Assessing the Impacts of Sea Level Rise in the Caribbean using Geographic Information Systems

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Numerous studies project that climate change will accelerate the rise in global sea levels, leading to increased coastal inundation, greater potential damage from storm surge events, beach erosion and other coastal impacts which threaten vital infrastructure and facilities that currently support the economies of island nations. There is a broad consensus amongst experts that small island developing states (SIDS) face the greatest risk to the projected impacts of climate change. Unfortunately, few sea level rise (SLR) impact assessment studies have been conducted in SIDS due to the limitations of the geospatial data with regard to currency, accuracy, relevance and completeness.

This research improves upon previous SLR impact assessment research by utilizing advanced global digital elevation models to create coastal inundation scenarios in one metre increments for 19 Caribbean Community (CARICOM) nations and member states, and then examine the implications for seven key impact indicators (land area, population, economic activity, urban areas, tourism resorts, transportation infrastructure and beach erosion). The results indicate that a one metre SLR would have serious consequences for CARICOM nations. For example under this scenario over 10% of the 73 identified study area airports and 30% of the 266 major tourism resorts were identified as prone to flooding. Projected effects were not found to be uniform across the region; low-lying island nations and mainland countries with coastal plains below ten metres were identified as the most vulnerable countries. Recommendations for adaptive actions and policies are provided.

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Dedication

This thesis is dedicated to Rupert No!

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List of Acronyms

AIMS	Caribbean and Africa, Indian Ocean, Mediterranean and South China Sea
AOSIS	Alliance of Small Island States
AR4	Fourth Assessment Report
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
CARICOM	Caribbean Community
CDMP	Caribbean Disaster Mitigation Project
COI	Indian Ocean Commissions
DFID	UK Department for International Development
ENSO	El Niño-Southern Oscillation
GHG	Greenhouse Gas
GIS	Geographic Information System
IPCC	Intergovernmental Panel on Climate Change
LiDAR	Light Detection And Ranging
PIF	Pacific Islands Forum
SEDU	Sustainable Economic Development Unit
SIDS	Small Island Developing State
SLR	Sea Level Rise
SRTM	Shuttle Radar Topography Mission
UNDP	United Nations Development Programme
UNDESA	United Nations Department of Economic and Social Affairs Pacific
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UNWTO	United Nations World Tourism Organization
WMO	World Meteorological Organization
WTO	World Trade Organization

1 Introduction

1.1 Study Context

According to the Fourth Assessment Report (AR4) of the United Nations Intergovernmental Panel on Climate Change (IPCC) "warming of the climate system is unequivocal, as is now evident form observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level" (2007, p. 72). Over the last 50 years, global surface temperatures have risen 0.74 °C, a trend set to continue and accelerate over the next century if anthropogenic greenhouse gas (GHG) emissions continue on current trajectories (IPCC, 2007). The effects of climate change go beyond a rise in global average temperatures, to include increased ice cap melting, increases in extreme weather events and rising sea levels (IPCC, 2007; United Nations Framework Convention on Climate Change [UNFCCC], 2007).

The impact of climate change on global and regional sea levels is complex. Recent studies on historic sea levels have concluded that one to two metre rises in global sea levels have occurred within 100 year periods (Cazenave & Nerem, 2004; Rahmstorf, 2007). The most recent IPCC projections have not suggested rises of this magnitude. The IPCC estimate of current sea level rise is around 3.4 mm/year, which is substantially higher than early model predictions of 1.9mm/year (IPCC, 2007). The IPCC AR4 projects an overall global sea level rise between 18 and 59 cm between 1993 and 2100 (IPCC, 2007). However, these predictions are widely thought to be quite conservative, as they assume a near-zero net contribution from melting Greenland and Antarctic ice sheets, and focus primarily on the thermal expansion of warming oceans (Pfeffer, Harper, & O'Neel, 2008; Solomon, et al., 2007). Recent studies that have attempted to factor in the response of continental ice to global warming have predicted that by the end of the 21st century, global sea levels could be as much as one and a half to two metres above present levels (Rahmstorf, 2007; Horton et al., 2008; Vermeer & Rahmstorf, 2009; Nicholls & Cazenave, 2010).

The IPCC AR4 predicts that rising sea levels will intensify coastal inundation, storm surge, erosion and other coastal impacts (wetland loss, salt water intrusion, damage coral reefs, affect vegetation and beach erosion), thereby threatening vital infrastructure and facilities that currently support the economies of coastal areas and especially island nations (IPCC, 2007, p. 52). While any rise in sea levels will inevitably affect all coastal nations to some degree, recent assessments by international experts have unanimously identified Small Island Developing States (SIDS) as facing the most severe effects to climate change (Yohe, et al., 2007; IPCC, 2007). The Caribbean region consists primarily of SIDS, which share many characteristics making them particularly vulnerable to the effects of climate change, rising sea levels and extreme events. These characteristics include small land mass, population and infrastructure concentrated in coastal regions, a limited economic base with a dependency on natural resources, and relative isolation (UNFCCC, 2007). Furthermore, the Caribbean has been identified as one of the most tourism-dependent regions in the world, and the tourism industry there is highly vulnerable to sea level rise, given the coastal proximity of most tourist resorts (Carey, 1991; Briguglio, 1995; World Resources Institute [WRI], 2002; Pelling & Uitto, 2001). Under even the most conservative IPCC scenarios, many SIDS would lose significant proportions of their land and their coastal infrastructure, with significant effects on populations, ecologies and economies (Kelman & West, 2009).

It is generally accepted that the effects of rising global sea levels on coastal environments will vary spatially, and this has prompted scientists to engage in more localized impact assessments (Kelman & West, 2009). For both geological and jurisdictional reasons, assessing the likely local effects of climate change and sea level rise is seen as the necessary first step to facilitating policy changes and identifying practical adaptation strategies (UN, 2005; IPCC, 2007). The IPCC defines climate change impact assessment as "the practice of identifying and evaluating, in monetary and/or non-monetary terms, the effects of climate change on natural and human systems" (IPCC, 2007, p. 876). Unfortunately, while several studies have attempted to study the impacts of SLR on a regional level, few have successfully incorporated SIDS on national scales, often focusing on larger non-SIDS areas (UN, 2005; Kelman & West, 2009; Dasgupta et al., 2009; IPCC, 2007).

The need for proper impact assessment research concerning the effects of sea level rise on SIDS was emphasised in the *Barbados Programme of Action* (1994), which pointed specifically to the need for developing Geographic Information Systems (GIS) and incorporating them within impact research (UN, 1994). More specifically, the *Barbados Programme of Action* stated the need to:

> "Map areas vulnerable to sea level rise and develop computer-based information systems covering the results of surveys, assessments and observations as part of the development of adequate response strategies, adaptation policies and measures to minimize the impact of climate change, climate variability and sea level rise" (1994, p. 11).

While the process is inherently difficult and complex, several studies have attempted to model the effects of sea level rise and storm surges on SIDS using GIS technology (Dasgupta et al., 2009; Nicholls et al., 1999). The first noteworthy study was that of Nicholls et al., (1999) which modelled the effects of sea level rises with regard to total area of coastal flooding, risks to population, wetland losses and protection costs on both global and regional scales. The study pointed to the Caribbean as one of the most vulnerable areas (globally) to rising sea levels. However, the authors noted that the coarse geospatial resolutions utilised in the study did not allow for detailed impact assessments on a national level. Perhaps the most useful assessment to date was conducted for the World Bank (Dasgupta et al., 2009); it utilized high resolution satellite elevation data to assess the effects of SLR using several indicators: land area, population, agriculture, urban extent, wetlands and GDP. The study confirmed that Caribbean SIDS were among those facing the greatest threat from rising sea levels, with The Bahamas identified as the most vulnerable island nation on earth. Unfortunately, several SIDS in the Caribbean region were excluded from these global sea level rise studies due to reported limitations in geospatial data (Nicholls et al., 1999; Dasgupta et al., 2009).

Despite the need for national level impact assessments on all Caribbean SIDS, no complete assessments have been completed to date. As previous mentioned, impact assessments are considered a crucial initial component of the process of climate change adaptation. Considering its potential vulnerability to SLR there is a need to fill this important knowledge gap for the Caribbean region.

1.2 Research Goals

The principal goal of this study is to improve upon previous impact assessments of rising sea levels in the Caribbean, by utilizing a GIS to create comprehensive impact assessment estimates for seven important indicators (land area, population, economic activity, urban areas, tourism resorts, transportation infrastructure and beach erosion). Within the general ambit of this goal, *three* main objectives can be specified:

i) To review previous methods of modelling SLR on large scales and incorporate these techniques (when appropriate) into the evaluation of Caribbean nations.

ii) To fill in Caribbean gaps in the World Bank Study by compiling impact assessment estimates for all 15 full member and four associate Caribbean Community (CARICOM) nations (with an emphasis on Caribbean SIDS).

iii) To improve upon the 2009 World Bank study with:

   a. Higher resolution satellite based digital elevation data (30 metre pixel resolution compared to 90 metre resolution).
   b. Updated geospatial impact element data sets for population and economic activity.
   c. New datasets, including detailed tourism infrastructure and a detailed inventory of CARICOM beach areas, which are vital to the regional economy.
   d. Conduct erosion estimates for all unconsolidated sand beach areas, using the widely used Brunn Rule.
   e. Compare the results to those of the World Bank study, and recommend strategies and further research for all CARICOM nations.

It is anticipated that the findings from this research will demonstrate the dramatic implications of anticipated sea level rises for all CARICOM nations and allow local and international policy makers to make informed decisions related to SLR adaptation.

1.3 Thesis Structure

This thesis is organized into six chapters. Chapter one defines the study context, research goals and thesis structure. Chapter two presents the current state of knowledge on climate change and sea level rise as it pertains to the Caribbean. This chapter also reviews previous SLR impact assessment studies and highlights the need for further research. Chapter three presents the research methods and data utilized to create the SLR models. Chapter four presents the results for each SLR modelling technique. Chapter five presents a summary of the findings for each of the SLR scenarios along with practical implications. The final chapter closes with recommendations for future research and concluding statements.

2 Literature Review

2.1 Introduction

This literature review is divided into three main sections. The first section presents an overview of the science underlying our current understanding of climate change and sea level rise, including historic levels dating from the last interglacial period to the present day. The projected impacts of sea level rise in different climate scenarios are also considered. The second section explores the literature related to climate change and sea level rise impacts and vulnerabilities, with specific reference to small island developing states. The third section looks specifically at the Caribbean region, and focuses on the projected impacts resulting from global climate change and rising sea levels there. The main focus of this section is a review of previous methods used for sea level rise impact assessment in the Caribbean.

2.2 Climate Change

Climate change may entail a shift in average weather conditions, or in the intensity and distribution of events, and can affect regions and/or occur on a global scale. In 1988, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) established the Intergovernmental Panel on Climate Change (IPCC). The IPCC was conceived both as a scientific intergovernmental body and as a network of the world's leading climate change scientists and experts, tasked with understanding and assessing information related to climate change. The IPCC has been instrumental in providing scientific reports on the current state of climate change and its potential socio-economic and environmental consequences on a variety of scales, regional and global. The IPCC has also been influential for policy makers, government officials and scientists around the world. Climate change, as defined by the IPCC, refers to "any change in climate over time, whether due to natural variability or as a result of human activity" (IPCC, 2007, p. 30). This definition differs from other definitions, notably that used by UNFCCC, for whom climate change refers to changes due directly or indirectly to human activity, altering the composition of the global atmosphere in ways distinct from, and in addition to, natural climate variability observed over comparable time periods (IPCC, 2007; UNFCCC, 2007).

According to the IPCC (2007), among the primary drivers of current climate change is "the chain from greenhouse gas emissions to atmospheric concentrations to radiative forcing to climate responses and effects" (p. 37). In other words, the long-term emission of greenhouse gases into the atmosphere, as a result of human technological and socio-economic development, increases the atmospheric concentration of these gases, which in turn affects the "absorption, scattering and emission of radiation within the atmosphere and at the Earth's surface" (IPCC, 2007, p. 37). The net effect of an increased retention of solar radiation is a marked increase in air, surface, and ocean temperatures around the globe, and the current increase can be traced almost entirely to human activity (IPCC, 2007; Strasdas, 2010). This temperature increase, in turn, has wider ranging effects including climate feedbacks that amplify human influence on the climate system. For example; due to the effects of rising temperatures on natural systems related to snow, ice and frozen ground, we see evidence of such contingent phenomena as the enlargement and increased number of glacial lakes, increasing ground instability in permafrost regions, the increasing frequency of rock avalanches in mountain regions, and the changes in Arctic and Antarctic ecosystems (IPCC, 2007).

Many natural systems are being affected by regional climate changes around the globe; a common thread linking these natural systems is the importance of temperature change with respect to the *severity* of the phenomena these systems produce, and the multiplication of extreme events caused by the relationships between them (IPCC, 2007). The existence of these interrelationships between natural systems makes clear the need for increased study into the causes and effects of climate change (Mimura, et al., 2007). One such relationship can be traced between the average temperature of the air and oceans and the sudden, accelerating increase in sea levels in the last three decades of the twentieth century (IPCC, 2007). As noted by Cazenave & Nerem (2004), this understanding of the widespread effects of climate change on the natural systems of the earth, due to the aggregation of natural and anthropogenic forces, is only possible because of recent advances in technology – which allow for more specific data to be collected with greater representational accuracy. This accuracy is important, as analysis has shown that even a seemingly small change in average temperature can have a substantial effect on sea levels (Dasgupta et al., 2009; FitzGerald et al., 2008; IPCC, 2007; United Nations, 1994).

2.3 Sea Level Rise

Global sea levels have varied greatly throughout the Earth's history, as a result of both geological and climatic changes (Cazenave & Nerem, 2004; FitzGerald et al., 2008; Grinsted et al., 2009). Geological records indicate that global sea levels have risen roughly 120 metres since the last glacial maximum (20,000 years ago) (IPCC, 2007). However, this rising trend has not been constant, as a variety of factors impact the rate of change. For example, sedimentary deposit records indicate that seas have historically risen rapidly during extreme warming events, with certain centuries witnessing one to four metre rises (IPCC, 2007). Geological records from the Mediterranean suggest that sea levels reached a relatively constant state around 6,000 years ago, with rises of only 0.1 to 0.2 mm/year over the last 3,000 years (IPCC, 2007). Within recent decades the rate of increase has accelerated rapidly, with the change over the decade 1993-2003 at +2.8(with a ranged error margin of ± 0.4) mm/yr (Cazenave & Nerem, 2004). The primary factor in this rise, according to the IPCC, is the global rise in average air and ocean temperatures (IPCC, 2007). Recognition of this causal relationship has led to climate change, and the various anthropogenic effects increasing the temperature of the atmosphere, coming under intense scientific scrutiny in recent years. This has resulted in a good deal of raw data from advanced satellite observations, as well as analysis and synthesis of this data as it pertains to sea level rise (IPCC, 2007; Gehrels, 2010; Horton et al., 2008).

2.3.1 Causes of Sea Level Rise

Responsibility for the rise in mean global sea levels can be assigned to both natural and anthropogenic forces, which contribute in distinct ways to the changes in climate that are associated with sea level rise (IPCC, 2007). Climate change itself is moderated by a multitude of diverse but interconnected factors. These can be natural, such as changes in solar activity, or they can be aspects of human development, such as economic and industrial systems. There are also systems which straddle the boundary between the two, such as the impact climate change has upon ecosystems, and the effects these in turn can have upon elements of climate change – for example the role water resources play in extreme weather systems (IPCC, 2007; Gehrels, 2010).

2.3.2 1.5 to 2 degrees counts

Given the increasingly accurate records of both air and ocean temperatures around the globe – due in part to advances in the technologies used to measure and analyse climatic data and in part to the greater effort made to compile them – seemingly minute differences in temperature can now be examined and correlated with data from every part of the earth to attribute rising sea levels to previously unobserved phenomena (Cazenave & Nerem, 2004). The increasing accuracy of measurements has made it clear that an increase of one and a half to two degrees Celsius in average air temperature can have a broad effect on a number of oceanic systems which affect sea levels; these include thermal expansion and the overall oceanic mass, which will be discussed in greater detail below (Cazenave & Nerem, 2004). And as noted by Vemeer & Rahmstorf (2009), this link between global sea levels and global temperatures entails a direct and intimate dependence; the results of their modelling indicate that present and future sea level rise can be attributed to as small an average temperature shift as one degree globally, with greater variance of temperature occurring at wider temperature intervals (Vermeer & Rahmstorf, 2009).

2.3.3 Thermal Expansion/Ocean Volume

The most direct effect of global temperature on sea levels occurs through the mechanism of thermal expansion – an increase in the volume of the oceans due to increased water temperature (Cazenave & Nerem, 2004; FitzGerald, Fenster, Argow, & Buynevich, 2008). The term thermal expansion refers to water's property of expanding as it warms – a distinct phenomenon, which combines with the increased mass of water in the oceans due to the melting of the continental ice sheets in the Arctic and other areas (IPCC, 2007; FitzGerald et al., 2008). It is estimated that thermal expansion will account for more than half of the increase in ocean volume and rise in sea levels over the next century (IPCC, 2007; Vermeer & Rahmstorf, 2009). But the more pessimistic the projection of climate change and effects, the less important the role of thermal expansion in the total projected increase, as increased water mass due to melting ice sheets plays a greater role.

2.3.4 Historic Sea Levels

From the end of the most recent glacial maximum 20,000 years ago to the present day, global sea levels have been rising at a rate of around six milometres a year resulting in an absolute rise of at least 120 metres (Cazenave & Nerem, 2004; Grinsted et al., 2009; Gehrels, 2010). This rising trend has not been constant however, as many factors impact the rate of change. Geological records indicate that seas often rise rapidly, for example during the 500 year event entitled 'meltwater pulse 1A' (mwp-1A) the average rate of rise was 40 mm/yr (IPCC, 2007).

The history of sea levels is not a science without controversy. Due to the method of collecting data on the rise and fall of sea levels over geologic time – the comparison of sedimentary and coral deposits within the remnants of glacial cycles – some aspects of historic sea level are open to varying interpretations. One disagreement arising from differing interpretations is that between the IPCC (2007) and Gehrels (2010) regarding sea level changes since the last glacial maximum. Gehrels contends that IPCC estimates are faulty on three counts: the global rise in sea levels since the last glacial maximum has been between 130 and 135 metres, not 120 metres; it continued further into history than the IPCC (2007) indicates; it was not uniform across the globe. Regardless of this differing interpretation, the overwhelming consensus in the literature is that current global sea levels will continue to rise over the coming century (IPCC, 2007; Pfeffer et al., 2008; Kelman & West, 2009; Nicholls et al., 1999).

2.3.5 Observed Sea Levels

The measurement of sea levels has grown more and more accurate over the last century. This is due to advances in both technique and technology, which together have allowed for the collection of increasingly more accurate and extensive data towards the latter half of the twentieth century (Gehrels, 2010; Rahmstorf, 2007). The two primary types of observations for recording sea level are tide gauge measurements, which have been performed in some parts of the world for over a century, and the more recent method of satellite altimeter measurement, which has only been available for slightly less than two decades (Cazenave & Nerem, 2004). There are limitations to the usefulness of tide gauge measurements – poor spatial distribution of locations at which measurements can be taken, and their attachment to land, which can also move vertically. So although they are useful for providing a measurement of sea level change relative to the earth's crust, they cannot be used to determine absolute sea level change without some problems (Cazenave & Nerem, 2004; Hill et al., 2007). Although corrections can be made (for example, by comparing tectonically active and inactive areas) the limitations of tide gauge measurements are defined by the inherent inaccuracies of the method (Hill et al., 2007). Satellite altimetry, on the other hand, allows for precise measurements through microwave frequencies, and does not rely upon the variable altitude of the earth's crust (Cazenave & Nerem, 2004). By combining these two sets of data, researchers can estimate the approximate sea level rise during the last decades of the twentieth century with increasing confidence. The overall determination of average sea level change over the twentieth century is 1.76 (with a ranged error margin of ± 0.55) mm/yr, with the single greatest contributing factors being thermal expansion (0.3—0.7 mm/yr of sea level rise) and the melting of mountain and polar glaciers producing 0.2—0.4 mm/yr sea level rise (Cazenave & Nerem, 2004).

2.3.6 Sea Level Rise Projections

There is relatively little dispute among the scholars and researchers referenced above concerning the overall trend of changes in climate, or the resulting changes in sea level; as long as greenhouse gas emissions continue, aggregate global temperatures will rise, and the rate of sea level rise will increase accordingly (IPCC, 2007; Vermeer & Rahmstorf, 2009; Cazenave & Nerem, 2004). The debate among researchers does not relate to whether or not anthropogenic factors will contribute to sea level rise, but only to the likely *rate* of sea level rise increase in the coming centuries. The most conservative estimates come from the IPCC (2007), who posit that a projected increase in global average temperature of approximately half a degree Celsius will result in a sea level rise of between 0.3 and 0.8m over two hundred years. Further rises due to thermal expansion would continue for a good deal longer, due to the time required for heat to transfer into the deep ocean (IPCC, 2007). Vermeer & Rahmstorf (2009) are convinced that the IPCC's projections understate the situation, and have constructed a model that predicts a rise in sea levels almost three times greater. Several other studies also project sea levels rising well beyond the IPCC estimates, with a maximum projected rise of more than two metres over the next 100 years (Grinsted et al., 2009; Jevrejeva et al., 2010). In fact, given their lowest estimate for future greenhouse gas emissions, these models suggest sea level rise is still likely to be approximately one metre and up to two metres with their highest emissions estimate (Vermeer &

Rahmstorf, 2009; Horton et al., 2008; Jevrejeva et al., 2010; Gehrels, 2010). Whether the low or high range projections prove accurate, it is certain that greenhouse gas emissions and climate change will have a significant and long term effect upon global sea levels.

2.4 Small Island Developing States (SIDS)

There are various definitions of what constitutes a Small Island Developing State (SIDS). In April 1994, the *Barbados Programme of Action (1994)* was adopted during the first *Global Conference on Sustainable Development of SIDS* (Kelman & West, 2009; UN, 1994). By its definition, small island developing states share the following characteristics: they are small low-lying coastal countries, are limited in size, have vulnerable economies and depend both on narrow resource bases and on international trade, with limited means to influence the terms of that trade (UN, 1994). Other definitions include further characteristics: small but growing and dense populations, remote locations, fragile ecosystems, high energy and transportation costs, expensive and disproportionate public administration infrastructure, vulnerability to natural disasters and susceptibility to the effects of climate change (Crump, 2008; McGillivray et al., 2008; UN, 1994; Kelman & West, 2009). And these definitions have been stretched to include ambiguous cases; Papua New Guinea, for example, is considered a SIDS even though it covers an area of 462,840 km^2 – over twice that of New Zealand, which is not a SIDS due to its level of economic development (Kelman & West, 2009). For the purpose of this research, a SIDS is defined in the same terms adopted by the United Nations in the *Mauritius Strategy* (2005): a coastal based state, whose physical and human geography may take various forms, but which share the essential characteristics of isolation, relatively small populations and limited domestic land based resources resulting in a need for sustainable economic and environmental practices.

Above all, these states are highly dependent on coastal-based economic activities, and therefore highly susceptible to the effects of sea level rise and storm surges (Kelman & West, 2009; UN, 2005; IPCC, 2007).

According to the United Nations Department of Economic and Social Affairs (UNDESA), there are approximately 52 small island developing states, of which 37 are identified as independent nations (Singh, 2008). These states are classified into three broad geographically-defined groups, in the Pacific, the Caribbean, and the Africa, Indian Ocean, Mediterranean and South China Sea (AIMS). Each of the geographic regions made up of developing island states is represented by a regional cooperative body: the Caribbean Community (CARICOM), the Pacific Islands Forum (PIF), and the Indian Ocean Commission (COI). Additionally, the majority (42) of these recognized SIDS are members of the Alliance of Small Island States (AOSIS), an intergovernmental organization that works closely with the United Nations on a variety of issues. Currently AOSIS members constitute 28% of the world's developing countries and over 20% of the United Nations' total member states (Kelman & West, 2009; Crump, 2008).

2.4.1 Economy of SIDS

A key feature shared by the majority of SIDS is their highly undiversified economic structure – historically and in the present day (Singh, 2008). Due to their relative isolation from larger mainland markets, their high transportation costs, small domestic markets and lack of economies of scale, SIDS' economic exports have historically consisted primarily of two products; sugar and bananas (Singh, 2008; Pelling & Uitto, 2001). These products have played an especially important role in the economies of the Caribbean states. However, in recent years producers in Central America have challenged the preferential arrangements that Caribbean banana farmers enjoyed in European markets, notably in Great Britain. In response to these challenges, Caribbean and AIMS SIDS petitioned the European Union, which eventually granted African, Caribbean and Pacific (ACP) banana farmers preferential treatment under the 1975 Lomé Convention (Armstrong & Read, 1998; Pelling & Uitto, 2001). Unfortunately, the World Trade Organization (WTO) has also been active in this dispute, and "in 1997 a WTO ruling on sugar and banana trade, sponsored by the US, jeopardize[d] the preferential relations between the European Union and Caribbean States under Lomé Conventions" (Pelling & Uitto, 2001, p. 56). Due to increased pressure from larger and cheaper producers, the once thriving banana and sugar economies of many SIDS have declined dramatically (Pelling & Uitto, 2001; Singh, 2008; Armstrong & Read, 1998). For example, Grenada's banana exports fell from 4,500 tonnes per year in 1995 to only 600 tonnes/ year in 1999 – an 87% decline (Ahmed, 2001).

The noticeable decline in traditional export industries forced many SIDS to explore other economic opportunities (Singh, 2008; UN, 1994). The abundance of potential recreational resources (sun, sand, sea, etc.) and large tracts of undeveloped coastal land were seen as a promising base for expanded tourism industries (Singh, 2008). Investment in the tourism industry was successful, increasing national wealth and creating a host of local jobs which have revitalized many island economies. The industry was able to flourish because of the abundance of local unskilled labour, and because shipping costs and trade agreements were no longer factors (Singh, 2008; Armstrong & Read, 1998). Over the last few decades, SIDS have witnessed significant gains in overall tourism revenue, which increased by approximately 60% between 1990 and 2000 (UNEP, 2004). The United Nations World Tourism Organization (UNWTO) (2006) reported that tourist arrivals rose from 14.1 million in 1990 to 27 million in

2004, a cumulative growth of 91.3%, in 31 of 37 independent SIDS (UNWTO, 2006; Singh, 2008). Overall, between 1986 and 2004, SIDS have enjoyed increases of 10% per annum in tourist arrivals and 11% in visitor expenditure, and the island tourism industry is now over three times more valuable than export goods (UNWTO, 2006; Craigwell, 2007). However, despite all the economic benefits the tourism industry has brought to many SIDS, the industry – much like the countries themselves – is vulnerable to a host of factors. These include competition, global economic downturns and, particularly, the problems inherent in remoteness and in vulnerability to the natural disasters to which SIDS are prone (Briguglio, 1995; Singh, 2008; Kelman & West, 2009; UN, 2005).

2.4.2 SIDS Vulnerabilities and Susceptibility to Climate Change and Sea Level Rise

According to the United Nations, the biodiversity of small island developing states is "among the most threatened in the world" (1994, p. 4). The threats facing these delicate ecosystems can for the most part be grouped into two categories– *short-term* (natural/environmental) *disasters,* and *long-term disasters* (impacts from climate change and sea level rise) (UNEP, 2004; UN, 1994; Kelman & West, 2009). The following section discusses these vulnerabilities in more detail, by showing how limited resources and environmental vulnerabilities invariably shape all aspects of SIDS life.

2.4.3 Short Term: Natural and Environmental Disasters

For the purpose of this research the definition of 'short-term vulnerability' has been confined to natural and environmental disasters, which pose an immediate threat to SIDS and which have shown a high level of recurrence historically. SIDS also face problems related to food security, HIV/AIDS, drug trafficking, terrorism, political instability and social unrest. (UNEP, 2004; Pelling & Uitto, 2001; UN, 2005). However, due in large part to SIDS' size, location and coastal based economies, natural and environmental disasters are often cited as the most pressing short-term danger facing them (UN, 1994; UNEP, 2004). The most damaging natural and environmental disasters experienced by SIDS are cyclones, volcanic eruptions, and earthquakes (UN, 1994). However, many SIDS also face short-term problems in the form of frequent storm surges and landslides, and the coastal erosion and infrastructure damage these cause (UN, 2005; UN, 1994; UNEP, 2004). More recently, the impact of human-made natural disasters such as oil spills has also been recognised as a severe threat to SIDS (UN, 2005; Crump, 2008). It is also important to note that while the effects of climate change can create a variety of short-term problems, including extended periods of droughts and flooding, the majority of climate change induced vulnerabilities are considered long-term hazards (Kelman & West, 2009).

The combination of small size, limited resources and susceptibility to natural disasters has led to SIDS being labelled 'high risk' business environments, which in turn has “led to insurance and reinsurance being either unavailable or exorbitantly expensive, with adverse consequences for investment, production costs, government finances and infrastructure” (UN, 1994, p. 8). Furthermore, many SIDS can no longer compete in the international market for agricultural products such as bananas and sugar, due to their limited economic and natural resource bases and their reliance on specialized coastal based economic activities (Crump, 2008; IPCC, 2007). The United Nations have recognised that, as a result, short-term problems can have serious and prolonged effects on gross domestic product (GDP), which can fall by 20-30% in a single year following a major short-term disaster (hurricane, earthquake, etc.) (UN, 1994).

2.4.4 Long-Term Vulnerabilities: Climate Change and Sea Level Rise

The negative effects of climate change and sea level rise constitute significant long-term threats to SIDS. While the adverse effects of climate change can be considered a short-term vulnerability in some instances (e.g. drought), it is recognised that "the long-term effects of climate change may threaten the very existence of some small island developing states" (UN, 2005, 4). However, there are several challenges entailed in separating long-term climatic trends form climate variability and climate cycles (Kelman & West, 2009). Climate cycles and variability are ongoing phenomena, producing seasons as well as such longer quasi-periodic cycles as the El Niño-Southern Oscillation (ENSO), which occurs roughly every five years (UNEP, 2004; Kelman & West, 2009). Climatic variability can also run in cycles that span centuries and millennia. These cycles are influenced by a variety of systems, fluctuations in solar output to shift in the Earth's orbit over time, commonly referred to as Milankovitch Cycles (Vermeer & Rahmstorf, 2009).

Several other factors can influence climatic variability and trends over extended periods of time, including extreme events such as meteor strikes and volcanic eruptions (Kelman & West, 2009). And of course human activities can also influence long term climate trends, mainly through the increased emission of greenhouse gases. However, this human input into climate changes is still less obvious than the effects of natural phenomena, and its role in recent changes in the earth's climate remains a matter of overwhelming scientific consensus rather than a self-evident everyday reality.

The most worrisome long-term consequence of anthropogenic climate change for SIDS in all regions is the potential for sea level rise (Horton et al., 2008; UN, 1994; IPCC, 2007; UNFCCC, 2007). This paper has already discussed the ways in which any rise in sea level poses a major threat to the economic well-being of many SIDS, since their populations, agricultural lands and infrastructures tend to be concentrated in coastal zones (UN, 1994; Kelman & West, 2009). It is predicted that global warming-induced sea level rise will cause extensive loss of land-area in SIDS with large tracts of low-lying territory; for example, a rise of one metre in sea levels would render Tuvalu and the Maldives uninhabitable (Kelman & West, 2009). Rising sea levels are also expected to damage coral reefs, affect vegetation, and compromise freshwater resources through increased saline intrusion (UNEP, 2004; Pelling & Uitto, 2001).

2.4.5 SLR Impact Assessment Research

Even under conservative SLR scenarios presented by the IPCC (2007) , several SIDS are still expected to lose significant proportions of their habitable land due to sea level rise, including Kiribati, the Marshall Islands, and Tokelau (Kelman & West, 2009). Larger SIDS such as Fiji and Puerto Rico, with a large proportion of their land area above the potential flood-lines, are still at risk due to high coastal concentrations of population and infrastructure (Kelman & West, 2009).

Unfortunately, there were no extensive impact assessments for SIDS on a global or regional scale at the time of the *Barbados Programme of Action* (Kelman & West, 2009). This prompted a mandate for all SIDS to make “available information concerning those aspects of climate change, as it may affect their ability to enable appropriate response strategies to be developed and implemented" (UN, 1994, p. 10). At present, relatively few studies have focused on large scale impacts of climate change and sea level rise for small island developing states, with the few studies that do exist focusing on several islands as case studies (Dasgupta et al., 2009; Nicholls & Cazenave, 2010; UN, 2005).

2.5 Climate Change and Sea Level Rise in Caribbean SIDS

The region known as the Caribbean lies within the Caribbean Sea, and consists of more than 7,000 islands organized into 27 territories (13 sovereign states, 2 overseas departments, and 14 dependent territories) with a population of 37 million inhabitants (CIA, 2010). Geographically, the Caribbean is quite large, covering 2,754,000 km^2 in area and containing both islands and Central/ South American nations located on the Caribbean and Cocos Plates, which together represent a combined land area of 239,681 km^2 (CIA, 2010). Politically, the Caribbean is often defined in terms of geographic and socio-economic factors, and in this sense includes Bermuda located in the Atlantic Ocean off North America, the Central American nation of Belize and the South American republics of Guyana and Suriname (Simpson et al., 2009; UN, 2005; UN, 1994).

The Caribbean region is primarily composed of Small Island Developing States, with 22 nations so identified by the United Nations Department of Economic and Social Affairs (UNFCCC, 2007). The region also contains the largest concentration of SIDS within the Alliance of Small Islands States (UN, 2005). However, not all Caribbean island states are considered SIDS– several overseas territories and economically 'developed' countries including the Cayman Islands are excluded mainly due to economic factors (Kelman & West, 2009). Conversely, several mainland nations – Belize, Guyana and Suriname – within the Caribbean basin are classified as SIDS due to socio-economic and environmental similarities (Kelman & West, 2009; Simpson et al., 2010).

2.5.1 Economy of Caribbean SIDS

The Caribbean region shares the same economic circumstances as many other SIDS; by international standards they suffer from limited natural resource bases, either because resources have been depleted over time or because markets have been lost to cheaper international competitors. Historically, the Caribbean was dominated by a plantation economy, with most countries exporting sugar and/or bananas and other fruit (Singh, 2008; Pelling & Uitto, 2001). However, as discussed above, competition from cheaper mainland producers and the loss of preferential trading rights effectively crippled these export industries, especially in former British Colonies (all full member CARICOM nations except Guyana, Haiti, and Suriname). Though limited in natural resources, several countries still generate substantial income from fisheries, timber, petroleum and mineral resources. The most notable mineral-related industries (oil and bauxite) are found in Cuba, Trinidad and Tobago, Jamaica and Antigua (Sustainable Economic Development Unit [SEDU], 2002).

Currently, agriculture accounts for the largest proportion of economic land-use activity in the Caribbean (Dasgupta et al., 2007). However, in recent decades the agricultural sector has seen a steady decline in the value of products produced and exported, and now caters primarily to domestic markets (Singh, 2008; Pelling & Uitto, 2001). The largest export market for agricultural food products in the Caribbean is that of fellow CARICOM member states (Ahmed, 2001).

2.5.2 Tourism in the Caribbean

Tourism is one of the world's largest and fastest growing industries (Narayan et al., 2010). The tourism industry is extremely important in many developing nations, particularly those that have a disproportionate share of sun, sand and sea (Carey, 1991). An abundance of aesthetically pleasing landscapes in the Caribbean has made the region one of the world's most popular travel destinations, and also one of "the most tourism dependent regions of the world" (Daye et al., 2008, p. 1).

Currently, the Caribbean tourism industry represents 14.8% of the entire GDP of the region, and accounts for approximately two million jobs, which is 12.9% of all employment (World Travel and Tourism Council [WTTC], 2004). However, World Resources Institute (WRI) statistics indicate that the economic importance of the tourism industry varies greatly within the region. The countries with the greatest reliance on tourism include Antigua and Barbuda, at 72%, St. Lucia 51%, The Bahamas 46% and Barbados 37% (WRI, 2002).

Initially, most nations within the Caribbean embraced tourism with open arms, since it was perceived as a way to diversify their national economies (UN, 2005; Carey, 1991). With increasing numbers of visitors a new market emerged, creating employment for local farmers, merchants, fisheries employees and general low-skilled workers (Briguglio, 1995). However, the tourism industry effectively transformed many countries into tourism-dependent economies (Daye et al., 2008; UN, 1994; Craigwell, 2007). The large amounts of capital required to build tourism infrastructure forced many islands to allow foreign investors to establish resorts, and in some cases monopolies (Singh, 2008). Many Caribbean nations also borrowed large amounts of capital from foreign sources in order to build infrastructure (Singh, 2008; McGillivray et al., 2008). The result is that foreign investors own two-thirds of all Caribbean hotel rooms (SEDU, 2002; Gmelch, 2003). More importantly; with the majority of tourism resources owned by foreign investors, whose stake is purely financial, the longevity of the tourism industry has been called into question due to high rates of economic leakage, coupled with the fact that a majority of high paying managerial jobs are reserved for expatriates who have a limited understanding of the host nations (SEDU, 2002; UN, 1994).

2.5.3 Regional Vulnerabilities: Climate Change and Sea level Rise

Despite the fact that the nations of CARICOM contribute much less than one percent of global greenhouse gas emissions, they are expected to be among the first to be seriously affected by climate change, in the form of rising sea levels (Yohe, et al., 2007; UNWTO et al., 2008; UNFCCC, 2007; IPCC, 2007). During the 20th century, the Caribbean was noted as having higher than average increases in air temperature (Mimura, et al., 2007). According to the IPCC AR4, the Caribbean region was projected to have the second highest increases in average air temperature when compared to the sub-continental regions of the world that contain small islands. As Figure 1 shows, the Caribbean region could experience a minimum increase of 0.94°C to a maximum of 4.18 °C above the observed levels between 1961-1990 (IPCC, 2007).

Figure 1: Projected change in air temperature (°C) by region, relative to the 1961-1990 period (Mimura, et al., 2007, p. 694)

Region	2010–2039	2040–2069	2040–2069
Mediterranean	0.60 to 2.19	0.81 to 3.85	1.20 to 7.07
Caribbean	0.48 to 1.06	0.79 to 2.45	0.94 to 4.18
Indian Ocean	0.51 to 0.98	0.84 to 2.10	1.05 to 3.77
Northern Pacific	0.49 to 1.13	0.81 to 2.48	1.00 to 4.17
Southern Pacific	0.45 to 0.82	0.80 to 1.79	0.99 to 3.11

The Caribbean region has also been identified as highly susceptible to changes in precipitation due to climate change. However, these changes are subject to large uncertainties and could range from a−49.3% to +28.9% between the 30-year period 2040 to 2069 relative to observed levels between 1961 to 1990 (Mimura, et al., 2007).

Caribbean SIDS are also vulnerable to the effects of natural and environmental disasters. Of particular concern is the risk associated with increased intensity of hurricanes and subsequent storm surges (Simpson et al., 2009). As global temperatures rise, "storms of a given magnitude reach higher elevations and produce more extensive areas of inundation" (FitzGerald et al., 2008, p. 604). Because of its proximity to the equator, sea level rise and storm surge impacts will be more pronounced in the Caribbean than some other coastal areas of the world (Mimura, et al., 2007).

Finally, while the effects of rising sea levels will vary according to geography, historical tide gauge levels have shown that Caribbean sea levels have risen consistently with global averages (Mimura, et al., 2007). Given that the Caribbean contains primarily low-lying islands with extensive unconsolidated flat coastlines, they have commonly been identified as vulnerable to coastal erosion (Simpson, et al., 2009, IPCC, 2007; Burke & Maidens, 2010; Dasgupta et al., 2009). Perhaps the most widely-used method for measuring shoreline response and retreat due to sea level rise is the one based on the Bruun rule (Brunn, 1988). The main premise of the Bruun rule is that any rise in mean sea level results in a retreat of unprotected sandy coastlines and beaches characterized by barrier islands and gently sloping terrain (Brunn P. , 1962; FitzGerald et al., 2008) The Bruun rule essentially states that the horizontal shore retreat is roughly 50 - 100 times that of the vertical increase in sea level (Brunn P. , 1962; Cooper et al., 2008). Several studies have found this method especially useful for modelling coastal erosion in the Caribbean (Fish et al., 2005; Daniel & Abkowitz, 2005). Most notable was the work of Fish et al., (2005) which incorporated the method with GIS measurements in a study of the island of Bonaire in the Netherlands Antilles. The study projected that a 0.5 metre rise in sea levels would result in massive erosion to coastlines that served as traditional sea turtle nesting sites (Fish et al., 2005).

This method has not been without controversy, however – with some studies criticizing the 2-dimensional aspect of the model and the assumption that coastlines contain primarily unconsolidated, highly erodible material (Cooper & Orrin, 2004; Cooper, Beevers, & Oppenheimer, 2008). Some smaller scale studies have used Bruun rule estimates as a 'baseline' and combined the results with additional data (sediment flow data, historical erosion data) to create more accurate estimates of long shore sediment transport and changes to beach morphology (Feagin et al., 2005; Addo et al., 2011). Despite some criticisms, the Bruun rule is still considered the most useful 'baseline' method for measuring coastal erosion due to sea level rise on large scales (e.g. Caribbean) (Fish et al., 2005; Feagin et al., 2005; FitzGerald et al., 2008).

Even under highly conservative IPCC sea level rise predictions, Caribbean SIDS are expected to experience massive negative consequences. In particular, Caribbean coastal communities will be effected by both the direct and indirect consequences of climate change and rising sea levels, including coastal erosion, loss of biodiversity, damaged coastal infrastructure, increased salinity of fresh water, warmer sea-surface temperature and diminished food supplies (Simpson et al., 2009; IPCC, 2007).

2.5.4 Caribbean Tourism and Climate Change.

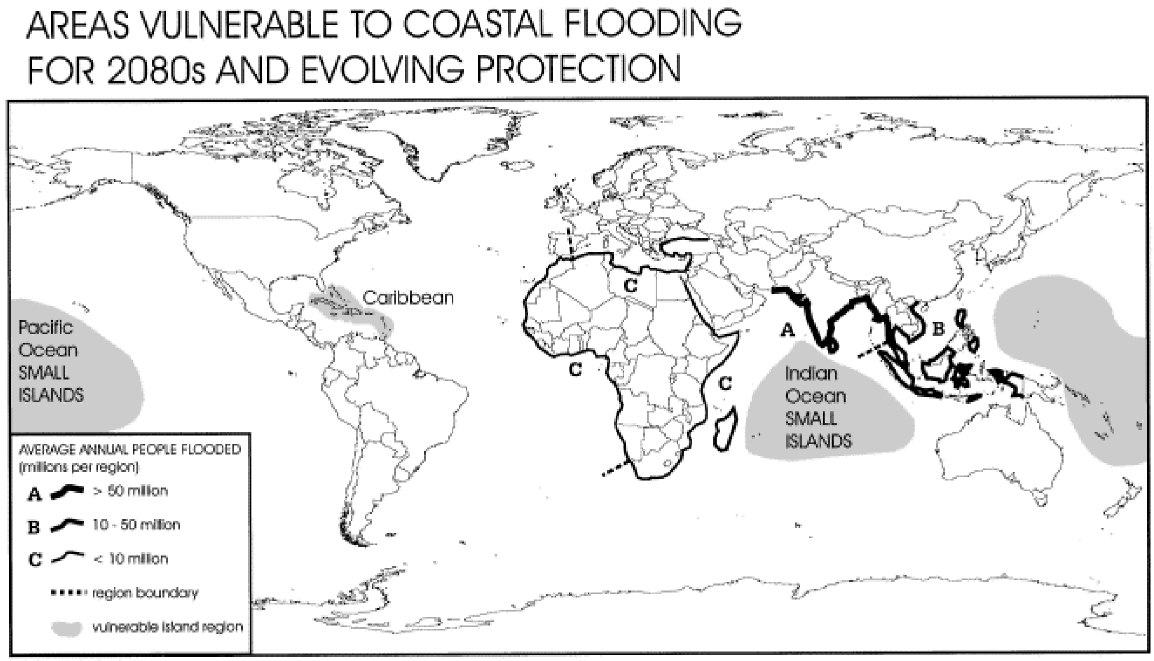
The sustained growth of the Caribbean tourism industry relies on the continued development of the focal elements and themes of the region, which centre on "sun, sand, sea and sex [which are] epitomized in the Caribbean holiday experiences" (Carey, 1991, 1). As a result, much of the Caribbean tourism industry is focused on coastal tourist resorts, which attempt to maintain undisrupted sea views and access to high-quality, pristine beach areas. But the industry's dependence on vulnerable, low-lying coastal areas places a great deal of the Caribbean region's key commercial infrastructure at risk to flooding from storm surge and beach erosion (Clayton, 2009).

Sea level rise is not the only climate-change related threat to the long-term sustainability of the tourism sector based around climate-sensitive ecosystems such as beaches and coral reefs. While the anticipated impact of climate change in the Caribbean is not expected to significantly impact the region's tourism industry over the next 15 years, the United Nations endorsed *Davos Declaration* presented at the International Tourism Ministers Summit, concluded that "climate change must be considered the greatest challenge to the sustainability of tourism in the 21st century" (UNWTO et al., 2008). Climatic factors can have a host of effects on local tourist industries. For example, they can threaten flora and fauna that attract tourists, or affect the length and quality of tourism seasons, because of tourist attitudes concerning acceptable temperature levels for a particular destination and its natural environment; this can either attract or deter visitors to a specific region (Scott & Lemieux, 2009).

2.5.5 Caribbean Impact Assessment Research

Impact assessment research on SIDS, both internationally and in the Caribbean, is necessary if island nations are to be able to prepare for the effects of climate change and sea level rise. Yet relatively few studies have been conducted to date (UN, 2005). While the technologies for modelling the risks and consequences of global sea level rise still need further development, some studies have attempted to make general projections – see for example, the work by Nicholls et al., (1999), based upon the IPCC Global Vulnerability Assessment (GVA), which projected the impact of rising sea levels in terms of coastal flooding, at-risk populations, protection costs and wetland loss. Their study utilized a set of assumptions to create a statistical model that was applied uniformly to 193 regional flooding polygons. The results indicated that the most vulnerable areas globally would be SIDS, and in particular the Caribbean islands (Figure 2). Under a 40cm flooding scenario (2080) it was estimate that 1.3 million people in the Caribbean would be at risk of flooding. Similarly it was estimated that 46% of global wetlands would be lost by a one metre rise in global sea levels.

Figure 2: Regional implications of sea level rise — the regions most affected by flood impacts given the HadCM2 (mean) scenario for the 2080s (Nicholls et al., 1999).



(a) Flood impacts

While this study marked an achievement in large scale SLR vulnerability assessment, the authors noted that "these data are at a coarse spatial resolution and several important assumptions about the characteristics of the flood plain and the occurrence of flooding are necessary to utilize it" (p. 70). The assumptions referred to were: 1) that the coastal flood plain has a constant slope, 2) that the population is distributed uniformly across the coastal zone, and 3) that if a sea defence is exceeded by a surge, the entire area behind the sea defence is flooded. Additionally, due to the variable resolution of the study, individual SIDS were not identified and the Caribbean was treated as a single regional entity.

To date, only a handful of studies have focused on the local impact of sea level rise on individual Caribbean islands. As previously mentioned, among these is the work of Fish et al.

(2005), which utilized a geographic information system (GIS) to predict the effects of SLR on sea turtle nesting habitats on Bonaire, Netherlands Antilles. The study surveyed 13 beaches identified as sea-turtle nesting sites. Using hand-held Garmin GPS units and levelling equipment, a digital elevation model (DEM) was created for each study site using the high-tide mark as a base for mean sea level (MSL). The study found that a sea level rise of 0.5 metre would result in a 32% loss of total beach area on Bonaire. However, the authors noted that "[t]he lack of available data on coastal processes and long-term beach profile changes on Bonaire (and many other countries in tropical areas) means that it is difficult to predict more precisely the likely long-term response of the island's beaches to sea level rise" (Fish et al., 2005, p. 489). Similar studies at the local level – for example the work by Daniel and Abkowitz (2005) – have also identified the lack of large scale geospatial data as a factor hampering research. Their study utilized a GIS to analysis the impacts of sea level rise on the southern peninsula of St. Kitts, using the Bruun rule. The study noted that despite providing detailed erosion modelling for the study site, additional high resolution GIS data layers were needed to "improve spatial accuracy of the system" (Daniel & Abkowitz, 2005, p. 68).

The most distinguished work to date has been that of Dasgupta et al. (2009), in their study for the World Bank entitled "The impact of sea level rise on developing countries: a comparative analysis". Unlike the work from Nichols et al. (1999), the study did not make assumptions about the distribution of population and land use. It was able to provide impact assessment estimates at both regional and local scales through the integration of high resolution (90 metre) satellite derived elevation data into a GIS. The study combined several dimensions in its analysis, including economic activity, agricultural activity, urban areas, impacted population and detailed coastline data on a national scale, and integrated these with high resolution geospatial data to generate impact scenarios were for individual countries, including some Caribbean SIDS. The most susceptible country globally in terms of total land loss was found to be The Bahamas, predicted to lose 11% of total land area with a one metre rise in sea levels, and 60% at five metres.

The most severely impacted Caribbean SIDS with a one metre rise, in terms of current population distribution/displacement, were projected to be Suriname, Guyana and The Bahamas, at 7.0%, 6.3% and 4.5% respectively. Furthermore, population displacement estimates at a three metre scenario projected that over 30% of Suriname and 25% of Guyana's total population would be displaced due to flooding. While not all Caribbean SIDS were included in the report, due to reported limitations in geospatial data, the findings have been an important tool for policy-makers (Simpson et al., 2009; Nicholls & Cazenave, 2010, Dagusta et al., 2009). The findings of this study have also served as a foundation for further SLR impact and adaptation research; "studies such as the World Bank assessment of adaptation costs in developing countries are useful starting points to address these problems." (Nicholls & Cazenave, 2010, p. 1520). However, Dasgupta et al. (2009) note that not all developing countries were included, and recommend that further studies be conducted to assess the impact of sea level rise on the population and infrastructure of additional coastal developing countries, specifically island states.

2.6 Chapter Summary

Existing research and projections suggest that the effects of climate change and rising sea levels will be particularly severe for Small Island Developing States (Cazenave & Nerem, 2004; Aboudha & Woodroffe, 2006; Dasgupta et al., 2009; Gehrels, 2010). Caribbean SIDS are projected to be among the hardest-hit, and to lose substantial land area and infrastructure under even the most conservative IPCC estimates (Dasgupta et al, 2009). The tourism-based economies of Caribbean SIDS are concentrated on vulnerable low-lying coastal areas (McGillivray et al., 2008; UNWTO et al., 2008). Several international organizations have pointed to the need to produce comprehensive impact assessments, in order to establish proper adaptation and mitigation policies (UN, 1994; UNEP, 2004). Unfortunately, a very limited amount of the required research has been performed to date. A handful of studies have attempted to utilize various techniques for the modelling of SLR, and even fewer have been able to assess countries on an individual basis, often due to the paucity of high resolution spatial data. For effective adaptation policies to be developed, additional research is required concerning the likely effects of rising sea levels on Caribbean SIDS.

The following chapter describes in detail the research approach adopted in this study, which involves building on methodology used by World Bank-funded studies to assess the impact of projected sea level rises. A variety of GIS methods will be used, along with high -resolution digital elevation data will be used for SLR impact modelling. Chapter four will then present the statistical and visual results from the SLR modelling research at varying scales. A comparison of each method and a summary of findings will be presented in chapter five, followed by recommendations for future studies and concluding statements in chapter six.

3 Methods :

This chapter describes the methodologies utilized to determine the various effects of rising sea levels on 19 CARICOM nations, using advanced geospatial modelling techniques. The objective of this research is to provide improved impact assessment data on SLR for all full member and several associate CARICOM nations. This research focuses primarily on the seven impact indicators (land area, population, economic activity, urban areas, tourism resorts, transportation infrastructure and beach erosion). This research builds on the World Bank (2009) global impact assessment study through the inclusion of updated impact indicators, and provides complete impact analysis for all full member CARICOM nations and several associate members. Also, a higher-resolution research grade elevation dataset is used to in an attempt to improve impact analysis results. A detailed comparison of the World Bank study data and the improved nation-scale datasets is undertaken in chapter five, along with a discussion of the practical implications of the study's results. The author believes that this study represents the first attempt to model the effects of SLR for all CARICOM nations using both a variety of impact indicators and high resolution digital elevation data sets. Finally, it should be noted that the datasets and methodologies presented in this thesis are not strictly confined to CARICOM nations. The datasets were largely extracted from global datasets. Similarly, tourism resort and erodible beach data (while developed for this study) can be replicated on a global scale. Given larger study scopes, the methodologies presented in the following study could be applied to SIDS on a global scale.

3.1 Study Area

This study incorporates data on all 15 Caribbean Community (CARICOM) full member nations and four associate members (Table 1). There are several reasons why these CARICOM nations were chosen as the study area for this analysis: most importantly, preliminary studies have shown that the region is one of the most vulnerable regions to the effects of climate change, especially to rising sea levels. Similarly, the region consists primarily of SIDS which have also been identified as highly susceptible to the negative impacts of climate change and SLR (UNWTO et al., 2008). At the same time, there is a critical lack of detailed analysis concerning the possible effects on the region as a whole.

Also, these CARICOM nations have also expressed strong support for the development of a comprehensive climate change strategic plan in co-operation with the United Nations Development Programme (UNDP), as well as the UK Department for International Development (DFID) (Strasdas, 2010; UNWTO et al., 2008; Simpson et al, 2010). The following study has omitted non CARICOM countries that did not partake in the UNDP and DFID partnership.

Table 1: Characteristics of CARICOM Nations.

Country Name	***Land Area (km²)***	***Population (2009)***	***GPD Millions USD (2009)***	***GPD Per Capita USD (2009)***
Anguilla*	91	14,553	$175,000,000	$12,200
Antigua & Barbuda	443	66,818	$1,522,000,000	$17,892
Barbados	430	276,768	$5,013,000,000	$18,130
Belize	22,996	276,098	$2,550,000,000	$7,718
British Virgin Is.*	151	32,633	$853,000,000	$38,500
Cayman Is.*	264	51,845	$2,250,000,000	$43,800
Dominica	751	70,113	$745,000,000	$10,176
Grenada	344	107,457	$1,103,000,000	$10,712
Guyana	214,969	760,848	$5,149,000,000	$6,687
Haiti	27,750	9,507,314	$11,976,000,000	$1,338
Jamaica	10,991	2,820,227	$23,797,000,000	$8,777
Montserrat	102	5,166	$29,000,000	$3,400
St. Kitts & Nevis	261	36,088	$726,000,000	$13,429
St. Lucia	616	163,205	$1,746,000,000	$10,177
St. Vincent & the Grenadines	389	108,768	$1,069,000,000	$9,976
Suriname	163,820	431,827	$4,510,000,000	$8,641
The Bahamas	10,100	340,420	$9,020,000,000	$26,473
Trinidad & Tobago	5,128	1,358,275	$25,922,000,000	$19,817
Turks & Caicos Is.*	948	22,512	$216,000,000	$11,500
Total	**460,544**	**16,450,935**	**$98,371,000,000**	
* Associate CARICOM Member				

Source: CIA World Factbook, IMF

3.2 Research Approach and Data Sources

This study models sea level rise scenario impacts on a wide variety of important impact indicator criteria: land area, population, economic activity, urban areas, tourism resorts, transportation infrastructure and beach erosion. The analysis was designed to be compatible with the methods used in the World Bank (2009) study of the vulnerability of selected developing countries to rising sea levels (Dasgupta et al., 2009). This will facilitate the comparison of CARICOM nations' vulnerabilities with those of other SIDS and other developing countries, using 90 metre Shuttle Radar Topography Mission (SRTM) elevation data. Including this analysis enables recreation of the SRTM DTM analysis, while ensuring all CARICOM nations are included – as the initial study only included Suriname, Guyana, The Bahamas, Belize, Jamaica and Haiti. In addition, in an effort to improve upon the World Bank study, an updated detailed analysis of the effects of rising sea levels on all 19 CARICOM nations will be carried out, using research-grade 30 metre Advanced Spaceborne Thermal Emission and Reflection Radiometre (ASTER) elevation data. As this study represents the first attempt at modelling the impacts of rising sea levels on all CARICOM nations using this high resolution satellite elevation data, detailed results on national levels from both analyses will be compared, with a discussion of similarities and differences presented in chapter five.

Table 2 details the complete list of geospatial datasets used in the impact assessment scenarios. A total of seven impact indicators were used in this study, of which five were obtained from public resources – including land area affected, population, economic activity, urban areas, and transportation infrastructure (major roads, airport runways). All of these impact indicators (except for transportation infrastructure) were identified by the World Bank study as 'critical impact indicators' (Dasgupta et al, 2009, p. 379). Due to the importance of tourism to the regional economy, a detailed tourism infrastructure dataset for all CARICOM nations was created (refer to section 3.4.4). In addition to inundation impacts (as done by the World Bank) a series of erosion scenarios was performed using the Bruun Rule. The infrastructure erosion was performed on several customized geospatial datasets, which included *major tourism infrastructure* and *unconsolidated beach areas*. The major methodological procedures are outlined below.

Table 2:Detailed List of Geospatial Data Sources.

Dimension and Description	Dataset Name	Unit	Resolution	Source(s)
Coastline and country Boundary	WVS	km²	1:250,000	NOAA/NASA
Elevation Data	ASTER GDEM SRTM GDEM	m² m²	30m 90m	NASA/METI NASA
Population Data (2010 Projections)	glp10ag	Population Counts (millions)	5km	CIESIN
Economic Activity (GDP Impact by Country)	GDP2000	Million US Dollars/ km²	5km	World Bank, based on Sachs et al. (2001)
Urban extent	Global Rural-Urban Mapping Project – GRUMP-3	km²	1km	CIESIN
Lakes, and Water Bodies	GHHS	km²	1:250,000	Global Self-consistent, Hierarchical, High-resolution Shoreline Database (Version 2)
Global Airports	DIAFF (Digital Aeronautical Flight Information File)	Count	n/a	NIMA (National Imagery and Mapping Agency)
Global Airport Runways (Amount of flooded runways)	DIAFF	km²	1:250,000	NIMA (National Imagery and Mapping Agency)
Roads (Percentage of road segments flooded)	VMap Worldwide Vector Data (v5)	km (length)	1:250,000	LandInfo Worldwide Mapping

Dimension and Description	Dataset Name	Unit	Resolution	Source(s)
Major Tourism Resorts (All major coastal resorts) *	UW SLR Data	Count	n/a	University of Waterloo
Aerial Imagery (Used for maps and tourism resort purposes)	UW SLR Data	n/a	Varying Scales	Google Earth Pro©
Surface Geology of the Caribbean Region	Geo6bg	km^2	1:250,000	USGS (United States Geological Survey)
Erodible Beaches*	UW SLR Data	km^2	1:250,000	University of Waterloo

* Data sources created in ArcGIS using geospatial data provided from Google Earth Pro© and online national/municipal sources. For more information refer to Appendix 1.

3.3 Satellite Derived Impact Scenario Data

In 2004, a study was conducted by the United States Geological Survey (USGS) involving the evaluation of Shuttle Radar Topography Mission (SRTM) and Advanced Spaceborne Thermal Emission and Reflection Radiometre (ASTER) digital elevation models (DEMs) in the Caribbean (USGS, 2004). The goal of the study was to validate high resolution DEMs for use in the Caribbean. The study performed a spatial validation of both datasets on the island of Grenada, using GPS control points and spatial analysis models. The results indicated that the SRTM database performed best overall, with a root mean square error (RMSE) of +-5.38 (USGS, 2004, p. 10). The study also argued that despite the SRTM data's higher RMSE, both methods were appropriate for terrain and storm surge modelling. However, the results indicated that ASTER Global Digital Elevation Model (GDEM) data did contain a significant proportion of anomalies due to cloud cover, which did not appear in the SRTM data. (USGS, 2004). Unfortunately, the study did not include detailed storm surge or SLR modelling results.

Despite the improved spatial resolution available in the ASTER GDEM compared to SRTM DEM data, the unknown locations of cloud interference represent a reason for caution regarding the use of ASTER GDEM on its own. Therefore, both methods are included in this study, in an effort to ensure the validity of the ASTER GDEM data for use on the Caribbean as a whole. Comparisons for each country are presented, with an emphasis on identifying countries with large numbers of anomalies, in chapter five.

The first satellite elevation dataset acquired was the coastal digital terrain model derived using tiles from the current (version four) CIAT SRTM 90 metre grid cell digital elevation model (DEM). A continuous sink filled digital terrain model DTM was established by creating a mosaic of all required tiles in ArcGIS. The resolution of the second terrain model was upgraded from 90 metre to 30 metre grid cells. As previously mentioned, in an effort to improve on the spatial resolution of the DEM utilised in previous studies, a research-grade ASTER GDEM dataset was used. METI and NASA consider version 1 of the ASTER GDEM as 'experimental' or 'research grade' due to the lack of extensive void-filling algorithms (METI et al., 2009). Fortunately, ongoing studies are currently being conducted throughout the academic community on the continued validation of the ASTER GDEM (METI et al., 2009). The ASTER GDEM is publicly available from NASA and the Japanese Ministry of Economy, Trade and Industry. The GDEM covers approximately 99% of the earth's surface from 83° South to 83° North.

3.4 Study Area and Country Boundary Preparation

A study area polygon was created for the greater Caribbean region. The study area polygon was used to clip large global datasets, in order to improve processing time and reduce data redundancy. CARICOM country boundaries were derived from the National Geospatial Intelligence Agency's World Vector Shoreline data set. All inland lakes, wetlands and ponds were masked out using geospatial data obtained from version two of the Global Self-consistent, Hierarchical, High-resolution Shoreline Database (GHHS).

3.4.1Data Inspection and Mapping Projection

Due to the small area of many CARICOM nations, careful inspection for data completeness was performed on all of the geospatial data files. The entire impact indicator datasets were collected from public sources except for those noted in Table two. Approximately 5,000 unnamed country boundary polygons (mainly small islands) were inspected and subsequently updated with corrected country identifications.

After inspection, all of the geospatial data was projected using the World Equal Area projection. The horizontal datum used for the study was the World Geodetic System 1984.

3.4.2 Creating the Coastal Digital Terrain Model (DTM)

A single Caribbean-wide coastal digital terrain model (DTM) was first created using the SRTM GDEM. A second digital terrain model was derived using tiles from the ASTER GDEM. However, due to the large nature of the ASTER GDEM, digital terrain model mosaics for the 19 CARICOM nations were split into six sub-regions (Table three).

Table 3: Group Names Used for ASTER GDEM Analysis (List of Grouped Countries).

• Bahamas_TC ○ Bahamas ○ Turks & Caicos • Belize ○ Belize • Cayman_Jam ○ Cayman Islands ○ Jamaica • Guy_Sur ○ Guyana ○ Suriname • Haiti ○ Haiti	• East_Islands ○ Angullia ○ Antigua & Barbuda ○ Barbados ○ British Virgin Islands ○ Dominica ○ Grenada ○ Montserrat ○ St. Kitts & Nevis ○ St. Lucia ○ St. Vincent & The Grenadines ○ Trinidad & Tobago

Once mosaics were created the data was explored to look for anomalies and quality issues as well as to check that the mosaic process did not affect the data quality. Although it was determined that the mosaic process did not alter any of the values of the ASTER GDEM there were some quality issues, which are discussed later in section 3.6.

3.4.3 Creating SLR Flood Scenarios

The following study was designed to account for the combined effects of long term sea level rise and the short term effects of increased wave height and storm surge events. Although hurricanes in the Caribbean are an annual occurrence, the maximum effects of storm hazards (surge, high winds and wave action) must be taken into consideration in order to properly estimate the total effects of rising sea levels. Flooding scenarios were based on maximum 100 year flooding scenarios derived from the Caribbean Disaster Mitigation Project (CDMP) Atlas of Probable Storm Effects in the Caribbean Sea (CDMP, 2002). Based on CDMP projections, maximum potential storm surge flooding within CARICOM reaches an average of 4 metres (CDMP, 2002). It is determined that the maximum potential flooding scenarios within the Caribbean for a 100 year period was six metres, including two metres from long-term sea level rise and four metres from short term storm surge events. Therefore, a series of one to six metre flooding scenarios was created from the processed DTM mosaics. Within each scenario, all inland elevation pixels were manually masked out to ensure that only contiguous coastal pixels were included in the analysis. Finally, all inland lakes and small depressions not connected by oceanic rivers were masked out to increase analysis results.

3.4.4 Creating Impact Indicator Geospatial Data

Two datasets were created specifically for use in the following study. The following impact datasets (major tourist resorts, erodible beach areas) were created using a series of online resources, including Google Earth Pro©, national/municipal tourism websites and other public use databases (real-estate, chambers of commerce, environmental NGOs). Careful attention was paid to both the location and elevation of each feature, in order to ensure that as much vulnerable infrastructure as possible was included in the analysis.

A thorough analysis of each CARICOM nation resulted in a geospatial dataset consisting of 906 coastal tourism resorts. Resorts were primarily identified by utilizing local and international databases combined with proper identification in Google Earth Pro©, major inland resorts, and resorts more than ten metres above sea level, were excluded – along with several small unidentifiable villas. A 50 metre buffer was applied to each resort feature. Multiple flooding scenarios were conducted (both with and without erosion), and resorts that contained a minimum of five percent of flooded DTM pixels were considered as negatively impacted.

In order to create a more comprehensive dataset, an inventory of all vulnerable (sandy) shoreline areas was conducted for each CARICOM nation. To account for the impacts of beach erosion, only erosion resistant geology (unconsolidated material) was included; areas containing armoured shorelines (sea walls, boardwalks) were also excluded from the erosion analysis. Beaches were manually digitized, using a combination of USGS surficial geology and Google Earth Pro© data. In total, over 1,100 beach areas were identified in the analysis, amounting to over 1,000 km of CARICOM sandy coastlines.

3.4.5 Beach Erosion

The widely-used Bruun Rule was performed on all identified erodible beach areas. The Bruun Rule is based on the assumption that an existing beach profile will remain largely constant and that as sea level increases, the sediment required to maintain this profile in deeper water is derived from erosion of the shore material. The readjustment of the beach profile to an equilibrium state produces inland retreat of approximate 50 to 100 times the vertical increase in sea level (Brunn, 1962). For example; for a one metre rise in sea levels, 50 metres to 100 metres of erosion is predicted. This analysis has applied the Bruun Rule very conservatively, by adopting the low end of the predicted erosion range (50 times vertical SLR), and by only calculating erosion exposure for unconsolidated beach areas that were visually identified in Google Earth Pro© satellite imagery and digitized by the research team. The beach erosion data were applied solely to ASTER GDEM data, as the SRTM GDEM 90 metre pixels was found to generalize large areas of both coastal and inland sections within the same pixel.

3.4.6 Calculating Impact Assessment Estimates

Impact estimates for the study were calculated by overlaying the DTM over the applicable surface datasets. Four GIS models were built to calculate the total affected values for each surface dataset. For the purpose of this study, an assumption was made that raster cell values contained an evenly distributed relation.

a) Polygon area (land area, city areas, airport runways)

Polygon features (within the study area) were overlaid with the DTM using The Geospatial Modelling Environment (GME), formerly known as Hawth's tools for ArcGIS. Using the results from the GME tool analysis, affected cells counts are converted into square kilometers to reveal the total area affected by sea level rise for each polygon. The total affected extent of land and urban areas is then summarized by country using ArcGIS. Land area and urban extent are considered 'affected' if they are projected to be either flooded or subject to storm surge within the defined parameters. Airport runways were identified as prone to SLR when a minimum of 5% of runway space was contained by flooded DTM pixels. The total number of airports affected within each country is presented as a percentage of the total.

b) Polygon percentage (Economic Activity, Population)

A separate GIS model was created for gridded data with non-spatial pixel values (millions of dollars and people). Raster cells were converted to polygon features and rounded to the closet value. An overlay and GME analysis were used to determine the amount of impacted DTM cells within each polygon. Population and economic estimates were then calculated using the following formula:

$$P / T * 100$$

P = The amount of affected cells in a polygon for a given flood scenario.
T = The total amount of cells within the polygon.

c) Lines (Road network)

A GIS model was created which identified road segments affected by flooded DTM cells. The length of each road segment was then calculated and summarized by country for each scenario in ArcGIS.

d) Points (Major Tourism Resorts)

A fifty metre buffer was applied to all surface point features. Point features that intersected with at least one flooded DTM cell were identified as vulnerable. As previously mentioned, resorts were considered to be impacted to SLR when a minimum of 5% of the resort area contained flooded pixels.

3.4.7 Adjusting Impact Assessment Estimates

In some instances, countries had accurate data pertaining to land area, economic activity (GDP) and population. The methods used in this study to adjust estimated values to known country totals was initially used by Dasgupta et al. (2009) using the following formula:

$$V_{adj} = CT_{mea} / CT_{cal} * V_{cal}$$

Where
V_{adj} = Exposed value adjusted;

Vcal = Exposed value calculated from vulnerability estimates;
CTmea = Country total obtained based on statistics;
CTcal = Country total calculated from surface datasets.

3.4.8 Data quality assessment

Due to the varying scales of the gridded data, the methods employed were designed to eliminate errors associated with different resolutions. However, the following methods were used to ensure data quality and error reduction:

a) The analysis results for **SRTM DTM** scenarios were compared to results presented by Dasgupta et al. (2009). If the results for overlapping countries (Suriname, Guyana, The Bahamas, Belize, Jamaica and Haiti) fluctuated more than 10% for a similar scenario, the GIS models were reviewed. After careful analysis, it was shown that all comparable countries were well within the 10% consistency threshold.

b) **ASTER** – A thorough analysis of each countries coastal area was performed by categorizing the ASTER data into elevation intervals of one metre. With an emphasis on the coastal areas, data that appeared to be produced from cloud interference (or general anomalies) were noted in the analysis.

3.5 Visual Aids

As a part of the study a series of maps was created, in order to facilitate visual understanding of the consequences of sea level rise in five possible scenarios, at one metre intervals. Each scenario highlighted the relative effects for each study site, focusing on the percentage of beach loss and impact to infrastructure. So that results can be shared with as wide an audience as possible, all GIS data will be compatible with several software applications, including Google Earth®. A series of comparison maps were also created where applicable.

3.6 Limitations

After preliminary inspection of the two DTMs, several limitations were observed among both datasets. As previously discussed, the SRTM DTM data contained a noticeable amount of data gaps, particularly along coastal regions. This limited the usefulness of the DTM, and did not allow beach erosion and coastal storm surge modelling. Secondly, the data was collected in 2000 and therefore does not take into account changes in terrain surfaces, such as urban expansion, the effects of floods and coastal erosion.

Despite the usefulness of the ASTER GDEM for coastal environments, the predicted inconsistencies in the data were found to be an issue. This was particularly the case with respect to Guyana and Suriname, where modelling results were significantly hindered by cloud interference. Additional random gaps were found in the data from the interior of some countries, adding to the uncertainty of the dataset as a whole. However, it is worth noting once more that the data is still research grade, and is currently undergoing void-filling and smoothing techniques at various academic institutions (Nikolakopoulous et al., 2006).

Due to these differences in scale and sporadic data anomalies the exclusive use of one satellite derived digital elevation model does not provide a best representation of the topological features. Due to data restrictions, results for both methods are provided in chapter four, with the exception of erosion scenario data, which is based exclusively on ASTER GDEM.

It is worth mentioning that some datasets contained relatively large amounts of precision variability, notably in the population and economic activity data. It should be noted that the following datasets are highly dynamic in nature and are also limited in the assumptions about precise (greater than 5km²) distribution of the respective data values. These datasets therefore contained a relatively lower confidence ranges (1km²). Due to the high variability of these datasets both in spatial and temporal scales, values were rounded to the nearest million (total population and US dollar value). The analysis would benefit from greater detailed (annual) national level geospatial datasets (at higher resolutions). This would provide better country level assessments for both population and economic vulnerabilities as it relates to SLR.

Finally, it is worth noting the temporal scale assumed within the various flooding scenarios. As mentioned in section 3.4.3 flooding scenarios were calculated between one and two metres (long term SLR impacts) and three to six metres (short term SS impacts). While all impact indicators were run for all flooding scenarios, it can be assumed that damaging impacts to certain indicators (e.g. tourism resorts, airports, roads) would be temporary and depend on the length of SS cover and severity of associated erosion.

3.7 Chapter Summary

Two geospatial methods for creating SLR flooding scenarios were conducted on islands in the Caribbean. First, an updated World Bank study using 90 metre SRTM data was conducted for all CARICOM nations. Second, this methodology was updated using more vulnerability indicators and 30 metre ASTER GDEM data. The next chapter will present the results from each method, focusing on particularly vulnerable countries within each impact scenario.

4 Results

4.1 Introduction

The results from the two SLR modelling techniques are outlined in the following two sections. The first section presents the results from the updated SRTM derived SLR modelling scenarios. The second section presents the results from ASTER based SLR modelling scenarios, with the inclusion of additional erosion scenarios.

4.3 SRTM Based DEM

The following section presents the results across the Caribbean for 19 CARICOM nations over six sea level rise scenarios, applied to seven impact indicators.

4.3.1 Land Area

In total, the CARICOM study nations cover a total of 460,544 km². Under a one metre sea level rise scenario, 1,376 km² where found to be flooded, representing only <1% of the entire study area (Table 4). Surprisingly, under a six metre flooding scenario the total area of land loss due to SLR was found to be only 3% (Table 4). These numbers are low because the study includes the relatively large countries of Guyana, Suriname and Belize, which account for over 87% of total land area in the CARICOM nations.

Despite the relatively low proportion of land area lost across the region as a whole, when the different scenarios were represented on individual nations, the projected losses for many countries were much more dramatic. For example: given a one metre sea level rise, The Bahamas was projected to lose 10% of its total land area, or 998 km²) (Table 4). Projected effects increased at a non-linear rate – with a projected 68% land loss at five metres, and over 80% at six metres. For other countries under the same scenario, including the Turks and Caicos Islands, Cayman Islands, and the British Virgin Islands, were estimated to experience losses of 70% , 48%, and 23% respectively (Table 4). All of these countries are made up of relatively low-lying islands located in the north-eastern region of the Caribbean basin.

The countries with smaller impact levels – between <1% and 3% – were found located either on mountainous volcanic islands, such as Montserrat, and St. Vincent and the Grenadines, or on islands with relatively larger land area, including Haiti, Guyana, and Suriname (Table 4).

Table 4: Land Areas Impacted (SRTM Flooding Analysis).

Country Name	**Total Area (km^2)**	**Percent Flooded 1m SLR**	**Percent Flooded 2m SLR**	**Percent Flooded 3m SLR**	**Percent Flooded 4m SLR**	**Percent Flooded 5m SLR**	**Percent Flooded 6m SLR**
Anguilla	91	1%	1%	2%	3%	4%	6%
Antigua & Barbuda	443	1%	2%	4%	7%	11%	16%
Barbados	430	0%	0%	0%	0%	0%	0%
Belize	22996	1%	3%	4%	5%	7%	8%
British Virgin Is.	151	5%	9%	13%	18%	21%	23%
Cayman Is.	264	1%	1%	5%	13%	27%	48%
Dominica	751	0%	0%	0%	0%	0%	0%
Grenada	344	0%	0%	0%	0%	0%	0%
Guyana	214969	0%	1%	1%	2%	2%	3%
Haiti	27750	0%	0%	0%	1%	1%	2%
Jamaica	10991	1%	1%	2%	3%	4%	5%
Montserrat	102	0%	0%	0%	0%	0%	0%
St. Kitts & Nevis	261	0%	0%	1%	1%	1%	2%
St. Lucia	616	0%	0%	0%	0%	0%	1%
St. Vincent & the Grenadines	389	0%	0%	0%	0%	0%	0%
Suriname	163820	0%	1%	1%	2%	3%	3%
The Bahamas	10100	10%	17%	30%	50%	68%	81%
Trinidad & Tobago	5128	0%	1%	1%	2%	3%	4%
Turks & Caicos Is.	948	4%	8%	22%	43%	59%	70%
Total	**460,544**	**1%**	**1%**	**2%**	**3%**	**4%**	**5%**

4.3.2 Population

In contrast to land-area losses, the most serious effects on population (in proportional terms) were projected for both small islands and larger mainland nations. Together, the 19 CARICOM nations have a population of 16,474,149, of whom 114,509, or 1%, were projected to be affected by a one metre sea level rise (Table 5). This proportion increased to 1,238,232 (8%) with a six metre flooding scenario, the countries projected to be most severely-affected were Suriname (64%), the Turks and Caicos Islands (52%), the Cayman Islands (49%) and The Bahamas (42%). Countries with lowest levels of projected population impact were generally found to be highly mountainous islands, with the exception of Barbados, which was estimated to experience a population disruption between <1% at a one metre scenario and 1% at six metres (Table 5). However, it should be noted that in the case of Barbados, it was found that the 90 metre (SRTM) coastal elevations contained data gaps along the eastern portion of the island, which encompasses the greatest density of population.

Finally, the populations of countries such as Jamaica and Haiti were projected to be relatively unaffected with 5% and 3% displaced by flooding at a six metre scenario (Table 5). But in terms of absolute numbers of individuals, these countries tended to be among the most severely affected, due to their larger populations with a combined total of 12,346,050 (Jamaica at 2,820,149 and Haiti at 9,525,901).

Table 5: Estimates for Impacted Populations from SRTM Flooding Analysis.

Country Name	Total Population (2008)	Percent Affected 1m SLR	Percent Affected 2m SLR	Percent Affected 3m SLR	Percent Affected 4m SLR	Percent Affected 5m SLR	Percent Affected 6m SLR
Anguilla	14,553	2%	4%	7%	11%	16%	21%
Antigua & Barbuda	86,754	1%	3%	4%	6%	8%	10%
Barbados	276,768	0%	0%	0%	0%	0%	1%

Country Name	Total Population (2008)	Percent Affected 1m SLR	Percent Affected 2m SLR	Percent Affected 3m SLR	Percent Affected 4m SLR	Percent Affected 5m SLR	Percent Affected 6m SLR
Belize	276,098	3%	6%	9%	11%	13%	15%
British Virgin Is.	32,633	1%	2%	3%	4%	5%	7%
Cayman Is.	51,845	1%	1%	4%	12%	27%	49%
Dominica	70,113	0%	0%	0%	0%	1%	1%
Grenada	107,457	0%	0%	0%	0%	1%	1%
Guyana	760,848	3%	8%	17%	26%	30%	32%
Haiti	9,507,314	0%	0%	1%	1%	2%	3%
Jamaica	2,820,227	1%	1%	2%	3%	4%	5%
Montserrat	5,166	0%	0%	1%	1%	1%	1%
St. Kitts & Nevis	36,088	0%	0%	1%	2%	3%	4%
St. Lucia	163,205	0%	0%	0%	0%	1%	2%
St. Vincent & the Grenadines	108,768	0%	0%	0%	1%	1%	2%
Suriname	431,827	8%	17%	31%	46%	58%	65%
The Bahamas	340,420	4%	8%	12%	18%	29%	42%
Trinidad & Tobago	1,358,275	0%	1%	1%	2%	4%	5%
Turks & Caicos Is.	36,605	2%	5%	10%	17%	24%	32%
Total	**16,484,964**	**<1%**	**>1%**	**3%**	**4%**	**6%**	**8%**

4.3.3 Economic Activity

Economic damage projections were calculated using economic activity data and methods established by the World Bank. Based on 2008 national estimates, the combined GDP of the 19 CARICOM nations was $104,000,000,000 (USD), with an average per-capita GDP of $13,446 (USD)

(Table 6). The spatial location of economic activity is represented in the gridded GPD dataset utilized in the 2009 World Bank study. This dataset allowed the GIS to determine where coastal economic activity would be dislocated by SLR. Collectively, the study site nations were projected to experience directed dislocation of >1% at a one metre scenario to 17% at six metres

(Table 6). At one metre, the hardest-hit countries were found to be Suriname, the Turks and Caicos Islands and The Bahamas, with losses at 6%, 5% and 5% respectively (Table 6). The countries facing the greatest proportional economic losses given a six metre scenario remained largely the same, with the exception of the Cayman Islands and Guyana, which jumped from 1% and 3% losses with a one metre rise to 57% and 32% at six metres (Table 6). It should be noted that economic loss estimates do not take into account the complexities of all aspects of countries' economies, and that more work therefore needs to be done to better-understand the full effects. For example, the economy of the Cayman Islands is highly diversified, and may be affected quite differently than those of the majority of other CARICOM nations (especially SIDS), which rely more heavily on coastal activities such as tourism and fishing.

Table 6: Estimates for Coastal Economic Impacts (SRTM Flooding Scenarios)

Country Name	***2008 Estimate ($USD)***	**Percent Economy Impacted at 1m SLR**	**Percent Economy Impacted at 2m SLR**	**Percent Economy Impacted at 3m SLR**	**Percent Economy Impacted at 4m SLR**	**Percent Economy Impacted at 5m SLR**	**Percent Economy Impacted at 6m SLR**
Anguilla	108,900,000	2%	4%	8%	13%	18%	25%
Antigua & Barbuda	1,627,000,000	1%	3%	4%	6%	9%	10%
Barbados	5,231,000,000	0%	0%	0%	0%	0%	1%
Belize	2,549,800,000	2%	5%	7%	9%	11%	13%
British Virgin Is.	8,534,700,000	0%	0%	0%	0%	0%	1%
Cayman Is.	1,939,000,000	1%	1%	5%	14%	31%	57%
Dominica	727,000,000	0%	0%	0%	0%	1%	1%
Grenada	1,181,000,000	0%	0%	0%	0%	1%	1%
Guyana	3,082,009,000	3%	8%	17%	25%	30%	32%
Haiti	11,570,000,000	0%	0%	1%	1%	2%	3%
Jamaica	24,199,000,000	1%	1%	2%	3%	4%	5%

Country Name	*2008 Estimate ($USD)*	Percent Economy Impacted at 1m SLR	Percent Economy Impacted at 2m SLR	Percent Economy Impacted at 3m SLR	Percent Economy Impacted at 4m SLR	Percent Economy Impacted at 5m SLR	Percent Economy Impacted at 6m SLR
Montserrat	29,000,000	0%	0%	0%	0%	1%	1%
St. Kitts & Nevis	732,000,000	0%	0%	1%	1%	2%	3%
St. Lucia	987,209,000	0%	0%	0%	0%	1%	2%
St. Vincent & the Grenadines	1,087,000,000	0%	0%	0%	1%	1%	2%
Suriname	4,364,000,000	6%	13%	25%	37%	47%	52%
The Bahamas	9,383,090,000	4%	8%	12%	19%	29%	42%
Trinidad & Tobago	26,536,000,000	0%	1%	1%	2%	4%	5%
Turks & Caicos Is.	216,000,000	5%	10%	20%	33%	48%	62%
Total	**104,083,708,000**	**1%**	**3%**	**5%**	**9%**	**13%**	**17%**

4.3.4 Urban Areas

The area of urban extent in the region was calculated using Global Rural-Urban Mapping (GRUMP) data provided from the Centre for International Earth Science Information Network (CIESIN). According to the CIESIN data, the 19 CARICOM countries contained 9,738 km² of classified urban areas, of which 136 km² (1.4%) would be flooded by a one metre sea level rise (Table 7). The amount of flooded urban extent with a three metres rise jumped to 630km² (7%) and was estimated to reach a maximum of 1709km² (18%) given a six metre scenario (Table 7). The countries projected to be most seriously affected were Guyana, the Cayman Islands, Suriname and The Bahamas, with between 40% and 60% of total urban extents flooded (Table 7). These findings are fairly consistent with the previous impact indicators, and reflect the fact that the urban settlement and economic activity of these countries are highly concentrated in coastal regions.

Several countries were projected to experience low levels of flooding in urban areas, even with a six metre rise in sea levels. Most notable was Barbados, which was only estimated to experience a 3 km² (1%) loss of urban extent (Table 7). However, as was previously mentioned, the SRTM data was found to be unreliable along the Barbados coastline. Other islands, including Montserrat and the Turks and Caicos Islands, were omitted from the modelling due to gaps in the CEISIN data.

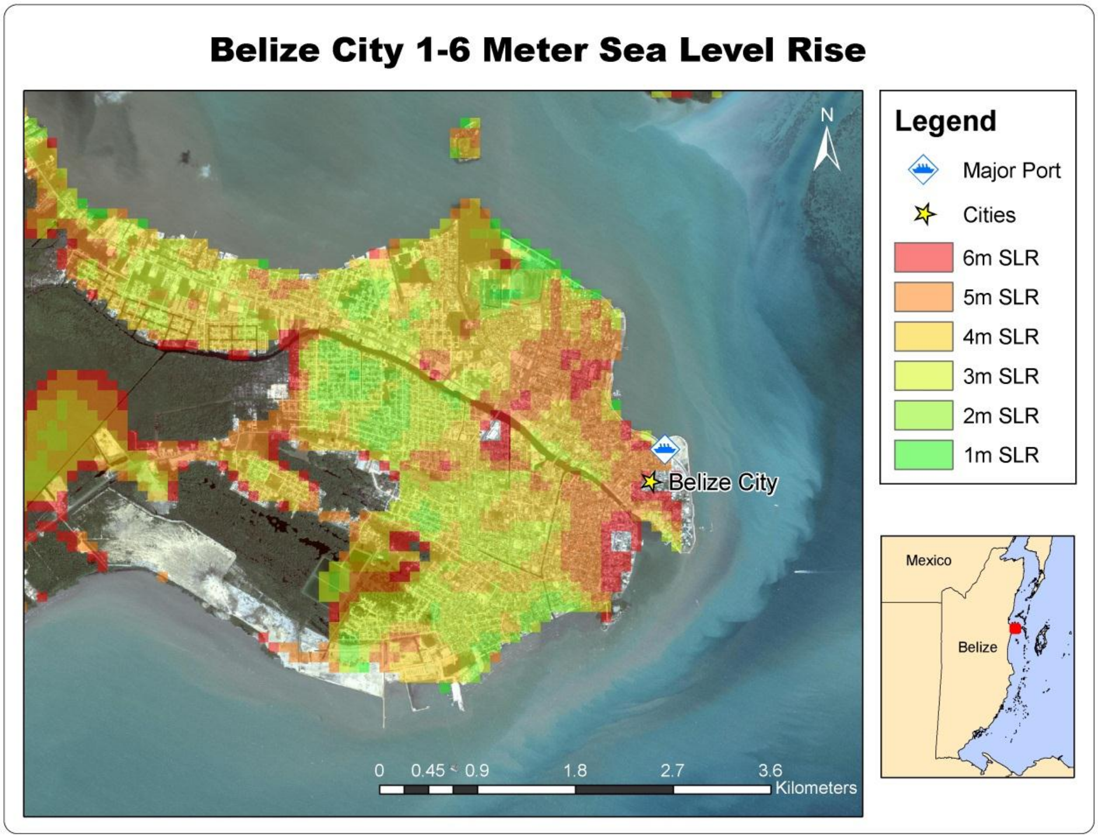
It is worth mentioning that some countries, including Belize, were estimated to lose modest amounts of urban extent (22%), but after closer inspection it was determined that that the loss of urban area in Belize was still very significant. For example, Belize City was projected to be left 95% under water by a four metre rise in sea levels (Figure 3).

Table 7: Total Amount of Urban Inundation (SRTM Flooding Analysis).

Country Name	Total (km²)	Percent Flooded at 1m SLR	Percent Flooded at 2m SLR	Percent Flooded at 3m SLR	Percent Flooded at 4m SLR	Percent Flooded at 5m SLR	Percent Flooded at 6m SLR
Anguilla	70	2%	2%	2%	5%	7%	9%
Antigua & Barbuda	273	1%	2%	5%	6%	7%	9%
Barbados	434	0%	0%	0%	0%	0%	1%
Belize	532	1%	4%	8%	12%	18%	22%
British Virgin Is.	54	0%	0%	0%	0%	0%	0%
Cayman Is.	188	0%	0%	3%	9%	21%	45%
Dominica	191	0%	0%	0%	0%	0%	0%
Grenada	161	0%	0%	0%	0%	1%	1%
Guyana	620	8%	21%	38%	48%	56%	61%
Haiti	468	0%	1%	1%	2%	5%	7%

Country Name	Total (km²)	Percent Flooded at 1m SLR	Percent Flooded at 2m SLR	Percent Flooded at 3m SLR	Percent Flooded at 4m SLR	Percent Flooded at 5m SLR	Percent Flooded at 6m SLR
Jamaica	2637	0%	1%	2%	3%	4%	5%
Montserrat	0	0%	0%	0%	0%	0%	0%
St. Kitts & Nevis	238	0%	0%	0%	0%	0%	0%
St. Lucia	359	0%	0%	0%	0%	0%	1%
St. Vincent & the Grenadines	132	0%	0%	1%	1%	1%	1%
Suriname	607	4%	9%	18%	32%	46%	56%
The Bahamas	503	3%	7%	13%	23%	33%	44%
Trinidad & Tobago	2271	0%	1%	1%	2%	3%	5%
Turks & Caicos Is.	0	0%	0%	0%	0%	0%	0%
Total	**9738**	**1%**	**3%**	**6%**	**10%**	**14%**	**18%**

Figure 3: Sea Level Rise Flooding for Belize City.



Note the extreme effects impacts under even modest (one to three metre) flooding scenarios.

4.3.5 Tourism Resorts

Large stretches of Caribbean coastline are highly susceptible to erosion, and beaches have experienced accelerated erosion in recent decades. Higher sea levels will amplify coastal erosion in these areas due to increased wave attack and storm surges. As a result, a great deal of tourism resort infrastructure is highly vulnerable to beach erosion. This poses a significant problem in the Caribbean, due to the region's heavy reliance on the tourism industry. Of the 906 tourist resorts examined in this analysis, 68 (8%) were identified as being vulnerable to a one metre rise (Table 8). Given a three metre rise, the projected number of affected resorts increases to 236 (26%), reaching 597 (66%) at six metres (Table 8).

In total, 11 countries would experience serious flooding of tourism infrastructure given a one metre rise. Of particular concern are heavily tourism-dependent countries such as Antigua and Barbuda and The Bahamas, where the estimated numbers of affected resorts were 16 (17%) and 15 (11 %) respectively (Table 8). Given a six metre scenario, the results were quite dramatic – with 97 resorts (98%) in Antigua and Barbuda and 83 (62%) resorts in The Bahamas affected (Table 8). In total, 18 out of 19 CARICOM countries were projected to experience significant resort flooding given a six metre rise in sea levels, with Montserrat being the only exception, mainly due to a lack of mass tourism infrastructure.

Table 8: Coastal Tourism Resorts Impacted from Flooding (SRTM analysis).

Country Name	**Number of Resorts**	**Percent Flooded with 1m SLR**	**Percent Flooded with 2m SLR**	**Percent Flooded with 3m SLR**	**Percent Flooded with 4m SLR**	**Percent Flooded with 5m SLR**	**Percent Flooded with 6m SLR**
Anguilla	60	8%	18%	33%	45%	63%	80%
Antigua & Barbuda	99	16%	29%	62%	95%	98%	98%
Barbados	75	3%	4%	5%	11%	29%	36%

Country Name	Number of Resorts	Percent Flooded with 1m SLR	Percent Flooded with 2m SLR	Percent Flooded with 3m SLR	Percent Flooded with 4m SLR	Percent Flooded with 5m SLR	Percent Flooded with 6m SLR
Belize	44	5%	23%	45%	57%	75%	77%
British Virgin Is.	14	0%	0%	21%	21%	29%	43%
Cayman Is.	63	0%	2%	8%	29%	38%	63%
Dominica	17	0%	0%	0%	0%	24%	35%
Grenada	45	4%	2%	2%	4%	11%	24%
Guyana	10	0%	10%	30%	70%	80%	80%
Haiti	28	4%	4%	7%	11%	18%	39%
Jamaica	105	10%	15%	21%	36%	55%	69%
Montserrat	1	0%	0%	0%	0%	0%	0%
St. Kitts & Nevis	22	0%	9%	23%	32%	55%	68%
St. Lucia	30	0%	3%	7%	17%	40%	70%
St. Vincent & the Grenadines	21	0%	0%	0%	10%	19%	29%
Suriname	19	32%	58%	68%	89%	95%	100%
The Bahamas	133	11%	20%	25%	35%	48%	62%
Trinidad & Tobago	24	8%	17%	29%	46%	75%	75%
Turks & Caicos Is.	96	6%	18%	36%	53%	68%	78%
Total	**906**	**8%**	**15%**	**26%**	**40%**	**54%**	**66%**

4.3.6 Transportation Infrastructure

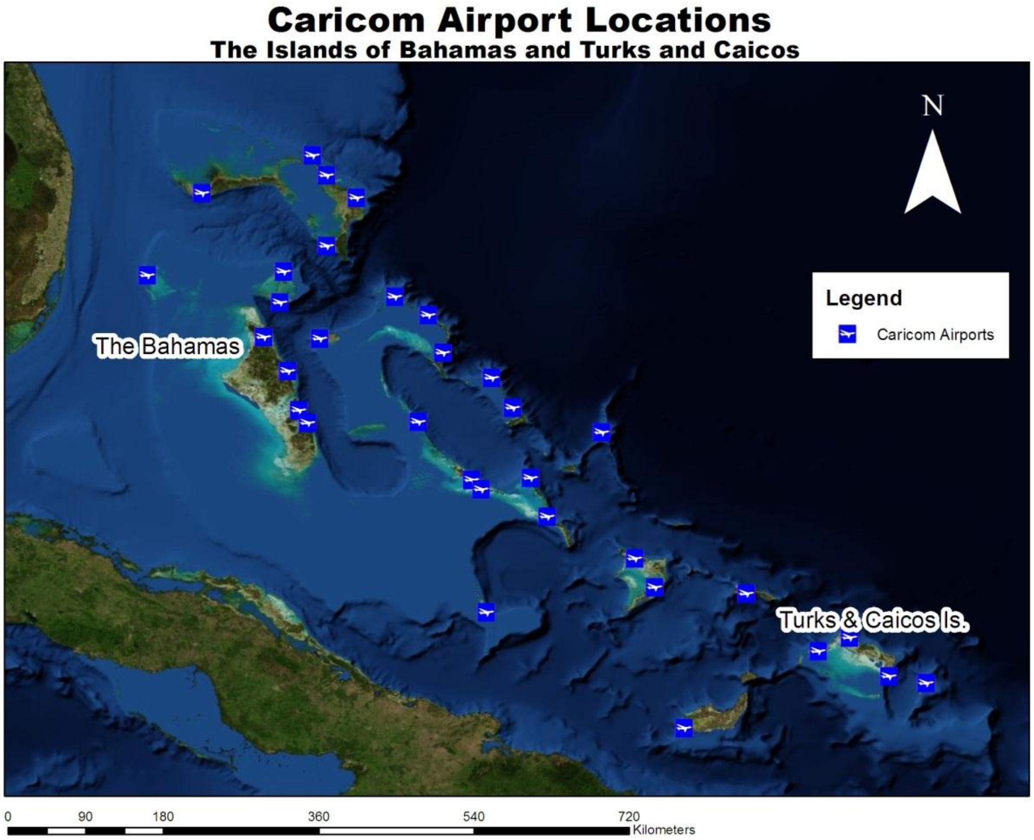
The Caribbean region possesses limited transportation resources, primarily because of the small size and isolation of many of the nations. The overwhelming majority of international travellers to Caribbean islands arrive via air, and airports require large tracts of relatively flat land, which can be in short supply on many Caribbean islands. As a result, many Caribbean airports tend to be located close to coastal areas, making them vulnerable to rising sea levels. The vulnerability of 73 runways was analysed at 67 CARICOM airports (Table 9). Under a one metre scenario seven runways were estimated to experience flooding, in The Bahamas (four), the British Virgin Islands (two) and Jamaica (one) (Table 9). Given a four metre rise, 36 runways

(50%) were estimated to experience flooding – with the majority (22) occurring in The Bahamas (Table 9). At a six metre flooding scenario, 14 CARICOM nations were projected to experience flooding to 54 runways (66%) (Table 9). The Bahamas was again set to experience the greatest impact – 29 runways, accounting for over 90% of national capacity (Figure 4).

Table 9: Airport Runway Flooding Impacts (SRTM Analysis).

Country Name	Runway Total	Percent Flooded at 1m SLR	Percent Flooded at 2m SLR	Percent Flooded at 3m SLR	Percent Flooded at 4m SLR	Percent Flooded at 5m SLR	Percent Flooded at 6m SLR
Anguilla	1	0%	0%	0%	0%	0%	0%
Antigua & Barbuda	1	0%	0%	100%	100%	100%	100%
Barbados	1	0%	0%	0%	0%	0%	0%
Belize	1	0%	0%	100%	100%	100%	100%
British Virgin Is.	2	100%	100%	100%	100%	100%	100%
Cayman Is.	2	0%	0%	50%	100%	100%	100%
Dominica	2	0%	0%	0%	50%	50%	100%
Grenada	1	0%	0%	0%	0%	0%	100%
Guyana	5	0%	0%	0%	0%	0%	0%
Haiti	2	0%	0%	0%	0%	50%	50%
Jamaica	5	20%	20%	40%	40%	40%	80%
Montserrat	1	0%	0%	0%	0%	0%	0%
St. Kitts & Nevis	2	0%	0%	0%	0%	0%	0%
St. Lucia	2	0%	0%	0%	0%	50%	100%
St. Vincent & the Grenadines	4	0%	0%	0%	50%	50%	50%
Suriname	2	0%	50%	50%	50%	50%	50%
The Bahamas	32	13%	25%	38%	69%	81%	91%
Trinidad & Tobago	2	0%	0%	0%	0%	50%	50%
Turks & Caicos Is.	4	0%	25%	25%	50%	100%	100%
Total	**72**	**10%**	**18%**	**29%**	**50%**	**63%**	**74%**

Figure 4: Locations of Airports in The Bahamas and The Turks and Caicos Islands.



Land transportation in the Caribbean consists primarily of national funded highway networks (Morrison and Faye, 2007). While railways historically played an important role in many Caribbean nations, their rail systems have degraded considerably, due to high costs of maintenance, small populations and the decline of export economies. Currently, the 19 CARICOM study nations are serviced by 12,111 km of major (national) highways (CIA,2010). Given a one metre flooding scenario, 185 km (2%) of highways were projected to experience flooding, with Guyana (68 km), Suriname (55 km) and The Bahamas (33 km) accounting for most of the losses (Table 10). The estimated losses to flooding increased to 738 km (6 %) with a three metre rise, with Guyana (255 km), Suriname (213 km) and The Bahamas (168 km) again the three hardest hit nations (Table 10). In total, 1738 km (14%) of major highways were projected to be flooded given a six metre rise in sea levels. Under this scenario, the hardest-hit countries by percentage of highway mileage were the Cayman Islands at 50% (35 km), The Bahamas at 43% (656 km), and the Turks and Caicos Islands at 36% (9 km) (Table 10). The countries facing the largest estimated net impacts were The Bahamas (657 km), Guyana (374 km) and Suriname (360 km) (Table 10). It can be assumed that these impact assessments are highly conservative, as transportation infrastructure is expected to continue to increase in step with the regions' rapidly growing population.

Table 10: Major Road Infrastructure Impacted from Flooding (SRTM Analysis).

Country Name	Total Road Length (km)	Percent Roads Flooded 1m SLR	Percent Roads Flooded 2m SLR	Percent Roads Flooded 3m SLR	Percent Roads Flooded 4m SLR	Percent Roads Flooded 5m SLR	Percent Roads Flooded 6m SLR
Anguilla	22	3%	3%	5%	5%	6%	6%
Antigua & Barbuda	82	1%	1%	1%	3%	6%	8%
Barbados	121	0%	0%	0%	0%	0%	0%
Belize	815	0%	1%	3%	5%	7%	10%
British Virgin Is.	42	0%	1%	1%	1%	1%	1%
Cayman Is.	73	0%	0%	3%	9%	27%	49%
Dominica	115	0%	0%	0%	1%	1%	2%
Grenada	102	0%	0%	0%	0%	1%	1%
Guyana	1,063	6%	15%	24%	30%	33%	35%
Haiti	3,613	0%	0%	1%	1%	1%	2%
Jamaica	2,004	1%	1%	2%	4%	5%	6%
Montserrat	41	0%	0%	0%	0%	0%	0%
St. Kitts & Nevis	71	0%	0%	0%	0%	0%	0%
St. Lucia	98	0%	0%	0%	1%	1%	5%
St. Vincent & the Grenadines	86	0%	0%	0%	0%	0%	0%
Suriname	1,526	4%	9%	14%	18%	21%	24%
The Bahamas	1,544	2%	5%	11%	19%	30%	43%
Trinidad & Tobago	673	0%	0%	1%	2%	3%	4%
Turks & Caicos Is.	24	8%	8%	11%	17%	24%	36%
Total	**12,112**	**2%**	**3%**	**6%**	**9%**	**12%**	**14%**

* Note, major road infrastructure was restricted to national highways only.

4.4 ASTER Based GDEM

The following section presents the SLR (one to six metres) results at the Caribbean level for 19 CARICOM nations over seven impact indicators.

4.4.1 Land Area

The ASTER GDEM analysis projected that given a one metre flooding scenario only 1,378 km² out of 460,544 km² of land area was vulnerable to SLR. The hardest hit countries in terms of total area under this scenario were The Bahamas at 465 km (5%), Guyana at 304km² (<1%), and Suriname at 161 km² (<1%) (Table 11). The highest proportional losses at one metre were found to be on the Turks and Caicos Islands with a 7% loss, and the British Virgin Islands with a 6% loss. With a three metre sea level rise, a total of 5,625 km² was projected to be flooded, representing 1% of the study area (Table 11). On the national level, the most affected nations by percentage were as follows; the Turks and Caicos at 24% (224 km²), the British Virgin Islands at 16% (24 km²) and The Bahamas with an estimated loss of 16% (1574 km²). Conversely, the hardest hit countries in terms of total land loss tended to be continental, with the exception of The Bahamas. Finally, under a six metre flooding scenario, an estimated 13,485 km² (3%) loss was projected, with the hardest hit countries by total land area being The Bahamas with 3323 km² (33%), Guyana with 2834 km² (1%) and Belize with 2572 km² (11%) total loss (Table 11). The nations with the highest percentage loss were all islands, with the Turks and Caicos, The Bahamas and the British Virgin Islands estimated to lose 46%, 33% and 28% of their territory respectively (Table 11).

Table 11: Land Areas Impacted (ASTER Flooding Analysis).

Country Name	Total Area (km^2)	Percent Flooded 1m SLR	Percent Flooded 2m SLR	Percent Flooded 3m SLR	Percent Flooded 4m SLR	Percent Flooded 5m SLR	Percent Flooded 6m SLR
Anguilla	91	6%	11%	15%	19%	23%	27%
Antigua & Barbuda	443	2%	5%	8%	11%	14%	18%
Barbados	430	1%	1%	1%	2%	2%	3%
Belize	22,996	1%	2%	4%	6%	9%	11%
British Virgin Is.	151	6%	11%	16%	21%	24%	28%
Cayman Is.	264	3%	5%	8%	10%	14%	18%
Dominica	751	0%	1%	1%	1%	1%	2%
Grenada	344	1%	2%	3%	4%	5%	6%
Guyana	214,969	0%	0%	1%	1%	1%	1%
Haiti	27,750	0%	1%	1%	2%	3%	3%
Jamaica	10,991	0%	1%	1%	1%	2%	2%
Montserrat	102	1%	1%	2%	2%	3%	4%
St. Kitts & Nevis	261	1%	2%	3%	4%	6%	7%
St. Lucia	616	1%	1%	1%	2%	2%	3%
St. Vincent & the Grenadines	389	1%	2%	3%	3%	4%	5%
Suriname	163,820	0%	0%	1%	1%	1%	1%
The Bahamas	10,100	5%	10%	16%	21%	27%	33%
Trinidad & Tobago	5,128	1%	2%	3%	5%	7%	9%
Turks & Caicos Is.	948	7%	15%	24%	32%	40%	46%
Total	**460,544**	**<1%**	**1%**	**>1%**	**2%**	**2%**	**3%**

4.4.2 Population

The population affected under a one metre flooding scenario was projected to be 116,828 or 1% of the study nations. In absolute terms, the most seriously impacted countries were found to be Haiti, The Bahamas and Trinidad and Tobago at 50,183, 15,867 and 13,477 inhabitants respectively (Table 12). Conversely, the countries with the largest proportions of their population affected at one metre were Anguilla at 8%, The Bahamas at 5% and the Turks and Caicos Islands at 4% (Table 12). Given a three metre rise, the effect on populations is projected to rise significantly: with 463,526 people (3%) affected. Under this scenario, the countries facing the largest absolute impact were Haiti, The Bahamas and Trinidad and Tobago with 220,053, 53,873, and 51,667 people respectively (Table 12). The countries with the highest proportion of affected populations at three metres were again projected to be Anguilla (24%), The Bahamas (16%) and the Turks and Caicos Islands (13%). Finally, given a six metre rise, the ASTER GDEM analysis projected that 1,098,225 people, representing 15% of the current study area population, would be affected (Table 12). Haiti was estimated to be the hardest hit country in absolute terms, with 485,580. The hardest hit country proportionally was projected to be The Bahamas, with an estimated displacement of 36% of the national population (Table 12).

Table 12: Estimates for Impacted Populations (2009) (ASTER flooding analysis).

Country Name	Total Population	Percent Affected 1mSLR	Percent Affected 2mSLR	Percent Affected 3mSLR	Percent Affected 4mSLR	Percent Affected 5mSLR	Percent Affected 6mSLR
Anguilla	**14,553**	8%	13%	19%	24%	29%	34%
Antigua & Barbuda	**86,754**	2%	5%	7%	10%	12%	15%
Barbados	**276,768**	1%	1%	1%	2%	2%	3%
Belize	**276,098**	1%	3%	6%	10%	13%	17%
British Virgin Is.	**32,633**	6%	10%	13%	16%	18%	20%
Cayman Is.	**51,845**	2%	4%	6%	9%	13%	18%
Dominica	**70,113**	1%	1%	2%	2%	2%	2%
Grenada	**107,457**	1%	2%	3%	4%	5%	6%
Guyana	**760,848**	1%	3%	5%	7%	9%	11%
Haiti	**9,507,314**	1%	1%	2%	3%	4%	5%
Jamaica	**2,820,227**	0%	1%	1%	2%	2%	3%
Montserrat	**5,166**	1%	1%	2%	3%	3%	4%
St. Kitts & Nevis	**36,088**	1%	3%	4%	5%	6%	8%
St. Lucia	**163,205**	1%	1%	1%	2%	3%	3%
St. Vincent & the Grenadines	**108,768**	1%	2%	3%	3%	4%	5%
Suriname	**431,827**	1%	3%	5%	6%	8%	11%
The Bahamas	**340,420**	5%	10%	16%	23%	29%	36%

Country Name	Total Population	Percent Affected 1mSLR	Percent Affected 2mSLR	Percent Affected 3mSLR	Percent Affected 4mSLR	Percent Affected 5mSLR	Percent Affected 6mSLR
Trinidad & Tobago	**1,358,275**	1%	2%	4%	6%	9%	12%
Turks & Caicos Is.	**36,605**	4%	9%	13%	18%	22%	25%
Total	**16,484,964**	**1%**	**2%**	**3%**	**4%**	**5%**	**7%**

4.4.3 Economic Activity

The economic activity assessment utilized a multitude of sources to obtain accurate 2009 gross domestic product (GDP) estimates for each CARICOM study nation. Based on these estimates, the total GDP for the region was $98,000,000,000, down 6% from 2008. Under a one metre flooding scenario economic dislocation was projected to total $2,300,000,000, which represents 2% of the regions GDP (Table 13). The hardest hit countries in terms of percentage loss were the British Virgin Islands, the Turks and Caicos Islands, and Anguilla – with losses of 9%, 8% and 8% respectively (Table 13). The economic losses given a six metre sea level rise were projected to be $13,600,000,000, or 14%. The countries hardest hit in proportional terms were the Turks and Caicos Islands, The Bahamas and Anguilla at 49%, 36% and 34% respectively (Table 13).

Table 13: Estimates for Coastal Economic Impacts (ASTER Flooding Scenarios)

Country Name	*2009 Estimate ($USD)*	Percent Economy Impacted at 1m SLR	Percent Economy Impacted at 2m SLR	Percent Economy Impacted at 3m SLR	Percent Economy Impacted at 4m SLR	Percent Economy Impacted at 5m SLR	Percent Economy Impacted at 6m SLR
Anguilla	175,000,000	8%	13%	19%	24%	29%	34%
Antigua & Barbuda	1,522,000,000	2%	5%	8%	10%	12%	15%
Barbados	5,013,000,000	1%	1%	1%	2%	2%	3%
Belize	2,550,000,000	1%	3%	5%	8%	11%	14%
British	853,000,000	9%	15%	19%	23%	27%	30%

Country Name	*2009 Estimate ($USD)*	Percent Economy Impacted at 1m SLR	Percent Economy Impacted at 2m SLR	Percent Economy Impacted at 3m SLR	Percent Economy Impacted at 4m SLR	Percent Economy Impacted at 5m SLR	Percent Economy Impacted at 6m SLR
Virgin Is.							
Cayman Is.	2,250,000,000	2%	4%	6%	9%	13%	18%
Dominica	745,000,000	1%	1%	1%	2%	2%	2%
Grenada	1,103,000,000	1%	2%	3%	4%	5%	6%
Guyana	5,149,000,000	1%	3%	5%	7%	9%	10%
Haiti	11,976,000,000	1%	1%	2%	4%	5%	5%
Jamaica	23,797,000,000	0%	1%	1%	2%	2%	3%
Montserrat	29,000,000	1%	1%	1%	2%	2%	2%
St. Kitts & Nevis	726,000,000	1%	2%	2%	3%	4%	5%
St. Lucia	1,746,000,000	1%	1%	1%	2%	2%	3%
St. Vincent & the Grenadines	1,069,000,000	1%	2%	3%	3%	4%	5%
Suriname	4,510,000,000	1%	2%	4%	5%	7%	9%
The Bahamas	9,020,000,000	5%	10%	16%	22%	29%	36%
Trinidad & Tobago	25,922,000,000	1%	2%	4%	6%	9%	12%
Turks & Caicos Is.	216,000,000	8%	17%	26%	34%	42%	49%
Total	**98,371,000,000**	**2%**	**4%**	**7%**	**9%**	**11%**	**14%**

4.4.4 Urban Areas

The urban extent data used for the updated ASTER GDEM analysis was also calculated from the Global Rural-Urban Mapping (GRUMP) dataset, which is provided by the Centre for International Earth Science Information Network. The ASTER analysis projected that 65 km² (1%) of urban extent would be vulnerable to flooding given a one metre flooding scenario. The greatest impacts in terms of total area were projected to occur on Trinidad and Tobago, The Bahamas and Jamaica at 19 km², 14 km² and 3 km² respectively (Table 14). The total amount of urban flooding increased to 292 km² (3%) with a three metre rise in sea levels, with Trinidad and

Tobago (45 km²), The Bahamas (52 km²) and Belize (28 km²) experiencing the greatest areas flooded (Table 14). A six metre sea level rise was projected to result in a total flooded area of 862 km², representing over 9% of the total urban extent for 18 CARICOM nations. The nation with the largest total area flooded was again estimated on Trinidad and Tobago, with 277 km², or 12% of total national urban extent (Table 14). The nation with the largest percentage loss of urban extent was The Bahamas with a 27% loss (Table 14). Once again, it should be noted that The Turks and Caicos islands were excluded from this impact assessment due to an absence of information in the GRUMP dataset.

Table 14: Total Amount of Urban Inundation (ASTER Flooding Analysis).

Country Name	Total (km²)	Percent Flooded at 1m SLR	Percent Flooded at 2m SLR	Percent Flooded at 3m SLR	Percent Flooded at 4m SLR	Percent Flooded at 5m SLR	Percent Flooded at 6m SLR
Anguilla	**70**	3%	6%	8%	11%	13%	16%
Antigua and Barbuda	**273**	2%	5%	8%	11%	13%	16%
Barbados	**434**	0%	0%	1%	1%	1%	2%
Belize	**532**	1%	2%	5%	10%	15%	20%
British Virgin Islands	**54**	2%	4%	5%	6%	7%	8%
Cayman Islands	**188**	1%	2%	4%	6%	10%	14%
Dominica	**191**	0%	0%	1%	1%	1%	1%
Grenada	**161**	0%	1%	1%	2%	2%	3%
Guyana	**620**	0%	1%	3%	4%	6%	8%
Haiti	**468**	0%	2%	3%	5%	7%	9%
Jamaica	**2,637**	0%	0%	1%	1%	2%	3%
Montserrat	**0**	0%	0%	0%	0%	0%	0%
St. Kitts and Nevis	**238**	1%	1%	2%	3%	4%	5%
St. Lucia	**359**	0%	1%	1%	2%	2%	3%
St. Vincent & the Grenadines	**132**	0%	1%	1%	1%	2%	2%
Suriname	**607**	0%	2%	4%	5%	7%	8%
The Bahamas	**503**	3%	6%	10%	15%	21%	27%
Trinidad and Tobago	**2,271**	1%	2%	4%	6%	9%	12%
Turks & Caicos Islands	**0**	0%	0%	0%	0%	0%	0%
Total	**9,738**	**1%**	**2%**	**3%**	**5%**	**7%**	**9%**

4.4.5 Tourism Resorts

This section builds upon the tourism resort database created specifically for this research. Of the 906 identified coastal resorts in the study nations, 266 (29%) were identified by ASTER as vulnerable to a one metre rise in sea level. The impact of SLR on coastal resorts is thus very extensive, even at one metre – especially for Belize, St. Kitts, and Nevis and Anguilla, where the estimated percentage loss of tourism resorts was 73%, 64% and 63% respectively (Table 15). The effects given a three metre rise were even more dramatic, with 434 resorts (48%) projected to be at risk. The most affected countries were Belize with 93%, St. Kitts and Nevis with 77% and the Turks and Caicos islands with 73% (Table 15). Finally, at six metres, 607 resorts, or 67%, of the regional total, were seen as under threat. The Bahamas, Turks and Caicos and Antigua and Barbuda faced the greatest absolute loss, with 242 resorts projected lost in the three countries. The countries with the greatest proportional loss were Belize with 95%, Trinidad and Tobago with 92% and St. Kits and Nevis with 91% of resorts expected to experience serious flooding (Table 15). It is worth noting that the absence of impacted tourism resorts in Guyana was due to artifacts generated from cloud cover during data collection (Figure 7).

Table 15: Coastal Tourism Resorts Impacted from Flooding (ASTER analysis).

Country Name	Number of Resorts	Percent Flooded with 1m SLR	Percent Flooded with 2m SLR	Percent Flooded with 3m SLR	Percent Flooded with 4m SLR	Percent Flooded with 5m SLR	Percent Flooded with 6m SLR
Anguilla	**60**	63%	70%	77%	77%	78%	82%
Antigua & Barbuda	**99**	10%	18%	34%	53%	60%	65%
Barbados	**75**	8%	32%	37%	45%	57%	68%
Belize	**44**	73%	86%	93%	93%	95%	95%
British Virgin Is.	**14**	57%	57%	64%	64%	71%	71%
Cayman Is.	**63**	17%	22%	27%	32%	40%	49%

Country Name	Number of Resorts	Percent Flooded with 1m SLR	Percent Flooded with 2m SLR	Percent Flooded with 3m SLR	Percent Flooded with 4m SLR	Percent Flooded with 5m SLR	Percent Flooded with 6m SLR
Dominica	**17**	0%	6%	6%	18%	18%	18%
Grenada	**45**	11%	18%	27%	38%	44%	58%
Guyana	**10**	0%	0%	0%	0%	0%	0%
Haiti	**28**	46%	61%	68%	71%	75%	79%
Jamaica	**105**	8%	18%	25%	32%	38%	48%
Montserrat	**1**	0%	0%	0%	0%	0%	0%
St. Kitts & Nevis	**22**	64%	77%	77%	77%	86%	91%
St. Lucia	**30**	7%	10%	17%	37%	37%	43%
St. Vincent & the Grenadines	**21**	10%	24%	43%	67%	71%	81%
Suriname	**19**	5%	11%	26%	42%	42%	47%
The Bahamas	**133**	36%	50%	59%	63%	71%	74%
Trinidad & Tobago	**24**	33%	63%	71%	83%	88%	92%
Turks & Caicos Is.	**96**	63%	72%	73%	80%	81%	82%
Total	**906**	**30%**	**40%**	**48%**	**56%**	**61%**	**67%**

4.4.6 Transportation Infrastructure

The following section outlines the impacts of SLR on airport runways using ASTER GDEM data. Airport runways were identified as vulnerable to flooding if more than five percent of the runway length was flooded. Given a one metre flooding scenario it was found that 26 runways (36%) were vulnerable to flooding (Table 16). However, within this scenario, the British Virgin Islands, Cayman Islands and Grenada were all identified as having 100% of national airports impacted (Table 16). The effects of sea level rise increased drastically given a three metre rise; 41 runways (56%) were identified as vulnerable. Finally, under a six metre flooding scenario the projections found 53 runways, 73%, to be vulnerable (Table 16). It should be noted that between a five and six metre flooding scenario only one runway in The Bahamas experienced a change.

Table 16: Airport Runway Flooding Impacts (ASTER Analysis).

Country Name	Run-way Total	Percent Flooded at 1m SLR	Percent Flooded at 2m SLR	Percent Flooded at 3m SLR	Percent Flooded at 4m SLR	Percent Flooded at 5m SLR	Percent Flooded at 6m SLR
Anguilla	1	0%	0%	0%	0%	0%	0%
Antigua & Barbuda	1	0%	100%	100%	100%	100%	100%
Barbados	1	0%	0%	0%	0%	0%	0%
Belize	2	50%	50%	50%	100%	100%	100%
British Virgin Is.	2	100%	100%	100%	100%	100%	100%
Cayman Is.	2	100%	100%	100%	100%	100%	100%
Dominica	2	0%	50%	50%	50%	100%	100%
Grenada	1	100%	100%	100%	100%	100%	100%
Guyana	5	0%	0%	0%	0%	0%	0%
Haiti	2	50%	50%	50%	50%	50%	50%
Jamaica	5	20%	60%	60%	60%	80%	80%
Montserrat	1	0%	0%	0%	0%	0%	0%
St. Kitts & Nevis	2	50%	50%	50%	50%	50%	50%
St. Lucia	2	50%	50%	50%	50%	100%	100%
St. Vincent & the Grenadines	4	50%	75%	100%	100%	100%	100%
Suriname	2	0%	0%	0%	0%	50%	50%
The Bahamas	32	38%	53%	63%	66%	72%	75%
Trinidad & Tobago	2	50%	50%	50%	100%	100%	100%
Turks & Caicos Is.	4	25%	50%	50%	75%	100%	100%
Total	**73**	**36%**	**51%**	**56%**	**62%**	**71%**	**73%**

The analysis of the effects of sea level rise on major highways used polyline data obtained from the Landinfo Global VMAP version five, obtained from the University of Waterloo Mapping Library. The impact statistics were expressed in terms of total length of flooded highway within each country. The total length of flooded highways given a one metre rise was estimated at 580 km, or 5% of the total length of roads in study countries (Table 17). The greatest percentage impact was found in Anguilla, with a projected 29% that nation's highways flooded. With six metres of flooding, the total length of affected highways rose to

1582 km, or 12% of all roadways (Table 17). The country with by far the greatest vulnerability to flooding was The Bahamas, with over 548 km of its highways flooded 36% of its existing total.

Table 17: Major Road Infrastructure Impacted from Flooding (ASTER Analysis).

Country	Total Road Length (km)	Percent Roads Flooded 1m SLR	Percent Roads Flooded 2m SLR	Percent Roads Flooded 3m SLR	Percent Roads Flooded 4m SLR	Percent Roads Flooded 5m SLR	Percent Roads Flooded 6m SLR
Anguilla	22	28%	30%	31%	33%	34%	35%
Antigua & Barbuda	82	2%	6%	8%	11%	14%	17%
Barbados	121	0%	0%	0%	0%	0%	0%
Belize	815	4%	6%	9%	12%	16%	20%
British Virgin Is.	42	8%	9%	9%	10%	11%	12%
Cayman Is.	73	2%	3%	4%	4%	6%	9%
Dominica	115	14%	15%	15%	16%	16%	17%
Grenada	102	0%	1%	1%	1%	1%	2%
Guyana	1063	12%	13%	14%	15%	17%	19%
Haiti	3613	1%	1%	2%	3%	3%	4%
Jamaica	2004	1%	2%	2%	2%	3%	4%
Montserrat	41	4%	4%	4%	4%	5%	5%
St. Kitts & Nevis	71	0%	0%	1%	2%	3%	4%
St. Lucia	98	0%	0%	0%	1%	2%	4%
St. Vincent & the Grenadines	86	1%	1%	2%	2%	2%	2%
Suriname	1526	7%	8%	10%	12%	14%	16%
The Bahamas	1544	14%	19%	23%	27%	31%	36%
Trinidad & Tobago	673	1%	2%	4%	6%	8%	11%
Turks and Caicos Is.	24	8%	9%	12%	16%	19%	24%
Total	**12112**	**5%**	**6%**	**7%**	**9%**	**11%**	**13%**

4.4.7 Erosion Scenarios

There remains considerable uncertainty concerning the magnitude and rate of both climate change and SLR; but as indicated in the previous discussion, the most recent studies project sea level rises of between one and two metres over the 21st century (Vermeer & Rahmstorf, 2009). The following erosion scenarios applied low-end (50 times vertical SLR) Bruun rule erosion calculations on unconsolidated beach areas and were overlapped with several impact indicators. The following section discusses the effects of SLR induced coastal erosion on key coastal tourist resorts and urban areas, given a one or two metre rise in sea levels.

4.4.7.1 Tourism Infrastructure

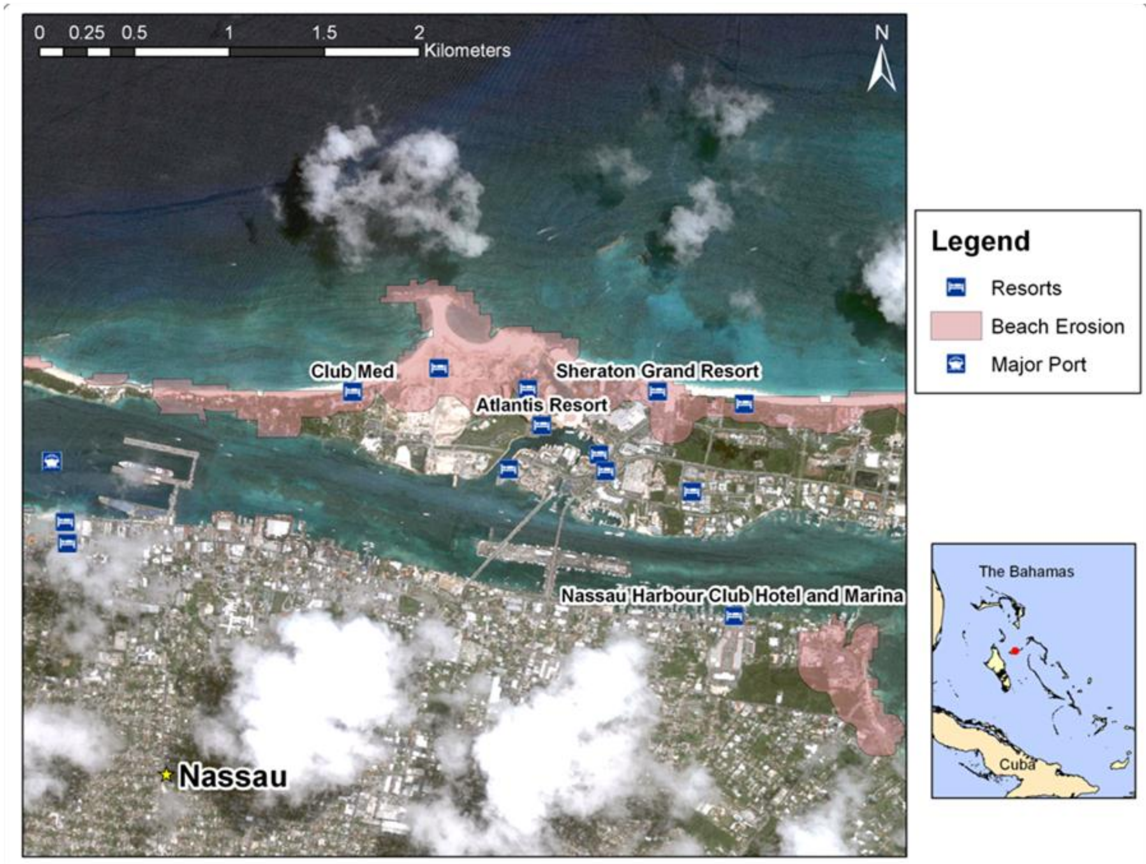
Beaches are critical assets for tourism in the Caribbean, and a large proportion will be lost to inundation and accelerated erosion well before resort infrastructure itself is damaged. Large stretches of Caribbean coastline are highly susceptible to erosion, and beaches have already experienced accelerated erosion in recent decades (Phillips & Jones, 2006). Higher sea levels will accelerate coastal erosion in these areas, by causing increased wave attack and storm surges. As a result, many tourist resorts could face financial problems related to beach erosion. Of the 906 tourist resorts examined in this analysis, 440 (or 49%) would be affected by a low-end Brunn Rule erosion scenario resulting from a one metre rise in sea levels. Given a two metre rise, an additional 106 resorts – over 60% of the total for the region – are projected to be at risk (Table 18). The countries with the greatest proportion of tourism infrastructure vulnerable to erosion associated with a one metre rise are Belize (73% of resorts at risk), Saint Kitts and Nevis (68%) and Anguilla (63%). Those with the largest absolute number of resorts likely to be affected by the erosion caused by a one metre rise were the Turks and Caicos Islands (78%), The Bahamas (77%) Barbados (44%) and Belize (44%) (Table 18). Given a two metre erosion scenario, the proportion of vulnerable resorts in some nations is projected to be above 90%;

including Belize (100%) and the Turks and Caicos Islands (91%) (Table 18). It is important to note that these figures are based on recognition of the fact that critical beach assets will be affected much earlier than hard tourism infrastructure. Indeed, if erosion is damaging tourism infrastructure, it means that nearby beaches have essentially disappeared. Figure 5 illustrates the erosion risk for high profile tourism infrastructure on Paradise Island, The Bahamas.

Table 18: Coastal Tourism Resorts Impacted from Flooding and Erosion (ASTER analysis).

Country Name	Major Resorts	Resorts Affected 1m SLR %	(Brunn) Resorts Affected 1m SLR %	Resorts Affected 2m SLR %	(Brunn) Resorts Affected 2m SLR %
Anguilla	60	63%	63%	70%	70%
Antigua and Barbuda	99	10%	34%	18%	44%
B.V.I.	75	8%	56%	32%	67%
Barbados	44	73%	95%	86%	100%
Belize	14	57%	36%	57%	43%
Cayman Is.	63	17%	24%	22%	40%
Dominica	17	0%	29%	6%	35%
Grenada	45	11%	31%	18%	42%
Guyana	10	0%	0%	0%	0%
Haiti	28	46%	50%	61%	61%
Jamaica	105	8%	32%	18%	50%
Montserrat	1	0%	0%	0%	0%
St. Kitts & Nevis	22	64%	68%	77%	82%
St. Lucia	30	7%	17%	10%	30%
St. Vincent & the Grenadines	21	10%	38%	24%	76%
Suriname	19	5%	11%	11%	11%
The Bahamas	133	36%	58%	50%	70%
Trinidad and Tobago	24	33%	63%	63%	67%
Turks and Caicos Is.	96	63%	81%	72%	91%
Total	**906**	**29%**	**49%**	**40%**	**60%**

Figure 5: Vulnerability of Tourism Resorts in Nassau and Paradise Island, The Bahamas to 1m SLR Induced Coastal Erosion.



Note, the armoured shorelines of Nassau do not show any signs of coastal erosion.

4.4.7.2 Urban Extent

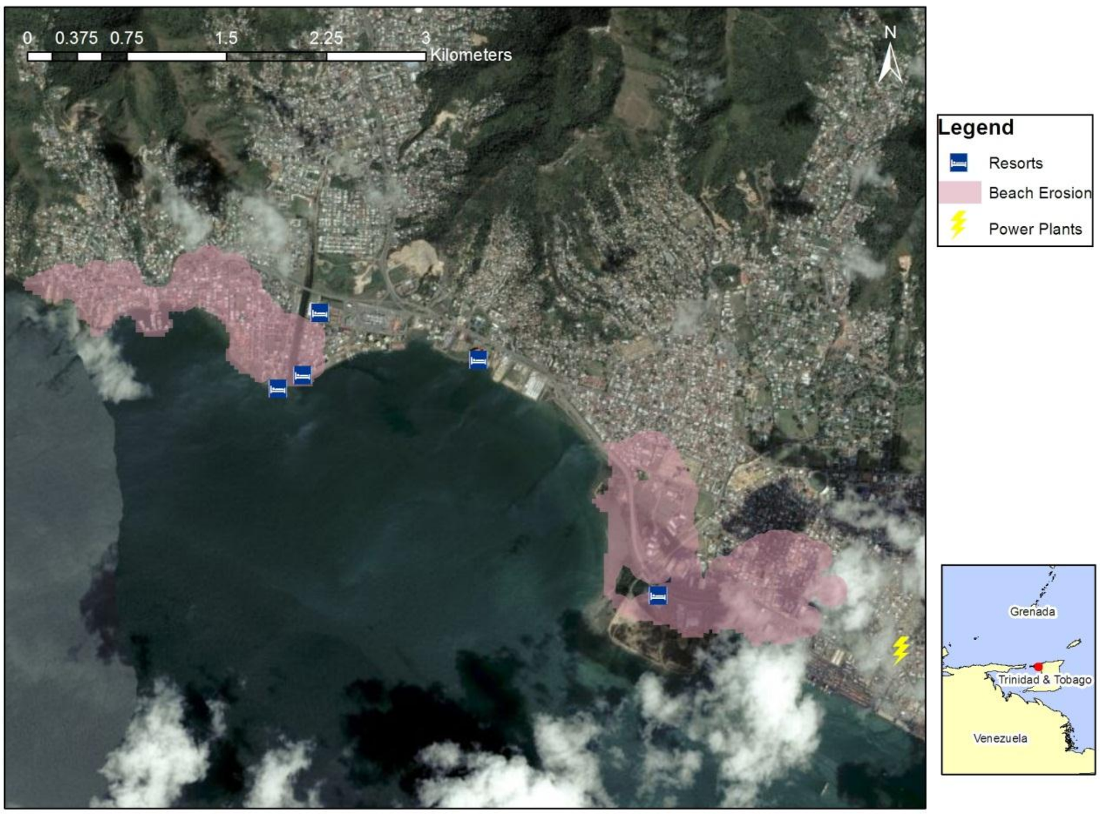
In the Caribbean region urban populations have been growing 50% faster than overall population growth since 1980, and this has resulted in highly urbanized populations concentrated in coastal areas – a trend likely to continue (SEDU, 2002). This fact defines the importance of establishing the likely effects of both rising sea levels and coastal erosion on areas of urban population over the next century. Urban erosion flooding scenarios excluded all armoured shores to ensure only erodible shorelines were included. Given a one metre sea level rise, it was projected that 98 km² (1%) of urban extent will be flooded due to the combined effects sea level rise and coastal beach erosion (Table 19). This represents an 32 km² in addition to the area projected to be flooded by one metre of sea level rise, with the largest impacts expected in Trinidad and Tobago (35 km²) and The Bahamas (12 km²). Given a two metre flooding scenario, with erosion, 315 km² of urban extent was found to be prone to flooding; this represents an increase of 205 km² over the standard two metre flooding scenario. The largest total changes were predicted for Trinidad and Tobago, where coastal erosion increased urban flooding estimates from 45 km² to 133 km² (Figure 6). Finally, the largest percentage increase was predicted to occur in The Bahamas where urban (coastal) erosion increased from 6% to 10% (Table 19).

Table 19: Total Amount of Urban Inundation with Erosion (ASTER Flooding Analysis).

Country Name	**Total (km²)**	**Percent Flooded at 1m SLR**	**(Brunn) Percent Flooded at 1m SLR**	**Percent Flooded at 2m SLR**	**(Brunn) Percent Flooded at 2m SLR**
Anguilla	**70**	3%	4%	6%	7%
Antigua and Barbuda	**273**	2%	2%	5%	5%
Barbados	**434**	0%	0%	0%	1%
Belize	**532**	1%	1%	2%	2%
British Virgin Islands	**54**	2%	2%	4%	4%
Cayman Islands	**188**	1%	1%	2%	2%
Dominica	**191**	0%	0%	0%	0%
Grenada	**161**	0%	1%	1%	1%
Guyana	**620**	0%	0%	1%	0%
Haiti	**468**	0%	0%	2%	2%
Jamaica	**2,637**	0%	0%	0%	0%
Montserrat	**0**	0%	0%	0%	0%
St. Kitts and Nevis	**238**	1%	2%	1%	3%
St. Lucia	**359**	0%	0%	1%	1%
St. Vincent & the Grenadines	**132**	0%	0%	1%	0%
Suriname	**607**	0%	2%	2%	4%
The Bahamas	**503**	3%	7%	6%	10%
Trinidad and Tobago	**2,271**	1%	1%	2%	2%
Turks & Caicos Islands	**0**	0%	0%	0%	0%

Country Name	Total (km²)	Percent Flooded at 1m SLR	(Brunn) Percent Flooded at 1m SLR	Percent Flooded at 2m SLR	(Brunn) Percent Flooded at 2m SLR
Total	**9,738**	**1%**	**1%**	**2%**	**2%**

Figure 6: Vulnerability of Tourism Resorts and Urban Areas in Port-of-Spain, Trinidad and Tobago to 1m SLR Induced Coastal Erosion.



Note the proximity of a power generation station to vulnerable flooded areas.

4.5 *Chapter Summary*

This chapter presented quantitative results concerning sea level rise in Caribbean countries. The analysis included data for all 19 CARICOM study countries, using satellite derived elevation data both at 90 metre and 30 metre resolutions. Overall, all study countries were estimated to experience negative impacts due to rising sea levels, even under the most conservative SLR scenarios. Projections based on sea level rises from one to six metres were generated, in order to account for long term sea level rise (one to two metres) and storm surge effects (three to six metres). The following chapter will discuss the differences in the analysis and provide insight on the implications from study results.

5 Summary of Findings

5.1 *Introduction*

The overall goal of this thesis was to model the potential effects of sea level rise on CARICOM nations with an emphasis on SIDS, and establish their particular vulnerabilities. This was achieved by acquiring and processing high resolution digital elevation data on two scales. The elevation data was then processed in a GIS, which was used in conjunction with a variety of impact indicator datasets. This chapter first discusses the similarities and differences between the two impact assessment analyses. This is followed by a summary of the analytical results from a practical perspective, with an emphasis on the real implications the results represent in the Caribbean.

5.2 *Impact Assessment Results Comparison*

Throughout the analysis, it has been clearly shown that virtually all of the 19 CARICOM SIDS would suffer negative effects from even a one metre rise in sea levels. When the combined effects of long term SLR and storm surge flooding is considered, the projected consequences are even more dramatic. The following section will discuss the similarities and differences evident between the SRTM and ASTER analysis results.

5.2.1 Similarities

In general, when considering smaller sea level rises, the elevation data from the SRTM DTM tended to generate lower impact indicators than the ASTER GDEM. However, as greater increases in sea level were postulated, the results converged. For example, under a one metre flooding scenario the SRTM data only identified 78 tourism resorts as vulnerable to flooding, compared to 266 identified using the ASTER GDEM. However, given a six metre rise, the SRTM identified 597 vulnerable resorts, compared to 607 in the ASTER GDEM. Similar results can be seen in the airport runway vulnerability assessment, where only seven runways were identified as being vulnerable to one metre of flooding in the SRTM data, compared to 26 identified in the ASTER GDEM projection. But given a six metre flooding scenario, both datasets indicated that 53 runways would be affected. Closer inspection revealed that both datasets identified the same runways. While differences in the ASTER and SRTM datasets exist along some coastal areas at one and two metre scenarios (due to differences in pixel resolution), the datasets gave relatively consistent results for a six metre flooding scenario. The majority of tourist resorts and airport runways were located outside of Guyana and Suriname where most of the data anomalies occurred.

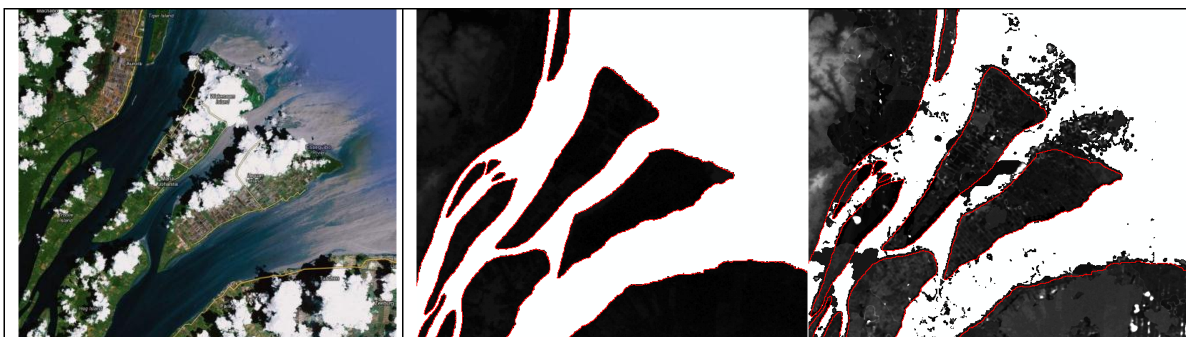
Of all the vulnerability indicators, the most uniform results at one metre were observed from the impacts of SLR on population: the SRTM DTM estimated a regional affected population of 114,509 while the ASTER GDEM estimate was 116,828. A similar consistency was found for the remaining scenarios – from two to six metres. This was due to the larger resolution of the population grid cells (five km^2) which eliminated any small scale anomalies in the two elevation datasets.

5.2.2 Differences

While the results discussed above were broadly comparable, those for several other impact indicators were quite divergent. Most notable were the discrepancies between the estimates for total affected land area. Given a one metre flooding scenario the SRTM DTM estimated that 2,782 m² of land would be flooded, while the ASTER GDEM estimated only 1,376 m². The greatest part of this discrepancy involved the countries of Guyana and Suriname, where the ASTER GDEM results were 832 m² lower than comparable SRTM estimates.

A detailed inspection of both datasets revealed that the most substantial differences observed between the SRTM 90 metre DTM and the 30 metre ASTER GDEM data set were due to the presence of data anomalies. These were the result of atmospheric interruptions, commonly referred to as residual cloud anomalies**.** The largest cluster of these anomalies in the ASTER data occurred along the coasts of Guyana and Suriname (Figure 7).

Figure 7: Comparison of SRTM DEM and ASTER GDEM Data with Google Maps Image.



Google Earth Image	SRTM DEM	ASTER GDEM

Note the atmospheric interruptions (cloud cover) in ASTER GDEM image. These anomalies cause incorrect elevation data (often larger).

The absence of these data anomalies in the SRTM (version 4) data is due to extensive void-filling. The SRTM dataset was collected over an 11 day period in 2000, using an Interferometric Synthetic Aperture Radar attached to Space Shuttle Endeavour. Over the last 11 years, numerous scientists and academics have developed algorithms to help fill voids in the SRTM data, effectively removing data anomalies and artifacts. The ASTER GDEM is a relatively new dataset (2009), and is still considered research grade.

5.2.3 Impact Assessment Comparison Conclusion

In a recent study on natural hazard risk reduction in St. Lucia, Mycoo (2011) noted that "one of the major problems affecting the quality of hazard mapping in the Caribbean is that of resolution". Through this research, we have seen that differences in scale can hinder the ability to model certain impact indicators that require accurate high resolution in coastal zones. As previously discussed, the validity of both SRTM DTM and ASTER GDEM has been established, but they had yet to be used for detailed SLR and storm surge impact assessment on a large scale. The results of this research provide the most comprehensive sea level rise impact assessment of the Caribbean to date. However, the usefulness of some impact indicators were somewhat limited due to discrepancies in results – particularly the estimates of total flooded land area**.** Despite some impact indicator discrepancies, the research conclusively shows that all CARICOM SIDS can expect to experience negative effects as a result of rising sea levels within the predicted range of one to two metres. As such, it is hoped that CARICOM nations can use this research as a tool for planning adaptive measures.

5.3 Practical Implications of Study Results

As discussed, the IPCC predicts that climate change is very likely to continue and accelerate in the course of the 21st century. While recent studies have called for a global response to manage and reduce greenhouse gases, the IPCC warns that even if increased global temperatures were stabilised at two degrees Celsius, the sea levels would continue to rise for many decades to centuries as a result of warmer air and sea temperatures, and the effects of this rise on coastal areas would continue to accrue.

The results of this study clearly show that under both analysis methods, the effects of rising sea levels and storm surge can be expected to negatively affect all CARICOM nations. What is more, low-lying nations such as The Bahamas, Cayman Islands and Turks and Caicos Islands, and countries with coastal plains below ten metres such as Guyana, Suriname, and Belize were at greater risk than other countries. Volcanic islands like Dominica, Montserrat, St. Lucia and St. Kitts and Nevis are at relatively little risk.

5.3.1 Land area

The potential loss of land area in the Caribbean poses a serious and potentially catastrophic problem. Already, many CARICOM nations struggle with a shortage of suitable, available land to accommodate growing populations. All CARICOM study nations are projected to experience some degree of land loss due to rising sea levels; unfortunately, study area countries with the smallest total land areas are projected to experience the largest proportional loss. The most dramatic inundation scenarios were projected for low-lying flat nations, notably The Bahamas, Turks and Caicos Islands, Cayman Islands, Anguilla and the British Virgin Islands. Among these islands, the greatest impacts were projected for The Bahamas and Turks and Caicos Islands, with an estimated 7-9% total land loss at a one metre flooding scenario.

But the effects of the loss of land area cannot be quantified meaningfully without looking at the types of land and infrastructure that would be impacted. The study found a general correlation between land loss and other factors, such as impact on coastal populations and the local economy. Generally speaking, total land loss translated into slightly smaller but significant impacts to coastal populations and local economies. For example, given a one metre flooding scenario, The Bahamas was projected to loose approximately 5-10% total land area, involving a 4% population displacement and an estimated economic loss greater than $420,000,000, representing roughly 4% of the national GDP. Similar correlations were observed in many other nations, including Belize, the Cayman and Turks and Caicos Islands. It is therefore clearly essential that the Caribbean consider adaptation programmes (coastal defence and managed coastal realignment, environmental risk assessment, disaster management plans) to ensure that future populations and economies can continue to grow, despite a shrinking amount of available land.

5.3.2 Population impacts

Rising sea levels will inevitably cause problems for coastal populations throughout the world. Currently, more than ten percent of the world's population lives in coastal regions, at elevations lower than ten metres above sea level (McGranahan et al., 2007). Sea level rise has been identified as an even greater threat to areas where populations are concentrated in coastal regions; this includes the Caribbean region, where over half of the population lives within the ten metre threshold. The total population displacement in the study area, given a one metre rise in sea levels, was estimated between 114,509 and 116,828 – representing approximately one percent of the total population. These findings are significantly lower (one million) than projections proposed by Nicholls et al., (1999) which used generalized coarse flooding polygons throughout the globe. Similarly, Nicholls et al., (1999) included the relatively large (population) countries of Cuba and the Dominican Republic which have a combined population of over 20 million (CIA, 2010). When additional factors, including storm surge (six metres), are considered, the potential number of people displaced increased to over 1,000,000. Once again, the low-lying nations of The Bahamas and the Turks and Caicos Islands were identified as facing the greatest impact, with a combined total of over 16,000 people displaced by a one metre rise. The threat posed to coastal populations in Caribbean SIDS is even further complicated by the limited size and elevation of many of the islands, particularly the eastern low-lying Leeward Islands (Anguilla, Antigua and Barbuda, St. Kitts and Nevis and the islands of The Bahamas and Turks and Caicos. Without proper adaptation, projected sea level could result in the displacement of hundreds of thousands of CARICOM residents.

5.3.3 Economic Activity

The economies of many CARICOM nations revolve around tourism, specifically coastal-based tourism. The economic importance of this sector has been growing at a rapid rate, and tourism already constitutes over 50% of the national GDP of several CARICOM SIDS. The initial economic impact assessment estimated losses of between 1.5 and 2.2 billion dollars (USD) with one metre of flooding. The hardest hit countries at this level were the Turks and Caicos, British Virgin Islands, and Anguilla, with total economic losses greater than 7% of national GDP for each country. Under the most extreme flooding scenario considered in this study (including storm surge) the average total economic loses (over both SRTM and ASTER analysis) were estimated at $15 billion, which represents around 15% of the current total regional GDP. Given current economic trends in the region, discussed above, coastal tourism can be expected to increase in importance in the Caribbean, and it can be assumed that the actual economic impact of SLR will be greater than these projections suggest. While a full economic impact assessment would yield further results, this study has provided an initial approximation of the economic effects of rising sea levels on the CARICOM countries.

5.3.4 Urban Areas

Over the last 30 years, urban areas within the Caribbean region have expanded by 50%, while agricultural lands have shrunk by 20% (SEDU, 2002). Because of the small land area of many of the Caribbean islands, the region is currently home to some of the most urbanised populations in the world, with over 70% of Caribbean residents living in urban areas (Martinez, 2010). While the effects of a one metre rise in sea levels were projected to be modest, entailing the loss of 1% to 1.5 % of total urban areas, several low-lying coastal plain countries were estimated to experience greater losses. For example, Guyana and Suriname can be expected to face urban land subsidence of 8% and 4% respectively given a one metre flooding scenario. This poses serious problems for these countries, in both of which over 90% of the population lives in coastal urban environments. The extent of the urban areas affected increases dramatically given a six metre flooding scenario, with Guyana, Suriname, The Bahamas and Cayman Islands all projected to lose 40% of their respective urban areas. In the absence of proper adaptive measures, rising sea levels can be expected to inundate large areas of coastal urban settlement, including high value properties and key strategic infrastructure.

5.3.5 Tourist Resorts

The primary tourist draw for most CARICOM destinations is coastal based tourism, based on the region's majestic beaches, favourable climate and the clear waters of the Caribbean Sea. However, this study has shown that the majority of the regions coastal resorts are highly vulnerable to economic and infrastructure losses due to rising sea levels and increased storm events. Even given the most conservative flooding scenario, a one-metre rise in sea levels, over 266 study area resorts were found to be vulnerable. This represents 30% of the region's coastal resorts. The majority of these resorts were located on the small low-lying eastern Caribbean islands of Anguilla, St Kitts and Nevis, Turks and Caicos and The Bahamas. These results point to a cause for specific concern, as tourism is particularly important to the economies of these countries. The study also indicates that *all* CARICOM nations can expect significant damage to coastal based tourism industries at the maximum flooding scenario. A maximum estimate of 607 resorts, representing 67% of all coastal resorts in the study region, is identified as prone to flooding. This level of dislocation would effectively cripple the economies of many countries in a region where tourism represents 15% of the economy, and is still growing in importance. The longevity of the Caribbean tourism industry is in the hands of policy makers, who must accept that climate change is occurring and incorporate effective policies into future tourism development.

5.3.6 Transportation Infrastructure

This study has examined the potential effects of sea level rise on key transportation infrastructure, focusing on major roads and airport runways. One of the major methods of transportation to the Caribbean for tourists is air travel. The study identified 10% of the study area's 73 airports as susceptible to flooding, given a one metre rise in sea levels. The majority of these were located on various islands in The Bahamas. When the maximum flooding scenario was considered, 73% the study area's airports, in 15 of 19 countries, were identified as being threatened with flooding. This poses a significant problem to many SIDS, particularly to volcanic islands like Dominica, Montserrat, St. Lucia and St. Kitts and Nevis, where there is a scarcity of readily available large tracts of flat land.

While air travel is often seen as a crucial method of tourist travel, road transportation plays a vital role in many of the region's countries. Rising sea levels are projected to have a serious effect on the major road infrastructure of many islands, with an estimated 12-14% of all major roads (1500-1700 km) impacted at the maximum flooding scenario. It has been noted that the maximum flooding scenario of six metres would in fact effectively flood entire sections of some islands, creating two separate land masses not mutually accessible by land transportation. For example, at Frigate Bay on the island of St Kitts, a six metre flooding scenario would effectively separate the north of the island from the heavily populated Basseterre region, effectively forcing the construction of expensive bridges or a reliance on sea transportation.

The effects of rising sea levels on the transportation sector have been examined extensively in this study, which shows that SLR can be expected to effectively cripple the current transportation infrastructure of many CARICOM countries.

5.3.7 Erosion Impacts

As one of the direct effects of rising sea levels and the increasingly severe storm surges, beach erosion has been identified as a major threat to Caribbean coastal communities and low-lying nations. Rising sea levels have been claimed to:

> "dramatically alter sandy beaches and barrier island coasts. These impacts go beyond simple inundation caused by rising ocean waters, and involve the permanent or long term loss of sand from beaches" (FitzGerald et al., 2008, p.604).

This study performed beach erosion scenarios given one and two metres of sea level rise – a conservative approach, as this does not include the additional impact of storm surge events. The study looked specifically at the impact of beach erosion on urban and tourism infrastructures. Overall, the low-lying nations of The Bahamas, Cayman and Turks and Caicos Islands were deemed to be facing the greatest proportional effects. While significant flooding was projected for countries (Guyana, Suriname and Belize) with coastal plains below ten metres, beach erosion is expected to be minimal due to the significant presence of mangroves and similar coastal vegetation. Beach erosion was expected to have a significant effect on the overall extent of urban subsidence in some countries – notably Trinidad and Tobago, where beach erosion is projected to result in a 34% increase in the total area affected.

The erosion scenarios identified coastal resorts as facing the greatest increase in physical and economic damage as a result of beach erosion. When the effects of erosion were considered, an additional 20% of all study area resorts were projected to experience significant beach and infrastructure damage, bringing the total affected to more than 60%. These figures are simply indicators of potential impacts; but the future of the Caribbean coastal tourism industry appears to be very grim unless proper adaptation and policy measures are incorporated throughout the region to ensure the longevity of this vital economic sector.

5.4 Chapter Summary

Due to data anomalies in the higher resolution ASTER GDEM, results from both elevation datasets were used in the final analysis. Throughout the study, projections generated from both datasets have conclusively shown that all study nations would be affected negatively by rising sea levels and storm surge events. Sea levels are set to increase at an accelerating rate over the next century, but proper adaptive measures and coastal protection schemes would enable coastal nations to ameliorate some of the adverse effects. The following section discusses some recommendations for adaptive measures designed to help CARICOM countries prepare for the consequences of rising sea levels and storm surge events.

6 Recommendations and Conclusions

This study has modelled the potential impacts of rising sea levels and storm surge events in the Caribbean, using a variety of geospatial data and several different SLR scenarios. The following chapter will detail how these results can be used to improve information bases, potentially leading to informed decisions and successful adaption policies and actions. The study's results can be used in the formulation of region-wide policies, and can allow individual CARICOM nations to take more effective action to ensure the preservation of vital shoreline infrastructure, beaches and other important coastal environments. Finally, the study can contribute to the development of more advanced, more detailed methods of measuring the potential impact of rising sea levels on larger geographic scales, which can be applied to SIDS in other regions of the world.

6.1 Future Research

This study has shown that even under a one metre flooding scenario, many CARICOM nations face extreme risks to population displacement, economic dislocation and large amounts of land loss. This study has shown the relative vulnerability of Caribbean nations given even the most conservative SLR scenarios. However, it is crucial that governments and multilateral agencies ensure that subsequent SLR studies make use of additional impact indicators, higher resolution spatial datasets and local level studies. This will ensure more accurate and detailed projections, which in turn will constitute a basis for better informed, more effective adaptation actions and policies.

6.1.1 Additional Impact Indicators

While this study has attempted to add to the range of indicators used in previous studies, notably the work by the World Bank (2009), a great many impact indicators have been omitted. For example, a detailed dataset of coastal protection defence structures (sea-walls, walkways, breakwater walls, etc.), with specific building types, year of construction and condition would be a useful addition to study results. The inclusion of such data would aid individual nations in determining whether existing sea-walls and other coastal protection infrastructure would be sufficient given certain SLR scenarios. The inclusions of this data would also allow individual nations to determine relative construction costs of coastal protection.

Another impact indicator which should be added to regional and local information systems is the location of water supply and sanitation infrastructure, and their vulnerability given different SLR scenarios: for example how rising sea levels and storm surge may disrupt or flood/pollute (via salt water intrusion) fresh water and sanitation systems. Many SIDS already struggle to provide satisfactory water supplies and sanitation systems to urban areas.

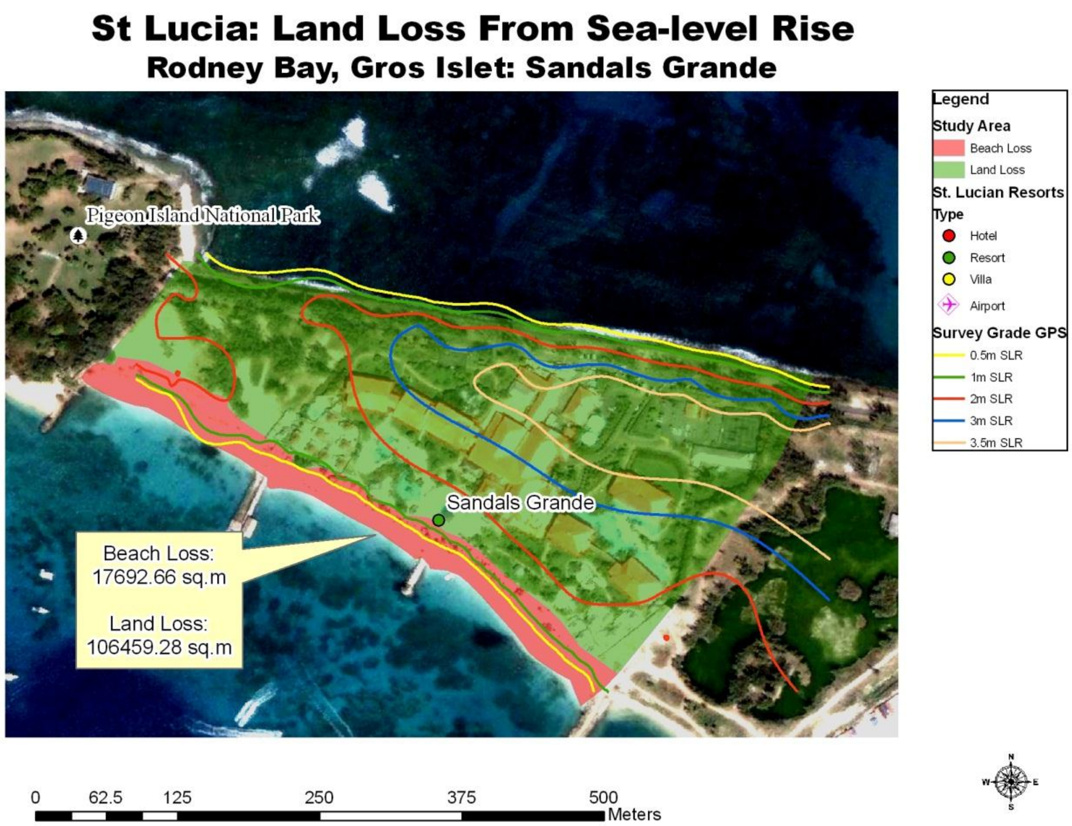
6.1.2 Local Level Studies

The research for the present study has generated comprehensive SLR impact overviews for each CARICOM nation. However, it is recommend that local level studies be undertaken for several key individual areas; this will lead to a better understanding of the effects of SLR and storm surge, and allow communities to engage with local governments and stakeholders to allow for the development of local and community-based action plans.

The results from the GIS analysis have clearly indicated that rising sea levels and storm surge pose a greater risk to some countries than to others. However, without higher resolution digital elevation data, it cannot be determined if the satellite DEM results under or over-estimated SLR impacts in the Caribbean. As part of additional research projects with the UNDP and CARIBSAVE, I have had the opportunity to perform survey grade GPS surveying of key coastal areas on the following 12 CARICOM nations: Anguilla, Antigua and Barbuda, The Bahamas, Barbados, Belize, Dominica, Dominican Republic, Grenada, Jamaica, Saint Lucia, Saint Vincent and the Grenadines and the Turks and Caicos Islands. The results from these survey grade GPS studies indicated that in every case the satellite DEM under-estimated the impacts of SLR in coastal areas. For example, in the satellite analysis, St. Lucia is projected to face a relatively small proportional risk, due to its mountainous terrain with several smaller impacts located in the north-eastern Gros Islet area. However, closer inspection at the local level revealed that the survey grade GPS study identified the relative vulnerability of the Gros Islet area, with a greater degree of SLR impacts witnessed in the Gros Islet area than shown in either the ASTER or SRTM data. The survey grade GPS data showed that rising sea levels could devastate this key tourism area, which includes the large Sandals Grande resort (Figure 8). It should be noted that while the survey grade GPS study provided elevation data accurate to ten to 20 centimeters, the restrictions of GPS technology limit its usage to smaller local area assessments. The results of this thesis research can also aid other CARICOM nations in identifying areas that would benefit from similar high resolution local area studies.

Furthermore, local level impact studies should utilize more detailed national level GIS data, including census data, property values, critical infrastructure at the building level and detailed planning data (future zoning, and proposed roads). The use of this detailed dataset on a national level combined with the satellite flooding results would aid policy makers in determine more detailed analysis of the socio-economic and infrastructure damage due to SLR. Similarly, more detailed beach erosion modelling techniques should be employed on local levels. The following study has shown that Bruun rule erosion modelling is satisfactory as a ‘baseline’ for erosion on large scales. There is a need to incorporate more advanced erosion models that build upon the Bruun rule by incorporating additional factors, such as sediment flow data and historical erosion data in a GIS (Feagin et al., 2005; Addo et al., 2011). The inclusion of such data would also allow policy makers to incorporate SLR into upcoming national and regional master plans.

Figure 8:Local Level SLR Study : Sandals Grande, Gros Islet, St. Lucia.



Note, the impacts of SLR at a 3.5 metre scenario were found to completely flood the Gros Iset area separating Pigeon Island National Park from the mainland.

6.1.3 Improved Geospatial Data

A further investigation of available reliable high-resolution elevation data should be a priority for future studies investigating SLR impacts in the Caribbean and around the world. The present study has provided a comprehensive assessment of two high resolution elevation datasets, at both 90 and 30 metre resolutions. While these datasets represent some of the best publicly available DEM's in the world, the issues of spatial resolution and data anomalies still create a degree of uncertainty. Recently, a study by Siart et al., (2009) confirmed the usefulness of combining SRTM and ASTER datasets to help reduce the issues related to data anomalies. Fortunately, as discussed above, the ASTER GDEM data is constantly undergoing void-filling processes which will help remove artifacts and anomalies. Pending the study grade rating of the ASTERM GDEM, it is recommended that additional studies using satellite DEM utilize both SRTM and ASTER elevation datasets for impact modelling.

The inclusion of more advanced digital elevation data would eliminate these anomalies, and ensure that governments, business owners and residents have the best available data to plan and prepare for the multitude of problems associated with climate change. Over the last two decades, LiDAR (Light Detection and Ranging) technology has utilized laser light to measure distances accurately – within ten centimeters. Initially, LiDAR technology was used to survey power line corridors to identify areas of infringing vegetation. However, as the technology was refined more uses were found for it, including mapping landforms and coastal areas. Recently, LiDAR technology has become an important tool in coastal areas for measuring both shoreline profiles, depths and flooding hazards. This technology is especially useful for regions with long shorelines, as hundreds of kilometres can be surveyed over a few hours by a single GPS base station.

Finally, the inclusion of more detailed socio-economic geospatial data (population, economic indicators, key coastal infrastructure, building footprints, property value values, proposed development, wetland and other fragile coastal ecosystems) at both national and local scales are required to ensure future impact estimates represent better valuation of the natural and structural asses at risk. A recent 2009 SLR impact study from the California Climate Change Research Center incorporated detailed socio-economic data including ‘critical infrastructure’ including hospitals, schools, emergency facilities, wastewater treatment plants and power plants. The inclusion of the aforementioned socio-economic data resulted in very detailed evaluations of infrastructure and environmental damage, including building replacement costs.

Regional co-operation for the procurement of reliable high geospatial data should be a priority for all CARICOM nations interested in improving their assessment of erosion processes and planning for improved coastal protection.

6.1.4 Adaptation Actions and Policies

It is hoped that this thesis will prove to be a vital component in the development of adaptation actions and policies throughout the Caribbean. First and foremost, this research should be seen as an on-going 'hazard atlas' for CARICOM nations. The results from this study can be incorporated into key policies regarding coastal structures, future community/tourism master plans and insurance policies. These results demonstrate that policies related to the development and construction of coastal protection systems should be investigated and implemented early; some coastal protection systems have taken 30 years or more to complete. Similarly, these results make clear the importance of reviewing and renewing planning and development policies at the local and regional level, in order to ensure that all new development on highly erodible coastal land areas is reduced or off-set to decrease the risks from beach erosion and rising sea levels.

It is recommended that additional research be conducted throughout the Caribbean to determine sustainable practices for tourism development, which satisfy the aesthetic needs of the tourist while simultaneously preserving the coastal environments by adhering to set-back regulations. Similarly, tourism master-plans should be updated, in order to deter future developments being built directly onto flat low-lying beach areas near the ocean. Finally, communication, awareness and education programs should be implemented for all stakeholders, including policy makers, developers, local media, planners, architects, private sector and local residents.

Additionally, it is recommend that CARICOM nations consider managed retreat as a viable adaption policy for major coastal infrastructure, especially coastal tourism resorts. Managed retreated is essentially an adaption strategy which promotes the development of coastal infrastructure (particularly tourism infrastructure) away from identified vulnerable coastal areas (IPCC, 2007). Managed retreat also includes the physical relocation of existing vulnerable coastal infrastructure. When applied correctly managed retreat can protect people and new developments from long-term SLR impacts. Adaptation through retreat can yield extreme benefits, including the saving on coastal defence infrastructure (including hard and soft engineering). The challenge of managed retreat adaption policies is that it requires all stakeholders to participate for maximum results (IPCC, 2007). To my knowledge, no community in the Caribbean (or globally) has developed a comprehensive managed retreat plan for SLR. Unfortunately, for some Caribbean islands, managed retreat may represent the only option to reduce the loss of coastal infrastructure due to rising sea levels.

6.1.5 Future Research - Next Steps

While further studies have been recommended, specifically the continued development of geospatial datasets and impact indicators, this research has provided a first comprehensive overview of the threats posed by rising sea levels and storm surges in the Caribbean in the foreseeable future. The following section has provided a brief overview of some of the necessary components for updated and relevant future work. The first recommendation was the inclusion of higher-resolution DEM datasets, particularly from LiDAR which can cover large areas in a short time span. Secondly, additional studies at the local level are required to allow for detailed SLR modelling, which could aid in developing appropriate adaption options (e.g. managed retreat) and allow policy makers to provide public consultations with stakeholders and residents regarding both the short term and long term expected impacts of SLR. Thirdly, improved socio-economic data was recommended to allow for more detailed impact assessments on total levels of critical infrastructure and fragile coastal environments. Finally, adaptation strategies and policies were recommended both at the local and national scale.

6.2 Conclusions

There is relatively little dispute concerning the projections of climate change and its effects on sea levels, as established by the collected body of scholars and researchers referenced above. As long as emissions continue, the rate of sea level rise will increase accordingly (IPCC, 2007; Cazenave & Nerem, 2004). As discussed above, even in a best-case scenario global sea levels are expected to rise much faster than the IPCC-predicted levels of 18 to 59 cm between 1993 and 2100 (IPCC, 2007; Rahmstorf, 2007). Several studies have proposed that the aggregate effects of continental glacial melt off and thermal expansion will result in up two metres of flooding over the next 100 years (Vermeer & Rahmstorf, 2009; Rahmstorf, 2007; Nicholls & Cazenave, 2010). Similarly, any rise in sea levels creates a greater potential for flooding and erosion on coastal areas from storm surges (Simpson et al., 2010).

Studies investigating the impacts of rising sea levels have historically excluded SIDS due to a lack of available geospatial data. The purpose of the present study was to build upon previous SLR impact assessment research by using multiple datasets, and by incorporating updated elevation models for all CARICOM nations. As anticipated, the results of this research have clearly shown that rising sea levels in the Caribbean will have negative consequences for all CARICOM countries (especially SIDS) – affecting land area, coastal populations, urban areas, transportation infrastructure, local economies and key coastal tourism resorts. The effects throughout the Caribbean were not found to be uniform; the study identified the low-lying islands (The Bahamas, Caymans Islands, Turks and Caicos Islands) and continental countries with coastal plains below 10 metres (Guyana, Suriname, and Belize) as most vulnerable to any rise in sea levels. The study has also provided detailed analysis of beach erosion as it pertains to coastal tourism resorts and urban areas, with implications for property values, insurance costs, destination competitiveness, marketing and wider issues of local social and economic well-being. For government and business decision-makers in the Caribbean, climate change is a new strategic reality that they must begin to confront.

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Appendix 1: Data Description

Dataset: Coastline and Country Boundary
Source: The National Geospatial-Intelligence Agency (formerly Defense Mapping Agency) and NOAA/NASA
URL: http://gcmd.nasa.gov/records/GCMD_WVS_DMA_NIMA.html
Description:

The World Vector Shoreline dataset is a polygon dataset containing worldwide coverage of shoreline and international country boundaries at a nominal scale of 1 :250,000. The World Vector Shoreline is a product of the National Geospatial-Intelligence Agency (formerly US Defense Mapping Agency). The product covers the entire globe and was created primarily from source material form the DMA's Digital Landmass Blanking (DLMB) data which was derived from the Joint Operations Graphics and coastal nautical charts produced in part by the DMA. Future versions of the WVS dataset are set to include the high tide mark, for a more comprehensive dataset of global land cover.

Dataset: ASTER GDEM (Advanced Spaceborne Thermal Emission and Reflection Radiometer)
Source: NASA and National Geospatial-Intelligence Agency (NGA)
URL: http://srtm.csi.cgiar.org/
Description:

The ASTER is a Japanese sensor on board the Terra satellite, which has been collecting surficial data since February 2000. ASTER can provide high-resolution images (between 15-90 meters) of the Earth in 15 different bands ranging from visible to thermal infrared light. The ASTER Global Digital Elevation Model (GDEM) was publically released in June of 2009 throughout a joint operation with NASA and METI. The ASTER GDEM provides the most complete mapping coverage of the earth to date, covering 99% of the surface. Previous efforts by NASA's SRTM covered approximately 80% of the Earth's surface at 90 metre pixel elevation. In contrast the ASTER GDEM provides terrain elevation measurements on a global scale at 30 metre intervals (pixel resolution). However, unlike the SRTM DTM the ASTER GDEM does vary in accuracy estimates, and is still in the pre-production phase, labeled “experimental” or “research grade” by NASA and METI. Further work is currently being undertaken to improve the true accuracies of the dataset to improve spatial resolution of the entire GDEM. The data are in ARC GRID format, in decimal degrees and datum WGS84.

Dataset: SRTM DTM (Shuttle Radar Topography Mission)
Source: NASA and Japan’s Ministry of Economy, Trade and Industry (METI)
URL: http://www.gdem.aster.ersdac.or.jp/
Description:

The Shuttle Radar Topography Mission (SRTM) is an international research effort which combined digital elevation models on a large scale (56° S to 60° N) covering over 80% of the Earth’s surface. The SRTM Digital Terrain Model (DTM) was created from terrain data collected during an 11-day STS-99 mission conducted in February of 2000. As with many satellite derived DEM’s, initial versions of SRTM DTM contained data anomalies (cloud areas) and no-data areas, located mainly in mountainous and desert regions. The no-data areas accounted for no more than 0.2% of the total area surveyed on the initial STS-99 mission. However, collaborated efforts in the scientific communities, utilize void filling algorithms, resulting in a void-filled SRTM dataset. This study used the most current version the CGIAR-CSI (Consortium for Spatial Information) version 4, released in 2009. The CGIAR-CSI version 4 of the SRTM DTM provided data in 3 arc second (approximately 90 metre resolution) for 80% of the Earth’s surface. The data is also noted for contains gaps filled, making it relevant for hydrological modelling. The data are in available in ARC GRID, ASCII and Geo TIFF format, in decimal degrees and datum WGS84.

Dataset: GDP

Source: DECRG of the World Bank based on Sachs *et al.* (2001)
URL: http://data.worldbank.org/data-catalog (Updated GDP stats only)
Description:

The GDP dataset is a gridded dataset with a resolution of $5km^2$ which was produced by DECRG for the World Bank. The dataset contains total levels of economic activity on the national level, measured by the respected Gross Domestic Product (GDP). For the Caribbean, only a few countries contained GDP for sub-national levels. The DECRG applied these estimates to population density, using the World Bank estimates of GDP based on the Purchasing Power Parity (PPP) for 2000. For this study, PPP was applied for 2009 and 2010 estimates using World Bank economic estimates. The data are in available in ARC GRID format, in decimal degrees and datum WGS84.

Dataset: GRPWv3 (Gridded Population of the World, Version 3) and GRUMPv1 (Global Urban-Rural Mapping Project)
Source: Center for International Earth Science Information Network (CIESIN)
URL: http://sedac.ciesin.columbia.edu/gpw
Description:

The development of the GPW v3 was an effort from CIESIN staff, students at Columbia University and support from NASA under contract NAS5-03117 for the continued operation and development of data from SEDAC (Socioeconomic Data and Applications Center). The current version of the GPW v3 is a gridded raster dataset at a resolution of $1km^2$. The GPW v3 depicts the distribution of human population across the global which was derived from the GRUMPv1 (Global Rural Urban Mapping Project) dataset. The GRUMPv1 incorporates urban and rural information, which allows now insight into urban population distribution and global extents of human settlements on a global scale.

The GPWv3 and GRUMPv1 provide a globally consistent and spatially explicit human population information and data for use, in research, policy making and communications application (http://sedac.ciesin.columbia.edu/gpw).

The GPWv3 population estimates are provided for 2005, 2010, 2015 making it a highly variable, but updated dataset. The GRUMPv1 data remains current and is updated on an annually basis, with the most recent projects of global urban-rural land cover produced in 2011. The GRUMPv1 data are stored in geographic coordinates of decimal degrees based on the World Geodetic System spheroid of 1984 (WGS84), 30 arc-second (1km) resolution. While the GPWv3 data are stored at 2.5 arc-minutes (5km).

Dataset: GSHHS (Global Self-consistent, Hierarchical, High-resolution Shoreline Database)
Source: National Geophysical Data Center (NGDC) and NOAA
URL: http://www.ngdc.noaa.gov/mgg/shorelines/gshhs.html
Description:

The GSHHS dataset provides a high-resolution shoreline dataset amalgamated from several NGDC and NOAA datasets (15 million data points and polygons). The shoreline dataset also includes detailed smoothed information about inland-lake boundaries and rivers. The polygon dataset is provided at a resolution of 1 :250,000 (with a working scale at 1 :100,000 in the Caribbean). The most current version was released on July 15, 2011. The data are in available in ESRI Shapefile (.shp) format, in decimal degrees and datum WGS84.

Dataset: DIAFF (Digital Aeronautical Flight Information File) Global Airports / Runways
Source: NIMA (National Imagery and Mapping Agency)
URL:https://www1.nga.mil/PRODUCTSSERVICES/AERONAUTICAL/DIGITALAEROFLIGHTINFOFILES/Pages/default.aspx

Description:

The Digital Aeronautical Flight Information File (DAFIF) is a flight information data base which contains global aeronautical data related to airports, heliports, navigational aids, airspace, enroute and terminal data covering both high and low enroute structures. The NOAA website claims that the DAFIF is the "ONLY" compressive digital data available for pilots on a global scale (https://www1.nga.mil/). The following study utilized data pertaining to all airports located in the study site CARICOM nations along with detailed polygon datasets of airport runways. The vertical datum was set at mean sea level with a WGS84 horizontal datum. The data was provided in ESRI Shapefile (.shp) for both feature types.

Dataset: Major Roads
Source: LandInfo World Mapping VMap (Worldwide Vector Data v5)
URL: http://www.landinfo.com/
Description:

The LandInfo VMap dataset was provided from the University of Waterloo Mapping library, which has data sharing rights for the dataset. The VMap features were extracted from an extensive global digitization performed by LAND Info. The road data was provided at a scale of 1:250,000 . An extensive classification process of each road is provided. However, not all minor Caribbean roads are present. Therefore only "major highways" or national highways were included in the dataset to ensure consistent for this particular impact indicator. The data was provided in ESRI Shapefile (.shp) format with a WGS84 horizontal datum.

Dataset: Surficial Geography of the Caribbean Region (geo6bg)
Source: United States Geological Survey (USGS)
URL: http://pubs.usgs.gov/of/1997/ofr-97-470/OF97-470K/spatial/doc/html/geo6bg.html
Description:

The geo6bg data set contains polygons that describe the geologic age of surface outcrops of bedrock of the Caribbean region (including all CARICOM study nations). This includes geology, oil and gas fields, geological provinces and sediment type. The dataset was created by the U.S> Geological Survey's Central Energy Resources Team in Denver, Colorado in 2004. The original source maps to provide the data were collected at a scale of 1:2,500,000 and were digitized into a GIS. The data are available in ESRI Shapefile (.shp) format with a WGS84 vertical datum. Due to the coarse resolution of the dataset, the geo6bg was used a general reference when digitizing the Erodible Beaches dataset.

Dataset: Major Tourism Resorts
Source: University of Waterloo
URL: N/A
Description:

The major tourism resort layer was created in Google Earth Pro © and then converted to ESRI Shapefile (.shp) format for use in ARC GIS. The dataset was created by using municipal mapping websites, reality websites and Google Earth Pro © to identify all resorts in coastal areas that were below 10 metres of elevation (SRTM DTM). A total of 906 major resorts, hotels and villas were identified in the dataset. The dataset is provided in both point and polygon ESRI Shaplefile (.shp) format. Resorts were buffered by 50 metres to allow for identification of flooding in tourism areas. The data was provided in a WGS84 horizontal datum.

Dataset: Erodible Beaches
Source: University of Waterloo
URL: N/A
Description:

The Erodible Beaches layer was created using the USGS geo6bg dataset as a reference to identify areas in the Caribbean with erodible surficial geology. Beaches were digitized using

Google Earth Pro© which was then converted to ESRI Shapefile (.shp) format. In total, over 1,100 beach areas were identified in the analysis, amounting to over 1,000 km of CARICOM sandy coastlines. The data was provided in a WGS84 horizontal datum. This is the first micro level effort at digitizing sandy beaches throughout the Caribbean for use in a GIS.