UNIVERSITY OF OTTAWA

Geographic Information Systems and System Dynamics - Modelling the Impacts of Storm Damage on Coastal Communities

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Abstract

A spatial-temporal model is developed for modelling the impacts of simulated coastal zone storm surge and flooding using a combined spatial mapping and system dynamics approach. By coupling geographic information systems (GIS) and system dynamics, the interconnecting components of the spatial-temporal model are used with limited historical data to evaluate storm damage. Overlapping cumulative effects layers in GIS (ArcMap) are used for describing the coastal community's profile, and a system dynamics feedback model (STELLA) is developed to define the interconnecting component relationships of the community. The component-wise changes to the physical environment, community infrastructure, and socioeconomic resources from the storm surge and seal level rise are examined. These changes are used to assess the impacts of the community system as a whole. For the purpose of illustrating this model, the research is applied specifically to the case of Charlottetown, Prince Edward Island, Canada, a vulnerable coastal city subject to considerable impacts from pending sea level rise and more frequent severe storm surge attributed to the changing climate in the coastal zone.

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Glossary

GIS	Geographic Information System
SD	System Dynamics
SSD	Spatial System Dynamics
DEM	Digital Elevation Model
CD	Chart Datum
SIC	Standard Industrial Code
DMTI	Desktop Mapping Technologies Inc.
EPOI	Enhanced Points of Interest
VBA	Visual Basic for Application
GUI	Graphical User Interface
Km/h	Kilometres per Hour
Mb	Millibars
ESRI	Environmental Systems Research Institute
DA	Dissemination Area
Geobase	An online portal for no fee access to quality geospatial data
STELLA	iSee Systems system dynamics software
ArcInfo	ESRI geographic information system software

1. Introduction

1.1 Background and Motivation

Recent history has provided powerful reminders of just how vulnerable coastal regions can be. On September 29th, 2003, Hurricane Juan hit Halifax, Nova Scotia with peak sustained winds of 154 kilometres an hour, resulting in eight deaths and over $200 million in damages to Nova Scotia and Prince Edward Island (Vasseur and Catto 2008). Then on August 29th, 2005, Hurricane Katrina struck the Gulf coast of the United States of America, hitting Florida, Texas and, most severely, New Orleans. Now recorded as the costliest hurricane in the history of the United States, the consequences of Hurricane Katrina were 1,836 deaths and an estimated $81 billion in damages (Knabb et al 2006). Between September 1st and September 14th, 2008, Hurricane Ike caused estimated damages of $29.6 billion in the United States, $7.3 billion in Cuba, $500 million in the Turks and Caicos, $200 million in the Bahamas, totalling roughly $37.6 billion and claiming 195 lives (Berg 2010).

Not only has the frequency of severe storm surges increased, but so has their intensity and duration (Mimura et al 2007). Storm surge, defined as “an increase in the ocean water level above what is expected from the normal tidal level that can be predicted from astronomical observations and is most often caused by winds and low pressure atmospheric storms” (Webster and Stiff 2008) are becoming commonplace. Due to the increased frequency, intensity and duration of storm surges, extremely vulnerable sites must be identified and research pertaining to the community and government response to storm surges must be conducted in order to limit the impending storm damage impacts.

The ability to forecast severe storms in Canada is adequate. But, there is growing anxiety that there is a lack of tactical connections between the current scientific knowledge about storm impacts on coastal communities and the institutions that are responsible for the storm response planning and adaptation of coastal communities (Canada 2008). This preparedness knowledge gap needs to be bridged in order for coastal communities to understand properly and be prepared for the increase frequency of intense storm activity. The previous paragraphs clearly indicate the enormity of the damage that storms do. They also indicate that currently, we do a very poor job of anticipating and preparing for storm impacts, and, consequently, provide minimal, if any, storm damage reporting.

This bridge required to prepare and adapt for pending storm impacts in the coastal zone is being forged by the International Community-University Research Alliance (ICURA) project, "Managing Adaptation to Environmental Change in Coastal Communities: Canada and the Caribbean", also known as C-Change. The project formally began its research program in June, 2009 and continues until 2015. This project brings together community members and university researchers, in both Canada and the Caribbean, to work together on research pertaining to coastal adaptation to the impacts of storm surge and sea-level rise. Various communities considered susceptible to these impacts, in Canada and the Caribbean, have been selected as sites for the C-Change project. One such site, Charlottetown, Prince Edward Island, was chosen for the C-Change project in part due to its unique position located on the convergence of three rivers which form Charlottetown harbour, which opens into the Northumberland Strait in Atlantic Canada. Charlottetown is the focus of the research in this thesis and is the application area in which the community damage impacts model is applied.

This research is not only being carried out at the University of Ottawa, but also in conjunction with the city of Charlottetown and the other C-Change partners, research associates and collaborators and co-applicants at selected coastal sites in Canada and the Caribbean. Within the C-Change project framework, it is understood that the results of this research rely heavily on visualization techniques as it is felt that a visual medium is the simplest way to demonstrate the findings to a more general audience in the coastal communities. One of the key objectives of the C-Change research is to provide a powerful tool for the decision makers and citizens of Charlottetown and other coastal communities in order to assist in storm response planning preparedness and adaptation to the changing coastal climate.

A vast, intricate problem such as this cannot be attacked simply from only one perspective. The path "to improving local capacity for planning adaptation and emergency preparedness lay in integrating local and traditional knowledge with available scientific, management, and institutional governance information" (Watson and Lane 2008). Interdisciplinary and multidisciplinary system approaches are necessary to connect the many facets required to discover problem formulation and resolution.

1.2 Research Question and Objectives

In order to assess, rank and evaluate aspects of a community's storm surge vulnerability and to estimate storm damage impacts, the site's spatial-temporal interactions with its environment must be taken into account. This research presents a model that proposes a system dynamics (SD) approach together with the spatial modelling of a vulnerable coastal community. The community profile will be represented as multiple, thematic, overlapping layers in a Geographic Information System (GIS) map. The goal of this model is to capture the storm impacts on all aspects of the community through a series of simulations depicted on a static map. These aspects include impacts to the biophysical, socioeconomic, and infrastructural aspects of the community.

Thus, the research question is:

> What are the expected impacts to the community profile that includes the physical environment, infrastructure and socioeconomics of the coastal community in the presence of storm surge and sea level rise and how can these impacts be effectively described using mapping techniques and spatial system dynamics?

In response to this question, the objectives of this research are to:

1) Define and examine the community spatial status quo profile
2) Define and model storm scenarios based on historical data
3) Identify community components at risk from storm scenarios
4) Establish and evaluate the interconnecting components of the spatial-temporal model and the cumulative effects on community components
5) Estimate damage values from the impacts on the community components

Final results of this thesis will be presented in the form of maps, tables, graphs and expected site damage evaluations. Although the development of the model will be general in nature, for the purpose of this study, the research will use data and profile model application illustrating the case of Charlottetown, Prince Edward Island, Canada.

1.3 Thesis Outline

The remainder of the thesis is made up of the following key components:

- Chapter 2 reviews the literature on the content and challenges of the geospatial analysis of vulnerable coastal communities. Specifically, it focuses on the topics of coastal vulnerabilities and threats, geographic information systems, system dynamics modelling, spatial system dynamics and Charlottetown's place as a coastal community of interest.

- Chapter 3 presents the research methodologies for storm damage model building as developed and applied in this study.
- Chapter 4 presents the modelling and analysis aspects for the multi-faceted system of coastal vulnerability for the case of Charlottetown.
- Chapter 5 presents the model process and results of the storm simulator and expected damage estimates for Charlottetown.
- Chapter 6 offers recommendations for future research.
- Chapter 7 closes the thesis with the summary and conclusions of this work.

The Bibliography cites all references used directly or indirectly in this research. And lastly, the Appendices accompanying the thesis document contain: the template for the Community Data Profile [A], the list of ArcGIS layers (their descriptions and their sources) [B], economic points by Standard Industrial Classification (SIC) major groups for Charlottetown's status quo [C], the social 'assets at risk' comparisons [D], ArcGIS Visual Basic for Applications graphical user interface code for storm surge model [E], the system dynamics models STELLA equations [F] and the complete storm simulation model trial results and descriptive statistics tables [G].

2. Literature Review

In the following subsections, an examination of the content and challenges of the geospatial analysis of vulnerable coastal communities will be conducted. Included in this examination are an overview of (2.1) coastal vulnerabilities and threats, (2.2) Geographic Information Systems, (2.3) systems dynamics, (2.4) spatial system dynamics, and (2.5) a sketch of the history of the application to Charlottetown's coastal activities. This chapter ends with a directed summary of the literature review [2.6] with particular relevance to the thesis methodology.

2.1 Coastal Vulnerability and Threats

"Many small islands are highly vulnerable to the impacts of climate change … They comprise small land masses surrounded by ocean, and are frequently located in regions prone to natural disasters, often of a hydrometeorological and/or geological nature."(Mimura et al. 2007, p.691) With Canada's vast coastline, there are many small islands or coastal communities that hold these characteristics. But what exactly does it mean to be vulnerable?

"Vulnerability to impacts is a multi-dimensional concept, encompassing bio-geophysical, economic, institutional and socio-cultural factors." (Klein and Nicholls 1999, p.183) With this in mind, vulnerability of a coastal zone can be defined by its measure of inability to manage, respond and adapt with the impacts of accelerated sea-level rise and climate change (IPCC-CZMS 1992). "Vulnerability assessment includes the susceptibility of the coastal zone to physical changes resulting from climate change, the anticipated impacts on socioeconomic and ecological systems, and available adaptation options." (Dolan and Walker 2003, p.2)

Dolan and Walker (2003) believe that in order to characterize the vulnerability from natural hazards and climate change on coastal communities, three broad definitions of vulnerability must be combined.

> "The first characterizes vulnerability in terms of exposure to hazardous events (e.g., droughts, floods) and how this affects people and structures... A second perspective views vulnerability as a human relationship not a physical one (i.e., vulnerability is socially constructed rather than determined by the occurrence of a physical event)… A third perspective integrates both the physical event and the underlying causal characteristics of populations that lead to risk exposure and limited capacity of communities to respond." (Dolan and Walker 2003, p.2)

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) has very high confidence that "small islands, whether located in the tropics or higher latitudes, have characteristics which make them especially vulnerable to the effects of climate change, sea-level rise and extreme events." (Mimura et al 2007, p.689) These characteristics include physical size, likelihood of natural disasters, proneness to climate extremes, exceedingly open economies and low adaptive capacities.

Another important characteristic of small islands is that almost without exception a high percentage of the settlements and infrastructure are located in a coastal area. And, coastal areas are known to have the highest risk of storm surges (Nordhaus 2006). Since small islands coastlines are very long in comparison to overall island area, they are usually home to the islands richest and most diverse natural resources. The island's principle city or town (including facilities such as hospitals and other emergency resources), its international airport (if it has one) and its governmental centre are all usually found in coastal locations. The result of having the coast as a centre for all of this activity naturally makes for heavy dependence on those coastal resources which, in turn, adds to the vulnerability of the island to storm surges.

“High concentrations of people in urban areas create various social, economic and political stresses, and make people more vulnerable to short-term physical and biological hazards” (Mimura et al 2007, p.693). Examples of these internal ‘human’ stresses that intensify an island’s vulnerability include “rapid population growth, attempts to increase economic growth through exploitation of natural resources such as forests, fisheries and beaches, weak infrastructure, increasing income inequality, unemployment, rapid urbanisation, [and] political instability”(Mimura et al. 2007, p.693). All of this simply compounds island and coastal community physical vulnerability.

Although the aforementioned stresses are vulnerability factors, the principle factor remains the natural hazard of storm surges which cause disproportionally large economic impacts on small islands (Bettencourt et al 2006). One of the reasons for this is the re-occurrence of storm surges. Often the largest challenge related to storm surges is the time it takes to recover. Due to the increasing regularity of these hazards, islands and coastal communities have less time to rebuild - both physically and economically. Agriculture can suffer due to soil salinisation, housing and building infrastructure can be irreparably damaged, forest biodiversity can drop and urban water systems can be soiled (Mimura et al 2007). If a hasty ‘quick-fix’ is applied, then a second storm surge (even if it is smaller) can deliver a devastating blow.

The resulting potential damages of a storm surge to a vulnerable coastal community are diverse and many. Some of the potential socioeconomic impacts are the “direct loss of economic, ecological, cultural and subsistence values through loss of land, infrastructure and coastal habitats; increased flood risk of people, land and infrastructure and the above-mentioned values; and other impacts related to changes in water management, salinity and biological activity.” (Klein and Nicholls 1999, p.183) But there are some damages that are not as easy to identify. As discussed above, storm surges have both short and long-term effects biologically, but they also have both "… short and long-term effects on human health, including drowning, injuries, increased disease transmission, decreases in agricultural productivity and an increased incidence of common mental disorders. Because the impacts are complex and far-reaching, the true health burden is rarely appreciated." (Mimura et al. 2007, p.701) Because of these potential negative human effects, preparation for emergency action is vital and must be taken before the crisis. Although not all the effects on human health can be avoided, there are some aspects that should be taken into consideration when making the emergency action plan. "Disaster affected region[s] tend to be chaotic. Communication is difficult and command structure can break down because of logistical or communication failure. Human behaviour … is hard to control and predict." (Simonovic and Ahmad 2005, p.25)

Small islands' economies often rely heavily on tourism and, with the decreasing costs of travel, it is an industry that is continuing to grow. A single storm surge (or worse, a series of surges) can not only have a negative impact on the physical capabilities of an island's tourism, but it can also have long run negative impacts in terms of the island's overall perception and visitor interest.

Visitor interest and overall perception are very minor concerns for the extreme cases of small island vulnerability. There are a growing number of small islands whose physical existence is in jeopardy. With rising sea levels and storm surge activity, islands such as Kiribati and Tuvalu in the Pacific Ocean are shrinking extremely quickly. "Rising seas are not an abstract notion … these nations face the loss of the very physical basis of their national sovereignty and the loss of their culture." (Pilkey and Young 2009, p.17) The recent UN Climate Change Conference (December 2009), COP15, in Copenhagen touched on this issue as well as many others and garnered tremendous media and public attention, which helped bring these ever-pressing issues to the forefront of international concern (COP15 2009).

When discussing sea-level rise or storm surge situations, a relative base water level must be considered. In this research, all surges are discussed in meters above chart datum (CD). That is to say, chart datum is the base level from which all other measurements are taken.

The literature in this area clearly shows that coastal communities are under threat and need to be better prepared for pending changes. "These changes are likely to lead to high costs of adjustment for local, regional, and national economies. Understanding such changes requires an increased modeling effort that incorporates physical, ecological, and economic processes." (Ruth and Pieper 1994) Thus, it is suggested that using simulation and exploring specific "what-if" scenarios, our understanding of the potential threats can be improved and it will be possible to be better prepared for future changes.

2.2 Geographic Information Systems

According to the Environmental Systems Research Institute (ESRI), "a geographic information system (GIS) integrates hardware, software, and data for capturing, managing, analyzing, and displaying all forms of geographically referenced information." (ESRI 2009)

Any analysis that includes spatial components or spatial information either uses GIS or could usually benefit from the use of GIS. That is why GIS is used in many different fields for a variety of uses. "Since they [GIS] can include physical, biological, cultural, demographic, or economic information, they are valuable tools in the natural, social, medical, and engineering sciences, as well as in business and planning." (Mark et al. 1997) GIS's increasing popularity is due to its ability to summarize data, its continuous development, its visual approach and its operating ease.

The underlying concepts of GIS date back hundreds of years in the fields of cartography and mapping, but GIS, as it is now known, is a recent phenomena. Originating only in the 1960s, GIS has progressed by leaps and bounds in its short history. Riding various waves of technology, GIS knowledge and use has grown exponentially both in the private and public sector.

GIS is far more than simply a mapping tool. GIS does map geographic information with other non-geographic data, but those links can extend far beyond the realm of traditional mapping. "GIS is not a single homogenous set of technologies and practices. There is enormous internal variation within the rubric captured by GIS, and there are important differences in the ways in which GIS functions as a social practice. That is, there is a sociology, political economy, and geography of GIS development and use." (Mark et al. 1997)

Much work on coastal vulnerability, coastal management, and flooding has already been done using GIS. *The Journal of Water Resources and Planning Management*, *The International Journal of Geographic Information Science*, *Natural Hazards Review*, *The Journal of Environmental Management*, *Nature Geoscience*, *Geomatics*, and *The Journal of Coastal Research* are just some of the academic journals that have contained many articles pertaining to GIS coastal work. But the bulk of this work has concentrated either only on the land aspect of the coastal issues or only on the ocean aspect, not the two together.

One GIS-related tool that has concentrated on the ocean is Google Ocean - which was released in February 2009. An add-on to the free and extremely popular Google Earth, Google Ocean allows the user to travel the depths of the ocean to see underwater volcanoes, follow marine wildlife or to investigate how the oceans are changing with the history feature. This free and user friendly application, coupled with the power of Google Earth (which lets users zoom down to street level almost anywhere on the planet), has changed how the general population looks at and accesses GIS. Google has bridged the gap between the academic/government institutions and the general public.

A good example of the public use of Google Earth to simulate the Earth's changing environment was that of the Sierra Club of Canada (BC Chapter), who created a model of the city of Vancouver and introduced a sea level rise of 6m (Sierra Club of Canada BC 2006). It was created in response to March 24, 2006 article in *Science,* which spoke of potential sea level rise due to melting glaciers.

Google Earth and its applications have grown in popularity, but this is not to say that Google has a monopoly in the area – far from it. There are a number of different GIS software packages. Some of the most commercially popular include ESRI, MapInfo, IDRISI, Manifold, InterGraphGeoMedia, SmallWorld, GRASS, MS MapPoint, and ERDAS Imagine. Of these, ESRI's ArcInfo has dominated the market for years and continues to do so due to its continual improvements and its unmatched functionality. Unfortunately, ArcInfo comes with a hefty price tag and high computer requirements, which limits its potential users.

The University of Ottawa does have access to ESRI's ArcInfo and, as it is the industry standard, this is the software that this study uses. Its availability, power and the necessity for the exchange of results and data with other parties using ArcInfo were the reasons why it was selected over other options. ArcInfo is also known for its ease of use alongside other programs and with other applications. This factor was very important in the GIS program choice, but that will be discussed more in the Spatial System Dynamics and Methodology sections.

2.3 System Dynamics

System dynamics (SD) originated with Forrester's *World Dynamics* (Forrester 1971). While attempting to model the entire Earth's sustainability in one complex problem, Forrester developed SD in order to give an understanding of complex dynamic systems in large scale problems. Forrester saw SD as a way to analyze and represent complex systems and their behaviour through a set of tools and a theory of system structure (Forrester 1971). His breakthrough work in this field, although controversial, has gone on and continues to influence much of the work in SD to this day.

SD has developed greatly as a modelling tool since Forrester. The System Dynamics Society offers an updated definition by stating that SD is "a methodology for studying and managing complex feedback systems" (System Dynamics Society 2009). Complex feedback systems will evolve and SD models can give insight into the dynamic feedback processes that are driving the evolution (Ruth and Pieper 1994).

The SD approach takes a holistic view of an entire system. Instead of concentrating simply on how one variable, X, affects one other variable, Y, SD concerns itself with how Y in turn affects X and any (and potentially every) other variable in the system. "A feedback system is influenced by its own past behaviour." (Simonovic and Ahmad 2005, p.29) Feedback systems involve chain reactions that spread far past the obvious affected party. This can lead to extremely complex situations involving many quantitative and qualitative variables, and non-linear relationships - which are in fact quite reflective of real life situations. The interactions are so important that "…amplifications and structural relationships between a system's elements could be more important in determining the aggregate system behaviour than the individual components themselves." (Simonovic 2002, p.253) The entire system must be studied in order to fully grasp the affects of any change in the system in question.

Feedback is the base of the entire SD approach (Sterman 2000). In order to understand this, feedback must be broken down further. There are two different types of feedback: negative and positive. When a variable in a system changes, a system with negative feedback will respond by changing that variable in the opposite way in an effort to bring the system back towards an equilibrium, whereas a system with positive feedback will respond by changing that variable even more in the same way. In short, negative feedback seeks stability and positive feedback amplifies the change.

A feedback relationship, whether positive or negative, can be a very powerful one. The effect of changes being introduced to a system and the "simulation of the model over time [are] considered essential to understand the dynamics of a system." (Simonovic and Ahmad 2005, p.29) Any dynamic system can have SD applied to it at any temporal and spatial scale (Sterman 2000).

The SD methodology is well documented and iterative in nature. In its most simple form the methodology can be regarded as having the following steps (System Dynamics Society 2009):

1) identify a problem
2) develop a dynamic hypothesis explaining the cause of the problem
3) build a computer simulation model of the system at the root of the problem
4) test the model to be certain that it reproduces the behaviour seen in the real world
5) devise and test in the model alternative policies that alleviate the problem
6) implement this solution

SD models can be very intricate and complex. But even the simplest SD models can be beyond cognitive barriers. One of Sterman's models, The Carbon Bathtub, is an extremely basic view of the Earth's growing carbon dioxide (CO_2) emissions (Kunzig 2009). In short, there is a bathtub containing the CO_2 in the Earth's atmosphere, in which a tap of CO_2 (coming from various causes, many of them human) is running, at the same time the plug has been removed so that the bathtub is draining (plants, oceans and rocks all take in CO_2). Currently, Sterman believes, this 'carbon bathtub' is filling much faster than it is draining, hence the current global climate crisis. Sterman has found that even his students at MIT have found the model itself hard to grasp. "Most thought that simply stopping emissions from rising would stop the rise of CO_2 in the atmosphere— as if a tap running steadily but rapidly would not eventually overflow the tub." (Kunzig 2009) Other universities have gone on to replicate the results that Sterman had with his students, suggesting that there is a general lack of understanding of SD flow models that needs to be addressed.

SD flow models may be confusing to some, but few who understand them would argue their importance. Dynamic systems, as mentioned earlier, often require an interdisciplinary approach in order to be understood. Different disciplines must be called upon and often models from one are adapted to another. Such was the case for Nordhaus's Dynamic Integrated model of Climate and the Economy (DICE) and Regional Integrated model of Climate and the Economy (RICE) models (Nordhaus and Boyer 2000). These models analyze the economics of climate change. The DICE model was the first model to have an integrated-assessment of the economics of climate change. Based on the economic model of Ramsay in the 1920s, these models attempt to consider the balance between what is used today and what will be left for the future. Many parallels were made in the DICE models order to mimic the Ramsey model. For example, concentrations of greenhouse gases were regarded as negative capital, and the lowering of emissions regarded as lowering the quantity of negative capital. The models contain the traditional economic sector, exactly like a typical economic model, but they also contain a geophysical model that incorporates the climate change modelling. One of the major results of the RICE and DICE studies was

"… to show the economic impacts of alternative climate-change policies." (Nordhaus1999, p78) These models were a huge advancement in terms of using an interdisciplinary systems approach to modelling environmental change.

In order to build the models in this research, a system modelling environment needs to be chosen. There are several different software packages available for this kind of work. These all use differential and difference equations and are able to easily solve simultaneous, nonlinear equations that describe the complex systems (Ruth and Pieper 1994). Three software packages, Vensim, Simile and STELLA, were considered for this project. The three have many things in common, but each has one factor that separates itself from the rest. Vensim's advantage is that it is free to the public. This would be an advantage when working with our partners in the communities. Simile's benefit is that it specializes in environmental and ecological modelling. ISee System's STELLA has the most user-friendly interface, produces the best graphics (flow charts, tables, etc), is quite compatible with other programs and many members of the research team were already familiar with it. STELLA was chosen for its presentation abilities, ease of use, ability to work with ArcGIS and familiarity to team members.

SD models, including economic factors, in this study are heavily influenced by Forrester, Sterman and Nordhaus and although SD is an essential part of this work, it is not enough on its own to accurately model the system of the vulnerable coastal community. "The strength of system dynamics approach is in representing temporal process. The SD models, however, do not adequately represent spatial processes." (Ahmad and Simonovic 2004, p.332) In order to overcome this limitation, GIS and SD must be used together.

2.4 Spatial System Dynamics

As SD is a broad methodology, it naturally has subdivisions that pertain to specific fields of study. "Traditional modelling approaches focus on either temporal or spatial variation, but not both ... To understand dynamic systems, patterns in time and space need to be examined together." (Ahmad and Simonovic 2004, p.331) In order to link environmental, social, cultural, and economic factors together both spatial and temporal aspects must be included. The integrated framework that is used in this study, meshes these fields together in an approach called Spatial System Dynamics (SSD).

The SSD methodology is not the sole approach to combining GIS and SD. For example, early attempts saw a time series approach taken which would concentrate on only one variable in the system. In this method, an entirely new base map would be drawn up after each change to the variable in question. This would produce a series of static maps over time (Grossman and Eberhardt 1992).

Another, and more dynamic, approach is based on the classic transport models of physics using partial differential equations to describe the dynamic relationships and cellular automata models to grasp the spatial aspects. Using these models, the spatial components are generally broken down into a grid of interconnected cells that will evolve over time (Ruth and Pieper 1994).

Toffoli and Margolus (1987) laid the ground work that many others (such as: Xia and Gar-On (2000)) would attempt to build upon. Using cellular automata as a modelling paradigm to spatially and temporally describe dynamic processes is possible but using cellular automata with GIS has proved to be very difficult to mimic real life situations.

In Ruth and Pieper's (1994) paper, *Modeling spatial dynamics of sea-level rise in a coastal area*, a base model was created to examine the need to combine the two disciplines of GIS and SD in the field of sea-level rise and coastal dynamics. The authors did not attempt to create a comprehensive, highly accurate model; rather, they built a flexible undemanding, yet vital, model that interdisciplinary research would be able to build upon. "Two requirements are essential for the implementation of such a model. First, the model must be dynamic, and second, it must represent and maintain the spatial relations within the area of study." (Ruth and Pieper 1994, p.375)

Although the concept of mixing spatial and system dynamics has been discussed from various approaches (Nyerges 1991; Despotakis, et al. 1991; Grossman and Eberhardt 1992, Groothedde 2000) over the last twenty years, this work will follow that of Ahmad and Simonovic (2004) because "the SSD approach addresses most of the limitations present in the existing methods." (Ahmad and Simonovic 2004, p.331)

Ahmad and Simonovic (2004) found that research combining GIS and SD could be divided into two limited categories. The first was the approach of introducing spatial dimensions in the system dynamics model, which fell short because the spatial dimensions could not be represented explicitly. The second was to translate SD model equations to run in GIS, but this was also limited because it lacked interactive power as changes could not be made during the simulation. "The links between GIS and modeling are still weak. No adequate software exists that incorporates aspects of both dynamic modeling and GIS in a manner sufficiently general yet powerful enough to be widely used." (Ruth and Pieper 1994) As a result, the spatial system dynamics approach for modelling dynamic processes in time and space was developed.

SSD combines the temporal strengths of SD with the spatial strengths of GIS "… to model feedback based dynamic processes in time and space."(Ahmad and Simonovic 2004, p.333)   Separately, the two both severely lack the other's strength and by attempting to integrate one into the other, some of the robustness is lost. Therefore, the only way to truly combine the separate strengths of these tools is to run them both simultaneously.

The SSD approach runs both programs separately but incorporates a two-way dynamic data and information exchange between the SD and the GIS, which provides feedback in space and time. "Initially, GIS provides spatial information to the SD model. The SD model, through dynamic modelling, identifies changes in the spatial features with time and communicates them back to GIS. These changes in space in turn impact decisions/policies in time. Thus, processes can be modeled in time and space in an integrated way while capturing the feedback." (Ahmad and Simonovic 2004, p.333) The SSD modelling process is shown in flow diagram form in Figure 2.1 from Ahmad and Simonovic 2004.

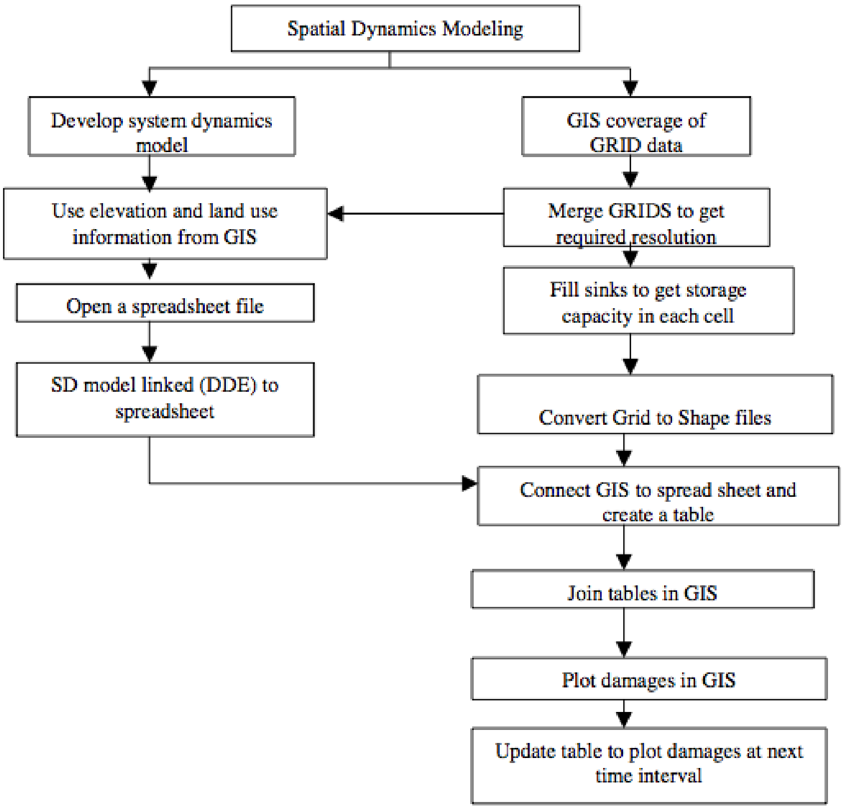

Figure 2.1: Flow Diagram of SSD (Source: Ahmad and Simonovic 2004, p.334)

The SSD approach is still in its infancy and has not been widely used. As GIS software continues to grow in popularity and more functions are added, a SD application will no doubt be developed. In the meantime, it is necessary to have full licenses to both programs, which is a deterrent as it restricts portability.

2.5 Charlottetown

2.5.1 Introduction

Charlottetown is Prince Edward Island's capital city, which is situated on Canada's Atlantic coast. With a population of 32,174 (2006), Charlottetown makes up nearly 24% of Prince Edward Island's total population (BC Stats Data Services 2007). Public administration and retail trade are the biggest industries in Charlottetown (versus agriculture, forestry, fishing, and hunting for the rest of Prince Edward Island). Charlottetown is known for its temporary boost in population during the tourism season in the summer months. A map of Charlottetown can be seen in Figure 2.2.

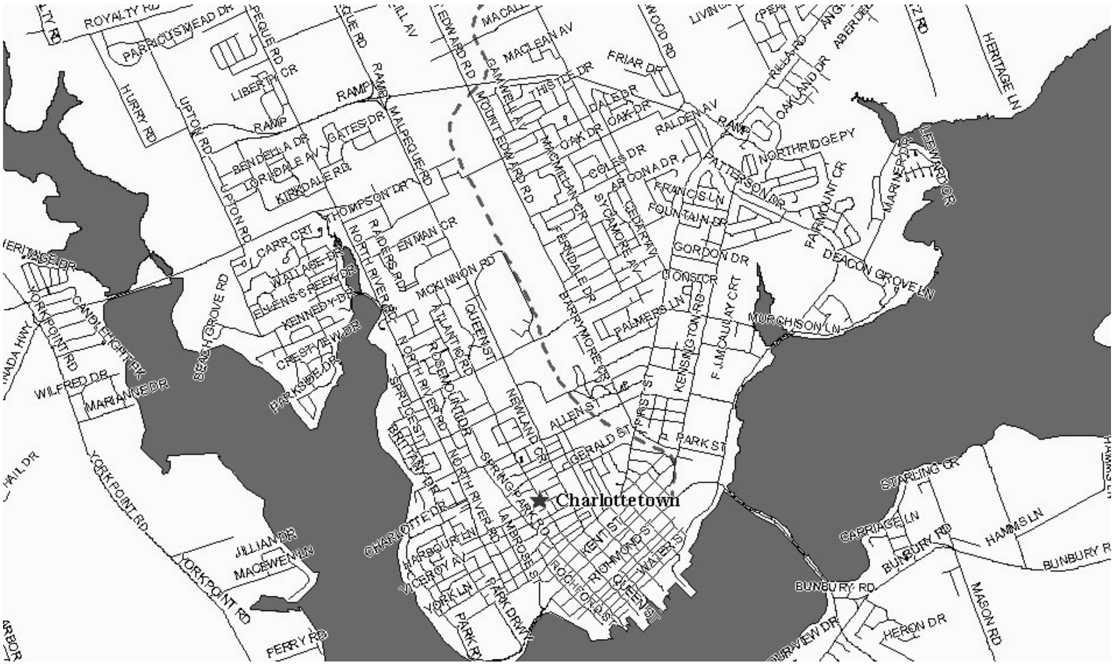

Figure 2.2: Map of Charlottetown (Source: PEI 2010)

There is a great risk to the higher-latitude coastal areas along the eastern seaboard to hurricane landfall and a study that may yield insights into the environment, structure, and motion of a high impact hurricane may prove to be extremely valuable (McTaggart-Cowan et al. 2005). "Mid-latitude islands [such as Prince Edward Island] … are exposed to impacts from tropical, post-tropical and extra-tropical storms that can produce storm-surge flooding, large waves, coastal erosion, and (in some winter storms) direct sea ice damage to infrastructure and property. Possible increases in storm intensity, rising sea levels, and changes in ice duration and concentration, are projected to increase the severity of negative impacts progressively…" (Mimura et al 2007, p.695).

2.5.2 Notable Studies on Charlottetown's Storm History

Charlottetown has always been exposed to storm surges, but in recent years the frequency of severe storms has seemed to have increased. An overview of the damages and properties of Charlottetown's most severe storms since 1950 can be found in section 2.5.3, a graph of Charlottetown's yearly average events from 1940 to 2004 can be seen in Figure 3, Charlottetown's top ten maximum observed water levels can be seen in Table 1 and Charlottetown's top ten storm surges can be seen in Table 2.

There have been two major studies done within the last decade that had major portions focused on Charlottetown. In 2002, the 'Coastal Impacts of Climate Change and Sea-Level Rise on Prince Edward Island' report was published by Martha M. McCulloch, Donald L. Forbes, Roderick W. Shaw, the CCAF A041 Scientific Team, Meteorological Service of Canada (Environment Canada), Geological Survey of Canada (Natural Resources Canada) and Rodshaw Environmental Consulting (McCulloch et al. 2002). Then in 2006, the 'Impacts of Sea Level Rise and Climate Change on the Coastal Zone of Southeastern New Brunswick' report was published, lead by Mr Réal Daigle with a 29 member research team and partnered with Environment Canada, Fisheries and Oceans Canada, Natural Resources Canada, Parks Canada Agency, New Brunswick Department of Environment, New Brunswick Department of Natural Resources, Centre of Geographic Sciences, Dalhousie University, Laurentian University, Mount Allison University, Université de Moncton, and the University of New Brunswick (Daigle et al. 2006).

McCulloch et al. (2002) were among the first to employ light detection and ranging (LiDAR) to obtain high-resolution, accurate representations of the topography in order to make predictions of vulnerable areas. "With LIDAR, an airborne system emits laser pulses toward the ground and measures the return time of the pulses; from this a range is calculated. By using precise GPS [Global Positioning System] technology to determine the location of the aircraft and an inertial reference system (IRS) to measure the attitude (pitch, yaw, and roll) of the aircraft, we can determine the location of individual laser returns." (Webster et al. 2003) The authors quote the overall accuracy of the system at ±30 centimetres in the horizontal plane and ±20 centimetres in the vertical plane.

These LIDAR data were used to develop a digital elevation model (DEM) of Charlottetown so that flood scenarios based on water levels resulting from storm surges could be simulated. The study chose three water level scenarios based on the January 21st, 2000 storm surge (scenario 1: 4.23 m CD), and then added extra height to the scenarios with respect to expected sea level rise (scenario 2: 4.70 m CD, scenario 3: 4.93 m CD based on 100 years of anticipated sea-level rise) (McCulloch et al. 2002).

In section 4.2.3 (Storm Surges at Charlottetown) of the latter report (Impacts of Sea Level Rise and Climate Change on the Coastal Zone of Southeastern New Brunswick), the researchers present a 45 year examination of Charlottetown's storm-surge climatology using tide gauge data which are "among the longest, most complete, and most reliable water level records in Canada" (Webster et al. 2003). When averaging the tide gauge statistics, it was found that storm surges above 60 cm occur eight times a year, storm surges above 100 cm occur once a year, storm surges above 120 cm occur three times a decade, and that there have been two events total which had storm surges greater than 150 cm. It was also found that there is an increase in frequency of storms in October and November, and that peak storm activity is in December and January.

The storm activity was also examined by decade. The researchers found that "storm surges appear to have become a little more frequent from the 1940s to the 1960s; in particular, the larger surges (>120 cm) not present at all in the 1940s and 1950s show up thereafter, although they remain uncommon events. The 1970s and 1980s were strong storm-surge years, with more than two 80 cm events on the average year, and the 1980s show more than one 100 cm event on average each year. The 1990s saw generally fewer storm surges, although there were a few particularly big events... The period since 2000 has also been very active." (Parkes et al. 2006, p.113 (4.2 in Daigle et al. 2006)) A graph of the average number of storm surges per year above storm surge height thresholds of 60 cm, 90 cm, 120 cm, and 150 cm by half-decade can be seen in Figure 2.3.

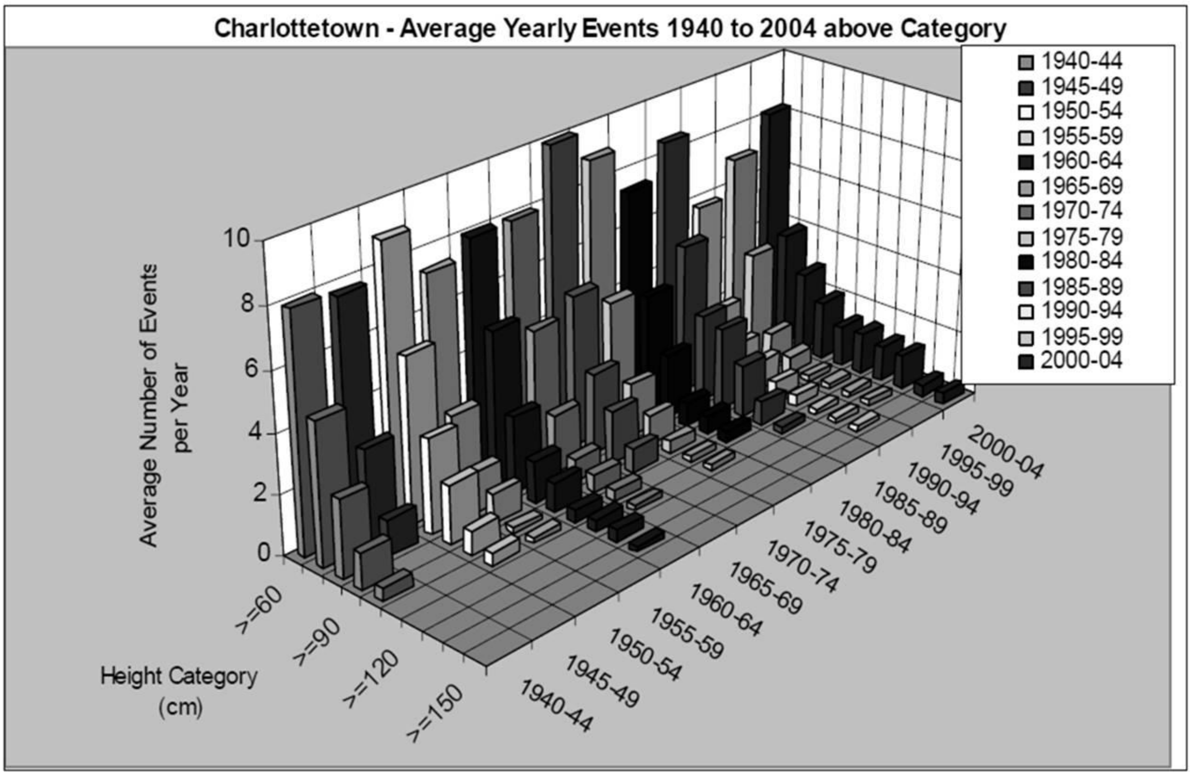

Figure 2.3: Average number of storm surges per year above storm surge height thresholds by half-decade.

(Source: Parkes et al. 2006, p.116 (4.2 in Daigle et al. 2006))

From the graph in Figure 2.3, it can be seen that Charlottetown has had a fair number of severe storm surges in its history. It is important to note that the Charlottetown waterfront only begins to flood with seawater if the water level is above 3.6 m CD (Webster et al. 2002). The highest predicted tide stands at 2.91 m CD, so a storm surge of at least 69 cm is needed to flood the waterfront (Parkes et al. 2006 (4.2 in Daigle et al. 2006)). The top 10 water levels from the 2006 analysis of

Charlottetown's storm climatology (covering the years 1911 to 2005) can be found in Table 2.1. Of these top 10, only 3 would flood the waterfront, but it must be noted that these 10 are not the highest storm surge heights (they are the highest observed water levels).

Table 2.1: Top 10 water levels in Charlottetown from 1911-2005 (Source: Parkes et al. 2006, p.120 (4.2 in Daigle et al. 2006))

Date	Maximum observed water level (m CD)	Storm surge height (m CD)
January 21, 2000	4.22	1.37
January 21, 1961	3.84	1.31
February 19, 2004	3.77	1.30
January 21, 1973	3.76	1.00
March 17, 1976	3.76	1.20
December 30, 1993	3.67	1.12
February 5, 1974	3.65	1.09
December 25, 1983	3.59	1.17
September 12, 2002	3.49	1.35
December 1, 1943	3.44	0.82

From this table, the trend of severe storms in recent years is not overly apparent; having had three of the top ten storm surge events in five years (2000-2004) but if Charlottetown's top ten storm surges are examined, such as in Table 2.2, it shows that extreme surges have indeed become more frequent as of late with six of the storm surge events being in the five year period from 2000-2004. It is also apparent from both tables that the winter months are in fact when the most severe storm surge events do occur.

The largest reason for the difference in the tables is due to tide cycles. In the fourth column of Table 2.2, it can be seen that storm events that coincide with high tide have a much higher maximum observed water level than those that coincide with a low tide. Tidal cycles play a very strong role in the severity of storm surges. The bottom four storm surges in Table 2.1 illustrate this fact perfectly. These four storm events have almost identical surge heights but have all occurred at different tide cycles; one at low tide, one a mid tide, one at nearly high tide and the last at high tide. So even though the variability of the storm surge height is minor, the maximum observed water heights vary from as low as 3.02 meters at low tide to 3.84 meters at high tide.

Table 2.2: Top 10 storm surges in Charlottetown from 1911-2005 (Source: Parkes et al. 2006, p.120 (4.2 in Daigle et al. 2006))

Date	Storm surge height (m CD)	Maximum observed water level (m CD)	Tide Cycle
January 17, 2004	1.53	3.31	Low
December 27, 2004	1.52	3.19	Low
December 19, 1963	1.43	3.01	Low
March 12, 1991	1.41	2.63	Low
January 21, 2000	1.37	4.22	High
September 12, 2002	1.35	3.49	Mid
January 21, 1961	1.31	3.84	Nearly High
January 15, 1996	1.30	3.02	Mid
October 29, 2000	1.30	3.33	Low
February 19, 2004	1.30	3.77	High

2.5.3 Historical Storm Damages

Thirteen storm events were examined using data from Environment Canada's Canadian Hurricane Center (Environment Canada 2009) and the Department of Fisheries and Oceans' Tides, Currents and Water Levels Data Archive (Department of Fisheries and Oceans 2010). The storm surge events are named either by their given storm name (if it has been named), or by a name that it is popularly known by (for example: White Juan) or simply by 'No Name' and the year of its landfall. These thirteen storm surge events were chosen based on each storm's damages, the availability of data, maximum observed water level, pressure, wind speed, storm speed, category and date. Each storm is described below in chronological order and a summarizing table (Table 2.3) can be found at the end of this section.

Able

On August 21, 1950 Tropical Depression Able (which had been a marginal Category 1 Hurricane when it first entered Canadian waters) landed at Prince Edward Island with a speed of 44 kilometres per hour, with winds of 55 kilometres per hour and with a maximum observed water level of 2.52 meters above chart datum. The impacts of Able on Charlottetown were that many of the streets were flooded and impassable and there was a power outage which lasted an estimated three to four days. (Environment Canada 2009, http://www.ec.gc.ca/hurricane/default.asp?lang=En&n=A0AC0965-1).

Carol

On September 8, 1953 Extratropical Storm Carol (which had been a Category 4 Hurricane at its peak) landed at Prince Edward Island with a speed of 63 kilometres per hour, winds of 110 kilometres per hour and a maximum observed water level of 2.95 meters above chart datum. The impacts of Carol on Charlottetown were that the wind knocked over trees (specifically large trees were uprooted in Kings Square, Water Street and Kent Street), roofs were blown off, a chimney was knocked off a residences home, there was some power outage due to cut telephone and power lines and the two ferries (Prince Edward Island – New Brunswick and Prince Edward Island – Nova Scotia) both had to be tied up at height of the storm (Environment Canada 2009, http://www.ec.gc.ca/hurricane/default.asp?lang=En&n=57B70220-1).

‘Kennedy Inaugural Storm’

Named as such due to its occurrence on the historical day that American President Kennedy did his inaugural address in Washington, USA, the ‘Kennedy Inaugural Storm’ landed at Charlottetown on January 21, 1961 and had a record setting maximum observed water level of 3.84 meters above chart datum and a storm surge of 1.31 meters (Parkes et al. 2006 (4.2 in Daigle et al. 2006)).

‘No Name 1962’

‘No Name 1962’ occurred on April 4, 1962 and had a maximum observed water level of 2.55 meters with 180 millimetres of rainfall overtop of snow. The impacts of ‘No Name 1962’ were felt all over the province with damaged and washed out paved highways (Environment Canada 2009, http://www.ec.gc.ca/eau-water/default.asp?lang=En&n=4FCB81DD-1).

Ginny

On October 30, 1963 Extratropical Storm Ginny made landfall on Prince Edward Island with a speed of 61 kilometres per hour, with winds of 150 kilometres per hour and a maximum observed water level of 3.15 meters above chart datum. The impacts of Ginny on Charlottetown were power outages and the stopping of ferry service between Prince Edward Island and Nova Scotia during the storm (Environment Canada 2009, http://www.ec.gc.ca/hurricane/default.asp?lang=En&n=C81C5991-1).

‘No Name 1964’

On December 2, 1964 ‘No Name 1964’ struck Charlottetown with winds of 160 kilometres per hour and a maximum observed water level of 2.47 meters above chart datum. Although not an impact directly on Charlottetown, the storm did have such an impact at sea that three fishing boats were capsized, two of which were large draggers, and a total of twenty-three lives were lost (Environment Canada 2009, http://www.ec.gc.ca/meteo-weather/default.asp?lang=En&n=6A4A3AC5-1).

Hortense

Category 1 Hurricane Hortense struck Prince Edward Island on September 15, 1996 with a speed of 48 kilometres per hour, winds of 130 kilometres per hour, pressure of 970 millibars, and a maximum observed water level of 2.89 meters above chart datum. All power was lost in Charlottetown as the high winds destroyed many power lines and also the ferry service was halted most of September 15th and part of September 16th (Environment Canada 2009, http://www.ec.gc.ca/hurricane/default.asp?lang=En&n=B4BCC134-1).

‘No Name 2000’

January 21, 2000, an extremely low pressure system (951 millibars) with strong northeasterly winds traveling up the east coast of the continent coincided with high tide striking Charlottetown with a record water level of 4.23 meters above chart datum (Natural Resources Canada 2009) and a storm surge height of 1.37 meters above chart datum (Parkes et al. 2006 (4.2 in Daigle et al. 2006)). The storm surge did severe damage to many public and private properties, the wharves in Charlottetown harbour, a power-generating station, a lighthouse and numerous gas stations. The total damage from this storm was estimated at $20 million (Natural Resources Canada 2009).

Subtrop

On October 29, 2000, Charlottetown was hit with its second extremely severe storm event of the year. Subtrop struck Charlottetown at a speed of 61 kilometres per hour, winds of 100 kilometres per hour, pressure of 978 millibars, 30-60 millimetres of rainfall, storm surge height of 1.30 meters (Parkes et al. 2006 (4.2 in Daigle et al. 2006)), and a maximum observed water level of 3.32 meters above chart datum. Many roads and bridges were washed out due to high winds and tides. Trees were knocked over, roofing shingles were pried off and eroded sediment was dispersed in various areas of the province. Also, thousands of pounds of lobster were beached along the coast of province (Environment Canada 2009, http://www.ec.gc.ca/hurricane/default.asp?lang=En&n=88E8D42D-1).

Gustav

On September 12, 2002, Category 1 Hurricane Gustav struck Charlottetown at a speed of 74 kilometres per hour, with winds of 150 kilometres per hour, pressure of 962 millibars, 61 millimetres of rainfall, storm surge height of 1.35 meters (Parkes et al. 2006 (4.2 in Daigle et al. 2006)), and a maximum observed water level of 3.489 meters above chart datum. Power was lost across Prince Edward Island and a vehicular accident, believed to be caused by the storm, left one man dead (Environment Canada 2009, http://www.ec.gc.ca/hurricane/default.asp?lang=En&n=91CCCE08-1).

Juan

On September 29, 2003, the high-latitude landfalling Hurricane Juan severely damaged Nova Scotia along with Prince Edward Island. Although Juan was a Category 2 hurricane when it struck Nova Scotia, it had been downgraded to a Post-Tropical Storm when it hit Prince Edward Island. Its path can be seen in Figure 2.4 and an overall description of the global damages can be found in Chapter 1. The complex storm that wreaked havoc through the Canadian Maritimes did most of its damage in Halifax but also hit Charlottetown. The American Meteorological Society's analysis of the storm "… suggests that high-amplitude prestorm ridging plays an essential role in the storm's evaluation by creating an environment both dynamically and thermodynamically favourable for the maintenance of tropical structures at high altitudes." (McTaggart-Cowan et al 2005)

Figure 2.4: Path of Hurricane Juan, 2003 (Source: www.stormpulse.com)

Juan hit Charlottetown with a speed of 59 kilometres per hour, with winds of 120 kilometres per hour, pressure of 982 millibars and a maximum observed water level of 2.927 meters above chart datum.

<u>'White Juan'</u>

On February 19, 2004 a severe storm struck the Maritime Provinces and became known as 'White Juan' due to its occurrence relatively soon after the large storm event of Hurricane Juan. 'White Juan' occurred at high tide in Charlottetown which gave the storm surge height of 1.30 meters and a maximum observed water level of 3.77 meters above chart datum, the third highest water level on record in Charlottetown (Parkes et al. 2006 (4.2 in Daigle et al. 2006)), which in turn caused widespread flooding to the city.

Hanna

The most recent storm event examined in this thesis struck Charlottetown on September 7, 2008 with a storm speed of 64 kilometres per hour, winds of 85 kilometres per hour, pressure of 995 millibars, 90 millimetres of rainfall, and a maximum observed water level of 2.462 meters above chart datum. The impacts of the storm were that several of Charlottetown's street were closed due to rainfall runoff flooding (including the two roads that lead out of Charlottetown, Trans-Canada Highway in Cornwall and Brackley Point Road in Harrington, which had a major affect on rush hour traffic) and the half meter submerging of parts of Joe Ghiz Park on Grafton Street (Environment Canada 2009, http://www.ec.gc.ca/ouragans-hurricanes/default.asp?lang=en&n=D4E915BC-1).

Table 2.3: Summary of 13 important storm events for Charlottetown

NAME	DATE	MAXIMUM OBSERVED WATER LEVEL (M CD)	SPEED (KPH)	WIND (KPH)	PRESSURE (MB)	TIDE CYCLE	TYPE
Hanna	07/09/2008	2.462	64	85	995		Extratropical
NN1964	02/12/1964	2.47		160			
Able	21/08/1950	2.52	44	55			Tropical Depression
NN1962	04/04/1962	2.55					
Hortense	15/09/1996	2.89	48	130	970		Hurricane Category 1
Juan	29/09/2003	2.927	59	120	982		Post-Tropical Storm
Carol	08/09/1953	2.95	63	110			Extratropical Storm
Ginny	30/10/1963	3.15	61	150			Extratropical Storm
Subtrop	29/10/2000	3.32	61	100	978	Low	Subtropical Storm
Gustav	12/09/2002	3.489	74	150	962	Mid	Hurricane Category 1
White Juan	19/02/2004	3.772				High	
Kennedy	21/01/1961	3.84				Nearly High	
NN2000	21/01/2000	4.216		70	945	High	

Table 2.3 lists 13 major storms in Charlottetown since 1950 by increasing maximum water level. It is interesting to note that the eighth column, which lists the type of storm, shows little correlation with the column for maximum observed water level. The type of storm (hurricane, post-tropical storm, subtropical storm, tropical depression, extratropical storm, or no known storm status) does not increase in severity as the maximum observed water level grows. For example, Hortense was a category 1 hurricane yet it only resulted in a maximum observed water level of 2.89 meters above chart datum while the Kennedy Inaugural storm was an extratropical storm and it resulted in a maximum observed water level of 3.84 meters above chart datum. The reason for this is mainly the tides and it is discussed more in Section 4.2. It is also interesting to note that of the 13 storms since 1950, 6 of them have occurred since 2000, which suggests that severe storm surges are growing in frequency.

2.5.4 Charlottetown Sea-Level Rise

Due to its very recent storm history and the trend of growing frequency and extremity of storm surges, it is believed that Charlottetown remains extremely vulnerable to extreme weather events. Other "factors contributing to this sensitivity include a soft sandstone bedrock, a sandy and dynamic shore zone (but sediment-starved in places), an indented shoreline with extensive salt marsh, low terrain behind the shore with significant flooding potential, documented high rates of shore retreat and ongoing submergence of the coast." (Webster et al. 2003) But it is not only the environmental factors that make Charlottetown so vulnerable. "These more northerly coastal areas also lack the experienced, extensive hurricane emergency management, evacuation, and mitigation infrastructures necessary in regions more commonly affected by major land falling hurricanes." (McTaggart-Cowan et al. 2005) Due to its location and its infrastructure and population densities on the coastal region, Charlottetown needs a variety of dynamic response plans.

Although this research concentrates on a coastal community's vulnerability to storm surges, it is important to note that Charlottetown is also in a position of concern in terms of coastal sensitivity to sea level rise. Natural Resources Canada defines coastal sensitivity to sea level rise as "… the degree to which a coastline may experience physical changes such as flooding, erosion, beach migration, and coastal dune destabilization." (Natural Resources Canada 2007) Figure 2.5 shows a map of Atlantic Canada centered on Prince Edward Island. The colour scheme depicts the sensitivity to sea level rise with sensitivity index scores from 0.8 to 56.7. "This sensitivity index is obtained by manipulating scores of 1 to 5 attributed to each of seven variables: relief, geology, coastal landform, sea-level tendency, shoreline displacement, tidal range, and wave height." (Natural Resources Canada 2007) The sensitivity index breaks down into three groups - 'Low' regions (0 - 4.9 on the sensitivity index), 'Moderate' regions (5.0 - 14.9 on the sensitivity index) and lastly, 'High' regions (15 and up on the sensitivity index) that are represented by the darkest shade on the map in Figure 2.5. It is plain to see that Charlottetown falls directly in the dark or highly sensitive areas. "Even in the absence of climate change, the present rate of sea-level rise around Prince Edward Island will bring future challenges to human interests and ecological systems in the coastal zone." (Webster et al. 2003)

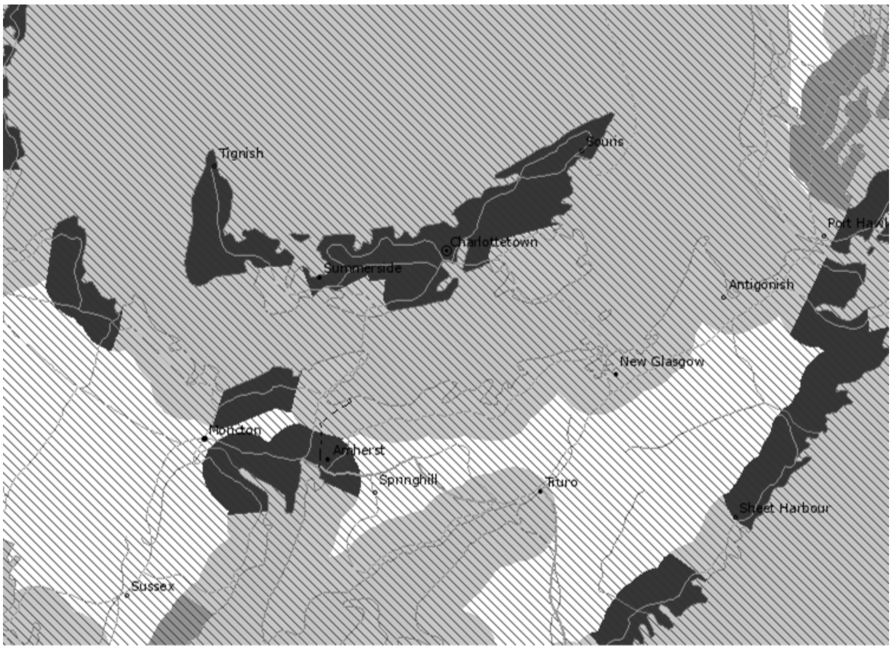

Figure 2.5: Coastal sensitivity to sea level rise (Source: http://atlas.nrcan.gc.ca/site/english/maps/climatechange/potentialimpacts/coastalsensitivitysealevelrise)

2.5.5 Charlottetown Data

In order to address the issue of potential impacts to Charlottetown's coast, a great deal of data must be collected. As previously mentioned, in order to grasp Charlottetown as a dynamic system, community data must be taken into account that encompasses all aspects of the community description. For this reason, coastal biophysical, land use, ocean use, residential, natural resources, transportation data, and more need to be collected. Much of these data are available through Statistics Canada, the Provincial Government of Prince Edward Island, DMTI, GeoBase and GeoConnections.

2.5.6 Connecting with the Participants

Using these data to grasp Charlottetown as a system is only one part of this research's objectives. Another key goal of the C-Change research is that of working with the decision-makers and citizens of Charlottetown to improve understanding of storm surges and sea level rise and how it affects the community. Climate change knowledge is still largely handed to the public and decision-makers from scientists with the formers only role being to implement suggested changes – this is an overly expert-driven process and it needs the participation of the community leaders and members to fully grasp and tackle the problem (Lubchenco 1998). Co-production of knowledge has been found to be necessary for the ownership and social robustness of problems and solutions (Burch et al 2009). Not only do 'non-experts' need to be involved in the research, but the decision-makers and community members also need to be taken into consideration when deciding how to present the results as they are the ones who implement the changes, therefore the research needs to be presented as clearly and as engagingly as possible.

A powerful technique for linking global science to a local community is through the use of visual aids of their own environment. Thus, in order to return a useful model to the research partners in Charlottetown, visualization approaches must be considered.

The visual recognition of impacts on one's community generates empathy, as opposed to sympathy, for the situation and this added context will make the impacts more meaningful (Leiserowitz 2004). In *Climate Change Visualization: Using 3D Imagery of Local Places to Build Capacity and Inform Policy* (Burch et al 2009), the authors speak of bridging "the divide between predictive, quantitative approaches and narrative-based qualitative methods" by "addressing climate change in a participatory way, with credible but easily accessible visuals, and at a scale that matters to people" (Burch et al 2009, p.65). The method taken in this British Columbia study was a three-step process to (i) localize, (ii) spatialize and (iii) visualize.

i. “Localize: translate or downscale global climate data to regional and local scales in a transparent, understandable manner for local policy makers and the public;
ii. Spatialize: describe the potential impacts of climate change in the landscapes where people live and work, and adaptation and mitigation options in these places, through spatial modelling and/or interpretive mapping at the local level;
iii. Visualize: communicate this information in an ethical, scientifically defensible, and dramatic manner (using 3D simulation of recognizable places) that not only educates viewers on the realities of climate change but also emotionally motivates behavioural change at the individual and community level.” (Burch et al 2009, p.66)

Using this three-step process, Burch et al (2009) presented key elements of the IPCC’s Special Report on Emissions Scenarios to an extended research team made up of scientists of various disciplines, government workers, members of academia, local residents, practitioners and stakeholders. There were four responses to the scenarios to choose from: Do Nothing, Adapt to Risk, Efficient Development, and Deep Sustainability. The authors found that “the extensive use of realistic visualisations maintained a high level of engagement among the public participants over a long and intense visioning session” and that there was a considerably more of the respondents who personally planned to take some assertive action (Burch et al 2009, p.70).

2.6 Summary

From the literature reviewed, coastal vulnerability to storms is an issue that cannot be ignored. The work of the IPCC scientists (Mimura et al. 2007) has created groundbreaking state of the art climate change research. The IPCC reports have now become a standard building block for all climate change research. Many other researchers, like Dolan and Walker in *Understanding Vulnerability of Coastal Communities to Climate Change Related Risks* (Dolan and Walker 2003), have also shown that low-lying coastal communities are extremely vulnerable to storm surges and sea level rise. It is also apparent that coastal vulnerability to climate change is a multi-dimensional concept that needs to be addressed by inter and multi-disciplinary research as discussed in Klein and Nicholls 1999 paper *Assessment of Coastal Vulnerability to Climate Change* (Klein and Nicholls 1999).

From the geographic information systems literature that was reviewed, it is clear that GIS is an imperative tool in modelling climate change and coastal areas. The flexibility and power of GIS as a modelling tool is apparent in the examples seen in Section 2.2, such as Google Ocean, the Sierra Club of Canada's Google Earth simulation (Sierra Club of Canada, BC Chapter 2006), and the plethora of GIS related journals. The different GIS software platforms available in today's market were also examined and from this ESRI's ArcInfo was chosen for this project for its ease of use alongside other applications, its robustness and its availability at the University of Ottawa.

Looking at the history of system dynamics starting with Forrester's *World Dynamics* (Forrester 1971) has provided an understanding of its origins and development as a discipline. By breaking down the system dynamics methodology and explaining it as a feedback process and then following the iterative steps in the process (System Dynamics Society 2009), it is easy to understand how this can be applied to this research's methodology concerning vulnerable coastal areas. Sterman's work in system dynamics is crucial to the development of this research's models (Sterman 2000). When looking at the economic aspects of this research's model, it is apparent that Nordhaus' system dynamics work with economics in the RICE and DICE models has had an influence (Nordhaus 1999). The literature review also examined the modelling of spatial dynamics in Ruth and Pieper's 1994 paper *Modeling Spatial Dynamics of Sea-Level Rise in a Coastal Area* (Ruth and Pieper 1994), Simonovic's 2002 paper *World Water Dynamics: Global Modeling of Water Resources* (Simonovic 2002), and Simonovic and Ahmad's 2005 paper *Computer-Based Models for Flood Evacuation Emergency Planning* (Simonivic and Ahmad 2005). The literature review also inspected the various modelling environments available to use for this research. Of the three software packages heavily considered (Vensim, Simile, and STELLA), STELLA was chosen due to its user-friendly interface, its stellar production of graphics, its compatibility with other programs and the fact that many members of the C-Change research team were already familiar with it.

By using GIS for the spatial mapping and the SD approach, it is believed that Ahmad and Simonovic's Spatial System Dynamics (Ahmad and Simonovic 2004) is the most useful method to run simulations pertaining to the environmental, social, economic, and cultural aspects of a coastal community's vulnerability to storm surge. Their integrated framework is not the only one available to link spatial and dynamic aspects, but it is unique in its approach. By running the two programs, ArcInfo and STELLA, separately but incorporating a two-way dynamic data and information exchange, a series of simulated situations can be examined, the vulnerability gauged, and eventually a response planned. The Spatial System Dynamics methodology is the base methodology that this research will build upon. The SSD flow model (Figure 1) has been taken into account and, although altered somewhat, plays an important role as a building block of this research.

It can also be seen from the literature reviewed that Charlottetown is a coastal community at risk. The IPCC's fourth assessment report states mid-latitude islands like Prince Edward Island are extremely exposed to severe weather events (Mimura et al. 2007), and the history of Charlottetown's storm surges as researched in *Coastal Impacts of Climate Change and Sea-Level Rise on Prince Edward Island* (McCulloch et al. 2002) and in *Impacts of Sea Level Rise and Climate Change on the Coastal Zone of Southeastern New Brunswick* (Daigle et al. 2006) shows very clearly that not only is Charlottetown prone to extreme storm surges, but that as time passes the events are becoming more severe and more frequent. With its low-lying location, its population and economic density on the coast and its storm history, Charlottetown needs to be prepared for a storm surge.

Lastly, the importance of visual recognition as a technique for linking global science to a local community was discussed based mostly on *Climate Change Visualization: Using 3D Imagery of Local Places to Build Capacity and Inform Policy* (Burch et al. 2009) but also with input from Leiserowitz's 2004 paper *Before and After 'The Day After Tomorrow': A U.S. Study of Climate Risk Percetions* (Leiserowitz 2004). The three-step process of (i) localize, (ii) spatialize and (iii) visualize and the principles behind it have had a strong influence on research results presentation of our work which will be used with the C-Change project when working with the community of Charlottetown.

3. Methodology

This chapter examines the city of Charlottetown's coastal vulnerability due to storm surge and sea level rise. To do so, the spatial and temporal aspects of the environmental, economic, social and cultural components of the city are examined. This study uses a system dynamics methodology so that the modelled feedbacks and interconnections of the community system impacts as a whole may be examined. The system dynamics methodology is coupled with the spatial approach of GIS software to yield a robust and specific description of community impacts from storms. A visual overview of the model components in the research methodology can be seen in Figure 3.1 and is explained in further detail in the sections below.

3.1 Model Components

The first step is to establish the components of the study. As there is a plethora of variables, biological as well as socioeconomic, that relate to coastal vulnerability, the scope of the problem must be narrowed down. In order to select the most relevant system components in describing and estimating storm and sea level rise impacts, first a preliminary all-inclusive list must be drawn up. All of the components on this list must be evaluated and ranked. From this list, the specific components of the study are chosen.

There are five major components to the model being presented in this research. Those components are: inputs, GIS, SD, SSD, and outputs. Each of those will be examined in the following sections. An illustrative overview of the model components and how they interact is found in Figure 3.1. The inputs to the model are from the Community Data Profile (Section 3.1.1) which are used in GIS model (Section 3.1.2) and the SD Model (Section 3.1.3). The GIS and SD models are linked to form a SSD model (Section 3.1.4) and finally the outputs of the model are presented in the form of layers, tables, impacts, damages, and maps.

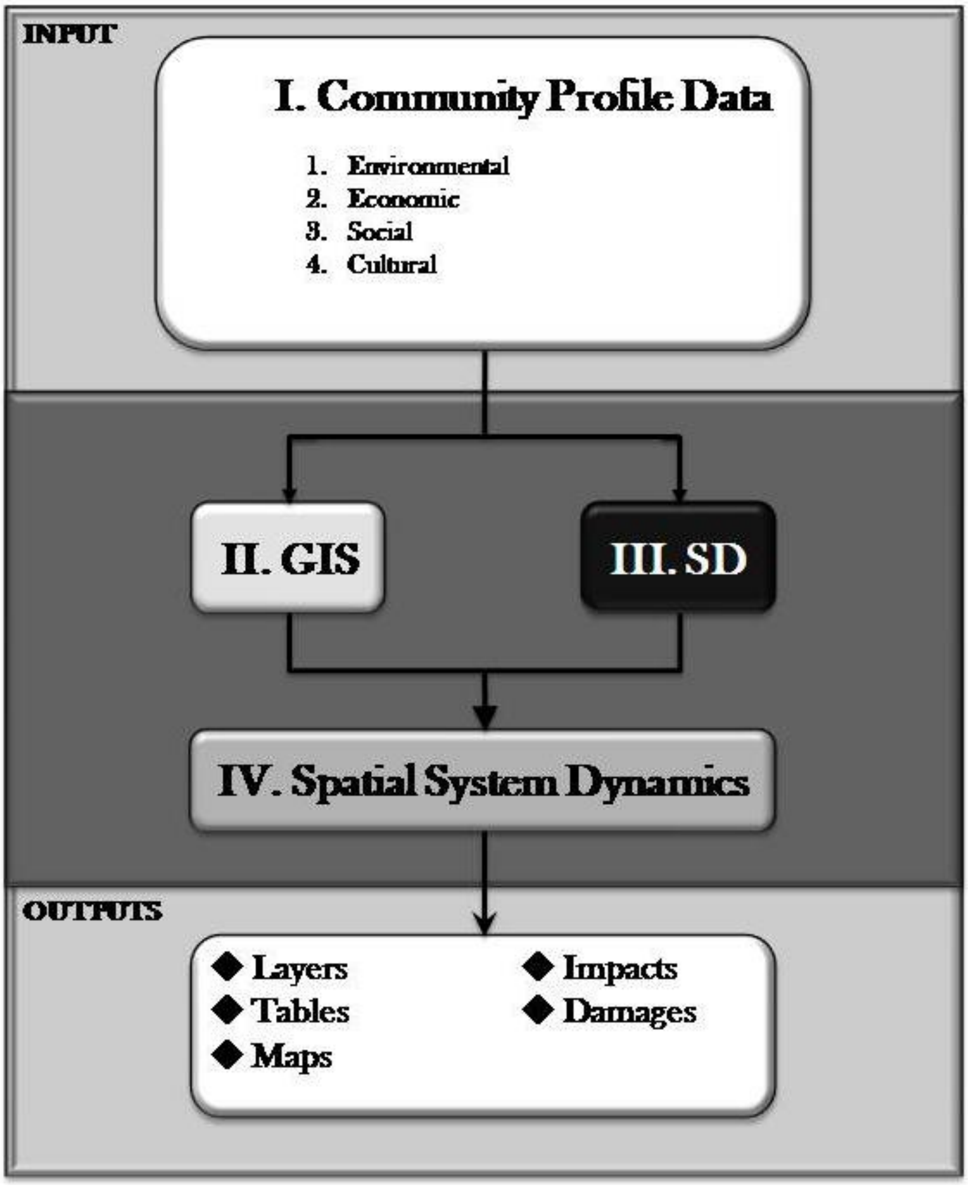

Figure 3.1: Model components

Figure 3.1 illustrates the flow of the major model components. The components are organized into three sections. The first is the inputs, which is made up of the Community Profile data. The second section contains the working models, first with the SD and GIS models separately and then connecting the two models as a SSD model. Lastly, the outputs are in the form of impacts, damages, layers, tables and maps.

3.1.1 Community Data Profile

In order to establish the components of the study, the available and/or required data must be collected. The principle resources for the socioeconomic data are from Statistics Canada, the University of Ottawa library, and the Prince Edward Island provincial government. The geospatial data are mainly from Desktop Mapping Technologies Inc. (DMTI), GeoConnections, the Prince Edward Island provincial government and Geobase (Geobase 2010). The data collected are displayed as part of the Community Profile Dataset, from which a 'base case' has been created to describe the multidimensional status of Charlottetown. The major dimensions of the Community Profile are as follows: (1) Environmental, (2) Economic, (3) Social, and (4) Cultural.

These dimensions arise from the four pillars of the Charlottetown Integrated Community Sustainability Plan (ICSP) established in 2010 by the City of Charlottetown in consultation with the community. The ICSP was developed "to provide the City of Charlottetown with a long-term, forward-thinking strategic plan … which provides direction for the community to realize sustainability objectives for its environmental, economic, social and cultural dimensions." (Stantec 2010, p.E-1) An overview of the main dimensions of the Community Profile can be found below, and the full document can be seen in Appendix A.

3.1.1.1 Environmental

The environmental dimension of the Community Profile is clearly of extreme importance. When introducing a storm surge or sea level rise simulation, the first and most obvious effects will be to the environment. The major data subsections of the Environmental dimension are: Topography, Hydrology, Coastal Geomorphology, Habitat and Species, Land Cover, Land Use, Marine Use, Natural Resources and

Climate. Each of these subsections contains specific elements vulnerable to storm surge or sea level rise impacts. Of these elements, elevation (which falls under the subsection of Topography) is the most crucial to this research. It is imperative that the elevation data be as accurate and precise as possible because the elevation data are the backbone of the GIS visual simulation model. For the purpose of this research, the best available elevation data are scale 1:50,000 for Charlottetown (Source: Geobase 2010). A visual of these data is shown in Figure 3.2 and its importance is discussed further in Section 3.1.2. DMTI supplies the bulk of the data for the subsections of the environmental section.

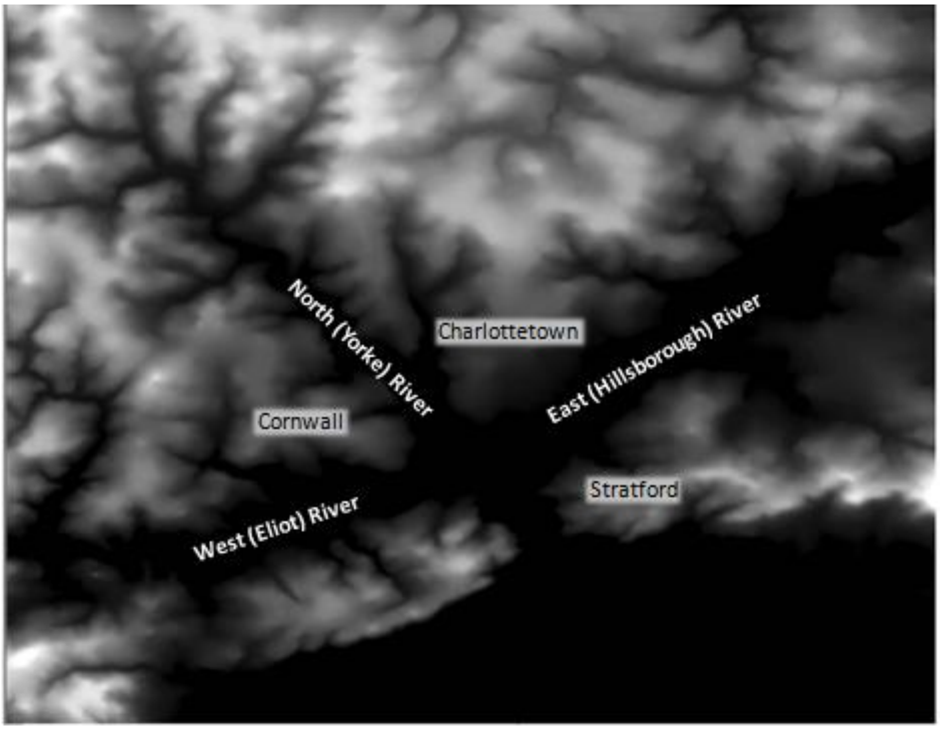

Figure 3.2: Elevation data for Charlottetown at scale of 1:50,000(Source: Geobase 2010)

Figure 3.2 depicts the elevation data for Charlottetown and surrounding areas. From the image it can be seen that the darker areas represent low elevation heights (with black areas being water at 0 meters above sea level CD) and the lightest areas represent the highest elevation areas. The communities of Charlottetown, Stratford and Cornwall are labelled on the elevation map.

3.1.1.2 Economic

The Economic section of the Community Profile contains the following subsections: Industry by Type, Industry Revenues, Built Environment, Public Works and Real-Estate/Property Values. Almost all of the data in these subsections is provided by DMTI and Statistic Canada through the 2006 census (BC Stats Data Services 2009, DMTI 2009a, DMTI 2009b).

To map the census data, a base map of Charlottetown's Dissemination Areas (DAs) was imported into ArcMap. Statistics Canada defines a DA as "a small, relatively stable geographic unit composed of one or more blocks. It is the smallest standard geographic area for which all census data are disseminated" (Statistics Canada 2002). DAs generally have populations of 400 to 700 persons. A map of Charlottetown's numbered DAs can be seen in Figure 3.3.

Figure 3.3: Census dissemination areas of Charlottetown (Source: Statistics Canada 2002)

Once imported into ArcMap, each DA is assigned properties from the census data information. For example in Figure 3.4, the boundaries of each DA can be seen in the upper section (or background) of the image, and the table of properties can be seen in the bottom section (or foreground). Each DA has a number associated with it which can be seen in the second column of the table. The columns that follow are different Economic properties of each DA, including: population, total population above 15 years of age in the workforce, employment rate, unemployment rate, and total median income for the population above 15 years of age. Each of the subsections, and their elements, mentioned above will be mapped as overlapping layers in ArcMap.

OID	DA	DAUID	Pop	Total Pop (15+) in Labour Force	Employment Rate	Unemploy Rate	Total Median Income (15+)
14	0130	11020130	513	315	72.6	3.2	21091
15	0131	11020131	593	385	81.3	2.6	30227
16	0132	11020132	344	200	57.4	10	33383
17	0133	11020133	699	395	76	3.8	32811
18	0134	11020134	290	180	71.4	0	40718
19	0135	11020135	371	205	62.7	9.8	40243
20	0136	11020136	396	190	55.2	5.3	23914
21	0137	11020137	378	215	60	7	18607
22	0138	11020138	404	185	46.4	13.5	20655
23	0139	11020139	409	225	68.3	6.7	39889

Figure 3.4: DAs and census data in ArcMap, the map shows Charlottetown's downtown DAs and the census map table shows the DA number (DA), Population (Pop), total population over 15 years of age in the labour force (Total Pop (15+) in Labour Force), Employment Rate, Unemployment Rate, Total Median Income for population over 15 years of age (Source: Statistics Canada 2002)

All of the census data can be mapped in this fashion and then used in the simulation process. The use of the census data in the SD model is discussed further in Section 3.1.3.

3.1.1.3 Social

The Social data comes from and are mapped similarly to the Economic data. Social data principally comes from Statistics Canada and the 2006 Census and are mostly mapped using the DAs as shown in Figure 3.3 and Section 3.1.1.2. The subsections of the social section are: Population Statistics, Education, Health Status, Occupations by Type, Employment Rates and Labour Earnings. These, and their elements, are mapped as separate overlapping layers in ArcMap. The Social data are also used in the SD model in a similar fashion to the Economic section, and that is discussed in Section 3.1.3.

3.1.1.5 Cultural

The Cultural component of the Community Profile has sub-components: Governance Systems, Community Dynamics, Community Groupings, Communications Resources, Language, Places of Significance, and Cultural Events. Spatially, the Cultural component will be represented by heritage sites, museums, churches, and art galleries. These will all be represented by points on the map and the data come from the DMTI dataset.

There is an abundance of cultural data available. The data selected are represented as overlapping layers in a GIS map (Section 3.1.2), as components of a SD model (Section 3.1.3), as part of the SSD model (Section 3.1.4), which is applied to the case of Charlottetown (Section 3.2), and finally the impacts of simulated storm surge and sea level rise on the elements are assessed (Section 3.3). As previously mentioned, a full list of the sections, subsections and elements of the community profile is available in Appendix A. Also, a list of the various overlapping layers used in ArcGIS (as well as their descriptions and their sources) is provided in Appendix B.

3.1.2 GIS Model

In November 2009, presented for GIS Day at the University of Ottawa, a coastal vulnerability sea level rise tool was created by the author using Visual Basic Applications (VBA) in ArcMap (Hartt 2009). The objective of this tool was to simulate sea level rise on a coastal region and to help assess what vulnerable coastal entities would be affected. By being able to input specific levels of sea level rise, a series of trials can be used to determine relative vulnerabilities and could therefore assist in creating a response action plan based on the outcomes of the simulations.

There were three necessary prerequisites for this tool. The first is that the ArcMap map file must contain a digital elevation layer. This layer is the basis for the sea level rise tool and therefore must be present (also, the more accurate the elevation data, the better). The second necessary input for the tool was a vulnerability layer. This was the layer in the ArcMap map file that contains the reference information, which the sea level rise may affect. An example of this is a layer containing points representing buildings, schools, hospitals or power plants. The vulnerability layer is whatever factor is considered susceptible to sea level rise. This layer can either contain points, lines (e.g., roads) or polygons (e.g., open spaces, parks). The third and final input to the tool was the amount of sea level rise (i.e., maximum water level) to be simulated (measured in meters). The graphical user interface for the tool can be seen in Figure 3.5.

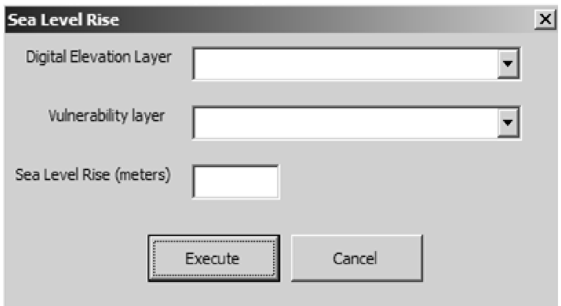

Figure 3.5: GUI of 'Sea Level Rise Tool' (Source: Hartt 2009)

The tool produced two outputs. The first output is a new layer in the ArcMap map file. A coloured (with 60% transparency) cover over all parts of the map that are covered by the provided sea level rise impact amount. An example of this output can be seen in Figure 3.6. The second output is a message box listing which of the vulnerable items (in the vulnerability layer) are flooded by the sea level.

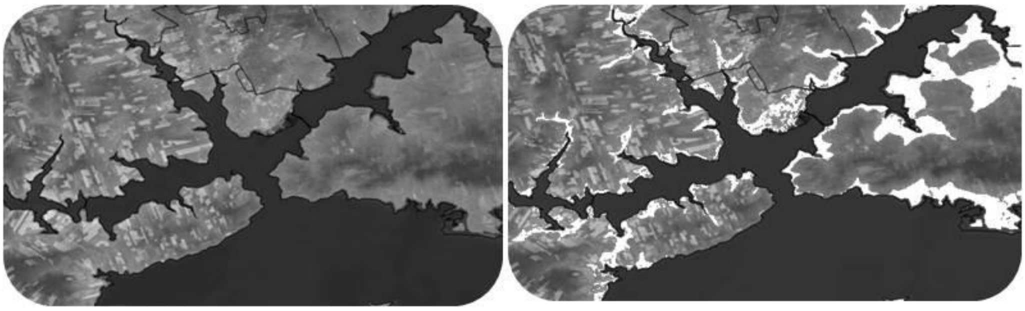

Figure 3.6: Charlottetown before (L) and after (R) 5m sea level rise - white areas indicate flooding (Source: Hartt 2009)

Building on this model, a new GIS model has been constructed and is fully explained in Section 4.6. The new model incorporates the various key components as overlapping cumulative effects layers (instead of all inclusively in a 'vulnerability layer'), and the user selection of one of six defined storm scenarios (instead of the amount of sea-level rise or water height input). More information on the storm surge scenarios and how they are developed are found in Section 4.2.

Using the sea level rise tool described above, sea level rise/storm surge buffer zones were created at maximum water levels of 3 meters, 4 meters and 5 meters. The maximum water levels were determined by examining the historical ranges of maximum water levels associated with storm surges. The buffer zones (or flood zones) are the area which, were there to be a sea storm water level of that specific maximum water level magnitude (relative to the CD), would be affected by said flooding. By coupling the buffer zones with the overlapping layer elements, it is possible to identify elements 'at risk'. The identification and cost of 'at risk' elements is discussed further in Sections 4.3 and 4.4. These buffer zones were created in ArcMap but converted to Google Earth for viewing purposes. The resulting image is illustrated in Figure 3.7.

Figure 3.7: Buffer zones of 3m, 4m and 5m in Charlottetown (Source: Google Earth)

3.1.3 SD Model and SSD Model

The SD model is constructed to define the interconnections between the key elements including costs, benefits, flows and feedbacks. Available historic results are used to correctly tweak the interconnecting relationships. The SD model is constructed around the same four components of the Community Profile and is able to determine what damages are resulting from direct impacts on each of the environmental, economic, social and cultural components and what damages are due to the interconnections between the components, or indirect damage impacts. The SD flow model is presented in Figure 3.8. This model was developed using the system dynamic software STELLA (iSee Systems 2009).

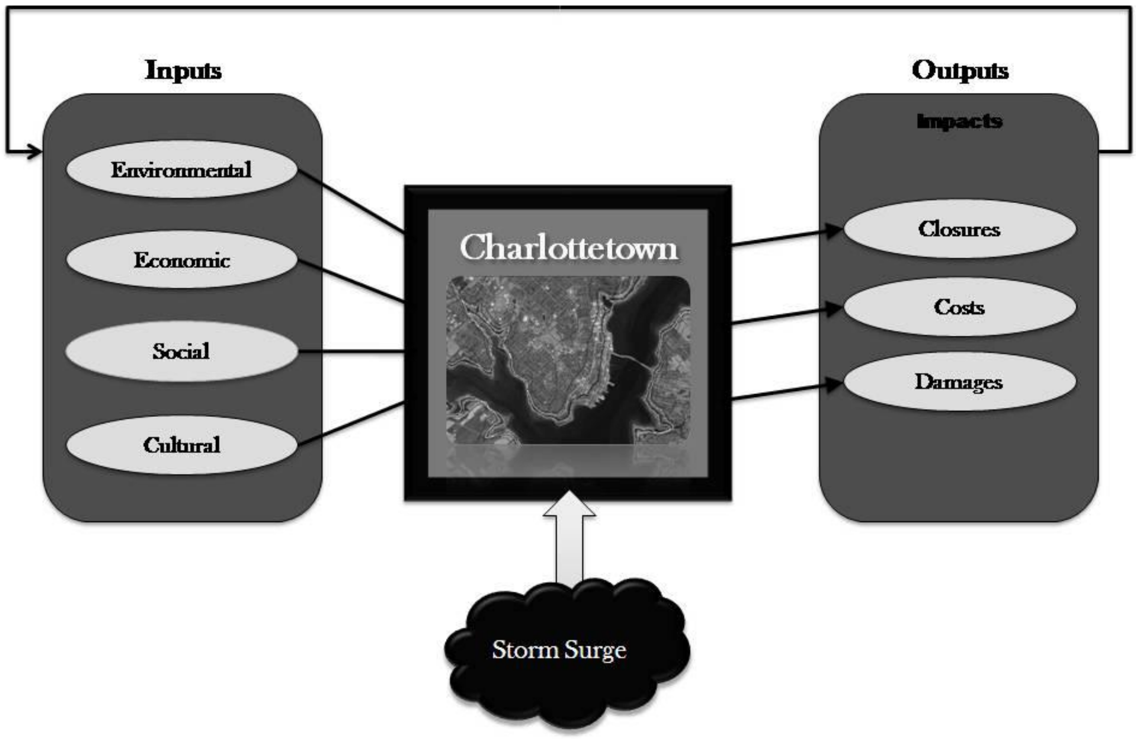

Figure 3.8: System dynamics flow model

Figure 3.8 illustrates the system dynamics flow model. The inputs are the Community Profile Dataset. The storm surge is introduced to the system and affects the input data describing the system. Along with the direct affect on the components of the system, there are also indirect effects from the storm surge as the components interact. The impacts of the storm surge are the outputs of the model and come in the form of closures, costs and damages. Due to these impacts, the components describing the system have been altered, and following the feedback loop at the top of the diagram, the inputs (descriptive Community Profile Dataset) have been altered by the impacts of the storm and thus the interaction amongst components will change and the outputted impacts will change. The system will continue to flow in this manner until for a set amount of time or until it reaches and equilibrium.

Finally, the two models, SD and GIS, will be linked and will provide feedback in space and time. The coupling of the two models, one spatial and one temporal, will result in a SSD model that has the strengths of both the GIS and SD models. The SSD flow model is presented in Figure 3.9. Ahmad and Simonovic (2004) Spatial System Dynamics methodology is used and expanded on to fit the data available for Charlottetown.

The results from the GIS model simulation are inputs to the STELLA SD model, which are connected as dynamic data and information exchange using Microsoft Excel. The SD model is then run and produces the final results as estimated storm damage for simulated storm scenarios affecting Charlottetown.

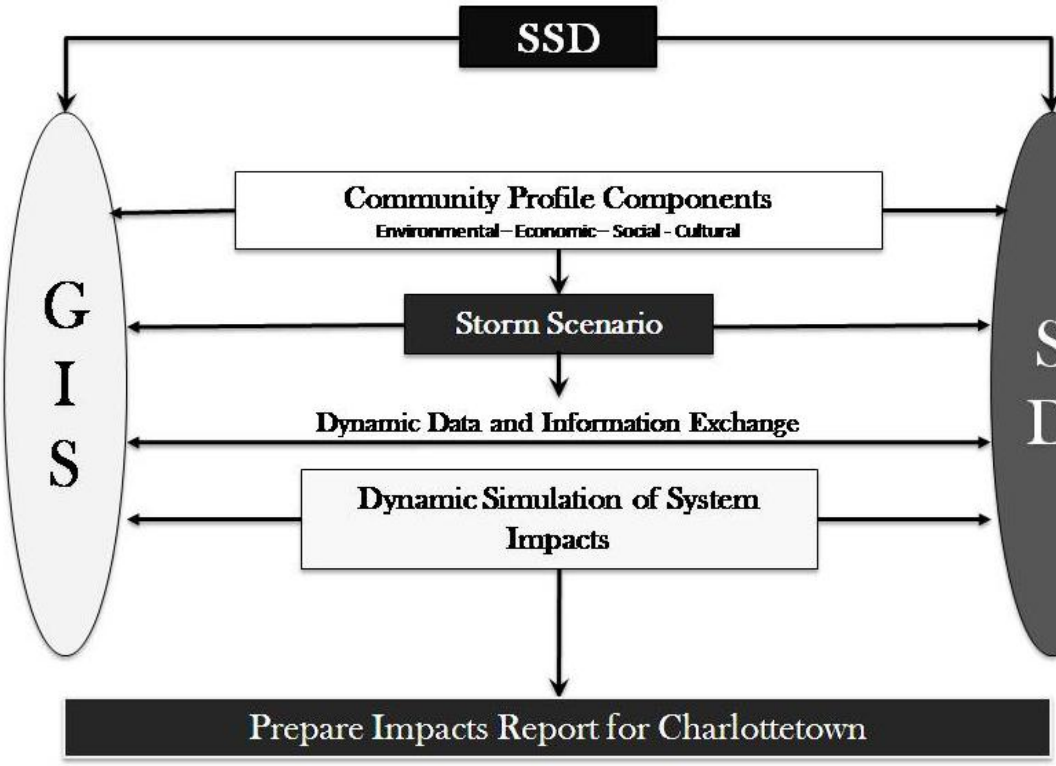

Figure 3.9: Spatial system dynamics flow model

Figure 3.9 illustrates the spatial system dynamics model. The figure shows that the SSD model runs both the GIS and SD models in parallel with the Community Profile Components and storm scenarios being inputted into both models. The two models share information through a dynamic data and information exchange. Together a spatial system dynamic simulation of the impacts is executed and an impacts report can be constructed.

3.2 Application

The base case of the interactions of the environmental, economic, social and cultural components of the city of Charlottetown, PEI, Canada are established and now various storm scenarios will be introduced to the system. The components are regarded as subsystems and each mapped on a separate layer in the GIS software. The shifting of existing spatial definitions in the system cause chain reactions to the subsystems and their interconnections are modelled in the SD system as direct and indirect impacts. These changes in the interconnections are evaluated as functions of the change and the resulting storm impacts and damage estimates.

3.3 Assess Impacts

From these interconnection evaluations, assessments of the impacts on the site from many different aspects are made. The impacts are the expected result of storm surge scenarios modelled on historical storm events in Charlottetown. The baseline description of the Community Profile is presented along the four major dimensions: environmental, economic, social, and cultural. The modelled storm scenario ultimately impacts each of the community profile dimensions and provides the basis for change and demonstration of the expected impacts from the storm scenarios.

The storm assessment model is capable of analyzing layered impacts of different storm events and highlighting the impacts on the community profile dimensions. The model can be seen as having three main stages: baseline, storm and recovery. The baseline will consider the model at a pre-storm or status quo stage. By comparing the baseline pre-storm indicators with the post-storm indicators, it will be possible to analyze the impacts of the different storms and report on the impacts in terms of estimated damages and added vulnerability. A visual summary of the three stages (baseline, storm and recovery) of the model can be seen in Figure 3.10.

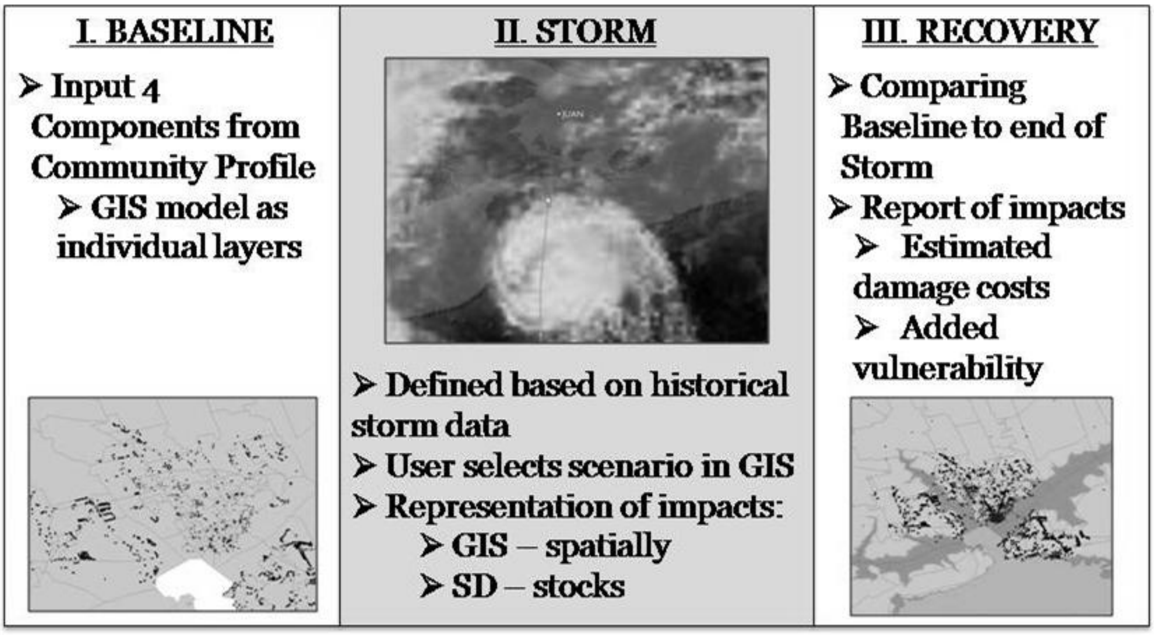

Figure 3.10: Three stages, baseline – storm – recovery, of the model

The impacts of the storm introduced in the second stage of the model come in two steps. The first are the direct impacts which affect the four components from the community profile immediately. The second sets of impacts are the indirect impacts. The indirect impacts are a result of the interconnections within the four components. Each step produces estimated storm damages and together they result in the total damages to the system. The results of modelled storm scenarios are presented in the following chapter.

4. Analysis

This chapter applies the general methodology described in Chapter 3 to the case of Charlottetown, Prince Edward Island. First, the available and applicable non-storm spatial data are organized using the Community Profile format and the mapping software ArcGIS, and is presented in Section 4.1 (Charlottetown Status Quo). Using the 13 historical severe Charlottetown storms described in Section 2.5.2, anticipated storm scenarios for Charlottetown are modelled in Section 4.2 (Storm Scenario Definitions). The impacts from each of the six modelled storms are described in Section 4.3 (Storm Scenario Impacts). Using the idea of 'cost at risk' from Milloy and MacDonald (2002) (SD10 in McCulloch et al. 2002) and the most severe Storm Scenario VI as a baseline, an "Assets at Risk" Baseline Analysis is done in Section 4.4. From this analysis and historic damage reports, the damages of the different storm scenarios are estimated in Section 4.5 (Damages). This chapter culminates with the full description of the GIS model (Section 4.6) and the SD model (Section 4.7).

4.1 Charlottetown Status Quo

In order to understand the impacts that occur to Charlottetown when confronted with a severe storm surge, it is necessary to have an apt understanding of the city at status quo – that is to say, an idea of the base case or the no storm situation that describes the multidimensional community profile. In this subsection, Charlottetown will be described in terms of the four pillars (environmental, economic, social and cultural) and their associated set of indicators. Once a well-rounded understanding of Charlottetown at status quo has been established, only then can the storm surge scenarios and their impacts be addressed.

4.1.1 Environmental Landmarks

Since storm surges and flooding are being examined in this study, Charlottetown's elevation is of upmost importance. Charlottetown is a low-lying city with much of its waterfront at 0 to 3 meters above sea level. Figure 4.1 shows Queen's county's elevation including the community of Charlottetown, Stratford and Cornwall. The area elevation in the entire region rarely attains the 18 meter to 36 meter levels. In fact, most of the city of Charlottetown is less than 18 meters above sea level. It is important to note that the best available elevations in this dataset (Source: Geobase 2010, Scale 1:50,000) are integer meters only, so no decimal values at all are recorded.

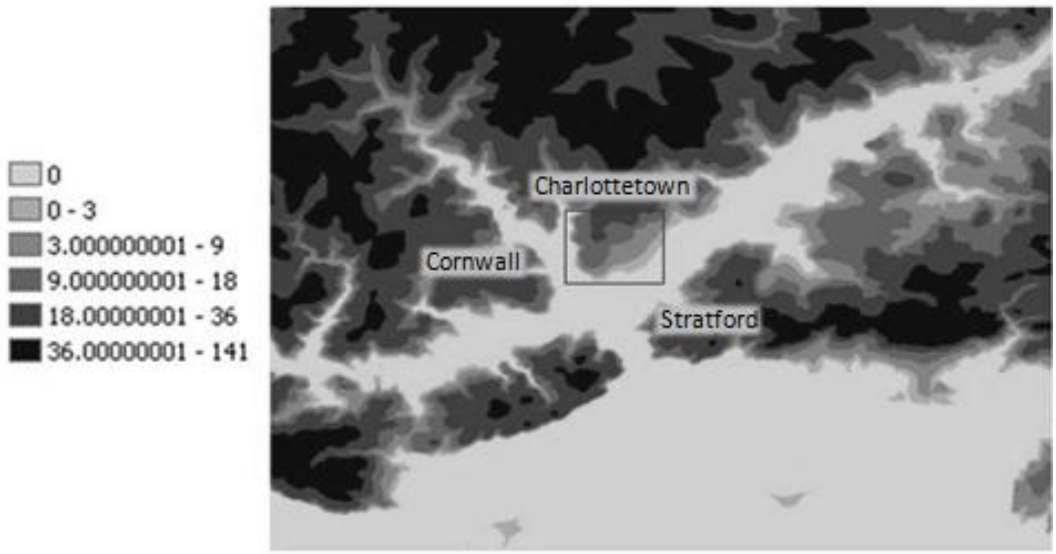

Figure 4.1: A large part of Queen's County's digital elevation model with a square highlighting the downtown Charlottetown area (Source: Geobase 2010)

Zooming in on the core of downtown Charlottetown (the outlined boxed area in Figure 4.1), as shown in Figure 4.2, demonstrates just how low-lying the Charlottetown harbor front and downtown area is. In this image (which follows the same legend as Figure 4.1 and integer meter elevation), it can be seen that Charlottetown's downtown is principally made up of elevations less than 9 meters above sea level. In order to get an understanding of how dense this area is, a satellite image of the same area is shown below in Figure 4.3.

Figure 4.2: Close up of downtown Charlottetown's elevation (Source: Goeboase 2010)

Figure 4.3: Satellite image of downtown Charlottetown (Source: Geobase (2010)

Figure 4.3 illustrates the density of Charlottetown and its development along its considerable and exposed waterfront that includes commercial and historic buildings, residential areas, transportations links (roads and bridges), park spaces, and the working harbor.

An important aspect of Charlottetown's environment is its parks. Charlottetown has many parks and green spaces as evident from Figure 4.3. Its three most well known parks are: Victoria Park (at the top of the downtown 3 rivers peninsula), Queen Elizabeth Park (along the western bank) and Confederation Landing Park (along the eastern bank). These parks fall within ideal downtown real estate, which also happens to be extremely vulnerable. Charlottetown's parks can be seen more clearly in Figure 4.4. The three major parks have been highlighted in the picture with squares around them (1- denotes Queen Elizabeth Park; 2- Victoria Park; and 3- Confederation Landing Park).

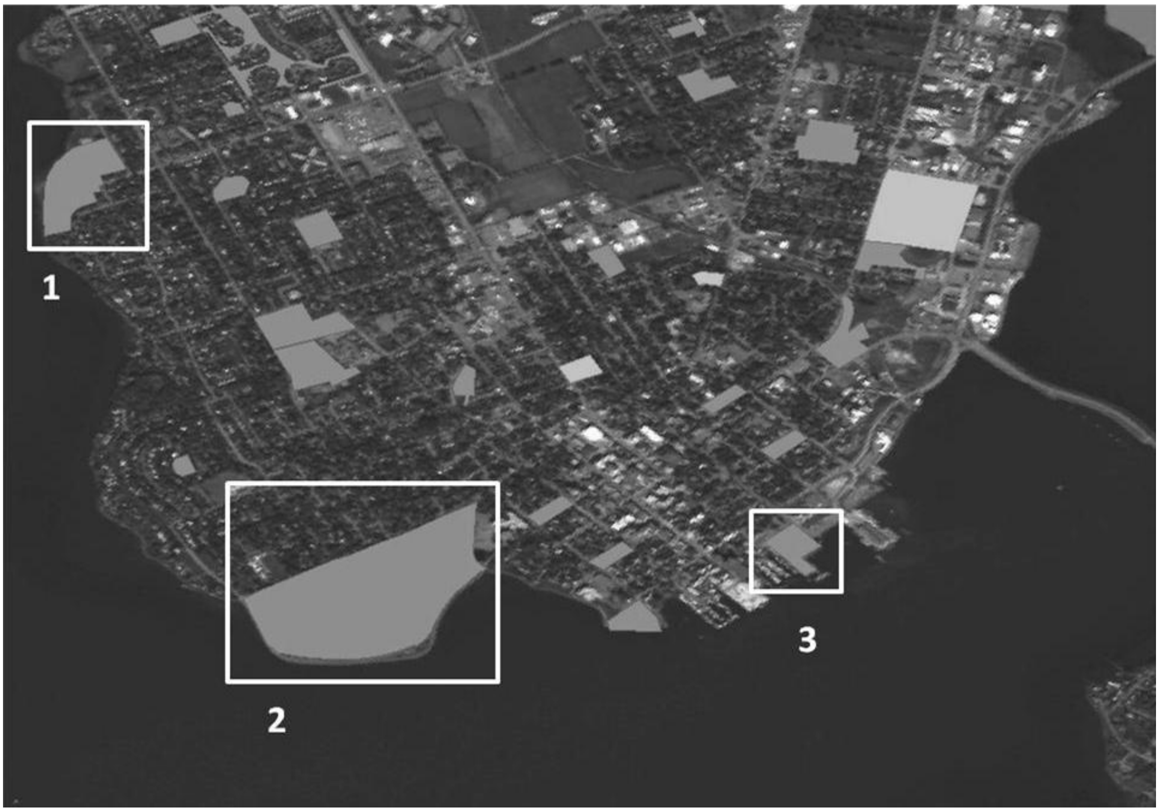

Figure 4.4: Charlottetown's parks - highlighting Queen Elizabeth [1], Victoria [2] and Confederation Landing [3] (Source: DMTI 2009a and www.geobase.ca)

4.1.2 Economic Landmarks

The second of the four pillars used in this study to profile the community is the economic pillar. In order to describe Charlottetown from this perspective three primary indicators are examined. The first indicator is the type of industry that exists in Charlottetown. The second indicator is the 'built environment' which encompasses commercial, government and residential structures. The third indicator is public works. No freely available data were found that referenced the residential sector directly so it could not specifically be represented spatially in this study. The remaining indicators are organized by Standard Industrial Code (SIC) major groups and divisions, which is an attribute of the DMTI Enhanced Points of Interest (EPOI) dataset (DMTI 2009b).

The DMTI dataset of EPOI includes 2041 different points in the economic 'built environment' layer for Charlottetown. These points represent many different types of businesses, public administration offices, public services outlets, and much more. The points are organized by SIC major groups and by SIC divisions. Using this standardized coding system, it is possible to present an overview of these economic indicators in Charlottetown without having to introduce all 2041 points individually. These highlighted points can be seen overlaid on the elevation data (of Figure 4.2) in Figure 4.5 and overlaid on the satellite image (of Figure 4.3) in Figure 4.6 below.

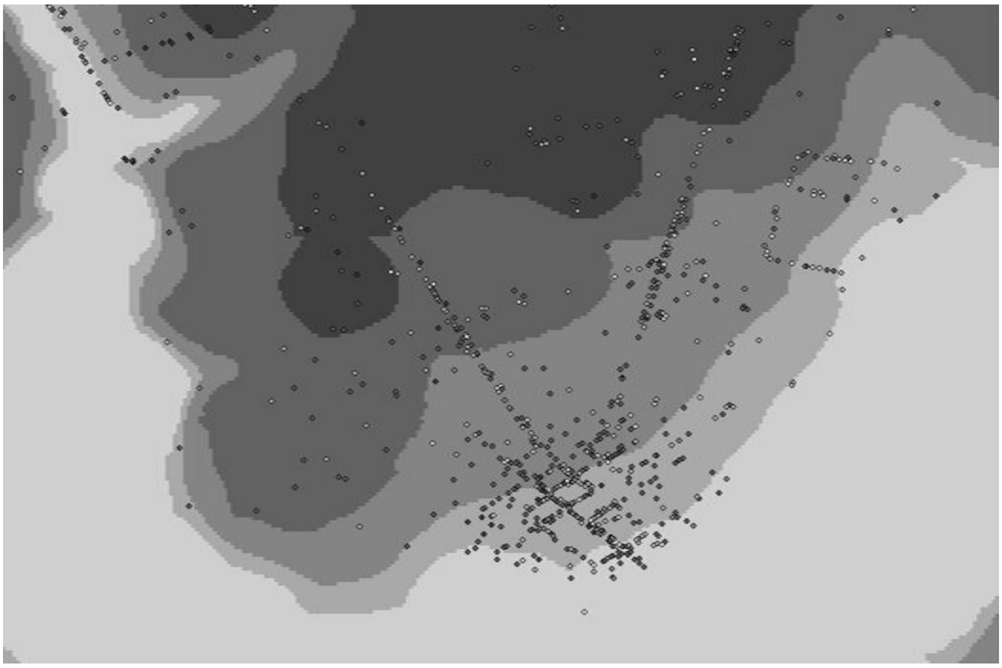

Figure 4.5: EPOI overtop of elevation map (Source: DMTI 2009b and Geobase 2010)

Figure 4.6: EPOI overtop of satellite image (Source: DMTI 2009b and Geobase 2010)

A glance of Figure 4.5 and Figure 4.6 shows that the bulk of the economic layer 'built environment' points are located in the central downtown core near the waterfront. Due to the number of the points, it is quite difficult to draw many conclusions about the different types of SIC divisions present (each different coloured point represents a different SIC division). Upon closer inspection, it is noted that there are 22 points from SIC division A (Agriculture, Forestry and Fishing); 1 point from SIC division B (Mining); 98 points from SIC division C (Construction); 83 points from SIC division D (Manufacturing); 77 points from SIC division E (Transportation, Communications, Electric, Gas, and Sanitary Services); 97 points from SIC division F (Wholesale Trade); 460 points from SIC division G (Retail Trade); 150 points from SIC division H (Finance, Insurance and Real Estate); 975 points from SIC division I (Services); and 98 points from SIC division J (Public Administration). This information is also summarized in Table 4.1 and the percentages of each SIC division can be seen visually in Figure 4.7.

Table 4.1: Number of economic points in each SIC division (DMTI 2009b)

Division Letter	Sic Division Name	No. of Points	%	Example	Address
A	Agriculture, Forestry and Fishing	22	1.08%	World Potato Congress	420 University Ave
C	Construction	78	3.82%	CTF Supply Ltd	3 Macausland Dr
D	Manufacturing	83	4.07%	Quality Furniture Finishing	54 Maple Ave
E	Transportation, Communications, Electric, Gas, and Sanitary Services	77	3.77%	Hambly's Rentals Ltd	86 Kensington Rd
F	Wholesale Trade	97	4.75%	Island Backhoe Services Inc	5 Fulton Dr
G	Retail Trade	460	22.54%	Big Burger	670 University Ave
H	Finance, Insurance and Real Estate	150	7.35%	Coldwell Banker Parker Realty	161 Maypoint Rd
I	Services	976	47.82%	Global Convention Services Ltd	18 Queen St
J	Public Administration	98	4.80%	Parks Canada	2 Palmers St
	Total	**2041**	**100%**		

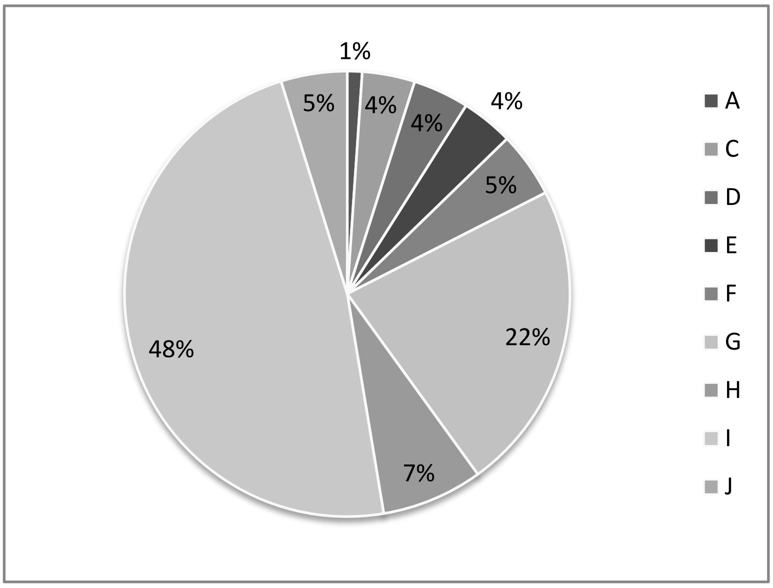

Figure 4.7: Percentage of economic points of interest in Charlottetown by SIC division (Source: DMTI 2009b)

Not only can these points be represented by their SIC division, but also more precisely by their SIC major group. Appendix C details the 2041 enhanced points of interest in Charlottetown by their SIC major groupings.

4.1.3 Social Demographics

Social indicators examined to describe Charlottetown's social layers included: (i) population statistics, (ii) employment statistics, (iii) occupation by type, (iv) transportation or commuting statistics and (v) education statistics. Data collected from the 2006 Canada Census were used. The smallest census division that can be represented spatially is the Dissemination Area (DA). In the case of Charlottetown, a DA consists of a geographical area containing between 290 and 837 people. Charlottetown contains 65 different DAs. A screenshot of Charlottetown's DAs can be seen in Figure 4.8. Note that the DAs are much smaller in geographical space in the downtown area as the population there is denser.

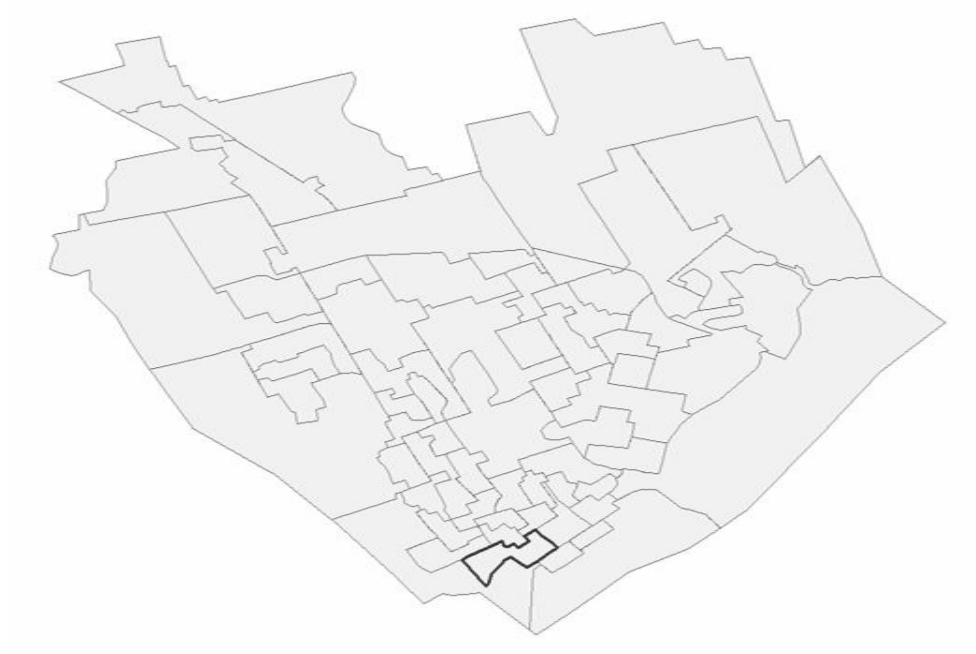

Figure 4.8: Charlottetown's DAs with DA 159 highlighted (Source: Statistics Canada 2002)

Each of the 5 social indicators (population, employment, occupation by type, transportation/commuting and education) has a number of measures which are listed in Table 4.2. All of the data for all 65 different DAs is retained. A single example of the DA data is highlighted in Figure 4.8 and provided in Table 4.2. For each measure of the 5 social indicators, the social data for DA 159 (which is located in downtown Charlottetown and highlighted above in Figure 4.8) are used as the example in Table 4.2. Figure 4.9 represents DA 159's social demographics statistics graphically.

Table 4.2: Social Indicators, their measures and DA 159 as an example (Source: BC Stats Data Services 2009)

No.	Social Indicator	Measures	DA 159
1	Population Statistics	Population	582
		Pop. In Labour Force Age 15 years and over	275

2	Employment Statistics	Employment Rate (%)	68.8
		Median Income ($ CDN 2006)	20395
		Median Family Income ($ CDN 2006)	57758
		Median Household Income ($ CDN 2006)	32037
		Work in Census DA	240
		Work out of DA	10
		Work from Home	0
		Management	20
3	Occupation by Type	Business, Finance, or Administration	50
		Natural/Applied Science	15
		Sales and Services	90
		Trades	25
		Unique to Primary Industry	0
		Processing, Manufacturing, or utilities	0
		Drive to Work	145
4	Transportation or Commuting	Passenger to Work	20
		Public Transportation	10
		Walk	100
		Bike to Work	0
		No Certificate, Diploma or Degree	10
5	Education Statistics	High School Certificate	10
		College or non-university Certificate	25
		University Diploma below Bachelors	0
		University Certificate, Diploma or Degree	30

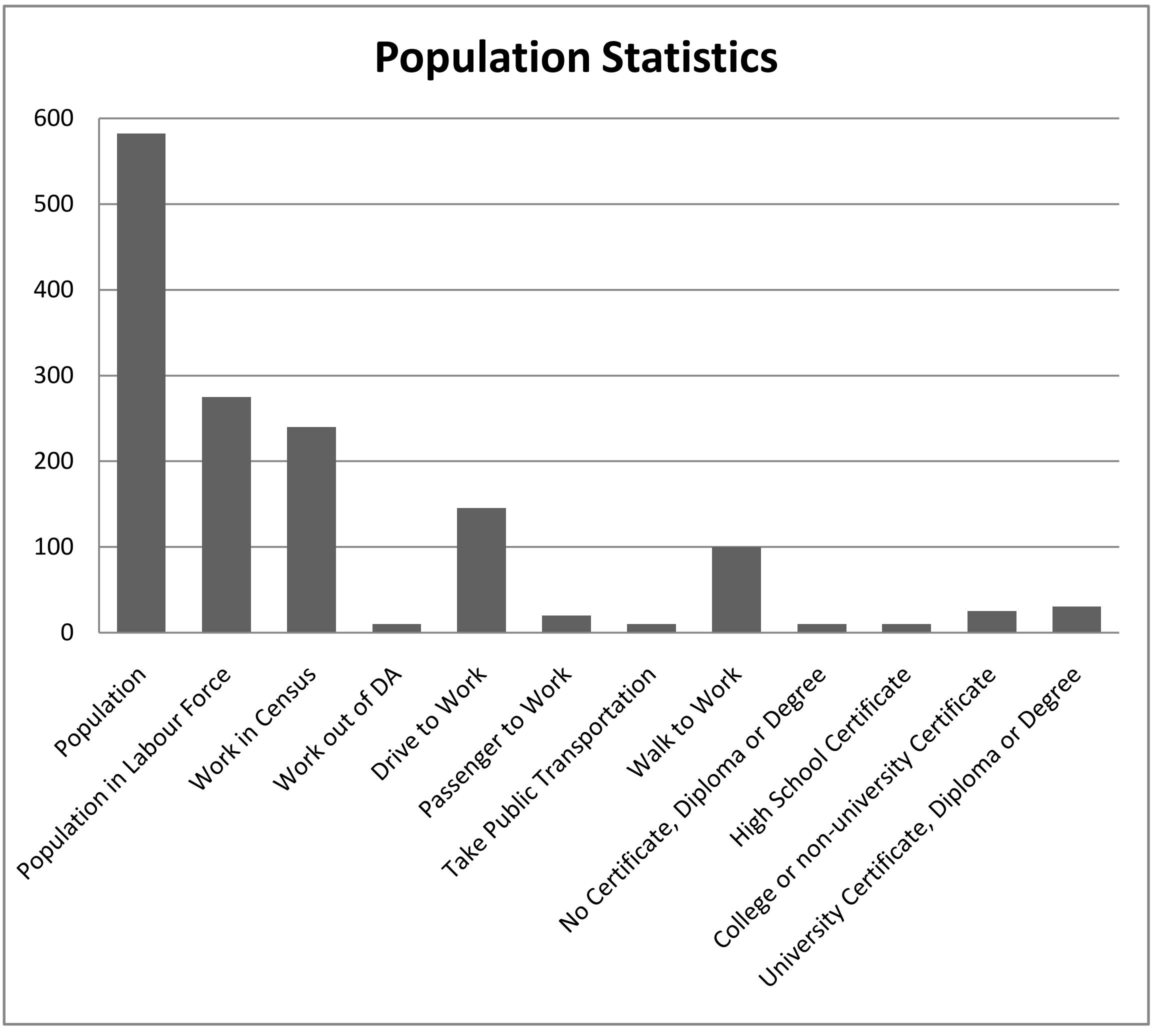

Figure 4.9: Select population statistics for DA 159

Figure 4.9 illustrates select population demographics for DA 159 in Charlottetown. It can be seen from the histogram that almost all of the population in labour force (age 15 years and over) work within their own DA. This is not true for all other DAs. DA 159 is situated in the dense downtown area where there are many businesses and job opportunities, DAs located further from the downtown core may have a lower percentage of population in labour force (age 15 years and over) working in their own DA.

4.1.4 Cultural Landmarks

The indicators used to grasp Charlottetown's cultural components are the following:

museums, art galleries, and botanical and zoological gardens; churches or religious places of worship; and from the census data, languages. For the first two indicators, they can be represented spatially by points on the map. As for languages, it can be represented using the DAs much like all of the social data in the previous section.

Figure 4.10: Cultural points over top of satellite image; white dots represent churches and grey dots represent museums, art galleries, botanical and zoological gardens (Source: DMTI 2009b and Geobase 2010)

Figure 4.10 shows the points for the first two indicators. There are 15 museums, art galleries, and botanical and zoological gardens in Charlottetown and 29 churches/places of worship. For the third indicator, language, the example of DA 159 is revisited; there are 415 English only speaking people and 30 French-English bilingual persons in DA 159.

4.2 Storm Scenario Definitions

As discussed earlier in this thesis, the storm definitions used in the simulations of storm impacts on Charlottetown will be based on a combination of the history of

Charlottetown's storm surge climatology and the work already done in the two major reports on Charlottetown's storm history and vulnerability (McCulloch et al. 2002 and Daigle et al. 2006). The reason that an existing storm surge scale, such as the Saffir-Simpson hurricane scale (NOAA 2010), is not used directly is that due to Charlottetown's positioning - a storm with a higher Saffir-Simpson ranking may not necessarily be more severe to Charlottetown than a lesser ranking storm in that index. The Saffir-Simpson hurricane scale only pertains to tropical cyclones, thus it is only invoked in the Atlantic Canada region for a storm maintaining hurricane strength into our waters or making landfall as a hurricane in the Atlantic Provinces. The 'No Name 2000' storm is the perfect example of this, as it is regarded as Charlottetown's most severe storm, yet did not rank on the Saffir-Simpson scale. The severity of the 'No Name 2000' storm is due to tides, ice blockages and other factors that are not taken into account in that scale.

In order to compensate for this apparent oversight for Charlottetown, storm scenarios are modelled using the empirical data that are available (speed, wind speed and pressure) specific to Charlottetown. Thus, the storm scenarios are principally based on the historic surge damages rather than a strictly analytical scale. A general summary table of the storm scenarios used in this model are presented in Table 4.3 below.

4.2.1 General Outline of Storm Scenarios

The general outline of the six storm scenarios is based on the three of the major factors contributing to storm surges: (1) speed of storm in kilometres per hour, (2) speed of wind in kilometres per hour and (3) atmospheric pressure in millibars. In order to determine the ranges of each factor for each scenario, the thirteen historical storm surge events in Charlottetown examined in Section 2.5.3 were used. For each category (speed, wind and pressure) the highest and lowest values from the thirteen storms were used to define the ranges for each of the modelled six storm scenarios set for Charlottetown. Once the extreme values were found, the six scenarios were defined by dividing that range into six parts.

The lowest historical value for storm speed among the thirteen historical Charlottetown storms examined was Tropical Depression Able, which had a recorded storm speed of 44 kilometres per hour in the area surrounding Charlottetown. The highest value for storm speed was Category 1 Hurricane Gustav with a storm speed of 74 kilometres per hour in the Charlottetown area. From these two values the ranges for the storm speed of the scenarios were determined. The ranges are: SSI: 45 kph – 50 kph; SSII: 50 kph – 55 kph; SSIII: 55 kph – 60 kph, SSIV: 60 kph – 65 kph; SSV: 65 kph – 70 kph, and SSVI: 70 kph – 75 kph.

Similarly, the highest value for wind speed among historical storms was the 'No Name' storm of 1964 with highest recorded wind speed at Charlottetown of 160 kilometres per hour. The lowest recorded wind speed value for the historical storms was Tropical Depression Able at 55 kilometres per hour. From these values, the modelled Storm Scenarios wind speed ranges for Charlottetown are: SSI: 55 kph – 75 kph: SSII: 75 kph – 95 kph; SSIII: 95 kph – 115 kph; SSIV: 115 kph – 135 kph; SSV: 135 kph – 155 kph; and SSVI: 155 kph – 175 kph.

For pressure, the lowest recorded values among the historical storms signalled more severe conditions was the 'No Name' storm of 2000 with 945 millibars and the highest pressure measure (least severe conditions) was Extratropical Storm Hanna at 995 millibars in the Charlottetown area. From these values, the ranges are: SSI: 1000 mb – 990 mb; SSII: 990 mb – 980 mb: SSIII: 980 mb – 970 mb: SSIV: 970 mb – 960 mb: SSV: 960 mb – 950 mb; and SSVI: 950 mb – 940 mb. The summary of the six modelled Storm Scenarios for Charlottetown are presented in Table 4.3. It is noted that Storm Scenarios I through VI represent storms of increasing severity along all storm indicators.

Table 4.3: General summary of six modelled storm scenarios input range values for Charlottetown storm simulations

Storm Scenario	Speed (kph)	Wind (kph)	Pressure (mb)
I	45-50	55-75	1000-990
II	50-55	75-95	990-980
III	55-60	95-115	980-970
IV	60-65	115-135	970-960
V	65-70	135-155	960-950
VI	70-75	155-175	950-940

4.2.2 Historical Storms for Charlottetown

It is clear from Table 4.3 that as the scenarios progress from I to VI, each of the monotonically increasing indicators grow more intense and signal a more intense storm surge and expected increasing damages impacts to Charlottetown. Scenario I is defined as the weakest speed and wind and the highest pressure whereas Scenario VI has the strongest speed and wind and the lowest pressure. These scenarios and impact descriptors are a general guideline to storm scenarios for Charlottetown that capture more than the Saffir-Simpson Hurricane Scale (NOAA 2010). In order to use Charlottetown's storm history to understand the different storms and their respective damages, the thirteen storms examined earlier in this paper are sorted by their empirical data and categorized by the six storm scenarios. Although no storm falls perfectly into a specific storm scenario range, they can be categorized in such a way that between their empirical data (speed, wind, and pressure) and the damages they caused, they can be identified as a Scenario I, Scenario II, Scenario III, Scenario IV, Scenario V or Scenario VI storm. The thirteen historical storms are sorted into the six scenarios by their known empirical data in Table 4.4.

Table 4.4: 13 historical Charlottetown storm events sorted by empirical data

<table>
<tr><th rowspan="2">Scenario</th><th>Historical</th><th colspan="2">Speed (kph)</th><th colspan="2">Wind (kph)</th><th colspan="2">Pressure (mb)</th></tr>
<tr><th>Storm</th><th>Scenario</th><th>Storm</th><th>Scenario</th><th>Storm</th><th>Scenario</th><th>Storm</th></tr>
<tr><td rowspan="2">I</td><td>Able</td><td rowspan="2">45-50</td><td>44</td><td rowspan="2">55-75</td><td>55</td><td rowspan="2">1000-990</td><td>-*</td></tr>
<tr><td>Hanna</td><td>64</td><td>85</td><td>995</td></tr>
<tr><td rowspan="3">II</td><td>NN1962</td><td rowspan="3">50-55</td><td>-</td><td rowspan="3">75-95</td><td>-</td><td rowspan="3">990-980</td><td>-</td></tr>
<tr><td>NN1964</td><td>-</td><td>160</td><td>-</td></tr>
<tr><td>Hortense</td><td>48</td><td>130</td><td>970</td></tr>
<tr><td rowspan="2">III</td><td>Juan</td><td rowspan="2">55-60</td><td>59</td><td rowspan="2">95-115</td><td>120</td><td rowspan="2">980-970</td><td>982</td></tr>
<tr><td>Carol</td><td>63</td><td>110</td><td>-</td></tr>
<tr><td rowspan="3">IV</td><td>Ginny</td><td rowspan="3">60-65</td><td>61</td><td rowspan="3">115-135</td><td>110</td><td rowspan="3">970-960</td><td>-</td></tr>
<tr><td>Subtrop</td><td>61</td><td>100</td><td>978</td></tr>
<tr><td>Gustav</td><td>74</td><td>150</td><td>962</td></tr>
<tr><td rowspan="2">V</td><td>White Juan</td><td rowspan="2">65-70</td><td>-</td><td rowspan="2">135-155</td><td>-</td><td rowspan="2">960-950</td><td>-</td></tr>
<tr><td>Kennedy</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>VI</td><td>NN2000</td><td>70-75</td><td>-</td><td>155-175</td><td>70</td><td>950-940</td><td>945</td></tr>
</table>

*- denotes no available data.

Empirical data describing the thirteen historical Charlottetown storms (highlighted in Table 4.4) were collected from Environmental Canada's Canadian Hurricane Centre (Environment Canada 2009). Where data were available, the indicators (speed, wind and pressure) were reported at their maximums in or around the city of Charlottetown.

As discussed at the beginning of Section 4.2, the thirteen historical Charlottetown storms cannot be classified solely on their quantifiable statistics and/or the storm designation from the Saffir-Simpson Hurricane Scale (evidence is that serious storms causing much damage are not 'graded' storms). Instead the storms are 'graded' principally by their damages rather than their empirical data. This is also due to the different amounts of empirical data available as some storms (e.g., White Juan, Kennedy Inaugural Storm) do not have any accompanying empirical data in the categories of speed, wind and pressure. Although the quantifiable statistics do hold some weight in the placing of storms in scenarios, it is ultimately the amount of damages that determine what scenario a storm falls into.

4.2.3 Storm Scenarios by Maximum Observed Water Level and Damages

The most important quantifiable consequence of all these storms leading to damage is the measure of the storm surges maximum observed water level. Due to the precise and complete data from the Charlottetown tidal gauge, the maximum observed water level of the thirteen historical Charlottetown storms examined in this thesis are known. The maximum observed water levels and damages of the thirteen historical storms are described storm by storm in Section 2.5.3 and a summary of the storms is provided in Table 4.3. The classification of the storms into the six defined storm scenarios (Table 4.4) is based on the maximum observed water level and the reported damages as shown in Table 4.5.

Table 4.5: Maximum observed water levels and reported damages from various media sources and the Canadian Hurricane Centre of 13 Charlottetown storms sorted by scenario

Storm Scenario	Historical Storm	Maximum Observed Water Level (m)		Reported Damages (Various media sources and the Canadian Hurricane Centre)
		Scenario	Storm	
I	Able	2 - 2.5	2.52	- street flooding - power outage

	Hanna		2.462	- heavy rainfall - street closure due to flooding - half meter water in Joe Ghiz Park (Grafton St)
II	NN1962	2.5 - 3	2.55	- damaged and washed out streets and highways
	NN1964		2.47	- most damage at sea - 3 fishing boats capsized
	Hortense		2.89	- All power in Charlottetown lost - many power lines destroyed - ferry service halted
III	Juan	3 – 3.5	2.927	- extensive tree damage - barn and silo damage - flooding - power outages lasting up to 5 days
	Carol		2.95	- large trees knocked over - roofs blown off - chimney knocked off - power outage due to destroyed power lines - ferry service halted
IV	Ginny	3.5 – 4	3.15	- extensive power outages - ferry service halted
	Subtrop		3.32	- many roads and bridges flooded - trees knocked over - roofing shingles pried off - thousands of pounds of lobster beached along coast

	Gustav		3.489	- power lost across PEI - vehicle accident cause by storm killed a man
V	White Juan	4 – 4.5	3.772	- widespread flooding
	Kennedy		3.84	- widespread flooding
VI	NN2000	4.5 - 5	4.216	- severe damages to public and private properties - damaged wharves in Charlottetown Harbour - damaged a power-generating station - dislodged a lighthouse - damaged numerous gas stations - Estimated at $20 million in damages

Examining the storms by the maximum observed water level and respective damages they produced in Table 4.5 shows the increasing severity in Scenarios I through VI. The most complete data set and the most useful for the GIS methodology is that of maximum observed water level, therefore this criterion was the primary basis for separating the six different scenarios by storm outcomes.

These trends (or lack of trends in the case of speed, wind and pressure) in the historical storm surges are largely due to the concurrent factor of the tides around Charlottetown. As discussed in the end of Section 2.5.2, the tides in Charlottetown play a pivotal role in the maximum observed water level and the severity of a storm surge. The fact that the three most severe storms, in terms of maximum water level and of overall damage, are not Saffir-Simpson recognized storms (e.g., Hurricane

Category 1 or 2, Post-Tropical Storm or Subtropical Storm), show dangerous and vulnerable Charlottetown really is to storm damage when these events coincide. If a larger, faster, storm were to hit Charlottetown at high tide without ice blockage, it is very possible that a new record maximum water level height could be achieved, higher than the 'No Name 2000' maximum observed water level of 4.216 meters above chart datum.

4.2.4 Lengths of Storm Scenarios

Lengths of severe storm surges in Charlottetown can vary from a few hours to days and the impacts of storm intensity can vary even more. For the purpose of this study, only the direct and immediate (initial physical damages) and indirect, semi-immediate (loss of income due to work closures for example) impacts are examined. Thus, for this research 'impact lengths' referred to for the scenarios relate only to the immediate and semi-immediate impacts of the storm scenario. In order to do this, the lengths of impacts of the six storm scenarios are fixed in this model framework. Using the lengths of historical storms as guidance, and following the principle of increasing severity used in modelling the other aspects of the scenarios, Scenarios I through VI have the following estimated impact lengths respectively: 1 day, 1.5 days, 3 days, 4 days, 5 days and 7 days. The storm surge lengths are provided in Table 4.6.

Table 4.6: Storm scenario length (days)

Scenario	I	II	III	IV	V	VI
Storm Length (days)	1	1.5	3	4	5	7

The details of the simulated Storm Scenarios for Charlottetown are not exact representations nor predictions nor historical nor expected storms. These storm scenarios are developed for modelling the potential impacts of storms on the community of Charlottetown and, as such, are based on the data of historical storm events. As such, our research focuses on the impacts of the storms on Charlottetown and the estimated damage that is expected to occur to the community and its profile. The research does not predict or foresee the frequency of the events.

4.3 Storm Scenario Impacts

The six storm scenarios have been depicted based on historical evidence. They are depicted descriptively and their expected damages are also examined from the viewpoint of the four pillars of the Community Profile (environmental, economic, social, and cultural). Currently, there is no recorded information about the categorized impacts of historical Charlottetown storms. This information is important for the purposes of preparing and adapting to pending storms in the future.

The six Storm Scenarios defined in Section 4.2 include the maximum observed and expected water levels. This information is imported into ArcGIS using Charlottetown elevation to provide 1:50,000 scale rough estimates of expected flood lines associated with the storm scenarios. Using these flood lines against Charlottetown's status quo data (described in Section 4.1), expected impacts are derived. Using the best available data on Charlottetown's elevation, flood level lines are estimated for maximum water levels corresponding to Scenario II (3 meters above CD) IV (4 meters above CD) and VI (5 meters above CD). Estimated flood lines for Charlottetown corresponding to the expected maximum water level for Storm Scenario I (2.5 meters), Scenario III (3.5 meters) and Scenario V (4.5 meters) are found by interpolating the integer flood line indicators from the 3, 4, and 5 meter lines.

The impacts examined in this section represent the immediate physical impacts of the storm scenarios, e.g., for points of interest impacted by the encroaching flood lines. Long-term impacts on employment, education, health status, etc., are not considered immediate physical impacts and are not covered here on the grounds that storm preparation strategies of interest to this study are more directly related to reducing direct and immediate damage possibilities. Commercial buildings, government buildings, parks, recreational areas, churches, museums, and other parts of the built environment are addressed more specifically in this section and are the basis for determining the expected damage impacts.

Storm scenario impacts are categorized by the four pillars of this study (environmental, economic, social and cultural) and closely reflect the presentation of indicators provided in Section 4.1 (Charlottetown's Community Profile Status Quo). Due to the lack of identifiable social structures, the social pillar is represented by buildings that are considered 'social services' according to the SIC major groups.

4.3.1 Storm Scenario I

Scenario I storms are characterized by storm movement speed of 45 kph to 50 kph, wind speeds of 55 kph to 75 kph, and atmospheric pressure of 1000 mb to 990 mb (Table 4.3). These storm characteristics lead to a maximum observed water level of 2.5 meters above chart datum. Storm Scenario I expects similar impacts to that of the historical storms Tropical Depression Able (August 21, 1950) and Extratropical Storm Hanna (September 7, 2008) which dumped heavy rainfall on Charlottetown leading to street flooding and local power outages (Tables 4.4 and 4.5). A Storm Scenario I storm surge and its descriptive impacts are expected to last approximately 1 day (Table 4.6).

Using the best data available, the immediate physical impacts of a Scenario I storm are examined in ArcGIS from interpolated results of integer levels rise of between 2 and 3 meters. This is discussed further in Section 4.3.7 below.

4.3.2 Storm Scenario II

Scenario II storms are expected to produce a maximum observed water level of 3 meters above chart datum. They are described by storm movement speed of 50 kph to 55 kph, wind speeds of 75 kph to 95 kph, and atmospheric pressure of 990 mb to 980 mb (Table 4.3). Expected impacts on Charlottetown from Scenario II storms are similar to the impacts to that of 'No Name 1964' (December 2, 1964), 'No Name 1962' (April 4, 1962), and Hurricane Category 1 Hortense (September 15, 1996). These storms generally had winds around 100 kilometres per hour (Table 4.4). Expected impacts from these scenario storms, based on the impacts of each of the categorized historical storms, are street and highway flooding, power outages due to the destruction of power lines, and cancelled ferry service during the duration of the storm and for a short period afterwards (Table 4.5). A Scenario II storm surge and its impacts are expected to last almost 2 full days (Table 4.6).

For Storm Scenario II, the estimated flood line is drawn on the map at 3 meters above sea level (denoted by the white line in Figure 4.11). The captured points of interest within this flood line are examined against the Charlottetown Status Quo (Section 4.1) indicators in terms of the four pillars of the Community Profile: environmental, economic, social and cultural and discussed in further detail below.

4.3.2.1 Environmental

Figure 4.11: Storm Scenario II environmental impact map with white 3 meter flood line (numbers refer to parks identified in Table 4.7) (Source: DMTI 2009a and Geobase 2010)

Figure 4.11 clearly shows that many Charlottetown parks would be impacted by the Scenario II storm surge and a maximum water level rise of 3 meters CD. The following parks are expected to be completely flooded by the resulting storm surge: Rochforth Square (7), Connaught Square (8), Confederation Landing (9), Joseph A. Schiz Memorial Park (13), and Hillsborough Park (10). This list of parks, their associated numbers (with respect to the map in Figure 4.11), their size (where small is 0 to 2.6 acres, medium is 2.61 to 7.54 acres, and large is greater than 7.54 acres) and their respective extents of flooding are provided in Table 4.7.

Table 4.7: Scenario II park flooding

No.	Name	Size	Amount Flooded
1	Lewis Point Park	Small	Partially (>50%)
2	Nature Trail	Small	Partially (>50%)
3	Kennedy Park	Small	Partially (<50%)
4	Grace Baptist Park	Small	Partially (<50%)
5	Central Field	Medium	Partially (<50%)
6	Route for Nature and Health	Small	Partially (>50%)
7	Rochforth Square	Small	Completely
8	Connaught Square	Small	Completely
9	Confederation Landing	Small	Completely
10	Hillsborough Park	Small	Completely
11	Royalty Oaks Natural Area	Small	Partially (<50%)
12	Queen Elizabeth Park	Medium	Partially (>50%)
13	Joseph A. Schiz Memorial Park	Medium	Completely
14	Victoria Park	Large	Partially (>50%)
15	Exhibition Ground	Large	Partially (>50%)
16	Belvedere Golf and Winter Club	Large	Partially (<50%)
17	East Royalty Park	Large	Partially (<50%)

The percentage of flooding to Charlottetown's three major parks (Victoria (14), Queen Elizabeth (12) and Confederation Landing (9), Figure 4.4) is provided in Table 4.8.

Table 4.8: Scenario II flooding of 3 major parks

Park	Percentage Flooded
Victoria Park	73%
Queen Elizabeth Park	60%
Confederation Landing	100%

As Confederation Landing is directly next to Charlottetown harbor downtown, it is no surprise that with even only a 3 meter expected maximum observed water level that it would be completely flooded. The other two major parks are also on the water, but not at quite as low-lying a position as Confederation Landing.

4.3.2.2 Economic

As noted in Section 4.1.2, the Standard Industrial Classifications (SIC) are used to describe the economic profile of Charlottetown (Charlottetown's Status Quo). The SIC is used here to describe how much of each industry is affected (i.e., falls within the water side of the predicted flood lines for Storm Scenario II). A map of the three meter flood line (denoted in white) overlaid on the satellite image for Charlottetown and the enhanced points of interest (EPOI) can be seen in Figure 4.12.

Figure 4.12: Storm Scenario II economic points with 3 meter white flood line (Source: DMTI 2009b and Geobase 2010)

There are 826 points affected in this storm scenario as indicated by points to the water side of the flood line. Due to the density of the points, it is not feasible to describe every different classification of the points in reference to the map. A summary of the affected points by each SIC division is provided in Table 4.9.

Table 4.9: Summary of Charlottetown affected economic points in Scenario II by SIC division

SIC Division		Points Affected
Label	**Description**	
A	Agriculture, Forestry, And Fishing	7
C	Construction	17
D	Manufacturing	30
E	Transportation, Communications, Electric, Gas, And Sanitary Services	26
F	Wholesale Trade	22
G	Retail Trade	185
H	Finance, Insurance, And Real Estate	74
I	Services	425
J	Public Administration	40
	Total	**826**

From Figure 4.12, it is clear that the majority of the economic points are located near the waterfront in the downtown core. This area is the most susceptible to flooding due to location and the low elevation. The bulk of the affected economic points are from the 'Services' SIC division, included in this division are service locations for doctors, dentists, service related retail, restaurants, and hair salons.

4.3.2.3 Social

The impacts to the census-related indicators of the social component of Charlottetown are difficult to grasp, but these indicators can give socially descriptive insight to the areas affected. Along with the description, the points in the SIC major group 'social services' are being considered (these points represent non-profit organizations, childcare establishments, counseling centers, learning centers, etc).

There are 33 social service points affected by the Storm Scenario II flood. Figure 4.13 displays these points on a map of the Charlottetown's DAs (the darker DAs have the majority of their area on the water side of the flood line) with the three meter flood line.

Figure 4.13: Social service points and DAs with Scenario II white 3 meter flood line (Source: DMTI 2009b and Statistics Canada 2002)

The size of a DA is based principally on population. The populations of DAs vary, but on average they contain approximately 500 people. It can be seen from Figure 4.13 that the DAs in the downtown core are quite small, meaning that they are quite densely populated. The DAs on the surrounding edges designate a larger spatial area because they extend to cover water (the two rivers – see Figure 3.2 for positioning of rivers surrounding Charlottetown). Median family income of the waterfront DAs are significantly higher than those of the other affected DAs. The two DAs on the Yorke River are especially high (both over $110,000), while one downtown non-waterfront DA has a median family income of only $27,764 (BC Stats Services 2009).

4.3.2.4 Cultural

The indicators used to identify spatially the cultural component are museums, art galleries, and botanical and zoological gardens; churches or religious places of worship; and from the census data by DA indicator for "languages". Since only immediate physical impacts are being examined, languages from the census data are not incorporated into this section. Figure 4.14 shows the points for museums, art galleries, botanical gardens, zoological gardens, and churches or religious places of worship over a satellite image of Charlottetown with the three meter flood line. There are a total of 19 cultural points which are immediately affected by the Scenario II storm surge and fall on the water side of the flood line.

Figure 4.14: Cultural points with Scenario II 3 meter white flood line (Source: DMTI 2009b and Geobase 2010)

There are many museums downtown Charlottetown, a few of the most vulnerable (i.e., closest to shore) are located between Victoria Park and the wharves (in Figure 4.14 these are represented by the points closest to the water downtown at the head of the peninsula). They include: the Green Park Shipbuilding Museum, Beaconsfield

Historic House, the Basin Head Fisheries Museum and Elmira Railway Station Museum. The most vulnerable religious point is St. Dunstan's Basilica which is located downtown (just above the wharves in Figure 4.14).

4.2.3 Storm Scenario III

Scenario III storms are expected to produce a maximum observed water level of 3.5 meters above chart datum. Scenario III storms are defined by speeds of 55 kph to 60 kph, wind speeds of 95 kph to 115 kph, and atmospheric pressure of 980 mb to 970 mb (Table 4.3). Scenario III storms are identified as expecting similar impacts to Post-Tropical Storm Juan (September 29, 2003) and Extratropical Storm Carol (September 8, 1953) (Table 4.4). The impacts of a Scenario III storm are expected to cancel island ferry service throughout the course of the storm and for a recovery period afterward, produce widespread power outages lasting days and destroying power lines, many road and bridge closures due to high winds and flooding, trees knocked over, damages to weaker buildings such as barns and silos, roofs blown off and chimneys knocked over. It is interesting to note that both storms describing Storm Scenario III occurred in autumn (Table 4.5). A Scenario III storm surge and its impacts are expected to last a full 3 days based on the historical evidence (Table 4.6).

Using the best data available, the immediate physical impacts of a Scenario III storm are examined in ArcGIS based on interpolated results found in Section 4.3.7.

4.3.4 Storm Scenario IV

Scenario IV storms are expected to produce maximum observed water levels to 4 meters above chart datum. They are characterized by speeds of 60 kph to 65 kph, winds of 115 kph to 135 kph and atmospheric pressure of 970 mb to 960 (Table 4.3). Expected impacts from Scenario IV storms are similar impacts on Charlottetown to that of Extratropical Storm Ginny (October 30, 1963), Subtropical Storm Subtrop

(October 29, 2000) and Hurricane Category 1 Gustav (September 12, 2002) (Table 4.4). The impacts from a storm of this magnitude would cause widespread flooding in the city washing out many roads and highways; it would cancel ferry services, knock over many trees, blow off roof shingles or potentially full roofs, damage pleasure crafts and small fishing vessels, damage power lines causing power outage and structural damage to weaker, older or coastal buildings (Table 4.5). A Scenario IV storm surge and its impacts are expected to last 4 days (Table 4.6).

For this scenario, the estimated flood line is drawn on the map at 4 meters above sea level (denoted by a white line in Figure 4.15). As before, this flood line is examined against the Charlottetown status quo (Section 4.1) indicators in terms of the four pillars: environmental, economic, social and cultural.

4.3.4.1 Environmental

Figure 4.15: Storm Scenario IV with 4 meter white flood line over map highlighting environmental indicators (Source: DMTI 2009a and Geobase 2010)

Figure 4.15 clearly shows that many parks would be impacted by the expected Scenario IV storm surge. The following parks expected to be completely flooded by the storm surge are: Nature Trail (2), Joseph A. Schiz Memorial Park (13), Route for Nature and Health (6), Rochforth Square (7), Connaught Square (8), Confederation Landing (9), and Hillsborough Park (10). This list of parks, their associated numbers, their size (where small is 0 to 2.6 acres, medium is 2.61 to 7.54 acres, and large is greater than 7.54 acres) and their respective extents of flooding can be seen in Table 4.10.

Table 4.10: Parks partially or fully flooded by Scenario IV storm surge

No.	Name	Size	Amount Flooded
1	Lewis Point Park	Small	Partially (>50%)
2	Nature Trail	Small	Completely
3	Kennedy Park	Small	Partially (<50%)
4	Grace Baptist Park	Small	Partially (<50%)
5	Central Field	Medium	Partially (<50%)
6	Route for Nature and Health	Small	Completely
7	Rochforth Square	Small	Completely
8	Connaught Square	Small	Completely
9	Confederation Landing	Small	Completely
10	Hillsborough Park	Small	Completely
11	Royalty Oaks Natural Area	Small	Partially (>50%)
12	Queen Elizabeth Park	Medium	Partially (>50%)
13	Joseph A Schiz Memorial Park	Medium	Completely
14	Victoria Park	Large	Partially (>50%)
15	Exhibition Ground	Large	Partially (>50%)
16	Belvedere Golf and Winter Club	Large	Partially (<50%)
17	East Royalty Park	Large	Partially (<50%)

The exact percentage of flooding to Charlottetown's three major parks (Victoria (14), Queen Elizabeth (12) and Confederation Landing (9), Figure 4.4 above) is provided in Table 4.11.

Table 4.11: Amount flooded in three major parks due to a Storm Scenario IV surge to maximum expected water level rise of 3 meters

Park	Percentage Flooded
Victoria Park	86%
Queen Elizabeth Park	73%
Confederation Landing	100%

As with the Storm Scenario II impacts depicted in Table 4.8, Confederation Landing is expected to be completely flooded by the expected storm surge. Victoria Park is almost completely flooded and Queen Elizabeth Park is almost three quarters flooded. All three parks have a close proximity to the water and thus are extremely vulnerable to storm surge.

4.3.4.2 Economic

As noted in Section 4.1.2, the Standard Industrial Classifications (SIC) are used to describe the economic profile of Charlottetown (Charlottetown's Status Quo). The SIC are used here to describe how much of each industry is affected (i.e., falls within the water side of the predicted flood lines for Storm Scenario IV). A map of the EPOI with the four meter flood line above CD over a satellite image can be seen in Figure 4.16 (denoted by the white line).

Figure 4.16: Economic points with Storm Scenario IV white flood line (Source: DMTI 2009b and Geobase 2010)

There are 950 points affected in this storm scenario (versus 846 for Storm Scenario II) as indicated by points to the water side of the flood line. Due to the density of the points, it is not feasible to describe every different classification of the points in reference to the map A summary of the affected points in each SIC division is provided Table 4.12.

Table 4.12: Number of economic points affected by Scenario IV storm by SIC division

SIC Division		Points Affected
Label	**Description**	
A	Agriculture, Forestry, And Fishing	7
C	Construction	18
D	Manufacturing	33
E	Transportation, Communications, Electric, Gas, And Sanitary Services	29
F	Wholesale Trade	27
G	Retail Trade	208
H	Finance, Insurance, And Real Estate	80
I	Services	506
J	Public Administration	42
	Total	**950**

From Figure 4.16, it is clear that the majority of the economic points are located near the waterfront in the downtown core. This area is the most susceptible to flooding due to location and the low elevation. Again, the bulk of the affected economic points are from the 'Services' SIC division.

4.3.4.3 Social

Along with the census-related indicator description, the points in the SIC major group 'social services' are being considered (these points represent non-profit organizations, childcare establishments, counseling and learning centers, etc). There are 38 social service points affected by the Scenario IV flood (versus 33 for Storm Scenario II and the 3 meter maximum water level rise). Figure 4.17 displays these points on a map of the Charlottetown's DAs (the darker DAs have the majority of their area on the water side of the flood line) with the four meter flood line.

Figure 4.17: Social service points and DAs with Storm Scenario IV white 4 meter flood line (Source: DMTI 2009b and Geobase 2010)

It can be seen from Figure 4.17 that the DAs in the downtown core are quite small, meaning that they are quite densely populated. This storm scenario impacts two more DAs (with the majority of their area on the water side of the flood line) than a Scenario II storm. The DAs on the surrounding edges are large because they extend to cover water (the two rivers).

4.3.4.4 Cultural

The points in the cultural section are made up of museums, art galleries, botanical gardens, zoological gardens, and churches or religious places of worship. Storm Scenario IV affects a total of 21 cultural points (versus 19 for Storm Scenario II and 3 meter expected maximum water level rise). Figure 4.18 shows the points overlaid on the satellite image of Charlottetown with the four meter flood line.

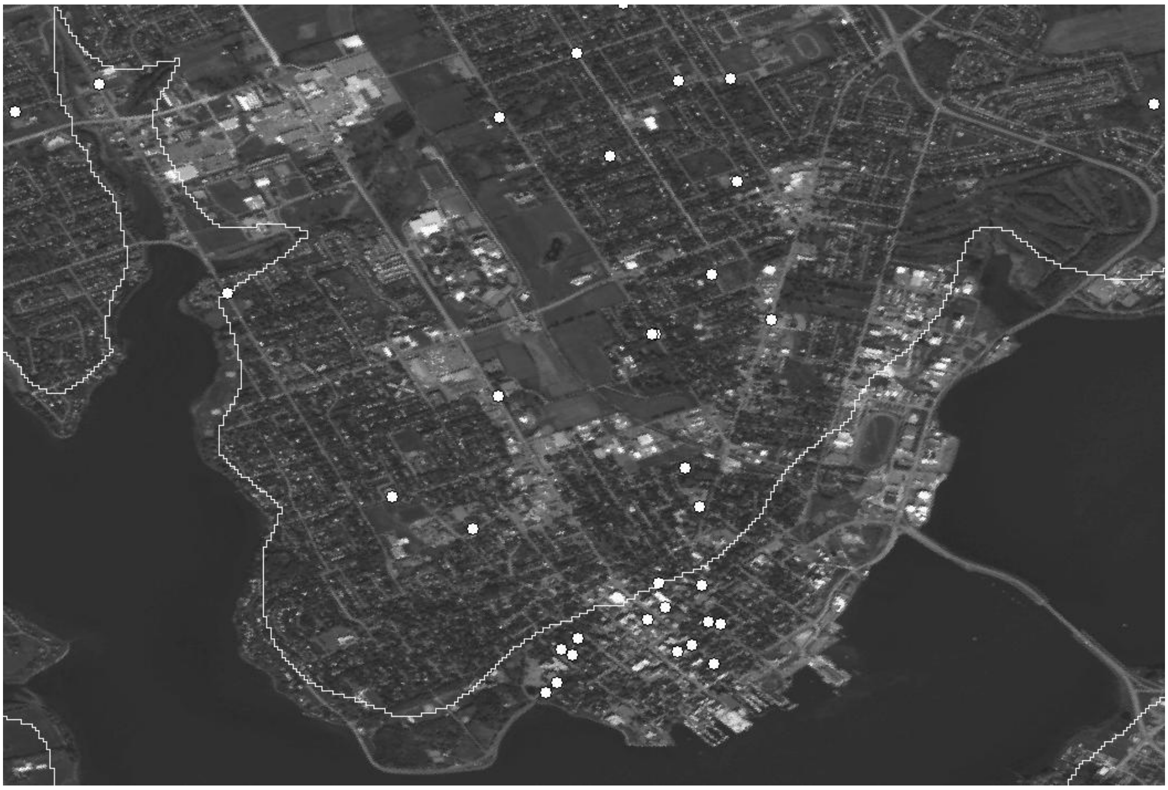

Figure 4.18: Cultural points with Scenario IV white flood line (Source: DMTI 2009b and Geobase 2010)

From Figure 4.18, it is clear that there is a dense grouping of the cultural points in the downtown area. In fact, 20 of the 21 points affected by the Scenario IV storm are located downtown.

4.3.5 Storm Scenario V

Scenario V storms are expected to produce maximum observed water levels to 4.5 meters above chart datum. Scenario V storms are characterized by speeds of 65 kph to 70 kph, winds of 135 kph to 155 kph, and atmospheric pressure of 960 mb to 950 mb (Table 4.3). Expected impacts from Scenario V storms are similar impacts to that of White Juan' (February 19, 2004) and the 'Kennedy Inaugural Storm' (January 21, 1961) - which both coincided with high or near high tide. The impacts of a storm surge of this strength caused severe widespread flooding in the city washing out and damaging many roads, highways and bridges, it would cancel ferry services, knock over many large old trees, blow off roofs shingles or full roofs, damage pleasure crafts and fishing vessels, damage power lines causing power outage across the city, and structural damage to weaker, older or coastal buildings (Table 4.4). A Scenario V storm surge and its impacts are expected to last 5 days (Table 4.5).

Using the best data available, the immediate physical impacts of a Scenario V storm are examined in ArcGIS, from interpolating the results of Storm Scenarios IV and VI as discussed in Section 4.3.7.

4.3.6 Storm Scenario VI

Scenario VI storms are expected to produce maximum observed water level of 5 meters above chart datum. They are described by speeds of 70 kph to 75 kph, winds of 155 kph to 175 kph and atmospheric pressure of 950 mb to 940 mb (Table 4.3). Expected impacts from Scenario VI storms are similar to and perhaps worse than impacts from 'No Name 2000' storm (January 21, 2000), which is presently the storm that caused the most damage recorded in Charlottetown's history with regards to maximum observed water level, pressure and overall monetary damage. A storm of this magnitude is expected to cause severe flooding to private and public properties (an estimate 460 properties were either flooded or at risk in the 'No Name 2000' storm (Milloy and MacDonald 2002 (SD2 in McCulloch et al. 2002))) which would necessitate evacuations; beaches, roads, and highways would be submerged, sea-ice pile-up on shore (if the storm event occurred in winter months), buildings flooded off their foundations, power loss due to damage of power lines, trees would be knocked over, roofs would be damaged, pleasure crafts and smaller fishing vessels damaged, wharves in the Charlottetown harbour would be damaged or destroyed, a power-generating station on the near shore would be damaged and forced to shut down, ferry service would definitely be halted, and many gas stations would be damaged or closed. The estimated cost of the damages in the 'No Name 2000' storm was more than $20 million to Charlottetown (Table 4.4). A Scenario VI storm surge and its impacts are expected to last 7 days (Table 4.5).

For this storm scenario, a white flood line is drawn on the Charlottetown map at five meters above sea level. This flood line is examined against the Charlottetown Community Profile Status Quo (Section 4.1) indicators in terms of the four pillars: environmental, economic, social and cultural.

4.3.6.1 Environmental

The environmental impacts of a Scenario VI storm surge are enormous if one were to examine every plausible aspect. In this research, the environmental impacts concentrate on only a few of the potential indicators. Figure 4.19 shows the five meter flood line over a satellite image of Charlottetown with the parks.

Figure 4.19: Storm Scenario VI 5 meters flood line over Charlottetown with parks (Source: DMTI 2009a and Geobase 2010)

Figure 4.19 clearly shows that the following parks have been completely flooded by the storm surge: Nature Trail (2), Route for Nature and Health (6), Rochforth Square (7), Connaught Square (8), Confederation Landing (9), Hillsborough Park (10), King's Square (19), Joseph A. Schiz Memorial Park (13), and Exhibition Ground (15). This list of parks, their associated numbers, their size and their respective extents of flooding is provided in Table 4.13.

Table 4.13: Charlottetown parks affected by Scenario VI storm surge

No.	Name	Size	Amount Flooded
1	Lewis Point Park	Small	Partially (>50%)
2	Nature Trail	Small	Completely
3	Kennedy Park	Small	Partially (<50%)
4	Grace Baptist Park	Small	Partially (<50%)
5	Central Field	Medium	Partially (>50%)
6	Route for Nature and Health	Small	Completely
7	Rochforth Square	Small	Completely
8	Connaught Square	Small	Completely
9	Confederation Landing	Small	Completely
10	Hillsborough Park	Small	Completely
11	Royalty Oaks Natural Area	Small	Partially (>50%)
12	Queen Elizabeth Park	Medium	Partially (>50%)
13	Joseph A. Schiz Memorial Park	Medium	Completely
14	Victoria Park	Large	Partially (>50%)
15	Exhibition Ground	Large	Completely
16	Belvedere Golf and Winter Club	Large	Partially (<50%)
17	East Royalty Park	Large	Partially (<50%)
18	Southview Park	Small	Partially (<50%)
19	King's Square	Small	Completely

For Charlottetown's three major parks: Victoria (14), Queen Elizabeth (12) and Confederation Landing (9), the precise flooded percentage is provided in Table 4.14 (compared to Table 4.8 and 4.11 above).

Table 4.14: Amount flooded in Charlottetown's three major parks by a Scenario VI storm surge

Park	Amount Flooded
Victoria Park	95%
Queen Elizabeth Park	83%
Confederation Landing	100%

Scenario VI storm surge impacts Charlottetown's three major parks quite severely. As with the other scenarios, Confederation Landing is completely flooded. With an expected 5 meter maximum observed water level, Victoria Park is extremely close to being fully flooded and Queen Elizabeth Park is also very heavily flooded with a flood percentage of almost 85%.

4.3.6.2 Economic

As before, SIC divisions were used to describe the economic profile of Charlottetown as in Section 4.1 (Charlottetown's Status Quo). The SIC divisions are used here to describe how much of each industry is affected (i.e., falls within the water side of the predicted flood lines for storm Scenario VI). A map of the white five meter flood line over a satellite image and the enhanced points of interest (EPOI) can be seen in Figure 4.20.

Figure 4.20: Economic points with Storm Scenario VI white five meter flood line (Source: DMTI 2009b and Geobase 2010)

There are a total of 1010 points affected in this storm scenario as indicated by points to the water side of the flood line. The points are too numerous to describe the EPOI points SIC division by division. A summary of the affected points in each SIC division is provided in Table 4.15.

Table 4.15: Economic points affected by Scenario VI storm surge by SIC division

SIC Division		Points Affected
Label	**Description**	
A	Agriculture, Forestry, And Fishing	9
C	Construction	18
D	Manufacturing	40
E	Transportation, Communications, Electric, Gas, And Sanitary Services	30
F	Wholesale Trade	28
G	Retail Trade	220
H	Finance, Insurance, And Real Estate	83
I	Services	540
J	Public Administration	42
	Total	**1010**

The majority of the points affected belong to the services division (540 points), seconded by the retail trade division (220 points). This should come as no surprise as these are the most abundant divisions to begin with, and these points are located in the dense downtown area of Charlottetown and the same is the case for Scenarios II and Scenario IV described previously.

4.3.6.3 Social

Along with the census-related indicator description, the points in the SIC major group 'social services' are being considered (these points represent non-profit organizations, childcare establishments, counseling and learning centers). There are 41 social service points affected by the Scenario VI flood (compared to 33 and 38 points respectively for Storm Scenarios II and IV described above). Figure 4.21

displays these points on a map of the Charlottetown's DAs (the darker DAs have the majority of their area on the water side of the flood line) with the five meter flood line.

Figure 4.21: Social service points and DAs with Storm Scenario VI white 5 meter flood line (Source: DMTI 2009b and Geobase 2010)

As noted previously, it can be seen from Figure 4.21 that the DAs in the downtown core are quite small in area, meaning that they are quite densely populated. This storm scenario impacts two more DAs (with the majority of their area on the water side of the flood line) than a Scenario IV storm (which is four more DAs than a Scenario II storm). The DAs on the surrounding edges are only so large because they extend to cover water (the two rivers). Median family income of the waterfront DAs are significantly higher than those of the other affected DAs. For example, the two DAs on the Yorke River are both over $110,000, while one downtown non-waterfront DA has a median family income of $27,764.

4.3.6.4 Cultural

The indicators used for the cultural component are museums, art galleries, and botanical and zoological gardens; churches or religious places of worship; and from the census data by DA, languages. Since only immediate physical impacts are being examined, languages from the census data are not incorporated in the current discussion.

Figure 4.22 shows the points for museums, art galleries, botanical gardens, zoological gardens, and churches or religious places of worship over a satellite image of Charlottetown with the five meter flood line. There are a total of 23 cultural points which are immediate affected by the Storm Scenario VI surge (compared to 19 and 21 points for Storms Scenarios II and IV discussed above).

Figure 4.22: Cultural points with Storm Scenario VI 5 meter white flood line (Source: DMTI 2009b and Geobase 2010)

Many of the cultural points affected by a Scenario VI storm surge reside in the downtown area. Of these, most are museums and historical sites. As the downtown area is the oldest part of Charlottetown, many of the historic sites relating Charlottetown as the birthplace of Canadian confederation are found here. Because of their proximity to the water, these sites are highly vulnerable.

4.3.7 Comparing and Interpolating Scenario Impacts

In order to determine the impacts of the scenarios that it is not possible to draw flood lines for (Scenarios I, III and V), first the known scenarios with known impacts must be compared. Once a comparison has been done, it is possible to interpolate the data and estimate the impacted spatial points of the remaining Storm Scenarios I, III, and V.

4.3.7.1 Environmental

Table 4.16 compares the number of fully and partially flooded parks, the precise estimated amount of flooding the three major parks, the amount of wooded areas partially and completely flooded, and the recreational tracks flooded.

Table 4.16: Comparison of environmental indicators for Storm Scenarios II, IV, and VI

	Scenario II	Scenario IV	Scenario VI
Number of Parks Fully Flooded	5	7	9
Number of Parks Partially Flooded	12	10	10
Victoria Park Flooding	72%	86%	95%
Queen Elizabeth Park Flooding	60%	73%	83%
Confederation Landing Flooding	100%	100%	100%

Estimations regarding the environmental impacts of storm Scenario I, III, and V can be made by interpolating from the Scenario II, IV and VI impact values. The Scenario I (2.5 meter flood) environmental storm impacts are estimated by drawing a two meter flood line (since only integer flood lines can be drawn using the best available elevation data) and interpolating between the impacts from the two meter flood area and the three meter Storm Scenario II flood area. Estimations for the remaining three scenarios using the same indicators can be seen in Table 4.17.

Table 4.17: Environmental indicator interpolation estimations for Storm Scenarios I, III and V flooding

	Scenario I	**Scenario III**	**Scenario V**
Number of Parks Fully Flooded	2	6	8
Number of Parks Partially Flooded	13	12	10
Victoria Park Flooding	65%	79%	90%
Queen Elizabeth Park Flooding	54%	66%	78%
Confederation Landing Flooding	100%	100%	100%

4.3.7.2 Economic

Table 4.18 compares the number of SIC points affected by each storm scenario organized by SIC division and uses the data found to interpolate values for the remaining storm scenarios (as well as the additional data for a 2 meter storm surge). The table uses the SIC division abbreviations (A through J), as per the SIC labels recorded in Tables 4.9, 4.12, and 4.15 above which have the full SIC Divisions name reference.

Table 4.18: Comparing number of economic points between all scenarios by SIC division

SIC Division	SS – I*	SS - II	SS – III*	SS - IV	SS – V*	SS - VI
A	4	7	7	7	8	9
C	11	17	17	18	18	18
D	22	30	31	33	36	40
E	17	26	27	29	29	30
F	17	22	24	27	27	28
G	139	185	196	208	214	220
H	54	74	77	80	81	83
I	346	425	465	506	523	540
J	32	40	41	42	42	42
Total	**642**	**826**	**885**	**950**	**977**	**1010**

*Interpolated values by SIC Division

4.3.7.3 Social

Similarly to the previous section, by interpolating the number of SIC points (within the 'social services' major group) between the known scenario impacts and that of a storm with a 2 meter surge, the remaining unknown scenario impacts (Scenarios I, III, and V) have be estimated. Table 4.19 demonstrates this comparison.

Table 4.19: Comparing and interpolating the number of affected social points per storm scenario

	Storm Scenario I	Storm Scenario II	Storm Scenario III	Storm Scenario IV	Storm Scenario V	Storm Scenario VI
Number of Social Services Affected	25	33	35	38	39	41

*Interpolated values by SIC Division

4.3.7.4 Cultural

In the same fashion that the impacts from the last two pillars (economic and social) were compared, so are the impacts from the cultural pillar. Cultural indicators, in this case, were considered museums, art galleries, and botanical and zoological gardens; churches or religious places of worship. By interpolating the number of points fitting these indicators descriptions between the known scenario impacts and that of a storm with a 2 meter surge, the remaining unknown scenario impacts (Scenarios I, III, and V) are estimated. Table 4.20 demonstrates this comparison.

Table 4.20: Comparing and interpolating cultural points affected by each storm scenario

	Storm Scenario I	Storm Scenario II	Storm Scenario III	Storm Scenario IV	Storm Scenario V	Storm Scenario VI
Cultural Points Affected	16	19	20	21	22	23

In this section, descriptions of each storm scenario were given and the estimated environmental, economic, social and cultural impacts from each of the storm scenarios have been determined using indicator points and flood lines. As the severity of the storm scenario increases, as do the number of points impacted in each of the four community profile pillars.

4.4 'Assets At Risk' Analysis

This section presents the analysis of determining monetary values for the 'assets at risk' of the community of Charlottetown subject to damage impacts from storms. Section 4.4.1 establishes Storm Scenario VI as the baseline scenario and analyzes the baseline 'assets at risk' by each of the four pillars of the Charlottetown Community

Profile. Section 4.4.2 compares the Storm Scenarios I through V against the baseline to determine their respective monetary 'assets at risk' value.

It is difficult to estimate the overall monetary damages to a community as a result of a coastal storm surge. The two main sources of information on local monetary damage data are insurance claims and media reports. Insurance claims are reliable, but can be expected to vastly underestimate the community damage values. At the other extreme, media reports do not tend to list or explain sources, thus making them less transparent and less dependable as storm damage estimates. Media reports tend to overstate damage. In the 2002 study, 'Coastal Impacts of Climate Change and Sea-Level Rise on Prince Edward Island', the authors chose to estimate the total 'cost at risk' of community assets instead of estimating direct monetary damages (Milloy and MacDonald 2002 (SD2 in McCulloch et al. 2002)). The authors used GIS to replicate the January 21, 2000 storm's flood plain of 4.23 meters to assess Charlottetown's 'cost at risk'. Anything in the flood plain was considered 'at risk' and its full value was used when calculating the monetary 'at risk' amount. This approach is adopted in this research to determine community vulnerability. The analysis is augmented by separating expected damages from different storms and according to the Community Profile categories, environmental, economic, social, and cultural.

4.4.1 Assets at Risk Baseline Analysis

The January 21, 2000 storm surge is considered a Scenario VI storm in this study, therefore the 'cost at risk' values determined by the scientific team on the 2002 study mentioned above will be used to form the Storm Scenario VI 'assets at risk' estimations for Charlottetown. These estimates provide the baseline from which the other five storm scenarios are evaluated.

The ‘assets at risk’ values are broken down into the four Community Profile pillars of the study (environmental, economic, social and cultural). As described in Section 4.3, the environmental indicators are represented by the three major parks in Charlottetown: Victoria, Queen Elizabeth and Confederation Landing. The economic indicators are the built environment, transport and public works. The social indicators are income lost and health cost. Lastly, the cultural indicators are heritage sites, churches, and museums. A full description and explanation of the assets at risk for each of the four pillars under Storm Scenario VI follows.

4.4.1.1 Environmental

The monetary figure for the assets at risk is the aggregate value of the major parks in Charlottetown (Victoria Park, Confederation Landing Park and Queen Elizabeth Park) as per the 2002 study. The values of the parks were determined “on the basis of the value of adjacent properties.” (Milloy and MacDonald 2002, pg. 22 (SD10 in McCulloch et al. 2002)). That is to say that property values adjacent to the parks were calculated and the average per square metre value was multiplied by the total size of the park, determining the ‘assets at risk’ monetary value of each park. The parks estimated ‘assets at risk’ value can be seen in Table 4.21. All value estimates are in 2002 Canadian dollars.

Table 4.21: Environmental ‘assets at risk’ for a Scenario VI storm surge (Source: Milloy and MacDonald 2002 (SD10 in McCulloch et al. 2002))

At Risk	Assets at Risk Value
Queen Elizabeth Park	$5.4 million
Victoria Park	$83.5 million
Confederation Landing Park	$3.1 million
Total Environmental Assets at Risk	$92.0 million

4.4.1.2 Economic

Like the environmental valuation of assets at risk, the economic assets at risk are also attributed to estimates from the Milloy and MacDonald (2002) (SD10 in McCulloch et al. 2002) report. The authors of Supporting Document 10 in *Coastal Impacts of Climate Change and Sea-Level Rise on Prince Edward Island* (McCulloch et al. 2002) estimated that transport (roads) 'assets at risk' value for Charlottetown is $12 million; public works (water pipes, sanitary pipes, force main (the pipe by which material is transferred from lift stations to the treatment plant), sewage lift stations) 'assets at risk' value is $10.648 million; and the built environment 'assets at risk' value is $54.024 million. Since all fall under the economic pillar for Charlottetown, their values are combined to give a total of $76.7 million. Table 4.22 describes this below.

Table 4.22: Economic 'assets at risk' for a Scenario VI storm surge (Source: Milloy and MacDonald 2002 (SD10 in McCulloch et al. 2002))

At Risk	Assets at Risk Value
Roads	$12 million
Water Pipe	$1.95 million
Sanitary Pipe	$2.223 million
Storm Sewer Pipe	$3 million
Force Main	$1.155 million
Sewage Lift Station (small)	$320,000
Sewage Lift Station (large)	$2 million
Built Environment	$54.024 million
Total Economic Assets at Risk	**$76.672 million**

4.4.1.3 Social

In order to value the social 'assets at risk' of a Scenario VI storm surge, the total amount of labour earnings that citizens affected by the flood would lose due to the impact of the storm was aggregated and the total additional health cost due to the impact of the storm was estimated. To do this, the Storm Scenario VI flood line was drawn through a map of the dissemination areas (DAs) of Charlottetown (as in Figure 4.21). A total of 36 DAs were affected by the flooding. A picture of this can be seen in Figure 4.23 (affected DAs are darker and have labels).

Figure 4.23: Storm Scenario VI Baseline 5 meter maximum water level flood lines on DAs (darker DAs affected by flood) (Source: Statistics Canada 2002)

From this flood line for Storm Scenario VI (5 meter maximum water level flood line), it is possible to determine what percentage of the dissemination area had been flooded. Since the population in the workforce is known for each DA, if we assume that the workforce population is equally dispersed in the DA, then by multiplying the percentage area of the DA flooded by the DA workforce population, an estimation of the workforce affected by the flood can be found. This is described by Equation (4-1).

$$Pop\ in\ Workforce\ Flooded\ \approx \left(\frac{DAFloodSize}{DASize}\right) * (DAWorkForcePop) \tag{4-1}$$

Since the median annual income of each DA is also known, the daily median income can be estimated by dividing the annual income by the number of working days in a year (260 days). Using the estimation found above for the population in workforce flooded (4-1) and multiplying it by the daily median income, the amount of pay lost per day is estimated. This is described below by Equation (4-2)

$$IncomeLostperDay\ \approx (Pop\ in\ Workforce\ Flooded) * \left(\frac{MedianAnnualIncome}{260\ WorkingDays\ \ /year}\right) \tag{4-2}$$

Equation (4-2) estimates the amount of pay lost per day. From the storm scenario length descriptions (Section 4.2.4, Table 4.6), Storm Scenario VI has an estimated duration of 7 days. Thus, the total amount of pay lost per DA can be estimated by multiplying Equation (4-2) by 7 days. This is shown in Equation (4-3).

$$Scenario\ VI\ Total\ Lost\ Income \approx (IncomeLostperDay) * (7\ Days) \tag{4-3}$$

The second social indicator for Charlottetown's 'assets at risk' is additional health cost. The vulnerable population affected by the storm surge is estimated by multiplying the percentage of the DA flooded by the population over 65 years of age and under 10 years of age. This population is multiplied by an estimated additional health cost of $200 per person to give the additional health cost per day. The additional health cost valuation includes the additional cost attributed to the storm isolation of individuals who need heath care, e.g., for doctors' and hospital appointments, prescription drug needs, and other care services. Finally this is multiplied by 7 days in order to find the total additional health cost of the storm scenario. The full equation for finding additional health cost is shown in Equation (4-4).

$$Total\ Health\ Cost \approx (\%Flooded) * \left(Pop_{65+,10-}\right) * (Health\ Cost) * (7\ Days) \quad (4\text{-}4)$$

These calculations must be done for all 36 affected DAs and then totalled in order to estimate the total lost income and total additional health cost for Charlottetown. The calculations for all the DAs are shown in Table 4.23.

Table 4.23: Lost Income in 7 Days due to flood per DA

DA	% of DA Flooded	Pop Work Force	Pop in Work Force Flooded	Median Income	Median Income per Work Day	Lost Income in 7 Days	Pop 65+ and 10-	Health Cost in 7 Days
131	0.83%	385	3.20	$30,227	$116.26	$2,605	135	$1,571
134	42.15%	180	75.86	$40,718	$156.61	$83,166	40	$23,602
135	9.83%	205	20.14	$40,243	$154.78	$21,826	80	$11,006
136	11.19%	190	21.26	$23,914	$91.98	$13,690	125	$19,585
137	21.81%	215	46.89	$18,607	$71.57	$23,492	85	$25,956
139	0.09%	225	0.19	$39,889	$153.42	$208	95	$114
148	29.06%	285	82.82	$20,119	$77.38	$44,861	160	$65,094
149	2.79%	285	7.94	$21,385	$82.25	$4,572	100	$3,901
150	80.89%	280	226.50	$20,049	$77.11	$122,260	100	$113,249
151	15.35%	245	37.60	$22,273	$85.67	$22,549	135	$29,008
152	91.56%	285	260.96	$18,380	$70.69	$129,135	105	$134,600
153	17.59%	275	48.38	$16,872	$64.89	$21,978	155	$38,179

154	100.00%	355	355.00	$17,044	$65.55	$162,901	95	$133,000
155	92.87%	215	199.66	$18,983	$73.01	$102,044	155	$201,520
156	100.00%	260	260.00	$16,777	$64.53	$117,439	110	$154,000
157	100.00%	310	310.00	$18,752	$72.12	$156,507	165	$231,000
158	100.00%	280	280.00	$14,729	$56.65	$111,034	120	$168,000
159	98.12%	275	269.83	$20,395	$78.44	$148,162	195	$267,867
160	69.34%	225	156.01	$17,119	$65.84	$71,902	120	$116,484
161	19.70%	235	46.29	$19,930	$76.65	$24,839	90	$24,820
162	69.57%	300	208.70	$20,993	$80.74	$117,958	70	$68,176
164	2.91%	330	9.60	$23,381	$89.93	$6,043	90	$3,666
169	3.59%	290	10.42	$29,986	$115.33	$8,413	115	$5,785
172	0.69%	235	1.62	$12,485	$48.02	$545	75	$725
173	3.90%	200	7.79	$27,952	$107.51	$5,863	90	$4,908
174	34.55%	440	152.01	$12,665	$48.71	$51,833	105	$50,786
180	83.03%	350	290.60	$38,686	$148.79	$302,671	330	$383,589
182	6.38%	220	14.03	$19,974	$76.82	$7,546	85	$7,590
183	37.33%	350	130.66	$34,831	$133.97	$122,530	115	$60,105
255	95.65%	230	219.99	$28,625	$110.10	$169,539	100	$133,906
256	9.70%	325	31.53	$23,464	$90.25	$19,920	175	$23,771
257	25.10%	360	90.35	$22,766	$87.56	$55,378	115	$40,406
258	12.13%	310	37.59	$27,336	$105.14	$27,665	115	$19,523
261	6.00%	400	23.99	$29,903	$115.01	$19,314	130	$10,915
265	84.06%	220	184.94	$36,578	$140.68	$182,126	185	$217,724
267	20.53%	250	51.33	$26,959	$103.69	$37,259	130	$37,371
Totals		10020	4174			$2,520,000	4390	$2,830,000

The summation the seventh (Lost Income in 7 Days) column of Table 4.23 gives $2.52 million as estimation for the total lost income of a Scenario VI storm. The final column of Table 4.23 (Health Cost in 7 Days) is summed to give an estimated total health cost attributed to Storm Scenario VI of $2.83 million.

4.4.1.4 Cultural

The 'assets at risk' value of the cultural pillar is also based on the findings from the 2002 study (Milloy and MacDonald 2002 (SD10 in McCulloch et al. 2002)). The authors found that 30 heritage properties (some historical, some entertainment, etc) had an estimated 'cost at risk' value of $8.581 million. This valuation is applied here as the cultural 'assets at risk' value. There was no listing of the 30 heritage properties that make up this 'at risk' value. In this research, 44 properties are considered cultural indicators and they are made up of churches and places of worship, art galleries, and museums.

4.4.1.5 Summary

The 'assets at risk' for a Scenario VI storm surge at Charlottetown is broken up by the four pillars of the study (environmental, economic, social, and cultural) and totalled in Table 4.24. Each of the four pillars percentage of the total is also in Table 4.24 and shown graphically in Figure 4.24. The total 'assets at risk' value for a Scenario VI storm surge is $182.6 million.

It is important to note that 'assets at risk' value is not the same as damages. 'Assets at risk' value is the maximum cost of everything at risk, whereas damages are what negative impacts have actually occurred to the assets themselves. Expected damages are therefore a fraction of 'assets at risk' values. These are discussed further below.

Table 4.24: Assets at risk per pillar for Storm Scenario VI (Baseline).

Environmental	Economic	Social	Cultural	Total
$92,000,000	$76,672,000	$5,351,277	$8,581,000	$182,604,277
50.38%	41.99%	2.93%	4.70%	100.00%

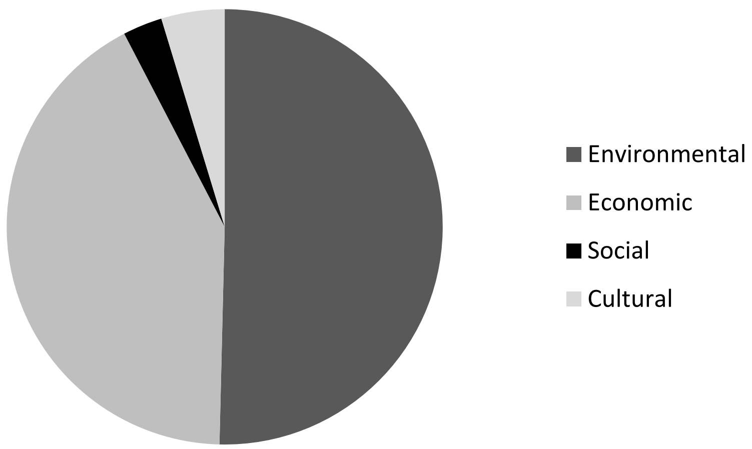

Figure 4.24: 'Assets at risk' values per pillar for Baseline Storm Scenario VI for Charlottetown

4.4.2 Assets at risk Comparisons

In the previous section, the 'assets at risk' value of a Scenario VI storm surge was found. These findings are used as a baseline against which to measure all other scenarios 'assets at risk'. The percentage of 'assets at risk' for each scenario is compared to the Storm Scenario VI baseline. The known data are used to interpolate results across all scenarios.

The 'assets at risk' value for each scenario has been found (in terms of each of the four pillars as we have done for Storm Scenario VI) and is displayed and explained pillar by pillar below.

4.4.2.1 Environmental

By using the estimated flood lines on the map in ArcGIS, the amount of expected flooding that occurs in the three parks (Victoria, Queen Elizabeth and Confederation Landing) can be determined. Figure 4.25 for Victoria Park, Figure 4.26 for Queen Elizabeth Park and Figure 4.27 for Confederation Landing Park show the flooding of the park areas by storm Scenario II (3 meter maximum water level rise), IV (4 meter maximum water level rise) and VI (5 meter maximum water level rise). This information is used to establish the percentage of each park that has been flooded relative to our baseline valuations at 5 meters of flooding. These details are shown in Table 4.25.

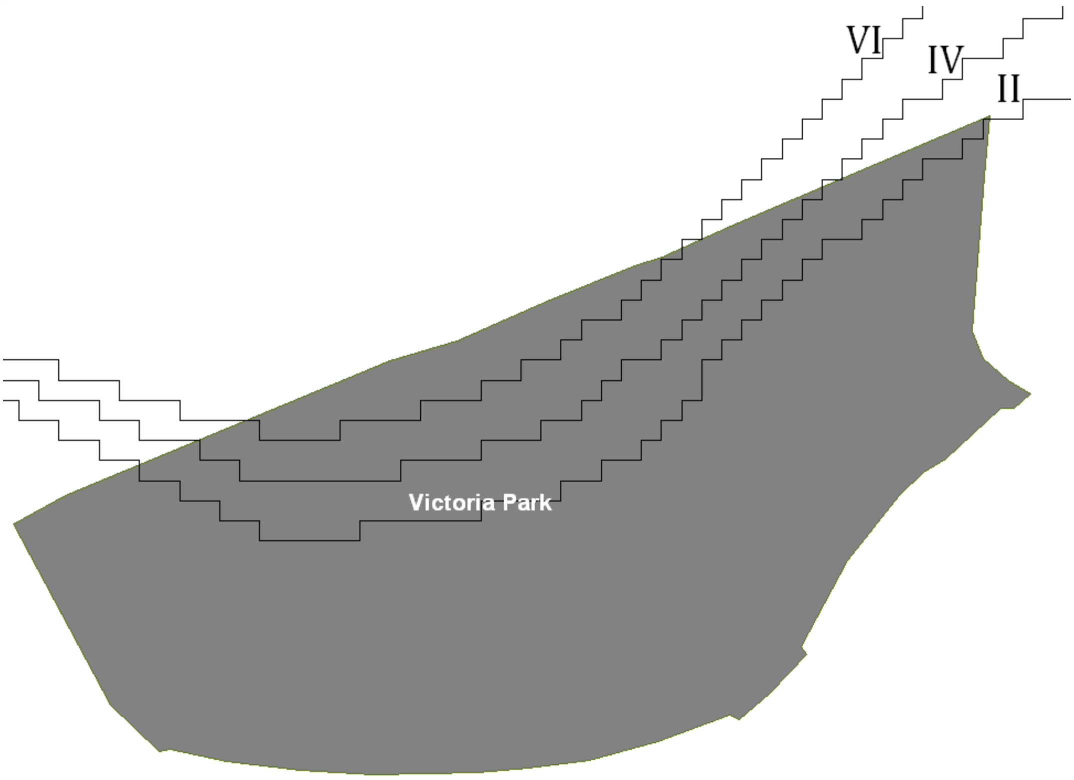

Figure 4.25: Victoria Park with flood lines (Source: DMTI 2009b)

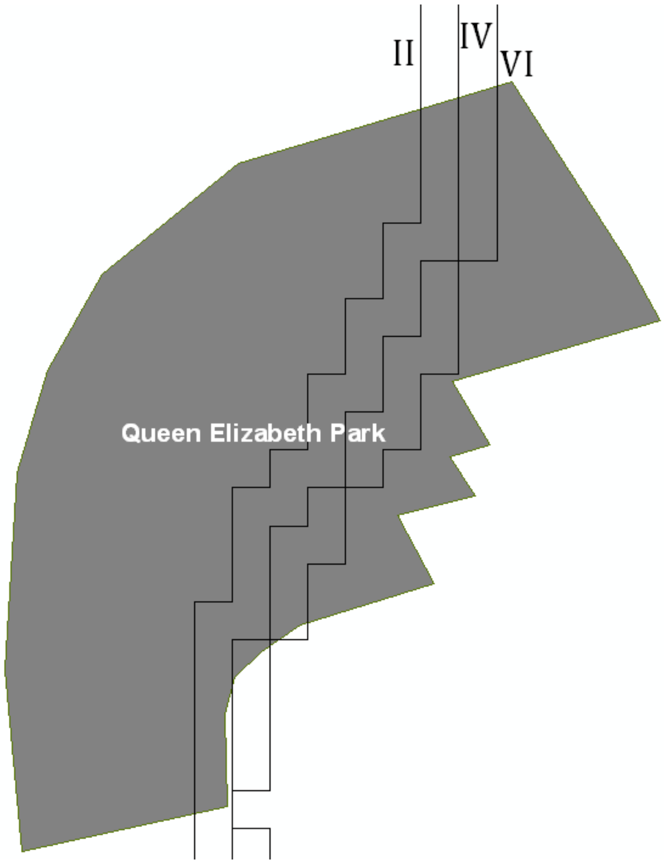

Figure 4.26: Queen Elizabeth Park with flood lines (Source: DMTI 2009b)

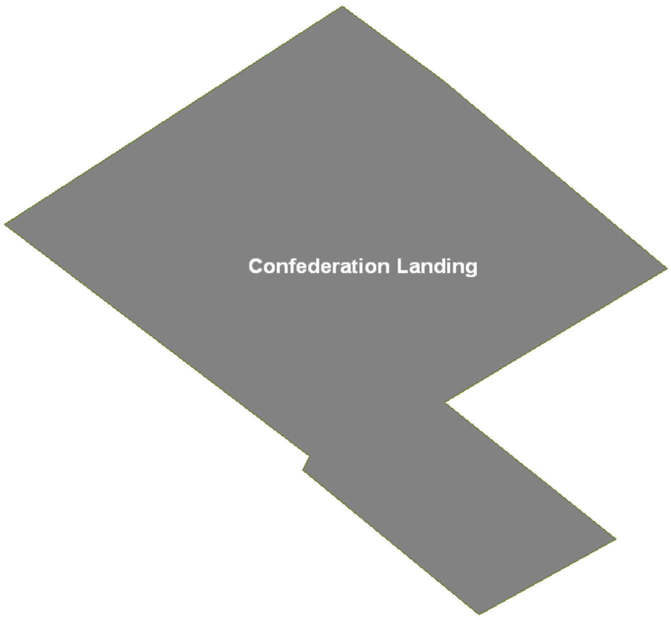

Figure 4.27: Confederation Landing Park without flood lines as it is completely flooded by all Storm Scenarios (Source: DMTI 2009b)

Table 4.25 provides the amount of expected flooding to each of Charlottetown's three major parks for Storm Scenarios II, IV and VI. It also sets Storm Scenario VI as the baseline valuation from the expected flooded amounts (Storm Scenario VI valuations compared to the other scenarios) and shows Scenario II and IV's percentage of expected flooding relative to the Scenario VI baseline.

Table 4.25: Flooded areas of Parks in Charlottetown

		Baseline (5m)	Scenario IV (4m)	Scenario II (3m)
Victoria Park	**Km^2**	0.458059	0.414512	0.349461
	%	100.00%	90.49%	76.29%
Queen Elizabeth Park	**Km^2**	0.08184	0.072147	0.058781
	%	100.00%	88.16%	71.82%
Confederation Landing Park	**Km^2**	0.033272	0.033272	0.033272
	%	100.00%	100.00%	100.00%

Total 'assets at risk' valuations of each scenario are made by knowing the percentages of flooded area against our baseline Scenario VI storm surge and knowing the 'assets at risk' value for the baseline surge. By multiplying the percent flooded of each park by the respective assets at risk Storm Scenario VI valuations, the assets at risk valuation of Storm Scenarios II (3m) and IV (4m) can be determined. After the individual parks' costs at risk have been found, they can be summed to find the total assets at risk for their respective scenarios. The results of this calculation are shown in Table 4.26.

Table 4.26: Assets at risk value per park with respect to Baseline

	Baseline (5m)	Scenario IV (4m)	Scenario II (3m)
Victoria Park	$83,500,000	$75,561,777	$63,703,570
Queen Elizabeth Park	$5,400,000	$4,760,433	$3,878,512
Confederation Landing Park	$3,100,000	$3,100,000	$3,100,000
Total	**$92,000,000**	**$83,422,210**	**$70,682,082**

From these figures it can be seen that Scenario IV (4m) has a total of $83.42 million 'assets at risk' valuation, which is roughly 90.68% of the baseline. Scenario II (3m) has a total of $70.68 million 'assets at risk' valuation, which is roughly 76.83% of the baseline.

4.4.2.2 Economic

The baseline Scenario VI 'assets at risk' value for the economic pillar was determined by summing the assets at risks of the roads, various public works and the built environment. It was determined that the total 'assets at risk' value is $76.672 million. From the flood lines established in ArcGIS, it can be determined what percentage of the roads, built environment and public works are flooded with respect to the baseline case (Scenario VI). A screenshot of the map of the roads and the flood lines can be seen in Figure 4.28. Then by multiplying these percentages across the known assets at risk figures, the assets at risks values for the other scenarios can be found. The details of the percentages and the values are found in Table 4.27.

Figure 4.28: Map of Roads with white flood lines (Source: DMTI 2009b and Geobase 2010)

Table 4.27 shows the 'assets at risk' values for the Storm Scenario VI baseline, and Storm Scenario IV and Storm Scenario II. It also sets the Storm Scenario VI as the baseline (100%) 'assets at risk' percentage and provides the respective 'assets at risk' percentages of Storm Scenarios II and IV.

Table 4.27: Economic 'assets at risk' percentages and values

		Baseline (5m)	Scenario IV (4m)	Scenario II (3m)
Roads	$	$12,000,000	$10,609,955	$9,227,149
	%	100.00%	88.42%	76.89%
Public Works	$	$10,648,000	$10,500,111	$8,281,778
	%	100.00%	98.61%	77.78%
Built Environment	$	$54,024,000	$50,912,324	$44,225,529
	%	100.00%	94.24%	81.86%
Total	$	$76,672,000	$72,022,389	$61,734,457
	%	100.00%	93.94%	80.52%

4.4.2.3 Social

By repeating the steps and equations used to find the baseline (Storm Scenario VI) social 'assets at risk' values (Section 4.4.1.3) but adjusting for length of the storm, the total lost income can be found for Storm Scenarios IV and II. The full table of the details can be found in Appendix D. Table 4.28 summarizes the findings by giving total assets at risk values and percentage assets at risk with respect to the baseline.

Table 4.28: Summary of social 'assets at risk' values and percentages

	Baseline	Scenario IV (4m)	Scenario II (3m)
$	$5,351,277	$2,775,978	$834,485
%	100.00%	51.88%	15.59%

These figures show that Storm Scenario IV and Storm Scenario II have 51.88% and 15.59% of the 'assets at risk' of the baseline (Storm Scenario VI) respectively.

4.4.2.4 Cultural

This study considers a total of 44 cultural points (including museums, art gallery, botanical garden, zoological garden, churches or places of worship) when applying the different storm scenarios. The baseline storm surge (Storm Scenario VI) affects 23 of these points for a total 'assets at risk' value of $8.581 million (Table 4.24). A map of the points and the flood lines can be seen in Figure 4.22. Table 4.29 below details the number of affected points from each Storm Scenario, the total 'assets at risk' pro-rated monetary value and the resulting percentage of the baseline 'assets at risk'.

Table 4.29: Cultural 'assets at risk' with respect to Baseline for Storm Scenarios II and IV

	Baseline (Scenario VI)	Scenario IV (4m)	Scenario II (3m)
#	23	21	19
$	8.581 million	7.834 million	7.089 million
%	100.00%	91.30%	82.61%

4.4.1.5 Summary

The 'assets at risk' relative to the baseline has been found for all four pillars of the study (environmental, economic, social, and cultural) in monetary. The 'assets at risk' values for Scenarios I, III and V are interpolated from the findings for Scenarios II, IV and VI. In order to estimate the 'assets at risk' values for Scenario I (2.5 meter flood line), values were interpolated from the impacts of a 2 meter flood line and the storm Scenario II 3 meter flood line. A summary table of the monetary findings can be seen in Table 4.30 and for the percentage findings in Table 4.31.

Table 4.30: 'Assets at risk' monetary comparison of 6 scenarios

Storm Scenario	Environmental	Economic	Social	Cultural	Total
I	$54,464,000	$54,897,152	$443,621	$5,969,802	$115,774,575
II	$70,683,600	$61,736,294	$834,485	$7,088,764	$140,343,143
III	$77,054,600	$66,880,986	$1,805,231	$7,462,038	$153,202,854
IV	$83,425,600	$72,025,677	$2,775,978	$7,834,453	$166,061,707
V	$87,712,800	$74,348,838	$4,063,627	$8,207,727	$174,332,992
VI	$92,000,000	$76,672,000	$5,351,277	$8,581,000	$182,604,277

Table 4.31: 'Assets at risk' percentage comparison of 6 scenarios with respect to Scenario VI

Storm Scenario	Environmental	Economic	Social	Cultural	Total
I	59.20%	71.60%	8.29%	69.57%	63.40%
II	76.83%	80.52%	15.59%	82.61%	76.86%
III	83.76%	87.23%	33.73%	86.96%	83.90%
IV	90.68%	93.94%	51.88%	91.30%	90.94%
V	95.34%	96.97%	75.94%	95.65%	95.47%
VI	100.00%	100.00%	100.00%	100.00%	100.00%

A graphical comparison of the scenarios by the four pillars can be seen in Figure 4.29.

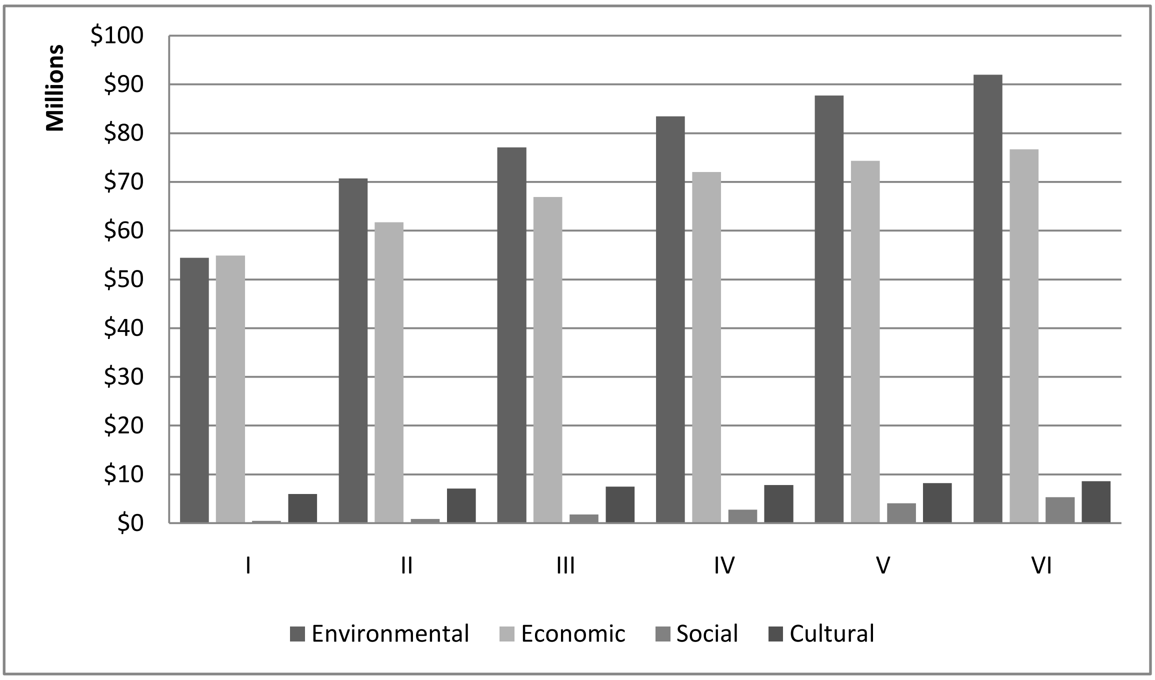

Figure 4.29: Comparison of the six scenarios' 'assets at risk' values by dimension

4.5 Estimated Storm Damages

To determine an 'assets at risk' monetary approximation, the full value of whatever is being measured is accounted for in the approximation as long as it is considered to be at risk. This differs from a damage approximation as the latter only considers what is actually affected, not everything that could potentially be damaged by the storm.

The 'assets at risk' percentages in Table 4.31 are full valuations of exposed assets. However it is recognized that when estimating damages, the length of the storm has a great deal of importance as it determines closure lengths, lack of work lengths, and event postponements. Length of storm was not considered in the 2002 study (McCulloch et al. 2002) as estimated valuations were the full worth for entire 'at risk' areas. When shifting from 'at risk' estimated values to estimated 'damage' values, length of storm surge impacts must be considered as the damages increase as semi-immediate (indirect) storm impacts extend. For example, the monetary damage value of the impacts of storm surge on a local business (lost income due to closure) will grow as the length of the storm impacts (and closure of the service facilities) grows.

As discussed in Section 4.1.2, the impacts of a storm surge scenario have a certain length associated with them. Table 4.6 provided each storm scenario's impact lengths, which are: 1 day, 1.5 days, 3 days, 4 days, 5 days, and 7 days for Storm Scenario I to Storm Scenario VI respectively. The percentage comparison of the 6 storm scenarios with respect to the baseline (Storm Scenario VI) can now be evaluated knowing that Storm Scenario I's impacts are expected to last $1/7^{th}$ as long as Storm Scenario VI, Storm Scenario II's impacts last $1.5/7^{th}$ as long, Storm Scenario III's impacts last $3/7^{th}$ as long, Storm Scenario IV's impacts last $4/7^{th}$ as long, and Storm Scenario V's impacts last $5/7^{th}$ as long. The evaluated percentages for assets at risk by scenario can be seen in Table 4.32.

Table 4.32: Re-evaluated percentage comparison of 6 scenarios with respect to Scenario VI adapted for length of storm

Scenario	Environmental	Economic	Social	Cultural	Total
I	8.46%	10.23%	8.29%	9.94%	9.23%
II	16.46%	17.25%	15.59%	17.70%	16.75%
III	35.90%	37.38%	33.73%	37.27%	36.07%
IV	51.82%	53.68%	51.88%	52.17%	52.39%
V	68.10%	69.26%	75.94%	68.32%	70.41%
VI	100.00%	100.00%	100.00%	100.00%	100.00%

From Table 4.32 it can be seen that overall Storm Scenario I has 9.23% of the assets at risk impact of the baseline Storm Scenario VI; Storm Scenario II has 16.75% of the assets at risk impact of the baseline Storm Scenario VI; Storm Scenario III has 36.07% of the assets at risk impact of the baseline Storm Scenario VI; Storm Scenario IV has 52.39% of the assets at risk impact of the baseline Storm Scenario VI; and Storm Scenario V has 70.41% of the assets at risk impact of the baseline Storm Scenario VI.

4.5.1 Media Reports, Insurance Claims and Government Payouts

Storm surge damages are extremely difficult to attribute and estimate. The three most common valuations for storm surge damages are: (1) insurance reports, (2) government payouts press releases, and (3) media reports. These reports often do not exist or are poorly sourced (i.e., only represent best guesses). Storm damage reports are sometimes declared for large cities. Damages for a smaller city or town are rarely cited or attributed. When recorded, storm damage reports often are presented as an aggregate overestimate, and provide no insight to how the total damages breakdown into categories, e.g., damage to building and infrastructure, damage to private property versus public goods, etc.

Insurance reports tend to undervalue grossly the damages of a storm because they only process (and pay out) for very specific types or amounts of damages. Many claims are not accepted, and much of the damage is likely to go unclaimed at all. Government reports and payouts are similar in that they tend to avoid blanket payouts for all damages. Therefore government payout figures after the fact also undervalue the total damage cost. Media reports may give more seemingly accurate numbers, but sources for reported numbers are rarely given and are arguably overestimates of actual damage, nevertheless, media reports are often the only reports available and they do give us some insight into the storm damage totals for the community.

Of the thirteen historical storms examined in this study for Charlottetown, only three have any reported damage totals associated with them. 'No Name 1962' has media reports citing $300,000 worth of damages (Environment Canada 2009). The 'No Name 2000' storm (which was used as the baseline in the assets at risk section) had a reported $20 million in damages from a federal government report (Natural Resources Canada 2009). Lastly, Post-Tropical Storm Juan (September 2003) has so many different reports from so many sources that it is unclear how much damage was done and where. This is an example of a well known and well documented storm that still has no consensus damage reports. From the plethora of media reports (some conflicting), it can be concluded that most of the damage was done to Halifax. The extent of damage at Charlottetown was quite small by comparison (Bowyer 2009; CBC News in Review 2003; Fogarty; Government of Prince Edward Island 2003; Natural Resources Canada 2010; News957 2010; Public Safety Canada 2010a; Public Safety Canada 2010b; Taplin 2010).

With respect to Juan, the most consistent damage value mentioned in the media reports was that Nova Scotia had a total loss of $100 million (CBC News in Review 2003; Natural Resources Canada 2010). Storm damage valuations were from government relief reports stating that Nova Scotia and Halifax Regional Municipality received a total $19.5 million for relief (News957 2010; Public Safety Canada 2010b) and that Prince Edward Island and Charlottetown received a total of $1.5 million for relief (Government of Prince Edward Island 2003; Public Safety Canada 2010a). Assuming an equivalent government damages payout rate for Halifax and Charlottetown from Juan, then these figures are used together in this research as proportions to estimate the actual damages from Post-Tropical Storm Juan for Charlottetown as $7.692 million.

Throughout this paper, the 'No Name 2000' Scenario VI storm has been the baseline case because of the wealth of work that has been done or reported on this storm as the most damaging storm in Charlottetown's recent history. The $20 million in damages is taken to be a good estimate as it comes consistently from both a federal government and academic source (Natural Resources Canada 2009, Henstra et al. 2009). In order to validate the scenario damage percentages presented in Table 4.32, the estimated monetary damages from Post-Tropical Storm Juan (which is a Scenario III storm in this research) and the 'No Name 2000' storm (which is classified as a Scenario VI storm) can be extrapolated to determine monetary damages for all other storm scenarios. Then the two sets of estimated damages can be compared.

These actual damage estimates were made in different years, thus in order to compare them, their discounted values to 2010 must be considered. The Bank of Canada Investment Calculator (Bank of Canada 2010) has been used to update the damage estimates as seen in Table 4.33.

Table 4.33: Updating storm surge damage estimates to 2010 dollars

Storm Surge	Storm Scenario	Original Estimate	Sources	2010 $ Estimate
'No Name 2000'	VI	$20,000,000	Natural Resources Canada 2009 Henstra et al. 2009	$29,604,886
Juan (2003)	III	$7,692,308	Bowyer 2009 CBC News in Review 2003 Government of PEI 2003 Natural Resources Canada 2010 Public Safety Canada 2010a Public Safety Canada 2010b Taplin 2010	$10,122,552

Based on the 'assets at risk' breakdown percentages (Table 4.32) and the actual damages to Storm Scenario VI ('No Name 2000') and Storm Scenario III (Juan) (as seen above in Table 4.33), monetary damages tables have been constructed for each of the storms.

4.5.1.1 Estimated Storm Damages based on 'No Name 2000'

Since the 'No Name 2000' storm was used as the baseline in the assets at risk analysis, the percentages derived from 'assets at risk' found in Table 4.32 can be used directly with the $30 million estimate to approximate the damages for the different storm scenarios by each of the community profile pillars. Table 4.34 provides the estimated actual damages for the six different storm scenarios apportioned by Community Profile pillar based on the reported 'No Name 2000' actual damage. Range of estimated actual damage is from approximately $2.7 million for Storm Scenario I to $30 million for the most severe Storm Scenario VI. Thus actual damages vary by a factor of 10 for the least damaging to the most damaging storms hitting Charlottetown based on the limited historical information. The full damage results for all the storm scenarios based on the $29,604,886 (2010) in damages for a Scenario VI storm can be found in Table 4.34.

Table 4.34: Estimated Storm Damages based on 'No Name 2000' storm

Storm Scenario	Environmental	Economic	Social	Cultural	Total
I	$1,376,495	$1,147,159	$80,065	$128,388	$2,732,108
II	$2,498,887	$2,082,551	$145,350	$233,076	$4,959,864
III	$5,380,142	$4,483,764	$312,942	$501,815	$10,678,663
IV	$7,813,664	$6,511,840	$454,490	$728,794	$15,508,788
V	$10,501,438	$8,751,807	$610,827	$979,487	$20,843,560
VI	$14,915,584	$12,430,518	$867,581	$1,391,202	$29,604,886

4.5.1.2 Estimated Damages based on Juan

This section re-evaluates storm scenario actual damages estimates based on the reported damages for post-tropical storm Juan. Juan has estimated damages in 2010 dollars of $10 million. A Scenario III storm, the 'assets at risk' percentages found in Section 4.4.2 can be adjusted so that Storm Scenario III is shown as the baseline (100%) for comparison to 'at risk' from other storm scenarios. Once adjusted, the other scenarios have percentages respective to Storm Scenario III. A full breakdown of the scenarios percentages with Scenario III as the baseline is shown in Table 4.35.

Table 4.35: Assets at risk percentages based on Juan

Scenario	Environmental	Economic	Social	Cultural
I	23.56%	27.36%	24.57%	26.67%
II	45.87%	46.15%	46.23%	47.50%
III	100.00%	100.00%	100.00%	100.00%
IV	144.36%	143.59%	153.77%	139.99%
V	189.72%	185.28%	225.10%	183.32%
VI	278.59%	267.49%	296.43%	268.32%

Using the estimated damage of $10 million and the percentages calculated in Table 4.35, the actual damage values of each storm by the four pillars are estimated. The total damages for each scenario vary from $2.6 million for Storm Scenario I to $28 million for Storm Scenario VI. As before, storm damages from the least to the worst severe for Charlottetown vary by a factor of 10 based on historical storm data. The full breakdown by the four pillars can be seen in Table 4.36.

Table 4.36: Estimated damages based on Juan

Scenario	Environmental	Economic	Social	Cultural	Total
I	$1,201,587	$1,162,895	$72,898	$126,852	$2,564,232
II	$2,339,137	$1,961,654	$137,126	$225,943	$4,663,861
III	$5,099,946	$4,250,251	$296,644	$475,681	$10,122,522
IV	$7,362,158	$6,102,925	$456,161	$665,895	$14,587,138
V	$9,675,619	$7,874,715	$667,754	$872,027	$19,090,115
VI	$14,207,958	$11,369,085	$879,346	$1,276,359	$27,732,748

4.5.1.4 Comparing Estimated Damages: 'No Name 2000' and Juan

When comparing the two different actual storm damage estimates for 'No Name 2000' and Juan, we can see that there is very little variation between the two. Actual damage estimates between the two baselines differ by approximately 7% between them. Table 4.37 compares the total estimated damages for each of the scenarios for the two storms being compared.

Table 4.37: Estimated actual damage estimates for each storm scenario based on alternative baseline storms, No Name 2000 and Juan

Scenario	'No Name 2000'	Juan	Difference
I	$2,747,624	$2,564,066	$183,558
II	$4,986,902	$4,660,223	$326,679
III	$10,830,861	$10,122,522	$708,339
IV	$15,583,826	$14,566,071	$1,017,755
V	$20,313,052	$18,989,667	$1,323,385
VI	$29,604,886	$27,680,478	$1,924,408

Based on the comparative analysis of the data poor historical estimates on community damage attributed to storms, it is concluded that the estimated damages for the 'No Name 2000' storm are relatively consistent with the estimations for Juan. Therefore, for this research, the estimated actual damage values are based on 'No Name 2000' that is considered as the baseline case for the damage estimation models in the upcoming sections of this thesis. The 'No Name 2000' estimated actual storm damage values from Table 4.34 have been graphically represented in a bar chart below in Figure 4.30.

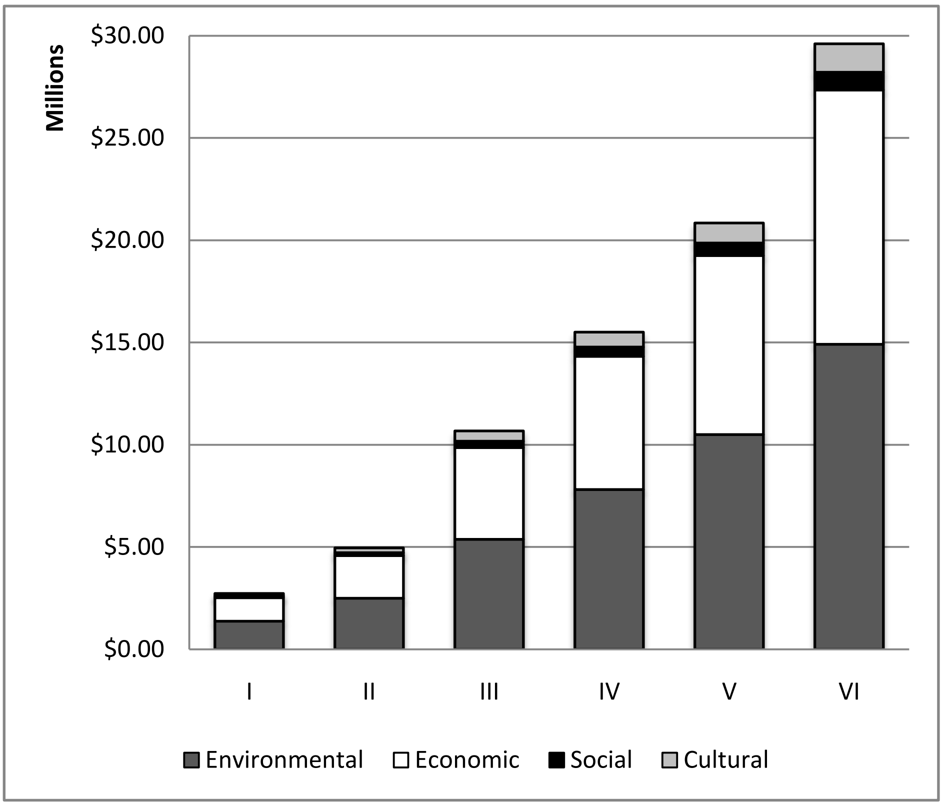

Figure 4.30: Estimated actual damages to Charlottetown by storm scenario based on 'No Name 2000' by Community Profile pillars

4.5.2 Estimated Damage Intervals

Damages have been estimated throughout this section, either in monetary form or as a percentage relative to the determined baseline. Estimated damages of different historical storms, 'No Name 2000' and Juan, have also been examined. These damages have been estimated scenario by scenario. However, a single estimation for a storm scenario cannot represent an entire continuum of storms in a given storm scenario category. Accordingly estimated damage intervals are determined for randomized storm severity with each storm scenario category. These intervals associate each scenario with not one damage estimate, but a range of possible estimates based on the relative intensity of the Storm Scenario event.

The variance in estimated damages grows with the severity of the storm. In order to determine the variance of actual estimated damages within each storm scenario, a constant coefficient of variation was assumed. Taking the percentages in Table 4.32 as mean estimates, the variance of storm damage within each storm scenario is attained. The equation for the coefficient of variation is shown in Equation (4.5).

$$Coefficient\ of\ Variation = C_v = \frac{\sigma}{\mu} = 0.1 \qquad (4\text{-}5)$$

The selection of 0.1 as the coefficient of variation constant was chosen in order to make the damage intervals as wide as possible with minimal overlap between storm scenarios. The intervals were determined by having the lower and upper bounds two standard deviation away from the mean. Table 4.38 contains the means and upper and lower bounds for each scenario by the four Community Profile pillars of the study (as a revised version of Table 4.32).

Table 4.38: Lower bound, mean, and upper bound of percent estimated damages relative to the Storm Scenario VI baseline (100%) as per Table 4.32

Scenario	Limit	Environmental	Economic	Social	Cultural
I	Low	6.77%	8.18%	6.63%	7.95%
	Mean	8.46%	10.23%	8.29%	9.94%
	High	10.15%	12.28%	9.95%	11.93%
II	Low	13.17%	13.80%	12.47%	14.16%
	Mean	16.46%	17.25%	15.59%	17.70%
	High	19.75%	20.70%	18.71%	21.24%
III	Low	28.72%	29.90%	26.98%	29.82%
	Mean	35.90%	37.38%	33.73%	37.27%
	High	43.08%	44.86%	40.48%	44.72%
IV	Low	41.46%	42.94%	41.50%	41.74%
	Mean	51.82%	53.68%	51.88%	52.17%
	High	62.18%	64.42%	62.26%	62.60%
V	Low	54.48%	55.41%	60.75%	54.66%
	Mean	68.10%	69.26%	75.94%	68.32%
	High	81.72%	83.11%	91.13%	81.98%
VI	Low	80.00%	80.00%	80.00%	80.00%
	Mean	100.00%	100.00%	100.00%	100.00%
	High	120.00%	120.00%	120.00%	120.00%

Applying this technique to the baseline estimated damages case ('No Name 2000' storm), the upper and lower bounds and means of the estimated monetary damages for all storm scenarios can be seen in Table 4.39 (comparable to Table 4.34).

Table 4.39: Lower bound, mean, and upper bound of estimated damages

Scenario	Limit	Environmental	Economic	Social	Cultural	Total
I	Low	$1,101,196	$917,727	$64,052	$102,710	$2,185,686
	Mean	$1,376,495	$1,147,159	$80,065	$128,388	$2,732,108
	High	$1,651,794	$1,376,591	$96,078	$154,066	$3,278,530
II	Low	$2,024,581	$1,687,151	$55,381	$188,692	$3,955,805
	Mean	$2,530,726	$2,108,938	$69,227	$235,865	$4,944,756
	High	$3,036,871	$2,530,726	$83,072	$283,038	$5,933,707
III	Low	$4,413,952	$3,678,293	$120,741	$411,382	$8,624,368
	Mean	$5,517,440	$4,597,866	$150,926	$514,228	$10,780,461
	High	$6,620,928	$5,517,440	$181,112	$617,074	$12,936,553
IV	Low	$6,371,583	$5,309,653	$174,291	$593,835	$12,449,362
	Mean	$7,964,479	$6,637,066	$217,864	$742,293	$15,561,702
	High	$9,557,375	$7,964,479	$261,437	$890,752	$18,674,043
V	Low	$8,311,228	$6,926,023	$227,349	$774,610	$16,239,210
	Mean	$10,389,035	$8,657,529	$284,186	$968,263	$20,299,013
	High	$12,466,842	$10,389,035	$341,023	$1,161,915	$24,358,815
VI	Low	$12,121,424	$10,101,187	$331,575	$1,129,722	$23,683,909
	Mean	$15,151,780	$12,626,483	$414,468	$1,412,153	$29,604,885
	High	$18,182,136	$ 15,151,779	$ 497,361	$ 1,694,583	$ 35,525,862

4.6 GIS Storm Simulation Model with Damages Report

In Section 3.1.2, a GIS model constructed using Visual Basic for Applications was discussed. The application had a digital elevation model, a 'vulnerability layer' (see Section 3.1.2 for more information) and a user-defined sea-level rise as inputs. From these, it would output a semi-transparent coloured layer over the flooded zones and return a message box stating which items of the vulnerability layer had been captured within the flood line area.

With respect to estimating categorized damages in this thesis, a GIS model has been created to estimate the actual damages caused by the different storm scenarios detailed in Section 4.2. The graphical user interface (GUI) of the model can be seen in Figure 4.31.

The first input is a combobox input for the 'Digital Elevation Layer'. By pressing the arrow, the user gets a list of all of the layers currently in their GIS environment, e.g., churches, museums, digital elevation model, satellite image. The user selects their digital elevation layer (named DEM for digital elevation model in Figure 4.3.1).

The next section in the GUI is 'Model Components', where the indicators are broken down by the four pillars of the study: environmental, economic, social and cultural. There is a combobox (which works the same as the digital elevation combobox) to input a layer for each of the community profile pillars. Each of the layers contains all the indicators (points, lines or polygons) for its respective Community Profile pillar.

Below the Model Components area are the Storm Scenarios. Here, the user can see the particulars of each storm scenario in the Details section, and can then select one of the storm scenarios using the option buttons on the left.

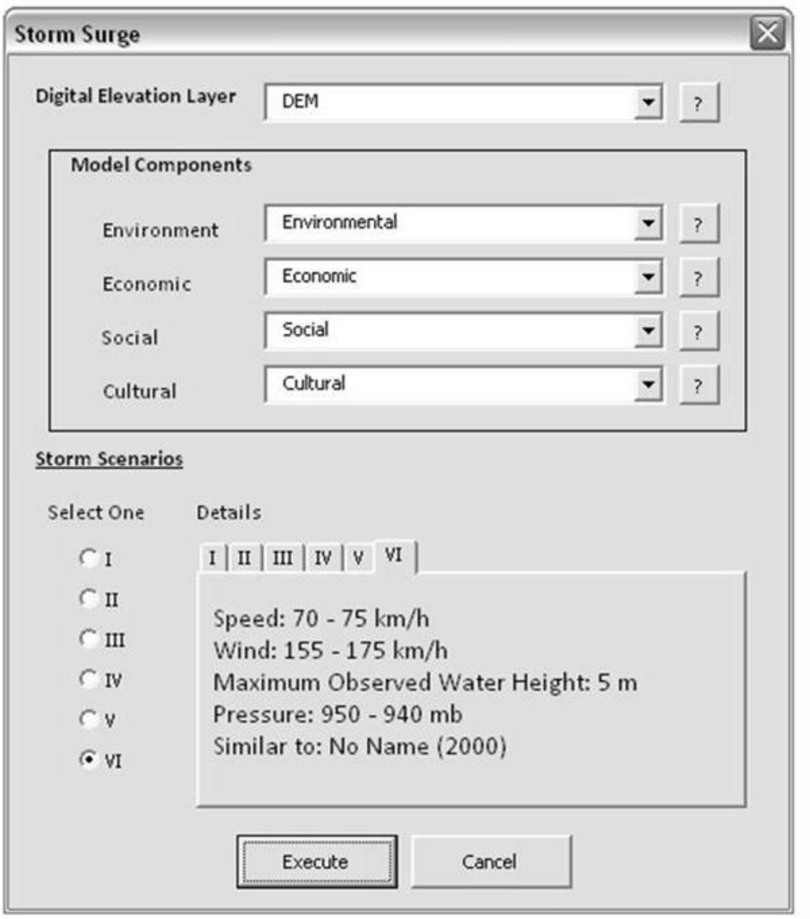

Figure 4.31: GUI for GIS storm surge simulation application in ArcGIS

Similar to the model detailed in Section 3.1.2, this model also makes flood layers (height depends on the storm scenario selected) and determines what features (points, lines or polygons) have been affected. The model first makes a baseline flood layer using Storm Scenario VI (5 meters). It determines how many features from the four input layers (one for each of environmental, economic, social and cultural) have been affected by the flooding. Then it repeats the process for whichever storm scenario has been selected. From this, a ratio for each of the four components is found. The ratio, denoted R_D, for each of the environmental, economic, social and cultural components is shown in Equation (4-6).

$$R_D = \frac{\#\,of\ \ affected\ \ features\ \ in\ selected\ \ scenario}{\#\,of\ \ affected\ \ features\ \ in\ baseline\ \ scenario} \tag{4-6}$$

These four ratios are then converted to sets of damage intervals using the same process as in Section 4.5.2 in order to add variability. As for Section 4.5.2, the sizes of the intervals grow with the severity of the storm using a coefficient of variation of 0.1.

Since each storm scenario is described physically by a range of speed, wind and pressure intervals, random numbers are generated to depict where in the Storm Scenario interval range each of the storm input drivers will fall. A random number, between 0 and 1, is generated for each of the three input characteristics of the storm. These three random numbers, weighted equally, make up a fourth scaled random number (between 0 and 1) representing the overall storm intensity within the selected storm scenario.

Using the monetary damage estimations made for a baseline Scenario VI storm, the ratio intervals and the storm intensity, damage estimates for each of the four components are found. Equation (4-7) shows the overall general equation for the damage estimates.

$$Damage\ Estimate = (Baseline\ Damage\ Estimate) * [L_D + (U_D - L_D) * S_I] \quad (4\text{-}7)$$

C_V represents the coefficient of variation ($C_V = 0.1$); L_D represents the lower ratio damage interval ($L_D = R_D - 2 * C_V * R_D$) and U_D represent the upper ratio damage interval ($U_D = R_D + 2 * C_V * R_D$); S_I represents the randomly generated storm intensity ($S_I = \frac{r_S + r_W + r_P}{3}$); and r_S, r_W, r_P represent the random number generated for the speed, wind and pressure respectively.

Once the user has made the necessary selections of input layers, selected a Storm

Scenario to simulate, and pressed 'Execute', a message box appears (Figure 4.32) that details the randomized attributes of the storm (speed, wind, and pressure) for the selected Storm Scenario and the calculated environmental, economic, social, cultural and total monetary damages caused by the storm surge. Once 'Ok' is pressed in the message box, the four pillar storm damage estimates are written to an Excel file and then the program closes. A sample output message box for a simulated Storm Scenario IV storm is provided in Figure 4.32.

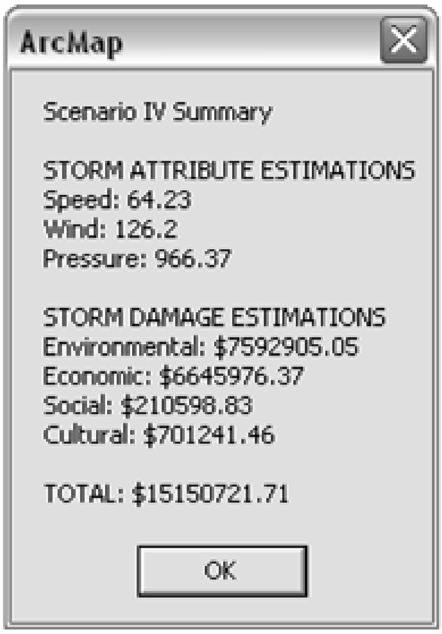

Figure 4.32: Message Box with results of storm surge GIS simulation

4.7 System Dynamics

The damage values in Table 4.34 and the methodology used to determine them show estimated total damages for Charlottetown. The total damage estimates account for the direct damages and the indirect damages. Direct damages occur immediately during the storm (e.g., floods, blown off roofs, washed out roads) while indirect damages are a consequence of the direct damages (e.g., necessary emergency repair work, emergency services, water damage from flooding). Total direct and indirect damage amounts were determined for each Community Profile pillar. These total damage estimates are all-inclusive; therefore, the damage values do take into account interaction between the indicators. In order to look at these storm scenarios and their damages from a system dynamics perspective, the interactions and feedbacks between them must be examined.

4.7.1 Model Considerations: Ideal versus Actual

It is noted that a full treatment of this problem as a systems dynamics model would require many more indicators and much more data. The ideal SD model framework would require (i) the specification of the interactions over a specified time frame which would be dependent on the Storm Scenario (longer time impacts with more severe storms); and (ii) the functional forms for all the interactions and parameters on the indirect effects. Unfortunately, the time impacts are not directly determinable from empirical data and would need to be estimated for Charlottetown. Also, the functional damage interactions are not directly knowable and may not be observable without careful scrutiny from future storm incidences (which would need an empirical system to be defined based on the Community Profile dimensions).

In the interim, for the purposes of this thesis and based on the need to provide estimates for preparedness, limited indicators and data are used to present a simple net present value time estimate for all indirect costs based on logical interactions as provided. The modelling exercise presented in this section illustrates interactions among the indicators that are hypothesized and will need to be discussed with Charlottetown City Planners interested in these issues as a further step in the C-Change project. The models conception was created in accordance with the precautionary approach (adopted by the Government of Canada (Canada Privy Council Office 2003)) and recognizes the need for planning and preparedness even if data are not readily available. This model is the first of its kind for the City of Charlottetown and is intended to raise discussion on future work and for the use of policy implications.

4.7.2 Model Description

Direct interactions between systems elements can still be fairly obvious without detailing the extent of the links and feedback. For example, take two indicators from each of the four pillars of this study (e.g., indicators are 'Level 1 Categories' from the C-Change Community Profile, Appendix A) and examine the interactions between them. For the Charlottetown model illustrated here, the interactions of two indicators from each of the four community profile pillars of the study are examined as illustrated in Figure 4.33 as an exercise which allows the interactions of the system to be explored and which will raise discussion and force further questions on what work needs to be done and how future storm damages need to be reported so that the community of Charlottetown can be as prepared as possible for future storm activity.

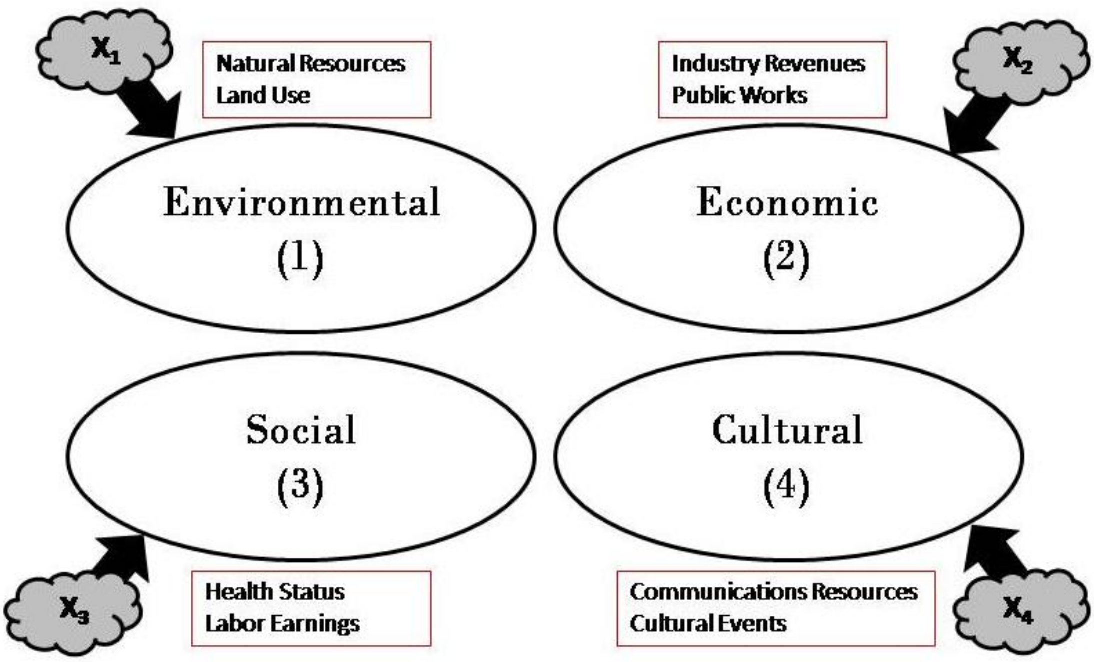

Figure 4.33: Four community profile pillars with two indicators each and Xi's as direct impacts

The indicators from the environmental pillar are: natural resources and land use. The indicators from the economic pillar are: industry revenues and public works. The indicators from the social pillar are: health status and labor earnings. And the indicators from the cultural pillar are: communications resources and cultural events. The four major components and their respective indicator pairs are shown in Figure 4.33 without any interactions among them.

All pillars of this systems dynamics Community Profile model will be directly impacted from a storm surge scenario. These are depicted by the grey clouds in Figure 4.33. The direct impacts of the storm on the environmental, economic, social and cultural components are represented by the storm impact direct affect variables: X_1, X_2, X_3, and X_4, respectively. Given the X_i's, there are also interactions between the pillars that realize indirect damage, e.g., the closure of roads and access links due to the storm prevent labour earners (in the social pillar - direct effect) to participate in economic activity (economic pillar) causing an indirect damage to the output of the community economics dimension.

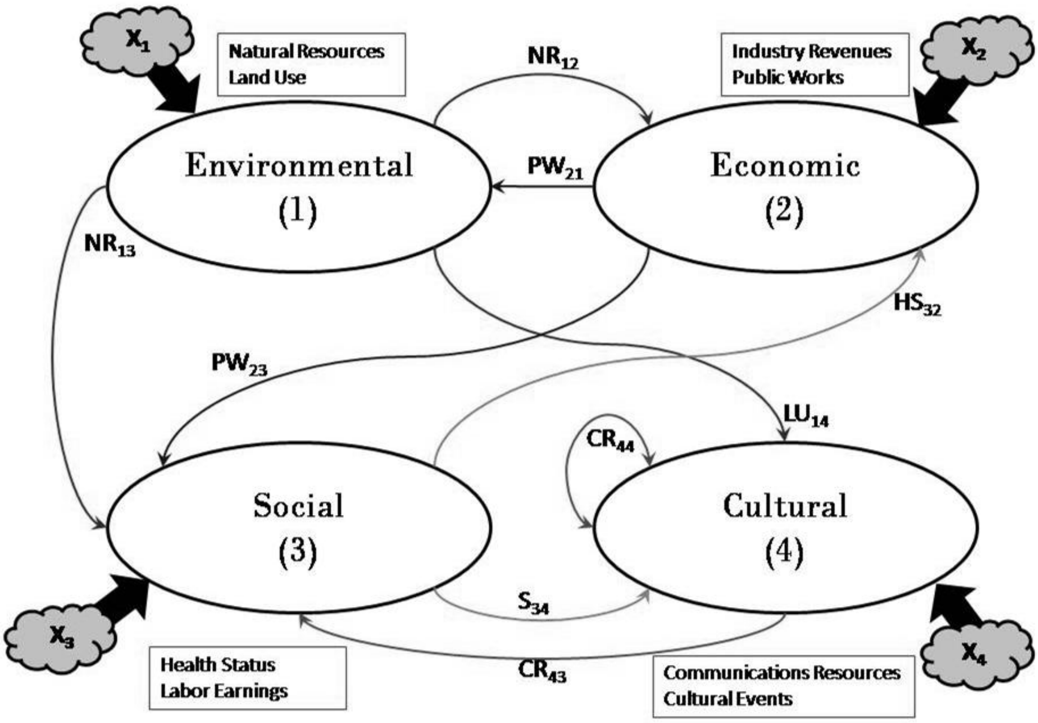

Figure 4.34: Interactions between all four pillars of the study

The connections detailed in this example, depicted with arrows in Figure 4.34 above, illustrate some of the storm related interactions that exist between these Community Profile pillar indicators in modelling direct and indirect damages. The system is illustrated by the Community Profile model; however there are no empirical data or evidence to describe the system more realistically. Thus to gain understanding of the system through the modelling exercise, it must be modelled abstractly, without a time component, based on logical deductions about the extent of systems components linkages and feedback. A brief description of each link's effect on each component in the systems diagram of Figure 4.33 is given below.

- **NR_{12}:** a direct impact on natural resources will negatively affect industry revenues as material supplies prices will rise and availability will fall, e.g., immediate effect on tourism.
- **NR_{13}:** a direct impact on natural resources will negatively affect the health status of the population, e.g., potable water could be contaminated.
- **LU_{14}:** a direct impact on land use affects parks, open spaces, beaches, scenic, historical, and cultural areas; this would affect the Cultural pillar, tourism events may be cancelled due to the storm.
- **PW_{21}:** a direct impact on public works affects the solid waste management systems, municipal wastewater systems, and storm water collection and disposal systems; if these overflowed or leaked, natural resources would be negatively affected as a result.
- **PW_{23}:** a direct impact on public works could mean that hospitals are affected and then the health status of the population could drop due to the lack of medical care. Also, if industry revenues are affected, in turn the population's labor earnings will be negatively influenced as the industry will not be able to continue to pay the same amount for labor, or employ as many people.
- **HS_{32}:** a direct impact on health status could overflow the hospitals (public works).
- **S_{34}:** a direct impact on the social component means that health status and labor earnings are affected, and if that is the case, cultural events will not be

well attended or potentially fully staffed.

- **CR_{43}:** a direct impact on communications resources could mean that people whose health status has been affected may not be able to communicate to get help.
- **CR_{44}:** a direct impact on communications resources affects cultural events as information pertinent to the event may not be able to be spread.

The illustration above attempts to describe interrelated links between the characteristics of the community as impacted by coastal storms. In order to attain a full grasp of storm damage and impacts on the community profile pillars, the interconnections, interactions and dynamics of the indicators must be examined further and accounted for through continued analysis and identification of affects on monitored indicators. Table 4.40 below more fully describes the links and their parameters developed for the illustrative case of Charlottetown described above.

4.7.2 The Links

Each of the arrows in Figure 4.34 are links or connections between Community Profile indicators. These links are realized as equations in the systems dynamics modelling exercise. Total damage for each community profile pillar is the result of direct damages on the Community Profile pillar plus the indirect damages coming from other Community Profile pillars links. The indirect damages are modelled as a percentage of the impending pillar's total damage. Using the example described above, four equations, one per pillar, for the total damages are presented in Equations (4-8) to (4-11) below including recognition of linkages illustrated in Figure 4.34.

$$D_{Environmental} = X_1 + PW_{2,1} * X_2 \tag{4-8}$$

$$D_{Economic} = X_2 + NR_{1,2} * X_1 + HS_{3,2} * X_3 \tag{4-9}$$

$$D_{Social} = X_3 + NR_{1,3} * X_1 + PW_{2,3} * X_2 + CR_{4,3} * X_4 \quad (4\text{-}10)$$

$$D_{Cultural} = X_4 + LU_{1,4} * X_1 + S_{3,4} * X_3 + CR_{4,4} * X_4 \quad (4\text{-}11)$$

where $D_{Environmental}$, $D_{Economic}$, D_{Social}, and $D_{Cultural}$ are the total estimate damages, the X_i's are the direct damages on each component and the indirect damages $Y_{a,b}$'s are denoted by the indicator constants multipliers *PW, NR, CR, S, LU,* and *HS* on the X_i's as the system interaction links.

This SD model is presented as a linear illustration of the direct-indirect damages from storm surge affects on Charlottetown. The model is used further to link to the GIS storm simulation model to capture the spatial effects of a storm surge on Charlottetown.

4.7.3 Direct Damages

Since the damage estimates determined in the GIS model are total damage estimates, the dynamics of the system can be used to find what the direct damages on each component are by re-arranging the system of equations above.

Following the description of the system (Section 4.7.1), estimates for the parameters of the links can be made. While there are no empirical data estimates of community storm damage to rely on, fuzzy logic was used first to conclude the size of the effects of the links (Sugeno and Yasukawa 1993). If a link will have a major impact on the total damage of the component then it would be considered 'large', if it will have a minor impact then 'small' and if it had an impact between the two then it would be considered 'medium'. The fuzzy logic estimations refer to the effect on the total damage, not necessarily to the size of the parameter value. Total damages for each component vary greatly. It is therefore assumed that the direct impacts will as well. Therefore, a 'large' effect on one component may result in a seemingly small parameter value due to the magnitude of the direct damages involved.

These estimations of the proportions are not meant to be predictions or collectively exhaustive measures, but are merely presented to illustrate the actual process that links independent impacts to overall damages. Both the parameter value estimations and the fuzzy logic size estimations, which both follow the description of the system, are found in Table 4.40.

Table 4.40: Estimations for SD model parameters

Links	From Pillar	To Pillar	Summary Description	Impact Factor Size	Parameter Value
NR_{12}	Env	Eco	Natural resources affects industry revenues	M	0.1
NR_{13}	Env	Soc	Natural resources affects health status	S	0.001
LU_{14}	Env	Cult	Land use affects cultural events	M	0.01
PW_{21}	Eco	Env	Public works affects natural resources	M	0.1
PW_{23}	Eco	Soc	Industry revenues affects labour earnings	L	0.01
HS_{32}	Soc	Eco	Health status affects public works (hospitals)	S	1.00
S_{34}	Soc	Cult	Labour earnings and health status affect cultural events	M	0.75
CR_{43}	Cult	Soc	Communications resources affects health status	M	0.04
CR_{44}	Cult	Cult	Communications resources affects cultural events	S	0.11

Coupling these estimations with the system of equations above, the equations for the storm damages on each of the four community profile pillars are provided in Equations (4-12) to (4-15).

$$D_{Environmental} = X_1 + 0.1 * X_2 \quad (4\text{-}12)$$

$$D_{Economic} = X_2 + 0.1 * X_1 + 1 * X_3 \quad (4\text{-}13)$$

$$D_{Social} = X_3 + 0.001 * X_1 + 0.01 * X_2 + 0.04 * X_4 \quad (4\text{-}14)$$

$$D_{Cultural} = X_4 + 0.01 * X_1 + 0.75 * X_3 + 0.11 * X_4 \quad (4\text{-}15)$$

These completed linkage equations define the systems dynamics model for the determination of direct (immediate) and indirect (semi-immediate) storm impacts. These inputs provide the basis for developing the systems dynamics model described in further detail below.

4.7.4 Direct Damages in STELLA

The system described in this section is modelled in the STELLA systems modelling environment (iSee Systems 2009). The direct damages (X_i's) and total damages (D_i's) are represented as "stocks" and the linking parameters (column 6 of Table 4.40 above) as "converters". The illustrative SD model is limited as the links are not specified over a time period, but by presenting a systems view of indirect and direct damages of a storm the model described below takes the first step in addressing this complex problem in this fashion and compels further discussion and research in this area. A screenshot of the STELLA illustrative model for Charlottetown storm damage estimation is shown in Figure 4.35.

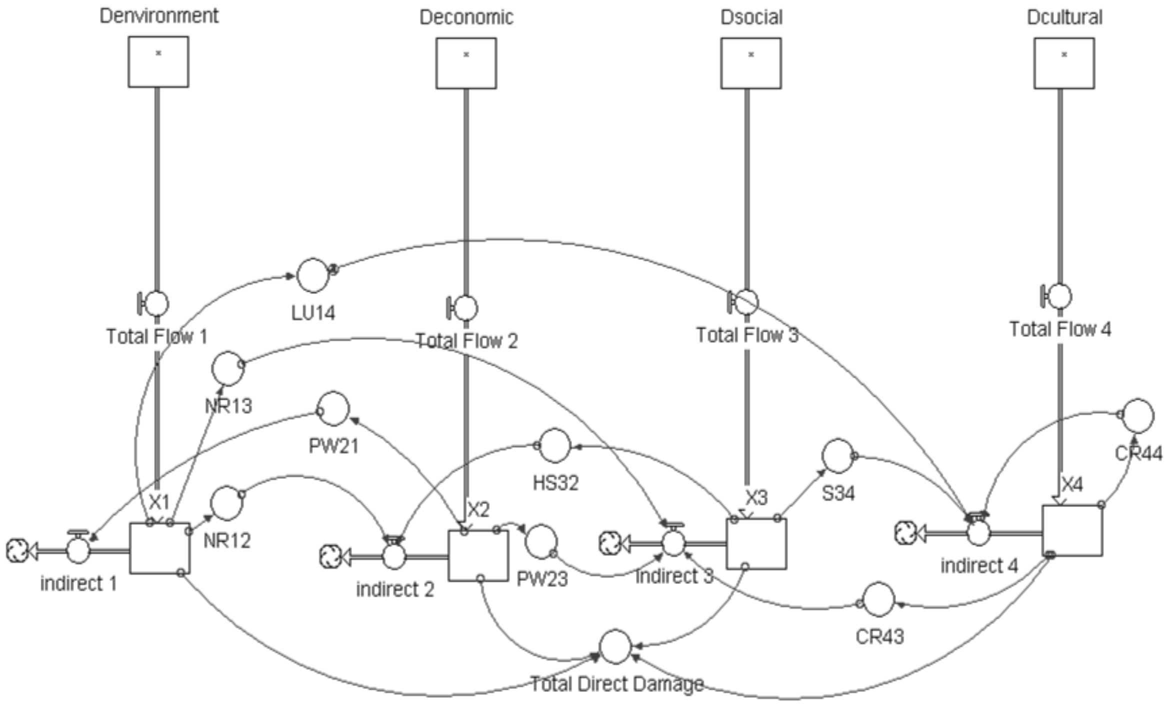

Figure 4.35: Screenshot of direct damages STELLA model

Figure 4.35 depicts the STELLA model used to determine the estimated actual direct damages. The stocks (boxes) at the top of the figure are the total damages (which are imported from the GIS simulation). Comparing this figure with Figure 4.34, the stocks at the base of Figure 4.35 are the direct damages which are represented by grey clouds in Figure 4.34. In both figures, the links are represented with arrows (in the case of Figure 4.35, there are converters, circles, in the center of the arrows to apply the calculations). The total damage stocks (D_i's) flow into the direct damage stocks (X_i's) and the indirect damages flow out (indirect i's), leaving only the direct damage totals for each Community Profile pillar.

4.7.5 Total Damages in STELLA

In this study, the total damages are estimated from the GIS storm simulation model described in Section 4.6. Direct storm damages are found through the SD model. As such, the original purpose of this research is to model the connections so that the total damages could be found from the direct ones. The same assumptions that are used to develop the model above can be used to examine a model that takes in the direct damages as inputs and finds the total damage estimate. Thus, for the purpose of modelling estimates of the community profile damages from storm, the direct impacts from storms are received as inputs to the storm system that determines estimated total damage due to direct and indirect storm damage. Using the same description of the system, the same links and the same assumptions, a model that is the reverse of the model in Section 4.7.4 can be seen in Figure 4.36.

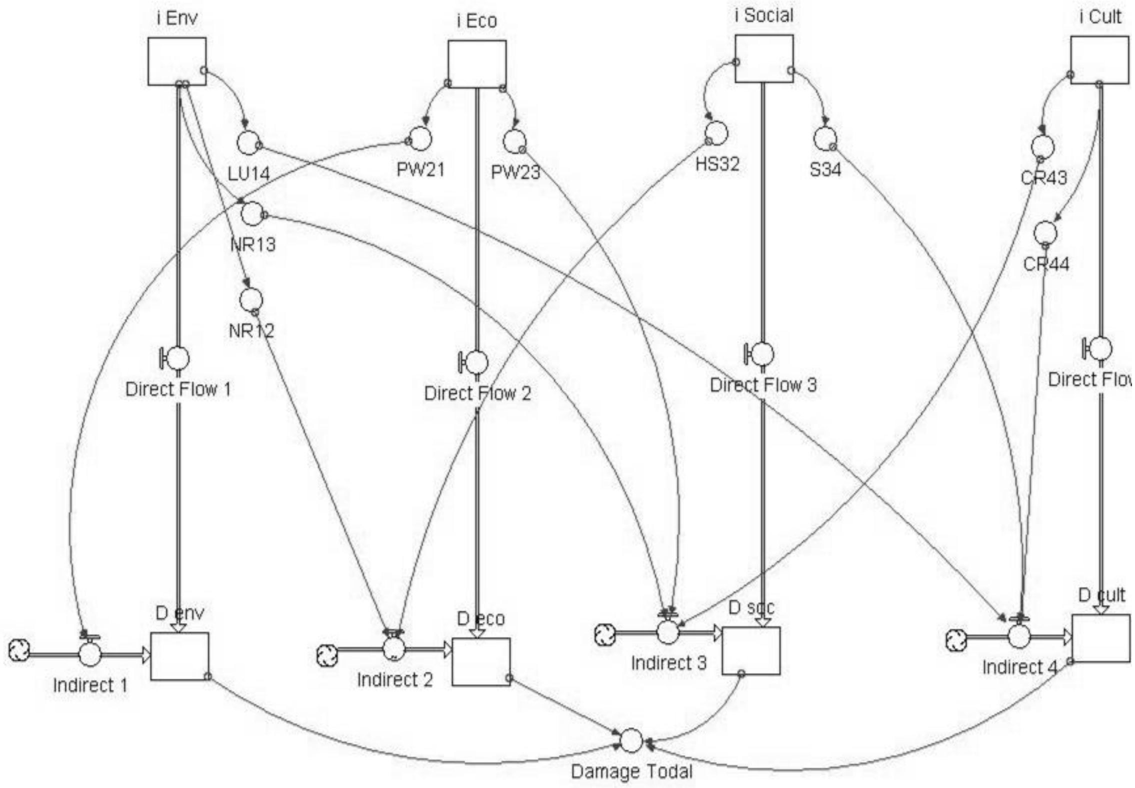

Figure 4.36: Total damages STELLA model

The STELLA model in Figure 4.36 receives the direct damages as inputs from the GIS storm simulation model in the top SD four stocks (I Env, I Eco, I Social and I Cult) corresponding to the community profiles. The direct damages flow fully into the four bottom SD stocks (D env, D eco, D soc, and D cult) which denote the total estimated storm damages. The converters take multiplicative proportions (defined in Section

4.7.3) of the direct damages and adjust the total damages. Lastly, the four component total damages are summed in the Damage Total converter.

4.8 Summary

This section has derived the GIS storm simulation model based on limited historical data and provided estimates of storm damage reports by Community Profile pillars for Charlottetown. The SD model associates direct storm impacts with interrelated damages and indirect storm impacts to the Community Profile.

The following chapter provides results for the Charlottetown storm scenario damage estimates via the linked SD and GIS storm simulation model components to arrive at a more detailed description of the expected storm impacts across all pillars of the Community Profile than is currently available. These results provide a comprehensive storm damage estimation system that is expected to be used to identify Charlottetown storm vulnerability and to instigate discussion of strategies for (i) adapting to pending damages from more frequent storms; and (ii) how to aptly report storm damages so that future policy planning can be more informed as to where damages are done.

5. Results

This chapter presents the combined process of the GIS storm simulation model, the SD model and the linking of the two models. Model linking is carried out through Microsoft Excel and is presented in detailed steps and model process flow chart (Figure 5.1). Sample trials of the combined simulation model for estimating storm damage for Charlottetown are summarized in Table 5.1 (Storm Scenario II), Table 5.2 (Storm Scenario IV) and Table 5.3 (Storm Scenario VI). Simulation statistics are described and presented in this chapter in the form of bar charts and boxplots.

The GIS model described in Section 4.6 and the STELLA model described in Section 4.7 are linked through the medium of the Microsoft Excel spreadsheet system. The GIS storm simulation model output from ArcGIS is written to Excel and the STELLA SD model is connected to an Excel table via a persistent import link in order to run a full simulation of the storm simulation and damage estimation system. The GIS-SD storm simulation model has overlapping ArcGIS layers (representing the Community Profile pillars and the Digital Elevation model (DEM)) and a user-selected pre-defined storm scenario as inputs via a GUI front end. The storm simulation model outputs total, direct and indirect estimated damages for Charlottetown by the four Community Profile pillars: environmental, economic, social, and cultural.

5.1 Model Process

The GIS-SD storm simulation model is presented in a ten step process beginning with user input to the GIS model and concluding with output damage estimations for Charlottetown. A flow diagram of the process is provided in Figure 5.1. The steps of the process are as follows:

1. User chooses the ArcGIS layers for the DEM, and the Community Pillars

(environmental, economic, social and cultural layers) in the GIS GUI (see Figure 4.31 for a screenshot of the GUI).

2. User selects a Storm Scenario I to VI to be applied to the map, and presses 'Execute'.
3. The number of affected features for a baseline storm (Scenario VI: 5 meter maximum observed water level) is found for each Community Profile pillar (environmental, economic, social and cultural), e.g., features include the number of churches and museums for the cultural pillar.
4. The number of affected features for the user chosen Storm Scenario I through VI) is found for each Community Profile pillar.
5. Determine the 'at risk' damage interval percentages for the ratio $\frac{\#\ of\ affected\ \ features\ \ in\ selected\ \ storm}{\#\ of\ \ affected\ \ features\ \ in\ baseline}$ (R_D) for each Community Profile pillar using a coefficient of variation (C_V) of 0.1, where the lower interval (L_D) and upper interval (U_D) are:
   i. $L_D = R_D - 2 * C_V * R_D$
   ii. $U_D = R_D + 2 * C_V * R_D$
6. Generate random numbers from a Uniform (0,1) distribution representing within Storm Scenario intensity for storm inputs: Speed(r_S), Wind(r_W), and Pressure(r_P). These three numbers are equally weighted to form the Storm Scenario Intensity factor, S_I ($S_I = \frac{r_S + r_W + r_P}{3}$).
7. Calculate the estimated damages for each Community Profile pillar using the damage estimations based on historical information (see Table 4.34) for the baseline Storm Scenario VI storm:
   i. $Damage\ Estimation = (Baseline\ Estimation) * [L_D +$
   $RD{-}LD{*}SI$
8. Export estimated damages for the environmental, economic, social and cultural components, as well as the total estimated damage, to the linked Microsoft Excel file.

9. Update the SD model in STELLA automatically from the Excel file.
10. Execute the SD model to obtain the total and direct damages for each of the components, as well as the total estimated damages (see Sections 4.74 and 4.7.5 for the two different SD models).

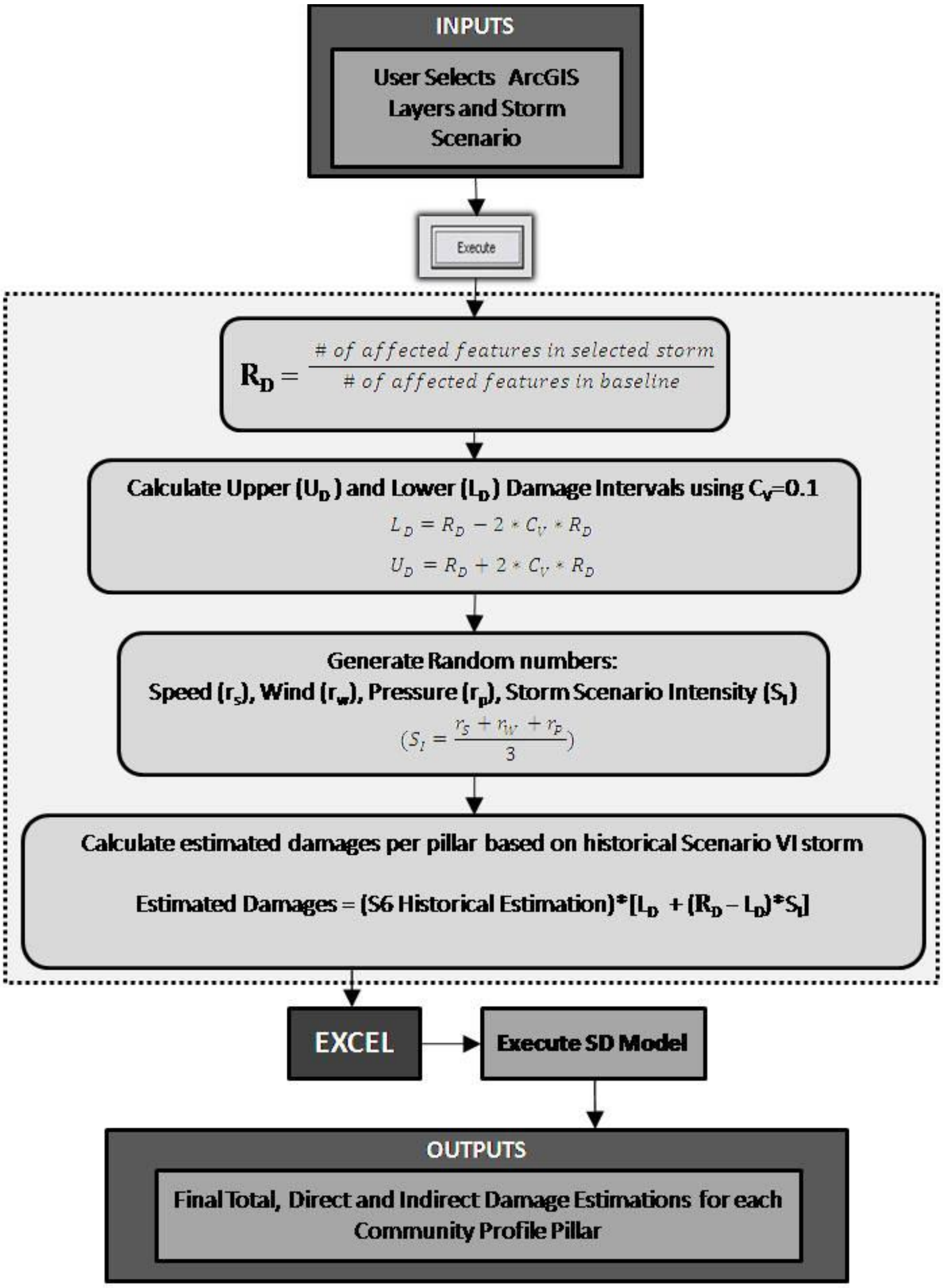

Figure 5.1: Flow chart of GIS-SD Storm Simulation Model

The flow chart of the GIS-SD storm simulation model is provided in Figure 5.1. The outlined boxes contain the inputs and outputs of the model and the dotted grey area represents the automated calculations done in ArcGIS via the Visual Basic for Applications (VBA) program in Microsoft Excel. A list of GIS layers and their sources used in the simulations in this research are provided in Appendix B and the VBA code used to run the ArcGIS model is provided in Appendix E. In order to run the model, ESRI's ArcMap, iSee Systems STELLA, and Microsoft Excel are required along with sufficient memory (3 gigabytes of RAM or more recommended) to run the three programs simultaneously.

5.3 Summary of Trials

This section presents a summary of the ten trials of the GIS-SD storm simulation model run for Storm Scenarios II, IV and VI and presented in the thesis as an illustration of the use of the model. The details from the trials provided from the model in this section are: Storm Scenario input (speed, wind, and pressure) and the estimated damages (total damage, total direct damage and total indirect damage). All other aspects of the trial runs for the thesis are provided in Appendix G.

Using the best available digital elevation data, only integer flood layers are applied to the Charlottetown map. Thus, only Storm Scenarios II, IV and VI (with flood levels of 3 meters, 4 meters and 5 meters respectively) simulations are run. Ten trials were run for each of these selected Storm Scenarios. The total estimated damages, total direct estimated damages, and total indirect estimated damages, speed, wind, and pressure for each trial of each Storm Scenario are displayed in Table 5.1 (Storm Scenario II), Table 5.2 (Storm Scenario IV) and Table 5.3 (Storm Scenario VI). The full listings of all trials for Storm Scenarios II, IV and VI by Community Profile pillar (total direct and indirect environmental, economic, social, and cultural estimated damage reports) are found in Appendix G – "GIS-SD Storm Simulation Model Results and Descriptive Statistics".

Table 5.1: Storm Scenario II summary of simulation results

	Storm Scenario Input			Estimated Damage Output		
Trial	**Speed (km/h)**	**Wind (km/h)**	**Pressure (mb)**	**Total Direct Damage**	**Total Indirect Damage**	**Total Damage**
1	54	86	986	\$3,579,812	\$678,627	\$4,258,440
2	52	81	989	\$3,372,748	\$639,374	\$4,012,122
3	50	91	989	\$3,474,843	\$658,728	\$4,133,571
4	54	76	985	\$3,282,170	\$622,203	\$3,904,373
5	55	92	984	\$3,675,115	\$696,694	\$4,371,809
6	56	93	981	\$3,612,388	\$684,803	\$4,297,190
7	56	83	986	\$3,588,949	\$680,359	\$4,269,308
8	55	76	987	\$3,394,187	\$643,438	\$4,037,625
9	53	81	987	\$3,383,421	\$641,397	\$4,024,819
10	54	81	983	\$3,292,487	\$624,159	\$3,916,646

The mean expected estimated total damage calculated in Section 4.5.1.1 (based on the 'No Name 2000' historical storm baseline) for a Storm Scenario II storm is \$4.96 million. From Table 5.1, the range of the Storm Scenario II total estimated damages from the trials of the GIS-SD storm simulation model is from \$3.9 million (with Storm Scenario II inputs of 54 km/h, 76 km/h and 985 mb for speed, wind and pressure respectively) to \$4.4 million (with Storm Scenario II inputs of 55 km/h, 92 km/h and 984 mb for speed, wind and pressure respectively).

Table 5.2: Storm Scenario IV summary of simulation results

	Storm Scenario Input			Estimated Damage Output		
Trial	**Speed (km/h)**	**Wind (km/h)**	**Pressure (mb)**	**Total Direct Damage**	**Total Indirect Damage**	**Total Damage**
1	65	132	966	$13,349,171	$2,544,884	$15,894,055
2	66	134	963	$13,150,345	$2,519,807	$15,670,152
3	64	136	963	$12,823,666	$2,444,703	$15,268,369
4	63	117	971	$12,371,234	$2,358,450	$14,729,684
5	64	115	966	$11,767,876	$2,243,426	$14,011,302
6	61	117	969	$11,338,581	$2,161,585	$13,500,166
7	62	116	963	$10,729,616	$2,045,492	$12,775,108
8	62	112	970	$12,358,109	$2,355,948	$14,714,057
9	66	123	963	$12,403,339	$2,364,571	$14,767,910
10	61	118	967	$11,286,586	$2,151,673	$13,438,258

The expected estimated total damage calculated in Section 4.5.1.1 (based on the 'No Name 2000' historical storm baseline) for a Scenario IV storm is $15.5 million. From Table 5.2, the range of the Storm Scenario IV total estimated damages from the trials of the GIS-SD storm simulation model is from a maximum estimate of $15.9 million (with Storm Scenario inputs of 65 km/h, 132 km/h and 966 mb for speed, wind and pressure respectively) to a minimum of $12.8 million (with Storm Scenario IV inputs of 62 km/h, 116 km/h and 963 mb for speed, wind and pressure respectively).

Table 5.3: Storm Scenario VI summary of simulation results

	Storm Scenario Input			Estimated Damage Output		
Trial	Speed (km/h)	Wind (km/h)	Pressure (mb)	Total Direct Damage	Total Indirect Damage	Total Damage
1	72	164	948	$24,972,833	$4,772,461	$29,745,294
2	72	168	942	$23,751,214	$4,539,002	$28,290,217
3	71	167	941	$22,701,145	$4,338,328	$27,039,473
4	73	174	943	$25,269,432	$4,829,143	$30,098,575
5	75	163	943	$24,701,779	$4,720,661	$29,422,440
6	76	168	947	$27,104,364	$5,179,810	$32,284,173
7	73	157	946	$23,487,832	$4,488,668	$27,976,500
8	74	174	949	$27,980,115	$5,347,171	$33,327,286
9	70	166	950	$24,795,810	$4,738,631	$29,534,441
10	73	169	946	$25,221,688	$4,820,019	$30,041,707

The expected estimated total damage calculated in Section 4.5.1.1 (based on the 'No Name 2000' historical storm baseline categorized as Storm Scenario VI) for a Scenario VI storm is $29.6 million. From Table 5.3, the range of the Storm Scenario VI total estimated damages from the trials of the GIS-SD storm simulation model is from a low of $27 million (with Storm Scenario VI inputs of 71 km/h, 167 km/h and 941 mb for speed, wind and pressure respectively) to a high of $33.3 million (with Storm Scenario VI inputs of 74 km/h, 174 km/h and 949 mb for speed, wind and pressure respectively).

5.3 Descriptive Statistics

This section presents an analysis of the GIS-SD storm simulation model trial results as presented in Tables 5.1 through 5,3 above. Histograms and boxplots of the results are used to represent the statistics of the thirty trials (ten for each of storm Scenario

II, IV and VI) visually. The full descriptive statistics (mean, maximum, minimum, variance, standard deviation and kurtosis) of the trial results by the four Community Profile pillars are provided in Appendix G.

The storm simulation results are summarized in Section 5.2. This includes various graphical representations of the results. Figure 5.2 shows a histogram of the mean total and direct damages by scenario.

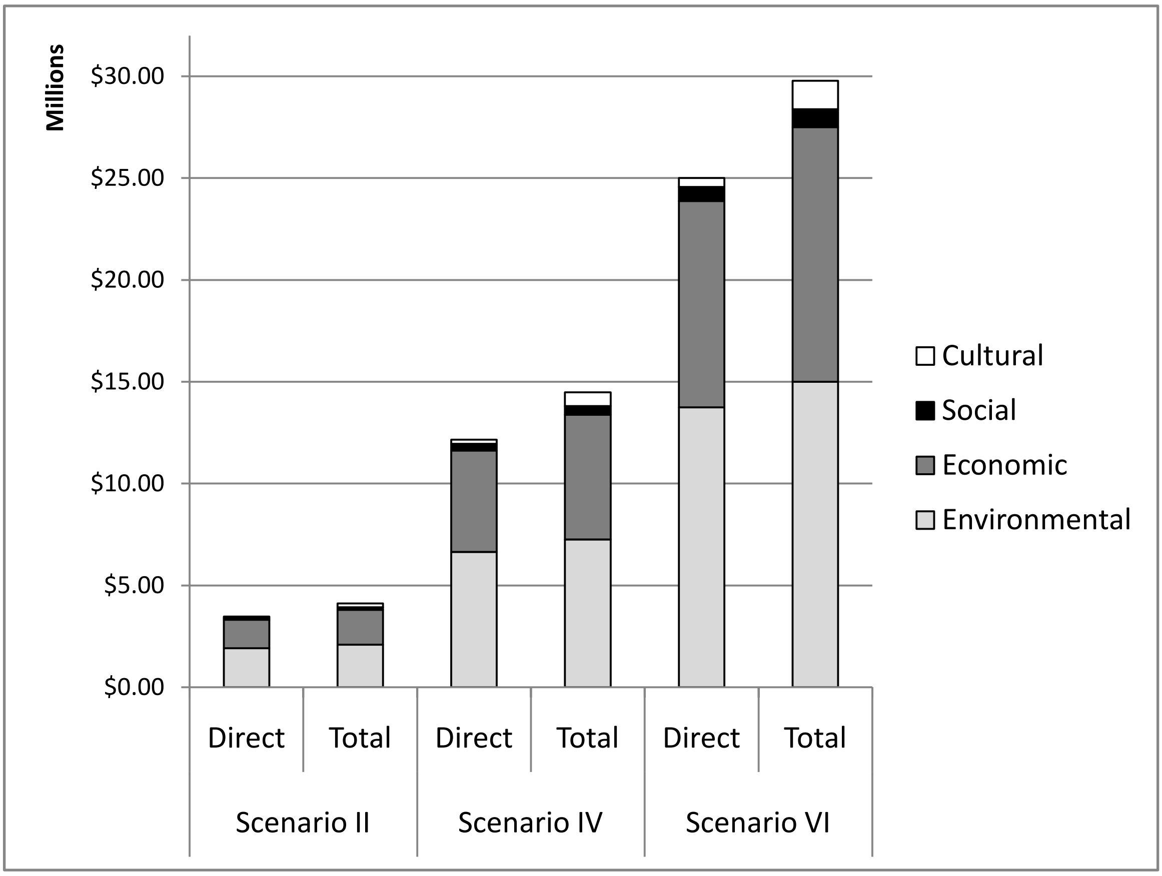

Figure 5.2: Mean direct and total estimated damages by Storm Scenario II, IV and VI and by Community Profile pillar

Storm Scenario II had mean total estimated damages estimated of $4.1 million with a standard deviation of $167 thousand. The maximum damage estimate was $4.3 million and the minimum damage estimate was $3.9 million. The mean total estimated damage values for the four Community Profile pillars (environmental, economic, social and cultural) were $2.1 million, $1.7 million, $118 thousand and $194 thousand respectively.

Storm Scenario IV had a much higher total estimated damage mean of $14.5 million with a standard deviation of $1 million over the ten trials of this Storm Scenario. The range of the data were also greater than the Storm Scenario II damage estimates with a maximum damage estimate of $15.9 million and a minimum damage estimate of $12.8 million. The total estimated mean values for the environmental, economic, social and cultural components were $7.3 million, $6.1 million, $422 thousand and $666 thousand respectively.

Lastly, Storm Scenario VI had a total estimated damage mean of $29.8 million with a standard deviation of $1.9 million over ten trials. The trials produced a maximum total estimated damage value of $33.3 million and a minimum of $27 million. For Storm Scenario VI total estimated damages, the mean values of the environmental, economic, social and cultural components were $15 million, $12.5 million, $873 thousand, and $1.4 million respectively.

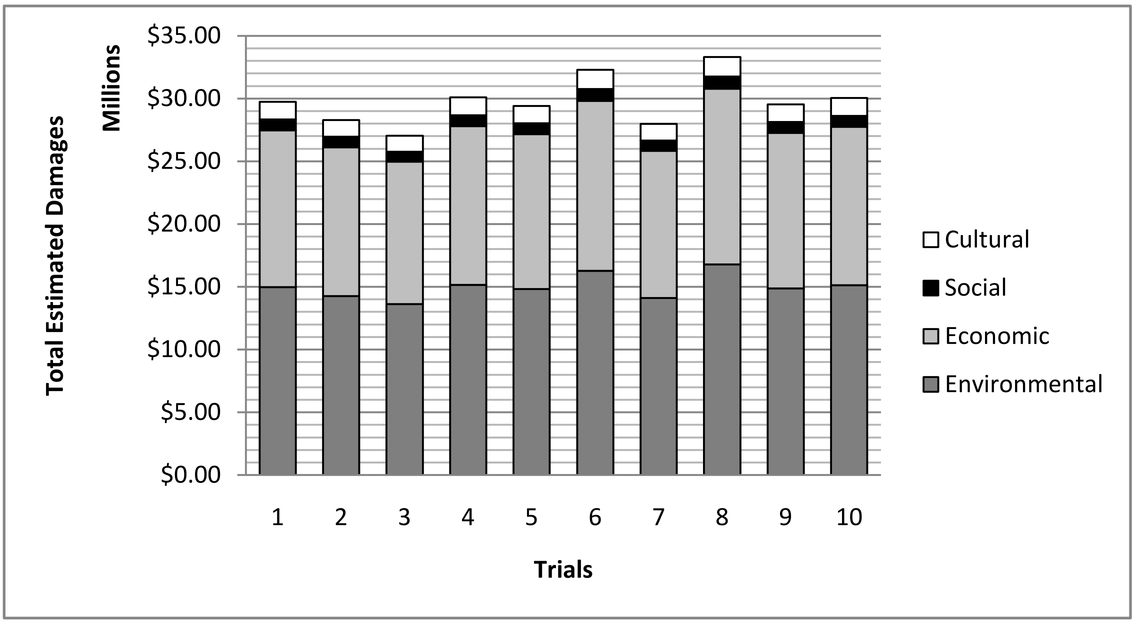

Figure 5.3: Storm Scenario VI total estimated damage trial results by Community Profile pillar

Figure 5.3 provides a closer inspection of the ten simulation trial results of Storm Scenario VI. Each section of the individual bars represents a Community Profile pillar of the study. It is clear that environmental and economic components make up almost the entire damage estimate. The trials vary slightly with a minimum total estimated damage of $27 million and a maximum of $33.3. Storm Scenario VI's total estimated damage trial results have a mean of $39.8, which can be seen in Figure 5.2, and a standard deviation of $1.9 million.

Figure 5.4 shows a boxplot of the total estimated damages for Scenarios II, IV and VI. The means are indicated with the circle and the boxes are formed by the upper and lower quartile limits. From this boxplot, it can be seen that the spread of the estimated damage increases with the higher storm scenario. The total estimated damage range for Storm Scenario II, Storm Scenario IV and Storm Scenario VI are: $467 thousand, $3.1 million, and $6.2 million respectively.

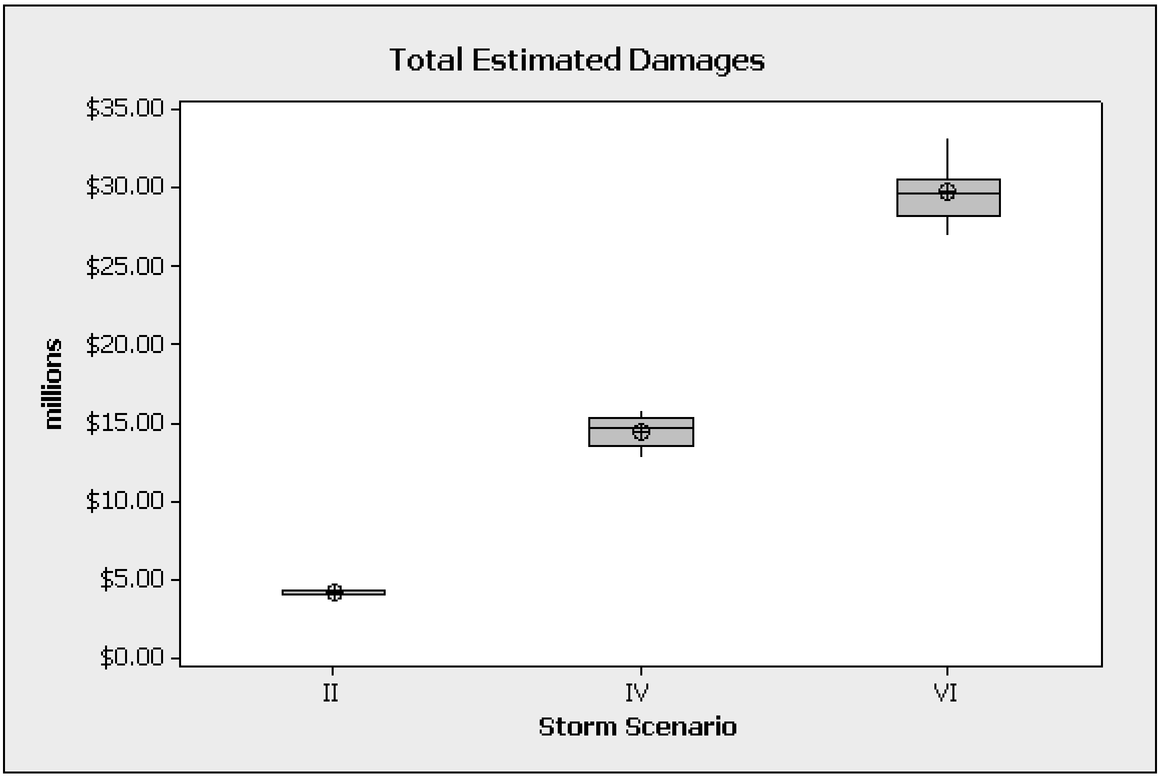

Figure 5.4: Boxplots of total estimated damage by Storm Scenarios II, IV, and VI

Figure 5.5 depicts a boxplot of the total estimated environmental and economic damages by scenario. Once again, it can be seen that the spread increases for both environmental and economic pillars with the higher Storm Scenarios. The Storm Scenarios seem to have equal median and means, which suggests that they have more symmetric damage estimate distributions.

Similar to the total estimated damages, the means of the three scenarios for both the environmental and economic pillars increase quite quickly. The difference in environmental mean damage estimates between Scenario II and Scenario IV is $5.1 million and the difference between Scenario IV and Scenario VI is $7.7 million. The difference in economic mean damage estimates between Scenario II and Scenario IV is $4.4 million and the difference between Scenario IV and Scenario VI is $6.4 million. As noted earlier, the environmental and economic estimated damages make up a large part of the total estimated damage. The percentage of the total estimated damage that is made up by the environmental and economic damage for all three scenarios is roughly 92%.

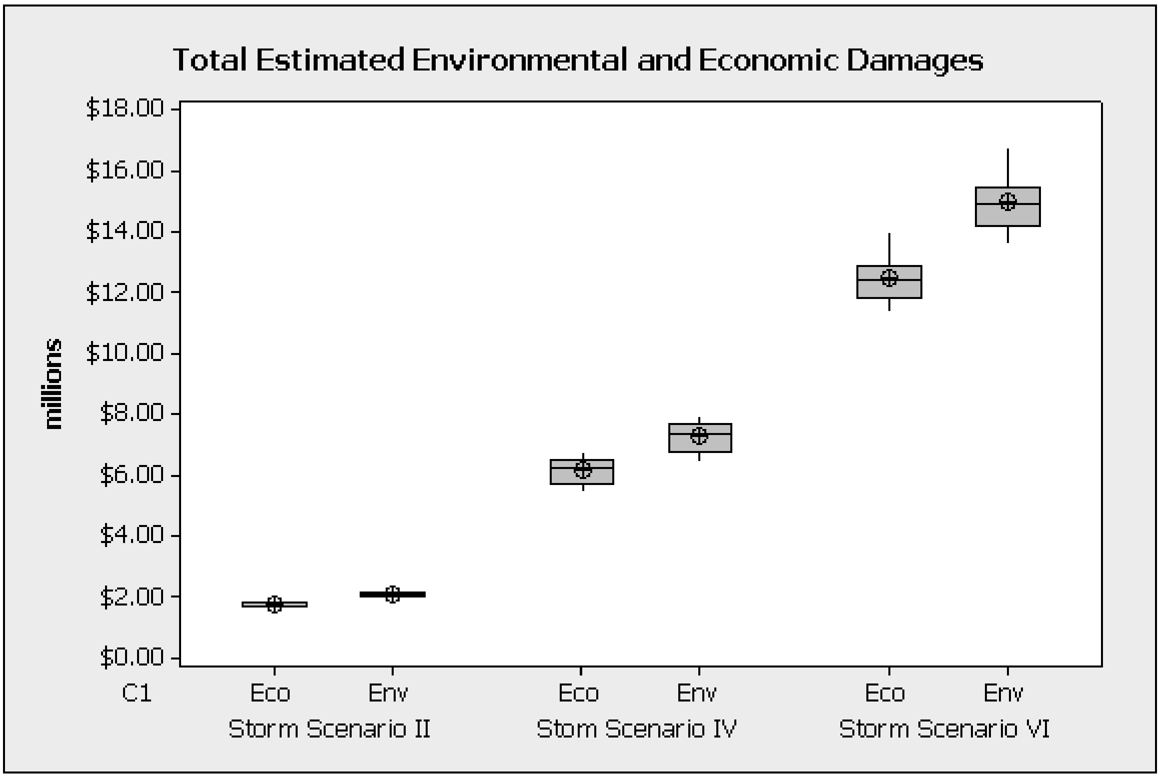

Figure 5.5: Total estimated environmental (Env) and economic (Eco) damage by Storm Scenarios II, IV, and VI

Three boxplots representing the total estimated social and cultural damages for Storm Scenarios II, IV and VI can be seen in Figure 5.6. Although the total estimated social and cultural damage totals are much lower than the previous boxplot examined, the relative spreads and increases are very similar to Figure 5.5. The trial results are distributed quite symmetrically as the means and medians seem very close, except for the cultural component of Storm Scenario IV which appears to be slightly skewed. The estimated social and cultural damage accounts for the smaller portion of total estimated damage and for all three scenarios the proportion of social and cultural estimated damage to total estimated damage is approximately 8%.

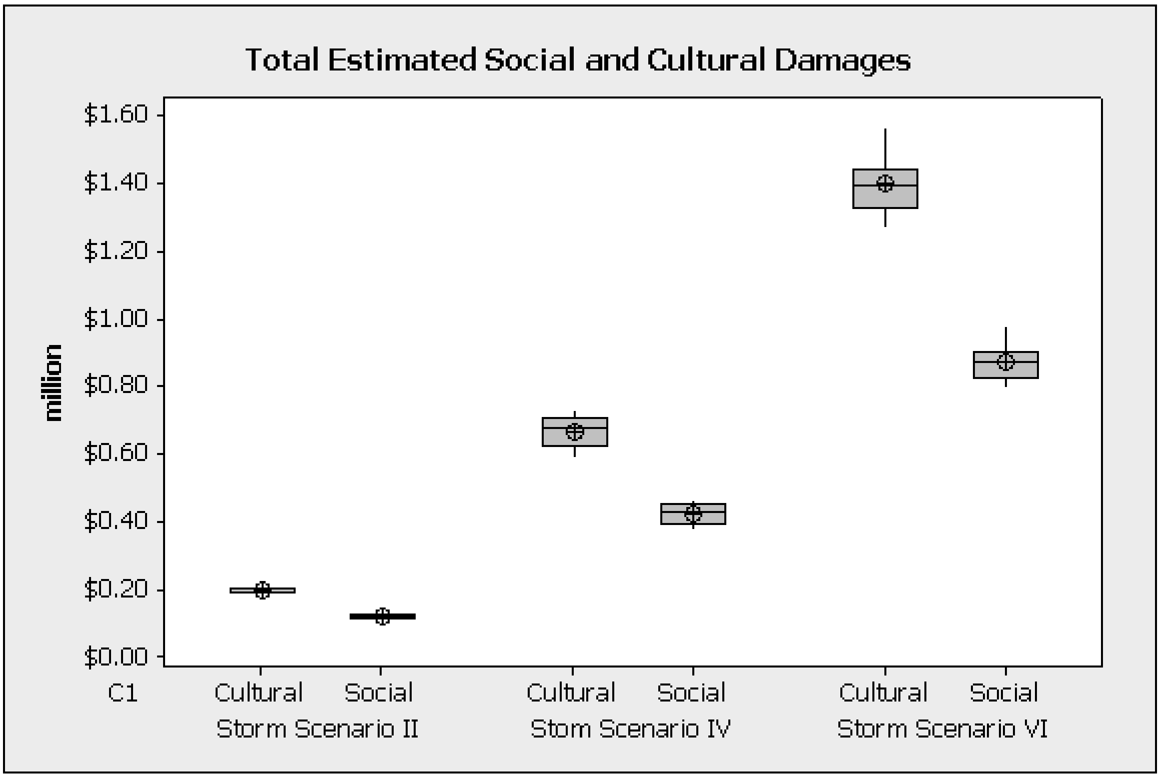

Figure 5.6: Estimated social and cultural damage by Storm Scenarios II, IV, and VI

Three sets boxplots were examined in this section. They were the total estimated damages and the estimated damages of each of the four Community Profile pillars of the study (environmental, economic, social and cultural). It is clear from the boxplots that there are many similarities between them. The total estimated damages are comparable between scenarios and, even more so, between components. In all cases, the ranges of damage estimates grow substantially with increasing Storm Scenarios from I to VI. The only major change between the three sets of boxplots is the constant linear ratios – which is due to the differences in damage estimates within each pillar component. Within each of the four components, the overall proportion of the total estimated damage of that component to the total overall estimated damage was constant across the three scenarios.

5.4 Summary of Results

The process of the GIS-SD storm simulation model is described from the user inputs, through the GIS VBA calculations and through the Microsoft Excel link to the STELLA SD model. It results in the total, direct and indirect estimated damages for each scenario by each of the community profile pillars.

The organization of ArcGIS layers (one for elevation and one for each of the Community Profile pillars), the selection of the Storm Scenario and the running of the model (in the ArcGIS and in the STELLA SD model) are all that is required from the user through the GUI. All of the calculations for Charlottetown storm damage estimates are done within the coding of the models.

The environmental and economic Community Profile pillars make up the majority of the overall total estimated damage. In all three sets of trial results for Storm Scenarios II, IV, and VI, the environmental and economic pillars were approximately 92% of the total estimated damages, with the cultural and social pillars making up the remaining 8% of total estimated damages.

The means of the trial results were comparable to the estimated historical damages based on the 'No Name 2000' baseline storm. The mean of the Storm Scenario II, IV and VI simulation trial results differed from the estimated historical damages of comparable Charlottetown storms by only $837 thousand, $1 million and $171 thousand respectively.

These results provide a mechanism for estimating Charlottetown vulnerability to storm severity through a structured damage reporting model process for estimating impacts on all aspects of the Charlottetown community system. This model recognizes the need for planning and preparedness even if data are not readily available. These results are designed to be of use to the City of Charlottetown in furthering their understanding of storm impacts, the reporting of damages and, ultimately, in preparing for strategies designed to lessen potential damages to the community through discussion, research and policy implications.

6. Recommendations for Further Research

This chapter examines areas of the research presented in this thesis that lead to further study. As an interdisciplinary systems study, this research called upon different fields to examine coastal vulnerability. From this interdisciplinary aspect, this research provokes further analyses and alternative research considerations. These include: (1) a review of the relevant data, (2) continued development of a comprehensive system dynamics model, (3) further analysis of the spatial systems dynamics methodology and (4) preparations for extreme weather events for the City of Charlottetown. These extended research considerations are discussed in more detail below.

6.1 Data

Data used in this research were taken from the best and freely available sources including Census of Canada, Geobase, Geogratis, and DMTI Spatial. However, it is recognized that more precise data for Charlottetown are available (e.g., McCulloch et al. 2002) that was not directly accessible for the purposes of this research and it is anticipated that the work done in this thesis could be easily linked with the higher resolution data. But, despite the lack of precision of the freely available data used in the thesis, the data were still extremely useful as a modelling tool to present the Charlottetown storm damage estimation modelling process and to discover gaps in the knowledge base. The objective of this thesis was not to find precise outcomes or exact Charlottetown storm damage estimates, but instead to provide a structured modeling framework – where there is presently none – to provide reasonable systemic estimates of anticipated storm damage using a spatial and community profile component-wise approach that is familiar to the community. As such, the best available data indeed served its purpose.

Further research and modelling application can be easily applied using more precise spatial data. Specifically, the digital elevation model used is the perfect example of this. Although free to use, only three of the six scenarios were possible to simulate directly due to the 1:50,000 scale crassness of the data that permitted only integer maximum water level estimates for Charlottetown. With more precise elevation data, e.g., 1:10,000 scale data, all six storm scenarios and intermediate (real valued) maximum water level rises could be simulated as potential flood layers. In fact, the scenarios could be modified in order to come closer to replicate historical storm surges and the results of the flood simulations more precisely. There is a need to explore and formulate clear definitions for potential differences in standards with respect to elevation data. The City of Charlottetown would benefit from such research as there is a need and desire to identify more precise potential flood lines from storm events, so as to not over or under estimate the threats to local residents and commerce from coastal storm surges.

The SD model could also be improved from a data standpoint. All SD models involving direct and indirect linkages would benefit greatly from the availability of more data and our understanding of system component links and feedback. As such, model complexity and improved accuracy between the connected GIS and the SD models could be stronger toward providing a more apt description of the system, albeit at the expense of more parameterization of the SD model to account for complexity.

Future data analysis will need a strong focus on the vulnerability of public infrastructure from both the GIS and SD modelling perspective. By capturing the community infrastructure in at-risk layers of the GIS and the dynamics of the SD model, a better understanding of the potential damage to infrastructure can be ascertained.

Another area lacking in data is that of the reports of damages. As discussed in Section 4.5.1, historically, storm damage has been poorly and incompletely reported. In fact, damages are often left unreported. When reports are found, they tend to be far from consistent or complete. For example, media reports are often not sourced and, insurance claims and government relief only cover a small fraction of total damages. There are many conclusions that could be drawn with more extensive data on damages from historical storms, especially from a community systems perspective, as presented in this thesis. The overall objective of modelling estimated damages as presented in this research is a first step toward recognizing community vulnerabilities, and anticipating and ultimately preparing adaptation strategies for extreme storm events that are the expected consequences of global climate change.

With different datasets, this research could also easily extend in various directions. In this thesis the Community Profile components for environmental, economic, social, and cultural and their respective indicators were chosen to provide balance among the components and to demonstrate how these elements needed to be included in the overall modelling process. The amount of environmental and socioeconomic data available to be used as the SD model components is vast and in this study only a small portion of these components were incorporated to illustrate model development. By choosing different and more extensive environmental, social, economical, and cultural aspects defining the coastal community profile, the scope of the study could change significantly.

6.2 System Dynamics

The SD model presented in this research was an illustrative model used primarily for (i) providing a simple, net present value time estimate for all indirect costs based on logical links, (ii) exploring the concept of a system of storm damages in order to force further questions, research and discussion on the topic, and (iii) the connection of the GIS and STELLA environments to create a Spatial System Dynamics model.

The ideal SD model framework would be more comprehensive and would require specification of the links over a specified time frame and the functional forms for all the linkages and parameters on the indirect effects. A larger, different set of linkages and parameters would be determined and modelled for a more dynamic and holistic model. The time impacts, linkages and parameters could be estimated for Charlottetown with the correct empirical data. The necessary data to construct a more functional, more dynamic model is believed to be available (e.g., McCulloch et al. 2002).

Further research combining storm probability models with a more comprehensive SD model could produce a more predictive model. In this thesis, a descriptive, rather than predictive model, was illustrated but in dissimilar research a model of this sort may be appropriate.

6.3 Spatial System Dynamics

There is still much to be done in the realm of connecting GIS and SD. The SSD methodology is a definite progression as it captures both the power of the GIS and SD environments, but it still has its shortcomings. The "curse of dimensionality" is an unresolved issue that affected both this research and that of Ahmad and Simonovic (2004). The issue of dimensionality makes complex systems, represented by even a few indicators, and multiple time steps quite difficult to handle. This difficulty is acknowledged in the work and results that Simonovic has done using this methodology (Shohan Ahmad, Personal Communication 2010). Similarly, the full SSD methodology including defined linkages with feedback and explicitly defined time steps for each DA was not fully applied to the work in Ahmad and

Simonovic (2004) or in this thesis.

Although the methodology of spatial system dynamics has yet to be used to its full capacity, the concept of coupling system dynamics and GIS into spatial system dynamics can potentially be applied to a plethora of situations and fields. It is felt that this realm of research has many opportunities and will continue to grow in subsequent years. The idea of a dynamic map that can apply the intricacies of system dynamics to its simulations has a vast amount of uses. Studies such as flooding, drought, migration, natural resource modelling, town/city planning, traffic engineering, and much more could all benefit from spatial system dynamics. The field of GIS is growing constantly and it will need to become more dynamic to accommodate these applications more effectively.

6.3 Extreme Weather Events

Lastly, as extreme weather events continue to propel coastal communities around the world into chaos, it is as apparent as ever that more preparation must be done and better response and adaptation plans must be made. Modelling vulnerable coastal communities, the determinants of related impacts such as waves or ice motion and examining storm histories are essential parts of those preparations - as is the clear need for more in depth and consistent storm damage reporting. Storm damage reporting as it stands is often little more than one aggregate monetary number with no obvious explanation (that is when there is a storm damage report at all). Without the knowledge of how and where storm damage occurs, communities will continue to be ill-prepared for severe storm damage. Enhanced storm damage reporting will be able to aide decision makers, affect policy and give insight to modellers attempting to identify vulnerabilities.

This research and the model for estimating storm damage is a first step toward identifying community storm event vulnerability. This identification leads to better preparation, strategy priority and evaluation. The C-Change project represents a significant step forward for preparing Canadian coastal communities. As well, large scale, media focused events such as the COP15 conference in Copenhagen (December 2009), and COP16 in Cancun (December 2010) present more focus on the pending plight of coastal communities and the impending consequences of more frequent and severe storm activity. But even more work and attention must be had, especially at the community level for which this thesis work is ever mindful, as this problem is only growing as coastal communities continue to be poorly prepared for extreme weather events.

7. Conclusions

This thesis examined a large, complex problem with limited data and, through the combination of several disciplines, was able to meet its objectives and provide a response to its posited research questions.

The four Community Profile pillars of the study (environmental, economic, social and cultural) were broken down and a list of indicators was established for each through the Community Profile (see Appendix A for full Community Profile dimensions, categories and items for Charlottetown). This Community Profile, developed by the author with feedback members of the C-Change team, is the result of evaluating possible indicators for each of the pillars and establishing and organizing a robust yet succinct list that captures the four pillars of all the C-Change communities.

Using the established Community Profile, the status quo of Charlottetown was defined and examined so that impacts to the community could be measured against the norm or community status quo. To examine the impacts, changes to the system had to be introduced. To do that, storm scenarios were defined. After examining the last fifty years of Charlottetown's storm history, six storm scenarios were modelled based on thirteen of Charlottetown's most severe and better documented storms. In order to introduce the storm scenarios, a GIS tool was created using Visual Basic for Applications that applies a flood line representing maximum water level rise to a map that has various indicators represented as multiple, thematic, overlapping layers. The impacts on the community due to each of the six storm scenarios were found in terms of the community components and in terms of the system as a whole.

The community's vulnerability to storm surge was examined from an "assets at risk" perspective. The most severe storm scenario was modelled as Storm Scenario VI, the base case, and assets at risk values were found for several indicators, the four pillars of the study and for the system as a whole. The remaining five scenarios (Storm Scenarios I through V) assets at risk were modelled as functions of the base case. The respective assets at risk (once again found for the same several indicators, the four pillars and for the system as a whole) were found in terms of monetary values and in terms of percentage against the base case.

Assets at risk monetary values exceed actual estimated storm damage values, so they do not paint an apt picture of the effects and impacts of a storm scenario on the community. But, the percentages of damage to assets by community pillar gave insight to the breakdown of damages by indicators and by the four pillars. These percentages were used with three different types of reported damage values for three historical storms (including media reports, government payouts and insurance claims). From the combination of the percentages and the reported damage values, the averaged monetary damage values for each of the storm scenarios, by the four pillars of the study and as a aggregate value, were estimated.

The research question stated at the beginning of this thesis asked:

> What are the expected impacts to the community profile that includes the physical environment, infrastructure and socioeconomics of the coastal community in the presence of storm surge and sea level rise and how can these impacts be effectively described using mapping techniques and spatial system dynamics?

It was found that by creating the community profile, establishing the status quo, using GIS to introduce storm scenarios modelled from historical data, and using a combination of spatial impacts, assets at risk analysis, and various sources of damage reports, that the impacts and damages of simulated coastal zone flooding from a storm surge on Charlottetown could be represented while noting changes to the environmental, economic, social and cultural components of the coastal community. The results of this are presented in Chapter 5 of the thesis as the evidence for developing a successful response to the research question.

This thesis used an interdisciplinary approach to learn that the combination of systems theory, geographic information systems, economic theory, model construction, and Visual Basic programming could be used to examine the impact that storm surges have on vulnerable coastal communities like Charlottetown. It was shown that by using historical data as a guide, simulations and models can estimate the changes, damages, and impacts that storms will have on a community. Not only is it possible to estimate these aggregate changes, damages and impacts, but also to do it in terms of environmental, economic, social and cultural components that define the community system.

The work done in this thesis is applicable to the other sites in the C-Change project and is expected to be used by other members of the C-Change team to describe and estimate community vulnerability and storm impacts and as they delve into multi-criteria decision analysis for strategic evaluation of adaptation alternatives, and more. The model process of this thesis is designed to be helpful for policy and adaptation planning in the hands of community planners and decision makers as a tool for their use.

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Appendix A: Community Data Profile Template

The C-Change project Community Profile template forms the basis for project community data for mapping, systems dynamics modelling, and multi-criteria decision making problem hierarchy. The 'Main Dimensions' of the Community Profile follow Charlottetown's Integrated Community Sustainability Plan's (Stantec 2010) four pillars. These four 'Main Dimensions' are: (i) environmental, (ii) economic, (iii) social and (iv) cultural. In the Community Profile, the 'Main Dimensions' are divided into 'Level 1 Categories' which capture the different areas of the 'Main Dimensions'. Within the 'Level 1 Categories' are the different 'Items' that describe the community. Table A.1 lists all of these elements, with 'Main Dimensions' in column 2, 'Level 1 Categories' in column 4 and 'Items' in column 6.

Table A.1: Dimensions, Level 1 Categories and Items of the Community Profile Template

	Main Dimensions		**Level 1 Categories**		**Items**
1	Environmental	**A**	Topography	**I**	Land Area
				II	Mean Elevation
				III	Lowest Point
				IV	Highest Point
				V	Slope
		B	Hydrology	**I**	Watershed Boundaries
				II	Lakes, Rivers, Streams
		C	Coastal Geomorphology	**I**	Length
				II	Physical Composition
				III	Bathymetry
				IV	Ports and Harbours
				V	Wave Climate
				VI	Sedimentation and Erosion
		D	Habitat and Species	**I**	Terrestrial
				II	Fresh and salt water wetlands

				III	Aquatic
				IV	Migratory species and routes
				V	Rare/Endangered
		E	Land Cover	**I**	Forests
				II	Wetlands
				III	Barrens
				IV	Grasslands and Pastures
				V	Flood Plains and Hazard Lands
		F	Land Use	**I**	Town Centres
				II	Industrial
				III	Commercial
				IV	Residential
				V	Agriculture
				VI	Forestry
				VII	Mineral extraction
				VIII	Transportation and utilities
				IX	Energy production
				X	Parks and open space
				XI	Beaches
				XII	Protected Areas
				XIII	Scenic/historical/cultural areas
				XIV	Tourism
		G	Marine Use	**I**	Aquaculture
				II	Marine Benthic
				III	Recreational Fishing
				IV	Commercial Fishing
				V	Recreational Boating
				VI	Transportation routes
				VII	Tourism
				VIII	Protected areas
				IX	Scenic/historical/cultural areas
		H	Natural Resources	**I**	Forests
				II	Native plants
				III	Wildlife
				IV	Arable land
				V	Minerals
				VI	Energy

				VII	Potable water
		I	Climate	**I**	Mean temperatures
				II	Mean precipitation
				III	Prevailing winds and wind speed
				IV	Storm events
				V	High tides and storm surges
2	<u>Economic</u>	**A**	Industry by Type	**I**	Agriculture and other resourced based occupations
				II	Constructions
				III	Manufacturing
				IV	Wholesale trade
				V	Retail
				VI	Finance and real estate
				VII	Heath care and social services educational services
				VIII	Other services
		B	Industry Revenues	**I**	Natural resources
				II	Tourism
				III	Commercial
				IV	Industrial
		C	Built Environment	**I**	Churches
				II	Community centres
				III	Schools
				IV	Public Libraries
				V	Private dwellings
				VI	Industrial structures
				VII	Commercial structures
				VIII	Retail structures
				IX	Coastal structures
				X	Fuel storage
				XI	Cultural/historical structures and architectural districts
		D	Public Works	**I**	Government buildings
				II	Fire fighting
				III	Policing
				IV	Hospitals
				V	Solid waste management

					systems
				VI	Municipal wastewater systems
				VII	Stormwater collection and disposal systems
				VIII	Potable water source, treatment and supply systems
				IX	Energy generation and supply systems
				X	Transportation systems
		F	Real-Estate Values	**I**	Residential property
				II	Coastal residential property
				III	Coastal tourism property
				IV	Commercial property value
				V	Industrial property value
				VI	Municipal tax base
				VII	Average value of owned dwellings
3	Social	**A**	Population Statistics	**I**	Population in 2006
				II	Population in 2001
				III	Population density per sq. km
				IV	Median age of the population
				V	Population change (%)
				VI	Aboriginal population
				VII	Population less than 14 years of age
				VIII	Population 15 – 59 years of age
				IX	Population over 60 years of age
		B	Education	**I**	No certificate, diploma, degree
				II	High school certificate
				III	College or non-university certificate
				IV	University diploma below Bachelors

				V	University certificate, diploma, degree
		C	Health Status	**I**	Morbidity rates
				II	Mortality rates/average age
				III	# of hospitals/clinics/hospices/other health care centers per capita
				IV	Number of residences without family doctor
				V	How does the community perceive their health/happiness
		D	Occupation by Type	**I**	Management
				II	Business, finance, or administration
				III	Natural/applied sciences
				IV	Social science, education, government, religion
				V	Sales and service
				VI	Trades, transport, and equipment
				VII	Unique to primary industry
				VIII	Processing, manufacturing, or utilities
		E	Employment and Earnings	**I**	Total population (over age 15) in labour force
				II	Employment/unemployment rate
				III	Median income (all census families)
				IV	Median income (all private households)
				V	Median earnings (age 15 and over)
4	<u>Cultural</u>	**A**	Governance Systems	**I**	Government agencies (federal, provincial, municipal, EMR, other)
				II	First Nations, aboriginal, Métis

				III	Other non-government organizations (co-management, advisory boards)
				IV	Enabling legislation (Planning Acts, Municipal By-laws, Environmental Protection Acts)
				V	Decision-making processes
		B	Community Dynamics	**I**	Community leaders
				II	Business leaders
				III	Important Families
				IV	Other traditional/significant people
		C	Community Groupings	**I**	Religious
				II	Language
				III	Family organization
				IV	Traditions/heritage
		D	Communications Resources	**I**	Community newspapers, other print media/news
				II	Local access cable TV Channel
				III	Local radio stations
				IV	Television (homes with television)
				V	Telephones (homes with, cell phone users)
				VI	Internet Access (homes with, schools with, public access)
		E	Language	**I**	English only
				II	French only
				III	French and English
				IV	No French or English
		F	Places of Significance	**I**	Sacred sites
				II	Historical sites
				III	Archaeological and anthropological Sites
		G	Cultural Events		

Appendix B: List of ArcGIS Layers

This Appendix lists the various layers imported to ArcGIS that were used to establish Charlottetown's Status Quo Community Profile (Section 4.1), assess the Storm Scenario impacts on Charlottetown (Section 4.3), determine Charlottetown's 'Assets at Risk' valuations for Storm Scenarios I through VI (Section 4.4), and to run the GIS storm simulation model (Section 4.6 and Chapter 5). The name, source, and descriptive details of all layers are provided in Table B.1 below.

Table B.3: List of ArcGIS layers, their type and their source

Name	Source	Type	Other
Environmental			
Elevation	Geobase.ca	Raster	Scale: 1:50,000
Major Parks	DMTI 2009a	Shapefile	Points
Parks	DMTI 2009a	Shapefile	Polygons
Economic			
Built Environment	DMTI 2009b	Shapefile	Points
Public Works	DMTI 2009b	Shapefile	Points
Roads	DMTI 2009a	Shapefile	Lines
Industry By Type	Census Canada 2006	Shapefile	Joined to Census DA data
Social			
Social Services	DMTI 2009b	Shapefile	Points
Occupation By Type	Census Canada 2006	Shapefile	Joined to Census DA data
Education	Census Canada 2006	Shapefile	Joined to Census DA data
Employment Social	Census Canada 2006	Shapefile	Joined to Census DA data
Cultural			
Museums Churches Art	DMTI 2009b	Shapefile	Points
Other			
Satellite Images	Geobase 2010	File System Raster (Landsat 7 Orthorectified Image)	Resolution: 30 meters

Appendix C: Economic Status Quo – Points in Standard Industrial Classification Major Groups

This appendix presents the breakdown of the economic dimension of the Charlottetown Community Profile as reported in Section 4.1.2 ("Charlottetown Status Quo: Economic") of the thesis. The total identified economic enhanced points of interest in Charlottetown are listed by their Standard Industrial Classification (SIC) Divisions. Below in Table C.1, the counts of the 1042 points are described by their SIC Major Group definition (DMTI 2009b).

Table C.1: Economic Status Quo Points in SIC Major Groups (Source: DMTI 2009b)

Major Group	Name	# of Points
01	Agricultural Production Crops	4
02	Agricultural Production Livestock And Animal Specialties	1
07	Agricultural Services	15
09	Fishing, Hunting, And Trapping	2
13	Oil And Gas Extraction	1
15	Building Construction General Contractors And Operative Builders	16
16	Heavy Construction Other Than Building Construction Contractors	4
17	Construction Special Trade Contractors	58
20	Food And Kindred Products	12
23	Apparel And Other Finished Products Made From Fabrics And Similar	5
24	Materials	3
25	Furniture And Fixtures	1
26	Paper And Allied Products	1
27	Printing, Publishing, And Allied Industries	16
28	Chemicals And Allied Products	3
30	Rubber And Miscellaneous Plastics Products	2
32	Stone, Clay, Glass, And Concrete Products	9
34	Fabricated Metal Products, Except Machinery And Transportation	7

	Equipment	
35	Industrial And Commercial Machinery And Computer Equipment	13
36	Electronic And Other Electrical Equipment And Components, Except Computer Equipment	4
37	Transportation Equipment	2
38	Measuring, Analyzing, And Controlling Instruments; Photographic, Medical And Optical Goods; Watches And Clocks	2
39	Miscellaneous Manufacturing Industries	3
41	Local And Suburban Transit And Interurban Highway Passenger Transportation	7
42	Motor Freight Transportation And Warehousing	26
43	United States Postal Service	12
44	Water Transportation	4
45	Transportation By Air	8
47	Transportation Services	10
48	Communications	8
49	Electric, Gas, And Sanitary Services	2
50	Wholesale Trade-durable Goods	68
51	Wholesale Trade-non-durable Goods	29
52	Building Materials, Hardware, Garden Supply, And Mobile Home Dealers	19
53	General Merchandise Stores	7
54	Food Stores	57
55	Automotive Dealers And Gasoline Service Stations	31
56	Apparel And Accessory Stores	53
57	Home Furniture, Furnishings, And Equipment Stores	47
58	Eating And Drinking Places	106
59	Miscellaneous Retail	140
60	Depository Institutions	35
61	Non-depository Credit Institutions	10
62	Security And Commodity Brokers, Dealers, Exchanges, And Services	24
63	Insurance Carriers	17
64	Insurance Agents, Brokers, And Service	22
65	Real Estate	42
70	Hotels, Rooming Houses, Camps, And Other Lodging Places	47
72	Personal Services	97
73	Business Services	112
75	Automotive Repair, Services, And Parking	78
76	Miscellaneous Repair Services	16
78	Motion Pictures	17
79	Amusement And Recreation Services	57
80	Health Services	124
81	Legal Services	69

82	Educational Services	69
83	Social Services	71
84	Museums, Art Galleries, And Botanical And Zoological Gardens	15
86	Membership Organizations	117
87	Engineering, Accounting, Research, Management, And Related Services	86
89	Services, not elsewhere classified	1
91	Executive, Legislative, And General Government, Except Finance	14
92	Justice, Public Order, And Safety	21
93	Public Finance, Taxation, And Monetary Policy	3
99	No classifiable Establishments	59

Appendix D: Social 'Assets at Risk' Comparisons

This appendix provides detail on the derivation of the social pillar "assets at risk" values for Charlottetown provided in Section 4.4.2.3 of the thesis. In this section, the lost income and additional health costs due to storm surge for a Scenario VI storm are calculated as the 'assets at risk' for the social community profile pillar. The Storm Scenarios II and IV social 'assets at risk' full calculations are provided below in Table D.1 (Storm Scenario II) and D.2 (Storm Scenario IV).

Table D.1: Storm Scenario II social 'assets at risk' for the 3 meter maximum water level rise for Charlottetown

DA	DA Size (km2)	Flood Size (km2)	% Flooded	Pop Work Force	Pop in Work Force Flooded	Median Income	Median Income per Work Day	Lost Income in 1.5 Days	Pop 65+/ 10-	Health Cost for 1.5 Days
134	4.38	1.64	37.41%	180	67.34	$40,718	$156.61	$15,820	40	$2,993
135	0.76	0.05	7.18%	205	14.71	$40,243	$154.78	$3,415	80	$1,148
137	1.41	0.15	10.60%	215	22.79	$18,607	$71.57	$2,447	85	$1,802
148	1.16	0.23	19.51%	285	55.59	$20,119	$77.38	$6,453	160	$6,242
150	0.46	0.20	44.25%	280	123.89	$20,049	$77.11	$14,331	100	$8,850
151	0.49	0.01	1.76%	245	4.31	$22,273	$85.67	$554	135	$475
152	0.16	0.03	19.71%	285	56.19	$18,380	$70.69	$5,958	105	$4,140
154	0.20	0.14	69.44%	355	246.53	$17,044	$65.55	$24,241	95	$13,194
155	0.30	0.17	56.92%	215	122.37	$18,983	$73.01	$13,402	155	$17,644
156	0.13	0.13	100.00%	260	260.00	$16,777	$64.53	$25,166	110	$22,000
157	2.44	2.44	100.00%	310	310.00	$18,752	$72.12	$33,537	165	$33,000
158	0.16	0.16	100.00%	280	280.00	$14,729	$56.65	$23,793	120	$24,000
159	0.46	0.39	84.26%	275	231.72	$20,395	$78.44	$27,265	195	$32,862
160	0.16	0.04	23.99%	225	53.98	$17,119	$65.84	$5,331	120	$5,758
169	0.32	0.00	1.01%	290	2.92	$29,986	$115.33	$505	115	$231
173	0.23	0.00	0.45%	200	0.90	$27,952	$107.51	$145	90	$81
174	0.74	0.19	25.22%	440	110.98	$12,665	$48.71	$8,109	105	$5,297
180	5.00	3.91	78.06%	350	273.23	$38,686	$148.79	$60,981	330	$51,523
182	0.38	0.01	1.62%	220	3.56	$19,974	$76.82	$411	85	$275
183	0.67	0.24	35.00%	350	122.50	$34,831	$133.97	$24,615	115	$8,050
255	7.16	6.60	92.16%	230	211.96	$28,625	$110.10	$35,004	100	$18,431

256	1.26	0.07	5.68%	325	18.45	$23,464	$90.25	$2,497	175	$1,987
257	1.62	0.28	17.47%	360	62.88	$22,766	$87.56	$8,259	115	$4,017
258	0.71	0.04	5.81%	310	18.02	$27,336	$105.14	$2,842	115	$1,337
261	4.91	0.21	4.30%	400	17.18	$29,903	$115.01	$2,964	130	$1,117
265	2.04	1.62	79.31%	220	174.48	$36,578	$140.68	$36,820	185	$29,344
267	0.35	0.03	7.60%	250	19.00	$26,959	$103.69	$2,956	130	$1,976

Table D.2: Storm Scenario IV social 'assets at risk' for the 4 meter maximum water level rise for Charlottetown

DA	DA Size (km2)	Flood Size (km2)	% Flooded	Pop Work Force	Pop in Work Force Flooded	Median Income	Median Income per Work Day	Lost Income in 4 Days due to Flood	Pop 65+/ 10-	Health Cost for 4 Days
131	2.30	0.00	0.17%	385	0.66	$30,227	$116.26	$307	135	$185
134	4.38	1.74	39.77%	180	71.59	$40,718	$156.61	$44,843	40	$12,726
135	0.76	0.61	79.75%	205	163.49	$40,243	$154.78	$101,220	80	$51,041
136	0.43	0.02	5.28%	190	10.03	$23,914	$91.98	$3,690	125	$5,279
137	1.41	0.23	16.16%	215	34.74	$18,607	$71.57	$9,946	85	$10,989
148	1.16	0.28	23.83%	285	67.91	$20,119	$77.38	$21,019	160	$30,499
150	0.46	0.29	64.18%	280	179.71	$20,049	$77.11	$55,430	100	$51,345
151	0.49	0.03	5.69%	245	13.95	$22,273	$85.67	$4,781	135	$6,150
152	0.16	0.09	57.48%	285	163.83	$18,380	$70.69	$46,325	105	$48,285
154	0.20	0.20	98.66%	355	350.26	$17,044	$65.55	$91,843	95	$74,985
155	0.30	0.26	85.23%	215	183.25	$18,983	$73.01	$53,517	155	$105,688
156	0.13	0.13	100.00%	260	260.00	$16,777	$64.53	$67,108	110	$88,000
157	2.44	2.44	100.00%	310	310.00	$18,752	$72.12	$89,433	165	$132,000
158	0.16	0.16	100.00%	280	280.00	$14,729	$56.65	$63,448	120	$96,000
159	0.46	0.42	92.20%	275	253.55	$20,395	$78.44	$79,555	195	$143,830
160	0.16	0.08	47.05%	225	105.86	$17,119	$65.84	$27,879	120	$45,165
162	0.17	0.05	28.66%	300	85.99	$20,993	$80.74	$27,772	70	$16,052
169	0.32	0.01	2.30%	290	6.66	$29,986	$115.33	$3,075	115	$2,114
173	0.23	0.00	1.78%	200	3.56	$27,952	$107.51	$1,532	90	$1,282
174	0.74	0.22	29.62%	440	130.33	$12,665	$48.71	$25,395	105	$24,881
180	5.00	4.04	80.66%	350	282.31	$38,686	$148.79	$168,020	330	$212,940
182	0.38	0.02	4.50%	220	9.91	$19,974	$76.82	$3,045	85	$3,063
183	0.67	0.24	36.09%	350	126.32	$34,831	$133.97	$67,691	115	$33,205
255	7.16	6.73	93.98%	230	216.16	$28,625	$110.10	$95,195	100	$75,188
256	1.26	0.10	8.14%	325	26.44	$23,464	$90.25	$9,546	175	$11,391
257	1.62	0.34	20.84%	360	75.02	$22,766	$87.56	$26,276	115	$19,172

258	0.71	0.07	9.53%	310	29.55	$27,336	$105.14	$12,429	115	$8,771
261	4.91	0.26	5.27%	400	21.06	$29,903	$115.01	$9,690	130	$5,476
265	2.04	1.69	82.80%	220	182.17	$36,578	$140.68	$102,512	185	$122,548
267	0.35	0.04	12.14%	250	30.34	$26,959	$103.69	$12,585	130	$12,622

Appendix E: Graphical User Interface Code

This appendix presents the Graphical User Interface (GUI) coding for the GIS-SD Storm Simulation Model developed for the thesis (as discussed in Chapters 4 and 5). In 2009, the author constructed a sea-level rise simulation tool for ArcGIS using Visual Basics for Applications (Hartt 2009). In this research, this tool was built upon to create the GIS Storm Simulation Model. The model is described in the thesis and a screenshot of the graphical user interface is provided in Section 4.6 ("GIS Storm Simulation Model with Damages Report"). Below, the complete Visual Basic for Applications (VBA) code for the model is presented with brief documentary comments (in bold typeface).

```
Private Sub cancel_Click()
    Unload Me
End Sub
Private Sub CommandButton1_Click()
```

Get entry to arcobjects.

```
Dim pMxdoc As IMxDocument
Set pMxdoc = ThisDocument
```

Declare variables.

```
Dim pMap As IMap
Dim pLayer As ILayer
Dim pLayerEnviro As ILayer
Dim pLayerEco As ILayer
Dim pLayerSocial As ILayer
Dim pLayerCult As ILayer

Dim RandomSpeed As Double
Dim RandomWind As Double
Dim RandomPressure As Double
Dim RandomIntensity As Double

Dim ExactSpeed As Double
Dim ExactWind As Double
Dim ExactPressure As Double
```

```
Dim WaterLevel As Double
Dim Length As Double
Dim Storm As String

Dim DamageEstimateEnviro As Double
Dim DamageEstimateEco As Double
Dim DamageEstimateSocial As Double
Dim DamageEstimateCult As Double

Dim AdjustSpeed As Double
Dim AdjustWind As Double
Dim AdjustPressure As Double

Dim pCountEnviroMax As Double
Dim pCountEnviro As Double
Dim DamageEnviro As Double
Dim pCountEcoMax As Double
Dim pCountEco As Double
Dim DamageEco As Double
Dim pCountSocialMax As Double
Dim pCountSocial As Double
Dim DamageSocial As Double
Dim pCountCultMax As Double
Dim pCountCult As Double
Dim DamageCult As Double

Dim Cv As Double

Dim EnviroRatio As Double
Dim EcoRatio As Double
Dim SocialRatio As Double
Dim CultRatio As Double
Dim TotalDamage As Double

Set pMap = pMxdoc.FocusMap
```

Retrieve the user selected layers and put that in an ilayer reference variable.

```
Set pLayer = getLayerByName(elevationbox.Text)
    If TypeOf pLayer Is IFeatureLayer Then
    MsgBox "Incorrect elevation file type. Please load an elevation layer."
```

```
ElseIf TypeOf pLayer Is RasterLayer Then

Set pLayerEnviro = getLayerByName(envirobox.Text)
Set pLayerEco = getLayerByName(ecobox.Text)
Set pLayerSocial = getLayerByName(socialbox.Text)
Set pLayerCult = getLayerByName(cultbox.Text)

Dim MaxWaterLevel As Double
MaxWaterLevel = 5
```

Take in User selection of storm scenarios and define variables based on selection.

```
    If sII.Value = False And sIV.Value = False And sVI.Value = False Then
        MsgBox "Please select a storm scenario"
        Exit Sub

    ElseIf sII.Value = True Then
        Storm = "II"
        WaterLevel = 3
        Length = 1.5 / 7
        DamageEstimateEnviro = 2494524.21
        DamageEstimateEco = 2178609.58
        DamageEstimateSocial = 63786.69
        DamageEstimateCult = 249981.35
        AdjustSpeed = 20
        AdjustWind = 80
        AdjustPressure = 10

    ElseIf sIV.Value = True Then
        Storm = "IV"
        WaterLevel = 4
        Length = 4 / 7
        DamageEstimateEnviro = 7851219.75
        DamageEstimateEco = 6777896.48
        DamageEstimateSocial = 217968.93
        DamageEstimateCult = 736740.42
        AdjustSpeed = 10
        AdjustWind = 40
        AdjustPressure = 30

    ElseIf sVI.Value = True Then
        Storm = "VI"
        WaterLevel = 5
```

```
            Length = 7 / 7
            DamageEstimateEnviro = 15151780.5
            DamageEstimateEco = 12626483.75
            DamageEstimateSocial = 414468.4
            DamageEstimateCult = 1412153.05
            AdjustSpeed = 0
            AdjustWind = 0
            AdjustPressure = 50

        End If

 Cv = 0.2

 pCountEnviroMax = 0
 pCountEcoMax = 0
 pCountSocialMax = 0
 pCountCultMax = 0

 pCountEnviro = 0
 pCountEco = 0
 pCountSocial = 0
 pCountCult = 0
```

Call "Flooded" function to determine number of affected features in baseline flooded area and selected flooded area for features of each community profile pillar.

```
pCountEnviroMax = Flooded(pMxdoc, pMap, pLayer, pLayerEnviro, MaxWaterLevel)
 pMap.DeleteLayer pMap.Layer(0)
 pCountEnviro = Flooded(pMxdoc, pMap, pLayer, pLayerEnviro, WaterLevel)
 pMap.DeleteLayer pMap.Layer(0)

 pCountEcoMax = Flooded(pMxdoc, pMap, pLayer, pLayerEco, MaxWaterLevel)
 pMap.DeleteLayer pMap.Layer(0)
 pCountEco = Flooded(pMxdoc, pMap, pLayer, pLayerEco, WaterLevel)
 pMap.DeleteLayer pMap.Layer(0)

 pCountSocialMax = Flooded(pMxdoc, pMap, pLayer, pLayerSocial, MaxWaterLevel)
 pMap.DeleteLayer pMap.Layer(0)
 pCountSocial = Flooded(pMxdoc, pMap, pLayer, pLayerSocial, WaterLevel)
 pMap.DeleteLayer pMap.Layer(0)

 pCountCultMax = Flooded(pMxdoc, pMap, pLayer, pLayerCult, MaxWaterLevel)
 pMap.DeleteLayer pMap.Layer(0)
 pCountCult = Flooded(pMxdoc, pMap, pLayer, pLayerCult, WaterLevel)
```

Determine Damage Ratios for each community profile pillar.

```
EnviroRatio = (pCountEnviro / pCountEnviroMax)
 EcoRatio = (pCountEco / pCountEcoMax)
 SocialRatio = (pCountSocial / pCountSocialMax)
 CultRatio = (pCountCult / pCountCultMax)
```

Generate random variables for speed, wind and pressure. Calculate Storm Intensity.

```
RandomSpeed = Rnd
 RandomWind = Rnd
 RandomPressure = Rnd
 RandomIntensity = ((1 / 3) * (RandomSpeed + RandomWind + RandomPressure))

 RandomSpeed = ((75 - 70 + 1) * RandomSpeed + 70)
 RandomWind = ((175 - 155 + 1) * RandomWind + 155)
 RandomPressure = ((1000 - 990 + 1) * RandomPressure + 990)
```

Calculate storm scenario input attributes.

```
ExactSpeed = VBA.Round(RandomSpeed - AdjustSpeed, 2)
 ExactWind = VBA.Round(RandomWind - AdjustWind, 2)
 ExactPressure = VBA.Round(RandomPressure - AdjustPressure, 2)
```

Calculate damage estimates for each of the community profile pillars.

```
DamageEnviro = VBA.Round(Damage(Cv, DamageEstimateEnviro, EnviroRatio,
RandomIntensity), 2)
 DamageEco = VBA.Round(Damage(Cv, DamageEstimateEco, EcoRatio, RandomIntensity), 2)
DamageSocial = VBA.Round(Damage(Cv, DamageEstimateSocial, SocialRatio, RandomIntensity),
2)
 DamageCult = VBA.Round(Damage(Cv, DamageEstimateCult, CultRatio, RandomIntensity), 2)
 TotalDamage = DamageEnviro + DamageEco + DamageSocial + DamageCult
```

Prompt user with storm input attribute and output damage summary.

```
MsgBox "Scenario " & Storm & " Summary" & vbCr & vbCr & "STORM ATTRIBUTE
ESTIMATIONS" & vbCr & "Speed: " & ExactSpeed & vbCr & "Wind: " & ExactWind & vbCr &
"Pressure: " & ExactPressure & _
vbCr & vbCr & "STORM DAMAGE ESTIMATIONS" & vbCr & "Environmental: $" & DamageEnviro
& vbCr & "Economic: $" & DamageEco & vbCr & _
  "Social: $" & DamageSocial & vbCr & "Cultural: $" & DamageCult & vbCr & vbCr & "TOTAL: $" &
TotalDamage
```

Run Excel function which opens Microsoft Excel workbook and writes damage estimate outputs.

```
Call Excel(DamageEnviro, DamageEco, DamageSocial, DamageCult)
```

Close tool once it has been run.
Unload Me

End If

End Sub

Excel Function

```
Function Excel(DamageEnviro As Double, DamageEco As Double, DamageSocial As Double, DamageCult As Double)

Dim ExcelSheet As Object
Set ExcelSheet = CreateObject("Excel.Sheet")
```

Make Excel visible through the Application object.

```
ExcelSheet.Application.Visible = True
```

Place text and damage estimates in cells of the sheet.

```
ExcelSheet.Application.Cells(1, 1).Value = "EnvDamage"
ExcelSheet.Application.Cells(1, 2).Value = DamageEnviro
ExcelSheet.Application.Cells(2, 1).Value = "EcoDamage"
ExcelSheet.Application.Cells(2, 2).Value = DamageEco
ExcelSheet.Application.Cells(3, 1).Value = "SocialDamage"
ExcelSheet.Application.Cells(3, 2).Value = DamageSocial
ExcelSheet.Application.Cells(4, 1).Value = "CultDamage"
ExcelSheet.Application.Cells(4, 2).Value = DamageCult
```

Save the sheet to C:\GIS_Output.xls directory.

```
ExcelSheet.SaveAs "C:\GIS_Output.XLS"
```

Close Excel with the Quit method on the Application object.

```
ExcelSheet.Application.Quit
```

Release the object variable.

```
'Set ExcelSheet = Nothing

End Function
```

Damage Calculation Function

```
Function Damage(Cv As Double, DamageEstimate As Double, Ratio As Double, RandomIntensity As Double)
```

```
Dim UpperBound As Double
Dim LowerBound As Double
```

Calculate Upper and Lower bounds of damage interval.

```
UpperBound = Ratio + (Cv * Ratio)
LowerBound = Ratio - (Cv * Ratio)
```

Calculate damage estimate.

```
Damage = (LowerBound + (UpperBound - LowerBound) * RandomIntensity) * DamageEstimate

End Function
```

Flooded Function

```
Function Flooded(pMxdoc As IMxDocument, pMap As IMap, pLayer As ILayer, pLayer2 As ILayer,
MaxWaterLevel As Double)

Dim pRasLayer As IRasterLayer
    Set pRasLayer = pLayer
    Dim pInRaster As IRaster
    Set pInRaster = pRasLayer.Raster
```

Create a RasterModel object.

```
    Dim pRasModel As IRasterModel
    Set pRasModel = New RasterModel
```

Set output workspace in the analysis environment.

```
    Dim pEnv As IRasterAnalysisEnvironment
    Set pEnv = pRasModel

    Dim pWS As IWorkspace
    Dim pWSF As IWorkspaceFactory
    Set pWSF = New RasterWorkspaceFactory
    Set pWS = pWSF.OpenFromFile("c:\temp", 0)
    Set pEnv.OutWorkspace = pWS
```

Bind the input raster.

```
    pRasModel.BindRaster pInRaster, "input1"


    If MaxWaterLevel < 0 Then
    Exit Function
    Else
        If IsNumeric(MaxWaterLevel) Then
```

Specify map algebra expression.

```
dvalue = "[out1] " & Chr(61) & " [input1] > " & MaxWaterLevel
pRasModel.Script = dvalue

End If
End If
```

Execute map algebra expression.

```
pRasModel.Execute
```

Get output rasters.

```
Dim pOutRaster1 As IRaster
Set pOutRaster1 = pRasModel.BoundRaster("out1")
```

Unbind input raster.

```
pRasModel.UnbindSymbol "input1"
```

Add outputs into ArcMap as raster layers.

```
Dim pOutRasLayer1 As IRasterLayer
Set pOutRasLayer1 = New RasterLayer

pOutRasLayer1.CreateFromRaster pOutRaster1
pMap.AddLayer pOutRasLayer1
```

Convert raster to shapefile.

```
Call RasterConvertHelper
pMap.DeleteLayer pMap.Layer(1)
```

Query to select Gridcode = 0.

```
Dim pLayer3 As ILayer
Set pLayer3 = pMap.Layer(0)
```

QI to ifeatureselection

```
Dim pFeatSelect As IFeatureSelection
Set pFeatSelect = pLayer3
Dim pDef As IFeatureLayerDefinition
Set pDef = pLayer3

Dim pQfilter As IQueryFilter
Set pQfilter = New QueryFilter
pQfilter.WhereClause = "Gridcode = 0"
```

```
pFeatSelect.SelectFeatures pQfilter, esriSelectionResultNew, False

Dim pActiveView As IActiveView
Set pActiveView = pMxdoc.ActiveView
pActiveView.Refresh
```

Create a new layer from selected parts of previous layer.

```
Dim pSelFLayer As IFeatureLayer
Set pSelFLayer = pDef.CreateSelectionLayer("Flood Layer", True, vbNullString, vbNullString)
pMap.AddLayer pSelFLayer        ' add new layer to the map

Dim FloodLayer As ILayer
Set FloodLayer = pMap.Layer(0)
```

Deletes the featurelayer that contained both the boolean parts of above and under new flood layer.

```
pMap.DeleteLayer pMap.Layer(1)
```

Intialize the Geoprocessor.

```
Dim pGP As IGeoProcessor
Set pGP = New GeoProcessor
```

Set OverWriteOutputs to True.

```
pGP.OverwriteOutput = True

Dim pResult As IGeoProcessorResult
```

Create the array of parameters.

```
Dim pParameterArray As IVariantArray
Set pParameterArray = New esriSystem.VarArray

pParameterArray.RemoveAll
pParameterArray.Add pLayer2
pParameterArray.Add "INTERSECT"
pParameterArray.Add "Flood Layer"
```

Execute SelectLayerByLocation Function.

```
Set pResult = pGP.Execute("SelectLayerByLocation_management", pParameterArray, Nothing)
ReturnMessages pResult
```

Set Flood layer transparency to 60%.

```
Dim Flood As ILayerEffects
```

```
        Set Flood = FloodLayer
        Flood.Transparency = 60

        pActiveView.Refresh

        Set pFeatSelect = pLayer2
        Flooded = pFeatSelect.SelectionSet.Count

End Function

Public Sub ReturnMessages(ByVal messages As IGeoProcessorResult)

    Dim I As Long
    Dim message As String

    For I = 0 To messages.MessageCount - 1
        message = messages.GetMessage(I)
        Debug.Print message
    Next

End Sub
```

Question button for cultural layer input.

```
Private Sub cultquestion_Click()
MsgBox "Select the layer that contains the cultural shapes (polygons, polylines or points) that are vulnerable to the storm surge.", vbQuestion
End Sub
```

Question button for economic layer input.

```
Private Sub ecoquestion_Click()
MsgBox "Select the layer that contains the economic shapes (polygons, polylines or points) that are vulnerable to the storm surge.", vbQuestion
End Sub
```

Question button for elevation layer input.

```
Private Sub elevationquestion_Click()
MsgBox "Select the raster layer that contains your projects elevation data.", vbQuestion
End Sub
```

Question button for environmental layer input.

```
Private Sub enviroquestion_Click()
MsgBox "Select the layer that contains the environmental shapes (polygons, polylines or points) that are vulnerable to the storm surge.", vbQuestion
```

End Sub

Question button for social layer input.

Private Sub socialquestion_Click()
MsgBox "Select the layer that contains the social shapes (polygons, polylines or points) that are vulnerable to the storm surge.", vbQuestion
End Sub

Private Sub UserForm_Initialize()

Get entry to ArcObjects.

Dim pMxdoc As IMxDocument
Set pMxdoc = ThisDocument

Load layers in each of the combobox drop down lists.

```
Dim pMap As IMap
Set pMap = pMxdoc.FocusMap
lcount = pMap.LayerCount
Dim pLayer As ILayer

    For I = 0 To lcount - 1
    Set pLayer = pMap.Layer(I)
    elevationbox.AddItem pLayer.Name

    Next
elevationbox.Text = elevationbox.List(0, 0)

    For I = 0 To lcount - 1
    Set pLayer = pMap.Layer(I)
    envirobox.AddItem pLayer.Name

    Next
envirobox.Text = envirobox.List(0, 0)

    For I = 0 To lcount - 1
    Set pLayer = pMap.Layer(I)
    ecobox.AddItem pLayer.Name

    Next
ecobox.Text = ecobox.List(0, 0)

    For I = 0 To lcount - 1
    Set pLayer = pMap.Layer(I)
    socialbox.AddItem pLayer.Name
```

```
        Next
socialbox.Text = socialbox.List(0, 0)

        For I = 0 To lcount - 1
        Set pLayer = pMap.Layer(I)
        cultbox.AddItem pLayer.Name

        Next
cultbox.Text = cultbox.List(0, 0)

End Sub

Function getLayerByName(inName As String) As ILayer
Dim pMxdoc As IMxDocument
Set pMxdoc = ThisDocument
Dim pMap As IMap
Set pMap = pMxdoc.FocusMap
lcount = pMap.LayerCount
Dim pLayer As ILayer

        For I = 0 To lcount - 1
        Set pLayer = pMap.Layer(I)
                If inName = pLayer.Name Then
                Set getLayerByName = pLayer
                Exit Function
                End If
        Next

End Function

Function RasterConvertHelper()
        Get the focused Map from MapDocument.
        Dim pMxdoc As IMxDocument
        Set pMxdoc = ThisDocument
        Dim pMap As IMap
        Set pMap = pMxdoc.FocusMap

        Get the input raster from the first layer in ArcMap.
        Dim pLayer As ILayer
        Dim pRasLayer As IRasterLayer
        Dim pInRaster As IRaster
```

```
Set pLayer = pMap.Layer(0)
If Not TypeOf pLayer Is IRasterLayer Then Exit Function

Set pRasLayer = pLayer
Set pInRaster = pRasLayer.Raster
```

Create a RasterConvertHelper operator.

```
Dim pRasConvertHelper As IRasterConvertHelper
Set pRasConvertHelper = New RasterConvertHelper
Dim pEnv As IRasterAnalysisEnvironment
Set pEnv = New RasterAnalysis
pEnv.SetCellSize esriRasterEnvMaxOf
```

Perform ToShapefile operation.

```
Dim pOutFClass As IFeatureClass
Set pOutFClass = pRasConvertHelper.ToShapefile(pInRaster, esriGeometryAny, pEnv)
```

Create a feature layer from output and add it into ArcMap.

```
Dim pOutFeatureLayer As IFeatureLayer
Set pOutFeatureLayer = New FeatureLayer
Set pOutFeatureLayer.FeatureClass = pOutFClass
pOutFeatureLayer.Name = "SLR FeatureLayer"
pMap.AddLayer pOutFeatureLayer

End Function
```

Appendix F: STELLA Equations

This appendix presents the detailed components of the System Dynamics (SD) model presented in the thesis (Chapters 4 and 5). The iSee Systems STELLA software was used for the building and application of the system dynamic models. Section 4.7 described the process of the two SD models (Model 1: "backward" and Model 2: "forward" models) presented in the thesis. Model 1 has total estimated damages as inputs and direct estimated damages as outputs, whereas Model 2 has direct estimated damages as inputs and total damages as outputs. Figure 4.35 (Model 1) and Figure 4.36 (Model 2) show screenshots of the two models in the STELLA environment. Appendix F-1 below provides the STELLA equations that form SD Model 1, and Appendix F-2 below provides the STELLA equations that form SD Model 2.

F-1: Model 1 STELLA Equations

Dcultural(t) = Dcultural(t - dt) + (- Total_Flow_4) * dt
INIT Dcultural = 1411729.73

OUTFLOWS:
Total_Flow_4 = 999999999999999999
Deconomic(t) = Deconomic(t - dt) + (- Total_Flow_2) * dt
INIT Deconomic = 12613931

OUTFLOWS:
Total_Flow_2 = 9999999999999999
Denvironment(t) = Denvironment(t - dt) + (- Total_Flow_1) * dt
INIT Denvironment = 15135664.28

OUTFLOWS:
Total_Flow_1 = 999999999999999
Dsocial(t) = Dsocial(t - dt) + (- Total_Flow_3) * dt
INIT Dsocial = 880381.79

OUTFLOWS:
Total_Flow_3 = 9999999999

X1(t) = X1(t - dt) + (Total_Flow_1 - indirect_1) * dt
INIT X1 = 0

INFLOWS:
Total_Flow_1 = 999999999999999
OUTFLOWS:
indirect_1 = PW21
X2(t) = X2(t - dt) + (Total_Flow_2 - indirect_2) * dt
INIT X2 = 0

INFLOWS:
Total_Flow_2 = 9999999999999999
OUTFLOWS:
indirect_2 = NR12+HS32
X3(t) = X3(t - dt) + (Total_Flow_3 - indirect_3) * dt
INIT X3 = 0

INFLOWS:
Total_Flow_3 = 9999999999
OUTFLOWS:
indirect_3 = NR13+PW23+CR43
X4(t) = X4(t - dt) + (Total_Flow_4 - indirect_4) * dt
INIT X4 = 0

INFLOWS:
Total_Flow_4 = 999999999999999999
OUTFLOWS:
indirect_4 = LU14+S34+CR44
CR43 = .04*X4
CR44 = .11*X4
HS32 = 1*X3
LU14 = .01*X1
NR12 = .1*X1
NR13 = .001*X1
PW21 = .10*X2
PW23 = .01*X2
S34 = 0.75*X3
Total_Direct_Damage = X4+X2+X1+X3

F-2: Model 2 STELLA Equations

D_cult(t) = D_cult(t - dt) + (Direct_Flow_4 + Indirect_4) * dt
INIT D_cult = 0

INFLOWS:
Direct_Flow_4 = 673081.25
Indirect_4 = LU14+S34+CR44
D_eco(t) = D_eco(t - dt) + (Direct_Flow_2 + Indirect_2) * dt
INIT D_eco = 0

INFLOWS:
Direct_Flow_2 = 6640795.84
Indirect_2 = NR12+HS32
D_env(t) = D_env(t - dt) + (Direct_Flow_1 + Indirect_1) * dt
INIT D_env = 0

INFLOWS:
Direct_Flow_1 = 11455372.81
Indirect_1 = PW21
D_soc(t) = D_soc(t - dt) + (Direct_Flow_3 + Indirect_3) * dt
INIT D_soc = 0

INFLOWS:
Direct_Flow_3 = 139647.45
Indirect_3 = NR13+PW23+CR43
i_Cult(t) = i_Cult(t - dt) + (- Direct_Flow_4) * dt
INIT i_Cult = 673081.25

OUTFLOWS:
Direct_Flow_4 = 673081.25
i_Eco(t) = i_Eco(t - dt) + (- Direct_Flow_2) * dt
INIT i_Eco = 6640795.84

OUTFLOWS:
Direct_Flow_2 = 6640795.84
i_Env(t) = i_Env(t - dt) + (- Direct_Flow_1) * dt
INIT i_Env = 11455372.81

OUTFLOWS:
Direct_Flow_1 = 11455372.81
i_Social(t) = i_Social(t - dt) + (- Direct_Flow_3) * dt

INIT i_Social = 139647.45

OUTFLOWS:

Direct_Flow_3 = 139647.45

CR43 = .04*i_Cult

CR44 = .11*i_Cult

Damage_Todal = D_cult+D_eco+D_env+D_soc

HS32 = 7*i_Social

LU14 = .01*i_Env

NR12 = .1*i_Env

NR13 = .004*i_Env

PW21 = .1*i_Eco

PW23 = .01*i_Eco

S34 = .75*i_Social

Appendix G: GIS-SD Storm Simulation Model Results and Descriptive Statistics

This appendix presents the detailed results for all trials of the GIS-SD Storm Simulation Model that were presented in summary form in the thesis. The results from the GIS-SD storm simulation model are summarized in Section 5.2 and descriptive statistics of the trial results are examined in Section 5.3 of the thesis. Below, the full trial results for the simulation of total estimated damages by community profile pillar of storm Scenario II, IV and VI are provided in Table G.1. Table G.2 provides a similar table with the full trial results for the simulation of the direct estimated damages by Community Profile pillar of storm Scenario II, IV and VI. The storm input attributes (speed, wind and pressure) for all simulation trials for Storm Scenario II, IV and VI by Community Profile pillar are provided in Table G.3. Descriptive statistics (mean, standard deviation, variance, minimum, maximum, and kurtosis) of the trial results for total and direct estimated damages by pillar and for the storm input attributes are provided in Tables G.4, G.5 and G.6 respectively.

Table G.1: Total estimated damage simulation results for 10 trials each of Storm Scenarios II, IV, and VI

Scenario	Trial	Environmental	Economic	Social	Cultural	Total
II	1	$2,160,285.12	$1,775,480.43	$121,957.33	$200,716.97	$4,258,439.85
	2	$2,035,329.22	$1,672,782.53	$114,903.04	$189,107.04	$4,012,121.83
	3	$2,096,939.82	$1,723,418.63	$118,381.22	$194,831.42	$4,133,571.09
	4	$1,980,668.64	$1,627,858.47	$111,817.21	$184,028.40	$3,904,372.72
	5	$2,217,796.65	$1,822,747.62	$125,204.10	$206,060.50	$4,371,808.87
	6	$2,179,943.01	$1,791,636.73	$123,067.10	$202,543.43	$4,297,190.27
	7	$2,165,798.39	$1,780,011.65	$122,268.58	$201,229.22	$4,269,307.84
	8	$2,048,266.87	$1,683,415.64	$115,633.42	$190,309.10	$4,037,625.03
	9	$2,041,770.35	$1,678,076.32	$115,266.67	$189,705.50	$4,024,818.84
	10	$1,986,894.57	$1,632,975.39	$112,168.69	$184,606.86	$3,916,645.51
IV	1	$7,967,422.30	$6,732,243.67	$462,996.75	$731,391.93	$15,894,054.65
	2	$7,851,786.86	$6,634,535.04	$463,053.42	$720,776.85	$15,670,152.17
	3	$7,653,776.37	$6,467,221.84	$444,770.84	$702,599.92	$15,268,368.97

	4	$7,383,742.73	$6,239,051.15	$429,078.41	$677,811.43	$14,729,683.72
	5	$7,023,630.24	$5,934,766.41	$408,151.82	$644,753.89	$14,011,302.36
	6	$6,767,406.40	$5,718,264.60	$393,262.34	$621,233.10	$13,500,166.44
	7	$6,403,946.66	$5,411,151.53	$372,141.25	$587,868.29	$12,775,107.73
	8	$7,375,909.20	$6,232,432.04	$428,623.19	$677,092.33	$14,714,056.76
	9	$7,402,904.94	$6,255,242.67	$430,191.95	$679,570.48	$14,767,910.04
	10	$6,736,372.97	$5,692,042.24	$391,458.95	$618,384.30	$13,438,258.46
VI	1	**Total Env**	**Total Eco**	**Total Soc**	**Total Cult**	**Total Dam**
	2	$14,986,324.96	$12,489,472.91	$871,695.32	$1,397,800.59	$29,745,293.78
	3	$14,253,225.45	$11,878,514.14	$829,053.81	$1,329,423.12	$28,290,216.52
	4	$13,623,073.70	$11,353,351.16	$792,400.38	$1,270,647.78	$27,039,473.02
	5	$15,164,315.73	$12,637,808.86	$882,048.34	$1,414,402.10	$30,098,575.03
	6	$14,823,664.18	$12,353,912.83	$862,233.98	$1,382,628.94	$29,422,439.93
	7	$16,265,467.65	$13,555,499.30	$946,097.99	$1,517,108.46	$32,284,173.40
	8	$14,095,168.10	$11,746,790.53	$819,860.24	$1,314,680.84	$27,976,499.71
	9	$16,791,010.32	$13,993,481.99	$976,666.73	$1,566,126.73	$33,327,285.77
	10	$14,880,092.73	$12,400,939.89	$865,516.21	$1,387,892.13	$29,534,440.96

Table G.4: Direct estimated damage simulation results for 10 trials each of Storm Scenarios II, IV, and VI

Scenario	Trial	Environmental	Economic	Social	Cultural	Total
II	1	$1,982,737.08	$1,437,494.59	$94,013.56	$65,567.25	$3,579,812.48
	2	$1,868,050.97	$1,354,346.57	$88,575.60	$61,774.69	$3,372,747.83
	3	$1,924,597.96	$1,395,343.43	$91,256.84	$63,644.65	$3,474,842.87
	4	$1,817,882.79	$1,317,974.40	$86,196.82	$60,115.68	$3,282,169.69
	5	$2,035,521.89	$1,475,763.86	$96,516.41	$67,312.80	$3,675,114.95
	6	$2,000,779.34	$1,450,575.33	$94,869.05	$66,163.90	$3,612,387.62
	7	$1,987,797.23	$1,441,163.23	$94,253.50	$65,734.59	$3,588,948.54
	8	$1,879,925.31	$1,362,955.53	$89,138.63	$62,167.37	$3,394,186.84
	9	$1,873,962.72	$1,358,632.62	$88,855.92	$61,970.19	$3,383,421.44
	10	$1,823,597.03	$1,322,117.24	$86,467.77	$60,304.64	$3,292,486.68
IV	1	$7,294,197.93	$5,472,504.69	$358,451.21	$224,017.03	$13,349,170.86
	2	$7,188,333.36	$5,386,302.93	$360,025.21	$215,683.46	$13,150,344.96
	3	$7,007,054.19	$5,257,073.36	$344,340.85	$215,198.04	$12,823,666.43
	4	$6,759,837.62	$5,071,598.47	$332,191.70	$207,605.94	$12,371,233.72
	5	$6,430,153.60	$4,824,251.57	$315,990.37	$197,480.79	$11,767,876.33
	6	$6,195,579.94	$4,648,261.62	$304,462.96	$190,276.64	$11,338,581.16
	7	$5,862,831.51	$4,398,615.61	$288,111.06	$180,057.37	$10,729,615.55
	8	$6,752,666.00	$5,066,217.93	$331,839.27	$207,385.69	$12,358,108.88
	9	$6,777,380.67	$5,084,760.23	$333,053.80	$208,144.72	$12,403,339.41
	10	$6,167,168.75	$4,626,945.99	$303,066.78	$189,404.08	$11,286,585.61

VI	1	$13,737,377.67	$10,119,145.09	$675,902.24	$440,407.79	$24,972,832.79
	2	$13,065,374.04	$9,624,137.79	$642,838.52	$418,863.96	$23,751,214.30
	3	$12,487,738.58	$9,198,643.41	$614,417.88	$400,345.50	$22,701,145.38
	4	$13,900,534.84	$10,239,328.95	$683,929.85	$445,638.46	$25,269,432.10
	5	$13,588,272.90	$10,009,312.43	$668,566.03	$435,627.63	$24,701,778.99
	6	$14,909,917.72	$10,982,854.55	$733,593.19	$477,998.36	$27,104,363.82
	7	$12,920,489.05	$9,517,413.48	$635,709.93	$414,219.09	$23,487,831.55
	8	$15,391,662.12	$11,337,714.23	$757,295.83	$493,442.64	$27,980,114.82
	9	$13,639,998.74	$10,047,414.41	$671,111.03	$437,285.91	$24,795,810.09
	10	$13,874,271.18	$10,219,982.78	$682,637.63	$444,796.47	$25,221,688.06

Table G.3: Storm Scenario attributes simulation results for the 10 trials of Storm Scenarios II, IV, and VI

Scenario	Trial	Speed (km/h)	Wind (km/h)	Pressure (mb)
II	1	54.23	86.2	986.37
	2	51.74	81.34	988.52
	3	50.08	90.98	988.96
	4	54.25	75.95	984.55
	5	55.18	91.6	984.11
	6	55.77	93.3	980.62
	7	55.7	82.64	985.77
	8	54.6	76.12	986.52
	9	52.81	81.26	986.85
	10	53.89	80.54	983.07
IV	1	64.98	132.32	966.48
	2	65.92	134.13	962.5
	3	64.17	135.58	962.68
	4	63.2	117.23	970.99
	5	64.06	115.33	966.33
	6	60.6	117.16	968.79
	7	61.71	115.96	963.25
	8	62.29	112.32	970.43
	9	65.88	123.43	963.06
	10	60.96	118.42	967.11
VI	1	72.46	163.67	947.84
	2	71.96	168.3	942.28
	3	71.12	167.25	940.89
	4	72.75	174.02	942.88
	5	74.71	162.96	943.19
	6	75.52	168.27	946.9
	7	72.57	157.06	946.17

	8	74.17	174.19	949.18
	9	70.14	166.41	950.08
	10	72.58	169.24	945.53

Table G.4: Total estimated damage statistics by Community Profile pillar component and by scenario for the simulation results for 10 trials each of Storm Scenarios II, IV, and VI

Scenario	Type	Environmental	Economic	Social	Cultural	Total
II	Mean	$2,091,369.26	$1,718,840.34	$118,066.74	$194,313.84	$4,122,590.19
	Standard Deviation	84837.92294	69726.01444	4789.46309	7882.483105	167235.8836
	Variance	7197473169	4861717089	22938956.7	62133539.9	27967840755
	Minimum	$1,980,668.64	$1,627,858.47	$111,817.21	$184,028.40	$3,904,372.72
	Maximum	$2,217,796.65	$1,822,747.62	$125,204.10	$206,060.50	$4,371,808.87
	Kurtosis	-1.563029537	-1.563029588	-1.56302895	-1.56302876	-1.563029505
IV	Mean	$7,256,689.87	$6,131,695.12	$422,372.89	$666,148.25	$14,476,906.13
	Standard Deviation	512109.9048	432718.2043	30696.7098	47010.56769	1022474.87
	Variance	2.62257E+11	1.87245E+11	942287992	2209993475	1.04545E+12
	Minimum	$6,403,946.66	$5,411,151.53	$372,141.25	$587,868.29	$12,775,107.73
	Maximum	$7,967,422.30	$6,732,243.67	$463,053.42	$731,391.93	$15,894,054.65
	Kurtosis	-0.947998192	-0.947998196	-0.95694813	-0.94799813	-0.949412375
VI	Mean	$15,001,800.71	$12,502,370.26	$872,595.48	$1,399,244.04	$29,776,010.49
	Standard Deviation	952918.1195	794153.6745	55427.4811	88880.33007	1891379.605
	Variance	9.08053E+11	6.3068E+11	3072205656	7899713074	3.57732E+12
	Minimum	$13,623,073.70	$11,353,351.16	$792,400.38	$1,270,647.78	$27,039,473.02
	Maximum	$16,791,010.32	$13,993,481.99	$976,666.73	$1,566,126.73	$33,327,285.77
	Kurtosis	0.267234996	0.267234987	0.26723482	0.267234807	0.267234978

Table G.5: Direct estimated damage statistics by Community Profile pillar component and by scenario simulation results for 10 trials each of Storm Scenarios II, IV, and VI

Scenario	Type	Environmental	Economic	Social	Cultural	Total
II	Mean	$1,919,485.23	$1,391,636.68	$91,014.41	$63,475.58	$3,465,611.89
	Standard Deviation	77865.32295	56452.75962	3692.066016	2574.93352	140585.0801
	Variance	6063008519	3186914069	13631351.47	6630282.64	19764164734
	Minimum	$1,817,882.79	$1,317,974.40	$86,196.82	$60,115.68	$3,282,169.69
	Maximum	$2,035,521.89	$1,475,763.86	$96,516.41	$67,312.80	$3,675,114.95
	Kurtosis	-1.563029518	-1.563029572	-1.56302869	-1.5630286	-1.563029551

IV	Mean	$6,643,520.36	$4,983,653.24	$327,153.32	$203,525.38	$12,157,852.29
	Standard Deviation	468838.0839	350878.3442	23994.47318	13820.6515	857369.4014
	Variance	2.19809E+11	1.23116E+11	575734743.1	191010408	7.35082E+11
	Minimum	$5,862,831.51	$4,398,615.61	$288,111.06	$180,057.37	$10,729,615.55
	Maximum	$7,294,197.93	$5,472,504.69	$360,025.21	$224,017.03	$13,349,170.86
	Kurtosis	-0.947998204	-0.943522868	-0.9434221	-0.7923957	-0.946680248
VI	Mean	$13,751,563.68	$10,129,594.71	$676,600.21	$440,862.58	$24,998,621.19
	Standard Deviation	873502.7517	643434.3822	42977.81353	28003.7023	1587918.649
	Variance	7.63007E+11	4.14008E+11	1847092456	784207345	2.52149E+12
	Minimum	$12,487,738.58	$9,198,643.41	$614,417.88	$400,345.50	$22,701,145.38
	Maximum	$15,391,662.12	$11,337,714.23	$757,295.83	$493,442.64	$27,980,114.82
	Kurtosis	0.267235005	0.267235003	0.267234779	0.26723472	0.267234988

Table G.6: Storm attributes statistics by component and scenario

Scenario	Type	Speed	Wind	Pressure
II	Mean	53.83	83.99	985.53
	Standard Deviation	1.81	6.26	2.52
	Variance	3.28	39.23	6.37
	Minimum	50.08	75.95	980.62
	Maximum	55.77	93.30	988.96
	Kurtosis	0.69	-1.29	0.22
IV	Mean	63.38	122.19	966.16
	Standard Deviation	1.94	8.65	3.22
	Variance	3.77	74.82	10.34
	Minimum	60.60	112.32	962.50
	Maximum	65.92	135.58	970.99
	Kurtosis	-1.41	-1.31	-1.45
VI	Mean	72.80	167.14	945.49
	Standard Deviation	1.62	5.12	3.28
	Variance	2.64	26.19	10.78
	Minimum	70.14	157.06	940.89
	Maximum	75.52	174.19	950.08
	Kurtosis	-0.26	0.59	-1.59