: towards disaster resilient societies, edited by: Birkmann, J., United Nations University Press, Tokyo, pp 9-54

Boruff BJ, Emrich C, Cutter SL (2005) Erosion hazard vulnerability of US coastal counties. Journal of Coastal Research 21(5): 932-942

Capobianco M, DeVriend HJ, Nicholls RJ, Stive MJE (1999) Coastal area impact and vulnerability assessment: The point of view of a morphodynamic modeller. Journal of Coastal Research 15 (3): 701-716

Cooper JAG, McLaughlin S (1998) Contemporary multidisciplinary approaches to coastal classification and environmental risk analysis. Journal of Coastal Research 14 (2): 512-524

Cutter SL (1996) Vulnerability to environmental hazards. Progress in Human Geography 20 (4): 529-539

Davidson-Arnott, Robin,(2010). Introduction to coastal processes and geomorphology. Cambridge: Cambridge UP

Davis, Richard A., and Duncan M. Fitzgerald, (2004). Beaches and Coasts. Malden, MA: Blackwell Pub

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

Desplanque C, Mossman D (2001) Bay of Fundy tides. Geoscience Canada 25 (1): 1-11

Desplanque C, Mossman D (1999) Storm tides of the Fundy. The Geographical Review 89 (1): 2 -33

Dolan AH, Walker IJ (2003) Understanding vulnerability of coastal communities to climate change related risks. Journal of Coastal Research, SI 39 (Proceedings of the 8th International Coastal Symposium)

Downing TE, Patwardhan A (2004) Assessing vulnerability for climate adaptation. In: Lim B, Spanger-Siegfried E (eds) Adaptation Policy Frameworks for Climate Change: Developing Strategies, Policies, and Measures. Cambridge University Press, Cambridge, pp 67- 90

Fonseca MS, Malhotra A (2010) WEMo (Wave Expose Model) for use in ecological forecasting. Applied Ecology and Restoration Research Branch NOAA, National Ocean Service URL: http://www.csc.noaa.gov/digitalcoast/tools/wemo/index.html; accessed March 21, 2012

Fussel HM (2007) Vulnerability: A generally applicable conceptual framework for climate change research. Global Environmental Change 17:155-167

Fussel HM, Klein RJT (2006) Climate change vulnerability assessments: an evolution of conceptual thinking. Climatic Change 75: 301- 329

Fussel HM (2004) Vulnerability in climate change research: A comprehensive conceptual framework. International and Area Studies working paper, University of California at Berkeley, CA

Garmendia E, Gamboa G, Franco J, Garmendia J, Liria P, Olazabal M (2010) Social multi-criteria evaluation as a decision support tool for integrated coastal zone management. Ocean & Coastal Management 53: 385-403

Gornitz VM, Daniels, RC, White, TW, Birdwell KR (1994) The development of a coastal risk assessment database: Vulnerability to sea-level rise in the U.S. Southeast. Journal of Coastal Research 12: 327-338

Greenberg DA, Blanchard W, Smith B, Barrow, E (in press) Climate change, mean sea level and high tides in the Bay of Fundy. Bedford Institute of Oceanography

Kasperson JX, Kasperson RE, Turner II BL (2009) Vulnerability of coupled human-ecological systems to global environmental change. In: Rosa EA, Diekmann A, Dietz T, Jaeger C (eds) Human footprints on the global environment: Threats to sustainability, The MIT Press, Cambridge, 231-294

Kasperson JX, Kasperson RE, Turner II BL, Schiller A, Wen-hua H (2005) Vulnerability to global environmental change. In: Kasperson JX, Kasperson RE (eds) Social Contours of Risk. Earthscan, London, pp 245-285

Kelly PM, Adger WN (2000) Theory and practice in assessing vulnerability to climate change and facilitating adaptation. Climatic Change 47: 325-352

Klein RJT, Nicholls RJ (1999) Assessment of coastal vulnerability to climate change. Ambio 28(2): 182-187

Klein RJT, Smit MJ, Goosen H, Hulsbergen CH (1998) Resilience and Vulnerability: Coastal Dynamics or Dutch Dikes? The Geographical Journal 164(3): 259-268

Kumar TS, Mahendra RS, Nayak S, Radhakrishnan K, Sahu KC (2010) Coastal vulnerability assessment for Orissa State, East Coast of India. Journal of Coastal Research 26(3): 523 – 534

Leonard LA, Reed DJ (2002) Hydrodynamics and sediment transport through tidal marsh canopies. Journal of Coastal Research SI 36: 459-469

Maryland Department of Natural Resources (2006) Shoreline Erosion Control Guidelines for Waterfront Property Owners. URL: http://www.mde.state.md.us/; Assessed April 21st.

McLaughlin S, McKenna J, Cooper JAG (2002) Socio-economic data in coastal vulnerability indices: Constraints and Opportunities. Journal of Coastal Research 36: 487-497

Metzger MJ, Leemans R, Schroter D (2005) A multidisciplinary multi-scale framework for assessing vulnerability to global change. International Journal of Applied Earth Observation and Geoinformation 7: 253- 267

Moller I (2003) The sea-defence role of intertidal habitats. In: Ledoux L (ed) Wetland valuation: State of the art and opportunities for further development. pp 73 -88

Moller I Spencer T (2002) Wave dissipation over macro-tidal saltmarshes: Effects of marsh edge typology and vegetation change. Journal of Coastal Research SI 36: 506 – 521

Nobi EP, Sivaprasad A, Karikalan R, Dilipan E, Thangaradjou T, Sivakumar K (2010) Micro level mapping of coastal geomorphology and coastal resources of Rameswaram Island, India: a remote sensing and GIS perspective. Journal of Coastal Research 26(3): 424- 428

Ozyurt G, Ergin A (2010) Improving coastal vulnerability assessments to sea-level rise: A new indicator based methodology for decision makers. Journal of Coastal Research 26(2): 265-273

Pendleton EA, Thieler ER, Williams SJ (2010) Importance of coastal change variables in determining vulnerability to sea- and lake-level change. Journal of Coastal Research 26(1): 176-183

Pendleton EA, Jeffress SW, Thieler ER (2004) Coastal vulnerability assessment of Assateague Island National Seashore (ASIS) to sea level rise. U.S. Geological Survey Open-File Report 2004-1020Electronic Book

Post J, Zosseder K, Strunz, G, Birkmann J, Gebert N, Setiadi N, Anwar HZ, Harjono H, Nur M, Siagain T (2007) Risk and vulnerability assessment to tsunami and coastal hazards in Indonesia: conceptual framework and indicator development. A paper for the international symposium on disaster in Indonesia, Padang, Indonesia 26-29 July 2007

Rao Nageswara K, Subraelu P, Rao Venkateswara T, Hema Malini B, Ratheesh R, Bhattacharya S, Rajawat AS (2008) Sea-level rise and coastal vulnerability: an assessment of Andhra Pradesh coast, India through remote sensing and GIS. Journal of Coastal Conservation 12: 195 – 207

Shaw J, Taylor RB, Solomon S, Christian HA, Forbes DL (1998) Potential impacts of global sea level rise on Canadian coasts. The Canadian Geographer 42(4): 365-379

Sterr H, Klein R, Reese S (2000) Climate change and coastal zones: An overview of the state-of-the-art on regional and local vulnerability assessment. URL: http://www.sterr.geographie.uni-kiel.de/downloads/ClimateChange.pdf; accessed on March 20, 2012

Thieler ER, Hammar-Klose ES (1999) National assessment of coastal vulnerability to future sea-level rise: Preliminary results for the U.S. Atlantic Coast: U.S. Geological Survey. Open-File Report 99-593 URL: http://woodshole.er.usgs.gov/project-pages/cvi/ accessed on March 20, 2011

Turner II BL, Kasperson RE, Matson PA, McCarthy JJ, Corell, RW, Christensen L, Eckley N, Kasperson, JX, Luers A, Martello ML, Polsky C, Pulsipher A, Schiller A (2003) A framework for vulnerability analysis in sustainability science. Proceedings of the National Academy of Sciences 100: 8074-8079 http://www.pnas.org/content/100/14/8074.full.pdf accessed on March 20, 2011

Vasseur L, Catto N, Burton D, Chouinard O, Davies J, DeBaie L, Duclos G, Duinker P, Forbes D, Hermanutz L, Jacobs J, Leger L, McKenzie K, Parlee K, Straatman J (2008) Atlantic Canada In: Lemmen, D.S., Warren, F.J., Lacroix, J., Bush, E. (eds) From impacts to adaptation: Canada in a changing climate 2007, Government of Canada, pp 119-170

van Proosdij D, Pietersma-Perrott B (2012) Shore zone characterization for climate change adaptation in the Bay of Fundy. Saint Mary`s University. URL: http://atlanticadaptation.ca/; accessed on March 18, 2012.

Wu SY, Yarnai B, Fisher A (2002) Vulnerability of coastal communities to sea level rise: A case study of Cape May County, New Jersey. Climate Research 22: 25-270

Chapter 3

A Relative Vulnerability Assessment Tool for Macrotidal Environments

Paper to be submitted to Journal of Coastal Research

3.0 Introduction

Communities throughout Atlantic Canada, and all over the world, are experiencing the effects of climate change, and it is assumed that these effects continue to increase. In order to limit the negative effects of climate change, policy makers and mangers need to understand the process happening at the coast (Vasseur et al., 2008). Determining vulnerable locations, allows for proper implementation of long term policy, such as placing restriction on construction in vulnerable areas, and short term policy, such as the dissemination of resources during an emergency.

In collaboration with the Atlantic Climate Adaptation Solution (ACASA) project, the overall purpose of this paper was to develop a globally applicable tool, within a geographic information system (GIS) that determines the relative vulnerability of a macrotidal coastal environment to the increased risk of storm surges associated with climate change, based on several physical and anthropogenic parameters. There have been several methods for assessing vulnerability developed; however, none have been developed specifically for coastal environments with an extreme tide range. Having an interactive tool for a macrotidal environment that assesses vulnerability dynamically, with increasing water level, is important to the ACASA project because many coastal communities in Atlantic Canada are located near such environments.

A review of the literature has uncovered several essential variables in coastal vulnerability research. The variables coastal slope and observed erodibility (called geology in many studies) were used in most studies including Aboudha and Woodroffe, (2010); Boruff, Emrich, and Cutter, (2005); Dolan and Walker, (2003); Garmendia et al., (2010); Gornitz et al., (1994); Kumar et al. (2010); McLaughlin, McKenna and Cooper (2002), Ozyurt and Ergin, (2010); Pendleton, Thieler, and Williams, (2010); Rao Nageswara et al. (2008) and Thieler and Hammar-Klose, (1999). The remaining variables chosen for this research, relative coastline exposure, width of foreshore, presence of vegetation at the coastline, presence of anthropogenic or natural protection at the coastline and morphological resilience have either never been included in a vulnerability assessment, or were included in very few. However, these variables are crucial in vulnerability classification due to their prevalence within a macrotidal environment.

The final variable, freeboard, has been determined as the most influential variable in assessing a macrotidal environment. Freeboard is the height of the coastline in relation to combined elevation of tide and storm surge height. This variable attempts to capture the influence of tide elevation on coastal vulnerability in a macrotidal setting. Previous studies have attempted to address tide elevation within coastal vulnerability assessment (Boruff, Emrich, and Cutter, 2005; Cooper and McLaughlin, 1998; Kumar et al., 2010; Pendleton, Thieler, and Williams, 2010; Rao Nageswara et al., 2008 and Thieler and Hammar-Klose, 1999; however, these studies used a 'mean tide' value. The potential impact of a storm surge is directly dependent on the current tide elevation. If a storm surge hits at high tide, a surge could cause a dramatic negative impact on the coastline;

however, the same storm surge at low tide could be harmless. Therefore current tide elevation, and not a mean tide elevation, would allow for more accurate description of vulnerable locations.

This paper details the application of the globally applicable vulnerability tool, developed within a GIS, as tested within the Cornwallis River Estuary in the Bay of Fundy, Canada; which has one of the highest tides in the world. The tidal range in the head of the Bay of Fundy reaches 16 m during certain astronomical conditions, even independent of atmospheric influences (Desplanque and Mossman, 2001). This paper first begins with outlining the data collection process, and the coastline classification scheme used throughout that process. After discussing the method for applying appropriate weights to the variables used for this research, the design of the vulnerability tool, using python scripting and the ArcGIS 9.3 tool set is discussed. Finally, the results and validation of the vulnerability tool are analyzed and discussed.

3.1 Methodology

3.1.1 Data Collection

Within the study area, three coastal zones have been identified. Similar to most other coastal locations, macrotidal environments consist of backshore, foreshore, and nearshore zones (the definition of these coastal zones is found in Table 3.1). Of these three zones, research was only conducted on the backshore and foreshore. The significance of conducting vulnerability assessment within the nearshore is limited. Within backshore and foreshore, four coastlines have been selected for analysis. These coastlines, shown in Figure 3.1, are the backshore, upper foreshore, middle foreshore and lower foreshore.

Instead of opting for an all-inclusive single coastline definition, these four coastlines were chosen due to the difference in characteristics between them. Within the same section of the coast, the coastline characteristics at the backshore will differ greatly from that of the lower foreshore and therefore, the interface between the tide and coastline will vary greatly. In order to appropriately assess vulnerability, the unique properties of each coastline need to be addressed.

Within a GIS, a polyline was created for each of the target coastlines. The backshore polyline was traced from a Digital Elevation Model (DEM) with a 2 m resolution, at an elevation of 8.15 metres, higher high water large tide (HHWLT) for the study area (Webster, McGuian and MacDonald, 2011). This HHWLT value was obtained from the Canadian Hydrological Service tide station #202, and converted from chart datum. The DEM was constructed from LiDAR point cloud data collected in 2003 by the Applied Geomatics Research Group (AGRG) and all elevations are referenced to Canadian Geodetic Vertical Datum of 1928 (CGVD28) and are considered to be orthometric heights; this is because the elevations are measured orthogonal to a geoid surface. To confirm the accuracy of the LiDAR elevations, a comparison was made with RTK (real time kinematic) GPS surveys conducted throughout the study area. The mean delta Z is 0.0 m with a standard deviation of 0.21 m for the LiDAR DEM (Webster, McGuian and MacDonald, 2011).

The four remaining lines were determined by air photo and satellite interpretation (van Proosdij and Pietersma-Perrott, 2012). The foreshore polylines were digitized using 2008 Quick bird satellite imagery (2.4 m resolution). Aerial photography (1 m resolution) from 2002 was used where satellite imagery was not available (van Proosdij and Pietersma-Perrott, 2012). Following the creation of these polylines, each line was divided into 250 m line segments. This was done to ensure the vulnerability classification was performed on a small scale, the smaller the line segment, the more precise the results.

In order to obtain up-to-date coastline data, in the Cornwallis River Estuary, a Trimble Yuma tablet computer with integrated global positioning system (GPS) and a geotag enabled camera was used to document coastline characteristics by van Proosdij and Pietersma-Perrott (2012). At locations of change, for example from a beach to a marsh, a picture was taken with GPS coordinates. These pictures, along with aerial and satellite photography, were used to determine the physical characteristics of each of the target coastlines at points along the Cornwallis River Estuary (van Proosdij and Pietersma-Perrott, 2012).

[redacted]	
[redacted]	The upper or inner, usually dry and narrow, zone of the shore or beach, lying between the high-water line of the mean spring tides and the upper limit of shore-zone process; it is acted upon by waves or covered by water only during exceptionally severe storms or unusually high tides. It is essentially horizontal or slopes landward, and is divided from the foreshore by the crest of the most seaward berm (van Proosdij and Pietersma-Perrott, 2012).
[redacted]	The lower or outer, gradually seaward sloping, zone of the shore or beach, lying between the crest of the most seaward berm on the backshore (or the upper limit of wave wash at high tide) and the ordinary low water mark; the zone regularly covered and uncovered by the rise and fall of the tide, or the zone lying between the ordinary tide levels (van Proosdij and Pietersma-Perrott, 2012).
[redacted]	Extending seaward or lakeward an indefinite but generally short distance from the coastline; specifically said of the zone extending from the low-water coastline well beyond the breakzone, defining the area of nearshore currents, and including the inshore zone and part of the offshore zone. Depths are generally less than 10 m (van Proosdij and Pietersma-Perrott, 2012).

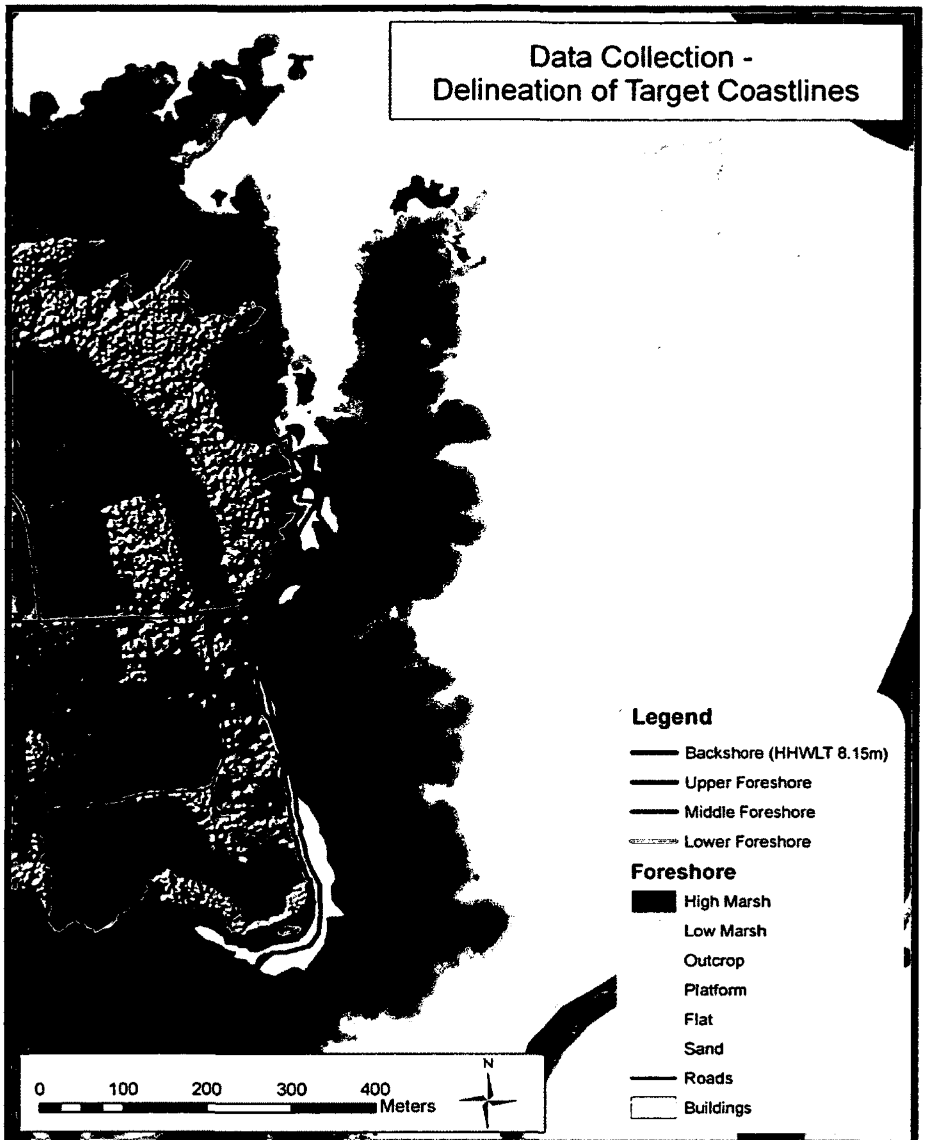


Figure 3.1 - Portion of the Cornwallis River Estuary, Nova Scotia, Canada. This figure illustrates the division of the four coastlines (Backshore, Upper Foreshore, Middle Foreshore, and Lower Foreshore).

3.1.1.1 Coastline Classification

Within the Cornwallis River Estuary, data were collected for each of the coastlines, based on a classification scheme developed for the ACASA project by van Proosdij and Pietersma-Perrott (2012). This classification methodology, modified from a scheme developed by the Geological Survey of Canada Coastal Information System (Owens, 1994; Sherin et al. 2003), was used extensively in designing a coastal vulnerability matrix for this study area, and subsequently, the development of the vulnerability assessment tool. The classification schemes used for both the backshore and the foreshore are found in Appendix A of this thesis.

Data for the variables observed erodibility, presence of vegetation at the coastline, presence of anthropogenic or natural protection at the coastline and morphological resilience came directly from attributes within the classification database described above. In conjunction with data collected with the Trimble Yuma tablet, analysis was performed within a GIS to calculate slope and width of foreshore values for each line segment. Coastal slope was calculated from a digital elevation model slope raster, with a 2 m grid cell size. Width of foreshore values were determined using foreshore polygons and transects cast by Analysis of Moving Boundaries Using R (AMBUR), which is a relatively new tool developed by Jackson (2010).

3.1.1.3 Wave Exposure Model

Previous studies by Aboudha and Woodroffe (2010) and Bryan et al. (2001) categorized exposure, from sheltered to exposed, based on orientation (in degrees) of the coastline segment to dominant wind and wave direction. Instead of estimating exposure based on orientation, this study goes further by calculating exposure values using a model where wave propagation is carried out by shoaling, wind generation and dissipation over downwind distance over water (fetch).

Relative coastline exposure was calculated using the wave exposure model version 4.0, developed by Fonseca and Malhotra (2010). WEMo was developed in order to accurately predict and represent the effect of exposure to wind waves. WEMo is a one-dimensional numerical model based on linear wave theory and ray tracing techniques (Fonseca and Malhotra, 2010). WEMo calculates wave energy, using local wind information and bathymetry data. It represents the total wave energy in one wavelength per unit wave crest width and the RWE units are $J \cdot m^{-1}$.

Propagation of water waves over irregular bottom bathymetry involves processes such as shoaling, refraction, diffraction and energy dissipation (Fonseca and Malhotra, 2010). However, to decrease complexity, the developers did not include refraction and diffraction of the waves, and propagation is carried out only by shoaling, wind and fetch. Fetch is the distance wind can travel over the surface of a body of water without encountering an obstacle. An increase in fetch length generally allows for the development in larger waves (Aboudha and Woodroffe., 2010; Cutter 1996). For this research, WEMo analysis was performed at increasing water levels, from 1 m to 10.15 m (8.15 m HHWLT plus a 2 m storm surge) for all four coastlines.

3.1.1.4 Coastal Vulnerability Matrix

There have been many approaches and methods applied in an attempt to uncover coastal vulnerability. A study by Usery et al (2010) used GIS and three parameters (elevation, land cover and population data) in order to illustrate sea level rise and storm surge impacts for low lying urban areas. Although the data used in this study was at a 30 m resolution, the application methods were intuitive and could be applied in cases of higher resolution, yielding more accurate results. Other studies by Wolf (2009), Harper et al. (2009) and McInnes et al. (2003) all use models in order to predict sea level rise, coastal vulnerability indexes and the impacts of storm surge. However, it is felt that the method of constructing a coastal vulnerability matrix, and developing a coastal vulnerability index score from that matrix is an efficient, less complex method of determine vulnerability to the impacts of storm surge within a macrotidal environment.

The earliest examples of determining coastal vulnerability via this method are by Gornitz et al. (1994) and Thieler and Hammer-Klose (1999). A vulnerability matrix provides the criteria for how each variable will be ranked, from 1 to 5, based on data gathered for the study area. Essentially, if a variable is perceived as having a low impact on vulnerability for the area, it is given a rank of 1, if it provides a high impact, it would receive a rank of 5. The method of ranking variables based on criteria outlined in a vulnerability matrix has been used by Aboudha and Woodroffe (2010), Boruff, Emrich, and Cutter (2005), Donlan and Walker (2003), Kosloski (2008), McLaughlin, McKenna, Cooper (2002), Ozyurt and Ergin (2010), Pendleton, Thieler, and Williams (2010), Pendleton, Williams, Thieler (2004), Rao Nageswara et al. (2008), and Titus and Anderson (2009). The coastal vulnerability matrix used for this study area is found in Table 3.6 and is preceded by a description of how each variable is used in vulnerability classification within this study.

Freeboard

Freeboard is the height of the coastline (either backshore, upper, middle or lower foreshore) above the total water level. Each coastline segment (250 m) is assigned a coastline elevation (relative to CGVD28) within the GIS. This elevation relates to the top of dyke, top of cliff, top of slope or some other coastline feature.

Within the vulnerability tool, the user inputs the selected tide elevation and storm surge values, which are combined to obtain a total water level (tide plus surge). This total water level is then compared with the coastline elevation in each coastline segment. If the coastline elevation is above the total water level, then there is limited vulnerability because the storm surge will not be overtopping the coast; alternatively, if the coastline elevation is below the total water level, then the ranking system is applied.

Due to increasing differential impact with increasing flood depth, the range divisions for freeboard were calculated using an exponential growth curve. The result is that each range class is 25% greater than the one below it, culminating in freeboard >1.25 m in class 5.

Relative Coastline Exposure

The coastline exposure values were calculated using a wave exposure model (WEMo 4.0). WEMo analysis was performed at increasing water levels, from 1 m to 10.15 m (8.15 m HHWLT plus a 2 m storm surge) at 0.5m intervals for all four coastlines. The output values are the amount of potential wave energy ($J \cdot m^{-1}$) reaching each segment, based on local wind (direction and speed), bathymetry and fetch length data. Segments receiving higher energy are considered to have a higher vulnerability. Coastline exposure is considered relative because these vulnerability ranges are only comparable within the study area. If the WEMo analysis is performed for a different location, the highest energy value may be greater than highest exposure values for this study area. This would require a re-calculation of ranges within the vulnerability matrix. However, within the study area, the ranges are comparable with each other, and illustrate an increase in exposure vulnerability with an increase in potential wave energy. The histogram identifying the ranges for relative coastline exposure is found in Figure 3.2. The natural breaks classification is a method which determines the most appropriate arrangement of values, within a data set, into ranges. This method seeks to minimize the value difference within ranges, but maximizes the variance between ranges. The natural breaks classification was utilized because the algorithm is best for clustering non-normally distributed data.

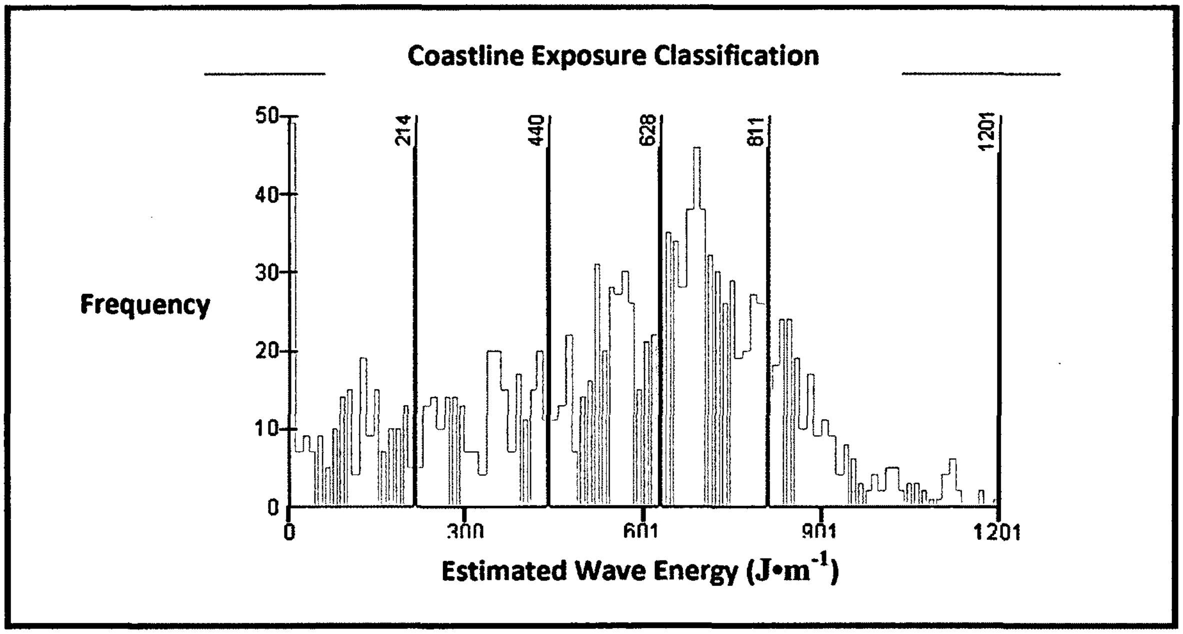


Figure 3.2 – Natural breaks classification for relative coastline exposure across all four coastlines.

Width of Foreshore

Particularly in macrotidal settings, foreshore zones act as buffers to storm surge events. Essentially, the narrower a foreshore, the less wave energy dissipation will occur prior to breaking at the target coastline and the higher the vulnerability. The vulnerability is considered lower along coastlines with a wide foreshore, because there is a higher likelihood that wave energy will be dissipated along these features (Moller, 2003; Moller and Spencer, 2002). The range divisions for width of foreshore are derived from natural breaks classification of foreshore values for all target coastlines (cumulative). The distribution of the width of foreshore values for all four coastlines is found in Figure 3.3.

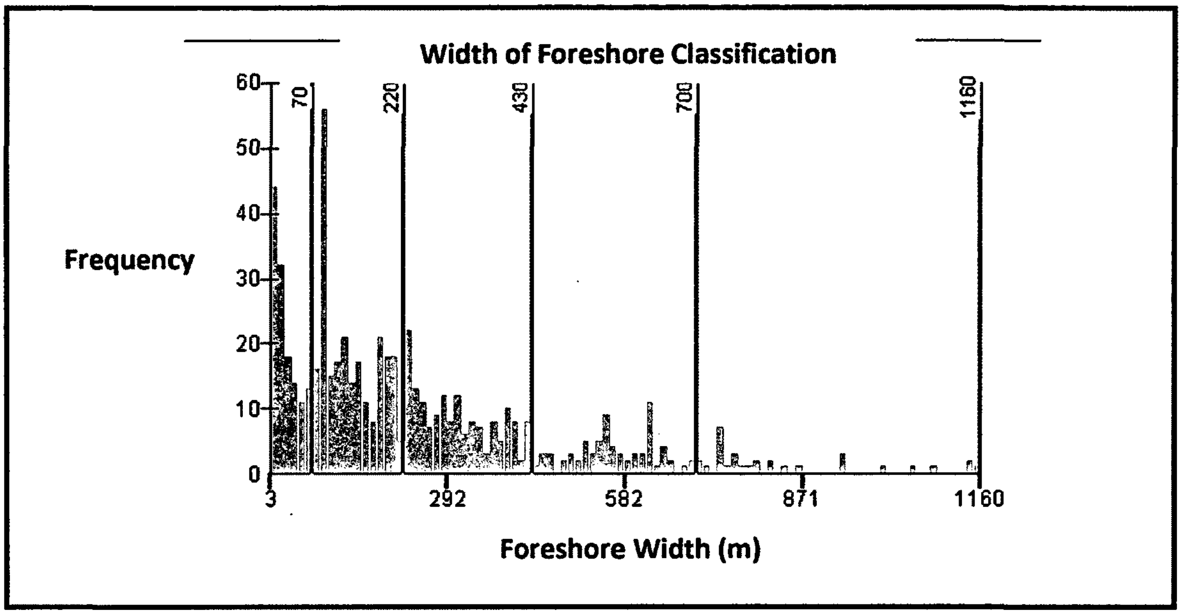


Figure 3.3 - Natural breaks classification histogram for width of foreshore values across all four target coastlines.

Presence of vegetation

In conjunction with foreshore width, vegetation plays an important role in dissipating wave energy and limiting erosion potential (Leonard and Reed, 2002; Moller, 2003). Through what is referred to as 'bio-shielding', vegetation in the coastline may act to dissipate wave energy and as well as being a stabilizer against erosion. The type of vegetation will influence how well these features act as a buffer. Although width of foreshore and presence of vegetation seem similar, it must be emphasized that width of foreshore is the physical width from the coastline (e.g. backshore) to the furthest extent of marsh vegetation; while vegetation refers to the type of vegetation found directly at the coastline and does not incorporate the vegetation which precedes it. Examples of a vegetated and un-vegetated coastline are found in Table 3.2.

Table 3.2 – Vegetated vs. Un-vegetated	
Vegetated	Un-vegetated
	
Photos from: van Proosdij and Pietersma-Perrott (2012).	

Table 3.2 – Example of a coastline that is considered vegetated and un-vegetated.

Coastal Slope

Coastal slope is used to describe the measure of steepness or gradient of a coastal segment. For this study, the slope values are in degrees, and were obtained through a 2 m slope raster created in ArcGIS 9.3; the higher slope values indicate a steeper slope and vice versa. Coastal slope is linked to the susceptibility of a coastal segment to erosion during a storm surge event; where steep slopes are more vulnerable than gentle slopes (Bryan et al., 2001; Kosloski, 2008). The intense wave action commonly associated with a storm surge at locations with steep slopes will cause an increase in erosion, and thereby increasing the vulnerability of the coastline. The distribution of coastal slope values for each coastline is found in Figure 3.4.

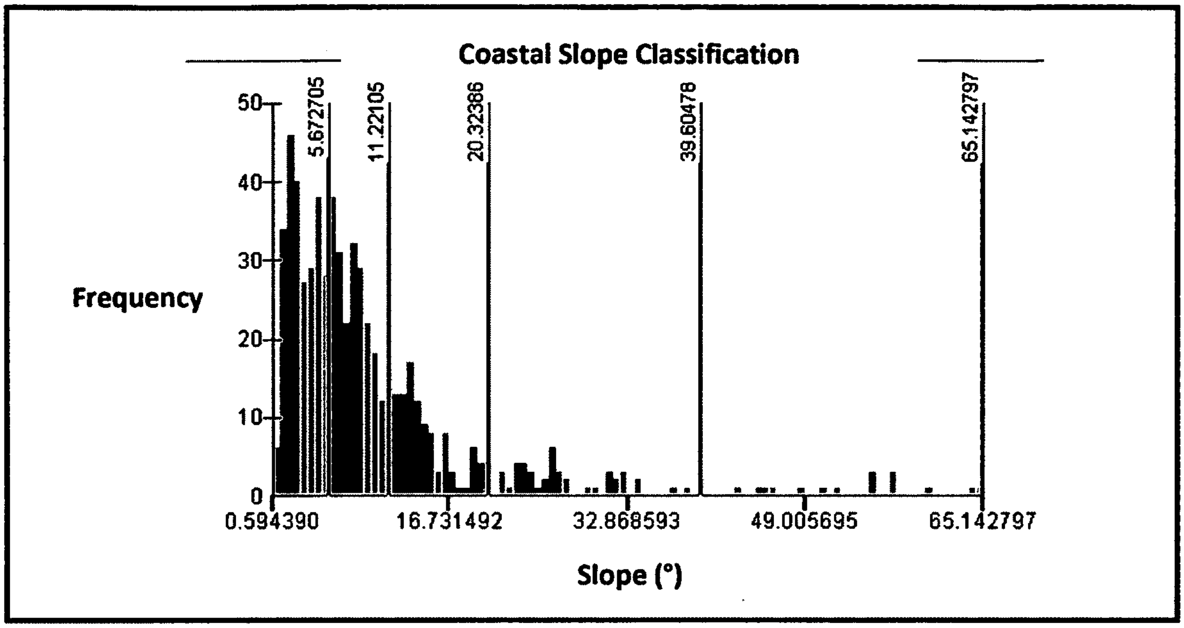


Figure 3.4 - Natural breaks classification for coastal slope values across all four target coastlines.

Observed Erodibility

This variable ranks the nature of the material (essentially stable verses unstable) and the presence of erosion activity throughout each coastline at the present time. The data are derived from direct field observations (van Proosdij and Pietersma-Perrott, 2012) according to the following definitions:

Highly stabilized: No visible signs of erosion.

Partially stabilized: Visible signs of erosion including cliffing, however very little to no vegetation is slumping away from the coastline.

Un-stabilized: Significant visible signs of erosion including cliffing, with vegetation slumping away from the coastline.

Therefore, zones of active erosion are considered less stable and have higher vulnerability to erosion. This does not preclude the possibility of erosion being initiated or accelerated in a future storm event. An example of a highly stabilized coastline is found on the left in Table 3.3 and an un-stabilized feature is seen on the right.

Table 3.3 – Stabilized vs. Not Stabilized	
Stabilized	Not Stabilized
	
Photos from: van Proosdij and Pietersma-Perrott (2012).	

Table 3.3 – Example of a coastline that is considered stabilized and not stabilized.

Anthropogenic or Natural Protection

There are many types of anthropogenic or natural coastline protection within this study area. Each coastline segment is classified according to the most protective element at any particular site. As well, it should be emphasized that these features are parallel to the coastline and not perpendicular. Within the matrix, the logic is as follows: a dyke with armouring (rank 1) is considered less vulnerable than a dyke without armouring (rank 2). A high or medium rock cliff is less vulnerable than a low rock cliff. High, medium and low refer to the physical height of the feature, high being >4 m, medium being 4-2 m and low being <2 m. The concept is the larger the object, the more protection it will offer. In addition, for cliff and slope, the lithology or nature of the material (solid or unlithified) is an important consideration. In this matrix, solid material is less vulnerable than unlithified. Examples of anthropogenic and natural coastline protection features are found in Table 3.4.

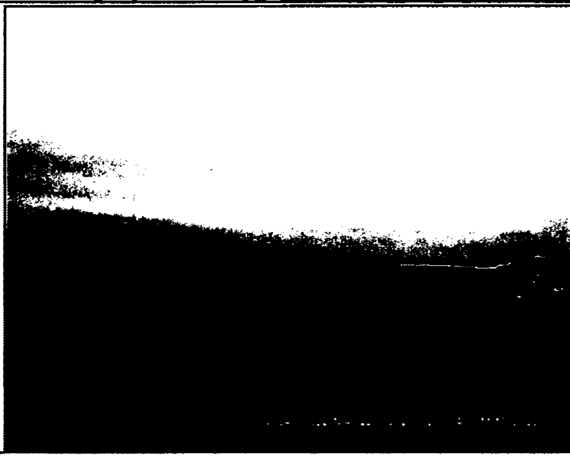
Table 3.4 – Anthropogenic and Natural Protection	
Anthropogenic - dyke	Rock outcrop
	
Photos from: van Proosdij and Pietersma-Perrott (2012).	

Table 3.4 – Example of a coastline that has anthropogenic and natural coastline protection

Morphological Resilience

The resilience is the ability of a coastline to cope with and recover from exposure to a short term hazardous event. There are many ways to address resilience, and for this research it is thought of in the sense of morphological resilience. Morphological resilience is the ability of a coastline to return to a state of equilibrium or original form following a hazard event. Ramped features may be able to cope with and recover from an impact event more than a cliffed feature (ramped features can gain material through depositional processes, cliffed features only lose material). As well, the stability of the feature is taken into account; the less stable a feature is, the more likely it will lose material through erosion. An example of ramped and cliffed features is found in Table 3.5.

Table 3.5 – Ramped Vs. Cliffed	

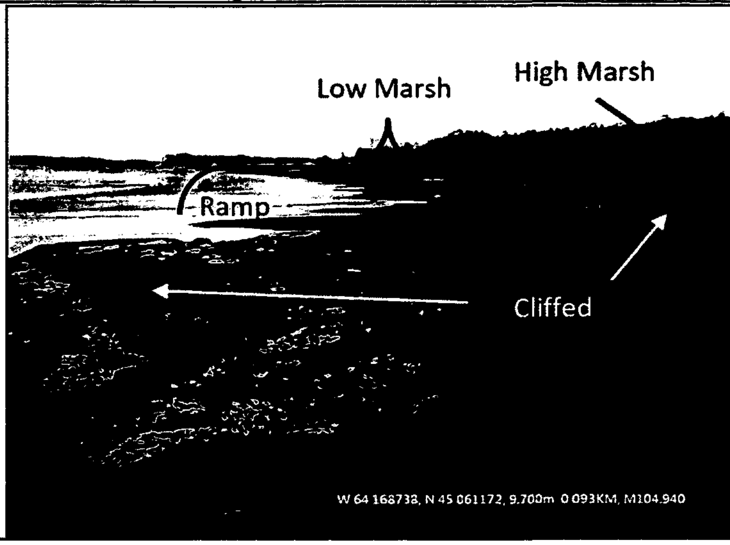



Photo from: van Proosdij and Pietersma-Perrott (2012).	

Table 3.5 – Example of coastal features that are considered ramped, and those that are considered cliffed.

[redacted]

[redacted] Unit	1	2	3	4	5
[redacted] m	0.01 – 0.15	0.16 – 0.40	0.41 – 0.75	0.76-1.25	>1.25
[redacted] J•m^{-1}	0-215	216-440	441-630	631-810	810-1200
[redacted] m	701-1160	431 - 700	221- 430	71-220	0 – 70
[redacted] °	6.4 – 0	12.4 - 6.5	20.4 - 12.5	37.4 - 20.5	70 - 37.5
[redacted]	Rock, highly stabilized	Un-lithified over rock	Un-lithified material, highly stabilized	Un-lithified material, partially stabilized	Un-lithified material, not stabilized
[redacted]	Forest	Shrubs	Agriculture	Marsh grass	Un-vegetated
[redacted]	Dyke with armoring or High/Med rock cliff	Dyke without armoring or High road or Low rock cliff	Medium road or High/Med unlithified cliff	Low road or Low unlithified cliff or Unlithified slope	No protection
[redacted]	Ramped, Highly Stabilized or Flat	Ramped, Partially Stabilized or Cliffed, Stable or Beach	Ramped, Unlithified Over Solid or Cliffed, Partially Stabilized	Ramped, Not Stabilized or Cliffed, Unlithified Over Solid	Cliffed, Not Stabilized

3.1.2 Weighting

Many studies investigated during the literature review did not apply weights to their variables. Studies such as Aboudha and Woodroffe (2010), Ozyurt and Ergin (2010) and Thieler and Hammar-Klose (1999) did not apply weights to the variables and assumed that each parameter contributed equally to the vulnerability of the system. However, this research has determined that a vulnerability assessment tool should include weights in its calculation because certain variables are more influential than others. For example, freeboard could be viewed as more influential in determining vulnerability to storm surges at the coastline than the observed erodibility. Placing an emphasis on freeboard over observed erodibility is particularly important in a macrotidal environment. Studies by Pendleton, Thieler, and Williams (2010), Rao Nageswara et al. (2008) and Gornitz et al. (1994) are examples of approaches in which weights were applied.

A variety of variables play a role in determining the overall vulnerability of a coastline. The diversity of coastal landforms, complexities of coastal processes, and the interaction of these features, all aid in the definition of coastal vulnerability. Due to the wide range of bio-physical parameters, it would be wrong to assume that all variables make an equal contribution to vulnerability. Therefore, it seems appropriate to apply weights on the variables to account for their differential influence in determining coastal vulnerability.

This study used a multi-criteria evaluation (MCE), in order to clarify the relationship between variables and also to calculate an appropriate weight for each. A MCE is a 'decision-aid and mathematical tool allowing the comparison of different alternatives or scenarios according to many criteria, often contradictory, in order to guide the decision-maker(s) towards a judicious choice' (Chakhar and Martel, 2003, p. 49). Essentially, a problem can have many solution or alternatives, each based on several criteria: the MCE aids in choosing a solution. The study by Garmendia et al. (2010) also explored the integration of MCE with a GIS in the context of coastal management. The coastal zone has multiple scales, complex physical process and complex issues; managing this area is extremely difficult. The MCE technique has been shown to be a useful tool in the search for new strategies to manage the coastal zone, which is characterized by complexities and conflicts.

3.1.2.1 Weighting Calculation – Ranking Method

As outlined by Malczewski (1999), there are several methods for determining weights for a given set of variables. The method used for this research is the ranking method. This is the simplest method for assigning weights, and it is based on rank order of the decision-maker's preference. The ranking method used in this research is rank-sum; and the method for calculating weights is shown in Equation 3.1. Although the usefulness of this method can be limited when a large number of variables are being considered; its application in this research is practical.

Equation 3.1

$$w = \frac{n - rj + 1}{\Sigma(n - rk + 1)}$$

Where:

w = weight

n = number of criteria under consideration

rj = the rank position of the criterion

Normalized by the sum of all weights $\Sigma(n - rk + 1)$

3.1.2.2 Relative Coastal Vulnerability Index

The vulnerability matrix allows for the variables to be incorporated into an equation that calculates a relative coastal vulnerability index (RCVI) score for each segment of a coastline. The method of developing an index score from the ranking of variables within a vulnerability matrix has been employed by Abuodha and Woodroffe, (2010); Gornitz et al. (1994); Kumar et al. (2010); Ozyurt and Ergin, (2010); Shaw et al. (1998) and Thieler and Hammar-Klose (1999) and many others. Within these studies, the term coastal vulnerability index was used, however, for this research 'relative' has been added. Relative is used to emphasise that the vulnerability classification is comparable to all four target coastlines within the study area, but not comparable to other study locations.

A RCVI allows the variables (which are both numerical and qualitative) to be related in a quantifiable manner that expresses the relative vulnerability of each segment within a coastline to the risk of storm surges associated with climate change (Pendleton, Williams and Thieler, 2004). The formula used to calculate the RCVI value for this research differs from the studies mentioned previously; here RCVI is taken to be the square root of the product of the ranked variables divided by the total number of variables (Equation 3.2).

Equation 3.2

$$CVI = \sqrt{\frac{(a * b * c * d * e * f * g * h)}{8}}$$

Where:

a = freeboard
b = relative exposure
c = coastal slope
d = width of foreshore
e = presence of vegetation
g = presence of anthropogenic or natural protection
h = morphological resilience

In this research, the eight variables have been grouped together under three conditions; exposure, physical and resilience. This grouping was determined based on the development of a conceptual framework for assessing vulnerability in a macrotidal environment (Tibbetts et al., submitted) and is found in Figure 3.5. Each condition is composed of the sum of corresponding variables. Each condition is then multiplied by a weight, according to its importance in calculating the coastal vulnerability index, as determined for this research. As shown in Equation 3.3, the Exposure Condition, equaling the sum of freeboard and coastal exposure, is deemed the most influential variable and is therefore given the highest weighted value.

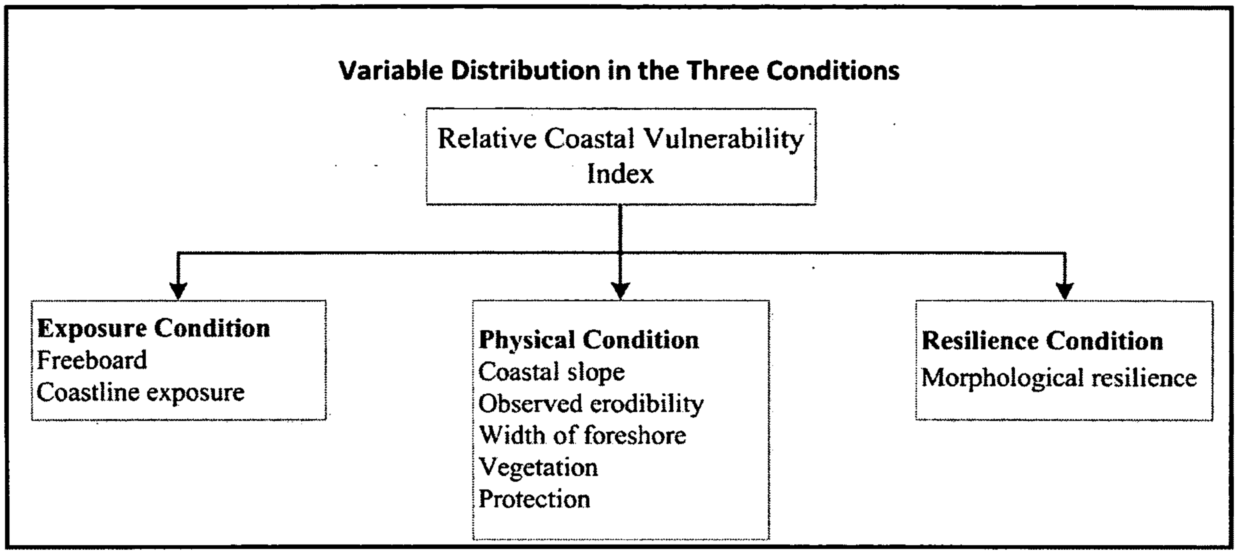


Figure 3.5 - Distribution of variables into three 'conditions', which are used within a formula to calculate coastal vulnerability.

Equation 3.3

Relative Coastal Vulnerability Index=

$$(\text{Exposure condition}*0.50) + (\text{Physical condition}*0.33) + (\text{Resilience condition}*0.17)$$

In order to categorize the RCVI values, five equal ranges were derived according to the lowest and highest possible RCVI scores (very low vulnerability to very high vulnerability). The RVCVI outputs were then assigned to the corresponding categories; illustrating the distribution of vulnerable areas throughout the study area.

Level of Vulnerability	**Corresponding RCVI Range**
Very High	11.51 – 14.10
High	9.10 – 11.50
Medium	6.60 – 9.09
Low	4.00 – 6.59
Very Low	1.49 – 3.99

It must be mentioned that the choice of method for categorizing the vulnerability index score will influence the overall distribution of vulnerable areas (Abuodha and Woodroffe, 2010). Creating equal ranges based on all possible RCVI values is one way of classifying relative vulnerability. However, this classification can be performed in a number of ways and with any number of classes (Bryan et al. 2001). Although the classification of the coastline into vulnerability categories seems arbitrary, the idea here is not to provide definite predictions, but rather to highlight, within the study area, locations which will likely be affected more severely than others. Whether you have four or five vulnerability categories, linear or non-linear classification, the end result is the same; some locations will always be more at risk than others.

3.2 Results and Discussion

With the guidelines (ranking system) set out in the vulnerability matrix, along with the equation for calculating relative coastal vulnerability, a Python computer programming script was created using Python version 2.5. This python script, which is fully integrated within the GIS, is core of the vulnerability assessment tool and is found within Appendix B of this thesis. The tool was run for all four target coastlines, at increasing water levels from 1.0 m to 10.15 m (HHWLT plus 2 m storm surge); the results shown in this chapter (Figure 3.6 – 3.10) are for the backshore only. In Figure 3.6, the distribution of RCVI throughout the entire study area at HHWLT is shown. The lowest RCVI (excluding locations where there is no impact) is 1.49 and only one coastal segment has this value. This segment is an armoured dyke, with a coastline elevation of 9.5 m and a foreshore width of over 700 m. The highest RCVI value is 11.94, obtained for a segment with unstable steep slope, with a coastline elevation of 7.6 m (0.5 m below HHWLT) and a narrow foreshore width.

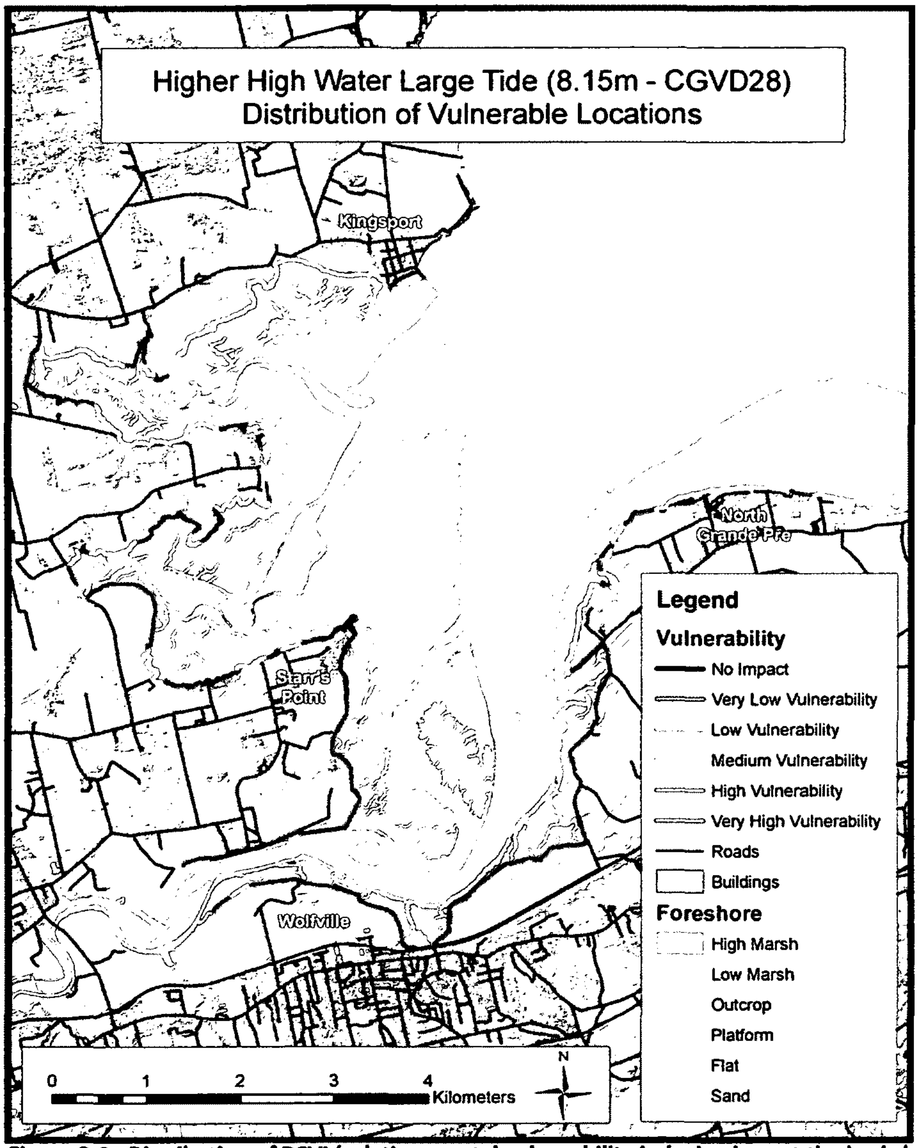


Figure 3.6 - Distribution of RCVI (relative coastal vulnerability index) values at the backshore for HHWLT.

The results of the vulnerability assessment tool are consistent with expectation in regards to the effects of tide elevation on potential impact of storm surge. As discussed in Greenberg et al. (in press) and Desplanque and Mossman (2001), tide elevation is highly influential in the overall impact of a storm surge. If a storm surge occurs at high tide, there is potential for a greater impact than if the same storm surge occurs at low tide. Compared to similar vulnerability assessment tools, this research goes further by assessing vulnerability dynamically. Previous studies assessed vulnerability at a static or mean tide elevation; this research has successfully designed a tool within a GIS, which accounts for changing tide elevation and its influence on storm surge potential. Figures 3.7 to 3.10, illustrate the change in vulnerability with increasing water level. This analysis is of the Wellington Marsh, located within the study area.

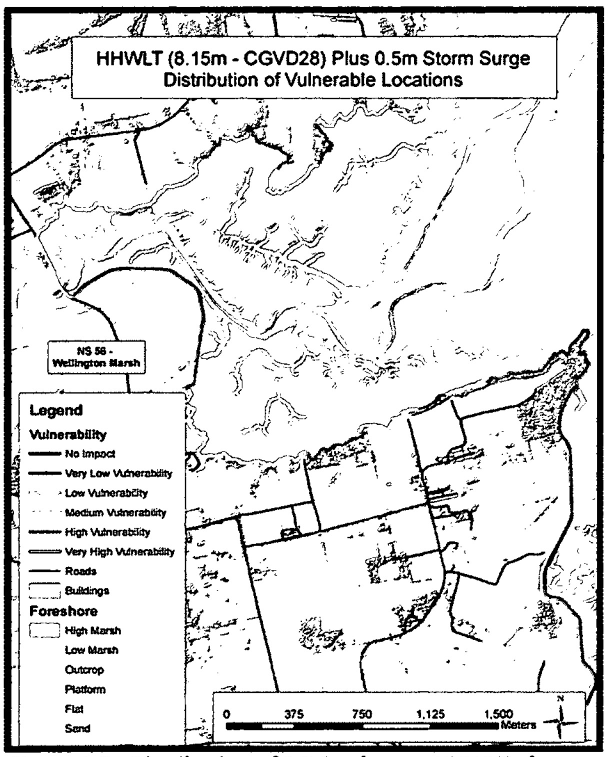


Figure 3.7 - Distribution of RCVI values at HHWLT plus 0.5 m storm surge, at the backshore at Wellington Marsh, in the study area.

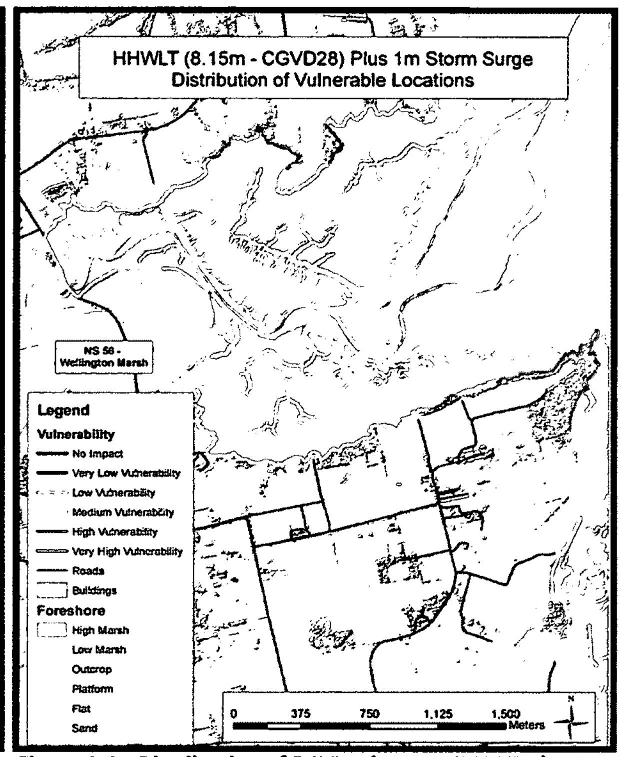


Figure 3.8 - Distribution of RCVI values at HHWLT plus 1 m storm surge, at the backshore at Wellington Marsh, in the study area.

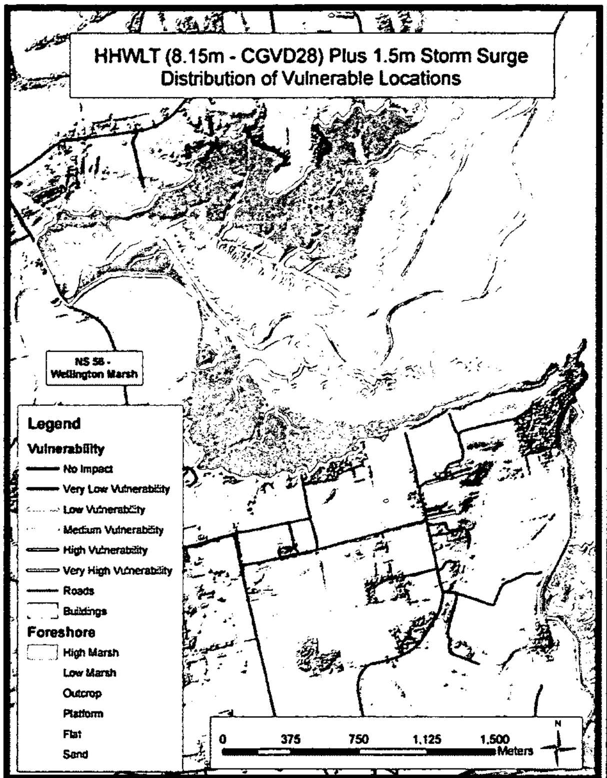


Figure 3.9 - Distribution of RCVI values at HHWLT plus 1.5 m storm surge, at the backshore at Wellington Marsh, in the study area.

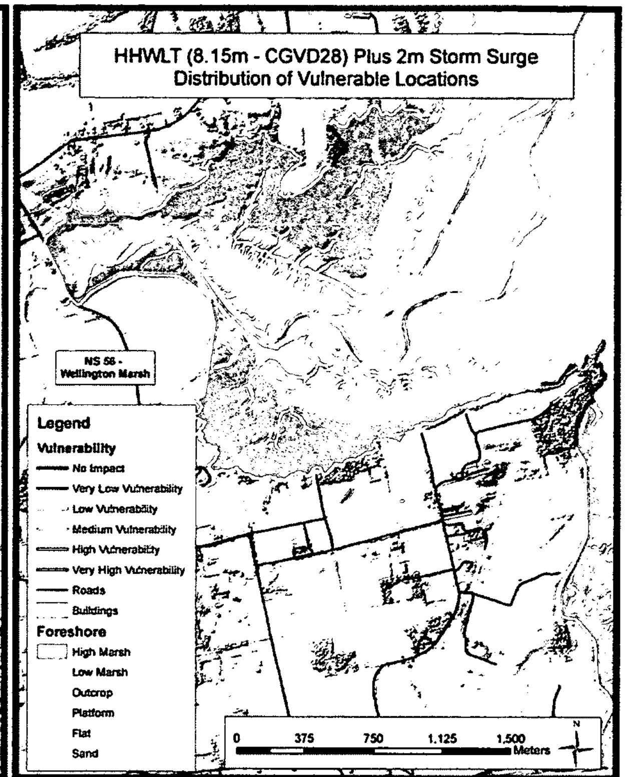


Figure 3.10 - Distribution of RCVI values at HHWLT plus 2 m storm surge, at the backshore at Wellington Marsh, in the study area.

The impact of water level on the potential for a negative impact from storm surge is seen in Table 3.7. This table resembles a risk matrix, which shows the mean RCVI value for each of the four target coastlines, with increasing water level. As illustrated in the table, the vulnerability at each coastline increases with increasing water level. Most importantly, a distinct total water level for the increase from low to higher vulnerability is determined for each coastline. Coastal managers and planners require this type of information when determining proper coastal adaptation solutions.

Table 3.7 – Hazard/Risk Matrix											
	Total Water Level (tide plus surge) in meters relative to CGVD28										
Coastline	1	2	3	4	5	6	7	8.15	8.65	9.15	9.65	10.15
Backshore												
Upper Foreshore												
Middle Foreshore												
Lower Foreshore												

Table 3.7 – The mean RCVI value for each water level, from a 1 m to 10.15 m. After 8.15 m (HHWLT) the total water level values correspond to a 0.5 m storm surge value. For example, 8.65 total water level would equate to HHWLT plus a 0.5m storm surge.

Vulnerability	Legend
Very High	
High	
Medium	
Low	
Very Low	
No Impact	

This understanding is further described in Figure 3.11, which graphs the percent of coastline, assigned a high and very high RCVI value, across all four target coastlines. This figure suggests that for each coastline, there is a distinct water level where the majority of coastal segments are no longer assessed as low to medium vulnerability, but become high and very highly vulnerable to the threat of storm surge. As expected, the backshore is the only coastline which is does not reach 100% high or very high vulnerability; this is due to the presence of dykelands throughout the backshore as well as higher coastline elevations and increased width of foreshore.

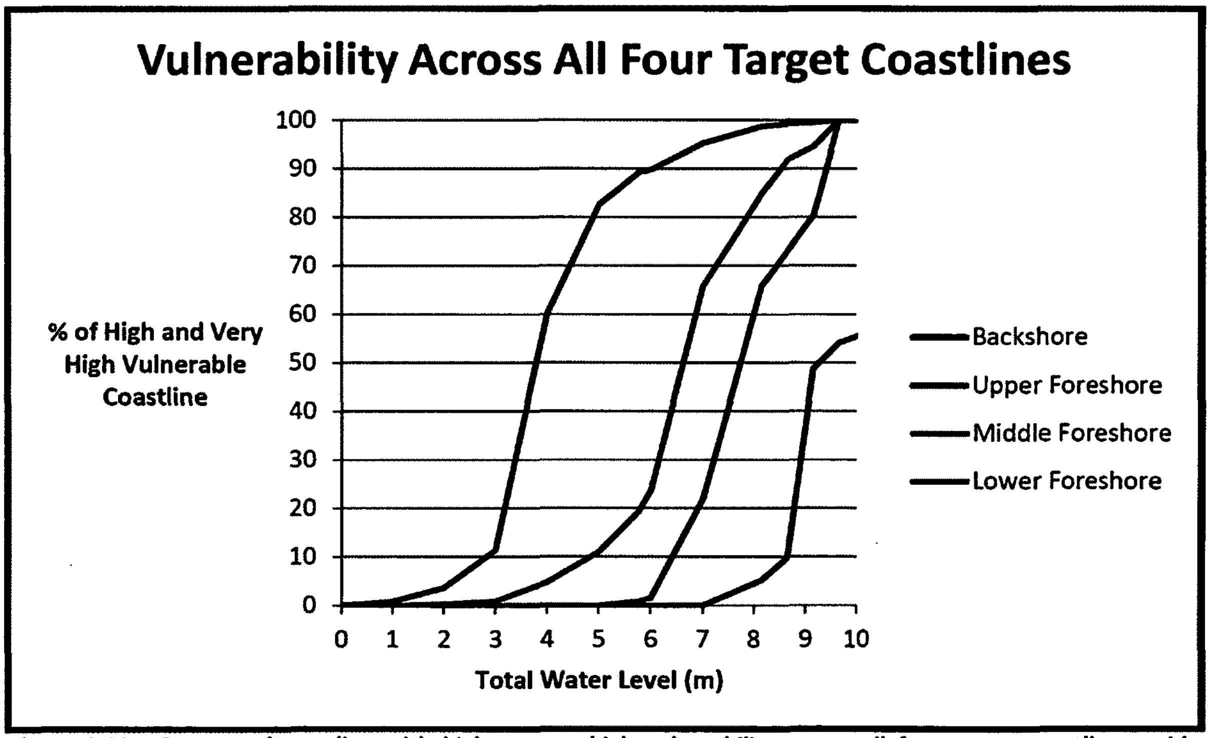


Figure 3.11 - Percent of coastline with high or very high vulnerability across all four target coastlines, with increasing water level. Water levels are referenced to Canadian geodetic vertical datum (CGVD28).This figure illustrate that at distinct total water levels, for example at 3m for the lower foreshore, the majority of coastline transcends from very low/low vulnerability to high/very high vulnerability.

3.2.1 Areas of Concern

The assessment tool is intended to highlight areas of concern throughout the study area, at varying total water levels (tide plus storm surge). Pin pointing areas of concern, allows coastal planners and managers to know where to allocate resources, and where to do further analysis. The following section highlights three areas of concern found in the Cornwallis River Estuary, at increasing water levels. The aim is to demonstrate how the end user is able to locate potential areas of concern, and determine why and how they are vulnerable.

NS 08 Grand Pre Marsh

In the north-east corner of NS 08 Grande Pre Marsh, there are coastline segments with high and very high vulnerability (Figure 3.12). The backshore at this location is predominately unlithified, partially stable, sloped and has a freeboard of approximately 0.5 m below the total water level (8.15 m). This location is highly exposed in terms of its orientation to the dominant wind patterns (Figure 3.13), and this is confirmed by the results of WEMo analysis. Of the ten most highly exposed coastal segments at this water level, nine are found in this location.

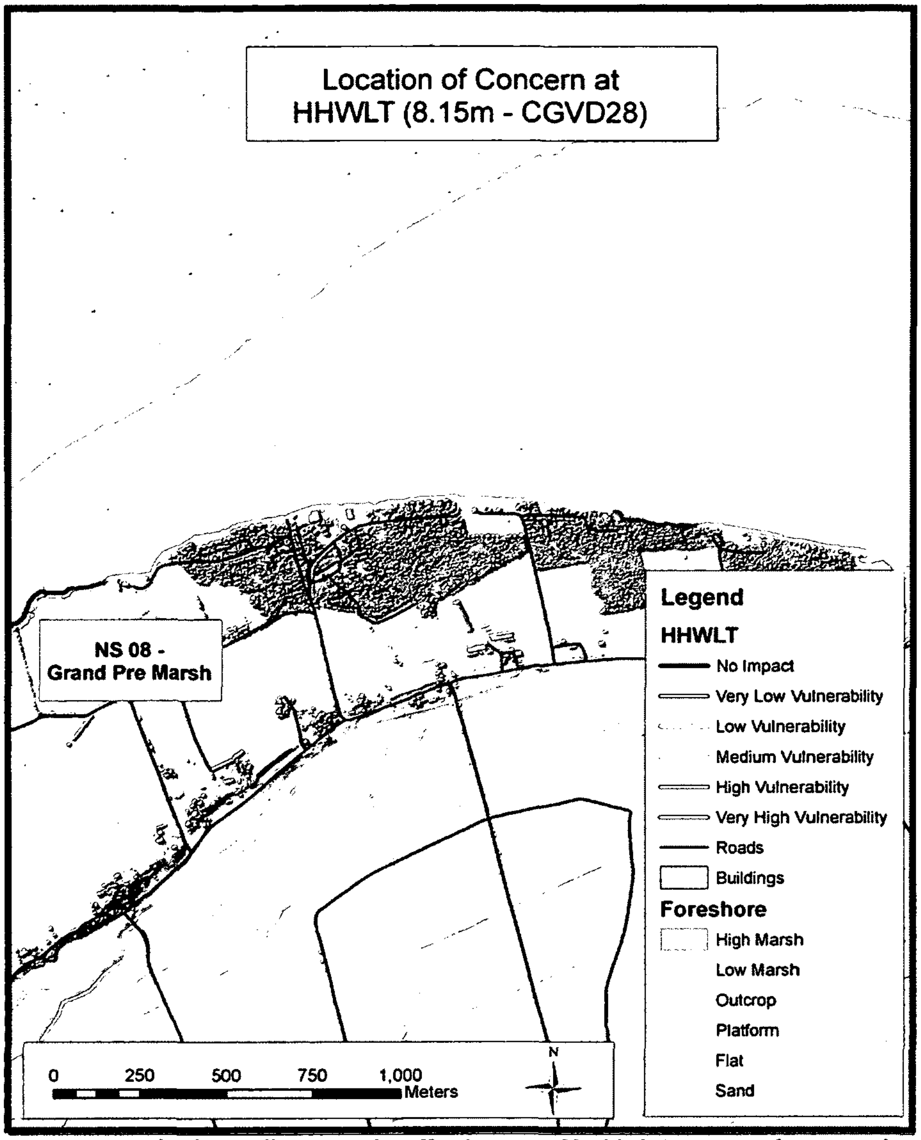


Figure 3.12 – This figure illustrates the effectiveness of highlighting areas of concern throughout the Cornwallis River Estuary, Nova Scotia at HHWLT (8.15 m CGVD28). This location is to the North East of the NS 08 Grand Pre Marsh.

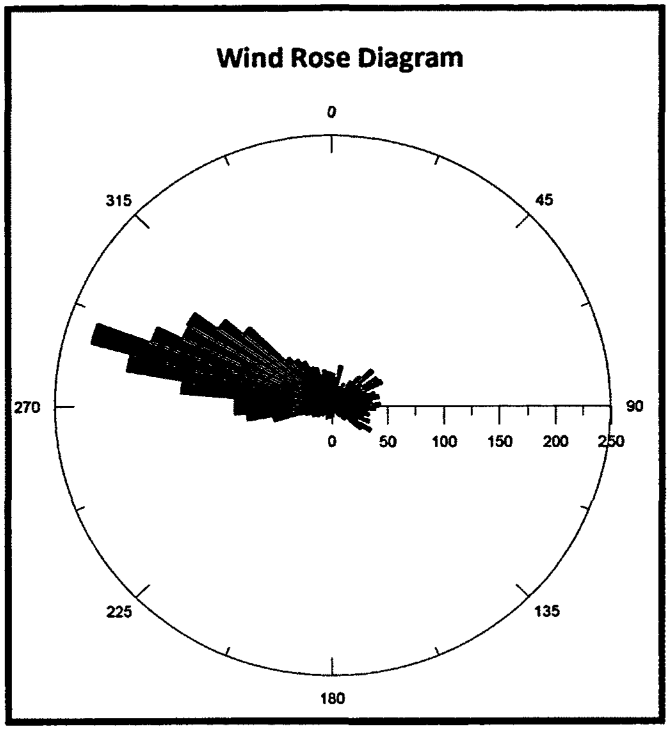


Figure 3.13 - Wind rose diagram created from wind speed and direction data, collected over the summer of 2009 at Starr's Point, Nova Scotia.

Near Lower Canard, Kings County, Nova Scotia

Although this location does have armouring, it is an unlithified, steep slope that is not stable (Figure 3.14). This location is prone to erosion, has little foreshore and vegetation to act as a buffer to the incoming wave advance. Due to the freeboard elevation of this coastal segment being below the total water level (8.65 m tide plus 0.5 m storm surge), along with the orientation of the coastline in reference to dominant wind pattern (Figure 3.13), this location is highly vulnerable. This location could also be assessed as a priority because road infrastructure is within 30 m of the backshore (Figure 3.14).

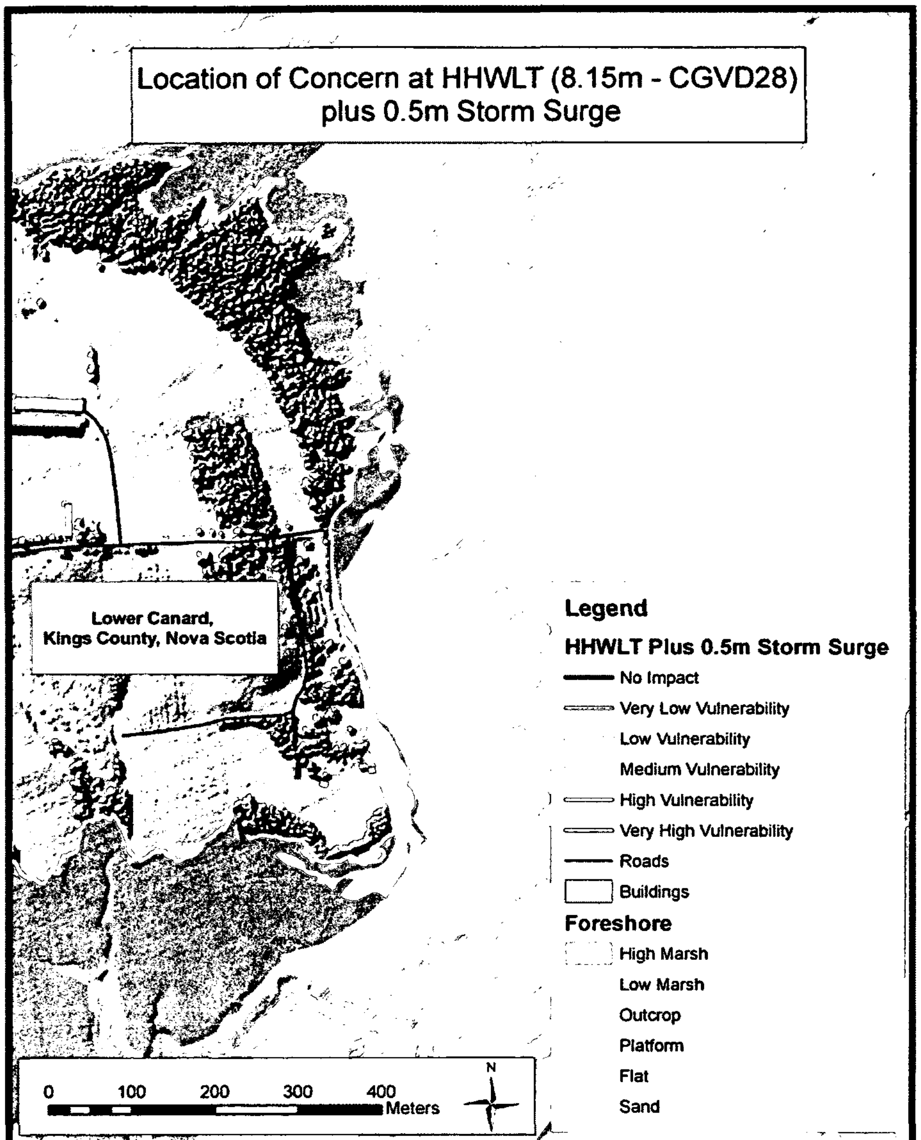


Figure 3.14 - This figure illustrates the effectiveness of highlighting areas of concern throughout the Cornwallis River Estuary, Nova Scotia at HHWLT (8.15 m CGVD28) plus a 0.5m storm surge. This location is near Low Canard, in King's County.

West of Kingsport, Nova Scotia

The vulnerability classification for this area is found in Figure 3.15. This location, to the west of Kingsport, in Kings County, Nova Scotia is at medium to high vulnerability to a 1 m storm surge at HHWLT. This location is predominately an unlithified, low slope feature that is partially stabilized. Although this location does have a wide foreshore, which allows for protection from waves, the coastline elevation is on average 1.5 m below the total water level for this scenario (9.15 m CGVD28).

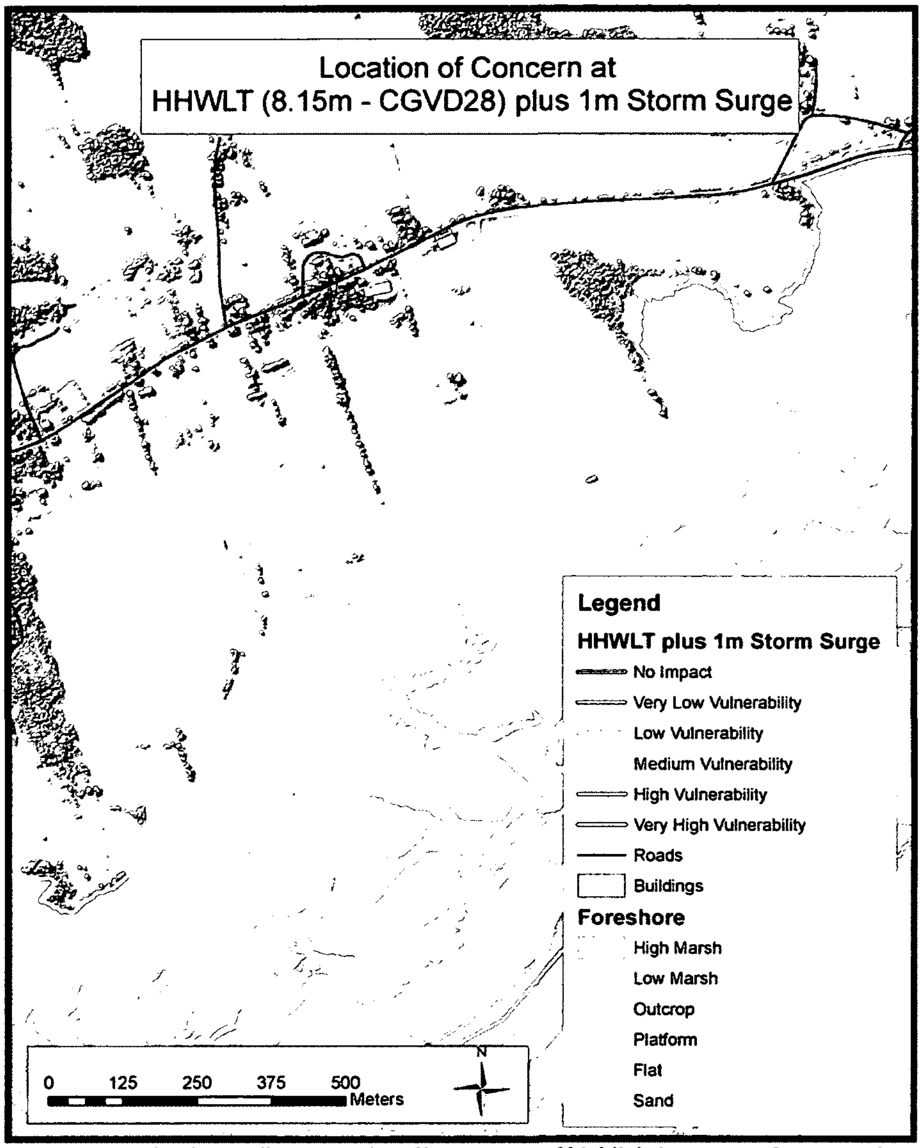


Figure 3.15 - This figure illustrates the effectiveness of highlighting areas of concern throughout the Cornwallis River Estuary, Nova Scotia at HHWLT (8.15 m CGVD28) plus a 1m storm surge. This location is to the West of Kingsport, in King's County.

4.2 Proof of Concept

To prove the concept of designing a vulnerability matrix and assigning RCVI values to coastline segments based on bio-physical variables is an effective tool for determining the relative vulnerability within a macrotidal environment, two methods were employed. Within the backshore, vulnerable locations were compared with known locations of concern. For this comparison, the total water level of 9.15 m (HHWLT plus 1m storm surge) was utilized. It is at this level that the assessment tool illustrates an increase in vulnerability throughout the backshore; this increase is seen in Figure 3.11. As seen in Figure 3.16 and 3.17, the locations of known concern are similar to the coastline segments being assessed as vulnerable by the tool.

Figure 3.16 is of the north-east corner of the NS 08 Grand Pre Marsh, the tool has assessed this location at a high vulnerability. The highest ranked variables, leading to this classification were the lack of foreshore, and coastal exposure. The Nova Scotia Department of Agriculture has deemed this location as an area of concern, highlighting that more rock armouring is needed to hinder erosion processes. Figure 3.17 is of NS 65 Bishop-Beckwith Marsh, and the tool has assessed this location as a medium vulnerability. The highest ranked variables, leading to this classification were lack of foreshore and freeboard height. The Nova Scotia Department of Agriculture has deemed this location as an area of concern, highlighting that dyke elevation needs to be increased. Although the assessment tool has only calculated this location at a medium vulnerability, the fact that it has not calculated it as a no or low vulnerability illustrates that the tool does highlight potential areas of concern.

As well, it should be noted that the number of known locations of concern highlighted by the Nova Scotia Department of Agriculture is lower than that of the results produced by the tool. This is most likely due to the results being analyzed at extreme water levels, greater than HHWLT. However, this estimation of vulnerability is beneficial to climate change adaptation. These locations are a concern because negative events (inundation and erosion) have occurred there in the past. The tool is mean to limit such negative impacts by highlighting vulnerable areas prior to an event, allowing coastal managers and planners to install measures to reduce the vulnerability.

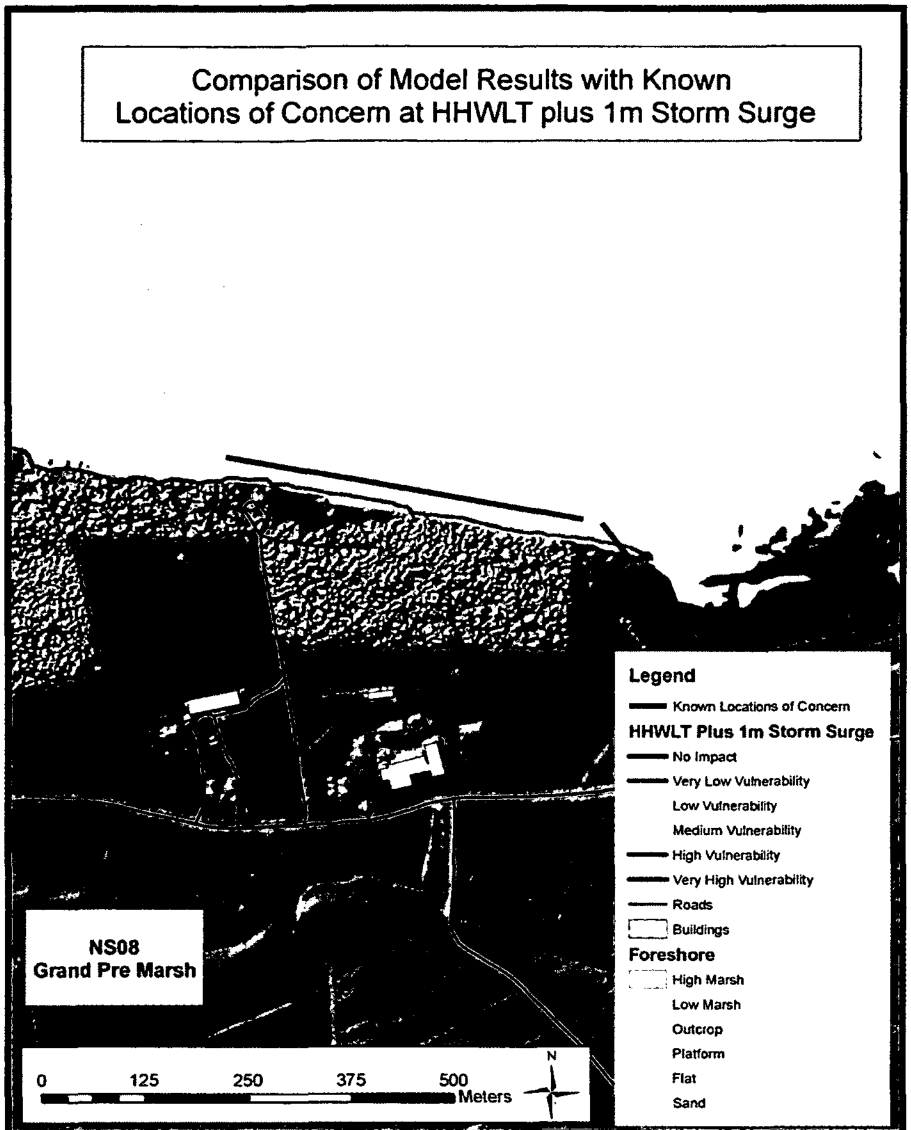


Figure 3.16 - Results of known locations of concern, as compared to the results produced for the backshore at HHWLT plus 1 m storm surge. The results of the model (high vulnerability) correspond to the known locations of concern, as observed in the field. This location has been deemed an area of concern by the Nova Scotia Department of Agriculture, due to presence of active erosion.

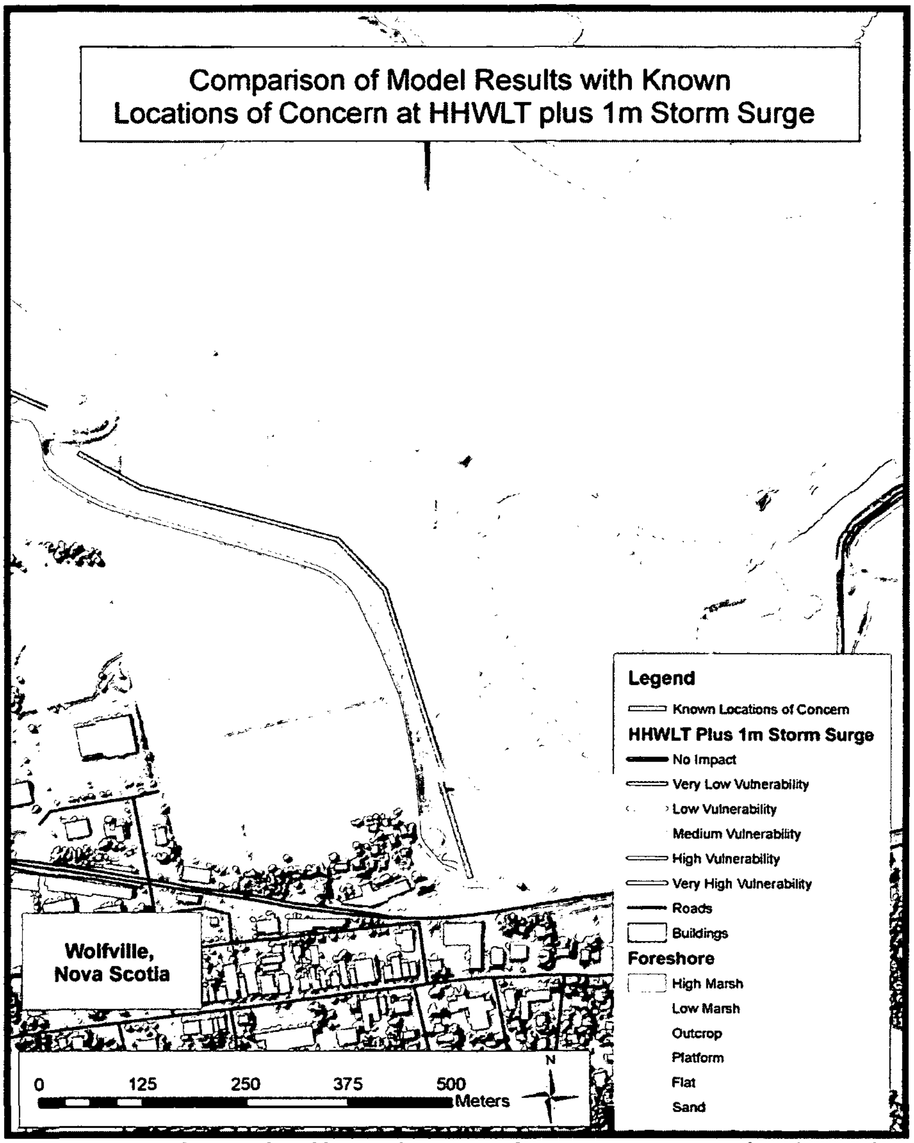


Figure 3.17 - Further results of known locations of concern, as compared to the results produced for the backshore at HHWLT plus 1 m storm surge. The results of the model (medium vulnerability) correspond to the known locations of concern, as observed in the field. This location has been deemed an area of concern by the Nova Scotia Department of Agriculture because dyke heights are below critical elevation.

High-energy waves, generated by wind and controlled by fetch length and water depth, break against a coastline, and cause coastal erosion. Coastal erosion does not only include the degradation of coastal features and removal of sediment, but also the transport and accumulation of the sediment elsewhere on the coast (O'Carroll et al., 2006). Within the foreshore (upper, middle and lower), vulnerable locations were compared with historic rates of erosion. The premise is that the locations which are continuously eroding will correspond to the areas which are consistently being assessed as high or very high vulnerability to the risk of storm surge. Digital lower foreshore coastlines were created for the years, 2008, 2002 and 1977 (based on the availability of satellite and aerial photography) in ArcGIS 9.3. The 2008 coastline was digitized from an ortho-rectified satellite image; the remaining shorelines were digitized from an air photo mosaic. Due to the multiple sources of coastline delineation, there is potential for error in each coastline position. Calculated trends of coastline position are only relatable as:

1. The data source from which they are derived.
2. Measurement errors that determine accuracy of position.
3. Sampling errors that account for variability of coastline position.
4. Statistical errors associated with compiling and comparing coastline positions.

(Morton, Miller and Moore, 2004; Moore, 2000; Crowell and Leatherman, 1999)

A position error equation was used to compute the precision of coastline position and is found in the equation below. The results of the equation, and the adjustments made to each year, are found in Table 3.5.

Equation 3.4

$$Esp = \sqrt{Er^2 + Ed^2 + Et^2 + Eo^2 + El^2}$$

Esp = Shoreline Position Error
Er = Rectification Error
Ed = Digitizing Error
Et = T-sheet Error
Eo = Shoreline Proxy Offset
El = LiDAR Position Error

[redacted]			
	2008	**2002**	**1977**
	5	5	5
	0	1	1
	0	0	0
	2	2	2
	2	2	2
	5.8	5.7	5.7

After addressing the shoreline position error for each coastline boundary, the erosion analysis was calculated through a software package called Analyzing Moving Boundaries Using R (AMBUR) developed by Jackson (2010). Throughout the entire study area, the AMBUR analysis has shown that the average net change is -3m (± 5.8 m), between 1977 and 2008; the result of the erosion analysis performed through AMBUR are found in Figure 3.18. The greatest net change is approximately -550 m (± 5.8 m) of erosion found within NS56 Wellington Marsh. The greatest amount of accumulation is approximately 150 m (± 5.8 m) and is located near the south-west corner of the NS08 Grand Pre Marsh. These results highlight locations that have predominantly experienced erosion; because high-energy waves are a leading factor in coastal erosion, it can be assumed that the locations with greatest erosion experience high-energy storm waves more frequently. Figures 3.19 and 3.20 are close-up views of marsh locations, which illustrate the erosion and accretion, throughout the study area.

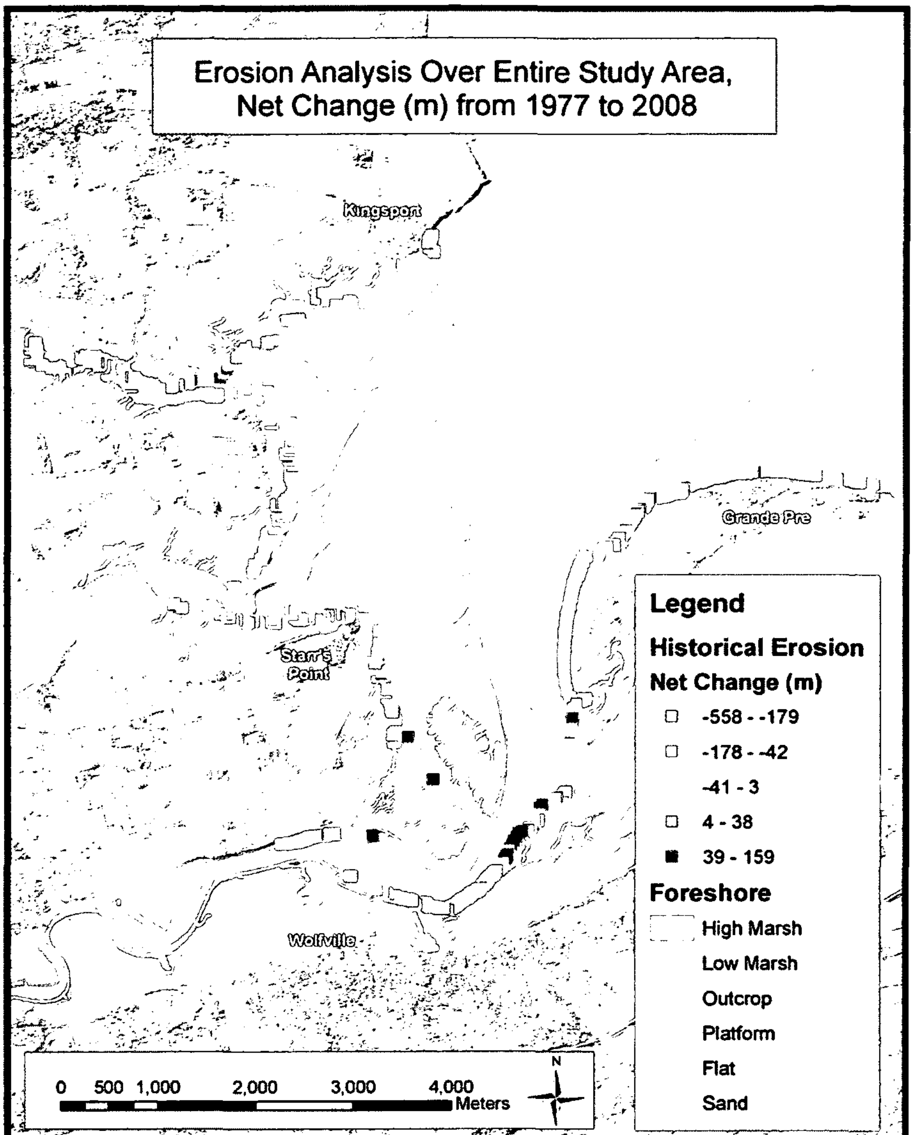


Figure 3.18 - Erosion analysis, performed through AMBUR, throughout the entire study area. This figure illustrates the net change in metres, from 1977 to 2008.

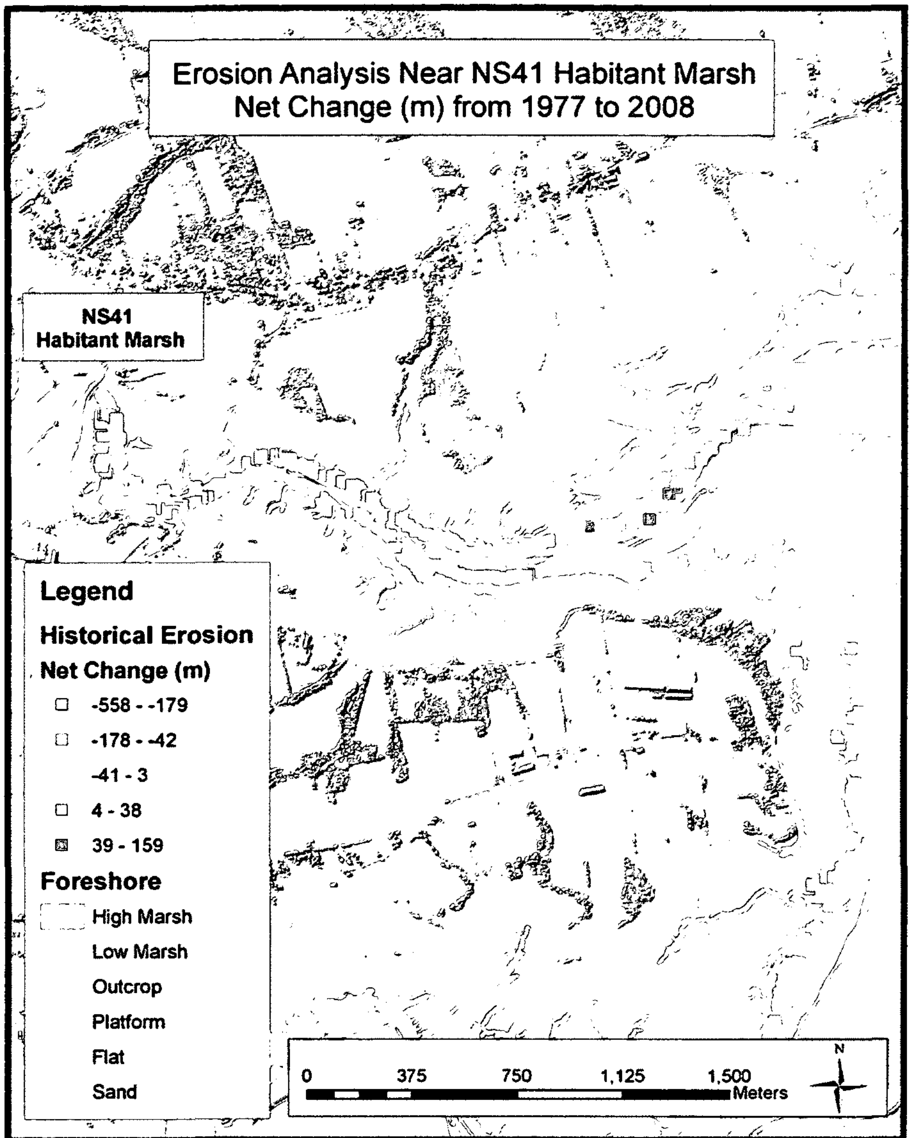


Figure 3.19 - A close up view of the AMBUR erosion analysis near the Habitant Marsh Area. This figure is meant to illustrate the distribution of erosion (net change in metres) within this area.

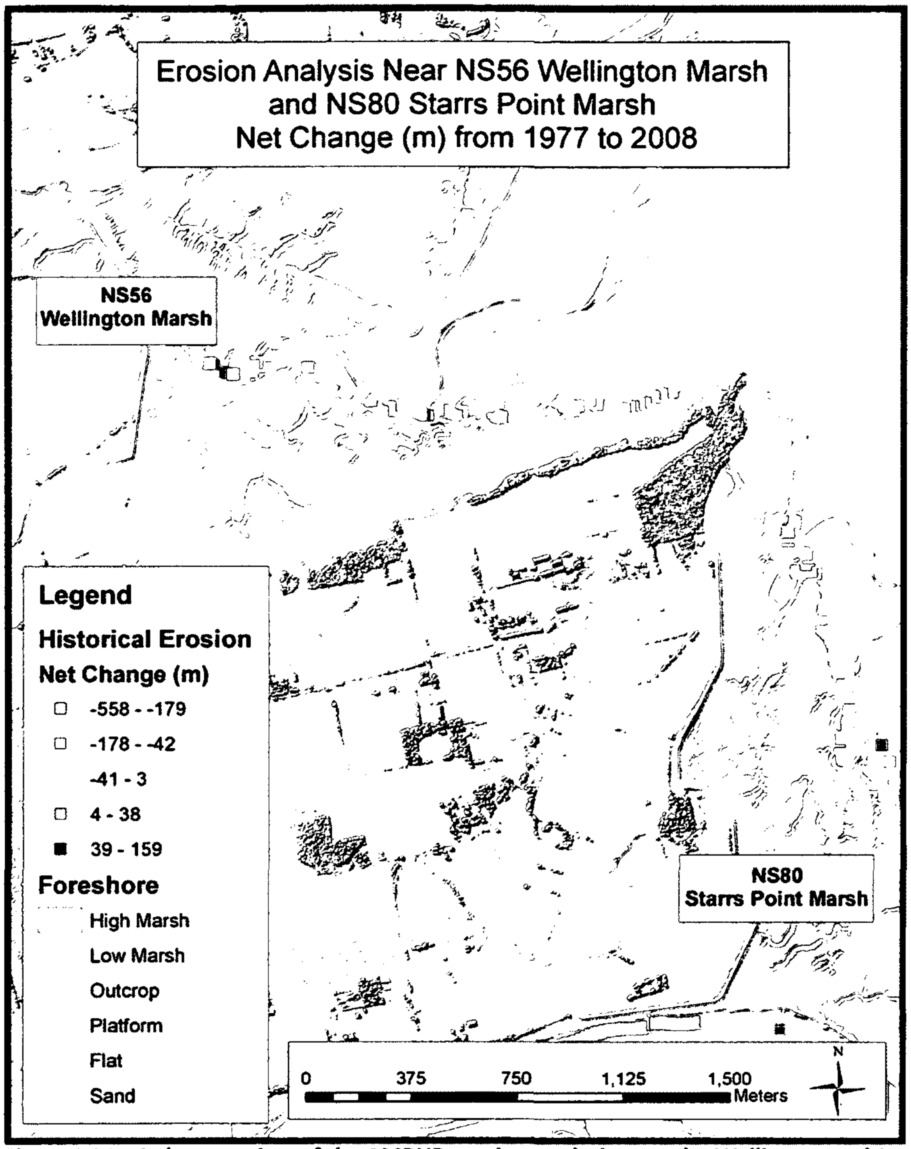


Figure 3.20 - A close up view of the AMBUR erosion analysis near the Wellington and Starrs Point marshes. This figure is meant to illustrate the distribution of erosion (net change in metres) within this area.

In order to prove the concept of this assessment tool, based on erosion analysis, a water level of 3 m was utilized; it is at this elevation that the tool assesses an increase in vulnerability throughout the lower foreshore. This increase is seen in Figure 3.11. As seen in Figures 3.21 and 3.22, the locations that have had the greatest negative change in shoreline movement are comparable to the assessment of vulnerability by the tool developed for this research. In Figure 3.21, as indicated by the solid oval, areas of erosion are comparable to locations that are being assessed as highly vulnerable. As shown by the dashed oval, zones of accretion are assessed as being no or low vulnerability. Figure 3.22 illustrates similar results, where zones of accretion are comparable to locations of low or no vulnerability.

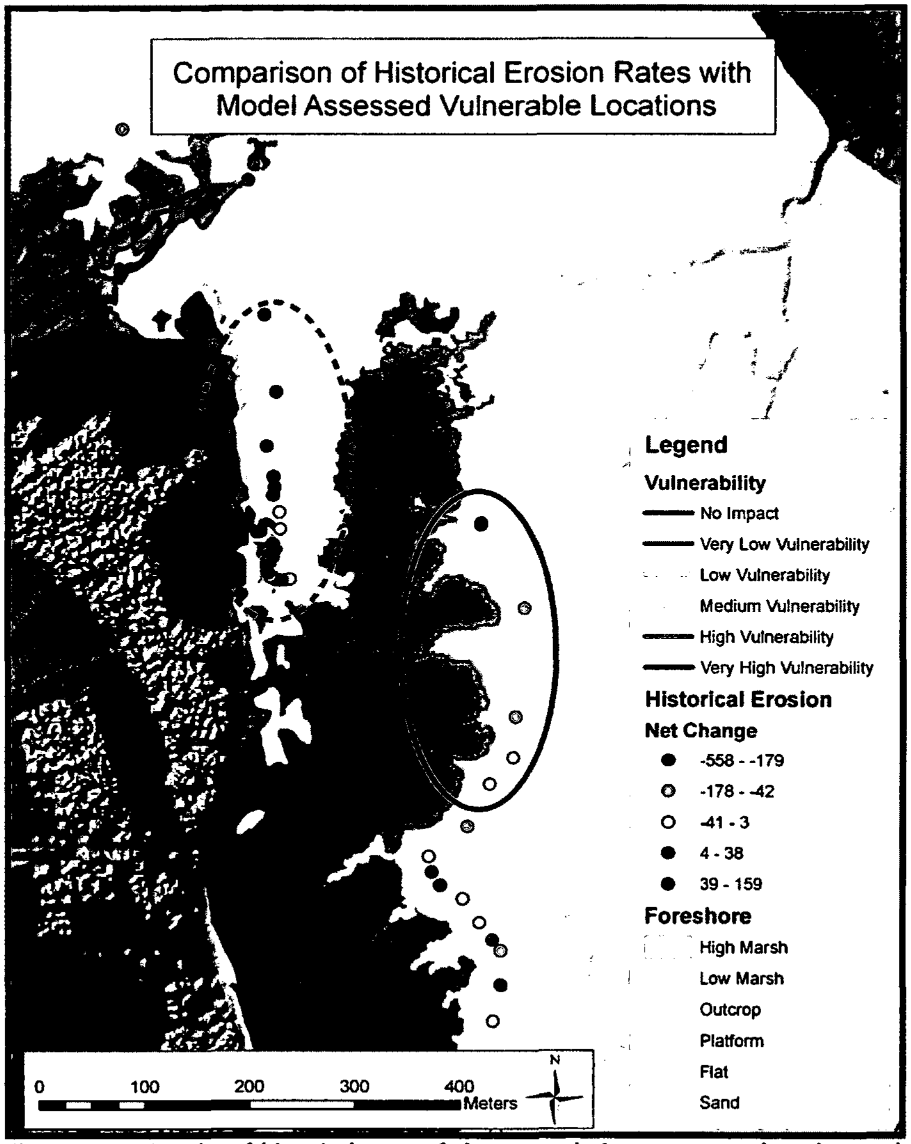


Figure 3.21 - Results of historical rates of change analysis, as compared to the results produced for the lower foreshore at 3 m total water level.

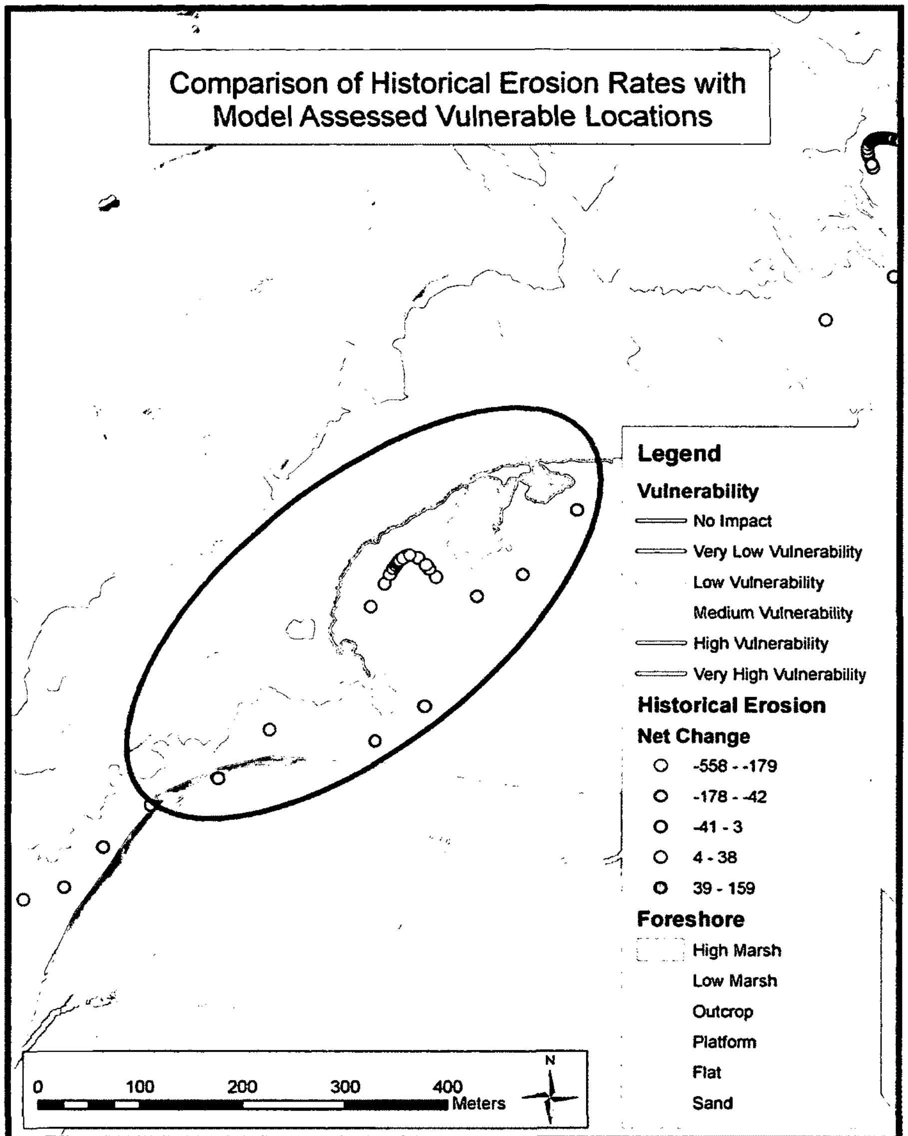


Figure 3.22 - Further comparison of historical rates of change analysis and results from the vulnerability assessment tool. The result from the model are the at 3m total water level for the lower foreshore.

The assessment results presented here are based on a relatively simple ranking approach but include several factors that influence the potential impact of storm surge on a macrotidal environment. The RCVI index is based only on bio-physical variables; with an emphasis on the influence of tide elevation (freeboard) and coastline exposure. The vulnerability maps produced by this research, give a visual representation of the distinction between the most vulnerable and least vulnerable locations for coastal managers and planners. Understanding that under these certain variables and conditions, certain parts of the coastline will be more vulnerable than others, allows for prioritization in installing adaptation measures, along with determining the most appropriate solutions (Aboudha and Woodroffe, 2010).

Previous studies suggest that with the integration of physical, social and economic variables, a broader (and potentially more accurate) assessment of vulnerability can be determined (Aboudha and Woodroffe, 2010; Cutter, 1996; Dolan and Walker, 2003; Sterr, Klein and Reese, 2000 and Wu, Yarnai and Fisher, 2002). Although the assessment tool developed here is based primarily on bio-physical characteristics, the efficiency of a GIS allows for simple assessment of socio-economic vulnerability. Once the user of the assessment tool, a coastal manager or planner, has determined vulnerable locations, a GIS query can select roads, buildings and populations adjacent to the location, and assign these features as 'at risk'. Understanding that infrastructure and populations may be at risk near a vulnerable feature allows for more comprehensive prioritization in adaptation solutions.

3.3 Conclusion

Climate change is driving the need for more effective adaptation solutions in the coastal zone. The initial step in determining the most appropriate adaptation strategies is a vulnerability assessment. The assessment tool designed in this research is a Python computer programming script, which assigns ranks to individual variables based on the biophysical characteristics of the coastline. These values were combined in order to calculate the relative vulnerability of the coast. This method yields quantitative results, based on both quantitative and qualitative data.

The relative coastal vulnerability index values were mapped to illustrate the coastal segments that are vulnerable according to the tide elevation and storm surge height (total water level). The vulnerability maps will provide insight and help guide decision making by coastal managers in implementation for adaptation solutions. One advantage of this tool is that it allows for guidance of long-term policy (i.e. placing restriction on building in vulnerable areas) and short-term policy (i.e. dissemination of resources in an emergency).

The vulnerability assessment tool designed for this research successfully highlights locations of concern, with increasing tide level, within a macrotidal environment, to the risks associated with a storm surge. Although these vulnerability classifications apply only to the study area, and compared with other possible study locations; simple changes to the python script and modification to the vulnerability matrix allows the tool to be used within other macrotidal environments. As well, the assessment tool is fully automated and is easily repeatable across all four target coastlines.

3.4 Literature Cited

Abuodha, P. A. O. and Woodroffe, C. D., 2010. Assessing vulnerability to sea level rise using a coastal sensitivity index: A case study from Southeast Australia. *Journal of Coastal Conservation*, 14, 189–205.

Boruff, B.J.; Emrich, C. and Cutter, S,L., 2005. Erosion hazard vulnerability of US coastal counties. *Journal of Coastal Research.* 21(5), 932-94.

Bryan, B.; Harvey, N.; Belperio, T. and Bourman, B., 2001. Distributed process modeling for regional assessment of coastal vulnerability to Sea-level Rise. *Environmental Modeling and Assessment*, 6, 57–65.

Chakhar, S. and Martel, J., 2003. Enhancing geographical information system capabilities with multi-criteria evaluation functions. *Journal of Geographic Information and Decision Analysis*, 7(2), 47 – 71.

Cooper, J.A.G. and McLaughlin, S., 1998. Contemporary multidisciplinary approaches to coastal classification and environmental risk analysis. *Journal of Coastal Research*, 14 (2), 512-524.

Cutter, S. L., 1996. Vulnerability to environmental hazards. *Progress in Human Geography*, *20*(4), 529-539.

Crowell, M. and Leatherman, S.P., (eds.), 1999. Coastal erosion mapping and management. *Journal of Coastal Research*, SI 28, pp. 1–196.

Desplanque, C. and Mossman, D., 2001. Bay of Fundy tides. *Geoscience Canada.* 25(1), 1-11.

Dolan, A.H., and Walker, I.J., 2003. Understanding vulnerability of coastal communities to climate change related risks. *Journal of Coastal Research*, SI 39 (Proceedings of the 8th International Coastal Symposium).

Fonseca, M.S. and Malhotra, A., 2010. WEMo (Wave Expose Model) for use in ecological forecasting. Applied Ecology and Restoration Research Branch NOAA, National Ocean Service. URL: http://www.csc.noaa.gov/digitalcoast/tools/wemo/index.html; accessed on May 30, 2011

Garmendia, E.; Gamboa, G.; Franco, J.; Garmendia, J.; Liria, P. and Olazabal, M., 2010. Social multi-criteria evaluation as a decision support tool for integrated coastal zone management. *Ocean & Coastal Management*, 53, 385-403.

Gornitz, V.M.; Daniels, R.C.; White, T.W. and Birdwell, K.R., 1994. The development of a coastal risk assessment database: Vulnerability to sea-level rise in the U.S. Southeast. *Journal of Coastal Research.* 12, 327-338.

Greenberg, D.A.; Blanchard, W.; Smith, B., and Barrow, E., in press. Climate change, mean sea level and high tides in the Bay of Fundy. Bedford Institute of Oceanography.

Harper, B.; Hardy, T.; Mason, L. and Frayer, R., 2009. Developments in Storm Tide Modelling and Risk Assessment in the Australian Region. *Natural Hazards*. 51(1), 225 - 238.

Jackson, C.W., Jr., 2010. Basic user guide for the AMBUR package for R, version 1.0a. Unpublished. URL: https://r-forge.r-project.org/projects/ambur/; accessed January, 20, 2012.

Kosloski, A., 2008. Planning for climate change and coastal zone management: Land use vulnerability, hazard, and exposure in Halifax Harbour, Halifax Regional Municipality. *Dalhousie University*, Master of Planning. URL: http://ccns.chebucto.org/Planning_CZM.pdf; accessed on March 20, 2012..

Kumar, T.S.; Mahendra,R.S.; Nayak, S.; Radhakrishnan, K. and Sahu, K.C., 2010. Coastal vulnerability assessment for Orissa State, East Coast of India. *Journal of Coastal Research.* 26(3), 523 - 534.

Leonard, L.A., and Reed, D.J., 2002. Hydrodynamics and sediment transport through tidal marsh canopies. *Journal of Coastal Research*, SI 36, 459 - 469.

Malczewski, J. 1999. *GIS and multicriteria decision analysis*. New York. John Wiley & Sons.

McInnes, K.L.; Walsh, K.J.E.; Hubbert, G.D. and Beer, T., 2003. Impact of sea level rise and storm surges on a coastal community. *Natural Hazards*, 30, 187 – 207.

McLaughlin, S., McKenna, J. and Cooper, J.A.G., 2002. Socio-economic data in coastal vulnerability indices: Constraints and opportunities. *Journal of Coastal Research*, 36, 487 – 497.

Moller, I., 2003. The sea-defence role of intertidal habitats. *In:* Ledoux, L., (ed.) *Wetland valuation: State of the art and opportunities for further development.*, University of East Anglia, Norwich, UK., pp. 73 -88.

Moller, I., and Spencer, T., 2002. Wave dissipation over macro-tidal saltmarshes: Effects of marsh edge typology and vegetation change. *Journal of Coastal Research* SI 36, 506 - 521.

Morton, R.A.; Miller, T.L., and Moore, L.J., 2004. National assessment of shoreline change: Part 1 historical shoreline change and associated coastal land loss along the U.S. Gulf of Mexico. U.S. Department of the Interior, U.S. Geological Survey Open-File Report 2004-1043. URL: http://pubs.usgs.gov/of/2005/1401/; accessed on March 20, 2012.

Morton. R.A., 2003. Factors controlling storm impacts on coastal barriers and beaches: A preliminary basis for near real-time forecasting. *Journal of Coastal Research,* 18 (3), 486-50.

Moore, L.J., 2000. Shoreline mapping techniques. *Journal of Coastal Research,* 16(1), 111-124.

O'Carroll, S., Bérubé, D., Forbes, D., Hanson, A., Jolicoeur, S. and Fréchette, A. 2006. Coastal erosion. *In:* Daigle, R. (ed.) *Impacts of sea-level rise and climate change on the coastal zone of Southeastern New Brunswick,* New Brunswick Department of Environment. pp. 324-401.

Owens, E.H.,1994. Coastal zone classification system for the national sensitivity mapping program. Internal Report, Environment Canada. Cat.No.En 40-488/1995E, Dartmouth, N.S.

Ozyurt, G. and Ergin, A., 2010. Improving coastal vulnerability assessments to sea-level rise: A new indicator based methodology for decision makers. *Journal of Coastal Research,* 26(2), 265–273.

Pendleton, E.A.; Thieler, E.R., and Williams, S.J., 2010. Importance of coastal change variables in determining vulnerability to sea- and lake-level change. *Journal of Coastal Research,* 26(1), 176–183.

Pendleton, E.A.; Jeffress S. W. and Thieler E. R., 2004. Coastal vulnerability assessment of Assateague Island National Seashore (ASIS) to sea level rise. *U.S. Geological Survey* Open-File Report 2004-1020, Electronic Book. URL: http://pubs.usgs.gov/of/2004/1020/images/pdf/asis.pdf; accessed on July 5, 2011.

Rao Nageswara, K.; Subraelu, P.; Rao Venkateswara, T.; Hema Malini, B.; Ratheesh, R.; Bhattacharya, S. and Rajawat, A. S., 2008. Sea-level rise and coastal vulnerability: an assessment of Andhra Pradesh coast, India through remote sensing and GIS. *Journal of Coastal Conservation*, 12, 195 – 207.

Shaw, J.; Taylor, R.B.; Solomon, S., Christian, H.A. and Forbes, D.L., 1998. Potential impacts of global sea level rise on Canadian coasts. *The Canadian Geographer*, 42(4), 365-379.

Sherin, A.G.; Fraser, P.; Solomon, S.; Forbes, D.L.; Jenner, K.A.; Hynes, S.; Lynds T. and Gareau. P., 2003. A decade in the life of a coastal information system. Proceedings, CoastGIS 2003: 5th International Symposium on GIS and Computer Cartography for Coastal Zone Management, Genoa, Italy URL: http://www.gisig.it/coastgis/papers/sherin.htm.; accessed on March 30, 2012.

Sterr, H.; Klein, R., and Reese, S., 2000. Climate Change and Coastal Zones: An Overview of the State-Of-The-Art on Regional and Local Vulnerability Assessment. URL: http://www.sterr.geographie.uni-kiel.de/downloads/ClimateChange.pdf; accessed on March 20, 2012.

Thieler, E.R., and Hammar-Klose, E.S., 1999. National assessment of coastal vulnerability to future sea-level rise: Preliminary results for the U.S. Atlantic Coast: U.S. Geological Survey, Open-File Report 99-593. URL: http://woodshole.er.usgs.gov/project-pages/cvi/; accessed on March 20, 2011.

Tibbetts, J.R.; van Proosdij, D. and Forbes, D., Submitted for Review. Conceptual Framework for Assessing Vulnerability in a Macrotidal Environment.

Titus, J.G. and Anderson, K.E., 2009. Coastal sensitivity to sea level rise: A focus on the mid-Atlantic Region. *Climate Change Science Program (U.S.)*, Executive Summary. URL: http://www.epa.gov/climatechange/effects/coastal/sap4-1.html; Accessed on March 20, 2012.

Usery, L.; Choi, J. and Finn, M., 2010. Modeling sea level rise and surge in low-lying urban areas using spatial data, geographic information systems, and animation methods. *Geospatial Techniques in Urban Hazard and Disaster Analysis.*

van Proosdij D. and Pietersma-Perrott B., 2012. Shore zone characterization for climate change adaptation in the Bay of Fundy. Saint Mary`s University. URL: http://atlanticadaptation.ca/ accessed on March 18, 2012.

Vasseur, L.; Catto, N.; Burton, D.; Chouinard, O.; Davies, J.; DeBaie, L.; Duclos, G.; Duinker, P.; Forbes, D.; Hermanutz, L.; Jacobs, J.; Leger, L.; McKenzie, K.; Parlee, K., and Straatman, J., 2008. "Atlantic Canada" *In:* Lemmen, D.S., Warren, F.J., Lacroix, J. and Bush, E. (eds.), *From impacts to adaptation: Canada in a changing climate 2007*, Government of Canada, pp. 119-170.

Webster, T.; McGuigan, K., and MacDonald, C., 2011. Lidar processing and Flood Risk Mapping for Coastal Areas in the District of Lunenburg, Town and District of Yarmouth, Amherst, County Cumberland, Wolfville and Windsor. Climate Change Directorate, Nova Scotia Department of the Environment. URL: http://atlanticadaptation.ca/node/128; accessed March 7, 2012.

Wolf, J., 2009. Coastal flooding: Impacts of coupled wave-surge-tide model. *Natural Hazards*, 49, 241 – 260.

Wu, S.Y.; Yarnai, B. and Fisher, A., 2002. Vulnerability of Coastal Communities to Sea Level Rise: A Case Study of Cape May County, New Jersey. *Climate Research*, 22, 255 – 270.

Chapter 4

Coastal Vulnerability Assessment in a Macrotidal Environment: A Synthesis

4.1 GIS and Coastal Management

This thesis documents two advances in the field of coastal vulnerability assessment, in the context of a macrotidal environment: First, a conceptual framework for assessing vulnerability within macrotidal environments and second, a GIS-based tool for decision-making support in coastal zone management.

Coastal management is effectively the management of space (Fedra and Feoli, 1998). Spatial management is the distribution and allocation of space, in reference to a multitude of uses, activities, processes and conflicts that can occur within the space. In 1995, the United Nations Environmental Program (UNEP) highlighted the tools and techniques unique to a GIS as an important management toolbox for providing solutions to solve major conflicts within the coastal zone (Fedra and Feoli, 1998). A GIS is a suite of tools which allow a user to capture, process and display spatially referenced data. This set of tools allows for the development of a management application or decision support system for spatially related problems (Fedra and Feoli, 1998; Thumerer et al., 2000).

The GIS-based assessment tool designed for this research accounts for the dynamic interaction between tide elevation and its influence on storm surge potential. Although previous coastal vulnerability assessments have been developed, none have emphasized the importance of changing tide elevation. As discussed previously in this thesis, this importance is amplified in a macrotidal environment, due to the range in tide elevations that are possible. As tide elevation increases, there is potential for an increase in coastal vulnerability to a storm surge (Desplanque and Mossman, 2001; Greenberg et al, in press).

The conceptual framework designed to address coastal vulnerability in a macrotidal environment attempts to address influence of tide elevation on the impact of a storm surge. Essentially, the tide elevation and the incoming wave characteristics act as a type of filter for vulnerability. These characteristics are used to describe the coastline's 'exposure condition'. The framework attempts to illustrate that if the tide elevation is low, exposure will be limited; as tide elevation increases, the coastline's vulnerability will also increase due to an increase in exposure. Although this concept seems simplistic, it is central to evaluating vulnerability in a macrotidal environment. This filtering action is seen in Figure 3.11 of Chapter 3, where for each coastline there is a distinct tide elevation where the majority of the coast being assessed is at high or very high vulnerability. The physical and resilience conditions are used to further define how the coastline is exposed to the hazard and therefore illustrates the overall vulnerability of the coastline.

Along with the conceptual framework, an intuitive GIS-based tool that determines the relative vulnerability of a macrotidal coastal environment to the increased risk of storm surges associated with climate change, assists coastal managers in identifying and understanding locations of weakness and prioritizing adaptation solutions. Knowing where to focus time and resources allows for a more efficient management of the coast, which could save money, infrastructure and most importantly, human livelihood (Hart and Knight, 2009; Thumerer et al., 2000). The assessment tool designed for this research was tested within the Cornwallis River Estuary, Nova Scotia, Canada, which has a maximum tidal range of 16 m (Desplanque and Mossman, 2001). The results of the tool were tested against locations of known dyke overtopping along the backshore. The comparison of these locations, along with historical erosion data calculated in AMBUR, has shown that the model does highlight areas of concern, and can be used as a vulnerability assessment tool.

Although this GIS-based assessment method can be used to highlight areas of concern in reference to storm surges within macrotidal environments, the tool has limitations. The vulnerability values calculated by the tool are for non-ice conditions. Historically, the Bay of Fundy is has been prone to ice conditions for several months during the year. Although the reasoning for excluding ice as a variable was explained earlier in this thesis, further analysis and research could include the factor of ice.

The results from Chapters 2 and 3 will aid the Atlantic Canada Adaptation Solutions (ACASA) project in achieving its main goals and objectives. The essential goal executed through this research was the development of a tool, in order to increase knowledge for more meaningful, and appropriate coastal adaptation solutions. The recommendations mentioned in this chapter, along with the tool itself, will help guide coastal managers and decision-makers. This tool is intended to aid in decision making within the context of ACASA, but also to provide an assessment method for vulnerability in macrotidal environments on a global scale.

4.2 Climate Change Adaptation Recommendations for Bay of Fundy, Nova Scotia

The climate change adaptation procedures introduced in Chapter 1 of this thesis (United Kingdom and Louisiana) are different in their application, but similar in objectives. Both aim to protect coastal communities from storms, storm surges and flooding under climate change. They do so with one common theme, which is the restoration of natural processes in order to offset climate change impacts. In the United Kingdom, the policy of managed realignment is suggested as the most appropriate method for coastal protection. Managed realignment also encourages a shift from the use of 'hard' structural defences to 'soft' engineering practices. This shift occurred due to the realization that natural processes play a fundamental role in coastal defence (DEFRA, 2009; DEFRA, 2005; DEFRA 2003). Similarly, the Louisiana's Master Plan for a Sustainable Coast, emphasizes the use of multi-line defences, with natural features being the initial buffer (CPRA, Chapter 3, 2007; Lopez 2006).

Nova Scotia has a draft policy which calls for no net loss of wetlands in the province. The draft policy was developed in response to the Environment Goals and Sustainable Prosperity Act in 2007 (Government of Nova Scotia, Nova Scotia Environment, 2009). The protection and restoration of Nova Scotia's wetlands has many benefits, such as providing important habitats for many species of marine and terrestrial wildlife and vegetation, filtering organic waste and bacteria from the ecosystem and minimizing erosion rates in some coastal areas. Another important benefit found in the policy is the protection wetlands provide from storm surges and other storm related events. According to the wetland conservation policy, the current level of salt marshes in Nova Scotia provide over $400 million worth of ecosystem services to Nova Scotia each year, including flood prevention/protection and a reduction in erosion rates (Government of Nova Scotia, Nova Scotia Environment, 2009). The benefit of restoring and using wetlands as natural barriers, which allow for protection from storm and storm surge events, is seen in Table 4.1.

Table 4.1 – Hazard/Risk Matrix – Coastline Exposure												
	Total Water Level (tide plus surge) in meters											
Coastline	1	2	3	4	5	6	7	8.15	8.65	9.15	9.65	10.15
Backshore												
Upper Foreshore												
Middle Foreshore												
Lower Foreshore												

Table 4.1 – The mean coastline exposure value (as calculated with WEMo) for each water level, from a 1 m to 10.15 m (CGVD28). After 8.15 m (HHWLT) the total water level values correspond to a 0.5 m storm surge value. For example, 8.65 total water levels would equate to HHWLT plus a 0.5m storm surge.

Vulnerability	**Legend**
Very High	
High	
Medium	
Low	
Very Low	
No Impact	

This table resembles a risk matrix, which shows the mean coastline exposure value for each of the four target coastlines, with increasing water level. All water levels are referenced to the Canadian Geodetic Vertical Datum (CGVD28). Coastline exposure was calculated use WEMo 4.0, a wave exposure model; this model uses local wind and bathymetry data (which includes the foreshore) in its calculations. Due to its use of bathymetry, the benefit of having a natural barrier as a buffer against storm surge events can be seen with coastline exposure.

As seen in Table 4.1, the backshore benefits from having a wide foreshore preceding it. In the terms of exposure, even at the highest water levels assessed for this study, mean exposure at the backshore remains very low. However, at the lower foreshore, where width of foreshore is almost non-existent, the mean exposure value is high. The vulnerability assessment results of the upper, middle and lower foreshore further demonstrate the influence of a wide foreshore on the vulnerability of a coastline. These results illustrate that at certain water levels, a foreshore buffer is no longer effective, and this is closely linked to the elevation of the coastline. In Figure 4.1, the assessment results for the lower foreshore at 3 m total water level are displayed. This figure shows that the majority of coastline is not categorized as high or very high vulnerability, only 12%. Figure 4.2, displays the results for the lower foreshore at 4 m total water level. The length of coastline categorized as high or very high vulnerability increases to approximately 75% at this water level.

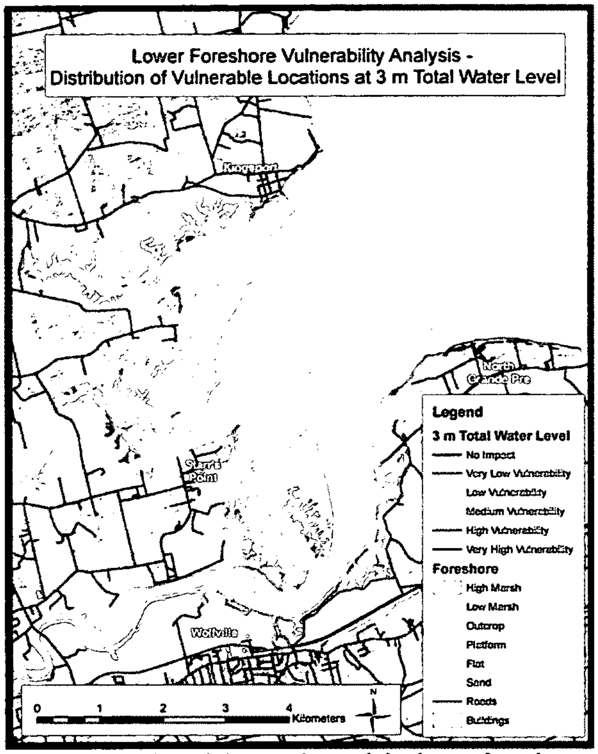


Figure 4.1 - Vulnerability analysis of the lower foreshore at 3 m total water level (CGVD28). The majority of the coastline is categorized at or below medium vulnerability, with approximately 12% being high or very high vulnerability.

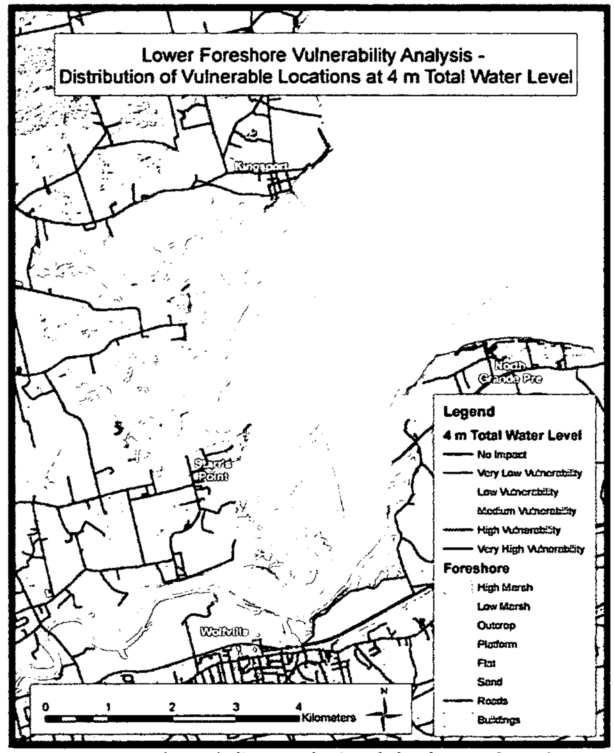


Figure 4.2 - Vulnerability analysis of the lower foreshore at 4 m total water level (CGVD28). At this water level, coastline categorized at high and very high vulnerability increases to approximately 75%

The average coastline elevation at the lower foreshore is 2.2 m. There is a dramatic increase in the percentage of coastline that is high or very high vulnerability because the water depth decreases the ability of marsh vegetation to impact wave propagation and absorbed wave energy. This understanding is further demonstrated in Table 4.1, where for the lower foreshore coastline there is a shift from no impact to very low vulnerability at the 2 m total water level and 3 m total water level threshold. A distinct threshold, where the foreshore no longer acts as a buffer, is found when analyzing the middle and upper foreshore results. Figure 4.3 shows the distribution of high and very high vulnerable locations throughout the middle foreshore at 6 m total water level. As seen in Figure 4.4, an increase to 7 m total water level accounts for percentage of coastline categorized as highly vulnerable increases from 24% to 75%. The average coastline elevation at the middle foreshore is 4.8 m. As seen in Table 4.1, the threshold from no impact to very low vulnerability occurs at this elevation.

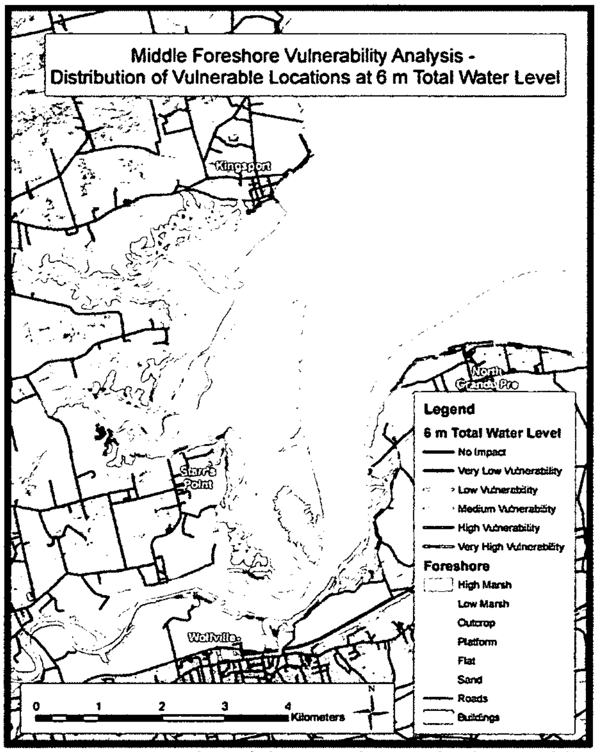


Figure 4.3 - Vulnerability analysis of the middle foreshore at 6 m total water level (CGVD28). The majority of the coastline is categorized at or below medium vulnerability, with approximately 24% being high or very high vulnerability.

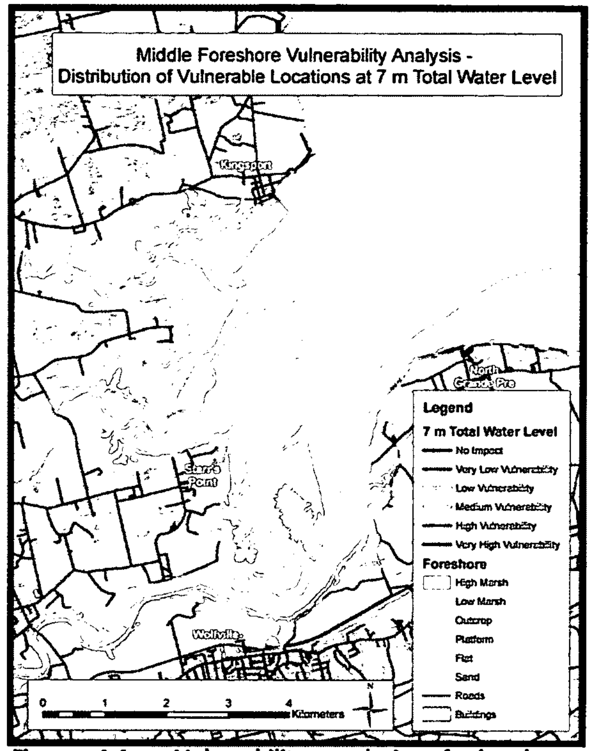


Figure 4.4 - Vulnerability analysis of the lower foreshore at 7 m total water level (CGVD28). At this water level, coastline categorized at high and very high vulnerability increases to approximately 75%

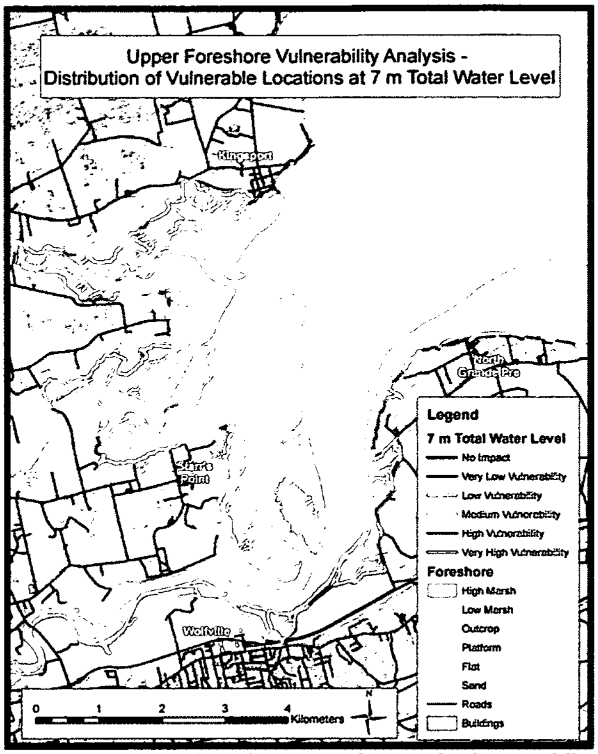


Figure 4.5 - Vulnerability analysis of the middle foreshore at 7 m total water level (CGVD28). The majority of the coastline is categorized at or below medium vulnerability, with approximately 21% being high or very high vulnerability.

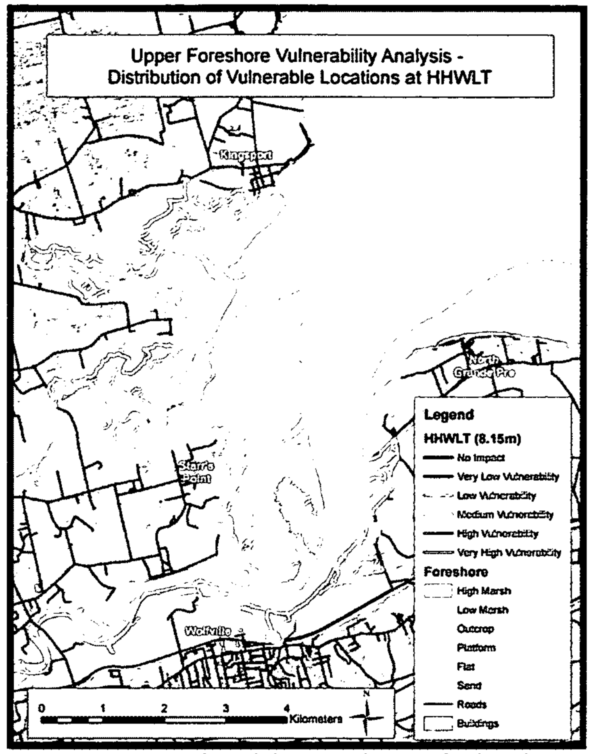


Figure 4.6 - Vulnerability analysis of the lower foreshore at HHWLT or 8.15 m total water level (CGVD28). At this water level, coastline categorized at high and very high vulnerability increases to approximately 65%

Figure 4.5 displays the distribution of vulnerable locations at the upper foreshore for 7 m total water level. At this water level, approximately 21% of the coastline is found to be high or very high vulnerability. Figure 4.6 shows the distribution of high and very high vulnerable locations at HHWLT, or 8.15 m total water level. The amount of coastline classified in this range increases to 65% with the water level. The average coastline elevation at the upper foreshore is 6.6 m. As seen in Table 4.1, the threshold from no impact to very low vulnerability occurs at this elevation.

Although the Environmental Goals and Sustainable Prosperity Act aimed to establish a no net loss of wetlands policy by 2009, the Nova Scotia Conservation Policy was not adopted until September 2011. The goal of this policy is to prevent the net loss of wetland in Nova Scotia through wetland conservation. The initial recommendation for climate change solutions would be to adhere to the policy the Government of Nova Scotia has set out, with a focus on conserving wetland environments as natural buffers to coastal storms and storm surges.

The concept of managed realignment would also benefit Nova Scotia. In areas where there are older coastal defences in place, it is potentially more cost effective to set back new defences away from the coast, and protect only the most vulnerable locations. Reinforcing older, potentially obsolete structures, or constructing new structures at current positions, may have a higher price in the end. As well, managed realignment allows for natural processes to occur. Natural development would lead to coastal features such as salt marshes, which provide protection from storm surge and flooding events.

4.3 Discussion

The purpose of this section is to discuss implications of possible alterations to the assessment tool developed for this thesis. The first section aims to assess alternative methods for displaying the final relative coastal vulnerability index (RVCI) values calculated by the tool. The simple act of assigning the RCVI values into categories from very low to very high vulnerability will have implications on how vulnerability is perceived by the end user. The final section assesses the implication of removing certain variables from the RCVI equation in order to demonstrate the overall influence of these variables.

4.3.1 Vulnerability Classification

As discussed in Chapter 3 of this thesis, there are alternative ways to develop ranges for which to place the vulnerability index values into. It is important to realize that the selection of these ranges can lead to quite different impressions on the degree of vulnerability. This has implications on how stake holders, coastal planners and others involved in climate change adaptation, perceive potential risks at the coast. This section explores 4 different methods for displaying the RCVI values that are calculated by this assessment tool; a comparison of the different methods at the backshore for HHWLT (8.15 m - CGVD28) is found in Figures 4.7 – 4.10.

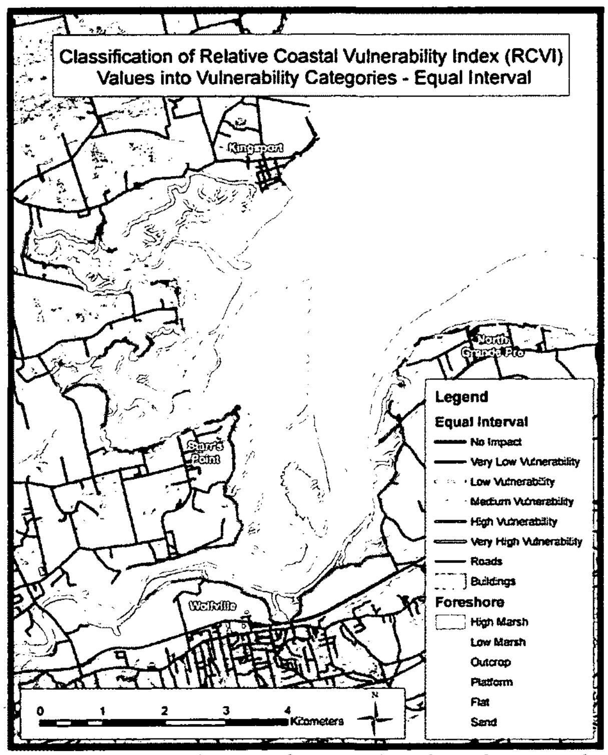


Figure 4.7 – Distribution of RCVI values based on equal interval ranges. This range method was used throughout this research.

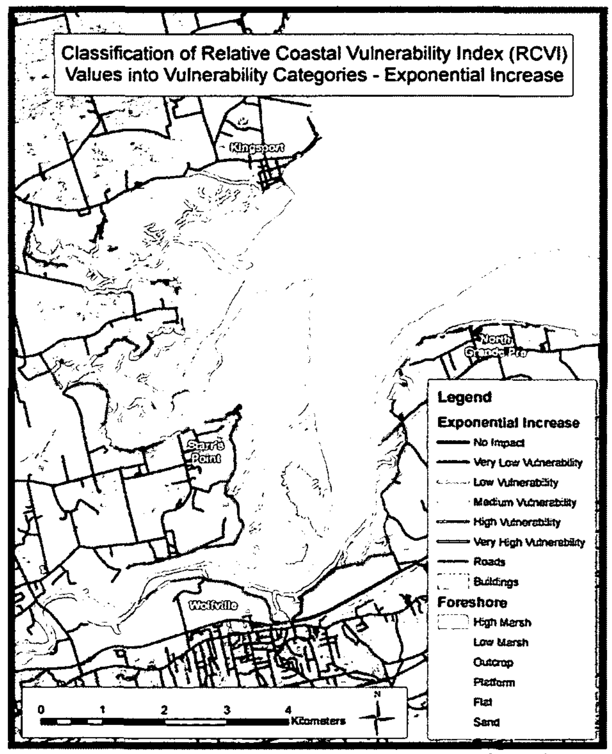
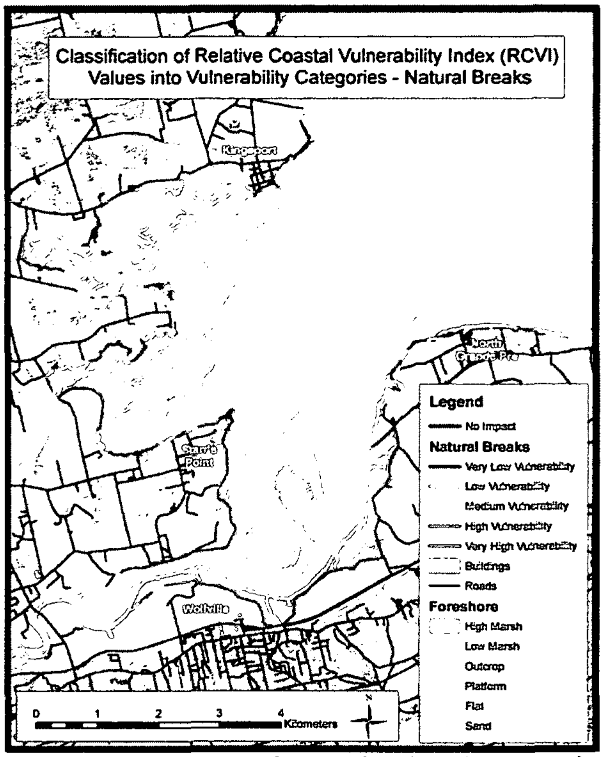


Figure 4.8 – Distribution of RCVI values based on exponentially increasing ranges. In this example, range size increases by 25%, with the smallest range being very low vulnerability and the largest range being very high vulnerability.



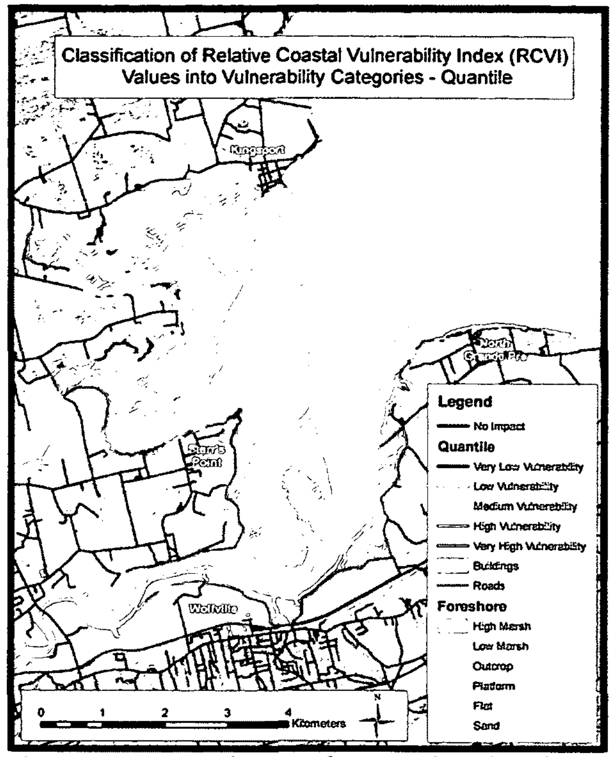


Figure 4.9 – Distribution of RCVI values based on natural breaks classification. This classification method uses an algorithm to calculation natural breaks (ranges) that are found within the data.

Figure 4.10 – Distribution of RCVI values based on quintile classification. This classification method assigns an equal number of features to each range.

For each of the methods, there are distinct ranges for classifying vulnerability; these range division are found in Table 4.2. With equal interval classification 5% (2271 km) of the backshore is found to be classified as high or very high vulnerability. Natural breaks and Quintile classification assigned 16% (7219 km) of the backshore at high or very high. Lastly, exponential increase classifies the 23% (10,339 km) of the backshore at high or very high vulnerability.

	Equal Interval	Exponential Increase	Natural Breaks	Quintile
	11.51 – 14.10	10.37 – 14.10	9.48 – 11.94	8.31 – 11.94
	9.10 – 11.50	7.37 – 10.46	7.81 – 9.47	7.81 – 8.30
	6.50 – 9.09	4.97 – 7.36	6.82 – 7.80	6.99 – 7.80
	4.00 – 6.49	3.05 – 4.96	5.48 – 6.81	6.16 – 6.98
	1.49 – 3.99	1.49 – 3.04	3.81 – 5.47	3.81 – 6.15

Table 4.2 – This table displays the range of RCVI values for each of the four classification methods investigated for this research. Each range corresponds to one of the 5 vulnerability categories (very low – very high).

Although several previous studies have utilized the quintile method for RCVI divisions (Aboudha and Woodroffe, 2010; Bryan et al., 2001; Pendleton, Thieler and Williams, 2010), this research assigned ranges based on equal interval. This method was selected due to the need to compare RCVI values across four coastlines (backshore, upper, middle and lower foreshore), where one coastline assessed in the studies mentioned. Having a consistent set of five equal ranges based on the lowest possible index value (1.49) and the highest possible index value (14.10), allows for comparison of vulnerability across each coastline. A classification of very high vulnerability, with equal interval, will always be a RCVI value between 11.51 and 14.10 across all four coastlines. This is not true with natural breaks or quintile classification and comparison between the coastlines is not possible.

4.3.2 Variable Analysis

The vulnerability index values, for this research, were calculated based on the sum of all ranked variables, and a weighted value for each variable's corresponding condition.

The grouping of variables within conditions and the weighting scheme for these conditions is found in Chapter 3 of this thesis. The final equation used to calculate the RCVI values is found below.

Equation 4.1

Relative Coastal Vulnerability Index=
(Exposure condition*0.50) + (Physical condition*0.33) + (Resilience condition*0.17)

In order to demonstrate the influence, if any, of certain variables in this calculation, additional iterations of the formula have been developed. The additional iterations to test the influence of certain variables are found in Table 4.3.

[redacted]	Iteration 1	Iteration 2	Iteration 3	Iteration 4
[redacted]	X	X		X
[redacted]	X	X	X	
[redacted]	X		X	X
[redacted]	X	X	X	X
[redacted]	X	X	X	X
[redacted]	X	X	X	X
[redacted]	X	X	X	X
[redacted]	X	X	X	X
[redacted]	1.49 – 14.10	1.16 – 10.82	1.49 – 11.60	1.49 – 11.60
[redacted]	5%	5%	2%	5%

Table 4.3 – This table displays the variables used within different iterations of the RCVI formula developed for this research. These iterations aid to test the influence of certain variables on the overall calculation of vulnerability within a macrotidal environment. As well, the range of index values along with the percentage of vulnerable coastline has been included. The comparison of RCVI range and percent of vulnerable coast, for each iteration, was conducted at higher high water large tide (HHWLT) at the backshore.

As seen in Table 3.3, the first iteration involves all 8 variables selected for this research. The second involves the removal of the width of foreshore and vegetation from this calculation. This was done to test the influence of width of foreshore and vegetation as a buffer to wave energy in a marcotidal setting. The underlying assumption is that a coastline with a wide foreshore and vegetation will be determined as having a lower vulnerability than one without these features. The third iteration incorporated all variables except for freeboard. As discussed in Chapter 2 and 3, freeboard is considered the most influential variable for determining vulnerability in a macrotidal environment. The final iteration excludes the coastline exposure variable. Excluding this variable from the calculation of vulnerability, provides the opportunity for the exposure values to be used as method of the validity for the assessment tool.

The comparison of these iterations was conducted at higher high water large tide (HHWLT) at the backshore. The first iteration is equal to the equation used throughout this research and extensive analysis for this iteration is found in Chapter 3 of this thesis. Iteration 2, the removal of width of foreshore and vegetation from the calculation resulted in an index ranging from the lowest of 1.16 to the highest of 10.82. The percentage of coastline found to be high or very high vulnerability is 5%. Not only does the percent of vulnerable coastline equate to iteration 1, but the exact same coastline segments make up this percentage. This means that excluding width of foreshore and vegetation within the RCVI equation does not alter the final results. Iteration 3, which excluded freeboard from the calculation of vulnerability, produced index values ranging from the lowest of 1.49 to the highest of 11.60. The percentage of coastline found to be high or very high vulnerability with this iteration is only 2%. This illustrates that including freeboard within

the final equation does significantly alter the final results. The final iteration aimed to exclude the coastline exposure variable to test its applicability for validating the final results of the tool. The coastline exposure values, as calculated using the Wave Exposure Model (WEMo) version 4.0, indicate the estimated level of wave energy for each 250 m segment of the coastline. By excluding this variable from the equation to calculate vulnerability, it allows these estimated energy values to be compared to the final outputs of the assessment tool. The hypothesis being coastline segments receiving high-energy values would equate to the locations being classified as high or very high vulnerability.

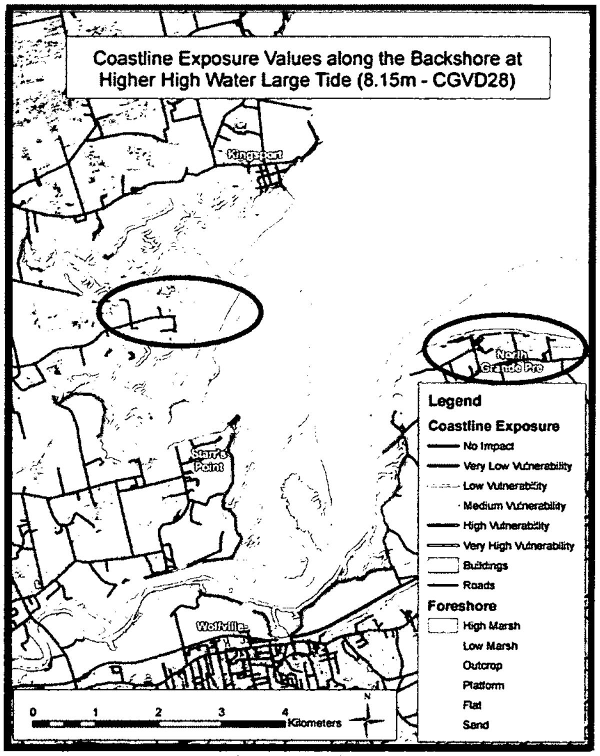


Figure 4.11 – Distribution of coastline values as calculated by WEMo. The coastline exposure values have been ranked from No Impact to very high vulnerability, based on the vulnerability matrix, found in Chapter 3. Solid ovals indicate the locations of highest exposure.

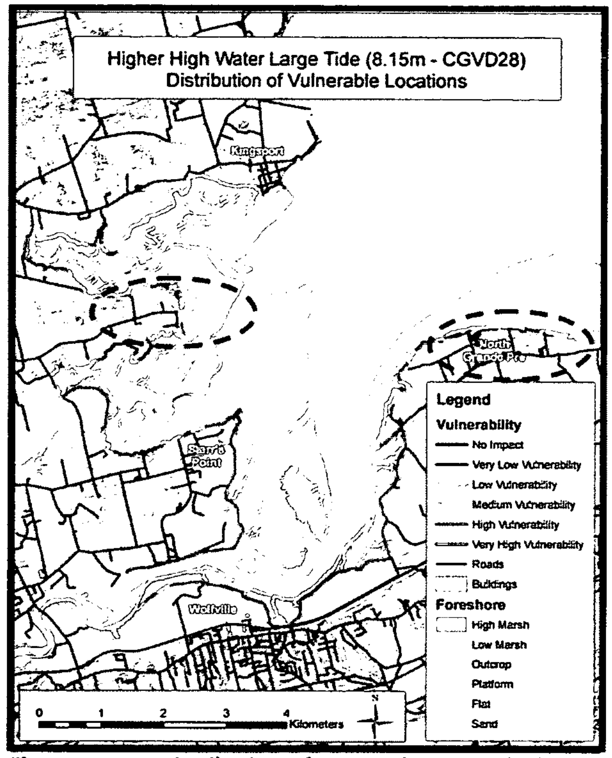


Figure 4.12 – Distribution of RCVI values as calculated by the assessment tool designed for this research.

The distribution of the coastline exposure values as calculated with WEMo is found in Figure 4.11. Visual interpretation of this figure shows that the highest exposure areas are found North of NS08 Grande Pre Marsh and along the coast near Lower Canard, Kings County, Nova Scotia (as indicated by the solid ovals). Figure 4.12 illustrates the most vulnerable locations, as calculated with the assessment tool, are also North of NS08 Grande Pre Marsh and Lower Canard (as indicated by the dashed ovals). Although visual interpretation to the two figures suggest that the coastline exposure values could be used as a method of validation, more extensive analysis of the results indicates little similarity between the two. Percentage of coastline at high or very high exposure (Figure 4.11) is at 12%, while the percentage is at 5% for the vulnerability assessment tool. As well, the percentage of coastline at low or very low exposure is at 82%, while the percentage is at 60% for the assessment tool. Future research should consider not including multiple variables within the three 'conditions' and applying a weight to the group; but rather apply a weighted value to the individual variables. Applying a weight to individual variables would more accurately illustrate the influence of certain variables in the overall calculation of coastal vulnerability.

4.3 Literature Cited

Abuodha, P. A. O. and Woodroffe, C. D., 2010. Assessing vulnerability to sea level rise using a coastal sensitivity index: A case study from Southeast Australia. *Journal of Coastal Conservation*, 14, 189–205.

Bryan, B.; Harvey, N.; Belperio, T. and Bourman, B., 2001. Distributed process modeling for regional assessment of coastal vulnerability to Sea-level Rise. *Environmental Modeling and Assessment*, 6, 57–65.

Coastal Protection and Restoration Authority (CPRA), 2007. Integrated ecosystem restoration and hurricane protection: Louisiana's comprehensive master plan for a sustainable coast, Baton Rouge. URL: http://coastal.louisiana.gov/index.cfm?md=pagebuilder&tmp=home&nid=24&pnid=0&pid=28&fmid=0&catid=0&elid=0; accessed on January 15, 2011.

Department for Environment, Food and Rural Affairs, (DEFRA), 2009. Flood and water management act. URL: http://www.defra.gov.uk/environment/flooding/policy/fwmb/; accessed on January 15, 2011.

Department for Environment, Food and Rural Affairs, (2005) Making space for water. Taking forward a new government strategy for flood and coastal erosion risk management in England. URL: http://www.defra.gov.uk/environment/flooding/policy/strategy/; accessed on January 15, 2011.

Department for Environment, Food and Rural Affairs, 2003. Managed realignment: Land purchase compensation and payment for alternative beneficial land use. URL: http://www.defra.gov.uk/environment/flooding/policy/guidance/realign.htm; assessed on January 15, 2011.

Desplanque, C. and Mossman, D., 2001. Bay of Fundy tides. *Geoscience Canada.* 25(1), 1-11.

Fedra, K. and Feoli, E., 1998. GIS technology and spatial analysis in coastal management. *EEZ Technology*, 3, 171-179.

Government of Nova Scotia, Nova Scotia Environment, 2009. Wetland conversation policy – Draft for consultation. URL: http://www.gov.ns.ca/nse/wetland/conservation.policy.asp; accessed on January 20, 2011.

Greenberg, D.A.; Blanchard, W.; Smith, B., and Barrow, E., in press. Climate change, mean sea level and high tides in the Bay of Fundy. Bedford Institute of Oceanography.

Hart, D.E. and Knight, G.A. 2009. Geographic information system assessment of tsunami vulnerability on a dune coast. *Journal of Coastal Research.* 25(1), 131–141.

Lopez, J., 2006. The multiple lines of defence strategy to sustain coastal Louisiana. New Orleans, LA: Lake Pontchartrain Basin Foundation.

Pendleton, E.A.; Thieler, E.R., and Williams, S.J., 2010. Importance of coastal change variables in determining vulnerability to sea- and lake-level change. *Journal of Coastal Research,* 26(1), 176–183.

Thumerer, T.; Jones, A.P., and Brown, D. 2000. A GIS based coastal management system for climate change associated flood risk assessment on the east coast of England. *International Journal of Geographical Information Science*, 14(3), 265 – 281.

Appendix A – Classification Scheme

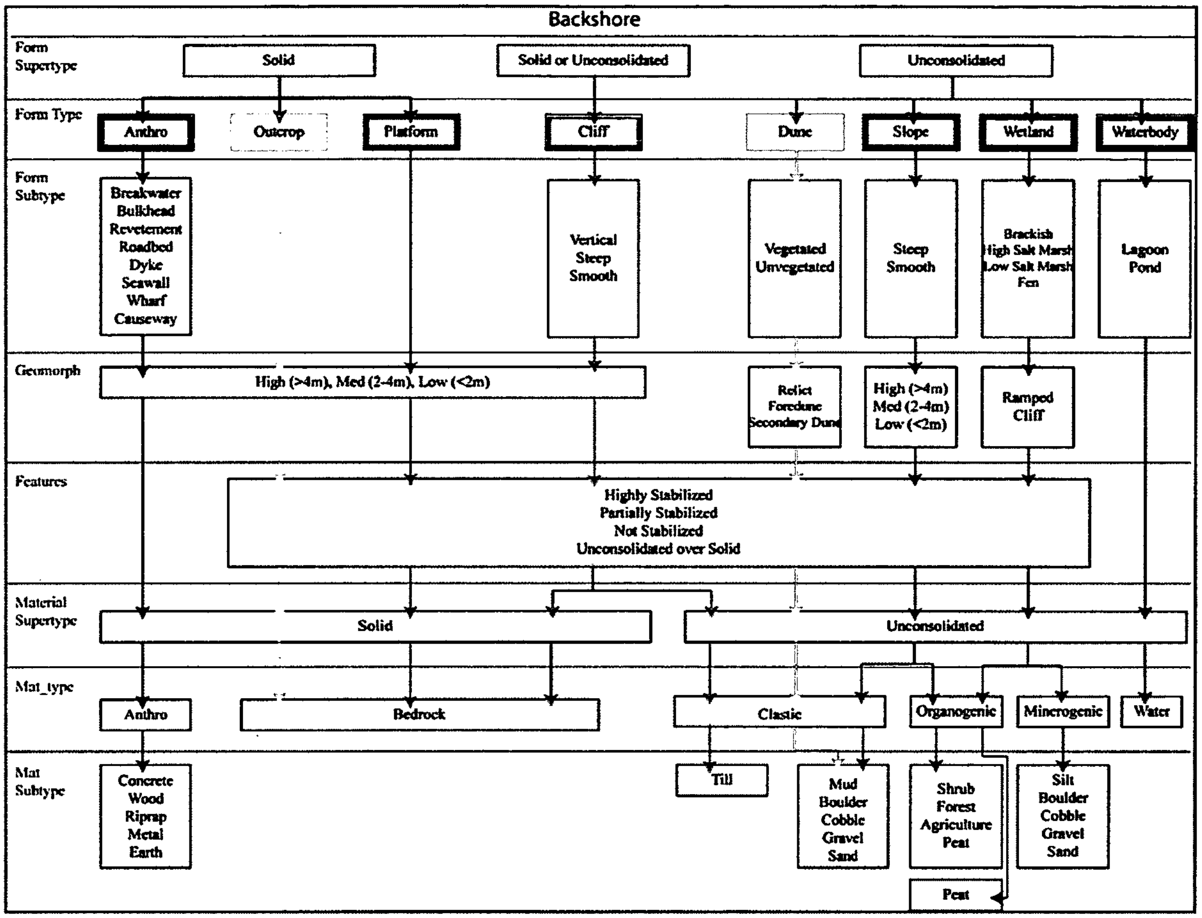


Figure 1 - Backshore classification scheme, designed by van Proosdij and Pietersma-Perrott (2012). This scheme was used extensively for the creation of the vulnerability matrix and Python script used to calculate vulnerability within the backshore of the Cornwallis River Estuary, Kings County, Nova Scotia.

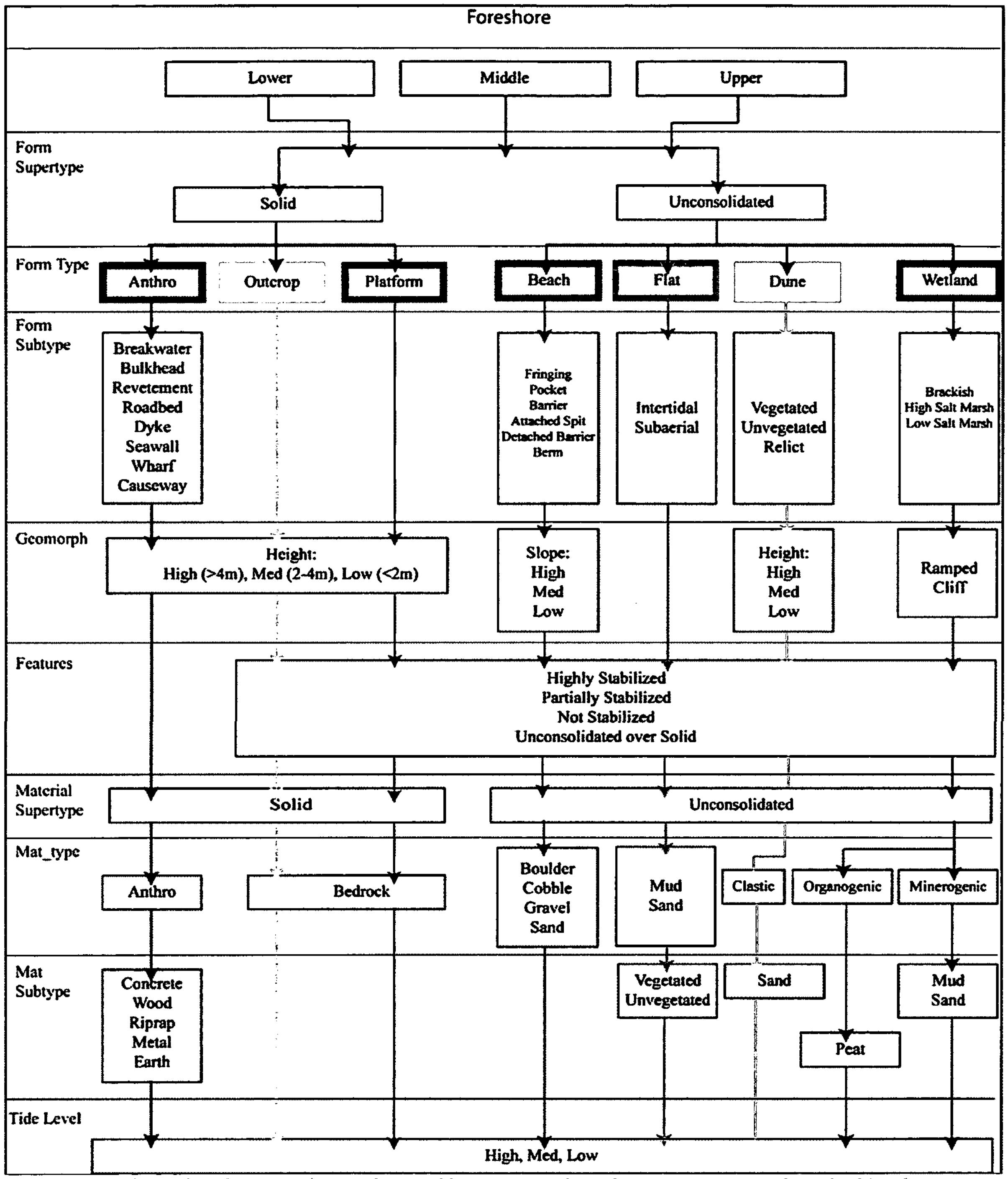


Figure 2 - Foreshore classification scheme, designed by van Proosdij and Pietersma-Perrott (2012). This scheme was used extensively for the creation of the vulnerability matrix and Python script used to calculate vulnerability for the upper, middle and lower foreshore of the Cornwallis River Estuary, Kings County, Nova Scotia.

Appendix B – Python Code

```
################################################################################
#
## Script  -    Coastal_Vulnerability_Analysis_Backshore.py
##
## Puprose -    This code is used to determine coastal vulnerability within the
backshore of the Cornwallis River Estuary in Nova Scotia, Canada. This is a
small portion of a project put together by the Atlantic Canada Adaptation
Soludations (ACAS) group, which aims to uncover areas of concern in regards to
climate change. The idea here is to use physical parameters, tide elevation,
coastal slope, coastal stability, shoreline exposure (fetch, wind direction,
maximum wave height),presence of anthropogenic barriers, presence of vegetation
and Foreshore width, to estimate areas of concern in the Cornwallis River
Estuary. The vulnerability is to storm surge potential, and
is highly influenced by the tide elevation input by the user.
##
This code/tool was developed in order to calculate vulnerability within a
macrotidal environment.These types of environments have extreme tidal ranges,
therefore, during any given tide cycle, the vulnerability to storm surge will
change. It is important to understand how these changes occur,and in which ares
they do.
##
## Description - The user is asked to input the target coastline (the coastline
to be analyzed), the tide elevation,and the storm surge height. The code then
searches through the attributes in the feature's table,and assigns a value to
each of the variables used to calculate vulnerability. Each variable is
assigned a value from 1 to 5 (based on a coastal vulnerability matrix),
depending on the data in each field.This value is then used in an equation to
calculate the Coastal Vulnerability Index(CVI) for each segment of the coast
line. The CVI is then arranged on a scale from 1 to 5; 1 being an areas that is
least vulnerable according to the tide height, storm surge height and physical
parameters, and 5 being areasthat are highly vulnerable based on the tide
height, storm surge height and physical parameters.
################################################################################
#

#Import native arcgisscripting module
#
import arcgisscripting, os, sys, string
from math import sqrt

# Create the geoprocessor object
#
gp = arcgisscripting.create(9.3)

# Set up workspace
#
gp.workspace = "G:\SMU\Grad
work\Coastal_Vulnerability\Vulnerability_Analysis\Vulnerability.gdb"

# Create variable for the geodatabase
```

```
#
Vulnerability_gdb = "G:\SMU\Grad
work\Coastal_Vulnerability\Vulnerability_Analysis\Vulnerability.gdb"

### Set Some Parameters
##
#
# The target coastline dataset
SourceData = gp.GetParameterAsText(0)

## The tide elevation used in analysis
# The tide elevation value is input as a centimeter value by the user
#
Tide_Elevation = gp.GetParameterAsText(1)


## The predicted storm surge level
# The tide elevation value is input as a centimeter value by the user
#
Storm_Surge = gp.GetParameterAsText(2)


## The featureclass to be created, using the variable Tide_Elevation to create
unique feature classes
#
OutFC = (SourceData + "_" + Tide_Elevation + "cm_" + "TE_" + Storm_Surge +
"cm_" + "SS")

# Load required toolboxes
#
gp.AddToolbox("C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Data Management
Tools.tbx")

# Copy Features
#
gp.CopyFeatures_management(SourceData, OutFC, "", "0", "0", "0")


### Add Vulnerability Field
##
#
gp.AddField_management(OutFC, "Freeboard", "DOUBLE", "", "", "", "",
"NULLABLE", "NON_REQUIRED", "")
gp.AddField_management(OutFC, "Coastline_Exposure", "DOUBLE", "", "", "", "",
"NULLABLE", "NON_REQUIRED", "")
gp.AddField_management(OutFC, "Width_of_Foreshore", "DOUBLE", "", "", "", "",
"NULLABLE", "NON_REQUIRED", "")
gp.AddField_management(OutFC, "Vegetation", "DOUBLE", "", "", "", "",
"NULLABLE", "NON_REQUIRED", "")
gp.AddField_management(OutFC, "Slope", "DOUBLE", "", "", "", "", "NULLABLE",
"NON_REQUIRED", "")
gp.AddField_management(OutFC, "Erodibility", "DOUBLE", "", "", "", "",
"NULLABLE", "NON_REQUIRED", "")
gp.AddField_management(OutFC, "Protection", "DOUBLE", "", "", "", "",
"NULLABLE", "NON_REQUIRED", "")
gp.AddField_management(OutFC, "Resilience", "DOUBLE", "", "", "", "",
"NULLABLE", "NON_REQUIRED", "")

gp.AddField_management(OutFC, "Physical_Condition", "DOUBLE", "", "", "", "",
"NULLABLE", "NON_REQUIRED", "")
```

```
gp.AddField_management(OutFC, "Exposure_Condition", "DOUBLE", "", "", "", "",
"NULLABLE", "NON_REQUIRED", "")
gp.AddField_management(OutFC, "Resilience_Condition", "DOUBLE", "", "", "", "",
"NULLABLE", "NON_REQUIRED", "")

gp.AddField_management(OutFC, "CVI", "DOUBLE", "", "", "", "", "NULLABLE",
"NON_REQUIRED", "")
gp.AddField_management(OutFC, "Vulnerability_Lin", "DOUBLE", "", "", "", "",
"NULLABLE", "NON_REQUIRED", "")
gp.AddField_management(OutFC, "Vulnerability_Expo25", "DOUBLE", "", "", "", "",
"NULLABLE", "NON_REQUIRED", "")


# Create update cursor to calculate vulnerability
#
rows = gp.UpdateCursor(OutFC)
row = rows.next()

while row:
    ## Declare vulnerability variables as being equal to zero.
    ## These variables will be used to calculate the vulnerability index for
each feature.
    #
    Exposure_Vul = (int(0))
    Freeboard_vul = (int(0))
    Slope_vul = (int(0))
    Protection_vul = (int(0))
    Observed_eroditibility_vul = (int(0))
    Vegetation_vul = (int(0))
    Foreshore_vul = (int(0))
    Resilience_vul = (int(0))
    Vulnerability_Lin = (int(0))
    Vulnerability_Epo25 = (int(0))



################################################################################
#

Based on the ACAS Coastal Classfication Scheme the following variables
need to be declared in order to calcuale the Coastal Vulnerabilty index.

################################################################################
#

    ## Row names (attributes) need to have variables declared.
    ## Each attribute can be called, depending on the classification
calculation being performed.
    ## The row names are taken from the Shorelien Classification System created
at Saint Mary's University, Halifax, NS, Canada.
    #
    Formsupertype = row.FormSupertype
    Formtype = row.FormType
    Formsubtype = row.FormSubtype
    Geomorph = row.Geomorph
    Comments = row.Comments
    Features = row.Features
    Mat_supertype = row.MaterialSupertype
```

```
    Mat_type = row.Materialtype
    Mat_subtype = row.MaterialSubtype

    ## Possible super_type and form_type classifications found in attribute
table.
    ## Strings are converted to variables which can be compared.
    #
    Solid = 'solid'
    Unconsolidated = 'uncondsolidated'
    Anthro = 'anthro'
    Outcrop = 'outcrop'
    Platform = 'platform'
    Cliff = 'cliff'
    Waterbody = 'waterbody'
    Slope = 'slope'
    Dune = 'dune'
    Wetland = 'wetland'
    Waterbody = 'waterbody'
    Flat = 'flat'

    ## Possible Form Subytpe variables, divided based on Form type.
    #
    ## Anthropological Features (solid)
    #
    Breakwater = 'breakwater'
    Bulkhead = 'bulkhead'
    Revetment = 'revetment'
    Roadbed = 'road bed'
    Dyke = 'dyke'
    Seawall = 'seawall'
    Wharf = 'wharf'
    Vertical = 'vertical'

    ## Cliff Features (solid or unconsolidated)
    #
    Vertical = 'vertical'
    Steep = 'steep'
    Smooth = 'smooth'

    ## Dune (unconsolidated)
    #
    Vegetated = 'vegetated'
    Unvegetated = 'unvegetated'

    ## Wetland (unconsolidated)
    #
    Brackish = 'brackish'
    HSM = 'high salt marsh'
    LSM = 'low salt marsh'
    Fen = 'fen'

    ## Slope (unconsolidated)
    #
    Steep = 'steep'
    Smooth = 'smooth'

    ## Water body (unconsolidated) - This data is not found in the Cornwallis
River Backshore data set, but is included in the Shoreline Classifcation.
    #
    Lagoon = 'lagoon'
```

```
    Pond = 'pond'

    ## Geomorph options, Geomorph describes the geomorphology (size, shape
etc.) of the feature.
    #
    High = 'high'
    Med = 'med'
    Low = 'low'
    Ramp = 'ramped'
    Cliff = 'cliff'
    Beach = 'beach'

    ## The following are Geomorph options, however are not found in the
Cornwallis River Backshore data set.
    ##
    Relict = 'relict'
    Foredune = 'foredune'
    Secondary_Dune = 'secondary dune'

    ## Possible 'Features' variables
    #
    High_stab = 'high'
    Highly_stab = 'highly stabilized'
    Part_stab = 'partially stabilized'
    Not_stab = 'not stabilized'
    Uncon_o_solid = 'unconsolidated over solid'

    ## Possible Material Supertype variables
    #
    Mat_solid = 'solid'
    Mat_uncond = 'uncondsolidated'
    Mat_uncon = 'unconsolidated'

    ## Possible Material Type options
    #
    Clastic = 'clastic'
    Minerogenic = 'minerogenic'
    Anthro = 'anthro'
    Bedrock = 'bedrock'
    Organogenic = 'organogenic'
    Water = 'water'

    ## Possible material subtype options
    #
    Shrub = 'shrub'
    Forest = 'forest'
    Agriculture = 'agriculture'
    Peat = 'peat'
    Till = 'till'
    Mud = 'mud'
    Boulder = 'boulder'
    Cobble = 'cobble'
    Gravel = 'gravel'
    Sand = 'sand'
    Silt = 'silt'
    Concrete = 'concrete'
    Wood = 'wood'
    Riprap = 'riprap'
    Metal = 'metal'
    Earth = 'earth'
```

```
    ## Convert user input tide elevation  and storm surge into a float values.
    #
    Tide_Elevation = float(Tide_Elevation)
    Storm_Surge = float(Storm_Surge)

    ####################################################
    ####                                            ####
    ####   Exposure Vulnerability classification    ####
    ####                                            ####
    ####################################################

    ## The variables Tide_Elevation and Storm_Surge are used to determine the
exposure vulnerability for each segment.
    ## WEMo (Wave Exposure Model) analysis was performed at various tide
elevations and storm surge hieghts.
    ## The values from this analysis have been attached to the attribute table
for the target feature class and is used
    ## here to determine the exposure vulnerability.
    #

    ## The Tide_Elevation and Storm_Surge elevation are added together to get a
total water depth value in centimetres.
    ## This value is then used to determine which row in the attribute table to
draw the exposure values from.
    #
    Tot_Water_Level = Tide_Elevation + Storm_Surge

    ## Declare a variable for the exposure value (value found in the
appropriate field within the featureclass based on the total water level)
    ## Set this value to Zero!
    #
    Exposure = (int(0))

    if Tot_Water_Level > 0 and Tot_Water_Level <= 100:
        Exposure = row.WL_100cm
        if Exposure == 0:
            Exposure_Vul = 0

        elif Exposure > 0 and Exposure < 215:
            Exposure_Vul = 1

        elif Exposure > 215 and Exposure < 440:
            Exposure_Vul = 2

        elif Exposure > 440 and Exposure < 630:
            Exposure_Vul = 3

        elif Exposure > 630 and Exposure < 810:
            Exposure_Vul = 4

        else:
            Exposure_Vul = 5

    elif Tot_Water_Level > 100 and Tot_Water_Level <= 150:
        Exposure = row.WL_150cm
        if Exposure == 0:
            Exposure_Vul = 0

        elif Exposure > 0 and Exposure < 215:
```

```
            Exposure_Vul = 1

        elif Exposure > 215 and Exposure < 440:
            Exposure_Vul = 2

        elif Exposure > 440 and Exposure < 630:
            Exposure_Vul = 3

        elif Exposure > 630 and Exposure < 810:
            Exposure_Vul = 4

        else:
            Exposure_Vul = 5

    elif Tot_Water_Level > 150 and Tot_Water_Level <= 200:
        Exposure = row.WL_200cm
        if Exposure == 0:
            Exposure_Vul = 0

        elif Exposure > 0 and Exposure < 215:
            Exposure_Vul = 1

        elif Exposure > 215 and Exposure < 440:
            Exposure_Vul = 2

        elif Exposure > 440 and Exposure < 630:
            Exposure_Vul = 3

        elif Exposure > 630 and Exposure < 810:
            Exposure_Vul = 4

        else:
            Exposure_Vul = 5

    elif Tot_Water_Level > 200 and Tot_Water_Level <= 250:
        Exposure = row.WL_350cm
        if Exposure == 0:
            Exposure_Vul = 0

        elif Exposure > 0 and Exposure < 215:
            Exposure_Vul = 1

        elif Exposure > 215 and Exposure < 440:
            Exposure_Vul = 2

        elif Exposure > 440 and Exposure < 630:
            Exposure_Vul = 3

        elif Exposure > 630 and Exposure < 810:
            Exposure_Vul = 4

        else:
            Exposure_Vul = 5

    elif Tot_Water_Level > 250 and Tot_Water_Level <= 300:
        Exposure = row.WL_300cm
        if Exposure == 0:
            Exposure_Vul = 0

        elif Exposure > 0 and Exposure < 215:
```

```
            Exposure_Vul = 1

        elif Exposure > 215 and Exposure < 440:
            Exposure_Vul = 2

        elif Exposure > 440 and Exposure < 630:
            Exposure_Vul = 3

        elif Exposure > 630 and Exposure < 810:
            Exposure_Vul = 4

        else:
            Exposure_Vul = 5

    elif Tot_Water_Level > 300 and Tot_Water_Level <= 350:
        Exposure = row.WL_350cm
        if Exposure == 0:
            Exposure_Vul = 0

        elif Exposure > 0 and Exposure < 215:
            Exposure_Vul = 1

        elif Exposure > 215 and Exposure < 440:
            Exposure_Vul = 2

        elif Exposure > 440 and Exposure < 630:
            Exposure_Vul = 3

        elif Exposure > 630 and Exposure < 810:
            Exposure_Vul = 4

        else:
            Exposure_Vul = 5

    elif Tot_Water_Level > 350 and Tot_Water_Level <= 400:
        Exposure = row.WL_400cm
        if Exposure == 0:
            Exposure_Vul = 0

        elif Exposure > 0 and Exposure < 215:
            Exposure_Vul = 1

        elif Exposure > 215 and Exposure < 440:
            Exposure_Vul = 2

        elif Exposure > 440 and Exposure < 630:
            Exposure_Vul = 3

        elif Exposure > 630 and Exposure < 810:
            Exposure_Vul = 4

        else:
            Exposure_Vul = 5

    elif Tot_Water_Level > 400 and Tot_Water_Level <= 450:
        Exposure = row.WL_450cm
        if Exposure == 0:
            Exposure_Vul = 0

        elif Exposure > 0 and Exposure < 215:
```

```
            Exposure_Vul = 1

        elif Exposure > 215 and Exposure < 440:
            Exposure_Vul = 2

        elif Exposure > 440 and Exposure < 630:
            Exposure_Vul = 3

        elif Exposure > 630 and Exposure < 810:
            Exposure_Vul = 4

        else:
            Exposure_Vul = 5

    elif Tot_Water_Level > 450 and Tot_Water_Level <= 500:
        Exposure = row.WL_500cm
        if Exposure == 0:
            Exposure_Vul = 0

        elif Exposure > 0 and Exposure < 215:
            Exposure_Vul = 1

        elif Exposure > 215 and Exposure < 440:
            Exposure_Vul = 2

        elif Exposure > 440 and Exposure < 630:
            Exposure_Vul = 3

        elif Exposure > 630 and Exposure < 810:
            Exposure_Vul = 4

        else:
            Exposure_Vul = 5

    elif Tot_Water_Level > 500 and Tot_Water_Level <= 577:
        Exposure = row.WL_550cm
        if Exposure == 0:
            Exposure_Vul = 0

        elif Exposure > 0 and Exposure < 215:
            Exposure_Vul = 1

        elif Exposure > 215 and Exposure < 440:
            Exposure_Vul = 2

        elif Exposure > 440 and Exposure < 630:
            Exposure_Vul = 3

        elif Exposure > 630 and Exposure < 810:
            Exposure_Vul = 4

        else:
            Exposure_Vul = 5

    elif Tot_Water_Level > 577 and Tot_Water_Level <= 600:
        Exposure = row.WL_600cm
        if Exposure == 0:
            Exposure_Vul = 0

        elif Exposure > 0 and Exposure < 215:
```

```
            Exposure_Vul = 1

        elif Exposure > 215 and Exposure < 440:
            Exposure_Vul = 2

        elif Exposure > 440 and Exposure < 630:
            Exposure_Vul = 3

        elif Exposure > 630 and Exposure < 810:
            Exposure_Vul = 4

        else:
            Exposure_Vul = 5

    elif Tot_Water_Level > 600 and Tot_Water_Level <= 650:
        Exposure = row.WL_650cm
        if Exposure == 0:
            Exposure_Vul = 0

        elif Exposure > 0 and Exposure < 215:
            Exposure_Vul = 1

        elif Exposure > 215 and Exposure < 440:
            Exposure_Vul = 2

        elif Exposure > 440 and Exposure < 630:
            Exposure_Vul = 3

        elif Exposure > 630 and Exposure < 810:
            Exposure_Vul = 4

        else:
            Exposure_Vul = 5

    elif Tot_Water_Level > 650 and Tot_Water_Level <= 700:
        Exposure = row.WL_700cm
        if Exposure == 0:
            Exposure_Vul = 0

        elif Exposure > 0 and Exposure < 215:
            Exposure_Vul = 1

        elif Exposure > 215 and Exposure < 440:
            Exposure_Vul = 2

        elif Exposure > 440 and Exposure < 630:
            Exposure_Vul = 3

        elif Exposure > 630 and Exposure < 810:
            Exposure_Vul = 4

        else:
            Exposure_Vul = 5

    elif Tot_Water_Level > 700 and Tot_Water_Level <= 750:
        Exposure = row.WL_750cm
        if Exposure == 0:
            Exposure_Vul = 0

        elif Exposure > 0 and Exposure < 215:
```

```
            Exposure_Vul = 1

        elif Exposure > 215 and Exposure < 440:
            Exposure_Vul = 2

        elif Exposure > 440 and Exposure < 630:
            Exposure_Vul = 3

        elif Exposure > 630 and Exposure < 810:
            Exposure_Vul = 4

        else:
            Exposure_Vul = 5

    elif Tot_Water_Level > 750 and Tot_Water_Level <= 800:
        Exposure = row.WL_800cm
        if Exposure == 0:
            Exposure_Vul = 0

        elif Exposure > 0 and Exposure < 215:
            Exposure_Vul = 1

        elif Exposure > 215 and Exposure < 440:
            Exposure_Vul = 2

        elif Exposure > 440 and Exposure < 630:
            Exposure_Vul = 3

        elif Exposure > 630 and Exposure < 810:
            Exposure_Vul = 4

        else:
            Exposure_Vul = 5

    elif Tot_Water_Level > 800 and Tot_Water_Level <= 850:
        Exposure = row.WL_850cm
        if Exposure == 0:
            Exposure_Vul = 0

        elif Exposure > 0 and Exposure < 215:
            Exposure_Vul = 1

        elif Exposure > 215 and Exposure < 440:
            Exposure_Vul = 2

        elif Exposure > 440 and Exposure < 630:
            Exposure_Vul = 3

        elif Exposure > 630 and Exposure < 810:
            Exposure_Vul = 4

        else:
            Exposure_Vul = 5

    elif Tot_Water_Level > 850 and Tot_Water_Level <= 900:
        Exposure = row.WL_900cm
        if Exposure == 0:
            Exposure_Vul = 0

        elif Exposure > 0 and Exposure < 215:
```

```
            Exposure_Vul = 1

        elif Exposure > 215 and Exposure < 440:
            Exposure_Vul = 2

        elif Exposure > 440 and Exposure < 630:
            Exposure_Vul = 3

        elif Exposure > 630 and Exposure < 810:
            Exposure_Vul = 4

        else:
            Exposure_Vul = 5

    elif Tot_Water_Level > 900 and Tot_Water_Level <= 10.15:
        Exposure = row.WL_950cm
        if Exposure == 0:
            Exposure_Vul = 0

        elif Exposure > 0 and Exposure < 215:
            Exposure_Vul = 1

        elif Exposure > 215 and Exposure < 440:
            Exposure_Vul = 2

        elif Exposure > 440 and Exposure < 630:
            Exposure_Vul = 3

        elif Exposure > 630 and Exposure < 810:
            Exposure_Vul = 4

        else:
            Exposure_Vul = 5

    else:
        Exposure_Vul = 5

    ######################################################
    ####                                              ####
    ####    Freeboard Vulnerability classification    ####
    ####                                              ####
    ######################################################

    ## Freeboard is the height of the coastal zone (backshore) in relation to
the total water level.
    ## Each coastline segment is assigned a shoreline elevation (relative to
CGVD28 datum) within the GIS.
    ## This elevation relates to the top of dyke, top of cliff, top of slope or
some other coastline feature in the backshore.

    ## The total water level (Tot_Water_Level) is equal to the current tide
elevation and
    ## the predicted storm surge wave height, which is input by the user.
    #
    Tot_Water_Level_new = Tot_Water_Level/100

    ## Declare an shoreline elevation variable equal to value found in row.
    ## Elevation at shoreline will be compared to elevation of tide and storm
surge (input by user),
```

```
    ## If tide is higher than elevation at shoreline, vulnerability will
increase.
    #
    Shoreline_Elevation = row.Shoreline_elv

    float(Shoreline_Elevation)

    Water_Depth = Tot_Water_Level_new - Shoreline_Elevation


    ## The vulnerability of a coastline at 2m water depth, is exponentially
greater than vulnerabiilty of a coastline at 0.15m water depth.
    ## Due to increasing differential impact with increasing flood depth, the
range divisions for freeboard were calculated using an exponential growth
curve.
    ## The result is that each range class is 25% greater than the one below it
cumulating in freeboard >1.25m in class 5.
    #
    if Water_Depth <= 0.00:
        Freeboard_vul = 0

    elif Water_Depth > 0.00 and Water_Depth <= 0.15:
        Freeboard_vul = 1

    elif Water_Depth > 0.15 and Water_Depth <= 0.38:
        Freeboard_vul = 2

    elif Water_Depth > 0.38 and Water_Depth <= 0.72:
        Freeboard_vul = 3

    elif Water_Depth > 0.72 and Water_Depth <= 1.23:
        Freeboard_vul = 4

    elif Water_Depth > 1.23 and Water_Depth <= 2.00:
        Freeboard_vul = 5

    else:
        Freeboard_vul = 5

    ####################################################
    ####                                            ####
    ####     Slope Vulnerability classification     ####
    ####                                            ####
    ####################################################

    ## Declare a slope variable equal to value found in row.
    ## The slope ranges were determined by using the Natural Breaks
classfication in ArcGIS.
    #
    Slope = (int(row.Slope_Deg))

    if Slope >= 0 and Slope <= 6.5:
        Slope_vul = 1

    elif Slope > 6.5 and Slope <= 12.5:
        Slope_vul = 2

    elif Slope > 12.5 and Slope <= 20.5:
        Slope_vul = 3
```

```
    elif Slope > 20.5 and Slope <= 37.5:
        Slope_vul = 4

    elif Slope > 37.5 and Slope <= 70:
        Slope_vul = 5

    else:
        Slope_vul = 5

    ############################################
    ####                                    ####
    ####         Coastline Protection       ####
    ####    Vulnerability classification    ####
    ####                                    ####
    ############################################

    ## Coastline protections refers to the potential of a backshore feature to
elminate or slow down wave progation and inundation.
    ## The mere presence of a protection feature would reduce vulnerability,
but as well the type, size and armouring of the feature would also help reduce
the vulnerability.
    ## The code uses the attributes of each feature found in the backshore to
determine its 'Coastline protection vulnerability'.

    ## This code first begins with determining if the featuers is soild or
unconsoliddated.
    ## There is an understanding that a feature which is solid, will have a
lower vulnerability than an unconsolidated feature.
    #
    if Formsupertype == Solid:
        ## There are three possible options for a solid backshore feature
(Anthro, Outcrop, Platform)
        #
        ## There are several anthropogenic features found at the coast.
        ## Some featuers, such as Dykes, Breakwaters, Seawalls, Revetments and
Bulkheads would help reduce vulnerability.
        #
        ## However, other featuers such as Roads, Causeways and Wharfs would
increase vulnerability.
        ## Ei. The presence of a road would not stop the storm surge, and would
become flooded.
        #
        if Formtype == Anthro:
            if Formsubtype == Dyke:
                ## if comments field is blank, this means there is no
armouring, therefore it is ranked as a 2.
                if Comments == '':
                    Protection_vul = 2

                ## if comments is not blank, then there is armouring, therefore
it is ranked as a 1.
                else:
                    Protection_vul = 1

            elif Formsubtype == Roadbed:
                if Geomorph == High:
                    Protection_vul = 2

                elif Geomorph == Med:
                    Protection_vul = 3
```

```
                elif Geomorph == Low:
                    Protection_vul = 4

                else:
                    Protection_vul = 5
            else:
                Protection_vul = 3

        ## Natural (non-anthropogenic) solid features can also reduce
vulnerability be slowing wave propagation or inundation.
        #
        elif Formtype == Outcrop:
            if Geomorph == High:
                Protection_vul = 1

            elif Geomorph == Med:
                Protection_vul = 1

            elif Geomorph == Low:
                Protection_vul = 2

            else:
                Protection_vul = 5

        elif Formtype == Platform:
            Protection_vul = 5

        elif Formtype == Cliff:
            if Geomorph == High:
                Protection_vul = 1

            elif Geomorph == Med:
                Protection_vul = 1

            elif Geomorph == Low:
                Protection_vul = 2

            else:
                Protection_vul = 5
        else:
            ## The other option for Form Supertype Solid is platform.
            ## Platforms are gentle sloping features, that would provide little
resistence.
            #
            Protection_vul = 5

    elif Formsupertype == Unconsolidated:
        if Formtype == Slope:
            Protection_vul = 4

        elif Formtype == Cliff:
            if Geomorph == High:
                Protection_vul = 3

            elif Geomorph == Med:
                Protection_vul = 3

            elif Geomorph == Low:
                Protection_vul = 4
```

```
            else:
                Protection_vul = 5
        else:
            Protection_vul = 5
    else:
        Protection_vul = 5

    ################################################
    ####                                        ####
    ####        Observed Eroditibility          ####
    ####     Vulnerability classification       ####
    ####                                        ####
    ################################################

    ## The observed eroditibility  of the feature refers to its ability to
resist erosion.
    ## The understanding here is that if a feature is highly stable, it is less
vulnerable.
    #

    if Mat_supertype == Mat_solid:
        ## If the material supertype is solid, the feature is highly stabilized
by default.
        ## Therefore the vulnerability from a stability standpoint is low.
        ## The material type options for Mat_solid are Anthro and Bedrock.
        # Future code my destinguish between material type in the anthro
category.
        Observed_eroditibility_vul = 1

    elif Mat_supertype == Mat_uncond:
        if Features == Uncon_o_solid:
            Observed_eroditibility_vul = 2

        elif Features == High_stab:
            Observed_eroditibility_vul = 3

        elif Features == Part_stab:
            Observed_eroditibility_vul = 4

        elif Features == Not_stab:
            Observed_eroditibility_vul = 5

    elif Mat_supertype == Mat_uncon:
        if Features == Uncon_o_solid:
            Observed_eroditibility_vul = 2

        elif Features == High_stab:
            Observed_eroditibility_vul = 3

        elif Features == Part_stab:
            Observed_eroditibility_vul = 4

        elif Features == Not_stab:
            Observed_eroditibility_vul = 5
    else:
        Observed_eroditibility_vul = 5

    ######################################################
```

```
####                                              ####
####   Vegetation Vulnerability classification    ####
####                                              ####
##################################################

    ## The presence of vegetation will act as a determent, or at least slow
down wave propagation and inundation.
    ## How vegetation does this is dependent on many things, but mainly the
type of vegeation.
    ## Therefore this code first finds if there is vegation, and if so, then
what type.
    ##
    if Mat_type == Organogenic:
        if Mat_subtype == Peat:
            Vegetation_vul = 4

        elif Mat_subtype == Agriculture:
            Vegetation_vul = 3

        elif Mat_subtype == Shrub:
            Vegetation_vul = 2

        elif Mat_subtype == Forest:
            Vegetation_vul = 1

        else:
            Vegetation_vul = 5

    else:
        ## Features such as dykes and road do not have a vegetation
classification and are therefore treated as low vulnerability.
        #
        Vegetation_vul = 0

    ##########################################################
    ####
####
    ####   Foreshore Width Vulnerability classification                ####
    ####
####
    ##########################################################

    ## The ranges for foreshore width were caluclated using natural breaks
within ArcGIS.
    ## The data has foreshore widths ranging from 0 meters to over 1143 meters.
    ## This data was divided into 5 vulnerability classes.
    #
    Foreshore_Width = row.Foreshore_Width

    if Foreshore_Width >= 0 and Foreshore_Width < 70:
        Foreshore_vul = 5

    elif Foreshore_Width >= 70 and Foreshore_Width < 220:
        Foreshore_vul = 4

    elif Foreshore_Width >= 200 and Foreshore_Width < 430:
        Foreshore_vul = 3

    elif Foreshore_Width >= 430 and Foreshore_Width < 700:
        Foreshore_vul = 2
```

```
    elif Foreshore_Width >= 700:
        Foreshore_vul = 1

    else:
        Foreshore_vul = 5

    ##########################################################
    ####                                                  ####
    ####     Resilience Vulnerability classification      ####
    ####                                                  ####
    ##########################################################


    ## Resilience of a feature is defined as its ability to cope with and
naturally recover from a hazardous event.
    ## Resilience is important because it helps further define the features
overall vulnerability.
    ## ei. If the physical parameters indicate that a feature is at low
vulnerability, assigning the same feature's
    ## capacity to resist a storm surge event, could more accurately predict
its vulnerability.
    if Formsupertype == Solid:
        if Formtype == Anthro:
        ## All anthropogenic features are given a rank of 5, because they can
not naturally recover from a threshold crossing hazardous event.
        ## Although the features area able to cope with an event, if the event
causes damage, the features can not naturally build themselves
        ## back to a state of equillibrium, and therefore they are considered
less resilient.
        #
            Resilience_vul = 1

        elif Formtype == Outcrop:
            ## Feature is able to cope with a hazard occuring due to its solid
structure, however, if material is removed, it can not be regained.
            #
            Resilience_vul = 1

        elif Formtype == Platform:
            ## Feature is able to cope with a hazard occuring due to its solid
structure, however, if material is removed, it can not be regained.
            #
            Resilience_vul = 1

        elif Formtype == Cliff:
            if Features == Highly_stab:
                Resilience_vul = 2

            elif Features == Part_stab:
                Resilience_vul = 3

            elif Features == Uncon_o_solid:
                Resilience_vul = 4

            elif Features == Not_stab:
                Resilience_vul = 5

            else:
                Resilience_vul = 5
```

```
    else:
        Resilience_vul = 5

elif Formsupertype == Unconsolidated:
    if Formtype == Cliff:
        if Features == Highly_stab:
            Resilience_vul = 2

        elif Features == Part_stab:
            Resilience_vul = 3

        elif Features == Uncon_o_solid:
            Resilience_vul = 4

        elif Features == Not_stab:
            Resilience_vul = 5

        else:
            Resilience_vul = 5


    elif Formtype == Slope:
        if Features == Highly_stab:
            Resilience_vul = 1

        elif Features == Part_stab:
            Resilience_vul = 2

        elif Features == Uncon_o_solid:
            Resilience_vul = 3

        elif Features == Not_stab:
            Resilience_vul = 4

        else:
            Resilience_vul = 5

    elif Formtype == Dune:
       Resilience_vul = 1

    elif Formtype == Wetland:
        if Geomorph == Ramp:
            if Features == Highly_stab:
                Resilience_vul = 1

            elif Features == Part_stab:
                Resilience_vul = 2

            elif Features == Uncon_o_solid:
                Resilience_vul = 3

            elif Features == Not_stab:
                Resilience_vul = 4

            else:
                Resilience_vul = 5

        elif Geomorph == Cliff:
            if Features == Highly_stab:
```

```
                    Resilience_vul = 2

                elif Features == Part_stab:
                    Resilience_vul = 3

                elif Features == Uncon_o_solid:
                    Resilience_vul = 4

                elif Features == Not_stab:
                    Resilience_vul = 5

                else:
                    Resilience_vul = 5

            else:
                Resilience_vul = 5

        elif Formtype == Waterbody:
            Resilience_vul = 1

        elif Formtype == Beach:
            Resilience_vul = 1

        elif Formtype == Flat:
            Resilience_vul = 1


        else:
            Resilience_vul = 5

    else:
        Resilience_vul = 5

    ## For this analysis, each variable has been grouped into 'Conditions'
    ## The conditions are 'Physical Condition', 'Exposure Condition' and
'Resilience Condition'
    ## The variables have been added together to determine the value for the
appropriate condition.
    ##
    #
    physical_condition = (Slope_vul + Protection_vul +
Observed_eroditibility_vul + Vegetation_vul + Foreshore_vul)

    exposure_condition = (Freeboard_vul + Exposure_Vul)

    resilience_condition = Resilience_vul

    ## Each condition does not affect vulnerability equally, and therefore
weights must be applied.
    ## The weighting scheme used here was determined through Multi-criteria
analysis, using the ranking method.
    ## The weighted conditions are used to calculate the CVI (Coastal
Vulnerability Index) for each segment.
    ##
    #
    CVI_temp = (exposure_condition*0.50) + (physical_condition*0.33) +
(resilience_condition*0.17)

    CVI = round((CVI_temp),2)
```

```
    ## The CVI is then categorized into a vulnerability rate between 1 and 5
    ## 1 is very low vulnerability and 5 is very high vulnerability.
    ## The ranges here were determined through forming five equal ranges
between the lowest and highest possible scores.
    ##
    #

    ## Because the tide elevation is the most important variable within a
macrotidal environment, if the tide vulnerability is
    ## equal to zero (eg. the water level is not reaching the shoreline), the
vulnerability is automatically set to very low vulnerability.
    #
    if Freeboard_vul == 0:
        Vulnerability_Lin = 0

    else:
    ## The following ranking scheme was concluded based on the possible outcome
of the variable ranking.
    ## If all the physical condition variables are added together, the lowest
possible score is 5, the highest is 25.
    #
    ## The lowest value the exposure condition can have are 0 (no tide, no
exposure, no value), the highest is five.
    #
    ## The lowest value the resilience condition can have is 1 and the highest
5.
    #
    ## After applying the weights and adding them together the lowest possible
CVI score is 2.82, and the highest
    ## possible score is 14.10.

    ## The range has been divided into five categories based on these values.


    ## These categories are based on a linear growth pattern; where each range
is equal to the one before it.
    #

        if CVI >= 1.49 and CVI <= 4.00:
            Vulnerability_Lin = 1

        elif CVI > 4.00 and CVI <= 6.50:
            Vulnerability_Lin = 2

        elif CVI > 6.50 and CVI <= 9.00:
            Vulnerability_Lin = 3

        elif CVI > 9.00 and CVI <= 11.50:
            Vulnerability_Lin = 4

        elif CVI > 11.50 and CVI <= 14.10:
            Vulnerability_Lin = 5

        else:
            Vulnerability_Lin = 5

    ## These categories are based on an exponential growth pattern; Where the
range is smaller for the lower CVI values
```

```
    ## and is lager at the higher end. This is because of the emphasis on
vulnerability risk at the higher end of the range.
    #
    if Freeboard_vul == 0:
        Vulnerability_Expo25 = 0

    else:

        if CVI >= 1.49 and CVI <= 3.04:
            Vulnerability_Expo25 = 1

        elif CVI > 3.04 and CVI <= 4.96:
            Vulnerability_Expo25 = 2

        elif CVI > 4.96 and CVI <= 7.36:
            Vulnerability_Expo25 = 3

        elif CVI > 7.36 and CVI <= 10.36:
            Vulnerability_Expo25 = 4

        elif CVI > 10.36 and CVI <= 14.10:
            Vulnerability_Expo25 = 5

        else:
            Vulnerability_Expo25 = 5


    ## Use the vulnerability variables to calculate the overall vulnerability.
    #
    row.Freeboard = Freeboard_vul
    row.Coastline_Exposure = Exposure_Vul
    row.Width_of_Foreshore = Foreshore_vul
    row.Vegetation = Vegetation_vul
    row.Slope = Slope_vul
    row.Erodibility = Observed_eroditibility_vul
    row.Protection = Protection_vul
    row.Resilience = Resilience_vul

    row.Physical_Condition = physical_condition
    row.Exposure_Condition = exposure_condition
    row.Resilience_Condition = resilience_condition

    row.CVI = CVI
    row.Vulnerability_Lin = Vulnerability_Lin
    row.Vulnerability_Expo25 = Vulnerability_Expo25

    rows.UpdateRow(row)
    row = rows.Next()

del row, rows
```