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Thesis

Risk Analysis in Coastal Communities Decision Making

Student Name

Seyedeh Sara Mohammadi

Thesis Supervisor: Dr. Daniel E. Lane

Telfer School of Management

University of Ottawa

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I would like to bestow this moment of happiness to my mother, father, and brother who are always on my mind and forever in my heart. I am living for you making your dreams come true.

I would like to thank all my wonderful friends because of all happy moments that we have spent together.

I would like to thank my beloved friend Mostafa because of the million things that he never knew he is doing.

Sara,

July 2014

Abstract

The analysis of decision making under risk involves (i) risk assessment - the preparation of appropriate probability assessments of stochastic events; (ii) risk management – the application of quantifiable measures of the impacts of the stochastic events under alternative strategies; and (iii) risk communication – through the governance of structured decision making processes, and tracking and monitoring of the event. This work involves the application of the steps of the risk analysis process on coastal communities facing short-term operational decisions and long-term strategic decisions to deal with the pending impacts of climate change. These impacts include the immediate impacts from the increased frequency of severe storms and storm surge, and the long-term impacts of rising sea levels. The analysis of risk is in support of coastal communities' decision support systems. This work is a part of the C-Change International Community-University Research Alliance (ICURA) program that is examining the adaptation of selected coastal communities in Canada and the Caribbean. In all these cases, the foundation to support community-based decision making for adaptation is required in the event of mounting evidence that coastal communities are especially susceptible to the changing climate, that coastal communities are under-resourced with respect to their abilities to respond to the climate threats, and that coastal communities are in need of defensible structures on which to make critical decisions on adaptation that will ensure community sustainability. The work draws on: (1) statistical, time-series analysis for predicting the event of storms; (2) the profiling of community threats and vulnerabilities, as well as community environmental, economic, social, and cultural priorities; (3) the calibration and interpretation of storm impacts through utility curve analysis; and (4) the application of the risk analysis to decision making in complex, multi-criteria environments. The significance of determining an appropriate time horizon for adaptation decision making impacts communities' outcomes. If strategic planning periods are too short, evidence from this research demonstrates that the often used strategy of Status Quo or 'Do Nothing' may be justified. However, a more strategic planning period clearly indicates that an active adaptation strategy to Accommodate or Protect the community from severe storms is much preferred to the 'Do Nothing' strategy or the unwelcome Retreat strategy in the face of more frequent severe storms. The community of Charlottetown, PEI, is considered as the application of this study.

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1 Introduction

This document presents research in the form of a thesis in partial fulfillment of the M.Sc. degree in Systems Science at the University of Ottawa.

1.1 Background and Motivation

In recent decades, climatic changes have manifested itself as sea level rise, changing precipitation patterns, more frequent intense weather events, storm surges and flooding, salinisation of fresh water aquifers and wells, coastal erosions, sedimentation of coastal waters, and pollution from flooded or destroyed infrastructure and storm runoff (Lane & Watson, 2011). The recent draft of the IPCC fifth assessment report similarly declares that these events are becoming more frequent.

At the end of October 2012, Hurricane Sandy slammed into the east coast of the United States of America. It had begun from the coast of Africa as a tropical depression on October 11 and gradually grew into an Atlantic category 3 hurricane by the time it hit Cuba on October 25. Moving up the eastern seaboard of the U.S., it made landfall in New Jersey on October 29 as a post-tropical cyclone with hurricane-force winds (Blake et al, 2013). The highest tides reported in New Jersey and New York were recorded 8.5 feet (2.6 m) over normal level at Sandy Hook, and more than 12.5 feet (3.8 m) at Kings Point on the western edge of Long Island Sound (Huffington Post Canada, 2013). Recorded as the second-costliest hurricane in northeastern U.S. in 40 years, hurricane Sandy destroyed 305,000 homes in New York State. The damages caused by Sandy are estimated to be at least $ 71.3 billion, with 121 deaths in overall (Irish Central, 2012).

The threats posed by changing climate on coastal population around the globe are inevitable. Over the coming decades, climate-driven changes are expected to become increasingly more frequent and severe. Hence, effective management of coastal risks and adaptation to the climate related changes are considered as immediate needs (Brian, 2008).

For every coastal community, there is a wide range of responses to climate change impacts in terms of cost, time, severity of climate event, and the vulnerabilities and threats to the area. The geographical situation of coastal communities differs among communities. Therefore, the threats and vulnerabilities of each area and the impacts of the changing

climate vary by region. Selection of proper adaptation strategies is influenced by these variations and should be considered in the unique context of the coastal community.

For example, short term and long term responses may be considered in order to deal with increasingly frequent and extreme rainfall events. Short-term solutions may include various responses such as better predictions and advanced warning systems, increased maintenance of storm sewers, reduction of storage levels in dams and reservoirs. As well, long term responses may involve replacement of aging infrastructures with upgraded sewer pipes, re-routing major arteries, and reduction of asphalt and concrete surfaces (Bruce et al., 2006).

The question that can arise here is which adaptation strategy suits the community and has higher priority in reducing the area exposure and the impacts of increasingly frequent and extreme rainfall. Responses to the climate change impacts are even more complicated if the condition under which the decision must be made is uncertain. What coastal communities are dealing with currently is making the correct decisions with limited and constrained resources for the uncertain and risky future.

Assessing and managing under risk related to alternative adaptation strategies enables coastal communities to find the answers to these fundamental questions. Evaluation and analysis of the adaptation alternatives are part of the risk assessment topic of this research. Assigning priority to multifaceted impacts and choosing vulnerability reduction strategies are supported by risk management. A practicable approach is provided by risk management to achieve an acceptable level of decision making under risk and uncertainty for comparing a range of factors and using predictive information (Bruce et al., 2006).

This research generates a framework to support an effective and reliable decision-making process through the means of a clearly defined risk analysis. To this end, community adaptation alternatives, which are currently seen as being less important, are more fully reviewed to take into account the probable severe storm events of the changing coastal climate, the impacts of severe storms, the community priorities, and the high opportunity cost of inaction in the face of change.

1.2 Research Questions and Objectives

The main focus of this research is to develop a framework for risk analysis in decision making and to provide coastal communities with a more reliable decision support process for

the severe events associated with the changing coastal climate, e. g., more frequent storms, and rising seas.

The main questions and objectives of this proposed research are as follows:

1) What are the threats and vulnerabilities facing coastal communities and what are the likelihood of occurrence and impact of severe coastal storm events?

Objective: develop the historical incidence of storm events for a particular coastal community and estimate the impacts on the profile of the community.

2) How can community adaptation strategies for the preparation of the changing coastal environment be evaluated and what is the appropriate time frame for the analysis of severe storm events to determine effective strategic actions?

Objective: apply risk analysis to the alternative adaptation strategies and design experiments to test (compare and contrast) the results of evaluated adaptation strategies assessing different planning horizons.

3) How can sustainable decisions be made under the uncertain future of climate change using effective risk analysis?

Objective: define effective risk analysis to model appropriate planning decisions, expected impacts, and realistic event probabilities.

1.3 Thesis Proposal Outline

This research document includes six chapters. The current chapter introduces background and motivation. As well, this chapter presents the main questions of the research and associated objectives. The second chapter, literature review, reviews coastal communities' threats and vulnerabilities, provides information on risk analysis, and discusses the application for the research as a case study. The third chapter on research methodology presents the proposed research process, and details the elements of risk analysis including risk assessment, risk management, and risk communication.

The fourth chapter presents analysis and results. Conclusions and recommendations for future research are provided in the fifth chapter. The bibliography, references, and appendices complete this research document.

2 Literature Review

This section reviews important components of this research in the literature. It is divided into five main sections: (2.1) profiling a coastal community, (2.2) vulnerabilities and threats to coastal communities, (2.3) risk analysis, (2.4) application, and (2.5) summary.

2.1 Profiling A Coastal Community

The community profile describes the community of interest. The community profile captures a number of pillars of the community and provides a more comprehensive picture of a community based on its assets. To profile the coastal community, a framework is needed to capture all of diverse aspects of community's vulnerabilities. This subsection describes coastal community profiles in the literature.

In order to integrate the multiple problems related to C-Change coastal communities, the International Community University Research Alliance (ICURA), "C-Change" (C-Change 2010) developed a framework for community profiling. Development of the C-Change community profile data template takes the community's requirements to prepare Integrated Community Sustainability Plans (ICSPs) as part of the request of municipalities for federal gas tax funding through the province (FCM, 2009). Four principle pillars are covered by the community data profile template of the ICSPs including the environmental, economic, social, and cultural pillars of coastal communities. These pillars are identified as the four "pillars of sustainability". Each pillar is broken into a number of items (Lane & Watson, 2010) as noted in Table 2.1.

Table 2.1Communities Data Profile Items. Source: (Lane & Watson, 2011)

Environmental	**Economic**
• Topography • Hydrology • Coastal Geomorphology • Habitats and Species • Land Cover • Land Use • Marine Use • Climate • Natural Resources	• Employment and Earnings • Occupation • Industry Sector • Industry Revenues ($) • Real Estate Values ($) • Public Works • Built Environment
Social	**Cultural**
• Population Statistics • Language • Health Status • Education • Employment • Communication Resources	• Places of cultural significance • Community groupings • Cultural events and festivals (dates, attendance numbers, area) • Governance Systems • Community dynamics

The main inspiration of the community data profile in the form of Spatial System Dynamics (SSD) comes from Ahmed and Simonovic (2004). The SSD modeling approach is a combined model of System Dynamics (SD) with Geographic Information System (GIS).

Hartt (2011) and Pakdel (2011) develop C-Change community profiles for Charlottetown, P.E.I., and Isle Madame, Cape Breton, Nova Scotia, using ArcGIS and link the geo-referenced asset-based layers to simple SD models. The ArcGIS is used to develop information for vulnerable areas in their respective communities under different climatic change scenarios. The SD model presents the dynamism inherent in the four key pillars and models components' interrelationships, either direct or indirect relationships, of the community using the STELLA SD software.

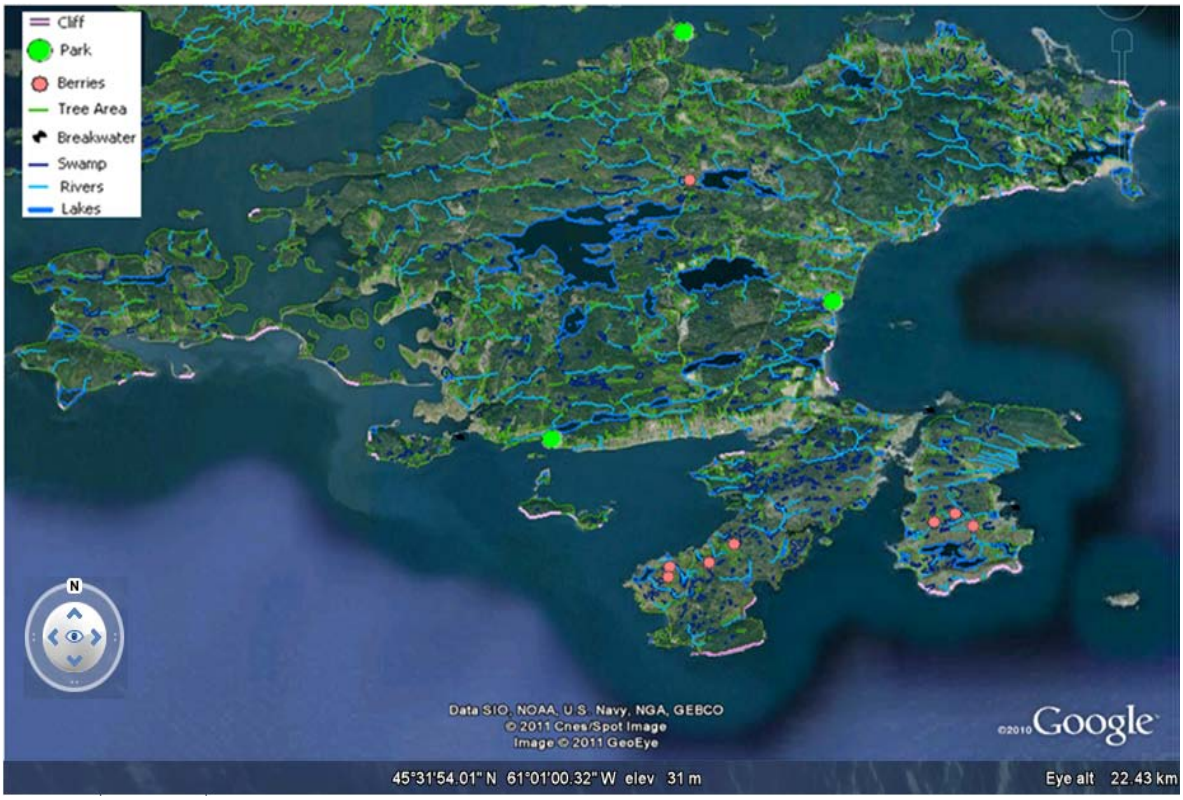

Figure 2.1. Isle Madame's Hydrology, Land Use, and Land Cover Item.
Source: (Pakdel, 2011, p. 58)

The environmental layers in the Isle Madame database, according to Pakdel's study, and the number of available points (or polylines) can be found in Appendix A-Isle Madame Environmental Pillar Components.

The United States Federal Emergency Management Agency (FEMA) describes community profile by five main factors that are prevalent in any community profile; geography, property, infrastructure, demographic, and response organization factor. However, FEMA customizes the community profile for any particular community. The key factors of a community profile are summarized in Table 2.2 below.

FEMA divides communities into different sectors (segments) based on the local geography. Since all areas of the community are not affected by a particular hazard, the segmentation allows communities to find the potential impacts of a specific hazard on different areas and better respond or adapt to climatic changes.

Table 2.2. The Key Factors of a Community Profile. Source: (FEMA, 2006)

Geography	Property	Infrastructure	Demographics	Response Organizations
• Major geographic features • Typical weather patterns	• Numbers • Types • Ages • Building codes • Critical facilities • Potential secondary hazards	• Utilities construction, layout, access • Communication system layout, features, backups • Road systems • Air and water support	• Population size, distribution, concentrations • Numbers of people in vulnerable zones • Special populations • Animal populations	• Locations • Points of contact • Facilities • Services • Resources

2.2 Vulnerabilities and Threats to Coastal Communities

In the following subsections, unified definitions are presented for vulnerability, threat (hazard), and disaster. Difficulties around measuring the vulnerabilities of coastal communities are discussed. Finally, the differences among the biophysical, social, and environmental vulnerabilities are specified by some examples.

2.2.1 Vulnerability, Threat, Adaptive Capacity, and Resilience Definition

"Vulnerability to climate change is the degree to which geophysical, biological and socio-economic systems are susceptible to, and unable to cope with adverse impacts of climate change"(IPCC, 2007, p. 783). Talking about the vulnerability of a specified system or a unit exposed to a specified hazard or a range of hazards is meaningful. A system or exposed unit may be a region, population group, community, ecosystem, country, economic sector, household, business or individual (Adger et al., 2004).

The term hazard (threat) here particularly refers to a physical demonstration of climatic changes. Hazards can be classified in three categories: 1) discrete recurrent hazards such as storms, droughts and extreme rainfall events, 2) continuous hazards, for example the rise in mean temperature over several years or decades, 3) discrete singular hazards, which are sudden climate change events related to the beginning of new climatic conditions that dominate for centuries or millennia (Adger et al., 2004).

According to IPCC (2007), adaptive capacity is defined as "the ability or potential of a system to respond successfully to climate variability and change and include adjustments in both behavior and resources and technologies" (p. 727). Adaptation strategies can be designed and implemented with respect to the adaptive capacity to reduce the negative impacts of climatic changes (IPCC, 2007).

Resilience is defined as the ability of a system to recover, recoup, or rebound from negative impacts of potential hazards within the time and in an efficient way. Resilience can be achieved through prevention and improvement of a system's fundamental structures and functions (IPCC, 2012).

2.2.2 Vulnerability Assessment

In studying climate change and its impacts, two main approaches can be considered; (i) the impact-led approach, and (ii) the vulnerability-led approach. Impact-led approach concerns with future exposure of human to climatic changes. Analysis of the underlying socio-economic and institutional elements, and political and cultural elements, in lesser degree, is defined as the vulnerability-led approach. It assesses people's ability to respond to and cope with climate hazards. Vulnerability assessment, in spite of impact-led approaches, does not require climate change models and information about climate change over time. Lack of this information is not an impediment in developing adaptation policies for future threats. The emphasis has moved from the impacts-led approach to the vulnerability-led approach as climate change and its impacts became more interesting (Adger et al., 2004).

Assessing vulnerability and adaptive capacity can be done on various scales ranging from household, local, regional, to national and global level (Adger et al., 2004). A conceptual framework is needed in order to assess them in a qualitative or quantitative manner. A qualitative approach is suitable for self-assessment such as practices for the purpose of identifying vulnerable systems, regions and groups at the sub-national level. The latter approach provides comparative indicators to compare the vulnerability and adaptive capacity of various systems. Indicators are "quantitative measures intended to represent a characteristic or a parameter of a system of interest" (Cutter et al. 2009, p.13) using a single value (Cutter et al., 2009). Cutter (2009) and Adger (2004) present indicators for measuring the vulnerability of a system in local and national level respectively.

Comparing the vulnerability and adaptive capacity of different countries based on national level indicators brings up some arguments. Since vulnerability has a very specific context and is distinguished within countries, then some argue that vulnerability at a national scale is not appropriate. Nevertheless, the processes that work at the national scale have effects on the vulnerability and adaptive capacity at the local level. For example, the economic well-being of vulnerable groups can be influenced by national economic policies. These policies can include the cost determination of essential needs such as food, education, and healthcare, and the market price of goods that are basic necessities of life for vulnerable groups (Adger et al., 2004).

The potential conflict between vulnerability indicators at the national level and the local level must not be ignored. The vulnerability of one group can be ameliorated by one action, however, that action has negative effect on the other groups. Likewise, national level indicators of adaptive capacity represent the factors and processes that ameliorate or exacerbate further adaptation. The national level is still the main political unit on which emission targets and political policies, and resource allocation are formed (Adger et al., 2004).

According to the dynamic nature of vulnerability, any measures should capture the steady-state situation and any trends in that situation. Vulnerability persistently evolves as a function of interaction between physical processes and the human pillar. Complexity in conceptualizing the understanding of vulnerability is a result of this dynamic character (Leichenko & O'Brien 2002)

The effects of changing climate are unevenly distributed in time and space. The national level functions as a broker between global and local scales. The local and global levels are respectively the level of experience (or impacts), and level of reality (where many influencing processes operate). The fundamental scale of vulnerability is local because of differentiation within the communities. Processes that function at a larger scale contribute significantly to form vulnerability at the local level. Analysis at the national level may encompass other levels. International trends and processes that affect vulnerabilities should be understood for national analysis. In addition, national indicators hide local differences in vulnerability. In attempting to generalize or select indicators on a bigger scale than the scale of the vulnerable area, scale issues become important. Therefore, identification of these

scaling issues and then aggregation to an ultimate spatial scale is contributed to any assessment of overall threat produced by climate problems (Adger et al., 2004).

Studies differ based on present-day and future patterns of vulnerability. Estimation of future patterns of vulnerability is conditioned on indistinct projection of environmental changes and socio-economic trends. Completely integrating socio-economic changes and environmental changes has been achieved by few studies. In measuring the vulnerability towards the goal of the effective resource allocation, the selection of indicators must be based on present-day exposure and capacity as accurately as possible. In order to select measurements of vulnerability to future hazards, using indicators based on observed impacts or diversity is not a good approach, instead a durable option should be taken into account (Adger et al., 2004).

Two general approaches can be considered for indicator selection. One is deductive research approach, which is based on the theoretical understanding of relationships. The other, which is called the inductive research approach, is based on identifying statistical relationships of a large number of variables and relating variables to vulnerability. However, conceptual understanding of vulnerability comes from both approaches. Inductive research finds the patterns in data that can be generalized, which is called theory. Since vulnerability cannot be measured directly, indirect measurements need to be applied to both approaches. They can be achieved through a focus on processes that form vulnerability (Adger et al., 2004).

According to Adger (2004), studies that were successful in closely integrating theory, conceptualization, and indicator selection are more commonly performed at the sub-national level.

2.2.3 Social, Environmental, Economical, and Cultural Vulnerability

Vulnerability in climate related changes falls into two categories:

1) Impact approach- the amount of damage (potential damage) to a system caused by a specific climatic event or hazard, e.g., storm, storm surge, and
2) Hazard approach- the state within a system before it faces the hazardous event.

The impact approach focuses on factors such as number of people at risk of flooding by forecasting sea level rise. In fact, this approach examines human exposure to a hazard rather

than the ability of people to deal with the hazard when it occurs. A combined approach is compatible with the IPCC Third Assessment Report's (TAR) definition of vulnerability, as a function of hazard, exposure, and sensitivity (IPCC, 2001). The vulnerability of a human system to a hazard, the probability occurrence of the hazard, the degree of human exposure to the hazard, and the sensitivity of the system to the hazard are considered in the combined approach (Adger et al., 2004).

Hazard and exposure have different meanings here: a region may frequently experience flood hazards but its population may have less exposure to these hazards by placing settlements out of flood plains and low-lying coastal areas (Adger et al., 2004).

The second view of vulnerability entails studies of those features that make human societies and communities vulnerable to hazards. It may be termed "social vulnerability", as it is determined by factors such as poverty and inequality, marginalization, food entitlements, and access to insurance and housing quality (Adger et al., 1999).

Determinants of social vulnerability can be viewed as two classifications; 1) generic determinants such as poverty, inequality, health, access to resources and social status, and 2) specific determinants to particular hazards. Social vulnerability of a system is independent of the hazards that it is exposed to, but it may involve the exposure and environmental variables, since exposure is related to places where people settled, and their community constructions and livings. Human activities can have an effect on environmental variables, since resources are used by populations. The environment is managed by humans to benefit them in the short or long term. To be brief, without people, there is no disaster (Adger, 1999; Adger, 2004).

Recent Oklahoma twisters happened in Moore, which reached around 474 km/h, had a path very similar to another destructive tornado that happened 14 years ago. The ridge Creek-Moore tornado, in 1999, was classified as the most devastating kind with a wind speed of 484 km/h. It killed 41 people and ruined thousands of homes (CBC News, June 2013). Globally, the potential damages of hurricanes show a significant rising trend since mid-1970s, and a trend to longer storm duration and intensity. Hurricanes are going to be more frequent; there is an increase about 75% in the number of category 4 and 5 hurricanes since 1970 (IPCC, 2007).

The ability of individuals and communities to recover from losses from hazards is affected by socioeconomic status. Poor people are more susceptible than wealthy people to hazards impacts. During the disaster, it is less probable that poor people have access to critical resources and lifelines, like communications and transportation. Even though the losses of the wealthy, in terms of monetary value of the economic and material losses, are more, the losses burdened on poor people are more severe (Cutter et al., 2009).

The severe impacts associated with Hurricane Katrina in August 2003 were a result of socioeconomic inequalities within the population rather than the intensity of the hurricane. The union of race and class (socioeconomic status) creates inequalities. The vulnerability of racial and ethnic minorities considerably increases by discrimination. If discrimination manifests itself in real estate, it may limit minorities to settle in areas exposed to certain hazards. Moreover, minorities may be forbidden in obtaining policies with more-reliable insurance companies. In particular, minorities who emigrated from non-English-speaking countries have language difficulties in their communication. It in turn can increase vulnerability to a disaster and recovering from a disaster (Bolin, 2007).

2.3 Risk Analysis

This section presents a discussion on the importance of risk analysis in adaptations to climate changes. It continues with descriptions of frameworks developed for risk analysis in regarding to climate variabilities and changes in the coastal zone.

2.3.1 Why Risk Analysis?

Identifying different vulnerabilities (the previous subsection) associated with climatic change hazards is the first step toward reducing future damages, vulnerabilities, and exposures. Understanding the risks associated with whether taking action or not assumes communities must also identify strategies to address potential impacts of future damages. In order to deliberate appropriate strategies, coastal communities need to determine the level of risk that underlies their position. Communities that are moved to act to protect their environments do not tolerate the Status Quo or inaction. Alternatively, under similar circumstances, communities that consider the Status Quo acceptable, are *de facto* asserting that the forecasts of potential impacts of future changes represent an acceptable level of risk.

The task of risk analysis is to ascertain clearly what would be the community's level of acceptable risk, and to encourage adaptive action in the case where future trends are expected to alter the status quo to unacceptable positions for the community.

The relationships between climate changes and events, vulnerability, exposure, disaster risk, and sustainable development are depicted in Figure 2.2, which is the core concept of SREX, the IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (IPCC, 2012).

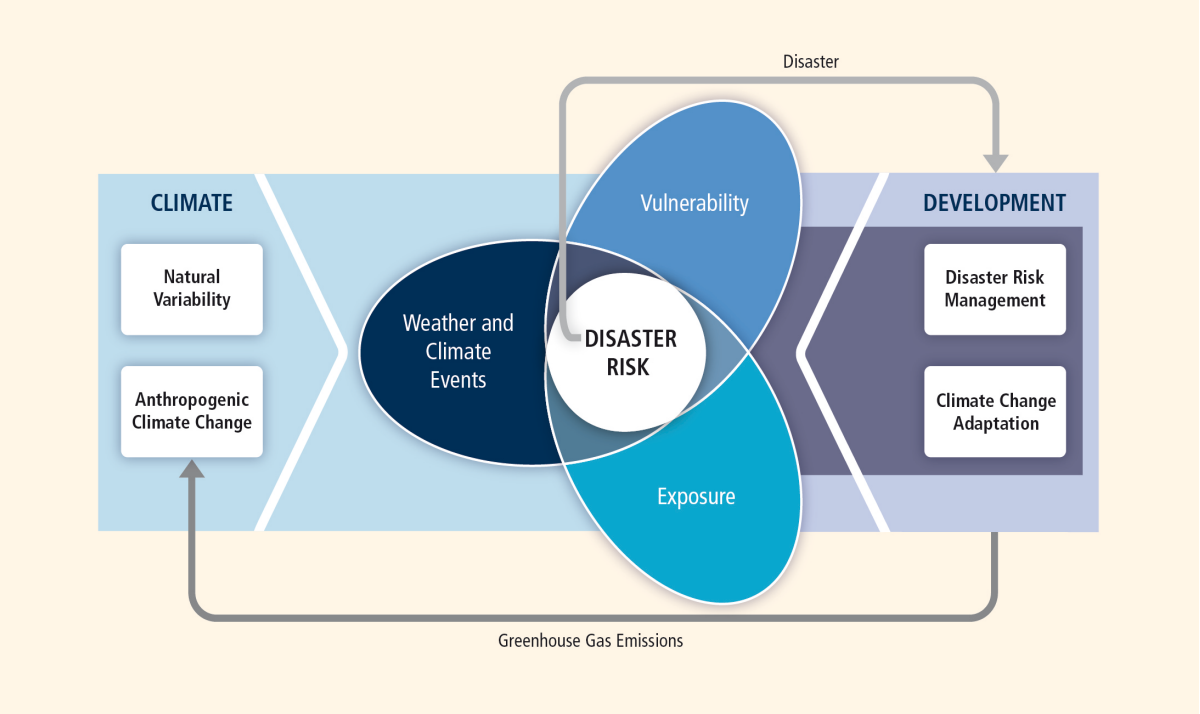

Figure 2.2. Systematization of Climate Change Related Events, Vulnerability, Exposure, Risk and Development. Source (IPCC, 2012)

Figure 2.2 illustrates the effect of natural climate variability and anthropogenic climate change on weather and climate events that can contribute to disaster events. Similarly, exposure and vulnerability of a society and the natural ecosystem have contributed (left to right forcing) to "Disaster Risk". Disaster Risk Management and Climate Change Adaptation decrease the exposure and vulnerability to weather and climate events (right to left resistance). This, in turn, reduces "Disaster Risk", as well as increases resilience to the risks that cannot be eliminated. In addition, "Disaster Risk" can be shrunk by lowering

anthropogenic climate change, which can be achieved by a suitable risk management and adaptation.

Disaster Risk Management and Climate Change Adaptation are stressed more in climate change studies in the recent years, because they have been demonstrated to not only save lives, but also incur lower costs compared to responding to a disaster, e.g.,

> "Estimates suggest that incorporating comprehensive disaster protection into new health facilities and schools would add only 4 percent to their cost." (UNCCC, 2008, p. 44)

2.3.2 Risk Analysis Overview

Risk analysis is broadly defined to include risk assessment, risk management and risk communication (Figure 2.3). Risk analysis is not only a systematic approach, which considers the interaction between all components, but also is an iterative and a repeatable approach. Applying risk analysis methods to climatic change issues improves the insight into the uncertainty, complexity, and risk features of climatic variabilities.

Figure 2.3. Structure of Risk Analysis

The following subsections discuss alternative applied risk analysis methods, namely the UK's CCRA risk assessment, FEMA Risk MAP method, Ontario Ministry of Municipal Affairs and Housing approach, and an alternative risk analysis framework for decision making. These are described in more detail below.

2.3.2.1 UK Climate Change Risk Assessment (CCRA)

Recent research on risk analysis related to climate changes was funded by the U.K. Department for Environment, Food & Rural Affairs (DEFRA), the Scottish Government, the Welsh Government, and the Department of the Environment Northern Ireland. This refers to substantive UK Climate Change Risk Assessment (CCRA, 2012a,b,&c). The CCRA uses current evidences to create an initial picture of how climate change may affect the UK in the future to decide how to respond. Taking account of new climate observations and improved understanding of future climate change and risk, the evidences and snapshots will be updated every five years. In other words, important risks to UK infrastructures (11 sectors) are shown in the absence of any actions. The projection is made in three time frames: 'the 2020s' (2010-2039), 'the 2050s' (2040-2069), and 'the 2080s' (2070-2099) (UKCCRA, 2012a).

The CCRA method provides the possibility of comparison of approximately 100 'risks' in 11 different sectors, where each 'risk' is a projection of uncertain future climate change on key issues of one particular theme. For example, water is a key issue in the agriculture and forestry theme. Each 'risk' is developed within one sector and can be considered as either opportunity or threat for that theme (UKCCRA, 2012a). For example increase in the water demand for irrigation of crops is considered as a 'risk' in agriculture and forestry (UKCCRA, 2012b).

UKCCRA compares 100 'risks' in terms of the magnitude of consequences and the confidence of future occurrences in the evidence base. The confidence ranges from "low" and "medium", to "high" and indicates how much confidence exists in the projected timing and intensity of each potential risk (UKCCRA, 2012a). The classification table for the confidence level on which CCRA relies is presented in Table 2.3.

Table 2.3. Summary Classification of Confidence. Source: (UKCCRA, 2012a, p. 29)

Class	Definition
High	Reliable analysis and methods, with a strong theoretical basis, subject to peer review and accepted within a sector as 'fit for purpose'.
Medium	Estimation of potential impacts or consequences, grounded in theory, using accepted methods and with some agreement across the sector.
Low	Expert view based on limited information, e.g. anecdotal evidence, or very simplistic estimation methods.

The key phases of the UKCCRA method are demonstrated as follows by Figure 2.4 below.

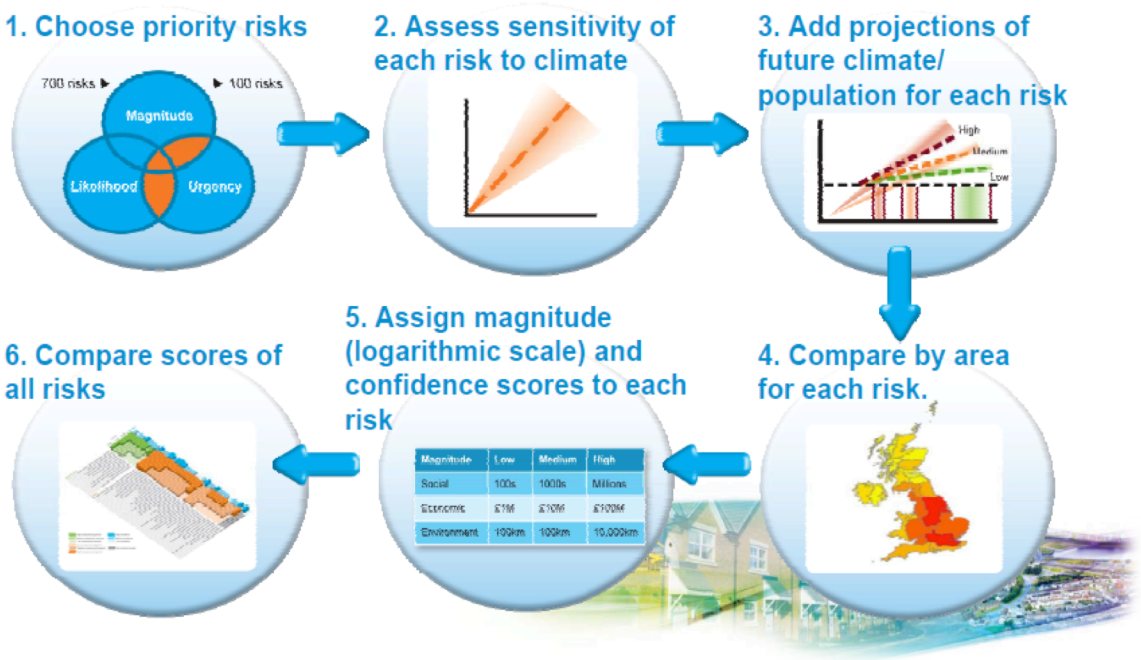

Figure 2.4. CCRA Method Overview. Source: (UKCCRA, 2012c)

The CCRA assesses the sensitivity of each 'risk' to climate changes by using sensitivity analysis, historical data, or expert elicitation methodology. In order to estimate the magnitude of consequences, CCRA projects the future climatic and socio-economic changes for every consequence. The sensitivity of the consequences to three different emission scenarios (High, Medium, and Low emission), the climatic change, and three variant populations (High, Principal, and Low), the socio-economic change, is estimated. The

consequences are evaluated for five complementary themes: (i) Agriculture and Forestry, (ii) Business, (iii) Health and Wellbeing, (iv) Buildings and Infrastructure, and (v) Natural Environment. The magnitude of consequences for each "risk metric" is computed by the following simple scoring function that assigns scores of 1 (low), 2 (medium), and 3 (high) to the various criteria (social, economy, environmental, likelihood, and urgency) to determine the overall score,

$$(\text{Social} + \text{Economic} + \text{Environmental})\ /9\ *(\text{Likelihood}/3)*(\text{Urgency}/3)*100 \quad (2.1)$$

The urgency defined here is the urgency with which adaptation decisions need to be taken, and the likelihood is the perceived probability of the impact occurrence.

Then the measured 'risk' level is compared with the UK magnitude classification table of the area (which is provided by the judgment and moderation of the project team) to determine the appropriate range for magnitude, which ranges from low to medium to high (UKCCRA, 2012a). One sample of the classification table created for damages and losses is presented in Appendix B-The UK's Guidance on Classification of Relative Magnitude.

For example, 'residential properties at significant risk of flooding' is considered as a high risk in 2080s. If the risk of flooding increases, peoples' home and well-being will be affected. Annual damages to UK properties will rise from £1.3 billion to £2.1-12 billion by 2080s, based on the future population growth and if no adaptive action is taken. Compared with the risk classification table, this risk stands in the high level (UKCCRA, 2012b).

By having the magnitude and confidence level for each 'risk' and by identifying the nature of the 'risk' (threat or opportunity), the final graph (like Figure 2.5) can be drawn. Providing a baseline level for risks and opportunities, the CCRA outputs enable UK decision makers to prioritize and evaluate different scenarios (UKCCRA, 2012a). The following figure illustrates the results of the UK study in the agriculture and forestry theme.

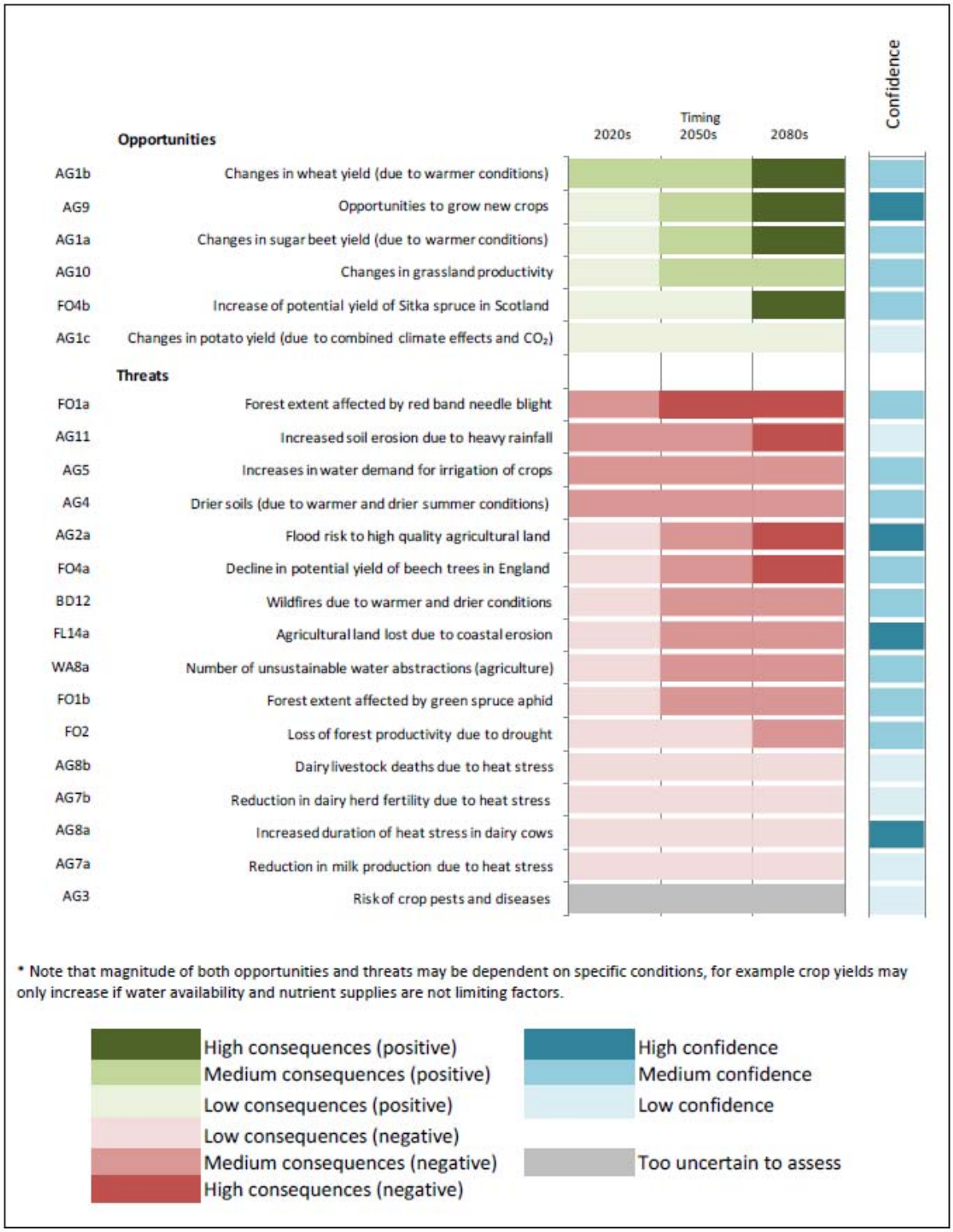

Figure 2.5. Example of an Onset Plot for Agriculture and Forestry Theme.
Source: (UKCCRA, 2012a)

The CCRA does not deploy quantities as estimates of the expected overall risk, i.e., the probability of the event times the magnitude of the consequence, and instead it uses categories and descriptive labels.

2.3.2.2 Federal Emergency Management Agency (FEMA)

The Federal Emergency Management Agency (FEMA) manages various risk analysis programs, which attempt to reduce the impacts of risky events by providing appropriate adaptation strategies. FEMA assesses the natural hazards whether caused by climate change or non-climate change origins. One of the climatic change related projects in being done by FEMA and delivered through FEMA's Risk Analysis Division is Risk MAP. Risk MAP is a procedure that includes newly designed strategies and products developed by FEMA to achieve goals and objectives of the Risk Map Multi-Year Plan (from 2012 to 2016). Risk MAP attempts to establish an integrated risk management approach and integrate national assessment flooding Risk Map that uses digital hazard data, web-accessible data, and updated information (FEMA, 2009).

The Risk Map lifecycle including risk identification, risk assessment, risk communication and risk mitigation is illustrated as follows in Figure 2.6.

Figure 2.6. Risk Map Lifecycle. Source: (FEMA, 2009)

The Risk MAP framework encompasses three key processes including Mapping, Assessment, and Planning. The risk identification and risk assessment can be captured by four steps: 1) develop GIS data to capture community assets, 2) develop hazard data which resulted in flood, 3) estimate losses such as economic losses, building damages, displaced population, and 4) develop a problem statement which outlines the vulnerable areas (Perkins, 2009).

Risk Map enables communities to assess the risks by using product and technologies that visualize the risks (FEMA, 2009). FEMA uses HAZUS-MH, which has GIS technology, to estimate the potential physical, economic, and social impacts of earthquakes, floods, and hurricanes (The description about risk assessment procedures here is beyond the scope of this research, since technical tools assist Risk MAP in this regard).

The risk assessment creates a link between flood mapping and planning. Planning is captured in Figure 2.5 by the elements of Risk Communication and Risk Mitigation. The evidence from mapping increases awareness in the community planning so that community members are better able to prepare for flood situations. This information is used in developing vulnerability reduction strategies that may be considered as mitigating the risk of flood impacts.

FEMA collaborates with local, state, regional, tribal, and national entities and other federal partners to either change the flood map or update the risk assessment or mitigation planning. In order to achieve data quality in the long-term, the flood map needs regular updating and very close communication with local communities to improve information concerning with buildings, street map redesign, and changes to residential living space (FEMA, 2012b).

Risk Map intends to reduce losses of lives and properties to coastal communities through more precise flood hazard data and risk assessments, and enhancement of local mitigation activities. Risk MAP aims to increase the public awareness about the risks and reinforce the local ability to make informed management decisions (FEMA, 2012b).

2.3.2.3 Ontario Ministry of Municipal Affairs and Housing

The Ontario Ministry of Municipal Affairs and Housing, in cooperation with Natural Resources Canada and Institute for Catastrophic Loss Reduction, developed a management guide for municipalities to understand and manage the risks related to climatic changes and

remaining uncertainties about future changes. This guide incorporates risk management for future planning and management activities related to climate adaptation (Bruce et al., 2006).

The general framework presented by the Ontario Ministry to manage risks is described in Figure 2.7.

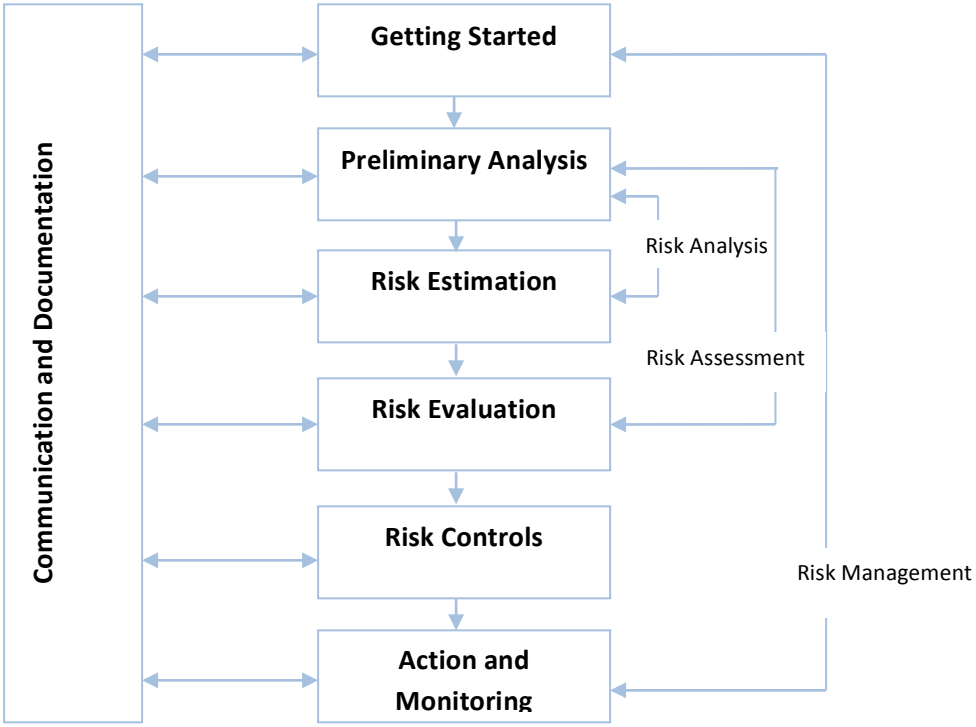

Figure 2.7. Risk Management Process. Source: (Bruce et al., 2006)

At a very early stage, hazards and vulnerabilities to an area and individual or any groups subject to decision making are identified. Risk scenarios are developed, one of which represents probable type of loss or impact could occur as a result of exposure to the hazard. Afterwards, the frequency or severity and consequences associated with each scenario are estimated. The frequency can be presented by either quantitative or qualitative methods.

The quantitative method describes likelihood in terms of either frequency or probability:

- Frequency: gives the number of times of occurrence over a chosen timeframe. 3/year, 1/decade, 10/week.
- Probability: states the outcome as a measure between 0 and 1, or as a percentage between 0% and 100%.

The qualitative method assesses likelihood relative to the other potential scenarios and ranges from "occurs very often" to "occurs almost never", e.g.,

- Very unlikely to happen: not likely to occur in a given year
- Occasional occurrence: may occur sometime but not often in a given year
- Moderately frequent: likely to occur at least once in a given year
- Occurs often: likely to occur several times in a given year
- Virtually certain to occur: happens often and will happen again in a given year (Bruce et al., 2006)

Consequences of each particular scenario on environment, economy, society, and culture, which have been defined as vulnerable assets of a coastal community to threats, are estimated. It can be presented by two choices; qualitative and quantitative measurement. Qualitative measures for consequences range from "very minor effects" to "extremely serious effects". If explicit data and values are accessible for losses and damages of a particular scenario, consequences can be presented based on these values (quantitative measures), such as death and fatalities, injuries and damages (Bruce et al., 2006).

Direct losses can be felt immediately after a disaster. For example, direct loses may include fatalities, injuries, community response cost, cleanup cost, temporary housing cost, and loss of agriculture stock. Indirect losses emerge much later, and are not caused directly by disaster. For instance, indirect losses may include mental illness, bereavement, loss of income, and reductions in business activities (FEMA, 212a).

The frequency and consequence of the results would differ between short-term horizon and long-term horizon. Selection of an appropriate time horizon for climatic changes is important.

For illustration, the consequences' ranking matrix for one particular scenario is shown as follows in Table 2.4:

Table 2.4. Impact Rating Matrix for One Particular Scenario. Source: (Bruce et al., 2006)

Impact / Degree	Social Factors			Economic Factors		Environmental Factors		
	Health & Safety	Loss of Livelihood	Cultural Aspects	Property Damage	Financial Impact	Water	Land	Ecosystem
Very Low			×	×				
Low		×			×			
Moderate	×				×			
Major				×		×		×
Very Severe							×	

Risk evaluation (assessment) matrix is used to define different level of risks as a result of hazard probability and hazard severity. Dividing risks into five categories: extreme, high, moderate, low, and negligible risks, the risk assessment matrix can be developed as follows.

Table 2.5. Risk Assessment Matrix. Source :(Bruce et al., 2006)

Impact Severity						
	Very Severe	Moderate Risk	High Risk	High Risk	Extreme Risk	Extreme Risk
	Major	Low Risk	Moderate Risk	High Risk	High Risk	Extreme Risk
	Moderate	Low Risk	Low Risk	Moderate Risk	High Risk	High Risk
	Low	Negligible Risk	Low Risk	Low Risk	Moderate Risk	High Risk
	Very Low	Negligible Risk	Negligible Risk	Low Risk	Low Risk	Moderate Risk
		Very unlikely to happen	Occasional Occurrence	Moderately Frequent	Occurs Often	Virtually Certain to Occur
Frequency/Probability						

- Immediate controls required
- High priority control measures required
- Some controls required to reduce risks to lower levels
- Controls not likely required
- Do not require further consideration

In the two last steps, operational aspects, costs, and benefits of each scenario are taken into account as supplementary information for prioritizing risk and identifying unacceptable risks. The residual risk scenario is assessed to unfold beneficial or adverse effects. Monitoring of the implementation of adaptation strategies (or risk control strategies) and risk management process, from the first to the last step, improves efficiently the decision making process (Bruce et al., 2006).

Stakeholders' feedback has an undeniable influence on all steps of the risk management process so that communication with stakeholders is an integral part of all steps. Stakeholders' perception of risk and its consequences must be contributed to the risk estimation step. In addition, ranking and prioritizing the risk in the risk evaluation step need stakeholders' participation (Bruce et al., 2006).

2.3.2.4 A Framework for Risk Analysis in Fisheries Decision Making

Among risk analysis frameworks published, Lane and Stephenson's paper (1998) can be mentioned as a valuable attempt toward a quantitative risk analysis. It modifies a fisheries management framework by including risk assessment, and risk management in decision making process.

A 5-year strategic plan is targeted in biological and socio-economic pillars. In order to achieve the target, different scenarios (decreasing, increasing, constant, and pulse) are developed. Degree of achievement is evaluated by performance measurements (i.e. indicators) for each pillar. For instance, harvestable stock size for juvenile and adults combined (of age 1+) and for adult (of age 4+) are performance measures for the biological pillar, and total labor (like employment) and cash position for harvesting and processing sectors are performance measurements for social and economic pillars (Lane & Stephenson, 1998).

The input values are provided by the deterministic model (best estimation) over 5 years for every exogenous scenario and performance measurement (Lane & Stephenson, 1998). Stochastic models are developed for estimating output performance, which capture uncertainties regarding the input variables and calculate the probability of possible outcomes under each scenario. For this purpose, Monte Carlo simulation is used to randomize key model elements (variables). It shows the probability distribution of decision alternatives (scenarios) for each performance measurement. Figure 2.8 illustrates one of the Monte Carlo graphs created for discounted cash (performance measurement) and different scenarios (Lane & Stephenson, 1998).

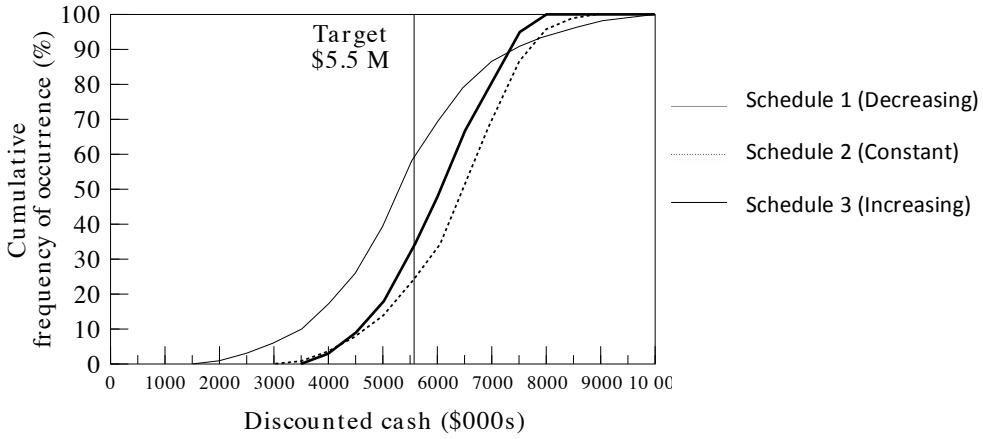

Figure 2.8. Cumulative Probability Distribution for Monte Carlo Simulation Modeling.
Source: (Lane & Stephenson, 1998)

Risk assessment uses the outputs of the Monte Carlo simulation experiment. The decision alternatives are evaluated in terms of their probability of meeting the target. More specifically, if all probabilities of one output performance, with respect to the target, are very low, it may not be considered acceptable by decision makers (Lane & Stephenson, 1998).

In order to capture relative acceptability of the risks previously assessed, a general utility function over all pillars is used (Equation 2.2). Utility functions are able to describe the preferences towards acceptability of one specific output under different circumstances. However, the fact that outputs are considered under uncertainties adds a special structure to the problem. In general, how a person values an alternative in one state as compared to another will depend on the probability that the state in question will actually occur. In decision making, utility curves can be drawn empirically by deep analysis of the decision

maker's preferences and trade-offs (Lane & Stephenson, 1998). In this case, the biological, economical and social aspects must be integrated into one utility function.

For comparing and evaluating the decision alternatives, decision makers start the risk management process, which uses the results from risk assessment and utility curve.

To identify the overall utility for each alternative, Lane & Stephenson' paper (1998), represents a linear multi-attribute function as described below (2.2).

$$U(\mu_j) = \sum_{i=1}^{4} \alpha_i U_i(\mu_j) \qquad (2.2)$$

$\propto_i$: The relative importance of each performance measure so that $\sum_{i=1}^{4} \propto_i = 1$, it can be obtained by asking trade-off questions from decision makers

μ_j: The alternative strategies for $j = 1, 2, 3$, where j=1 indicates the "decreasing", j=2 indicates the "constant", and j=3 indicates the "increasing" TAC strategies

$U_i(\mu_j)$: The expected utility value for performance measurement i and strategy j

For different weights assigned to the utility function $(\propto_i)$, the solution will vary. Hence, the optimal solution can be obtained by a set of weights. The optimal strategy over the majority of the weights space is "constant" strategy (Lane & Stephenson, 1998).

2.3.3 Utility Function

The desirability of possible outcomes to the decision makers (i.e. coastal communities) is presented in the form of a utility function.

> ""Utility'' is an abstract measure of the relative strength of preference/desirability for a particular outcome" (Lane & Stephenson, 1998).

In order to represent the decision makers' preferences for different outcomes, binary (preference) relations $\succsim$ can be defined. If we assume X={outcomes or attribute levels}, then the binary relations can be defined over all possible pairs (e.g. (x, y)) of X*X space. Mainly, three binary relations can be assumed:

1) $x \succ y$ denotes a strict preference for x over y

2) $x \sim y$ denotes indifferent preference between x and y

3) $x \succsim y$ denotes weak preference for x over y,

Practically, defining binary relations is neither easy nor efficient, as it is very time consuming in complex situations. So, in practice, preferences are represented numerically with utility values. The utility value labeling requires a coherent view from the beginning to the end. If two attributes, x and y, are assumed, then

$$x \gtrsim y \Leftrightarrow u(x) \geq u(y) \quad (2.3)$$

Simply, this means that the greater is the outcome, the more the preference. However, the preference may show decrease, increase, or indifferent trend as an attribute level goes up. For instance, the preference may increase as the annual growth (attribute) goes up to 15, the desirability may decrease as the growth goes above the 15, because additional growth would result in the disruption of the area or be indifferent for any value above 20 (Keeney, 1944).

The expected utility involves the probability of the occurrence of an event. For instance, a lottery game is assumed that yields either $1 billion gain or $2 billion cost when each event has 0.5 chance of occurring. The expected value or the risk of participating in the lottery game costs $1.5 billion. Different people have different desirability towards the two options; either participate in the lottery game or not. The following figure demonstrates different attitudes toward risk; risk aversion, risk neutral, and risk seeking (proneness).

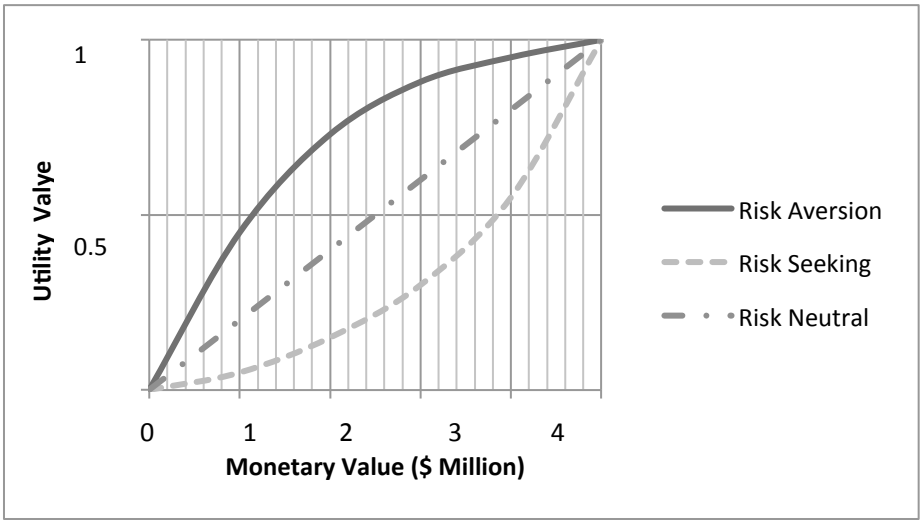

Figure 2.9. The Three Risk Attitudes. Source: (Keeney, 1944)

A person who prefers the cost of $1.5 billion instead of the lottery game is a risk averse, a person who prefers the lottery game is a risk seeking, and a person who is indifferent is a risk neutral (Keeney, 1944).

2.4 Applications

This research analyzes the risk for the C-Change coastal community of Charlottetown, P.E.I. Risks for Charlottetown are motivated by severe storms and sea level rise to adapt to the changing coastal environmental situation. The specifications of the community are described in more detail below.

2.4.1 Charlottetown, Prince Edward Island

On the southern shore of Prince Edward Island is located Charlottetown city. The city is concentrated on the harbor where three rivers are merged (C-Change, 2011). The population of the Charlottetown community reaches to 34,562 residents (Statistic Canada, 2011).

The Charlottetown harbor opens to Northumberland Strait. It is protected against Northumberland Strait and the Gulf of St. Lawrence, however sea level and storm surge are increasing (Shaw, 2001).

As a tourism destination for Canadians and non-Canadians especially in summer, Charlottetown has numerous historic sites. Recreational fishing and boating and indoor and outdoor festivals in Charlottetown harbor attract a great number of tourists, not to mention parks and green spaces (Approximately 400 acres in the urban area) and an extensive system of walking and recreation trails throughout the city (C-Change, 2011; Shaw, 2001).

Charlottetown is the main center of industrial and commercial activities in the province. The well-developed waterfront area, where commercial businesses, houses, and public resources are established, is situated in the most vulnerable zone to storm surge. Therefore, the property of both residential and commercial sectors in Charlottetown is in danger of storm surge events (Shaw, 2001).

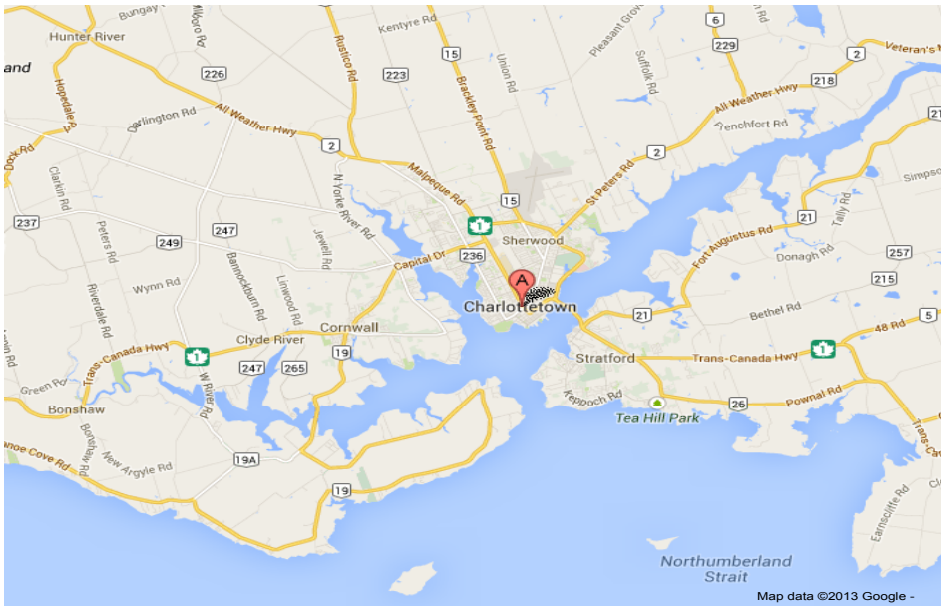

Figure 2.10. Charlottetown, Prince Edward Island. Source: (GoogleMAp, 2013)

The Prince Edward Island's coastline is covered by sedimentary rocks. Composed of sandstones and claystones, these sedimentary rocks are easily eroded. Erosion happens by the action of wind, water, and ice. The erosion is a constant process that changes the boundary of the water and land. Wind erosion mostly happens along the beaches and deserts where no plants exist. Average coastline erosion on the south and east shores of P.E.I is 0.5 meters (1.6 feet) per year, while this amount reaches to 1.5 meters (5 feet) per year on the north and west shores. This happens, because the north and west coasts have higher degree of exposure to storm conditions (Government of PEI, 2012).

Prince Edward Island mostly relies on groundwater to supply drinking water. Rapid extraction of groundwater can accelerate water salinization. On the other hand, the water table of coastal communities usually is adjacent to oceans. Hence, intrusion of seawater accompanied by water table position can easily contaminate wells (Natural Resources Canada, 2008).

2.5 Summary

This section provides a summary of those approaches being reviewed in the literature and are contributed in this research methodology. This research creates a framework that analyzes the risks of severe storm events, and manages adaptation strategies suitable to be

pursued in short and long term, with a focus on the case of Charlottetown. FEMA's and CCRA's approaches toward future climatic changes are multi-hazard approaches. Both studies are dealing at the country scale, however FEMA is involving different entities of the country to enable the impact assessments of any climatic changes over all scales. This thesis research studies the community of Charlottetown, which has smaller scale than a country (or national), and considers a single hazard approach, namely, severe coastal storm events.

CCRA believes that a "risk" can be either threat or opportunity of climate change, which is represented by the magnitude of consequence, and confidence in evidence. The Ontario Ministry of Municipal Affairs and Housing defines risk as a result of likelihood and impact that can be either direct or indirect. In this research, the risk is defined as a combination of likelihoods and negative impacts (threats) of storm events, including direct and indirect impacts. The approach of this research risk assessment is a vulnerability-led approach to measure the existing vulnerability of the community in the case of any future storms.

The main steps discussed in Ontario Ministry framework are to be covered by this research; risk assessment, risk management, and risk communication. Nonetheless, the splitting boundary of these steps will have minor differences in this research. Risk communication is separated from the two other main steps, in spite of Ontario Ministry framework within which risk communication has direct effect on the result of every step. In this research, risk communication is considered as the last main step that improves the result of risk management step.

In order to discover the multidimensional vulnerability of communities to severe storm events, the GIS-SD method result presented by Hartt (2011) is used in this research, since identification of vulnerable areas is dependent on the community profile and assets. In an analogous manner, Risk MAP study uses GIS technology to identify the vulnerable areas and assets at risk. The vulnerability is assessed in terms of four pillars: environmental, economic, social, and cultural pillar of coastal communities.

The measures of vulnerability are generally presented in the form of quantitative indicators by Adger. Aggregating a long list of indicators by normalizing or weighting methods requires a huge effort. Furthermore, the vulnerability measurement is not meaningful in the absence of community profile. So, the vulnerability assessment should be studied with respect to climate-sensitive assets of that community.

According to Lane and Stephenson (1998), multi-attribute utility functions can be used to compare and prioritize adaptation strategies with respect to community's preference and performance measurement. Those Adaptation strategies that maximize community's preference and minimize the negative impacts can be discovered.

Taking into account the UK study, the evolution of impacts of each threat or opportunity is shown over different projected years. The impacts and likelihoods of climatic changes are assessed in different time frames to enhance the insight of the community to put in place a proper strategy, at the right time.

3 Methodology

The thesis research methodology presents the treatment of risk analysis. This chapter begins with a brief description about the research process that includes the components of risk analysis, namely, risk assessment, risk management, and risk communication. Each of the components of the research process is broken down to the techniques and details that will be used throughout the research.

This thesis research uses estimates of the probabilities and impacts of future storm events and hazards on the coastal community of Charlottetown. This information is then used in a risk analysis to provide advice to the community on adaptation strategies that take into account the community's attitude towards risk, the appropriate planning period, and the results of the risk analysis to evaluate and rank the alternative adaptation strategies.

This chapter on the thesis research methodology is divided into five sections. Section 3.1 presents the research process and the structured risk analysis. Sections 3.2 through 3.4 provide the specifics of the risk analysis including the detailed methodologies for the components: (3.2) risk assessment (the likelihood and impacts of predicted storms); (3.3) risk management (the weighted utility of the alternative adaptation strategies), and (3.4) risk communication (the selection of the planning period and sensitivity analysis). Finally, Section 3.5 presents the criteria used to rank the decision alternatives, namely, the defined measurements for community vulnerability, resilience, and adaptive capacity.

3.1 Research Process

This section provides and overview of the three main components of the ris analysis that will guide the research model: (1) risk assessment, (2) risk management, and (3) risk communication. These components are discussed in more detail in the subsections below.

3.1.1 Risk Assessment

Risk assessment identifies the probability of occurrence of the natural hazards threatening the coastal community, and estimates and analyzes the consequences or impacts of these hazards on the coastal community. The purpose of risk assessment is to highlight the

likelihood of the impacts on selected communities associated with severe coastal storms. As noted in the literature review (Section 2.5), Charlottetown is vulnerable to severe storm hazards. The consequences of storm hazards are assessed in terms of the four pillars of the community profile, namely: community environment, society, culture, and economy.

3.1.2 Risk Management

Risk management requires the identification of community priorities and notes the importance of dealing with threats that impact the community pillars with higher relative importance to the coastal community. In so doing, risk management permits the evaluation and ranking of those strategies that accordingly address those threats of greater importance to the community. The risk management procedure of the research process requires that the planning horizon for the decision and the assessed probabilities of the events be taken into account in order to evaluate the adaptation strategies. It is recognized that the length of the planning horizon impacts the likelihood of occurrence of extreme severe storm events over that periods, and therefore the need to consider adaptation actions in response.

3.1.3 Risk Communication

Risk communication extends the management of risk (as described above) to consider the impacts of decisions taken, including monitoring and learning from the observations that follow with regard to how well those decisions match projections. Risk communication is captured in the exchange of information among the interested groups within coastal communities about impact and probability of a severe storm event, and adaptation to that event. The purpose of risk communication then is to monitor decisions made under risk management in order to understand and improve future decision making. The sensitivity of the decisions taken under different experiments, different planning periods, and observations are analyzed and useful feedback is provided.

The following sections provide further details of the risk analysis process and its component parts, as discussed above for risk assessment, risk management, and risk communication.

3.2 Risk Assessment

Risk assessment requires data and information on storm hazards measurement of the vulnerability and impacts of storms on the community, and a probability assessment of outcomes of the hazardous events. This data makes up the main part of the information to be collected and evaluated to complete the risk assessment phase of risk analysis. The following subsections present risk assessment information in more detail for: 1) the predicted likelihood of storm occurrences, 2) coastal community vulnerability assessment, and 3) storm scenario impacts.

3.2.1 Likelihood of Storm Occurrences

In order to predict the likelihood of storm hazard occurrence, the probability distributions of storm events must be determined. This distribution relies on historical data. Historical data on severe storm events and storm surge for Charlottetown are extracted from publicly available data at Environment Canada (Environment Canada, 2009).

Beigzadeh (2014) fits a probability distribution to the regular event of "maximum observed water levels" (MOWL) that describes severe storm occurrences for Charlottetown for the period from 1911 to 2005. The MOWL distribution is used to simulate the severity of periodic coastal storms. Storm events with MOWL greater than or equal to 2.5 meters are defined as "severe storms". The degree of storm severity, i.e., the value of MOWL, determines the extent of the impacts on the community. As such, historical evidence from past storms is used to estimate the impacts of storms of differing severity. The mean of the historical (1911-2005) MOWL for Charlottetown is 3.165 meters, and the historical variance of the data is 0.15 square meters. The expected number of "severe storms" in each year is between 4 and 6 storms (Beigzadeh, 2014).

Goodness-of-fit tests were applied to the Charlottetown data using the *EasyFit* software application (MathWave Technologies, 2013). These tests included Kolmogorov-Smirnov, Anderson-Darling, and Chi-Squared tests for determining best-fit to the MOWL series in comparison to theoretical distributions. The Gumbel extreme event distribution (exponential density function variate) was identified as the best fit for describing the annual maximum MOWL phenomenon for Charlottetown over the history of MOWL values from 1911 to 2005 (Beigzadeh, 2014).

The Gumbel distribution function best characterizes the estimate of the likelihood of future severe storm events (in terms of annual maximum MOWL) as Charlottetown has experienced between 1911 and 2005. The Gumbel distribution function is used by Fisheries and Ocean Canada Oceanography to model the Canadian Atlantic coast to estimate the scale parameters of present sea-level extremes (Zhai et al., 2013).

The probability density function for the best-fit function to the Charlottetown historical database for annual maximum MOWL storms between 1911 and 2005 is shown in Figure 3.1. The best-fit function was determined as a Gumbel max distribution with parameters: (1) location parameter (mode) - alpha=2.99; and (2) scale parameter- beta= 0.303.

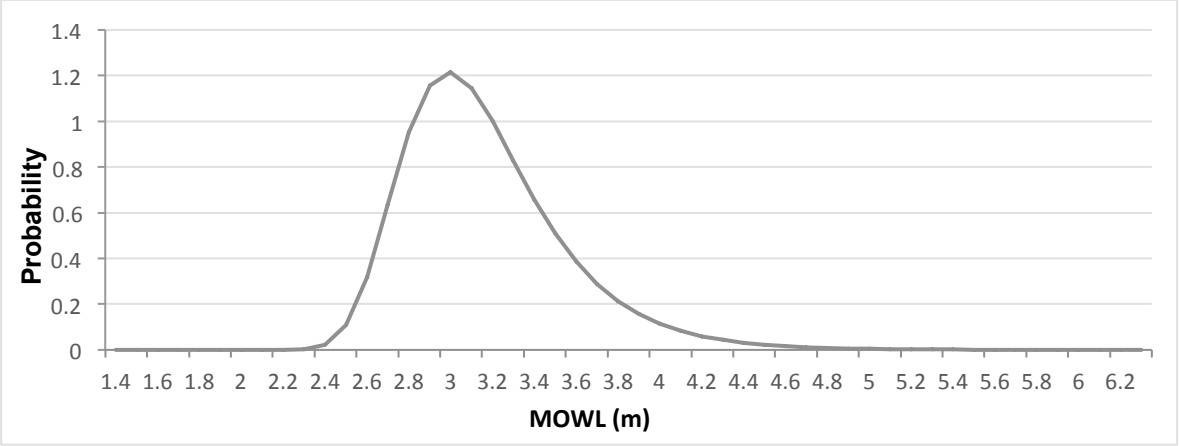

Figure 3.1. Gumbel Maximum Characteristics Probability Density of Historical Storms for Charlottetown 1911-2005. Source: (Beigzadeh, 2014)

According to the Gumble max of Figure 3.1, the likelihoods of Charlottetown severe storm events with MOWL less than 2.2 meters and greater than 5.0 meters are effectively zero. The actual maximum MOWL for Charlottetown is 4.22 meters that was observed during the January 2010 No Name storm (see also Table 3.1 and 3.2 below). The maximum predicted MOWL for Charlottetown is just above 5.2 meters, estimated to occur as a one time occurrence (per year) by the end of the 21st century (Milloy & MacDonald, 2001). From the parameterized Gumbel max distribution, the series of future storm events for Charlottetown with severity given by the random variable *MOWL* is simulated by using the inverse transformation of the cumulative probability distribution function corresponding to the Gumbel max function (NTRAND, 2014) as follows,

$$MOWL = \alpha - \beta \times ln\left(ln\left(\frac{1}{U(0,1)}\right)\right) \quad (3.1)$$

The inputs to the inverse function are random variables that are uniformly distributed on the [0,1] interval, *U(0,1)*. The series of independently generated Gumbel max storms, i.e. *MOWL* demonstrated by the annual historical series of maximum MOWL values for Charlottetown, can be simulated for different time spans. In Figure 3.2, as an example of a single randomized trial, the MOWL series is simulated over 50 years of independent annual simulated values.

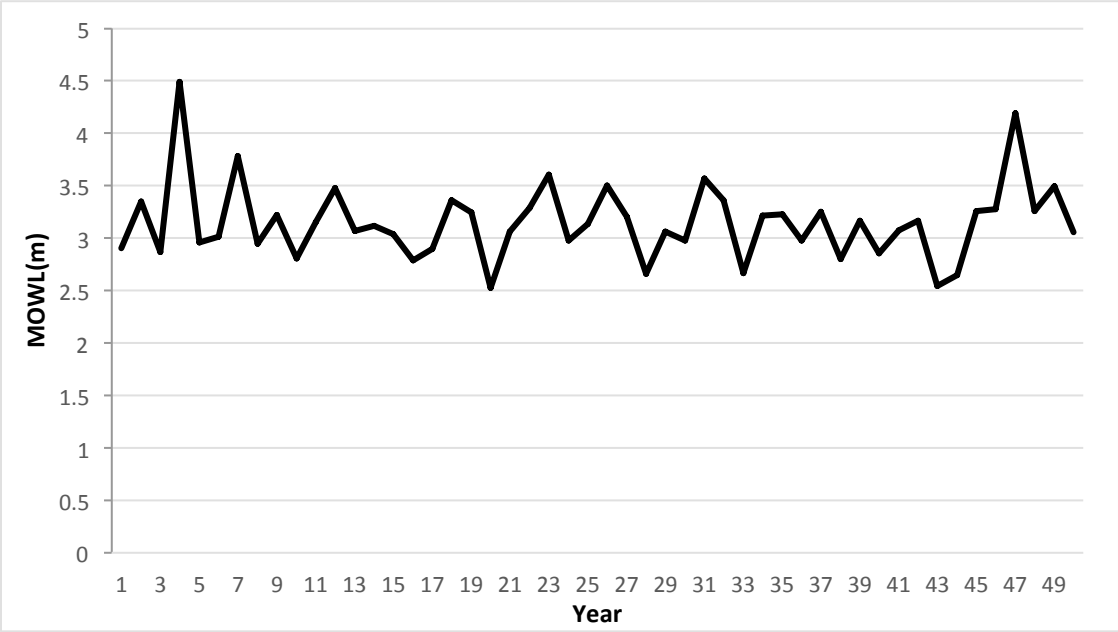

Figure 3.2. A Simulated Series of Annual Storm Events for Charlottetown Over 50 Years.
Source: (Beigzadeh, 2014)

3.2.2 Coastal Community Vulnerability Assessment

In the development of the model, different storm scenarios are assumed based on a historical comparative view of the historical data. Storm scenarios define the extent of expected storm severity possibilities and determine the vulnerability of the coastal community through estimating coastal community impacts.

Storm scenarios are generally defined by: (i) storm speed, (ii) wind speed, and (iii) pressure as determinants of the severities of the storm events. Thirteen storm events are highlighted from historical data available for Charlottetown between 1950 to 2010 (Hartt,

2011). The empirical data characterizing these storms are extracted from Environmental Canada's Canadian Hurricane Centre (Environment Canada, 2009), the Department of Fisheries and Oceans' Tides, and Currents and Water Levels Data Archive (Department of Fisheries and Oceans, 2010). Each of these storms is reported by the maximum speed, wind, and pressure values in or around the Charlottetown area during the storm event. Based on Hartt's storm classification, these thirteen historical storms fall into six different Storm Scenarios from lowest (I) to highest storm severity (VI).

Not all of the thirteen historical storms fall completely into the six Storm Scenarios. Therefore, they can be classified by using theirs empirical data (speed, win, pressure), and the amount of damages that they caused. The quantifiable statistics of thirteen storms do not only underlie the classification to six Storm Scenarios, presented in Tables 3.1 and 3.2. The amount of damages determines what scenario a storm falls into, however the quantifiable statistics are considered in placing of the thirteen storms in the six scenarios (Hartt, 2011).

Table 3.1. The Thirteen Historical Charlottetown Storm Events Sorted to Six Storm Scenarios.
Source: (Hartt, 2011)

Storm Scenario	Historical Storm	Speed (Kph)		Wind (Kph)		Pressure (Kph)	
		Scenario	Storm	Scenario	Storm	Scenario	Storm
I	Able	45-50	44	55-57	55	1000-990	-
	Hanna		64		85		995
II	NN1962	50-55	-	75-95	-	990-980	-
	NN1964		-		160		-
	Hortense		48		130		970
III	Juan	55-60	59	95-115	120	980-970	982
	Carol		63		110		-
IV	Ginny	60-65	61	115-135	110	970-160	-
	Subtrop		61		100		978
	Gustav		74		150		962
V	White Juan	65-70	-	135-155	-	960-950	-
	Kennedy		-		-		-
VI	NN2000	70-75	-	155-175	70	950-940	945

- Indicates no available data.

Storms are summarized by their Maximum Observed Water Level (MOWL). The maximum observed water level of the thirteen historical Charlottetown storms, are extracted from data at the Charlottetown tidal gauge. These are displayed in Table 3.2 below.

Table 3.2. Classification of the Maximum Observed Level of Water into Six Storm Scenarios.
Source: (Hartt, 2011)

Storm Scenario	Historical Storm	Date	Maximum Observed Water Level (m)		Reported Vulnerabilities (Various Media Sources And the Canadian Hurricane Centre)
			Scenario	Storm	
I	Able	21 August 1950	2-2.5	2.52	-Street flooding -Power outage -Heavy rainfall -Street closure due to flooding -Half meter water in Joe Ghiz Park (Grafton St)
	Hanna	7 September 2008		2.462	
II	NN1962	4 March 1962	2.5-3	2.55	-Damaged and washed out streets and highways
	NN1964	2 December 1964		2.47	-Most damage at sea - 3 fishing boats capsized
	Hortense	15 September 1996		2.89	-All power in Charlottetown lost -Many power lines destroyed -Ferry service halted
III	Juan	29 September 2003	3-3.5	2.927	-Extensive tree damage -Barn and silo damage -Flooding -Power outages lasting up to 5 days
	Carol	8 September 1953		2.95	-Large trees knocked over -Roofs blown off -Chimney knocked off -Power outage due to destroyed power lines -Ferry service halted
IV	Ginny	30 October 1963	3.5-4	3.15	-Extensive power outages -Ferry service halted
	Subtrop	29 October 2000		3.32	-Many roads and bridges flooded -Trees knocked over -Roofing shingles pried off -Thousands of pounds of lobster beached along coast
	Gustav	12 September 2002		3.489	-Power lost across PEI -Vehicle accident cause by storm killed a man

V	White Juan	10 February 2004	4-4.5	3.772	-Widespread flooding
	Kennedy	21 January 1961		3.84	-Widespread flooding
VI	NN2000	21 January 2000	4.5-5	4.216	-Severe damages to public and private properties -Damaged wharves in Charlottetown harbor -Damaged a power -Generating station -Dislodged a lighthouse -Damaged numerous gas stations -Estimated at $20 million in damages

As noted in Table 3.2, from the least severe Storm Scenario (I) to the most severe Storm Scenario (VI), the MOWL increases indicating increased severity and damages. Thus, MOWL is considered as the summary variable for continuously increasing severity in storm scenarios, as described below for selected scenarios.

Storm Scenario II is characterized by MOWL values exceeding 2.5 meters up to 3 meters. The impacts caused by these water levels in Charlottetown (as seen in the No Name 1964, No Name 1962, and Hurricane Category 1 Hortense actual storm in Table 3.2) have resulted in street and highway flooding, power outages due to the destruction of power lines, and cancelled ferry service during 2 full days, the expected duration of this storm, and for a short period afterwards.

Storm Scenario IV is characterized MOWL values exceeding 3.5 meters and up to 4 meters. The impacts of these storms on Charlottetown are attributed to Extratropical storm Ginny, Extratropical storm Subtrop, and Hurricane Category 1 Gustav (Table 3.2). These storms caused widespread flooding in the city washing out many roads and highways, cancelled ferry services, knocked over many trees, blew off roof shingles or potentially full roofs, damaged pleasure crafts and small fishing vessels in the harbourfront marinas, damaged power lines causing power outage and structural damage to weaker, older or coastal buildings.

Storm Scenario V, the most sever storm scenario, is described by MOWL values exceeding 4.5 meters. The impacts of this storm scenario are expected to be worse than what was recorded for No Name 2000 storm (Table 3.2). Charlottetown residents are expected to

face severe flooding to private and public properties that would require evacuations; beaches, roads, and highways would be submerged; sea-ice would pile-up on shore (if the storm event occurred in winter months); and buildings would flooded off their foundations. In addition, Charlottetown would experience power loss due to damages to power lines, trees knocked over, significant damages to roofs, damaged pleasure crafts and smaller fishing vessels in harbourfront marinas. Wharves placed in the Charlottetown harbor would be damaged or destroyed, a power-generating station near the shoreline would be damaged and forced to shut down, ferry service would definitely be halted, and many gas stations would be damaged or closed.

3.2.3 Storm Scenario Impacts

The question now asked is how much of monetary damages of storms impact the vulnerable area and damage incidences of Charlottetown (as referred to above for the selected scenarios). The impacts of coastal communities are a function of different possible storm scenarios, and the adaptation strategies adopted to counteract the storms. Given the level of storm severity, it is necessary to estimate the extent of the impact of storms on the coastal community and community pillars.

The impacts of storm events are estimated with respect to the four pillars of the community profile, namely: economy, environment, society, and culture, as shown in Table 3.3 (Hartt, 2011).

Table 3.3. Mean Total Estimated Damages for Charlottetown Using Hartt's Estimates (2011) and Functional Form Values

Storm Scenario	Community Profile Pillar			
	Environmental Damage Estimates ($ Million)	Economic Damage Estimates ($ Million)	Social Damage Estimates ($ Million)	Cultural Damage Estimates ($ Million)
SS I	$1.75	$1.417	$0.983	$0.162
SS II	$2.1	$1.7	$0.118	$0.194
SS III	$4.908	$4.067	$0.282	$0.452
SS IV	$7.3	$6.1	$0.422	$0.666
SS V	$11.358	$9.467	$0.660	$1.055
SS VI	$15.00	$12.5	$0.873	$1.4

Using Charlottetown as a case, estimates of monetary damages to each pillar are computed using the MOWL data combined with the Geographic Information System,

ArcGIS. GIS mapping is used by Hartt (2011) to detect the extent of floods and to examine the content of flooded areas. *ArcGIS* uses Charlottetown elevation data to provide expected flooded areas associated with different water levels (MOWL) associated with the storm scenarios. The total damages of the storm scenarios, under the Status Quo or "Do Nothing" adaptation strategy, are derived by examining the content of the flooded areas. Generally, damages are a fraction of a community's assets at risk, since not all assets at risk are damaged by storm hazards (Hartt, 2011).

Total Damage is estimated in monetary terms for MOWLs of 3 meters, 4 meters, and 5 meters, corresponding to Storm Scenarios II, IV, and VI for Charlottetown (Hartt, 2011). Total Damages for the remaining storm scenarios are estimated by interpolating their MOWL.

The following subsections describe each pillar's estimated monetary damage estimates for alternative MOWL values, i.e., storm severity.

3.2.3.1 Environmental Pillar Storm Damage Estimates

Total estimated damages to the Charlottetown environmental pillars are estimated for Storm Scenarios II, IV, and VI, assuming no adaptation strategy in place, i.e., status quo (Hartt, 2011). Total damage estimates for other Scenarios I, III, and V are interpolated with respect to Total Damage computed for other Scenarios (Hartt, 2011). Total Damages to the environmental pillar as a fraction of MOWL values are plotted in a graph represented in Figure 3.3. The point estimates for the storm scenarios are used to describe the fitted functional form of the exponential curve where y denotes monetary damages (in millions of constant 2010 dollars), and x denotes the MOWL (in meters).

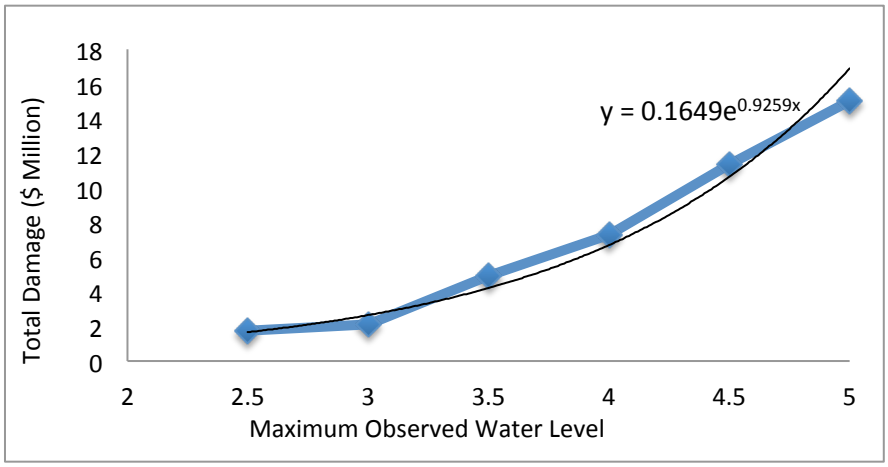

Figure 3.3. "Total Estimated Damage" (in $Million) to Charlottetown's Environmental Pillar As a Function of Storm Severity Variable MOWL. Source: Derived from Hartt (2011)

The value of Total Estimated Damage for an MOWL of 2.5 meters, corresponding to lowest severe Storm Scenario I, is approximately $2.1 million. The damage associated with "No storm" scenario is zero, i.e., MOWL=0. The trendline associated with Hartt's (2011) estimated point data series, as shown in Figure 3.3, is exponential, indicating that the values rise at a continually increasing rate as MOWL increases. The fitted trendline is used to assign value to total environmental pillar damages caused by any MOWL in the range of 0 to 5 meters, the range of acceptable and predicted values within the Charlottetown case.

3.2.3.2 Economic Pillar Storm Damage Estimates

Total estimated damages to the economic pillar of Charlottetown for Storm Scenarios II, IV, and VI, under the Status Quo strategy (no adaptation), are estimated by Hartt at $1.7 million, $6.1 million, and $12.5 million respectively (Hartt, 2011). Total damages corresponding to Storm Scenarios I, III, and V are interpolated, as above using Total Damages estimates of other storm scenarios. All Total Damages to the economic pillar as a function of MOWL values are represented in the graph shown in Figure 3.4.

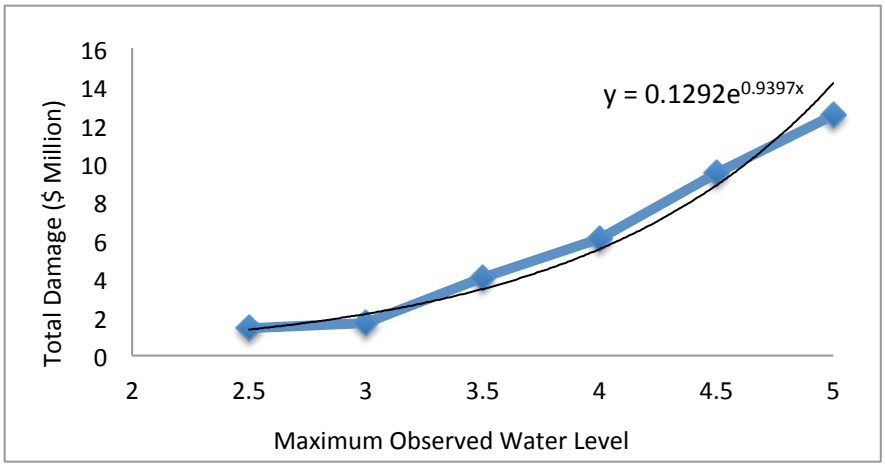

Figure 3.4. "Total Estimated Damage" (in Million) to Charlottetown's Economic Pillar As a Function of Storm Severity Variable MOWL. Source: Derived from Hartt (2011)

Similar to the environmental pillar, the data series follows an exponential trend, as shown in Figure 3.4.

3.2.3.3 Social Pillar Storm Damage Estimates

The social pillar of Charlottetown under the Status Quo (no adaptation) strategy would receive expected total damages of $118, $422, and $873 thousand corresponding to Storm Scenarios II, IV, and VI, respectively (Hartt, 2011). Given Total Damage of Storm Scenarios II, IV, and VI, total damages of other storm scenarios can be found by interpolating, as above. The Total Estimated Damages to social pillar and MOWL values are shown in the graph of Figure 3.5.

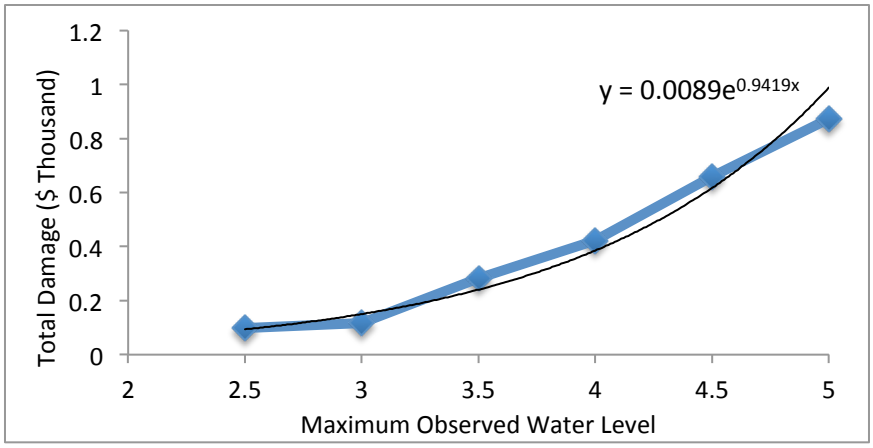

Figure 3.5. "Total Estimated Damage" (in $Thousands) to Charlottetown's Social Pillar As a Function of Storm Severity Variable MOWL. Source: Derived from Hartt (2011)

Similarly, the data series of social damages as a function of storm severity follows an exponential trend, as shown in Figure 3.5.

3.2.3.4 Cultural Pillar Storm Damage Estimates

According to Hartt's results, total estimated damages to the cultural pillar of Charlottetown caused by Storm Scenarios II, IV, and VI, under Status Quo strategy, are $194 thousand, $666 thousand, and $1.40 million. Similar to the other pillars, Total Estimated Damage values of Storm Scenarios I, III, and V can be found by Total Damage computed for other storms. Total Damage to the cultural pillar and corresponding MOWL value for the six Storm Scenarios are displayed in Figure 3.6.

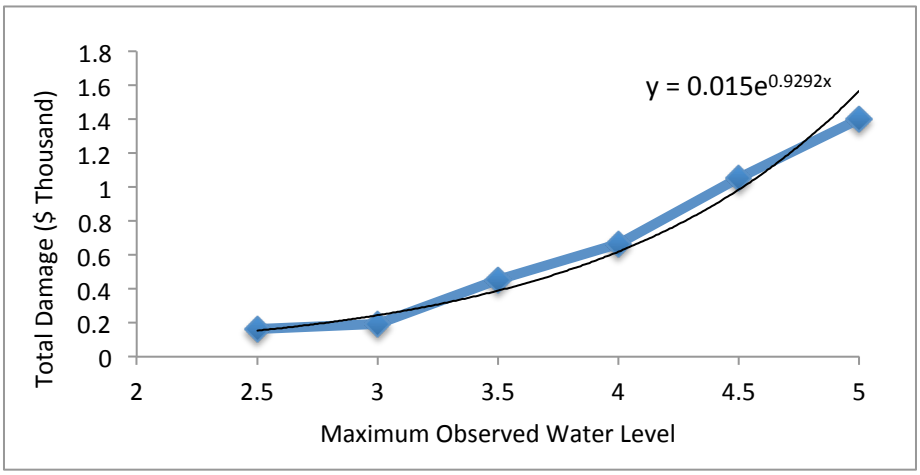

Figure 3.6. "Total Estimated Damage" (in $Thousands) to Charlottetown's Cultural Pillar As a Function of Storm Severity Variable MOWL. Source: Derived from Hartt (2011)

Analogously, the best-fit data series shows an exponential trend, as exhibited in Figure 3.6.

3.3 Risk Management

The expected damage impacts to coastal communities from severe storms provide the basis for adaptation strategy evaluation. The main purpose of risk management is to evaluate those strategies expected to reduce vulnerability and damage impacts, especially to those community pillars that are more of interest or priority to the community. To carry out this evaluation, multi-attribute utility theory is employed to find the highest weighted utility values applied comparatively to alternative adaptation strategies.

The following subsections provide detailed information on: 1) the definition of alternative adaptation strategies, 2) utility curve construction, and 3) the application of multi-attribute utility theory for evaluating decision options.

3.3.1 Alternative Adaptation Strategies

Alternative adaptation strategies are intended to mitigate the impacts of severe storms. These strategies are developed and compared with the status quo option of doing nothing in response to pending storms. The amount of vulnerability reduction and the cost of implementation for each option count for important factors in decision making. Mostofi (2011) did a comprehensive study around the multi-criteria evaluation of adaptation strategies in the case of Little Anse, located in Isle Madame, Cape Breton. In his study, he evaluated new breakwater strategies as adaptation options for the community. Mostofi (2011) considered the alternative adaptation strategies, as follows:

1) "**Protect**"- improving the engineered systems in an attempt to overcome the storm impacts;
2) "**Accommodate**"- building a bypass or bailout strategy that would reduce (but without attempting to fully eliminate) community vulnerability to storm surge impacts;
3) "**Retreat**"- moving community households that are known to be more vulnerable to severe storms in order to get them "out of the way" of the storm; and
4) "**Status Quo**" – do nothing.

Alternative strategies for Charlottetown are categorized according to this broad breakdown of options (Pilkey & Young, 2009). Details of the adaptation strategies for Charlottetown are defined further below.

1) Protect- building storm surge barriers is considered as a representative Protect strategy option for Charlottetown. Storm surge barriers are hard engineered structures that can be built across a river mouth or harbor entrance. They have movable or fixed barriers (or gates) to close in case of rising water levels. The water and boats are allowed to move through the barriers (or gates) during normal conditions. The cost estimation of building storm surge barriers in Charlottetown is deemed to be comparable to the cost estimation done

for the Steveston or False Creek dike, breakwater, storm surge barriers and sea gates construction in the Vancouver area of British Columbia (Delcan, 2012). The estimated cost components of storm surge barriers are shown in Table 3.4.

Table 3.4. The Cost Estimation of Storm Surge Barriers for Charlottetown.
Source: Based on (Delcan, 2012)

Cost Components	Costs ($ Million)
Capital Cost	50
Site Investigation, Project Management and Engineering	8
Contingency	17
Total	75

The site investigation, project management and engineering cost ranges from 15% to 20% of capital cost, and contingency costs are typically between 30% and 50% (Delcan, 2012).

It is also assumed that the storm surge barriers protect Charlottetown against all severe storms with MOWLs below or equal to 3.6 meters. Figure 3.7 displays the adjustment to storm damage for a single trial of storms with Gumbel max generated MOWLs over a 50 year period. The Protect option applied here assumes that all MOWLs below or equal to 3.6 meters are equivalent to MOWL of zero (yielding no storm damage). Storms with MOWLs above the 3.6 meters level are assumed to impact Charlottetown with damages as if the barriers were not present.

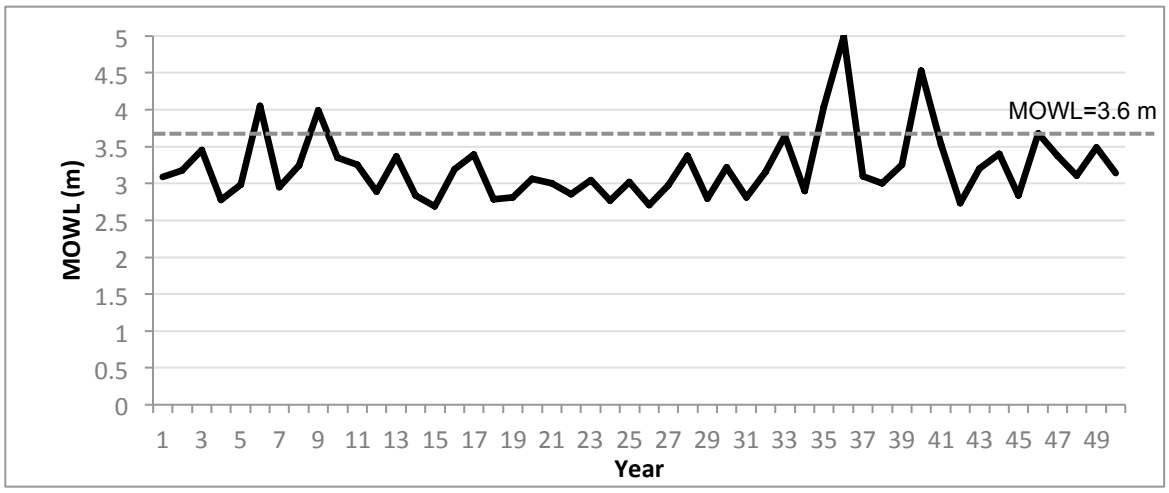

Figure 3.7. MOWL Series Simulation Under Protect Strategy Over 50 Years

For example, MOWL of 3.6 meters under the Do Nothing strategy causes estimated damages of $5 million to the environmental pillar (Figure 3.3), while this MOWL under the Protect strategy and sea barriers in place is assumed to cause damages of zero to the environmental pillar.

2) Accommodate- elevating the building structures above the designated Flood Construction Level (FCL) is considered as part of the accommodation strategy option for Charlottetown. As such, the Accommodate strategy acknowledges the potential impact of storms, and seeks opportunities to mitigate the negative effects. Accommodate is sometimes referred to as flood proofing. This can be achieved in many ways depending on the particular characteristic of the costal community. For example, elevating the habitable spaces within the building, or placing the entire building on stilts, or building new foundation walls are part of an accommodation adaptation strategy. For Charlottetown, it is assumed that the capital cost of this strategy is $65 million, typically less than the capital cost of building storm barriers in the Protect strategy. The estimated cost components related to a flood proofing strategy for Charlottetown are listed in Table 3.5.

Table 3.5. The Cost Estimation of Accommodation Flood Proofing for Charlottetown

Cost Components	Costs ($ Million)
Capital Cost	45
Site Investigation, Project Management and Engineering	6
Contingency	14
Total	65

Further, with the storm mitigation effect of flood proofing, it is assumed that severe storm impacts of a MOWL under the Accommodate strategy are reduced to 75% of the generated storm impacts, for the same MOWL, under the Do Nothing strategy. Figure 3.8 illustrates the change to a single Gumbel max series of MOWLs over a 50-year span.

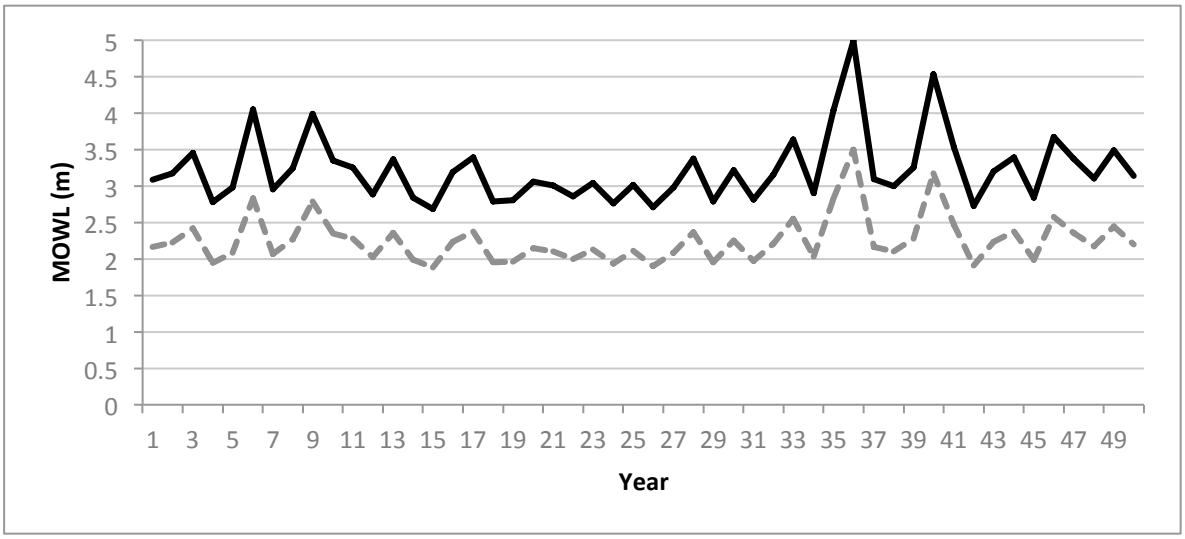

Figure 3.8. MOWL Series Simulation Under Accommodate Strategy with 75% Storm Impacts Over 50 Years

For instance, the MOWL of 3.6 meters under the Do Nothing strategy causes estimated damages of $5 million to Charlottetown's environmental pillar. However, the resulting MOWL of 2.7 meters (0.75*3.6) under the Accommodate strategy would cause an estimated damage of only $2 million to the environmental pillar (Figure 3.3).

3) Retreat- moving the houses and buildings out of coastal waterfront areas exposed to flood hazard characterizes the retreat strategy option for Charlottetown. Further, property development would not be carried out in high potential flooding areas over time, and the area would become an alternative land use area, e.g., recreational park land, or natural wetlands areas. Retreat also necessitates community resettlement for those who are displaced and expropriated from their lands and residential and commercial sites. It is assumed that the Retreat strategy has a capital cost to Charlottetown of $90 million. As such, Retreat is assumed the most expensive adaptation strategy in comparison to the others defined for Charlottetown above. The estimated cost components of Retreat strategy are listed in Table 3.6.

Table 3.6. The Cost Estimation of Retreat Strategy for Charlottetown

Cost Components	Costs ($ Million)
Capital Cost	60
Site Investigation, Project Management and Engineering	9
Contingency	21
Total	90

It is assumed that the Retreat strategy not only protects the Charlottetown city on the face of any MOWLs below or equal to 2.5 meters, but it also decreases the severity of MOWLs to 85% of MOWLs under the Do Nothing strategy. Figure 3.9 shows the assumed shifts to the effective MOWLs for the Retreat strategy compared to the single series of the Gumbel max generated storms over the 50 years span.

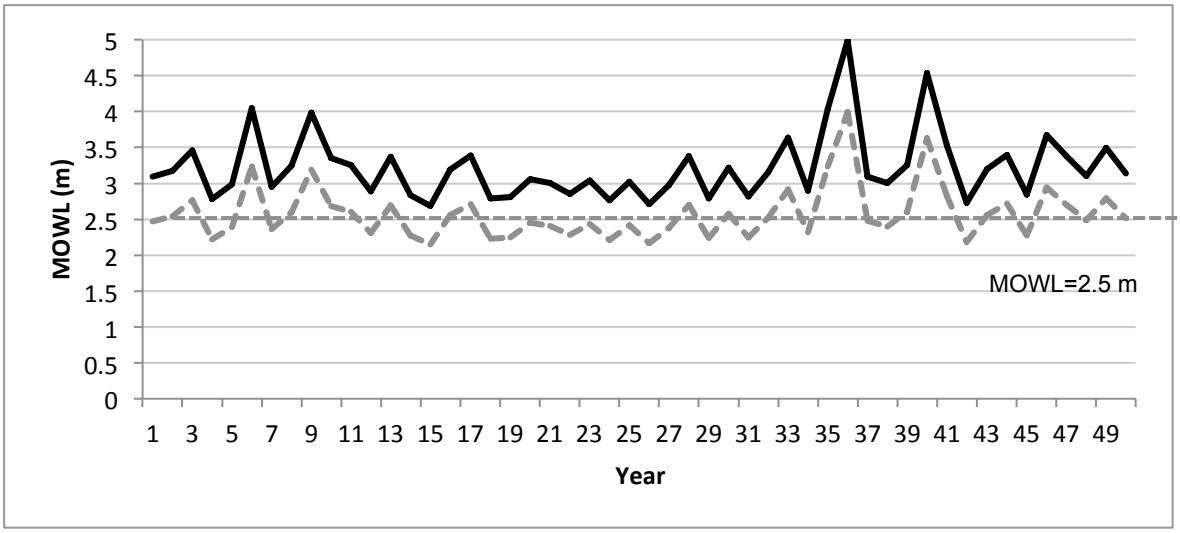

Figure 3.9. MOWL Series Simulation Under Retreat Strategy Over 50 Years

For instance, the MOWL of 3.6 meters under the Do Nothing strategy causes estimated storm damages of $5 million to the environmental pillar (Figure 3.3), while the MOWL of 3.1 meters (0.85*3.6) under the Retreat strategy would have an estimated cost impact of only $2.2 million in damages to Charlottetown's environmental pillar.

Since, there are no studies available around building aforementioned strategies in Charlottetown, the cut-off level and mitigation rate considered for the Accommodate and the Retreat strategies are based on estimates for related coastal communities.

3.3.2 Utility Curve Development

Decision makers are assumed to possess an inherent utility function that defines their trade-offs of the monetary values including the losses associated with a severe storm. This utility function captures the decision maker's characteristic risk profile. Utility functions can be classified in terms of decision makers' attitude towards risk. Individuals differ in how much they are willing to trade-off risky events. Three general characterizations of behavior towards risk are as follows: (a) risk aversion, (b) risk neutrality, and (c) risk seeking behavior. In addition, a mixture of these three kinds of risk behaviour is possible in the construction of a decision maker's practical utility curve as a function of the impact or estimated storm damage amounts. The classification of common risk attitudes are presented below following the seminal work of Raiffa (1970).

a) **Risk Averse**: when the calculated expected monetary value (consequence) of a lottery (reference probability-based outcome) is preferred to that lottery, the decision maker is referred to as being risk averse. For example, if the reference lottery pays off damages of $20 million (lose outcome) or $0 damages (win outcome) with equal probabilities (%50), a risk averse decision maker will prefer to pay some amount more than the cost of $10 million (the expected monetary or "risk neutral" value of the lottery) in order to avoid having to participate in this lottery (Raiffa, 1970).
b) **Risk Neutral:** when the expected monetary value (consequence) of any lottery (reference probability-based outcome) is equal to that lottery, the decision maker is referred to as being risk neutral. In the lottery example above, a risk neutral person is indifferent between participating in the $20 million (lose outcome) or $0 damages (win outcome) with equal probabilities (%50), and and paying exactly $10 million to avoid the lottery (Raiffa, 1970).
c) **Risk Seeking:** when the expected monetary value (consequence) of any lottery (reference probability-based outcome) is less preferred than that lottery, the decision maker is referred to as being risk seeking. A risk seeking person would pay less than the $10 million risk neutral amount to avoid participating in the $20 million (lose outcome) or $0 damages (win outcome) with equal probabilities (50%) lottery,

because they value the equivalent outcome at lower than the $10 million loss (Raiffa, 1970).

All utility curves are monotonically increasing, meaning that the community always prefers more of a good thing (i.e., less damage costs), rather than less (i.e., more damage costs). The best possible outcome (i.e., the maximum, or the less negative impact) on a specific pillar receives a utility anchor value of 1.The worst outcome (i.e., the minimum, or the most negative impact) receives a utility anchor value of 0 (Ishizaka & Nemery 2013). These anchor points frame the construction of the decision maker's context specific utility curve.

For example, consider Figure 3.10 below. For a $500 payoff, risk averse, risk neutral, and risk seeking persons assign different utility values to this same monetary value as its equivalent trade-off utility value, i.e., from Figure 3.10, dimensionless utility values of 0.67, 0.5, and 0.23 respectively. The utility value for a risk neutral person is less than the utility value for the risk averse person and greater than the utility value for a risk seeking person. On the other hand, for a given utility value of 0.5 (the probability of "winning" the maximum dollar value), a risk averse person is willing to pay an amount less than $500 as its equivalent to taking part in the basic Win (maximum)-Lose (minimum) lottery, a risk neutral person is willing to pay exactly $500 (the equivalent of the expected value of the Win-Lose lottery); and a risk seeking person is willing to pay an amount greater than $500 to participate in the same 0.5 probability of Win lottery.

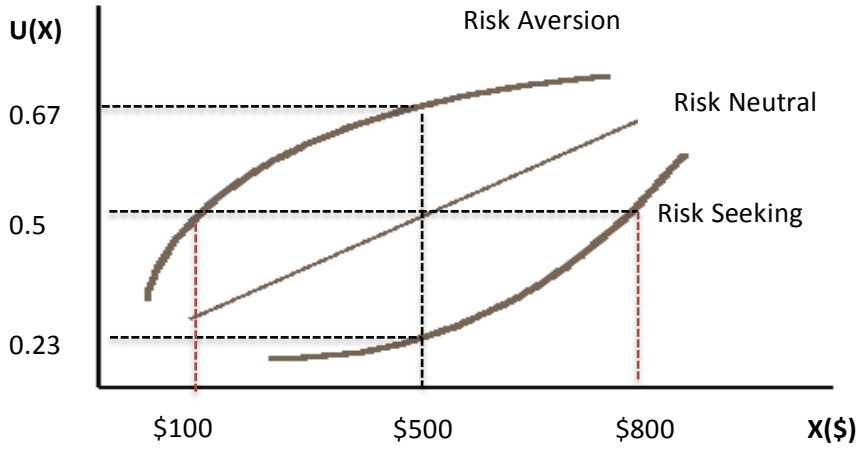

Figure 3.10. The Utility Values With Respect to Different Behaviors Towards Risk.
Source: (Raiffa, 1970)

Utility analysis makes it possible to incorporate various risk profiles into the community's analytic decisions. Every member of the community has a different attitude towards the risk in any specific context. These different preferences of risk need to be aggregated to represent the overall community's risk perception over the range of outcomes. In this research, the utility functions are established for every pillar separately over all possible outcomes for storm damage expressed as monetary impacts, with respect to the community's perception of risk. In this case, the aggregated community utility curve is described by an X-axis representing the monetary impacts (i.e., total storm damages) that originate from the estimates derived in Section 3.2 above for severe storm events for Charlottetown. The utility curve Y-axis represents the community's utility corresponding to the storm impact levels.

The assumed pattern of the community's utility curve for each community profile pillar is an S-shaped function. This characteristic curve exhibits concavity for lower level of damages (high utility outcomes) and convexity for more serious and larger expected damages (low utility outcomes). The concave and convex shapes have a psychological interpretation. The community may not be willing to undertake appreciable actions when the estimated amounts of expected damages are relatively low and the opportunity to improve utility is small. On the other hand, the community is more willing to undertake appreciable actions in order to avoid large monetary damages and to realize the significant gain in utility by moving away from the high potential damages cases.

The higher utility values on a monotonically increasing community utility curve correspond to a lower amount of damages, indicating that protecting more of an asset is preferable to the community. Moving along the X-axis, the amount of the damages decreases and the corresponding asset position increases.

The following subsections describe the characteristic community utility curves for each of the community profile pillars – environmental, economic, social, and cultural.

3.3.2.1 Environmental Pillar Utility Curve

The utility curve for the community's environmental pillar demonstrates different utility values. Monetary values of damages to the environment, computed in Section 3.2.3, are translated into utility value by assuming that the higher monetary storm damage value has the lower utility value, as shown in Figure 3.11 a and b. For improved function estimation

purposes, the environmental utility curve is separated into two parts: part (a) applies to environmental damages from $20 million (max) to $7 million; part (b) applies to environmental damages from $7 million to $0 (min), as described in Figure 3.11 below.

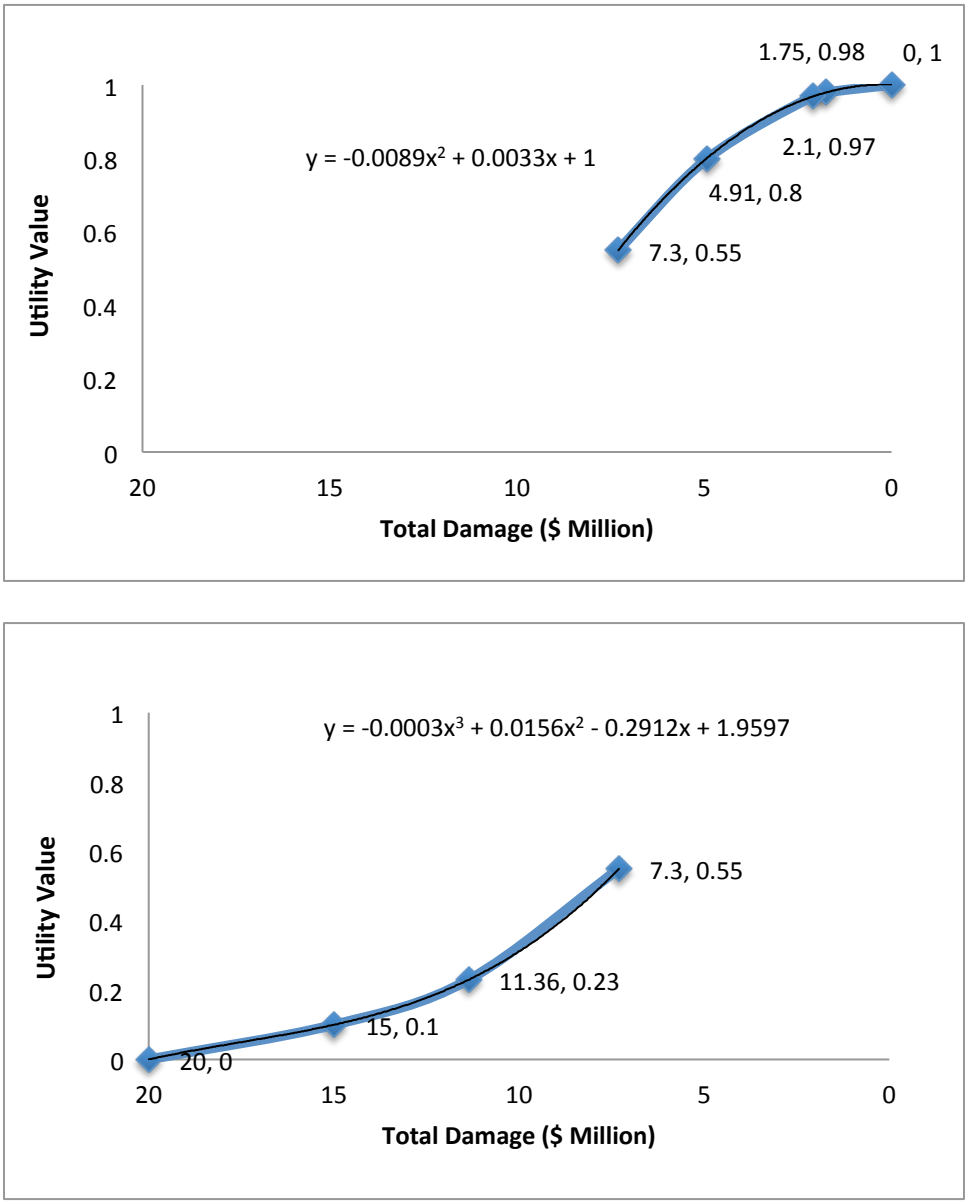

Figure 3.11. Environmental Pillar Utility Curve for Charlottetown Community; (a) Applies to Environmental Damages from $20 Million (max) to $7.3 Million; and (b) Applies to Environmental Damages from $7.3 Million to $0 (min)

The maximum expected environmental damage amount of $20 million is assigned a utility curve anchor value of zero. The environmental utility curve is divided into two parts to provide more accurate trendlines for utility value estimations. The minimum expected

damage value of $0 is assigned the highest utility score of zero. Beyond the utility inflection point, (at $7.3 million, 0.55 utility), the utility curve rises with decreasing marginal utility as damages decline. Thus, the community becomes relatively indifferent between damages less than $5 million where utilities exceed high end values of 0.80 utility. The rapidly rising utility at low levels (below 0.50 utility) and high corresponding damages (exceeding $10 million) suggests that utility gains can be made by avoiding high damages. The utility gains (and damage reductions) may be achievable by adopting preferred adaptation strategies that will reflect this expected utility gain. Figure 3.11 provides the trendlines for the best estimates of fit to the utility values (y) as a function of the storm damages (x).

3.3.2.2 Economic Pillar

The utility values are assigned to the impacts on the economic pillar, which uses the result of vulnerability assessment of Section 3.2.3. The utility curve for the community's economic pillar is shown in Figure 3.12 along with the trendline for the best estimates of fit to the utility values (y) as a function of the storm damages (x).

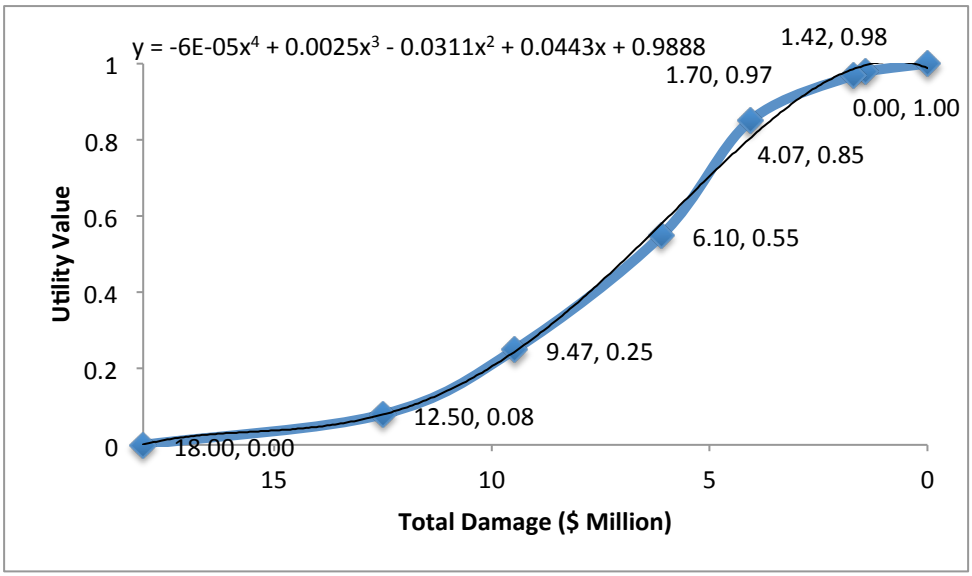

Figure 3.12. Economic Pillar Utility Curve for Charlottetown Community

The highest utility value is one and the lowest is zero. The lowest utility of zero corresponds to $18 million value of expected economic damage. The highest MOWL observed in the simulated storm data is 5.2 m with economic damage of $17.12 million. The maximum damage amount is set at $18 million. Beyond the utility inflection point, at ($5

million, 0.60 utility), the economic marginal utility is decreasing with declining damages. For utility values greater than 0.85, the community gradually becomes indifferent between expected economic damages less than $4.07 million. On the other hand, the rapidly rising utility curve at low levels (above 0.08 utility) and high corresponding damages (exceeding $6 million) suggest that utility can be gained by avoiding the high damages. Achieving to this expected utility gain and economic damage reduction might be feasible by adopting appropriate adaptation strategies.

3.3.2.3 Social Pillar

The damages incurred to Charlottetown's social pillar, computed in section 3.2.3, are interpreted to utility values. The curve is monotonically increasing, meaning that lower damages are preferred by the community, as shown in Figure 3.13 along with the trendline for the best estimates of fit to the utility values (y) as a function of the storm damages (x).

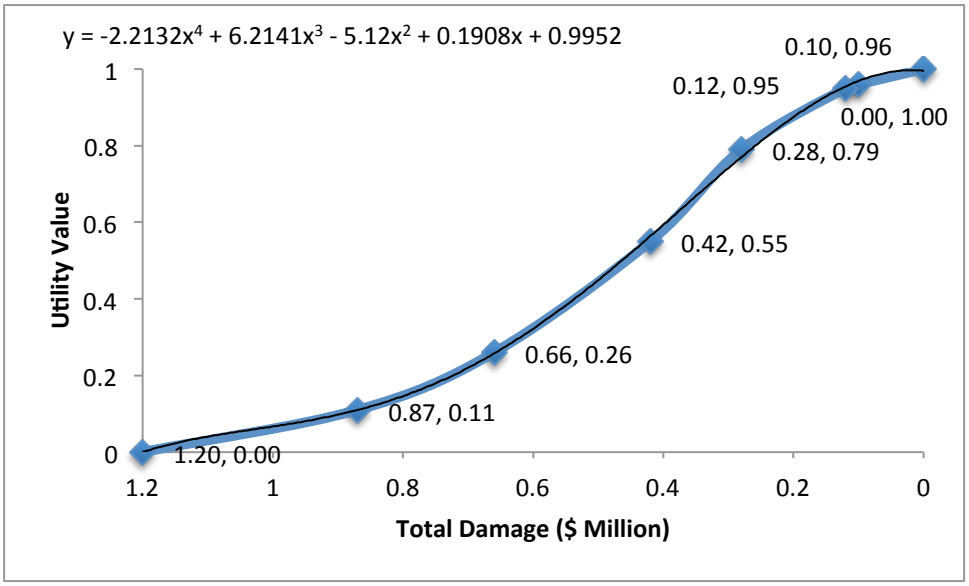

Figure 3.13. Social Pillar Utility Curve for Charlottetown Community

The utility score of zero is assigned to the expected damages amount of $1.2 million amount of expected damage, and the utility value of one is assigned to the expected social damage of zero value. Beyond the utility inflection point, at ($350 thousand, 0.60 utility), the social marginal utility is decreasing with declining damages. Hence, the community gradually becomes indifferent between expected social damages less than $280 thousand. In

addition, the marginal social utility starts rising rapidly at utility score of 0.1 and corresponding social damage of $900 thousand. Therefore, the social utility values can be augmented by avoiding high social pillar damages.

3.3.2.4 Cultural Pillar

The utility curve for the Charlottetown cultural pillar reflects negative impacts caused by storm events, as shown in Figure 3.14 along with the trendline for the best estimates of fit to the utility values (y) as a function of the storm damages (x). Monetary values of damages to the cultural pillar, computed in Section 3.2.3, are used for utility values assignment.

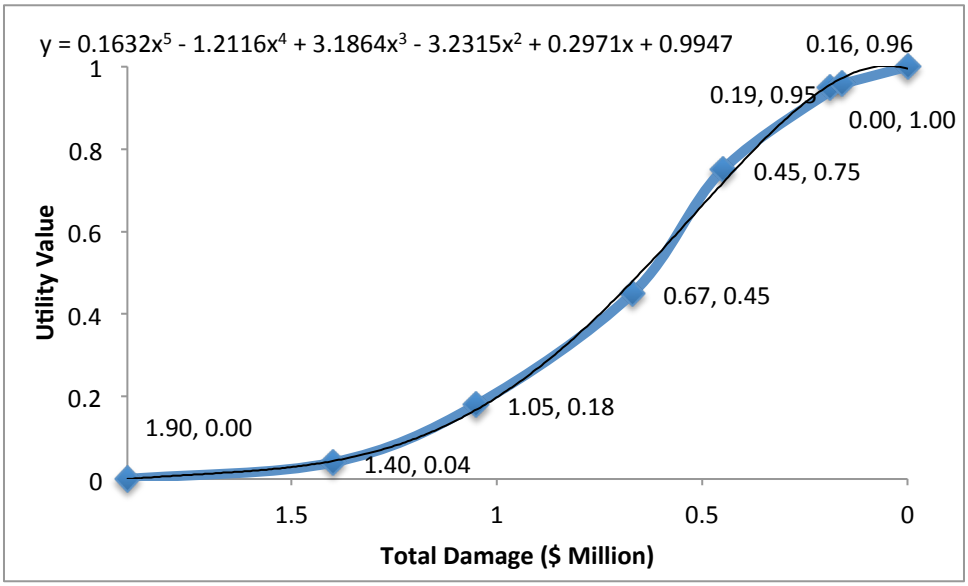

Figure 3.14. Cultural Pillar Utility Curve for Charlottetown Community

The utility value is at its highest level of 1, for zero amounts of expected cultural damage. The utility score for damage of $1.9 million is zero, the minimum utility value. The highest MOWL observed in the simulated storm data is 5.2 m with cultural damage of $1.9 million. Above the inflection pint, at ($600 thousand, 0.50 utility), the utility curve rises with slowly decreasing marginal utility with declining damages. The uprising utility at low levels (below 0.45 utility) and conforming damages (exceeding $670 thousand) shows that utility can be gained by avoiding the high damages.

3.3.3 Application of Multi-Attribute Additive Utility

In practice, decision makers pursue several objectives simultaneously. These objectives sometimes have different levels of importance to the decision maker, or are even in contradiction with each other. This leads to considering different attributes to describe the possible consequences in a multidimensional objective space such as the multiple pillars of the coastal community adaptation problem (Abdellaoui et al., 2009).

Consider, for example a decision maker prioritizing a set of alternative adaptation strategies applicable to a specific community. Let **A** denote the set of alternatives, where

A = {Protect, Accommodate, Retreat, Do Nothing} (3.1)

Let multi-attribute set $\boldsymbol{x}$ denote the corresponding set comparable utility values attached to each alternative A_i, where

$$\boldsymbol{x} = \{u_{En}(f_{En}(A_i)), u_{Ec}(f_{Ec}(A_i)), u_{Soc}(f_{Soc}(A_i)), u_{Cult}(f_{Cult}(A_i))\} \quad (3.2)$$

The functional attributes are component utility values for the (1) environmental, (2) economic, (3) social, and (4) cultural pillars. For instance, $f_{En}(A_i)$ reflects the utility associated with the impacts for the adaptation strategy A_i with respect to the environmental pillar. The overall objective is to seek out the adaptation strategy with the largest expected utility for the given decision problem (Ishizaka & Nemery, 2013; Abdellaoui et al., 2009).

For each adaptation strategy, the utility values over all pillars are aggregated with the Additive Utility Function:

$$U(A_i) = \sum_{j=En}^{Cult} \mathcal{W}_j \, . \, U_j(f_j(A_i)) \quad (3.3)$$

where $0 \leq U_j(f_j(A_1) \leq 1$, and j denotes the pillar, j=1,2,3,4 and $\mathcal{W}_j$ shows the degree of the importance of each pillar to a coastal community such that $\sum_{j=En}^{Cult} \mathcal{W}_j = 1$. In other words, these weight factors represent the trade-offs between each of the four pillars from the coastal community's perspective (Ishizaka & Nemery, 2013).

Utility values are assessed for different adaptation strategies applicable to the research applications, and under various potential storm scenarios. In addition, the implementation cost for each adaptation strategy is estimated. One utility function has been developed (as

noted above) for each community profile pillar by using historical data for impacts caused by various historical storm events for Charlottetown (Hartt, 2011).

To illustrate, suppose that the monetary values of impacts for two adaptation strategies ("Do Nothing" and "Protect") are obtained, as shown in Table 3.7, after completing the risk assessment as described above.

Table 3.7. Example Vulnerability Assessment for the Four Pillars

	Vulnerabilities to (Impacts of) Storm Hazards ($ Million of Losses)			
Adaptation Strategies	**Environmental Pillar**	**Economic Pillar**	**Social Pillar**	**Cultural Pillar**
Do Nothing	6	7	6	8
Protect	5	4	2	6

The example component utility values corresponding to each community pillar can be gained by the separate utility curves, as illustrated in Figure 3.15 with assignment for "Protect" strategy.

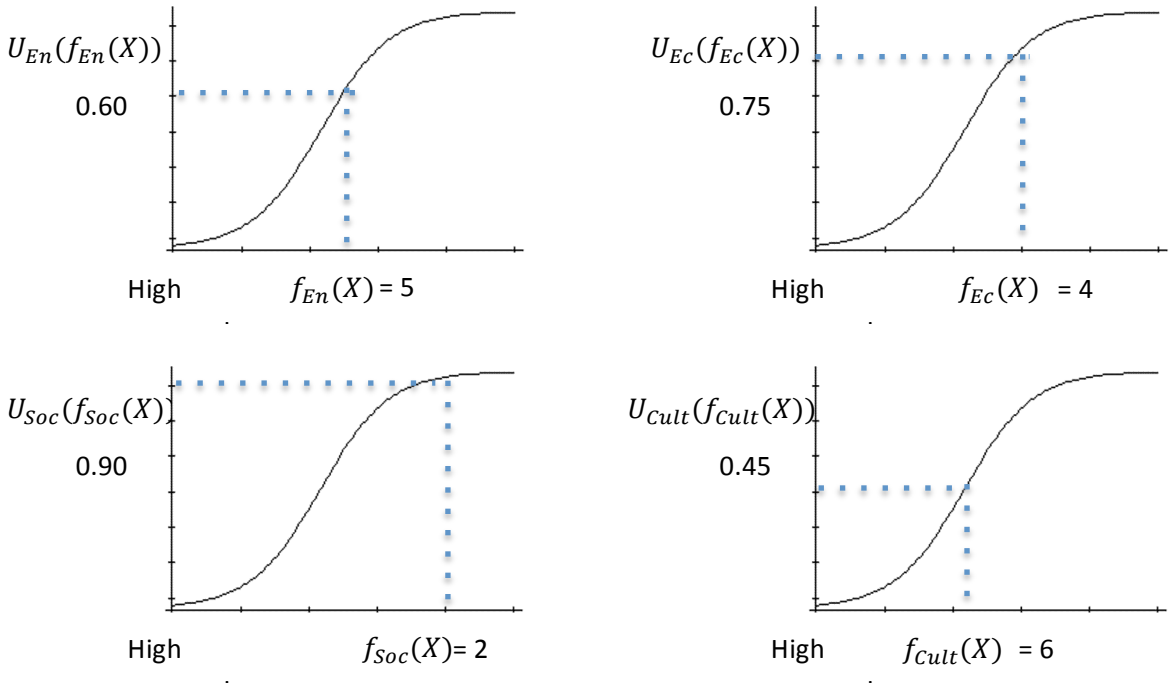

Figure 3.15. Example Component Utility Values Under the "Protect" Strategy

The weights assigned to each pillar are obtained from the coastal community's

predetermined priority across the community pillars. Exercises describing the expression of community priorities are provided in the C-Change Working Paper for the Communities of Practice Workshops in Ottawa (October 2012) and Petit de Grat (May 2013), (C-Change 2012; C-Change 2013).

Figure 3.16 represents example weights allocation, $\mathcal{W}_j$ for all j, with respect to the coastal community's perspective towards the community profile pillars, in a pie diagram.

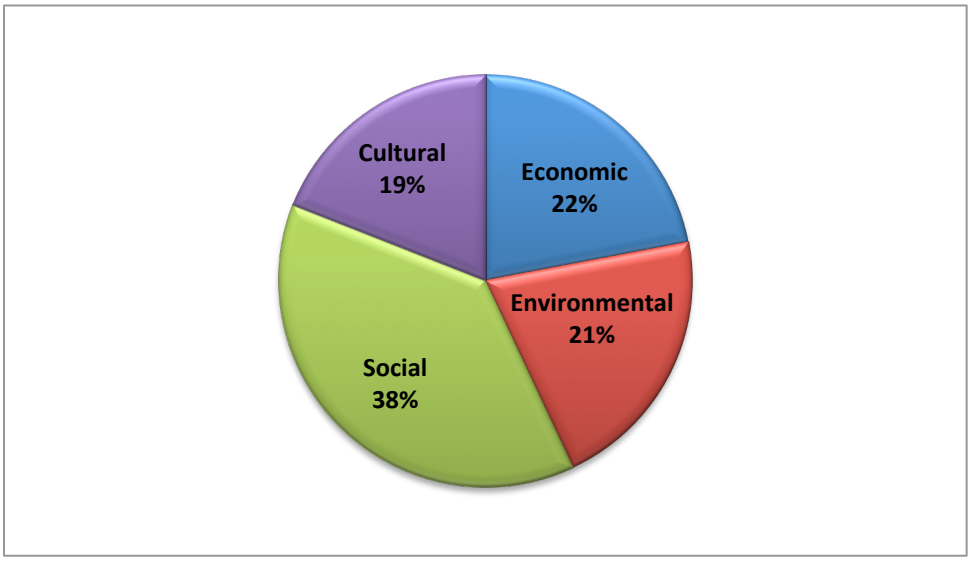

Figure 3.16. Weight Allocation to the Four Pillars by Local Government. Source: (Lane, 2013)

Given the vulnerabilities (Table 3.7), utility values (Figure 3.15), and the weights (Figure 3.16), the value of the additive utility function for each strategy can now be computed as per equation 3.3 above. The example computation is presented in Table 3.8.

Table 3.8. Weights and Utility Values Under Two Different Strategies

Utility Value $U_j(f_j(A_i))$	**Environmental**	**Economic**	**Social**	**Cultural**	**Total Weighted Utility**
Do Nothing $U_j(f_j(A_0))$	0.45	0.30	0.35	0.15	0.32
Protect $U_j(f_j(A_1))$	0.60	0.75	.90	0.45	0.72
Weights $(\mathcal{W}_j)$	0.21	0.22	0.38	0.19	1.0

In this illustrative case, the higher the total additive utility value, the more preferable the strategy. The "Protect" strategy receives the larger total additive utility value, therefore it is preferable to the "Do Nothing" strategy with respect to the coastal community profile and its

preference to the community.

It is noted that in this case, the Social pillar is the most important pillar to the community since it is assigned the greatest weight (0.38). Reduction in the vulnerability of the Social pillar to severe storm events is the first priority for the community. Thus, adopting the "Protect" strategy may be a more suitable choice in comparison to the "Do Nothing" strategy. The impacts of storm hazards on the community are reduced and utility improved (0.90 versus 0.35 from Table 3.8).

Finally, we consider the evaluation of multi-attribute utility over time. The Total Annual Discounted Average Utility (TADAU) measures the total utility of a strategy option by discounting annual total weighted values to the current year applying an annual discount rate. Higher TADAU values indicate a preferred strategy. Sensitivity analysis is applied to the effect of alternative values for the annual discount rate (Chapter 4).

3.4 Risk Communication

Coastal communities' decision makers may reach different conclusions when considering different time frames or planning periods over which their decisions are made. Identifying an effective time frame and analyzing the sensitivity of decisions to this time horizon is an important consideration for decision makers of coastal communities. The following subsections provide more information regarding: 1) experimental design, and 2) sensitivity analysis of the problem.

3.4.1 Experimental Design

One significant factor that should be taken into consideration around sustainable decision making is defining an effective time horizon over which to evaluate the adaptation strategies. The number of severe storm events, the severity of storm events, and the likelihood that these events may happen within a restricted planning period may alter the way in which decisions are evaluated and ultimately, taken.

In the present study, changing the time frame has effects on the expected storm event occurrences. To find an effective time horizon, different methods can be applied such as benchmarking, or studying coastal communities' historical data on storm events and looking for intervals between two similar storm events.

In order to find an appropriate time horizon for Charlottetown storm planning period, four planning periods are defined. These are denoted as: 1) short-term, 2) short-to-medium-term, 3) medium-term, and 4) long-term planning period. The following table shows the duration of each proposed planning period. A discussion of the rationale and practice of using these planning periods follows.

Table 3.9. Durations of Different Planning Periods for Charlottetown

No.	Time Horizon Description	Duration (in Years)
1	Short-Term	3
2	Short-to-Medium-Term	5
3	Medium-Term	10
4	Long-Term	20

Significant milestones regarding Charlottetown strategic planning can be extracted from Charlottetown documents and reports. The mayor and council of Charlottetown are elected every four years (as for all municipalities in Canada). It is deemed that every elected mayor needs one year to plan for the remaining 3-year mandate. Hence the rationale behind the 3-year plan.

According to the Charlottetown Official Plan (Charlottetown Official Plan, 1999), which is a foundation for the city's future growth, a five-year capital budget is considered to provide the council and staff with forward thinking that considers their strategic action plans. In addition, Charlottetown's Integrated Community Sustainability Plan (ICSP, 2010) defines a periodic review, revision, and update as necessary every five years.

The Charlottetown Water Conservation Plan, which initiates Charlottetown sustainable water use, is currently being developed under a 10-year plan (Sustainability in Action Report, 2011). Finally, based on the overarching vision for the Parks in the Charlottetown area, the management plan for Victoria Park is determined over a thirty-year time frame (Victoria Park Comprehensive Master Plan, 2013).

The above discussion provides rationale for the alternate range of planning periods. The selection of planning periods in Table 3.9, between three and twenty years, reflects this range of options currently in place for various planning programs of Charlottetown. These planning periods will be reflected in the analysis and evaluation of environmental changes for the city in this research and are presented in the research methodology as part of the analysis experimental design.

3.4.2 Storm Simulation

Using the inverse function of the characteristic Gumbel maximum distribution, the Maximum Observed Water Level (MOWL) for Charlottetown annual storms can be generated successively and independently by year (Section 3.2.1 above and Beigzadeh, 2014). In this case, it is assumed that what is being simulated is Charlottetown's maximum annual severe storm, i.e., the most severe storm each year. The simulated MOWL over fifty years, as an example, is displayed in Figure 3.17.

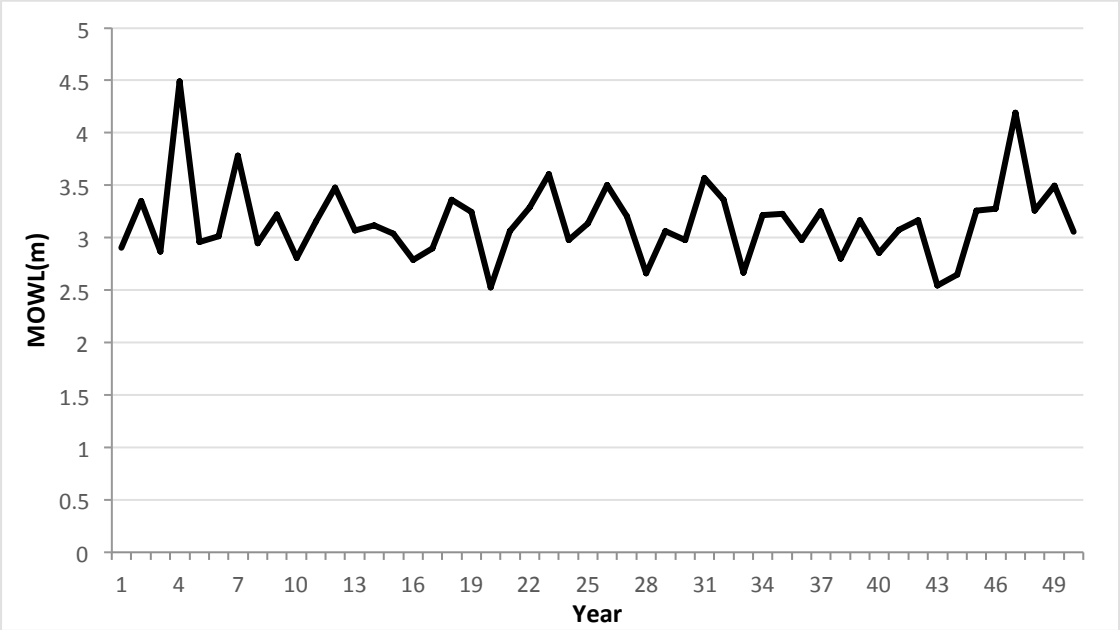

Figure 3.17. Simulation of Charlottetown Severe Storm MOWL Over 50 Years

The sequence of MOWL over 50 years can be broken into different successive planning periods, which are equal to the predefined planning period lengths. For instance, for a 3-year planning period, the MOWL time series is broken into time intervals of 3 complete years, which yields sixteen successive 3-year trials in 48 years. Therefore, ten, five, and one trial(s) can be taken out of fifty years in the case of having 5-year, 10-year, and 30-year planning period, respectively.

3.4.3 Experimental Planning Period Sensitivity Analysis

Projection of different time horizons opens a new perspective on coastal communities' decision making. The sensitivity analysis described here as an experiment

compares different planning periods ranging from short time frame to longer time frame and describes the research process that will be applied to the complete risk analysis presented in Chapter 4 below.

The experiment in planning period sensitivity analysis obeys the following rule over all planning periods.

Rule: Decision making in all planning periods are characterized by one of three different action categories are examined below to illustrate the impact of the planning period on decision making. The maximum of the simulated (or independently and randomly predicted) MOWL throughout the selected planning period is considered as the significant severe storm event for the assumed planning period. Further, it is assumed that maximum MOWLs less than or equal to 3.5m for Charlottetown are not of particular concern to the community. These are assigned to the "No Concern" category. Any maximum MOWLs greater than 3.5m and less than or equal to 4.5m are assigned to the community's "Concern" category. Maximum MOWLs greater than 4.5m are assigned to the "Much Concern" category.

Consider for example, in the case of 3-year planning period, three storm events are observed, i.e. simulated, as shown Table 3.10.

Table 3.10. Maximum of MOWL Throughout a 3-Year Planning Period

Year	MOWL	Maximum of MOWL	Designation
1	3.3	3.9	Concern
2	3.1		
3	3.9		

Among the three MOWL values generated for this 3-year period, 3.9m is the highest or maximum MOWL simulated, which falls into the "Concern" category. Thus, this 3-year predicted series is designated as "Concern". Applying this categorization rule to multiple storm series, predicted for the 3-year planning period, yields the average community response to the predicted results over this short planning period. The summary of the average community status for the different planning periods of Table 3.9 are presented below for a hundred trials, and the results are compared together in the description below. Randomized trials for the classification table created for a 3-year planning period is presented in Appendix C- The Sensitivity of the 3-Year Planning Period.

3-Year Planning Period Results

In order to present the relative frequency of the three categories, over a set of a hundred 3-year predicted planning periods, the aforementioned rule is applied. The results of the categorization for 100 3-year intervals are presented in Figure 3.18 below.

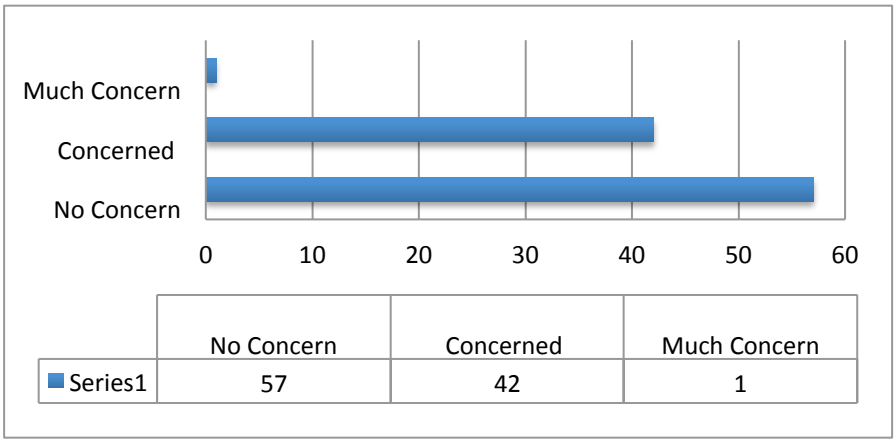

Figure 3.18. The Frequencies of Three Categories Given 3-Year Intervals

According to the bar chart of Figure 3.18, the number of trials yielding the "No Concern" category is highest (57 of 100 3-year planning period trials) than the two others. This indicates that for the Charlottetown predicted storm series of Section 3.2.1, the planning period of 3 years tends to categorize a severe storm occurrence as of less concern to the coastal community. This may indicate that the prediction window of the short planning period does not stimulate adaptation action.

5-Year Planning Period Results

A hundred series of 5-year periods are obtained for generating predictions of the maximum MOWL by applying the rule to the MOWL time series (Section 3.2.1) for the 5-year planning period. The frequencies of their corresponding categories are illustrated in Figure 3.19.

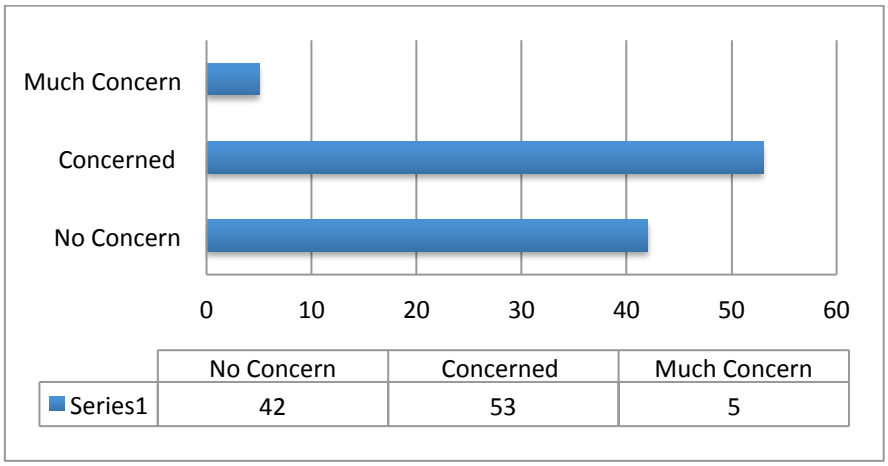

Figure 3.19. The Frequencies of Three Categories Given 5-Year Intervals

The relative frequency of "No Concern" periods in the shorter, 3-year planning period (Figure 3.18) has shifted toward having more "Concern", with a small increase in the "Much Concern" category in comparison to the 3-year planning period results. This indicates that the longer planning period allows for more opportunity for the community to experience severe and damaging storm events for which they are inclined to develop adaptation strategies.

10-Year Planning Period Results

After generating one hundred trials of maximum MOWL storms for intervals of 10 years as the planning period, and applying the aforementioned rule, the bar chart Figure 3.20 is constructed.

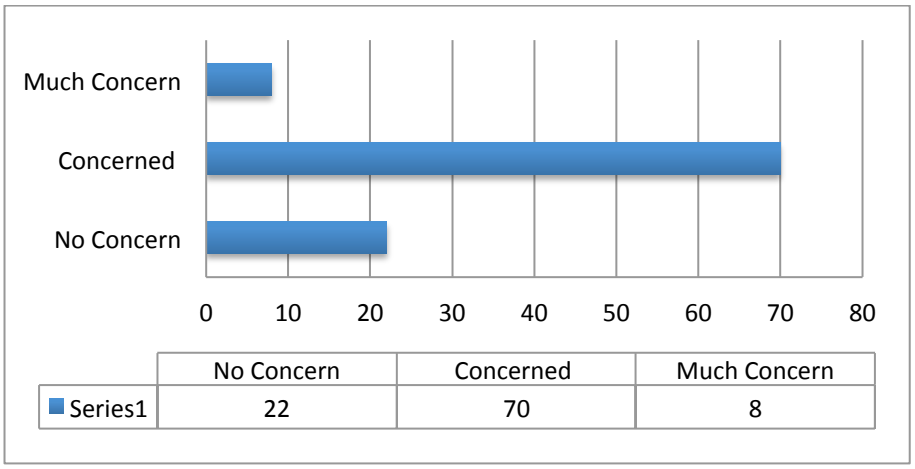

Figure 3.20. The Frequencies of Three Categories Given 10-Year Intervals

In this case, there is still more of a shift from "No Concern" periods to "Concerned" and to "Much Concern" periods, and a movement away from "No Concern" cases. The relative frequency of "Much Concern" periods is greater than the 5-year planning period and the 3-year intervals. Thus, the 10 year planning period reflects the need for an adaptation strategy.

30-Year Planning Period Results

Similar to the previous trend in increasing planning periods, the maximum MOWL time series is divided into 100 trials of 30-year planning period intervals. Applying the rule produces the following bar chart of Figure 3.21.

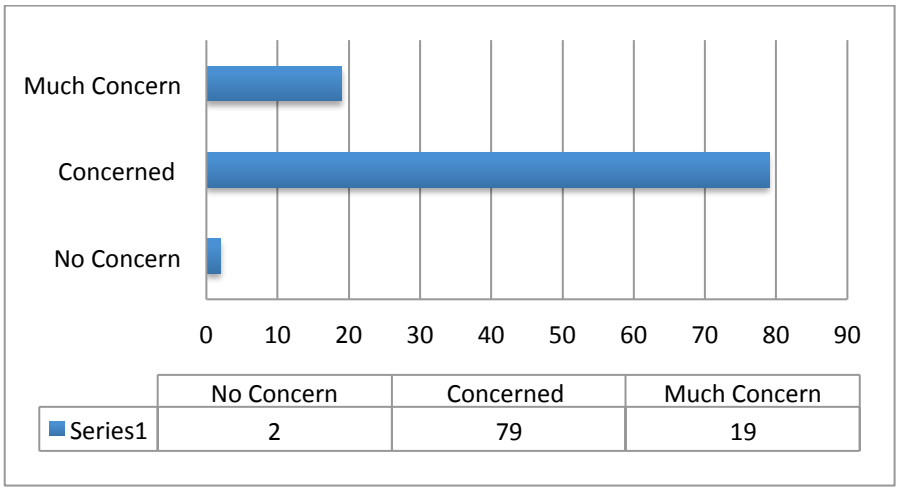

Figure 3.21. The Frequencies of Three Categories Given 30-Year Intervals

The number of "No Concern" periods is nearly reduced to zero, and the relative frequencies of "Much Concern" and "No Concern" are increased in comparison to previous planning periods. As before, this would indicate that the increased observation of severe storms over the wider predictive periods would stimulate the preference toward adaptive action.

3.4.4 Ranking of Decision Adaptation Strategies – Vulnerability, Resilience, and Adaptive Capacity

The decision that would be made based on the results of frequencies of the three categories in the experiment above is sensitive to the length of the planning period, e.g. frequencies of three categories in a longer planning period are different from a short time frame. On the other hand, the decision would also be affected by the amount of damages of storm events to the four community pillars, which are translated to the utility values. Further,

the community's weight on the pillars would affect the decision making output. To make a sustainable and systematic decision, these variations affecting the output of decision making should be captured in the ranking process of decision alternatives.

Adaptation strategies score higher according to their capabilities of lowering the vulnerability level of the community to storm events, while pushing up the resiliency of the community. The degree to which Charlottetown is vulnerable to storm events is measurable by the monetary value of damages. The vulnerability of the city is the gap between two circumstances; having storm events, and having no storm events. This can be expressed in terms of utility values. The status of Charlottetown without storms is considered – as in the case of the no damage results for each pillar (Sections 3.3.2 and 3.3.3 above) as the highest utility for $U=1$ for all pillars. The utility that arises when storm events occur and no adaptation strategies are applied (i.e., the Do Nothing strategy) is $U_s<1$. The difference, denoted as $V(0)$, the Vulnerability gap is denoted as:

$$V(0) = 1 - U_s \rightarrow \text{the Vulnerability gap} \qquad (3.4)$$

The resiliency of Charlottetown for a given adaptation strategy is then logically expressed as the difference between the total amount of damage without recourse to any adaptation strategy and the reduced vulnerability under the selected adaptation strategy. The purpose of this study is to find those adaptation strategies that boost the resiliency of Charlottetown to storm events, and decrease the vulnerability of Charlottetown to storm events with respect to the city's adaptive capacity. Resilience, $R(A)$ corresponding to adaptation strategy A, may be expressed in utility terms as follows:

$$R(A) = V - V(A) \rightarrow \text{reduced vulnerability from applying A} \qquad (3.5)$$

Finally, the adaptive capacity of adaptation strategy A for Charlottetown is measured in utility terms as the relative extent to which strategy A is able to reduce the vulnerability gap, $V(0)$. Adaptive capacity, $AC(A)$ expressed as a percentage of the utility value ratio given by:

$$AC(A) = R(A) * 100/V(0) \rightarrow \% \text{ adaptive capacity} \qquad (3.6)$$

An adaptive strategy, A, that reduces the vulnerability gap from $V(0)=0.5$ to $R(A)=0.25$ in utility terms, has an $AC(A)$ of 50%.

These indicators for vulnerability, resilience, and adaptive capacity will be applied to the subsequent analysis of Charlottetown's adaptive management and adaptation strategy evaluation in Chapter 4.

4 Analysis and Expected Results

This chapter is divided into four sections. Section 4.1 describes the steps and designs of experiments used to evaluate adaptation strategies within different time horizons. Section 4.2 presents the analyses of the experiments, and Section 4.3 examines the sensitivity of experiments to different factors that may affect the decision making. Finally, Section 4.4 discusses the summary of the results of the sensitivity analysis and experiments.

4.1 Analysis

As discussed in Chapter 3, experiments are arranged to evaluate the effect of different planning periods on decision making. The decision output is the recommended course of action to deal with Charlottetown's adaptation to environment change. The Total Annual Discounted Average Utility (TADAU) is used as the measure to evaluate the performance of adaptation strategies over all planning periods. The experiments are structured for a set of planning periods, (3,5,10, and 20-year planning periods) as defined in Section 3.4.1, Table 3.9, and where the four adaptation strategies, discussed in Section 3.3.1, are each evaluated for each planning period.

The TADAU is computed as a function of its main components including: MOWLs generated by inverse Gumbel max distributions (Section 3.2.1), the estimated impact of storm events (Section 3.2.2) and its respective utility value (Section 3.3.2), the planning periods, and the list of applicable alternative adaptation strategies. Other components affecting the TADAU calculation are described in Section 4.1.2.

4.1.1 The Experiment

Encompassing four adaptation strategies and four time planning periods, sixteen experiments are designed. In order to illustrate the structure of these experiments, the 3-year planning period problem under the Do Nothing strategy is explained below.

For the 3-year planning period, the probability of occurrences of three annual storm events are randomized and their respective MOWLs are generated by using the inverse Gumbel max function (Section 3.2.1). The yearly damages to the four pillars are computed with respect to the generated storm's MOWL as described above. The expected utility value

for every pillar is then determined by the amount of damage, using the utility curves (Section 3.3.2). The annual expected utilities of the four pillars are weighted by the given priorities of the community profile pillars and then summed up to produce the total annual weighted expected utilities. The total annual weighted expected utility values are averaged over 100 trials to generate the Total Annual Average Utility. Finally, the three values obtained as Total Annual Average Utilities are discounted and averaged over three years to produce the Total Annual Discounted Average Utility (TADAU). These steps are repeated for other adaptation strategies (Protect, Accommodate, and Retreat) within this 3-year planning period.

4.1.2 Year To Year Changes

Annual damages and utility values are affected by four factors throughout the experiments. These four factors are: (1) amortization of capital costs; (2) the annual rate of damage carryover; (3) mitigation impacts of adaptation strategies; and (4) the annual utility discount rate. Each of these items is discussed further below.

4.1.2.1 Amortization of Capital Cost

The annual amortization cost is assumed to be a fraction of the capital cost extended over the planning period. Where applicable, the capital cost is injected yearly as amortization cost to the community's economic pillar. The amortization costs of adaptation strategies are shown in Table 4.1.

Table 4.1. The Amortized Capital Costs of Alternative Strategies Over the Planning Periods

Adaptation Strategies	Total Cost ($ Million)	Annual Amortization Cost ($ Million)			
		3-Year Planning Period	5-Year Planning Period	10-Year Planning Period	20-Year Planning Period
Do Nothing	0	-	-	-	-
Protect	75	25	15	7.5	3.75
Accommodate	65	21.67	13	6.5	3.25
Retreat	90	30	18	9	4.5

For instance, in a three-year time frame, the annual amortization cost applied to the Charlottetown economic pillar is $25 million, $21.67 million, and $30 million under "Protect", "Accommodate", and "Retreat" strategies, respectively.

4.1.2.2 Annual Rate of Damage Carryover

A proportion of damage incurred every year of the planning period is carried over to subsequent years as per the Annual Rate of Damage Carryover. In addition to annual damages caused by storm events, the monetary values of annual damages to the four community pillars (Environmental, Economic, Social, and Cultural) are incremented by carried-over damages. Table 4.2 illustrates the amount of damage carried over to subsequent years at an annual carryover rate of 25%.

Table 4.2. The Amount of Damage Carryover - 3-Year Planning Period

Protect Strategy	Damages Caused by Storms ($ Million)			Additional Damage Carryover to Subsequent Years ($ Million)		
	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3
Environmental	1.76	1.52	1.84	-	0.44	0.49
Economic	1.43	1.23	1.49	-	0.36	0.40
Social	0.10	0.09	0.10	-	0.02	0.03
Cultural	0.16	0.14	0.17	-	0.04	0.04

Therefore, the monetary values of damages to the economic pillar are incremented every year not only by amortization cost of the adaptation strategy, but also by carryover damages costs of past years. The annual total damage to each pillar illustrated in Table 4.3 includes the damage carryover and the amortization cost for the Protect strategy.

Table 4.3. Total Amount of Damages After Applying Cost Carryover and Amortization Cost

Protect Strategy	Damages Caused by Storms ($ Million)			Total Damages ($ Million)		
	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3
Environmental	1.76	1.52	1.84	1.76	1.96	2.33
Economic	1.43	1.23	1.49	26.43	26.59	26.89
Social	0.10	0.09	0.10	0.10	0.11	0.13
Cultural	0.16	0.14	0.17	0.16	0.18	0.21

4.1.2.3 Mitigation Impacts of Adaptation Strategies

In addition, the degree of MOWLs under "Protect", "Accommodate", and "Retreat" strategies is adjusted by the cut-off level and mitigation rate as shown in Table 4.4.

Table 4.4. Impacts of Adaptation Strategies on MOWL

Adaptation Strategies	MOWL Cut-Off level (m)	MOWL Relative Mitigation Rate
Do Nothing	-	-
Protect	3.6	-
Accommodate	-	0.75
Retreat	2.5	0.85

The cut-off level and the mitigation rate are discussed above in Section 3.3.1.

4.1.2.4 Utility Discount Rate

In order to discount the future value of expected utility over the planning period to its present value, the Utility Discount Rate (UDR) is taken into account. The annual average utility values are discounted over the planning period span by the following formula:

$$\sum_{1}^{i} \frac{u_i}{(1+UDR)^{i-1}} \quad for\ i = 3,5,10,20 \tag{4.1}$$

The Utility Discount Rate set initially in the experiments is 3%. This parameter is included in the model sensitivity analysis.

4.1.3 Experimental Design

The output of decision making is ranked according to the value of Total Annual Discount Average Utility (TADAU) so that the higher valued adaptation strategy takes precedence. In order to find TADAU under the 3-year planning period problem, the designed experiment includes three annual MOWL values. The required components and steps to compute TADAU for one trial of the Protect strategy are presented in the table below.

Table 4.5. The Calculation Steps of TADAU for Protect Strategy Under 3-Year Planning Period, Also See the Appendix D-TADAU Values Computations for the 3-Year Planning Period

Year	1				2				3			
MOWL	0.00				4.00				0.00			
Community's Pillars	Environmental Pillar	Economic Pillar	Social Pillar	Cultural Pillar	Environmental Pillar	Economic Pillar	Social Pillar	Cultural Pillar	Environmental Pillar	Economic Pillar	Social Pillar	Cultural Pillar
Annual Damage ($ Million)	0.16	6.73	1.85	17.7	17.7	17.7	0.01	0.39	0.11	0.02	0.62	0.17
Expected Utility Value	1.00	0.62	0.98	0.00	0.00	0.00	1.00	0.61	0.97	1.00	0.53	0.97
Community's Importance Weight	21%	22%	38%	19%	21%	22%	38%	19%	21%	22%	38%	19%
Total Annual Weighted Expected Utility Value	0.75				0.74				0.74			
TADAU	**0.72**											

As shown in the table, the expected utility value of each pillar is assigned a community's importance weight, and accumulates over the three years to produce the total annual weighted expected utility value. Then, the weighted expected utilities are discounted using (Equation 4.1), and averaged over three years to yield the TADAU value. These computation steps are repeated for the four adaptation strategies under the 3-year planning period problem.

The output of decision making depends on the simulated future trends of storm events. For example, alternative values of MOWLs in Table 4.5 imply different impacts, and utility values. To increase the accuracy of the results, the annual maximum MOWL storm events are simulated n=100 times, and the amount of damages and equivalent utility values are averaged over all trials. The 95% confidence interval for the mean of the Total Annual Weighted Expected Utility Values of 3 years is calculated. The average and standard deviation of annual weighted utilities for 100 trials of the Protect strategy, accompanied by LCI and UCI values, are shown in the table below.

Table 4.6. LCI and UCI of the Protect Strategy within the 3-Year Planning Period

	Year 1	Year 2	Year 3
Average	0.75	0.75	0.74
St. dev.	0.10	0.08	0.10
LCI	0.54	0.59	0.54
UCI	0.95	0.91	0.94

4.1.4 Sampling

This subsection presents the results of the TADAU analysis and decision strategy rankings for each set of planning periods: 3,5,10, and 20 years. The summary of the results is presented graphically from the spreadsheet analyses for each planning period as illustrated by the Appendix D - TADAU Values Computations for the 3-Year Planning Period.

4.1.4.1 3-Year Planning Period

In the case of 3-year time frame, the four alternative strategies are compared with respect to their TADAU value as illustrated in Figure 4.1.

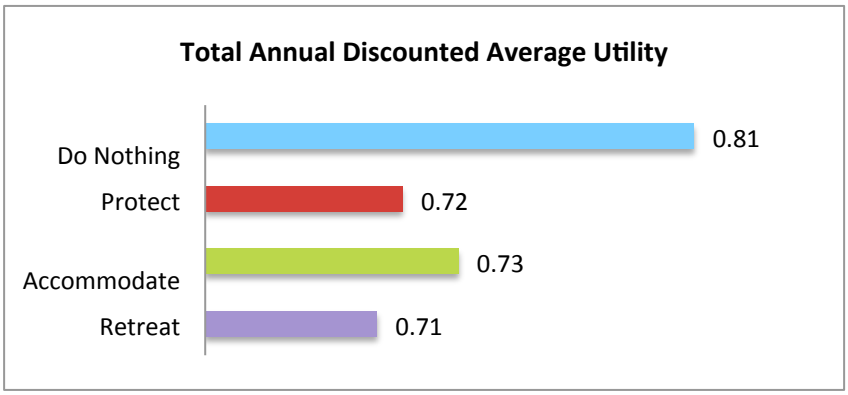

Figure 4.1. Adaptation Strategies TADAU Priorities for the Case of the 3-Year Planning Period

According to this 3-year planning period summary results graph, the Do Nothing strategy takes precedence in comparison to other strategies. In the first three years, the amount of damages reduced under other adaptation strategies (Protect, Accommodate, and Retreat) cannot compensate their amortization cost over the 3-year planning period, and the annual damage carryover.

On the other hand, the trend of Annual Total Average Utility, the average of weighted expected utilities from the first year of the planning period to the third year over the n=100 trials (before discounting), shows declining results for the Do Nothing strategy over the three

years, as illustrated in Figure 4.2. At the same time, it is noted that the rank order of the adaptation strategies (Accommodate, Protect, and Retreat) remains consistent and relatively stable year-over-year in the 3-year horizon.

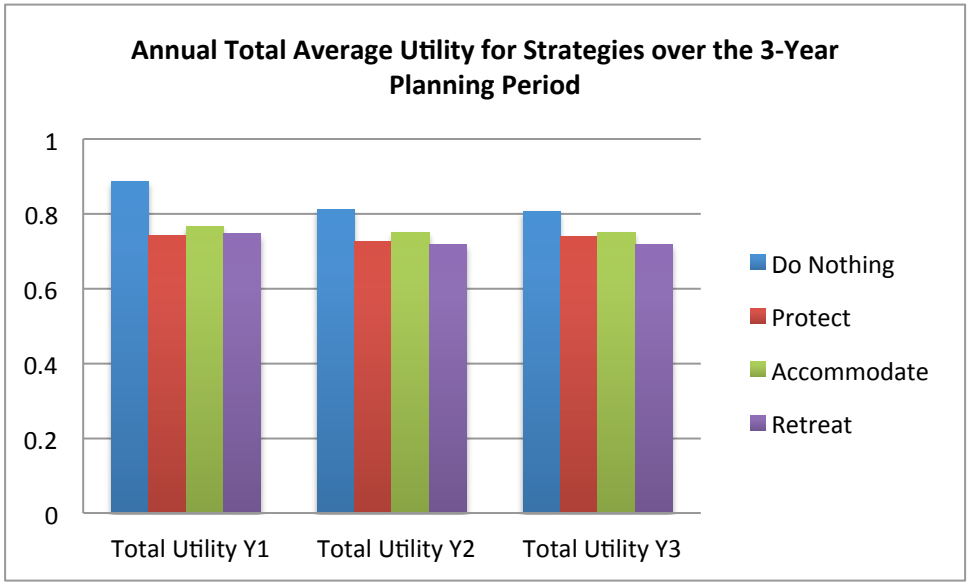

Figure 4.2. Annual Total Average Utility for Strategies Over the 3-Year Planning Period

4.1.4.2 5-Year Planning Period

For the 5-year planning horizon, the four alternative strategies are compared with respect to their TADAU value discounted over the five years as displayed in Figure 4.3.

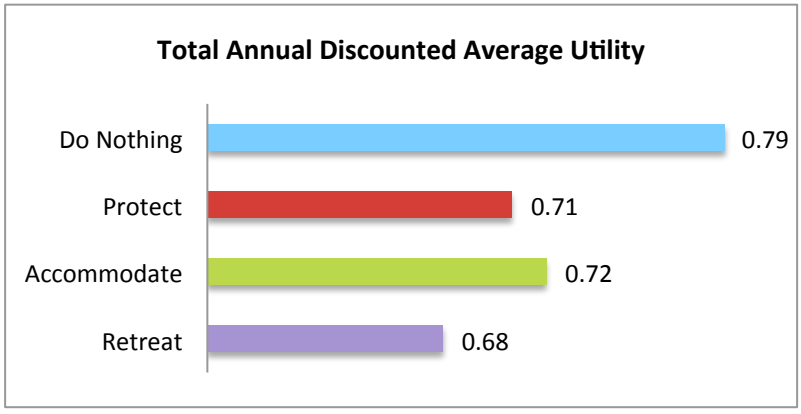

Figure 4.3. Adaptation Strategies TADAU Priorities for the Case of the 5-Year Planning Period

Similarly to the 3-year planning period results, the Do Nothing strategy still produces the highest TADAU strategy for the community in comparison to the other strategies. However,

also in comparison to the 3-year planning period problem, the TADAU for the Do Nothing strategy is reduced in value for the 5-year planning period. As well, its undiscounted value diminishes each year over the five years of the planning period, as noted in Figure 4.4. Although the TADAU under the Do Nothing strategy, as before, remains greater each year than with the other adaptation strategies, its declining value approaches the stable ranking of the adaptation strategies, as before, and shows Accommodate preferable to Protect which in turn is preferable to the Retreat strategy.

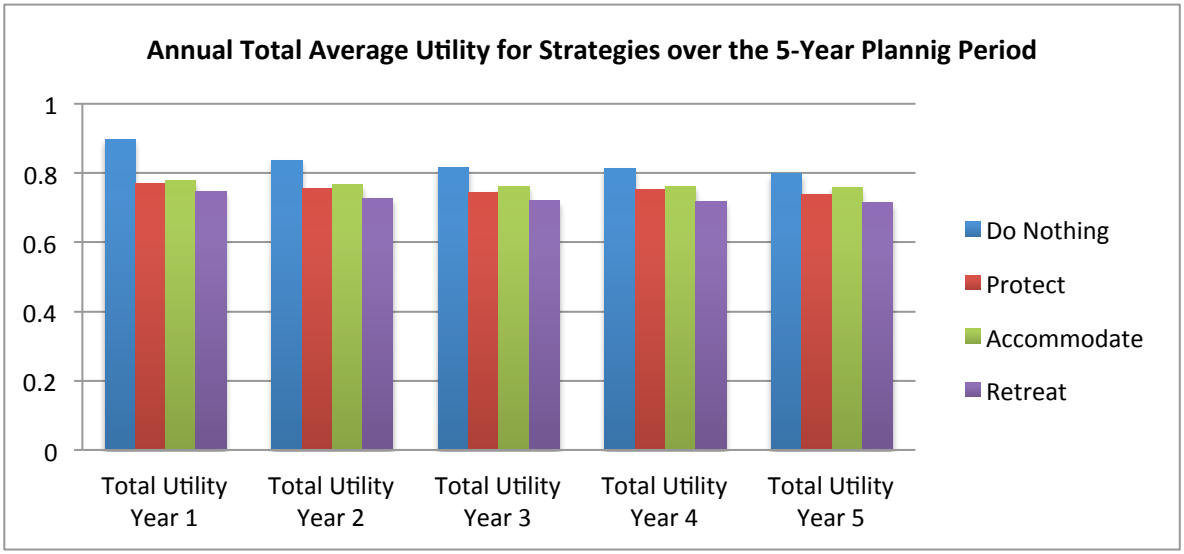

Figure 4.4. Annual Total Average Utility for Strategies Over the 5-Year Planning Period

4.1.4.3 10-Year Planning Period

Figure 4.5 represents the summary results for the four alternative strategies with their TADAU values for the 10-year planning period.

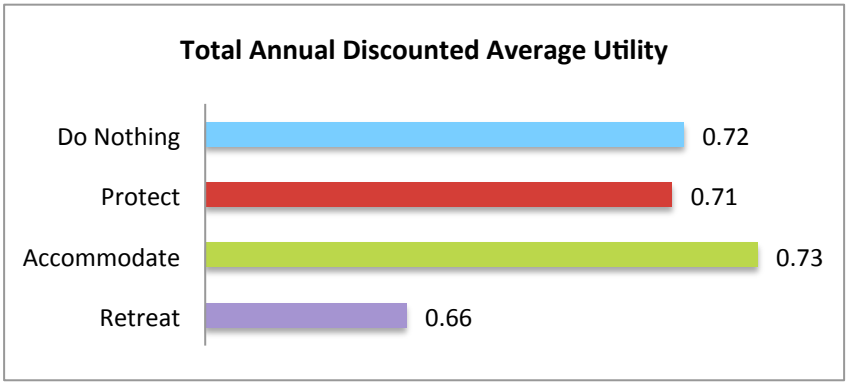

Figure 4.5. Adaptation Strategies TADAU Priorities for the Case of the 10-Year Planning Period

In the 10-year planning period, the Accommodate strategy receives the highest ranking among other strategies with the largest TADAU value. Notably, the capital costs of the adaptation strategies are amortized over the 10 years of the planning period, which in turn reduces the amount of annual damage carryovers incurred to the economic pillar. In addition, the extent to which the amount of annual storm damages are reduced under the Accommodate strategy pays off in utility terms in comparison with the other strategies facing the same predicted storms. The capital cost of Accommodate strategy has been paid off over time by damage reduction.

According to Figure 4.6 the Accommodate strategy has the highest position in comparison to other strategies annually and over each year of the planning period.

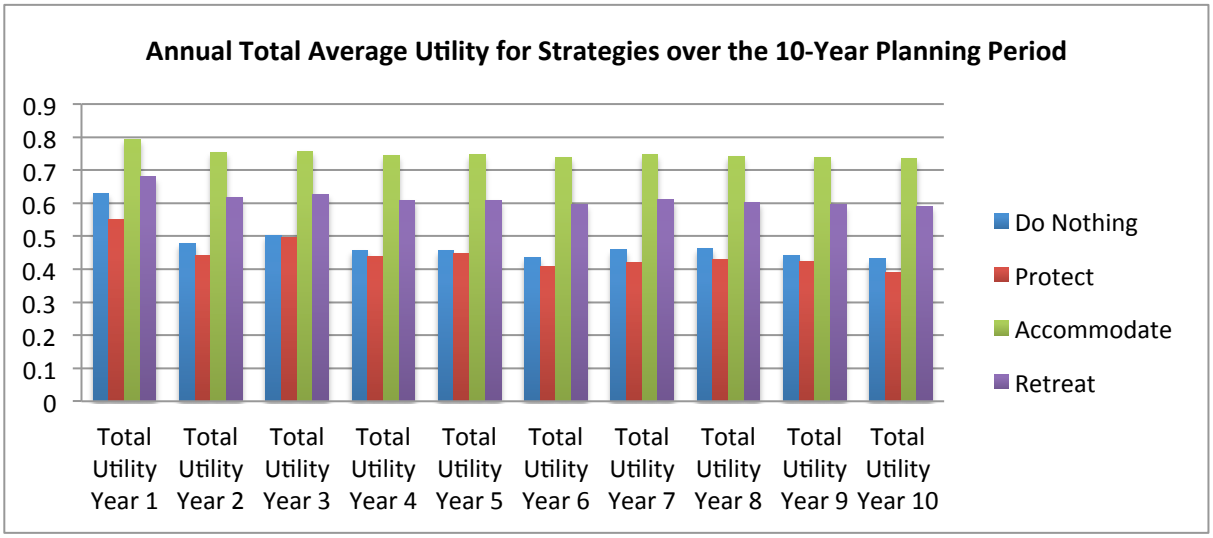

Figure 4.6. Annual Total Average Utility for Strategies Over the 10-Year Planning Period

4.1.4.4 20-Year Planning Period

Figure 4.7 presents the summary TADAU value results for the four adaptation strategies over the 20-year time horizon.

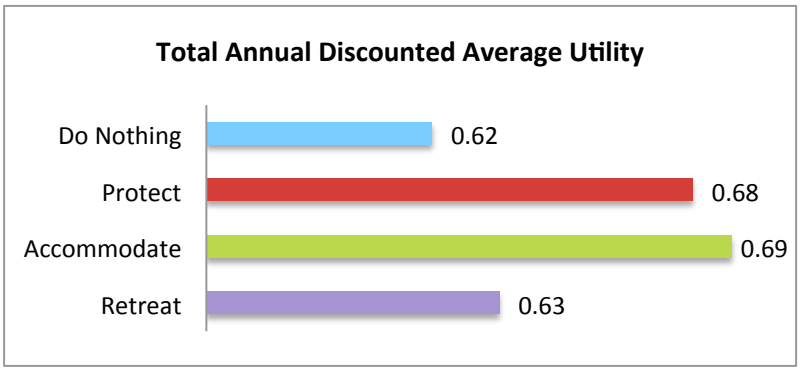

Figure 4.7. Adaptation Strategies TADAU Priorities for the Case of the 20-Year Planning Period

Figure 4.7 indicates that the Do Nothing strategy is now the least preferable of all strategies. Accommodate emerges as the most beneficial, followed by Protect and Retreat. The damage reduction under these three strategies exceeds the amortized capital cost, and annual damage carryover. The annual total undiscounted average results are illustrated in Figure 4.8.

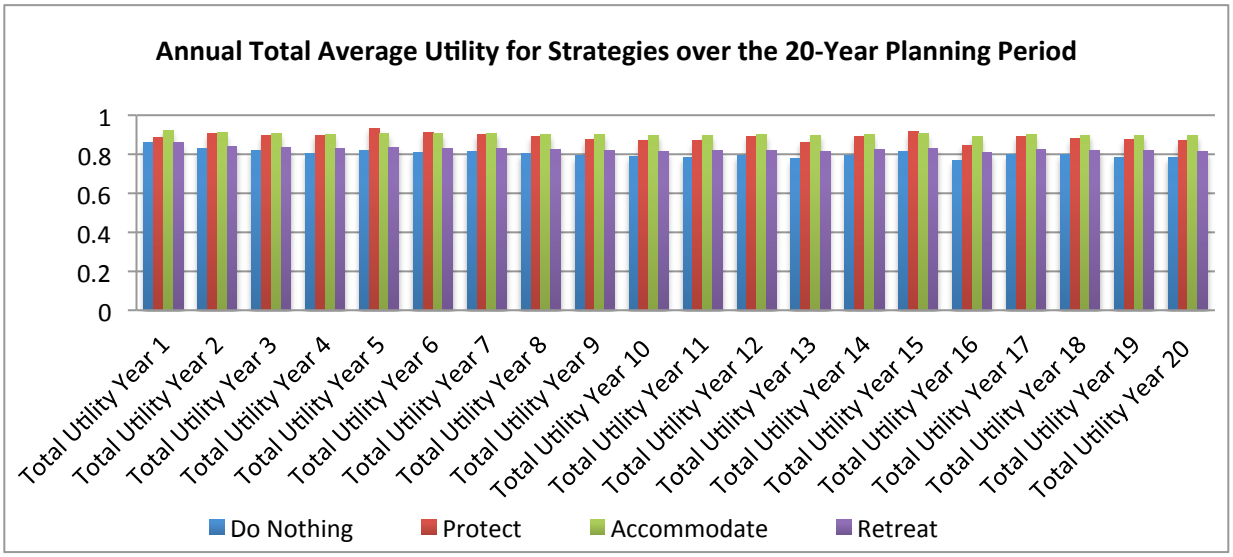

Figure 4.8. Annual Total Average Utility for Strategies over the 20-Year Planning Period

According to the annual trend of average utility value for each strategy, Accommodate is preferable almost every year followed closely by the Protect adaptation strategy. The Do Nothing places last in each of the 20 years over the planning period.

4.2 Results

The input-output experiments done for all adaptation strategies over all different planning periods are summarized and compared across the set of planning periods in Table 4.7.

Table 4.7. TADAU Values of Adaptation Strategies for Different Planning Periods Using Historical Storm Series

Planning Period	Do Nothing	Protect	Accommodate	Retreat
3-Year	0.81	0.72	0.73	0.71
5-Year	0.79	0.71	0.72	0.68
10-Year	0.72	0.71	0.73	0.66
20-Year	0.62	0.68	0.69	0.63

The correspondence priority of each strategy within a planning period depends on the TADAU value of that strategy. The strategy with highest comparable TADAU value within a specific planning period ranks in the first place. Generally, the 3-year time frame houses the greatest TADAU values of all adaptation strategies. The Do Nothing strategy is more preferable than others when considered using 3-year and 5-year perspectives; however, its dominance diminishes noticeably as the planning period increases. The Accommodate strategy changes little in the TADAU value over the set of planning periods, ranging from a low of 0.69 (20-year planning period) to a high of 0.73 (3-year planning period). The Accommodate strategy dominates all strategies when the planning period equals and exceeds the 10-year mark.

Apart from the priority of strategies within a specific time frame, the TADAU values of strategies over various planning periods imply a decreasing trend in total utility values, as shown in Figure 4.9. The decline in the totals reflects the heightened possibility of an extreme event.

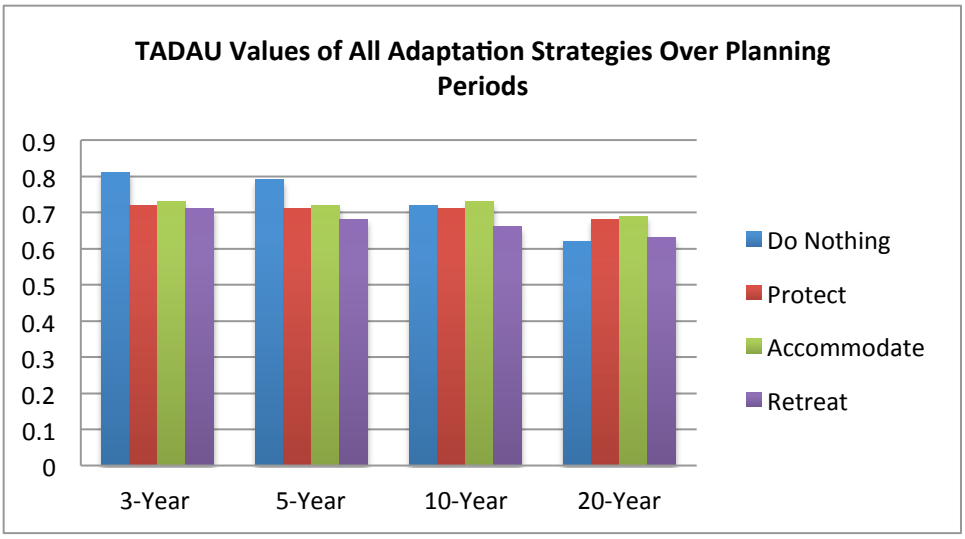

Figure 4.9. The TADAU Values of Alternative Adaptation Strategies Throughout Different Planning Periods - Historical Storm Series

4.3 Sensitivity Analysis

The uncertainty inherent in future storm events, the impact of adaptation strategies, and Charlottetown policies necessitate implementing a sensitivity analysis of the simulated results for the set of planning periods presented above. The research is interested in highlighting critical variables and parameters that have considerable and undeniable impacts on the results of decision making. For the purpose of the sensitivity analysis, several factors are expected to change including;

(1) The storm series and the predicted severity of Charlottetown storms;

(2) The rate of annual damage carryover;

(3) The amortization period for the capital costs of the active adaptation strategies (Protect, Accommodate, and Retreat);

(4) The annual discount rate on multi-year total utility values;

(5) The capital cost of the active adaptation strategies;

(6) The storm mitigation impacts of the active adaptation strategies; and

(7) The importance weights assigned to the community profile pillars (environmental, economic, social, and cultural).

The discussion below presents the results of the itemized sensitivity analyses on decision making under the alternative planning periods.

4.3.1 Storm Series

The sensitivity of decision making outputs to the Charlottetown severe storm series is compared, with consideration for: (i) no storms; (ii) the projection of the historical storm series (1911-2005) (as assumed in the analyses to this point); and (iii) the prediction of more severe storms for Charlottetown.

For the case of more severe storms predicted in the future, the revised parameters for the Gumbel max characteristic probability distribution function are: (1) location parameter (mode) – alpha = 3.75; and (2) scale parameter – beta = 0.303. The recent pattern of storm events shows an increase in hurricane intensity, in terms of number of occurrence and severity, and rainfall rate (Knutson & Tuleya, 2004). Therefore, the more severe storm series leads to a forward shift in the Probability Density of historical storms (parameters: alpha = 2.99; and beta = 0.303) as displayed in Figure 4.10.

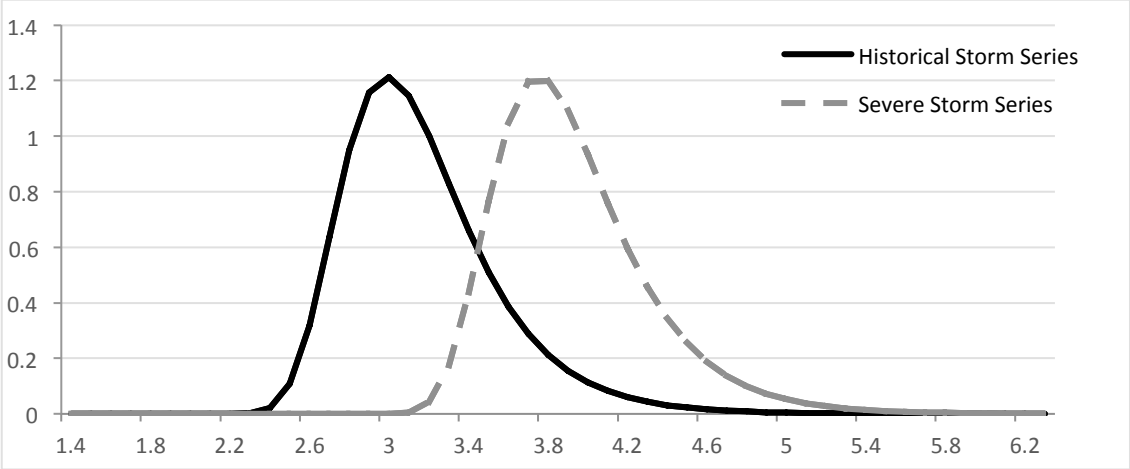

Figure 4.10. Historical Storm Series Vs. Severe Storm Series for Charlottetown

As a result of this shift, the priorities of adaptation strategies change for the aforementioned planning periods. These results are summarized in Table 4.8.

Table 4.8. TADAU Values of Adaptation Strategies for Different Planning Periods Using the More Severe Storm Series

Planning Period	Do Nothing	Protect	Accommodate	Retreat
3-Year	0.54	0.47	0.69	0.62
5-Year	0.47	0.41	0.66	0.57
10-Year	0.42	0.39	0.66	0.54
20-Year	0.35	0.36	0.62	0.51

Over all planning periods, the Accommodate strategy takes immediate precedence in comparison to all other strategies. The Retreat strategy is elevated to the second rank. The Do Nothing is the third best option over all planning periods except the 20-year period over which it is the least favorable option.

Similar to the original analysis, the TADAU values for strategies over various planning periods reflect a declining trend in total utility values, as shown in Figure 4.11.

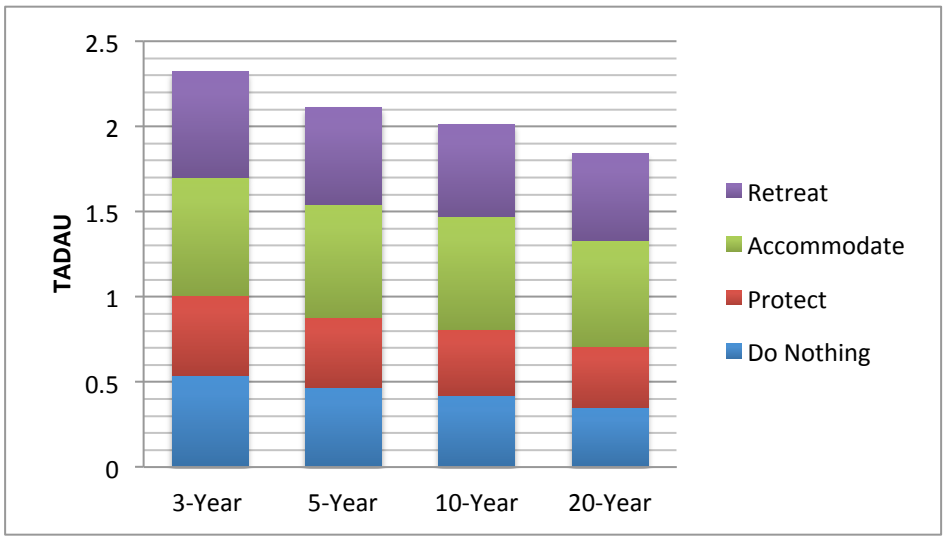

Figure 4.11. The TADAU Values of Alternative Adaptation Strategies Throughout Different Planning Periods-Severe Storm Series

In the absence of storm events, i.e., no severe storms for Charlottetown, the maximum MOWLs yearly are all zero- and ideal circumstance. As a result, the TADAU value for the Do Nothing strategy is equal to one over all planning periods.

4.3.2 Annual Damage Carryover

Consider the sensitivity of the strategy rankings for different planning periods when the degree to which damages transferred to successive years changes. The assumed value of annual damage carryover (25%) is replaced with 40% and the results are recalculated for all planning period trials. Theses results are presented in Table 4.9.

Table 4.9. TADAU Values of Adaptation Strategies, Given Annual Damage Carryover of 40%

Planning Period	Annual Damage Carryover=40%			
	Do Nothing	Protect	Accommodate	Retreat
3-Year	0.80	0.72	0.73	0.70
5-Year	0.72	0.69	0.71	0.66
10-Year	0.65	0.70	0.71	0.63
20-Year	0.57	0.68	0.68	0.61

The priorities of adaptation strategies within a specific time frame remain the same using the original annual damage carryover assumption of 25%. As before, the Do Nothing strategy is dominant for the 3-year and 5-year time horizons, while the Accommodate strategy is dominant for 10-year and 20-year time frames.

Table 4.10 represents the TADAU values for the four strategies with a small annual damage carryover of 10%.

Table 4.10. TADAU Values of Adaptation Strategies, Given Annual Damage Carryover of 10%

Planning Period	Annual Damage Carryover=10%			
	Do Nothing	Protect	Accommodate	Retreat
3-Year	0.84	0.72	0.74	0.72
5-Year	0.82	0.71	0.73	0.70
10-Year	0.76	0.73	0.74	0.68
20-Year	0.67	0.70	0.71	0.66

In this case, the Do Nothing strategy has the highest TADAU ranking over the first three planning periods: 3, 5, and 10 years. The small amount of damage transferred annually to successive years, has the effect of "slowing down" the transition towards preference for the Accommodate strategy, and the erosion of the preference for the Do Nothing strategy, although the dynamic appears to be similar.

4.3.3 Amortization Period

In the original analyses, the amortization period of the active adaptation strategies (Protect, Accommodate, and Retreat) that each requires capital investment, has been considered equal to the planning period length. The effect of this assumption is to attribute the entire cost of these active strategies to the planning period. Thus short planning periods incur more immediate costing than the longer periods.

Assuming the amortization period is attributed to the life of the adaptation strategy asset, and stays unchanged over all planning periods, e.g., equal to 10 years for all planning periods, the TADAU values of adaptation strategies would be recomputed with the resulting values shown in Table 4.11.

Table 4.11. TADAU Values of Adaptation Strategies, Given Amortization Period of 10 Years

Planning Period	Do Nothing	Protect	Accommodate	Retreat
3-Year	0.81	0.77	0.80	0.73
5-Year	0.79	0.77	0.79	0.72
10-Year	0.72	0.71	0.73	0.66
20-Year	0.62	0.63	0.64	0.58

Spreading the amortization cost of strategies over 10 years pushes up the TADAU values of the active adaptation strategies, and reduces the relative preference of the Do Nothing strategy for the 3-year and 5-year planning periods, aligning the Accommodate strategy with the Do Nothing.

The strategy ranking remains unchanged relative to the original case within all planning periods expect the 20-year period in which Do Nothing comes to a higher position than before. The high capital cost of the Retreat strategy amortized over 10 years now pushes its priority down to fourth position.

4.3.4 Utility Discount Rate

The annual discount rate for multiyear utility values may be affected by unpredictable government interest rates and monetary policies to decrease or increase the value of future assets. The discount rate used in the original analysis is assumed to be 3%. In this sensitivity analysis, this rate is replaced by 10% and 0%. The results of these evaluations are presented in Table 4.12 and Table 4.13.

Table 4.12. TADAU Values of Adaptation Strategies in Effect of UDR=10%

Planning Period	UDR=10%			
	Do Nothing	Protect	Accommodate	Retreat
3-Year	0.78	0.68	0.69	0.67
5-Year	0.69	0.62	0.64	0.60
10-Year	0.56	0.55	0.56	0.51
20-Year	0.38	0.39	0.42	0.43

Generally, for Table 4.12 with the increased discount rate, the TADAU values of all strategies are decreased. However, the order of strategies remains the same over all planning periods. In contrast, for a decreased discount rate, UDR of 0%, the TADAU values of strategies are increased as shown in Table 4.13.

Table 4.13. TADAU Values of Adaptation Strategies in Effect of UDR=0%

Planning Period	UDR=0%			
	Do Nothing	Protect	Accommodate	Retreat
3-Year	0.85	0.75	0.76	0.73
5-Year	0.84	0.76	0.77	0.73
10-Year	0.82	0.82	0.83	0.75
20-Year	0.81	0.89	0.90	0.83

As the before, the ranked strategy priorities remain unchanged in comparison with the original analysis with UDR = 3% over all planning periods. Thus, the results are relatively insensitive to changes in the discount rate for annual multiyear utilities. The Do Nothing strategy takes the first priority within 3 and 5 years, while the Accommodate strategy takes precedence over other strategies for the 10-year and 20-year planning periods.

4.3.5 Total Cost of Strategies

It is likely that the actual capital cost of strategies alters from the total capital cost estimation provided in the original analysis. In order to evaluate the response of utility values to various pricing, two different sets of capital costs are considered. The TADAU values are presented in Table 4.14 where the capital cost of Protect, Accommodate, and Retreat is increased for all active adaptation strategies to $100, $80, and $105 million, respectively (from original values of $75 million, $65million, and $90 million, respectively).

Table 4.14. TADAU Values of Adaptation Strategies, Given Higher Capital Cost

Planning Period	Do Nothing	Protect	Accommodate	Retreat
3-Year	0.81	0.72	0.73	0.70
5-Year	0.79	0.70	0.71	0.68
10-Year	0.73	0.69	0.71	0.65
20-Year	0.63	0.67	0.68	0.62

In the case of cost increases, the Do Nothing strategy is ranked first among other strategies over all planning periods except the 20-year period in which the Accommodate strategy is the leading strategy followed closely by Protect. The high capital cost of the

Retreat strategy decreases its rank to fourth, and pushes Do Nothing up to third place for the 20-year planning period.

The TADAU values shown in Table 4.15 reflect the reduced capital costs of $50, $40, and $75 million for Protect, Accommodate, and Retreat strategies, respectively.

Table 4.15. TADAU Values of Adaptation Strategies, Given Lower Capital Cost

Planning Period	Do Nothing	Protect	Accommodate	Retreat
3-Year	0.82	0.72	0.74	0.71
5-Year	0.79	0.74	0.76	0.69
10-Year	0.72	0.77	0.78	0.68
20-Year	0.63	0.71	0.72	0.65

In this case, the ranking of strategies remains unchanged in comparison with the original analysis over all planning periods excluding the 10-year time frame. The Accommodate and Protect strategy receive the first and second rank in the 10-year time frame, instead of Do Nothing in the second place. Thus, the Do Nothing strategy deteriorates more noticeably as the preferred strategy, losing ground to Accommodate and Protect.

4.3.6 Storm Mitigation Impacts of Active Adaptation Strategies

The storm cut-off impact levels and the relative storm mitigation rate of the active adaptation strategies may vary over time, i.e., the adaptation strategies may mitigate storms impacts in the community to a greater or lesser extent than the engineered prediction of reduced storm impacts. To take into account varying levels of storm mitigation, two different value sets for the cut-off level and the mitigation rate are considered. Lower and higher set of values is applied to compare to the original levels presented in Table 4.4. The changed mitigation impacts are displayed in Table 4.16 as “low” and “high” cut-off and mitigation rate levels.

Table 4.16. Impact of Low and High Cut-Off Levels and Mitigation Rates on MOWL

Adaptation Strategies	Low Protect		High Protect	
	Cut-Off level (m)	Mitigation Rate	Cut-Off level (m)	Mitigation Rate
Do Nothing	-	-	-	-
Protect	3.2	-	4	-
Accommodate	-	0.85	-	0.50
Retreat	2	0.90	3	0.75

The effect of the low level and rate on priorities of adaptation strategies are measured by the TADAU values and shown in Table 4.17.

Table 4.17. Impacts of Low Protect on TADAU Values of Adaptation Strategies

Planning Period	Do Nothing	Protect	Accommodate	Retreat
3-Year	0.82	0.68	0.71	0.69
5-Year	0.79	0.67	0.69	0.66
10-Year	0.72	0.67	0.69	0.64
20-Year	0.63	0.64	0.66	0.61

A decrease in the cut-off level and mitigation rate increases the vulnerability level of the community to storm events and yields more storm damages to the active adaptation strategies (Protect, Accommodate, and Retreat). The results are reflected in lower TADAU values of these three strategies, while TADAU values of Do Nothing do not change from the original analyses. Therefore, the Do Nothing option retains the highest preferred level over all planning periods except the 20-year time frame in which Accommodate is the favoured option.

The new TADAU values are presented in Table 4.18, now reflecting higher cut-off levels and mitigation rates.

Table 4.18. Impacts of High Protect on TADAU Values of Adaptation Strategies

Planning Period	Do Nothing	Protect	Accommodate	Retreat
3-Year	0.81	0.73	0.75	0.74
5-Year	0.79	0.73	0.75	0.72
10-Year	0.72	0.75	0.77	0.71
20-Year	0.62	0.72	0.73	0.69

The order of strategies within all planning periods do not change except a minor shift in ranking for the 10-year time frame; the Protect strategy holds the second place within the 10-year planning period instead of having Do Nothing in the second place. Thus, the improved performance of the adaptation strategies moves these more rapidly to a more preferential position with the same dynamic as for the original case analysis.

4.3.7 Weights on Pillars

The degree of importance assigned to each community profile pillar may vary according to the influence of community leaders and under different contexts. For example, the

business/Industry sector, or the Environmental Non-governmental Organization (ENGO) sector each express different weights attributed to each pillar. Two sets of alternative weights are presented in Table 4.19 contrasting the expected perspective of the local government with weights attributed to the Business sector and the ENGO sector.

Table 4.19. Alternating The Weights Allocated to Different Pillars of Charlottetown

Community Pillars	Local Government	Business Sector	NGO
Environmental	21%	21%	38%
Economic	22%	38%	22%
Social	38%	22%	21%
Cultural	19%	19%	19%

The experiments are repeated with respect to the Business sector weight allocation and the new TADAU values are displayed in Table 4.20.

Table 4.20. TADAU Values of Adaptation Strategies, Given Business/Industry Weights

Planning Period	Do Nothing	Protect	Accommodate	Retreat
3-Year	0.82	0.57	0.58	0.56
5-Year	0.79	0.57	0.59	0.54
10-Year	0.73	0.64	0.65	0.56
20-Year	0.63	0.66	0.67	0.59

Since the weight of the economic pillar is considerably increased, the economic damages including the substantial active adaptation strategy investments subsumed over the planning period contribute to these results. The rank of Do Nothing jumps up by one level over the 10-year and 20-year time frames compared to the original analysis. At the same time, the Accommodate strategy takes second place over the 10-year planning period, and Do Nothing rises up to third place in the 20-year planning period. The low TADAU values of Protect, Accommodate, and Retreat reflect how large the damages to the economic pillar yields lower relative utility overall.

The new TADAU values of adaptation strategies are presented in Table 4.21 according to the NGO weight allocation

Table 4.21. TADAU Values of Adaptation Strategies, Given ENGO Weights

Planning Period	Do Nothing	Protect	Accommodate	Retreat
3-Year	0.83	0.72	0.73	0.71
5-Year	0.79	0.71	0.72	0.69
10-Year	0.72	0.71	0.73	0.66
20-Year	0.63	0.69	0.70	0.64

In this case, the order of preference of the adaptation strategies does not change throughout the planning periods in comparison to the original analysis results. As such, the original solution is relatively insensitive to an increase weight on the environment pillar and decreased weight on the social sector. In contrast, the results are sensitive to increased weighting on the economic sector due to the appreciable cost of the active adaptation strategies.

4.4 Summary of Results

The sensitivity analyses highlight those factors that affect the priority of adaptation strategies significantly. For example, and as noted above, the ranked order of adaptation strategies changes considerably when the historical storm series is substituted by the more severe storm series. With this replacement, the Accommodate strategy takes precedence over all planning periods, from the 10-year planning period and beyond to occupy the first place with the severe storm series.

Within the 10-year planning period, the rank of the "Do Nothing" strategy is altered from its initial rank in the original case in some sensitivity analysis scenarios including lower annual damage carryover, higher utility discount rate, higher capital cost, lower cut-off and mitigation levels, and higher weights on economic pillar (Industry/business weights). However with the change of other factors, there is no noticeable shift in preference for the Do Nothing and Accommodate options over the set of planning periods; the Do Nothing strategy is the most preferred option within the 3-year, and 5-year planning period, while the Accommodate strategy receives the first rank within the 10-year, and 20-year planning periods.

The resilience of the community under the four adaptation strategies is compared in Figure 4.12. The resilience, here presented, is a function of TADAU values of the original analyses (historical storm series), as discussed in subsection 3.4.4.

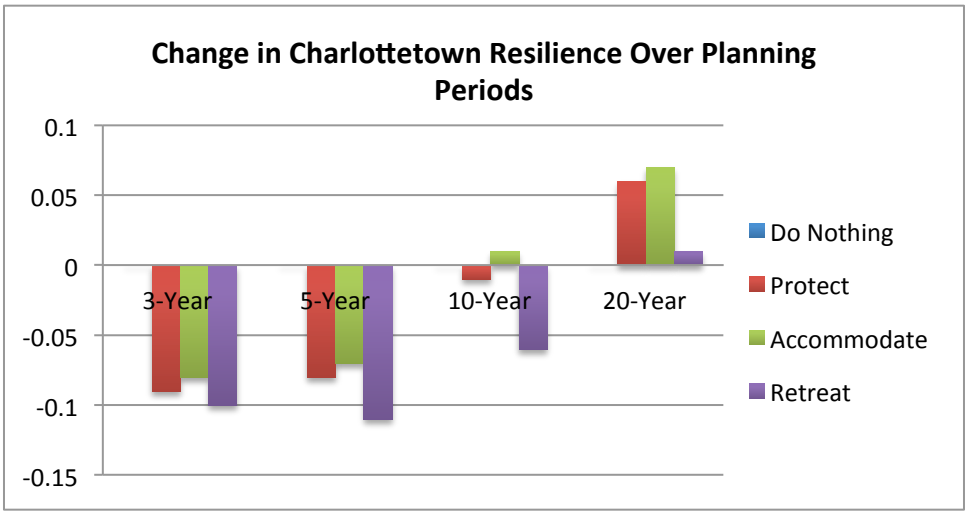

Figure 4.12. Changes in Resilience of Charlottetown Over Planning Periods-in the Case of Do Nothing, Protect, Accommodate, and Retreat Strategies

None of the strategies improve the community's resilience within 3 and 5 years, and not even over 10-year planning horizon except for the Accommodate strategy. The resilience values are negative, meaning that other strategies still could not perform better than the Do Nothing strategy. The reduced vulnerability from applying strategies starts either at 10 or 20 years. Starting at 10 years, and continuing to 20 years, the Accommodate strategy improves the resilience more than other strategies. The Charlottetown's resilience improvement and vulnerability over 20 years under each adaptation strategy versus the Do Nothing strategy is shown in Figure 4.13.

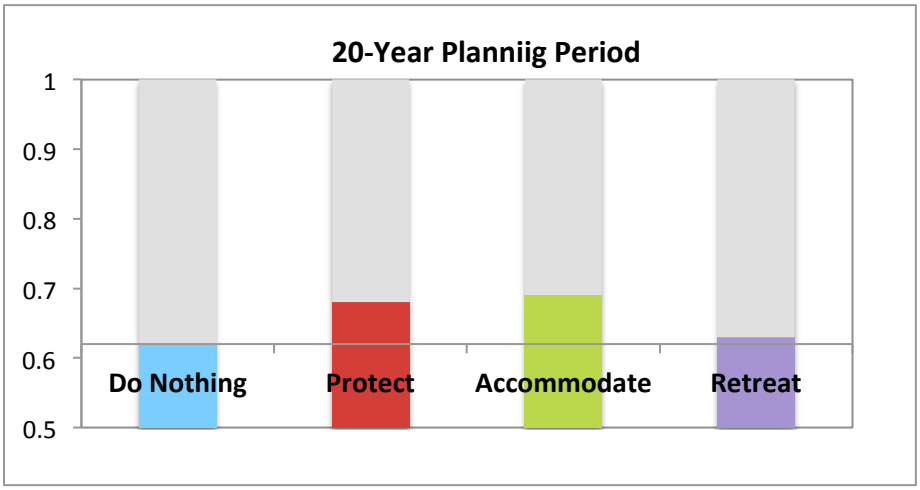

Figure 4.13. Charlottetown's Resilience Under the Four Adaptation Strategies in 20-Year Planning Period

The three adaptation strategies (Protect, Accommodate, and Retreat) increase the Charlottetown's resilience. However, the Accommodate strategy improves the resilience more than others. The adaptive capacity of all strategies within 20 years is shown in Table 4.22.

Table 4.22. Adaptive Capacity Enhancement in the 20-Year Planning Period

	Do Nothing	Protect	Accommodate	Retreat
Adaptive Capacity	0.0%	18.8%	22.6%	2.7%

Using the Equation 3.6, the adaptive capacity of the community can be computed. There is no adaptive capacity for 3 years and 5 years, since there is no improvement in Charlottetown resilience over these planning periods. In the 20-year planning period, the adaptive capacity of Charlottetown is improved by the Protect, Accommodate, and Retreat strategies. Compared to other strategies, the Accommodate strategy significantly increases the capacity of Charlottetown to be adaptive where the community's vulnerability is equal to Do Nothing.

5 Conclusions and Recommendations

This chapter presents the thesis conclusions and recommendations for the application of risk analysis for the management of adaptation strategies for the case of Charlottetown. Section 5.1 gives a brief summary of the research, Section 5.2 discusses the research objectives, as presented in Chapter 1, and, finally, Section 5.3 presents recommendations for future research.

5.1 Summary

This research presents a framework for structured risk analysis for the quantitative evaluation of adaptation decisions in the event of storms for Charlottetown, P.E.I. The results of the research provide feedback on the implications of alternative planning periods to direct the decision making process in coastal communities to undertake with full knowledge, the rationale behind wise and safe steps towards management adaptation to environmental change in the future. This research encourages the coastal community to prepare for storm events by lengthening the planning periods when considering environmental change. Longer term and strategic thinking permits coastal communities like Charlottetown to plan more effectively for the most appropriate adaptation strategies that are designed to reduce the vulnerability of coastal communities to the changing environment.

Recent evidence is convincing that coastal communities are becoming more frequently threatened by more severe storm events. At the same time, because severe storms are characterized as “extreme events”, coastal communities tend to overlook the importance of a more suitable strategic time frame in their decision analyses in favor of pressing short term and more amenable issues. In order to manifest the effect of the time horizon on the results of the decision making outputs experiments are designed, within a risk analysis framework, to examine the decision evaluation results of different planning periods ranging from short term to longer term. The results indicate that shorter time periods lead to decision alternatives that undervalue active adaptation options and suggest that inaction (“Do Nothing”) is less costly and not likely – over the short run - to result in major negative impacts. On the other hand, the risk analysis shows that longer and more strategic planning periods diminish the benefits of the “Do Nothing” strategy in favor of more highly valued

active adaptation strategies. In this case, the Accommodate or soft engineering adaptation strategy generally rises above the other options followed by the hard engineering alternative of Protect. The Retreat option, in all cases analyzed to date, is considered to be the last resort and one that is generally unacceptable compared to the other alternatives.

This research identifies the key role of determining the community's effective planning period for coastal environmental planning problems in the application of the coastal community of Charlottetown.

5.2 Research Objectives

The research objectives originally presented in Chapter 1, Section 1.2 are described below. The presentation of this thesis represents the response to these research questions and their associated objectives, as summarized below.

> *Objective 1: develop the historical incidence of storm events for a particular coastal community and estimate the impacts on the profile of the community.*

To simulate the future pattern of storm events for Charlottetown, the historical incidence of storm events from 1911 to 2005 is used, as measured by the Maximum Observed Water Level, MOWL. The Gumbel max distribution, with parameters: (1) location parameter (mode) – alpha = 3.0 (historical 1911-2005 storm mode), or 3.75 (predicted more severe storms, as noted for the more recent period 1960-2005); and (2) scale parameter – beta = 0.303, are applied as the generator of the series of future storm events for Charlottetown by using the inverse transformation of the cumulative probability distribution function of the Gumbel max function. The extent to which Charlottetown is vulnerable to the six Storm Scenarios is assessed with respect to community profile pillars, namely, the environmental, economic, social, and cultural pillars of the community. The damage impacts by pillar (in nominal dollars) of recent severe storms are compared to their corresponding MOWL values in order to associate the expected storm damages for each pillar to the storm severity as measured by MOWL. The results show exponential trends in the damage estimation for each pillar of potential storm events as MOWL increases. All together, the pillar damages provide the community of Charlottetown with the risk assessment of storm events on the community as a whole.

Objective 2: apply the risk analysis to the alternative adaptation strategies and design experiments to test (compare and contrast) the results of evaluated adaptation strategies assessing different planning horizon.

The risk analysis framework is described in Chapter 3 for the case of no storms, storms with adaptation, and storms without adaptation, as prepared as part of the research process. Running an experiment of hundred simulation trials of every planning period (3,5,10, and 20 years) highlights the importance of having longer planning periods because of capturing more storms of "Concerned" and "Much Concern" rather than "Concerned". To compare and contrast adaptation strategies, Total Annual Discounted Average Utility (TADAU) is used as a measure of the overall performance of adaptation strategies within the prespecified planning periods. TADAU values are weighted by the order of importance of the community profile pillars, averaged over a hundred trials, and discounted annual over the planning period length. The utility values translate estimated damages of severe storm events on every pillar and invoke the community's perception of risk according to the S-shaped utility curves of Chapter 3. Experiments are designed to evaluate the effects of different planning horizons on the ranking of alternative adaptation strategies. Under every planning period, the adaptation strategy with the higher TADAU value receives the first priority of the community to be undertaken.

Objective 3: define effective risk analysis to model appropriate planning decision, expected impacts, and realistic event probabilities.

The risk analysis framework takes into account probabilities of occurring storm events, expected impacts of storm events, the priority order of community's pillars, the community's overall attitude toward risk, and the different planning periods to evaluate the adaptation strategies for Charlottetown. Even though the uncertainty in occurrence of storm events can affect the results of decision making (e.g., the Do Nothing strategy vs. other adaptation strategies), the planning periods are required to be defined as 'long enough' to propose – and act - sustainable decisions. Factors affecting decision alternatives are examined in the sensitivity analyses (Section 4.3) to improve the community's practices of sustainable decisions.

The following subsection presents the thesis results in the form of recommendations for the case of Charlottetown as: (i) policy considerations for future planning; and (ii) recommendations for future research.

5.3 Recommendations

In this section, policy recommendations for the community of Charlottetown are suggested in subsection 5.2.1, and the opportunities for future research work in this area are recommended in subsection 5.2.2.

5.3.1 Policy Recommendations

The City of Charlottetown – as for all coastal communities - is recommended to improve their preparedness by running "practices", such as table top exercises, or mock-ups of real emergency events around the structured stages of risk analysis, namely, risk assessment, risk management, and risk communication steps. The degree to which the community's pillars are vulnerable to future uncertain storm events, and the likelihood of occurring storm events should be specified. The level of acceptable risk for each community's pillar should be discovered, and community's different attitudes toward risky events should be collected and aggregated. The order of the community's pillar priorities should be discovered for the different members that characterize these communities.

The cut-off level, mitigation rate, and costs of adaptation strategies applicable to the community should be precisely computed. Further, examples of adaptation strategies should only take into consideration those adaptation strategies applicable to and for the City of Charlottetown.

The definition of the community for "future" needs to define a more strategic, longer term planning period. The estimation of TADAU should be set as the comparative measure of performance to evaluate adaptation strategies under predefined planning periods.

5.3.2 Considerations and Future Research

The considerations presented in this subsection focus on the difficulties in conducting this research. A review of this research leads to opportunities for future research in Charlottetown and other communities similar to Charlottetown.

Damage Estimation: The functions used to estimate the damages of MOWLs could be more precise. Research into determining the underlying storm scenarios that cover a wider variety and range of storms with their associated impacts would be beneficial to preparedness planning. Similarly, and with respect to existing actual data, the extent of damages recorded for every pillar needs to be determined to reflect close to actual feedback. More accurate results with respect to previous maximum damages, and the fitting of cost functions to the utility curves represent important areas of applied research. Other elements of damage information include the damage carryovers, and the amortized capital costs of the active adaptation strategies. Further, research in this area will be of considerable use to the application of the proposed model to other coastal communities.

Resources at The Community: With regard to community implementation, research into the capabilities of the leadership of the community to understand and apply the modeling results of this thesis would assist in indicating the appropriate ways and means of the community. While all of the analysis in this research are carried out within an Excel spreadsheet, it should be tested whether or not this particular platform is compatible with the community' resources before proceeding beyond to the risk analysis, etc.

Level of Acceptable Risk: The level of acceptable risk for the community can be determined by a series of active (e.g., cold phone call) or passive (e.g., on-line link) solutions that could provide utility curve construction information in the future. Many factors can affect the community's attitude toward risky storm events, such as the experience of managing through a recent severe storm, or mounting evidence from other observations that future storm events will happen.

Cost of Adaptations: In this research, the capital cost of the Protect strategy is defined as analogous to the cost estimation of the Steveston or the False Creek dike, breakwater, storm surge barriers, and sea gates constructions. Similarly, the capital costs of other adaptation strategies are assumed to be related to the Protect strategy. In reality, the actual costs of these strategies for Charlottetown may be quite different than proposed. Better estimates for the implementation of specific strategies with respect to the capital costs as well as the safety and engineering costs is an important area for future research.

Sensitivity Analysis: The factors specified in the sensitivity analysis in this thesis are designed to reflect possible changes in the Charlottetown context and related model parameters. With ever changing policies and regulations and a lack of actual empirical data, these factors might be adjusted to a higher or lower level than the current one. Further research on the sensitivity of the ranked adaptation solutions to changes in model parameters would provide better understanding of the results and develop more robust answers under uncertainty. Finding the switching points for all strategies is a recommended analysis for Future Research. Different S-shape utility curves could be analyzed as an extension of the model sensitivity analysis.

The ranked results of the different adaptation strategies for the Protect, Accommodate, and Retreat strategies depend on the relative capital costs of the respective strategies. The thesis estimates strategy costs based on a review of comparable hard and soft engineering projects applied to comparable coastal areas. Future research would investigate site specific engineering and more precise cost valuations.

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Appendices

A. Isle Madame Environmental Dimension Components

Environmental items (i.e. indicators), layers, the number of available points or polylines, and approximate length and area of each point are presented in the table below. Data have been extracted from GeoNova, 2006, by Pakdel (2011).

Table A.1. Isle Madame Environmental Pillar Items. Source: (Pakdel, 2011, p. 59-60)

Environmental Item	Element (layer)	Number of Points/polylines	Approximate Length /Area
Hydrology, Land Use & Land Cover	Rivers	581	700 km
	Lakes	304	22 sq km
	Break water	3	5 km
	Swamp	661	15 sq km
	Ditch	2	-
	Provincial park, Park, Tree area	1382	90 sq km
	Berries point	8	-
	Cliff line	39	14.3 km
	Culvert	122	-
	Cut line	51	-
	Dump line	5	-
Marine Use	Seal haulout (Habitat)	19	-
	Beaches (Habitat)	13	-
Habitat and Species	Herring (Fish)	24	-
	mackerel (Fish)	25	-
	perch (Fish)	34	-
	Pollock (Fish)	23	-
	flounder (Fish)	24	-
	dogfish (Fish)	12	-
	cod (Fish)	15	-
	Rockweed (Habitat)	301	40.5 km
	Kelp (Habitat)	23	3.8 km
	Squid (Fish)	11	-
	Lobster bottom (Habitat)	16	59 Sq km
	Recreational Clam beds (Habitat)	2	2.3 Sq km
	Shellfish closure (Habitat)	7	14 Sq km

	Scallop bottom (Habitat)	10	7.1 Sq km
	Mussels (Fish)	3	0.2 Sq km
	Sea urchins (Habitat)	10	1.4 Sq km
	EelRichmondCoStdFields (Fish)	67	-
	gaspereau (Fish)	34	-
	salmon (Fish)	18	-
	smelt (Fish)	56	-
	capelin (Fish)	6	-
	trout (Fish)	41	-
	tern nesting (Bird)	2	-
	osprey nesting (Bird)	2	-
	eider nesting (Bird)	17	-
	cormorant nesting (Bird)	3	-
	eagle nesting (Bird)	1	-
	gull nesting (Bird)	1	-
	Heron nesting (Bird)	1	-

B. The UK's Guidance on Classification of Relative Magnitude

UKCCRA provides a national overview of potential risks and opportunities caused by climatic changes for UK up to 2100. It uses the recent evidences and projection of UK climate to do the assessment. To compare the risks and opportunities, CCRA uses the "order of magnitude" that enables the comparison of socio-economic scenarios. The table presented below is an instance for classification used by UKCCRA to describe magnitudes of consequences. It provides qualitative descriptions, which includes Low, Medium, and High classes.

Table B.1. Sample for Classification of Relative Magnitude. Source: (UKCCRA. 2012a, p. 37)

Class	Economic	Environmental	Social
High	• Major and recurrent damage to property and infrastructure • Major consequence on regional and national economy • Major cross-sector consequences • Major disruption or loss of national or international transport links • Major loss/gain of employment opportunities *~ £100 million for a single event or per year*	• Major loss or decline in long-term quality of valued species/habitat/landscape • Major or long-term decline in status/condition of sites of international/national significance • Widespread Failure of ecosystem function or services • Widespread decline in land/water/air quality • Major cross-sector consequences *~ 5000 ha lost/gained* *~ 10000 km river water quality affected*	• Potential for many fatalities or serious harm • Loss or major disruption to utilities (water/gas/electricity) • Major consequences on vulnerable groups • Increase in national health burden • Large reduction in community services • Major damage or loss of cultural assets/high symbolic value • Major role for emergency services • Major impacts on personal security e.g. increased crime *~million affected* *~1000s harmed* *~100 fatalities*
Medium	• Widespread damage to property and infrastructure • Influence on regional economy • Consequences on operations & service provision initiating contingency plans • Minor disruption of national transport links • Moderate cross-sector consequences • Moderate loss/gain of employment opportunities *~ £10 million per event or year*	• Important/medium-term consequences on species/habitat/landscape • Medium-term or moderate loss of quality/status of sites of national importance • Regional decline in land/water/air quality • Medium-term or Regional loss/decline in ecosystem services • Moderate cross-sector consequences *~ 500 ha lost/gained* *~ 1000 km river water quality affected*	• Significant numbers affected • Minor disruption to utilities (water/gas/electricity) • Increased inequality, e.g. through rising costs of service provision • Consequence on health burden • Moderate reduction in community services • Moderate increased role for emergency services • Minor impacts on personal security *~100s thousands affected,* *~100s harmed,* *~10 fatalities*
Low	• Minor or very local consequences • No consequence on national or regional economy • Localised disruption of transport *~ £1 million per event or year*	• Short-term/reversible effects on species/habitat/landscape or ecosystem services • Localised decline in land/water/air quality • Short-term loss/minor decline in quality/status of designated sites *~ 50 ha of valued habitats damaged/improved* *~ 100 km river quality affected*	• Small numbers affected • Small reduction in community services • Within 'coping range' *~10s thousands affected etc.*

C. The Sensitivity of the 3-Year Planning Period

To simulate annual MOWL for Charlottetown storm events, the inverse function of the characteristic Gumbel max distribution is used. A hundred trials with the length of 3-year are run and three expected MOWLs are recorded for every trial. The maximum of MOWL of every trial is selected to show the highest estimated storm for Charlottetown in a 3-year planning period. Storms are classified to three categories of "No Concern", "Concerned", and "Much Concerned" with respect to the value of MOWL anticipated. To illustrate, the experimental results are shown for 10 successive 3-year planning periods over 30 years in Table C.1.

Table C.1. Frequency of Three Categories observed in a 3-Year Planning Period

Year	Annual MOWL	Max MOWL	Action
1	3.479	3.479	No Concern
2	3.286		
3	3.098		
4	3.148	3.148	No Concern
5	2.561		
6	3.044		
7	3.057	3.057	No Concern
8	2.933		
9	2.876		
10	3.594	3.594	Concerned
11	3.163		
12	2.812		
13	3.585	3.585	Concerned
14	3.159		
15	2.753		
16	3.002	3.183	No Concern
17	2.916		
18	3.183		
19	3.131	3.131	No Concern
20	2.588		
21	3.008		
22	2.780	2.983	No Concern
23	2.983		
24	2.746		

25	3.829	3.829	Concerned
26	3.280		
27	3.188		
28	2.798	3.274	No Concern
29	3.274		
30	2.841		

D. The TADAU values Computations in a 3-Year Planning Period

Given a 3-year planning period, the four adaptation strategies (Do Nothing, Protect, Accommodate, and Retreat) are compared with respect to their TADAU value. The steps for calculating TADAU value of the Protect strategy in a 3-year period are described. The expected annual MOWL for every year is simulated by the inverse Gumbel max function with parameters: Alpha-2.99, and beta-0.303, which uses random variables uniformly distributed on the (0,1) intervals (Formula 3-1). The cut-off level of the Protect strategy is 3.6 m, meaning that any MOWLs less than or equal to 3.6 meters is replaced by zero. Table D.1 illustrates the new MOWLs under the Protect strategy over 10 trials.

Table D.1. Changes in MOWLs under Protect Strategy Over 10 Trials of 3-Year Planning Period

Trial	Random Number			MOWL (m) Under Do Nothing			MOWL (m) Under Protect		
	Year 1	Year 2	Year 3	Year1	Year2	Year3	Year1	Year2	Year3
1	0.19	0.97	0.80	2.84	4.00	3.45	0.00	4.00	0.00
2	0.15	0.25	0.10	2.80	2.89	2.74	0.00	0.00	0.00
3	0.98	0.12	0.09	4.29	2.77	2.73	4.29	0.00	0.00
4	0.28	0.34	0.48	2.92	2.97	3.08	0.00	0.00	0.00
5	0.53	0.06	0.52	3.13	2.68	3.12	0.00	0.00	0.00
6	0.14	0.59	0.32	2.79	3.19	2.95	0.00	0.00	0.00
7	0.66	0.06	0.19	3.26	2.68	2.84	0.00	0.00	0.00
8	0.24	0.54	0.96	2.88	3.14	4.01	0.00	0.00	4.01
9	0.36	0.04	0.16	2.94	2.65	2.80	0.00	0.00	0.00
10	0.10	0.66	0.26	2.74	3.26	2.90	0.00	0.00	0.00

Annual damage to every Charlottetown's pillar is estimated by the trendline equations fitted to damage data set over MOWL. The equations are shown in the Table D.2.

Table D.2. The Trendline Equations Fitted to Damage Data Set Over MOWL

Community Pillar	Trendline Equations
Environmental Pillar	$0.1649e^{0.9259x}$
Economic Pillar	$0.1292e^{0.9397x}$
Social Pillar	$0.0089e^{0.9419x}$
Cultural Pillar	$0.015e^{0.9292x}$

Annual damages to all pillars of the community are transferred to the next years by annual rate of damage carryover (25%). In addition to this carryover, the economic pillar

takes into account the amortization cost of the Protect strategy distributed over the planning period length. Table D.3 presents the amount of damages to every pillar.

Table D.3. Annual Estimated Damages by Pillar With Respect to MOWL- Protect Strategy

Trial	MOWL (Meters)			Environmental Damages ($Millions)			Economic Damages ($Millions)			Social Damages ($Millions)			Cultural Damages ($Millions)		
	Yr1	Yr2	Yr3	Yr1	Yr2	Yr3	Yr1	Yr2	Yr3	Yr1	Yr2	Yr3	Yr1	Yr2	Yr3
1	0.00	4.00	0.00	0.16	6.73	1.85	17.7	17.7	17.7	0.01	0.39	0.11	0.02	0.62	0.17
2	0.00	0.00	0.00	0.16	0.21	0.22	17.7	17.7	17.7	0.01	0.01	0.01	0.02	0.02	0.02
3	4.29	0.00	0.00	8.76	2.35	0.75	17.7	17.7	17.7	0.51	0.14	0.04	0.81	0.22	0.07
4	0.00	0.00	0.00	0.16	0.21	0.22	17.7	17.7	17.7	0.01	0.01	0.01	0.02	0.02	0.02
5	0.00	0.00	0.00	0.16	0.21	0.22	17.7	17.7	17.7	0.01	0.01	0.01	0.02	0.02	0.02
6	0.00	0.00	0.00	0.16	0.21	0.22	17.7	17.7	17.7	0.01	0.01	0.01	0.02	0.02	0.02
7	0.00	0.00	0.00	0.16	0.21	0.22	17.7	17.7	17.7	0.01	0.01	0.01	0.02	0.02	0.02
8	0.00	0.00	4.01	0.16	0.21	6.78	17.7	17.7	17.7	0.01	0.01	0.39	0.02	0.02	0.62
9	0.00	0.00	0.00	0.16	0.21	0.22	17.7	17.7	17.7	0.01	0.01	0.01	0.02	0.02	0.02
10	0.00	0.00	0.00	0.16	0.21	0.22	17.7	17.7	17.7	0.01	0.01	0.01	0.02	0.02	0.02

Similar to damage estimations, the corresponding expected utility values of damages are found by trendlines fitted to the utility curves. The equations of trendlines for the four pillars' utility curves are shown in Table D.4.

Table D.4. The Trendline Equations Fitted to Utility Curves of Different Pillars

Community Pillar	Trendline Equations
Environmental Pillar	$-0.0089x^2 + 0.0033x + 1$ (Damages below $7.3million) $-0.0003x^3 + 0.0156x^2 - 0.2912x + 1.9597$ (Damages over $7.3million)
Economic Pillar	$-6E\text{-}05x^4 + 0.0025x^3 - 0.0311x^2 + 0.0443x + 0.9888$
Social Pillar	$-2.2132x^4 + 6.2141x^3 - 5.12x^2 + 0.1908x + 0.9952$
Cultural Pillar	$0.1632x^5 - 1.2116x^4 + 3.1864x^3 - 3.2315x^2 + 0.2971x + 0.9947$

The annual expected utility values of all pillars are weighted by order of priority of community pillars and accumulated over the four pillars (total annual weighted expected utility). The weights considered for the base case are: Environmental=21%, Economic=22%, Social=38%, and Cultural=19%, as shown in Table D.5.

Table D.5. Total Annual Weighted Expected Utility of 3-Year Planning Period- Protect Strategy

Annual Expected Utility of Environmental			Annual Expected Utility of Economic			Annual Expected Utility of Social			Annual Expected Utility of Cultural			Total Annual Weighted Expected Utility		
Yr1	Yr2	Yr3	Yr1	Yr2	Yr3	Yr1	Yr2	Yr3	Yr1	Yr2	Yr3	Yr1	Yr2	Yr3
1.00	0.62	0.98	0.00	0.00	0.00	1.00	0.61	0.97	1.00	0.53	0.97	0.78	0.46	0.76
1.00	1.00	1.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	0.78	0.78	0.78
0.40	0.96	1.00	0.00	0.00	0.00	0.44	0.94	0.99	0.35	0.94	1.00	0.32	0.74	0.78
1.00	1.00	1.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	0.78	0.78	0.78
1.00	1.00	1.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	0.78	0.78	0.78
1.00	1.00	1.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	0.78	0.78	0.78
1.00	1.00	1.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	0.78	0.78	0.78
1.00	1.00	0.61	0.00	0.00	0.00	1.00	1.00	0.61	1.00	1.00	0.53	0.78	0.78	0.46
1.00	1.00	1.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	0.78	0.78	0.78
1.00	1.00	1.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	0.78	0.78	0.78

Total annual weighted expected utilities are averaged over 100 trials to compute Annual Total Average Utility. Annual Total Average Utility are discounted, using formula 4.1, over the 3-year period and generate three TADAU values for the Protect strategy. The annual discount rate is 3% for the base case. To find TADAU values of other strategies, these steps are repeated, as shown in Table D.6.

Table D.6. Annual Total Average Utility and TADAU Values of All Strategies Over a 3-Year Planning Period

Strategies	**Annual Total Average Utility**			**Total Annual Weighted Average Utility**
	Year1	Year2	Year3	
Do Nothing	0.89	0.82	0.81	0.82
Protect	0.75	0.74	0.74	0.72
Accommodate	0.76	0.75	0.75	0.73
Retreat	0.74	0.72	0.72	0.71

A 95% confidence interval is defined over Total Annual Weighted Expected Utility of all adaptation strategies and planning periods. The average, standard deviation, Lower Control Interval (LCI), and Upper Control Interval (UCI) over a 100-trial of 3 years are represented in the following table.

Table D.7. The Average, Standard Deviation, LCI, and UCI Within the 3-Year Planning Period

	Do Nothing			Protect			Accommodate			Retreat		
	Yr1	Yr2	Yr3	Yr1	Yr2	Yr3	Yr1	Yr2	Yr3	Yr1	Yr2	Yr3
Average	0.90	0.83	0.81	0.75	0.75	0.74	0.76	0.75	0.75	0.74	0.73	0.72
St. dev.	0.08	0.14	0.11	0.10	0.08	0.10	0.01	0.02	0.02	0.04	0.02	0.06
LCI	0.74	0.56	0.60	0.54	0.59	0.54	0.74	0.72	0.70	0.66	0.69	0.61
UCI	1.05	1.09	1.02	0.95	0.91	0.94	0.79	0.78	0.79	0.82	0.78	0.82

The following table shows the LCI and UCI of TADAU values for all strategies in 3 years, given the confidence interval of 95%.

Table D.8. The LCI, and UCI of TADAU Values Within the 3-Year Planning Period

	Do Nothing	Protect	Accommodate	Retreat
LCI	0.65	0.49	0.69	0.62
UCI	1.02	0.93	0.78	0.80