Ecosystem-based Adaptation to Climate Change

A Cost-Benefit Analysis

<u>Team:</u>
Sarah Clark
Teo Grossman
Nick Przyuski
Cassidee Shinn
Danielle Storz

<u>Client:</u>
Conservation International
David Hole
Lee Hannah

<u>Faculty Advisor:</u>
Naomi Tague

Bren School of Environmental Science & Management
University of California at Santa Barbara

Ecosystem-based Adaptation to Climate Change
A Cost-Benefit Analysis

As authors of this Group Project report, we are proud to archive this report on the Bren School's website such that the results of our research are available for all to read. Our signatures on the document signify our joint responsibility to fulfill the archiving standards set by the Bren School of Environmental Science & Management.

PROJECT MEMBERS

____
Sarah Clark

____
Teo Grossman

____
Nick Przyuski

____
Cassidee Shinn

____
Danielle Storz

The mission of the Bren School of Environmental Science & Management is to produce professionals with unrivaled training in environmental science and management who will devote their unique skills to the diagnosis, assessment, mitigation, prevention, and remedy of the environmental problems of today and the future. A guiding principal of the School is that the analysis of environmental problems requires quantitative training in more than one discipline and an awareness of the physical, biological, social, political, and economic consequences that arise from scientific or technological decisions.

The Group Project is required of all students in the Master's of Environmental Science and Management (MESM) Program. It is a three-quarter activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Final Group Project Report is authored by MESM students and has been reviewed and approved by:

____

ADVISOR: Naomi Tague **DATE**

Table of Contents

Table of Figures

Abstract

The global climate is changing rapidly due to the accumulation of anthropogenic greenhouse gas emissions (GHGs) in the atmosphere. Planned adaptation is society's a priori defense against climate-driven threats. Conservation and development organizations are seeking a way to aid communities in their planned adaptation efforts, while trying to conserve ecosystems. These organizations are interested in the use of Ecosystem-based Adaptation (EbA), which is defined as reducing the impacts of climate change through the conservation and restoration of natural ecosystems. This project addresses planned adaptation to increased sea level rise and tropical cyclone variability for coastal communities in the South Pacific islands. Our project aims to fill the information gap pertaining to the economics of EbA in comparison to traditional engineered approaches to adaptation. Specifically, we assessed the role of mangrove forests and seawalls in coastal protection and conducted a Cost-Benefit Analysis to compare their economic efficiency.

Executive Summary

Overview

The global climate is changing rapidly due to the accumulation of anthropogenic greenhouse gases (GHGs) in the atmosphere, a fact supported by the Intergovernmental Panel on Climate Change (IPCC). The effects of this rapid climatic shift will be broad, diverse and felt across the planet in a myriad of ways. Strategic societal responses to climate change can be divided into (1) mitigation of GHG emissions and (2) adaptation to a shifting climate.

Adaptation responses will vary across the planet as a result of the range of possible future climate impacts. Conservation International (CI) is specifically interested in the role of Ecosystem-based Adaptation (EbA) and its relative value and effectiveness as compared to other adaptation approaches. Other comparable approaches can be placed into two main categories: hard and soft. The latter refers to policy changes and the former to engineered infrastructure.

Increased risk of coastal flooding is one of the potential impacts from climate change and there is a spectrum of adaptation strategies to lessen these impacts. South Pacific Islands are particularly vulnerable due to their high coastal population density, low-lying coastlines, and location in the cyclone belt. We specifically chose the island of Viti Levu in Fiji for a cost-benefit analysis case study because of the presence of both EbA and engineered adaptation approaches there.

Cost-benefit analyses can incorporate data on the economic realities of implementing EbA projects versus engineered projects in a particular country or region based on funding opportunities. Because EbA is a relatively new field of practice and inquiry, there are areas that are significantly lacking with regard to reliable data. Economic data, in particular, is sparse.

To address this problem we asked the following question: "What is the most economically efficient form of adaptation for climate driven threats to coastal communities of South Pacific Islands?" For our case study, we examined tropical storms in the South Pacific Ocean, where we modeled storm surges as the climate stressor. We chose to do so because literature supports that in many instances, storm surge represents the most destructive part of a tropical storm. We utilized mangrove forests as our representative Ecosystem-based Adaptation and seawalls as our representative engineered approach.

Methods

Our methodology for approaching this problem statement focused on two main components:

1. A storm surge to damages model that incorporated adaptation approaches
2. A Cost-Benefit Analysis (CBA) of adaptation approaches.

For storm surge damages we modeled changes in storm surge height under four IPCC storylines: A1F1, A2, B1 and B2. The model was based on historic surge return intervals and incorporated SLR, a change in storm intensity, and tides. In addition we modeled how each adaptation approach would reduce surge by incorporating a range of mangrove attenuation coefficients and seawall heights. We then modeled a relationship that could convert the height of a surge to the potential economic damage of that surge in Fiji.

In the CBA, we assessed the value of the surge reduction of each adaptation approach by finding the difference in damages between implementing each adaptation approach and a no adaptation scenario, which yielded a coastal protection value for both approaches. We then summed the coastal protection value, project costs, and mangrove ecosystem service co-benefits over a 40-year time horizon. Subtracting the costs from the benefits and then discounting allowed us to calculate the Net Present Value (NPV) for both mangrove and seawall projects. This CBA was the basis for our management recommendations.

Sensitivity Analysis

Due to the large degree of uncertainty in many aspects of the model, we incorporated a sensitivity analysis into the model. We chose to vary the protective capacity of the adaptation responses, the expected nature of future climate conditions, and the surge-to-damage relationship. Some of the most important findings are the various ways in which the model is or is not sensitive to the different variables and functions.

Results & Conclusions

After averaging across uncertainty in climate scenarios, adaptation effectiveness, and flood impact costs (among other variables) our model finds that the mean NPV for constructing seawalls is generally higher than it is for conserving or restoring mangrove systems. Within the range of uncertainty, there are scenarios in which mangroves outperform seawalls. In these scenarios, the mangrove forest would need to be mature and provide wave attenuation levels near the high end of our estimates.

It is important to note the difference between the physical and economic components of disaster modeling. A Cost-Benefit Analysis necessarily includes factors beyond the damage reduction potential of an adaptation project. Availability of investment and maintenance capital for these projects becomes an important consideration, given the large disparity between the costs of seawall construction (high) and mangrove conservation/restoration (low). While a high quality seawall may provide the greatest protection value, the costs for such a project may be out of reach for poorer communities. As a result, one of the key advantages to the EbA approach is their relative affordability and overall flexibility given a range of possible futures.

The single largest driver of variability in the model is tidal range. Since a manager can't control for these, the more important variability driver is the surge-to-damage function. A locally derived quantitative understanding of the economic risk associated with a given storm surge appears to be crucially important for determining accurate costs and benefit values. Note that the uncertainty surrounding future climate conditions does not impact the results of the analysis in any significant way.

Fundamentally, the project confirms that ecosystem-based adaptation approaches can have a role to play in the larger effort to adapt to a changing climate. As data quality increases a more rigorous comparison between seawalls and mangroves is possible. Obviously increased data quality allows decision makers to more confidently make management choices. Nonetheless, the utilization and interpretation of the results may vary given the decision-maker's mandate, their risk appetite, priorities and resources. These subjective forces mean that there is no one "right" recommendation from our results, but rather a suite of data that can contribute to more informed decision-making, particularly given better data in the future.

Significance of Project

The global climate is changing rapidly due to the accumulation of anthropogenic greenhouse gas emissions (GHGs) in the atmosphere. According to the Intergovernmental Panel on Climate Change (IPCC): "These changes in atmospheric composition [greenhouse gases and aerosols] are likely to alter temperatures, precipitation patterns, sea level, extreme events, and other aspects of climate on which the natural environment and human systems depend" (IPCC 2007). It is evident that such change is in fact already occurring (IUCN 2010, Chang 2011).

Short- and long-term biological, climatic and physical changes brought upon us by the current (and still rising) level of GHGs in the atmosphere require urgent consideration. Although adaptation to climate variability is not a new human endeavor, it has only fairly recently emerged as part of the general public discourse, which adds new and profound uncertainty to effective action. It is important to note that adaptation is a strategy separate from the direct mitigation of GHG emissions. Planned adaptation is society's a priori defense against risks caused by climate variability, whether those risks are to agricultural crops, flood plain communities, coastline integrity or any other number of resources. Adaptation will play a vital role in a world already committed to an estimated 2˚ C rise in mean global temperature. (IUCN 2010, Hansen 2008).

While global climate change will impact numerous systems, coastal regions represent a particularly significant area of concern. Global mean sea level is projected to rise by an average of 2-3 mm/year during the 21st century, although local impacts will vary (IPCC 2007). Low lying islands and coastal regions are likely to experience large-scale changes in the distribution of habitable land due to coastal inundation. The degree to which this coastal inundation will impact coastal communities will depend upon the realized level of relative sea-level rise (RSLR), taking into account land subsidence and tectonic activity, and the human populations and infrastructure that fall within the potential flood zone. To take coastal Asia as an example, there are 11 mega-deltas with an area of over 10,000 km^2 of extreme socio-economic importance as population-dense economic hubs, spanning a number of countries (IPCC 2007). According to the IPCC, under a conservative estimate of sea-level rise (40 cm), the number of people susceptible to coastal flooding in Asia will increase from 13 million per year to 94 million per year by 2050.

These staggering numbers only account for the relative contribution of sea level rise to coastal inundation and do not address the potential for increased tropical storm frequency and intensity. Increasing the frequency and severity of extreme climatic events can quickly transform an insignificant mean change in sea level rise into a substantial impact once storm surge is accounted for. There is some evidence (although the debate is significant) that since the 1970's hurricane destructiveness has increased due to longer storm lifetimes and greater intensities (Emanuel 2005). The increase in severity appears correlated with increased sea surface temperatures, a trend expected to continue (Emanuel 2005).

There is no panacea to the problem of increasing climate variability. There is significant uncertainty surrounding what successful adaptation looks like, what will be cost-effective and what is feasible to implement (Berrang-Ford 2011). This project addresses planned adaptation to climate-driven threats to coastal communities in the Pacific Islands. We conducted an economic analysis of the relative costs of two different adaptation options: a traditional engineered or built approach and an ecosystem-based adaptation alternative (EbA), in which the ecosystem services provided by an existing or restored natural system are utilized to serve the same function as the engineered alternative.

While in some instances climate impacts may be so severe or rapid that infrastructure enhancement or evacuation may be the only feasible options, there may be instances where EbA provides a cheaper, effective solution over the long run. In addition, EbA has a number of potential co-benefits associated with it through ecosystem service (ESS) provisions that make the approach attractive in comparison to well-documented negative ecological impacts of engineered coastal protection endeavors (Airoldi et al 2005, Stancheva et al 2011). The use of a cost-benefit analysis tool will help to begin uncovering patterns in the effectiveness or efficiency of different options over the long run.

Considering EbA as a possible alternative to engineered approaches is a useful exercise for decision-makers trying to balance conservation priorities with development pressures and risk reduction. With limited resources, efficient solutions to adaptation will be essential to saving lives and infrastructure, ensuring sustainable development and protecting biodiversity. From a policy perspective there is a substantial need to focus on "win-win" endeavors, particularly given the levels of uncertainty associated with the local impacts of global climate change. This project attempts to provide preliminary analyses, a strategic case study and a platform for future research.

Project Objectives

1) Given a range of possible scenarios for future climate change impacts, develop a model of the physical impacts and the associated economic damages of storm surges on the coast of Fiji.

2) Incorporate adaptation approaches (engineered and ecosystem-based) into the model and project economic damages avoided with the presence of each.

3) Conduct a Cost-Benefit Analysis comparing adaptation measures in Fiji that accounts for the Net Present Value of the EbA approach and the engineered approach.

Similar Projects

Because this is a relatively new field of research, there are very few projects that attempt the same set of comparisons as described above. Many endeavors focus on a single component of the larger question, but the beginning-to-end comparison of engineered vs. EbA approaches are few and far between. Obviously, societies have been responding to extreme weather throughout human history and many of these efforts are well documented (e.g. Orlove 2005, Dovers 2008). Efforts to document the economic value of coastal protection mechanisms from weather related extreme events such as hurricanes are also fairly well established, with a particularly good overview of the field by Nicholls et al 2010. Similarly, there is an increasing body of literature documenting the value of various natural systems explicitly for their adaptive capacity related to climate driven threats (Shepard et al 2011, Hale et al 2009, Kathiresan & Rajendran 2005). Coastal wetlands, particularly mangroves, receive substantial attention for their adaptive value (Adger et al. 2005, Hoang Tri et al 1998, Costanza et al 2008) and research on salt marshes & seagrass beds is increasing (Shepard et al 2011). The grey literature is also well populated, with UNEP, IUCN, Conservation International, The World Bank and others producing reports documenting the value of natural systems for their adaptive capacity and providing multiple case studies. However, efforts to document the intersection of these two approaches (economic aspects of coastal protection and the adaptive capacity of natural systems) in the peer-reviewed or grey literature are significantly lacking, likely due to the nascent development of the field and a dearth of reliable data.

Luisetti et al (2011) provide a glimpse of what a peer reviewed assessment of these types of projects looks like, performing a CBA for an EbA project involving two managed realignment and coastal wetlands restoration projects on the eastern coast of England. Managed realignment or retreat refers to the process of purposefully removing engineered coastal defenses to allow areas of land (often reclaimed from the sea to begin with) to become floodplains or tidal marshes in order to better protect other areas either further inland or along the coast. Managed retreat can be thought of as a form of EbA as it utilizes the buffering capacity of the newly created wetlands for the same protection as the previously existing engineered coastal defense. The paper is unique in the economic detail and spatial explicitness of the analysis, due to an uncommonly high level of available data. They find that the NPV of the projects is positive (a good sign) and increases as the time horizon increases to a 100-year timeframe. The authors are also careful to point out that their results should not be extrapolated elsewhere, given the high degree of local variability within the different case studies.

An additional set of related projects are those focused on valuing Ecosystem Services (ESS). In some ways, EbA research and analysis can be thought of as Ecosystem Services research and analysis viewed through a lens of climate change. In particular, the Natural Capital Project at Stanford University has been engaged in high level ESS work for years. They've recently developed the inVEST platform, a spatially explicit ecosystem services modeling software. inVEST includes a storm surge and inundation modeling component within the coastal protection module and discussions with the developers indicate that there are plans to add an economic component to the model (Mary Ruckelshaus, Managing Director, Natural Capital Project. Personal Communication, 2012).

The Field of Adaptation

Strategic societal responses to climate change can be divided into (1) mitigation of GHG emissions and (2) adaptation to a shifting climate. The physical realities of the climate change process are such that even if all GHG emissions ceased today, the climate forcing still in the pipeline points towards a global mean temperature increase of roughly 2° C (Hansen 2008). Given the projected pace and duration of climate change, adaptation efforts are currently seen as vital activities to complement climate mitigation.

Adaptation to local or regional climatic variability is a large part of human history (Orlove 2005). Societies have consistently dealt with periodic drought, flooding and large storms without full understanding of their timing or duration (Dovers 2008). However, there is a distinction between this in-the-moment style of adaptation and planned or prospective adaptation in which the trends in climate variability are relatively well understood within a given range of uncertainty. Prospective adaptation to climate change can rely on societal past and present-day experience to understand what approaches are feasible, effective and may potentially provide sufficient risk-reduction in the future.

Despite the rapidly growing interest in planned adaption and a fairly robust literature on the theory of adaptation, sophisticated and in-depth analysis and reporting on case studies and practical implementation is surprisingly sparse. In a recent meta-analysis of 1,741 articles on climate change only 87 were related to planned adaptation to climate change in human systems (Berrang-Ford 2011). The most recent IPCC Assessment Report also notes that reporting on climate adaptation has been haphazard (IPCC 2007). In addition, what planned adaptation has occurred has been mostly in developed countries and largely in areas such as the Netherlands under significant threat of sea level rise, limiting the scope of research (IPCC 2007, Berrang-Ford 2011). However, available information, analysis, and study is trending in the right direction, with additional resources emerging regularly.

Terminology of adaptation revolves around discussions of vulnerability, risk, susceptibility, adaptive capacity, etc. (Fussel & Klein 2006, Ionescu et al. 2009). Conservation International determines the ultimate impact of a climate threat by assessing an area's vulnerability, adaptive capacity and the particular threat in that area (David Hole, personal communication 2011). The IPCC Third Assessment Report (2001) defined a potential climate impact (see Figure 1) through a vector's exposure and sensitivity to that impact, combined with adaptive capacity (IPCC 2001).

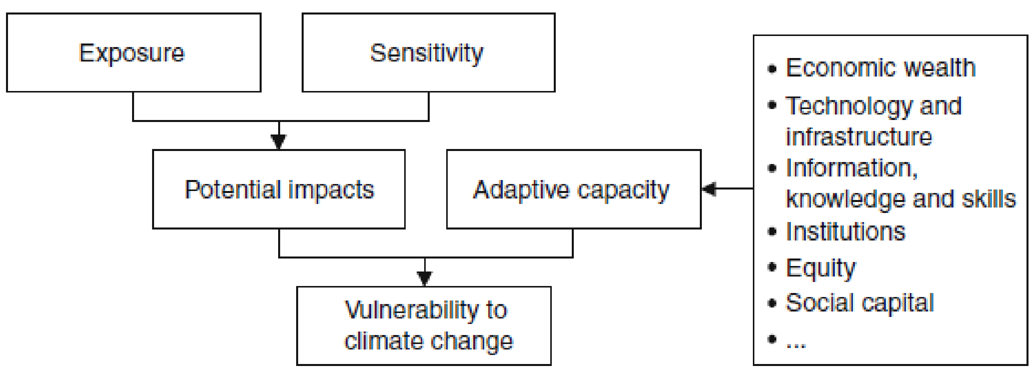

Figure 1. Defining a potential climate impact depends upon a vector's exposure and sensitivity to that impact in addition to its adaptive capacity (IPCC 2001)

Once a climate impact is defined, adaptation is still not a simple concept. Smit et al. (2000) explain: "As adaptation to climate change and variability has been subjected to more intensive inquiry, analysts have seen the need to distinguish types, to characterize attributes, and to specify applications of adaptation. For example, adaptation can refer to natural or socio-economic systems and be targeted at different climatic variables or weather events" (224). There are two main uncertainties that drive this classification of adaptation: variation and uncertainty in climate change itself and uncertainty about the vulnerability to a certain climate change impact in a given system and location. The IPCC Fourth Assessment Report (2007) states, "…the assignment of probabilities to specific key impacts is often very difficult, due to the large uncertainties involved."

Smit et al. (2000) approach adaptation as a three stage process, asking the questions: (i) adapt to what? (ii) who or what adapts? (iii) how does adaptation occur? They point out that "intervening factors" can cause the same climate threat to have different effects in two different areas (e.g. based on local infrastructure, geology, politics etc.), which is why it is crucial to define the system of interest including its location and scale. How adaptation occurs is equally important, including whether it is planned, prior to a climate impact, or a retroactive response (IUCN 2010, Smit et al. 2000).

At present, adaptation theory and, to some extent, practice has split into three categories:

- Soft (policy) approaches
- Hard (engineered) approaches
- Ecosystem-based approaches

Considering the location of large population centers and valuable economic activities on many coastlines as well as the saliency of the potential impacts, coastal protection has come to the forefront in climate change adaptation strategies (Nicholls 2004). As this project focuses on the risk and response to coastal climate stressors, the following discussion of adaptation approaches will focus exclusively on coastal zone adaption. It is generally accepted that the three most likely responses to increased coastal flooding are protection, accommodation, or retreat (IPCC 2007). Protection corresponds to hard & EbA approaches, while accommodation and retreat imply soft (policy) approaches. The efficacy of these responses depend upon on a variety of factors unique to the location of interest, including resource availability, capacity to implement, and financial ability for adopting the strategy, to name a few.

Soft Approaches to Adaptation

Soft adaptation refers to policy and behavioral shifts. It encompasses community-based plans, national policies, and international treaties for adapting to climate change and reducing vulnerability risks. Soft approaches are often the first adaptation step that vulnerable communities and countries take and can be used in conjunction with hard and EbA approaches. A common example is early warning systems, which operate at the community level. The elements of the system include: "risk knowledge, monitoring and warning, dissemination and communication, and the capacity to take appropriate action" (Buytaert et al. 2009). Flood or catastrophe insurance is also considered a typical soft approach, utilizing risk-based pricing signals to drive adaptive behavior. Some island countries are thinking beyond these options and focused on the worst-case scenarios of climate change, including the possibility of completely relocating communities and/or the whole country. Globally, many countries have made great strides in the last decade towards comprehensive goals and policies on this topic. The World Bank is already financially supporting numerous countries' soft adaptation projects and climate change mitigation plans (World Bank 2009). Additionally, the United Nations Development Programme (UNDP) and Global Environment Fund (GEF) jointly support international "Community-based Adaptation" projects. For example, one pilot project is focusing on integrating risk-reducing practices into community management of agro-ecosystems (Baldinelli 2010). The UN and GEF also provide funding for country level

National Adaptation Plans of Action, which are required to be filed by developing nations in order to access adaptation funding. Note that the scope of this project excludes the rigorous analysis or inclusion of a soft adaptation approach.

Hard Approaches to Adaptation

Hard approaches rely upon the creation and maintenance of man-made infrastructure. Common examples of hard approaches to aid communities in adapting to climate change include, but are not limited to, dams, irrigation systems, reservoirs, dykes, seawalls, levees, river channelization, and rip-rapping (river bank stabilization with rocks) (Sommer et al. 2001). Coastal inhabitants have frequently turned to engineering to protect communities from inundation. Infrastructure has ranged in complexity from simple sea walls designed as a breakwater for wave action to more intricate levee systems like those found in Denmark and New Orleans with sophisticated engineering designed to literally hold back the sea.

Hard approaches have been the approach of choice for more developed societies that can afford the technology and infrastructure. The World Bank funded a large international study on understanding the potential economic impacts of climate change to help vulnerable countries develop sound policies (The International Bank for Reconstruction and Development & The World Bank 2010). These studies highly favored hard approaches. Yet, research has begun analyzing whether hard approaches are the most cost-effective and risk-reducing when compared to the other two approaches. In particular, there is a significant expense associated with most large-scale engineering projects as well as various associated negative impacts from these efforts.

In certain instances, engineered infrastructure is the only available option. One recent example is the MoSE system under construction in Venice, Italy. These massive floodgates are intended to prevent the city and its inhabitants from severe flooding from the rising seas and the land subsidence occurring under the streets (UNESCO 2000). The hydraulic-powered, mobile floodgates lay flat on the lagoon floor so long as normal tidal conditions are present but are designed to self-deploy if the tide reaches a height above one meter (UNESCO 2000). In this sense, the gates are designed to allow natural tidal flow up to a certain threshold. The price tag for the MoSE is estimated at $2.6 billion, not including maintenance, and rising (Parry 2009). Obviously this level of funding is not typically available for coastal infrastructure construction, especially in the developing world.

In the developing world, there have been some large-scale projects to mitigate the effects of coastal flooding although they appear to be the exception rather than the rule. One example is the Safe Island Project recently completed near the Maldives. This initiative converted an uninhabited island into a fully functioning relocation community for over 6,000 tsunami-displaced citizens of the Maldives. The total relocation and construction effort cost was approximately $45 million (Riyaz & Park 2010).

Not all coastal engineering projects involve relocating whole island communities or building large-scale automatic floodgates. Where vulnerability is less severe, small-scale projects can be completed for much lower costs. For instance in Vietnam, infrastructure enhancement for Cai Lan and Hai Phong, is estimated to be $2 billion and $3 billion dollars, respectively, to raise the height of quay walls, improve drainage systems, and increase the maintenance of port structures (EACC report 2010). In some cases, these figures are still considered high and one attractive aspect of ecosystem-based adaptation is the reduction in these maintenance costs.

Hard infrastructure in the coastal zone often conflicts with the natural processes in the region leading ultimately to a reduction in ecosystem health and the services these systems provide (Hsu et al. 2007). For example, studies of coastal armoring via seawalls or breakwaters indicate physical impacts including increased levels of erosion downdrift and sediment delivery disruption as well as ecological disruptions including significant near shore habitat degradation, reductions in regional species diversity and an increase in non-native and potentially invasive species (Airoldi et al 2005, Stancheva *et al* 2011).

Ecosystem-based Adaptation

Conservation International defines Ecosystem-based adaptation (EbA) as: "…the use of natural systems as a way to buffer the worst impacts of climate change, maintain the resilience of natural ecosystems, their ecosystem services and the species that support them, and help people adapt to changing conditions" (CI 2011). EbA seeks to mitigate the impacts of climate change through the conservation and restoration of natural ecosystems. Natural ecosystems tend to be inherently resilient to environmental change, although the degree to which they can cope is situation dependent; where as man-made infrastructure tends to be constructed for its rigidity. EbA is seen as a potential win-win option by many conservation organizations due to a belief that "biodiversity can (and should) play a role in societal adaptation [to climate change]" (IUCN 2010). It should be noted that, while outside the scope of this study, adaptation of natural systems for their own sake is of equal interest in the academic arena (Berrang-Ford 2011).

In addition to assisting society to adapt to a particular climate stressor, ecosystems provide natural capital such as timber products, clean water, and fisheries upon which populations depend (World Bank 2009). These additional ecosystem services are also commonly referred to as 'co-benefits', because they are attained 'for free' alongside the specific adaptive function in question. The co-benefits associated with EbA are seen as one of the major advantages to the approach (IUCN 2010).

As any restoration of ecosystems likely involves some human engineering, a dividing line must be drawn between this and engineered infrastructure. This project delineates the difference by defining engineered or hard adaptation as: "The implementation of planned, man-made infrastructure to mitigate the impacts of climate change."

EbA for Coastal Protection

It has been suggested that wetlands, mangroves, oyster reefs, barrier beaches, coral reefs, and sand dunes can protect coastlines from flooding and storm surge in a more cost effective manner than traditional engineered infrastructure (Adger et al. 2005).
In coastal Asia, conservation and restoration projects focused on mangrove forest and coral reef ecosystems have received substantial funding for their ability to protect low-lying coastal areas from coastal flooding. According to the Ramsar Convention on Wetlands (2005), mangrove forests provide approximately $300,000 per kilometer in coastal protection for Malaysia (World Bank 2009).

Healthy coral ecosystems in tropical Asia have become the focus of conservation groups not only for their high biodiversity but additionally for their ability to shelter coastlines (World Bank 2009). Coral Reefs have long been thought to attenuate wave action through increasing the frictional drag, generated by the bottom topography, on wave energy. Sheppard et al. 2004 found that the coastline of the Seychelles Islands that was protected by reef fronts greater than 500 meters in width experienced reduced wave energy hitting the shoreline by an order of magnitude when compared to reef fronts less than 100 meters in width. Previous studies have shown that in addition to reef width and rugosity, the frictional drag imposed on wave energy increased as a function of live coral cover (Sheppard 2004).

In some cases, EbA is used in conjunction with infrastructure to ensure both protection of coastal inhabitants and their livelihoods. In Vietnam, the Vietnamese Red Cross, in cooperation with the Danish and Japanese Red Cross, recently finished a nine-year mangrove replenishment project that restored over 18,000 hectares of mangrove forest along 110 kilometers of the coastline (IFRC 2002). The new mangrove forest was planted on the seaward edge of a 3200-kilometer sea dyke system for a total cost of $4.35 million. Thus far, the mangrove forests have saved an estimated $7.3 million per year in sea dyke maintenance and substantially reduced the destruction caused by Typhoon Wukong in 2002 (IFRC 2002).

Because EbA is a relatively new field of practice and inquiry, there are areas that are significantly lacking with regard to reliable data. Economic data, in particular, is sparse. These data are increasingly necessary if decision makers are to consider investing in EbA approaches for their communities. Cost-benefit analyses can supply data on the economic realities of implementing EbA projects in a particular country or region based on funding opportunities. Cost data is crucial to both seek finances for and evaluate the efficacy of climate adaptation plans. To move forward with projects, "Innovative financial mechanisms are needed…but remain challenging because of the complexity of evaluating adaptation costs and benefits, and the sensitivity of political negotiations related to international adaptation finance" (Vignola et al. 2009: 692), emphasis added. Martin et al. 2009 add, "There is an urgent need for more detailed assessments of these [adaptation] costs, including case studies of costs of adaptation in specific places and sectors" (7). Practical limitations in data such as these present serious impediments to implementation of EbA by limiting project managers' abilities to demonstrate feasibility.

Fiji Background

Figure 2.1 The Fiji Islands (Fiji Visitors Bureau, 2000)

Figure 2. Map of The Fiji Islands (Fiji Visitors Bureau, 2000)

Fiji Demographics:

The Republic of Fiji is an island nation consisting of more than 320 islands, 105 of which are inhabited, dispersed across an area of 1.3 million square kilometers (SOPAC Fiji Country Profile & World Bank 2000). Fiji's total land area is approximately 18,274 square kilometers, of which 87% is contained in two main islands, Viti Levu (10,400 km2) and Vanua Levu (5,540 km2). (CIA Factbook). The capital city of the Fiji Islands is Suva, located on the southern shore of Viti Levu. On Viti Levu, approximately 86% of the 750 kilometers of coastline lie less than 5 meters above mean sea level (World Bank 2000).

According to the 2007 census, Fiji's annual population growth is 0.8 percent and the total population was nearly 840,000 (statsfiji.gov.fj). Approximately 70% of the population lives on Viti Levu, making it both the political and economic center of the nation (Agrawala et al 2003 & Climate Change The Fiji Islands Response 2005). Despite increasing urbanization, the population is split almost uniformly between the urban and rural sectors. Whether urban or rural, approximately 90% of Fiji's population may be considered coastal dwellers (Fiji National Paper 2002).

Economy:

The economy of the Republic of Fiji is diverse with a strong tourism service sector as well as diverse industry sectors including sugar, agriculture, garment and mining (SOPAC Fiji Country Profile). The largest fixtures of the Fijian economy are the production and export of sugar cane and the tourism sector. In 2010, the GDP of Fiji was US$3.869 billion. Of this, 16.1% came from agriculture and 24.4% came from industry. In 2001, agriculture and industry/services employed 70% and 30%, respectively, of the labor force (CIA FACTBOOK).

Climate:

Fiji has a tropical marine climate with only slight seasonal variations in daily temperatures aligning with the wet (20-20.5^{o}C) and dry seasons (23.8-31^{o}C) (Fiji Meteorological Service 2003). The annual wet/dry season annual cycle from November to April and May to October, respectively, is highly dependent upon the position of the South Pacific Convergence Zone as well as ENSO phase conditions (World Bank 2000).

Coinciding with the traditional wet season, large-scale precipitation events occurring during tropical cyclones are common on Fiji between November and April. In fact, the highest concentration of South Pacific cyclones occurs in Fijian waters (Agrawala et al 2003). These heavy precipitation events frequently cause inland and coastal flooding. During disaster years, Fiji has reportedly lost F$20 million per year from 1972-2004 and up to F$170 million per event due to cyclone and other storm damage (Feresi et al. 1999).

Climate Projections:

Fiji is a Small Island Developing State (SIDS). As such, it is particularly susceptible to the impacts of climate change and only a minor contributor to the global climate change drivers. The results of two separate General Circulation Models (GCMs) the CSIRO9M2 and the DKRZ are commonly used to model the potential impacts of climate change for Fiji (Figure 3) (Climate Change the Fiji Islands Response 2005). The CSIRO9M2 has been validated for the South Pacific Region and the DKRZ typically displays an alternative for the expected precipitation regime for the South Pacific (Climate Change the Fiji Islands Response 2005).

Global sea level rise (SLR) projections are the best available indicators of the impact of rising seas on the Fiji Islands. Investigators typically choose two emission scenarios – an extreme, worst-case scenario (A2) and a mid-range (best guess) scenario (B2) (Figure 4) from the IPCC Special Report on Emission Scenarios (SRES) (Climate Change The Fiji Island Response 2005). The A2 scenario describes a world in which the global population is continuously increasing and the per capita economic growth is fragmented and slower than in other scenarios. The B2 storyline also displays a continuously increasing global population but at a much slower pace than the A2 storyline and the economic growth per capita occurs at a slower rate, relative to the A2 storyline, with an emphasis placed on environmental protection and social equality (IPCC 2007).

GCM	Emissions Scenario	2025		2050		2100	
		Temp [°C]	**Rainfall [%]**	**Temp [°C]**	**Rainfall [%]**	**Temp [°C]**	**Rainfall [%]**
CSIRO9M2	**B2 (mid)**	**0.5**	**3.3**	**0.9**	**5.7**	**1.6**	**9.7**
	A2 (high)	**0.6**	**3.7**	**1.3**	**8.2**	**3.3**	**20.3**
DKRZ	**B2 (mid)**	**0.5**	**-3.3**	**0.9**	**-5.7**	**1.6**	**-9.7**
	A2 (high)	**0.6**	**-3.7**	**1.3**	**-8.2**	**3.3**	**-20.3**

Figure 3. General Circulation Models (GCMs) for Fiji

Year	2025	2050	2100
Scenario			
B2 (mid-range, best guess)	**11 cm**	**23 cm**	**50 cm**
A2 (high-range, worst case)	**21 cm**	**43 cm**	**103 cm**

Figure 4. IPCC Storylines for SLR

Broadly applying these SLR numbers to the Fiji Islands is inappropriate due to localized areas of uplift and subsidence (Nunn 1990, Nunn & Peltier 2001). The volcanic nature that formed the islands is still at work in certain areas and the relative levels of uplift and subsidence varies within the island chain as a whole and even between individual islands.

Rainfall and tropical cyclone activity are another correlated set of climate change stressors that will potentially impact the coastal communities of Fiji. However, the GCMs are too coarse to reliably predict the change in either and cannot yet account for the changes in ENSO variability, which is a large driver of both (Agrawala OECD 2004, Climate Change The Fiji Islands Response 2005).

Tides, Waves & Surges

Researching the effects of storms on a coast requires an understanding of tides, surges, waves, their interactions and their contribution to a storm's damage potential. Varying combinations of these parameters may also demonstrate which adaptation approach is most cost effective for protection. Water level, or still water level, is the combination of the astronomical tide, surge and wave setup. Extreme water levels occur when the tide is at its highest and there is a positive surge. Additionally, the wave climate will have a localized effect on the increase of water levels.

Tides

Tide is the varying height in water levels observed throughout the day. Gravitational forces from the sun and moon, the earth's rotation, and local bathymetry determine tidal fluctuations (Besley 1999). Locations that only experience one high and one low tide in a 24-hour period have a diurnal tide. Suva Peninsula experiences a semi-diurnal tide, where there are two high tides and two low tides every day, which are usually of unequal magnitude (Solomon & Kruger 1996). The compounding gravitational effect of both the sun and moon simultaneously results in the maximum tidal range, called the spring tide. Conversely, when the tide's range is at its minimum, it is called the neap tide. The spring-neap cycle corresponds to the half period of the lunar cycle (Besley 1999). In engineering designs for coastal protection, the spring high tide is used to represent extreme water levels for 'worst case' scenarios. Additionally, because tides are correlated with the repeated rotation of the earth and gravitational effects, tide levels are easier to predict. Regional tide charts are widely available, including one for Suva Peninsula.

Estimating a storm's damage potential is complicated by tides. Storms can occur at any time, therefore at any tide level. Although a high percentage of storms will occur during a median tidal level, there are chances that they will hit during a high spring tide.

Waves

Waves are characterized by the parameters of height, period (or frequency) and direction. Ocean waves have a typical range of wave periods from 2 seconds (short wind waves) to 25 seconds (long swell) (Barstow & Haug 1994). A swell consists waves that are barely, if at all, affected by the local wind, and have been generated elsewhere or not recently. Waves caused by underwater impacts of earthquakes, landslides, or volcanic eruptions are called tsunamis. Note that wind-driven waves are the most common and relevant to this analysis and are therefore are described in more detail.

Waves generated by wind depend on the wind speed, fetch (distance over which the wind acts upon) and duration of the wind in a given direction (Barstow & Haug 1994). Bathymetry, currents, refraction (wave redirection), and shoaling (surface waves entering shallower water will increase wave height) will affect wave set up, and ultimately water levels too (Besley 1999). Furthermore, waves have kinetic energy, which moves in the direction of the wave. They also affect the potential energy of the water column (World Meteorological Organization 1998). As waves break on a reef or shore, that energy and momentum are transferred causing a drop in water level at the point of breaking, but an increase in water level that approaches the shore (Solomon & Kruger 1996).

Wind waves are classified as either capillary, standing, or breaking (Kortenhaus et al. 1996). Capillary waves are the ripples seen on the surface of water when the wind blows. Standing waves remain in a constant position because of a collision between waves in opposing directions (Kortenhaus et al. 1996). These usually are the result of waves reflecting off seawalls, ships, or other structures. A breaking wave is one whose base (trough) can no longer support its top (crest) due to increased wave height and instability, causing it to collapse. Breaking waves are further categorized down to spilling or plunging, based on their breaking characteristics (World Meteorological Organization 1998).

Wave breaking is a difficult phenomenon to model and the physics of it has yet to be fully realized (Besley 1999). Nevertheless, the wave climate of locations should be considered when evaluating coastal protection measures. Waves have the ability to transfer a lot of energy and are therefore important forces acting on coastal protection structures via overtopping (described below) and the movement of sediment (Besley 1999). Parameters describing individual waves, such as wave volume, speed, and period, are useful in estimating the resiliency and stability of coastal armoring approaches (Hughes & Nadal 2009).

Surge

A storm surge is different from other coastal impacts such as waves and tides. The National Oceanic and Atmospheric Administration defines storm surge as: "an abnormal rise of water generated by a storm, over and above the predicted astronomical tides" (NOAA "Overview"). Normally this number is the difference in water level above local mean sea level. When the absolute water level is included a storm surge is referred to as a storm tide, because the tide level is included (Figure 5 & 6). Storm tide is used to make it simpler to visualize the height of water reaching the coast. However, storm surge serves as a better unit of comparison for multiple storm surges since they will have occurred at different tide levels.

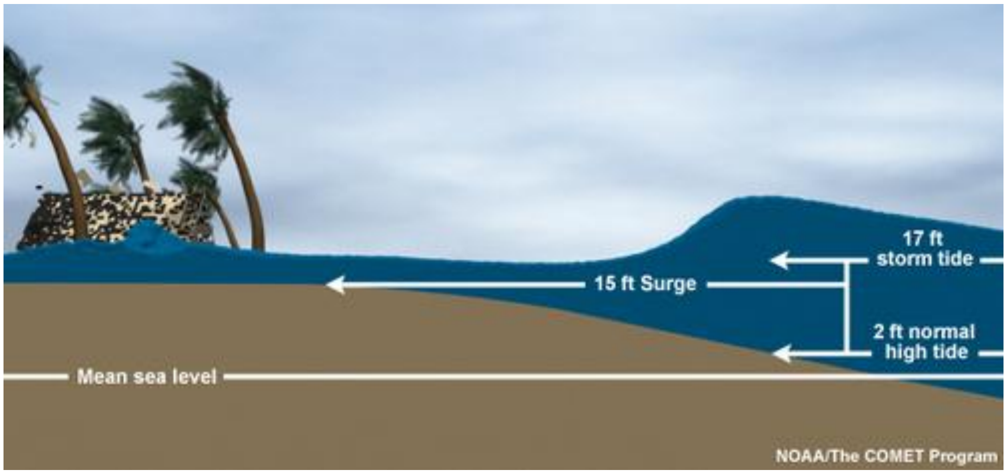

Figure 5. Diagram of the relationship between tide, storm surge and storm tide

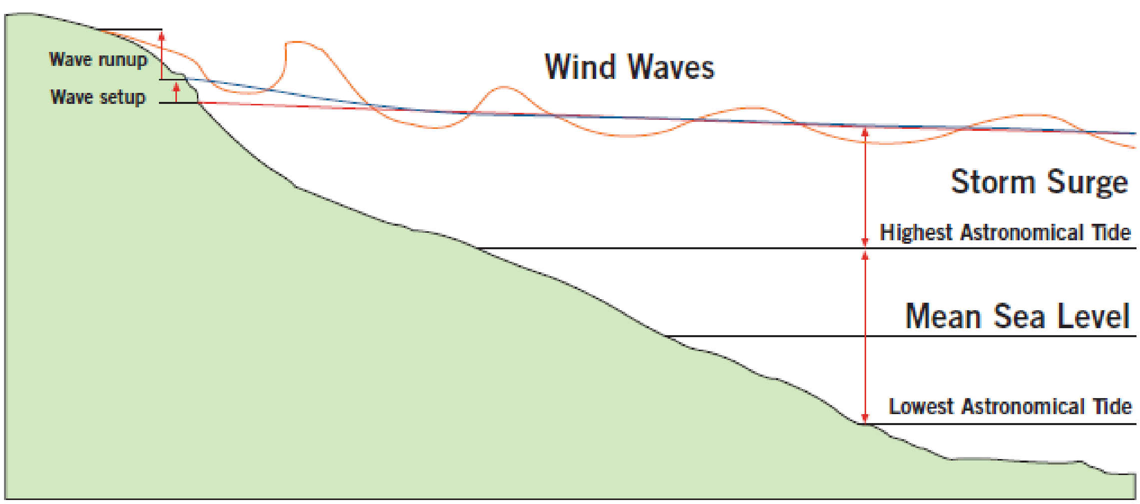

Figure 6. SPSLCMP "Extreme Events"

The height of a storm surge is determined by many factors. These include: storm intensity, forward speed, size, angle of approach to the coast, central pressure, the shape and characteristics of coastal features, and width and slope of the continental shelf (Figure 7) (NOAA). The biggest determining factor of surge size however is wind. High-speed winds during a tropical storm push water towards shore and can create extremely high waves (FEMA 2010).

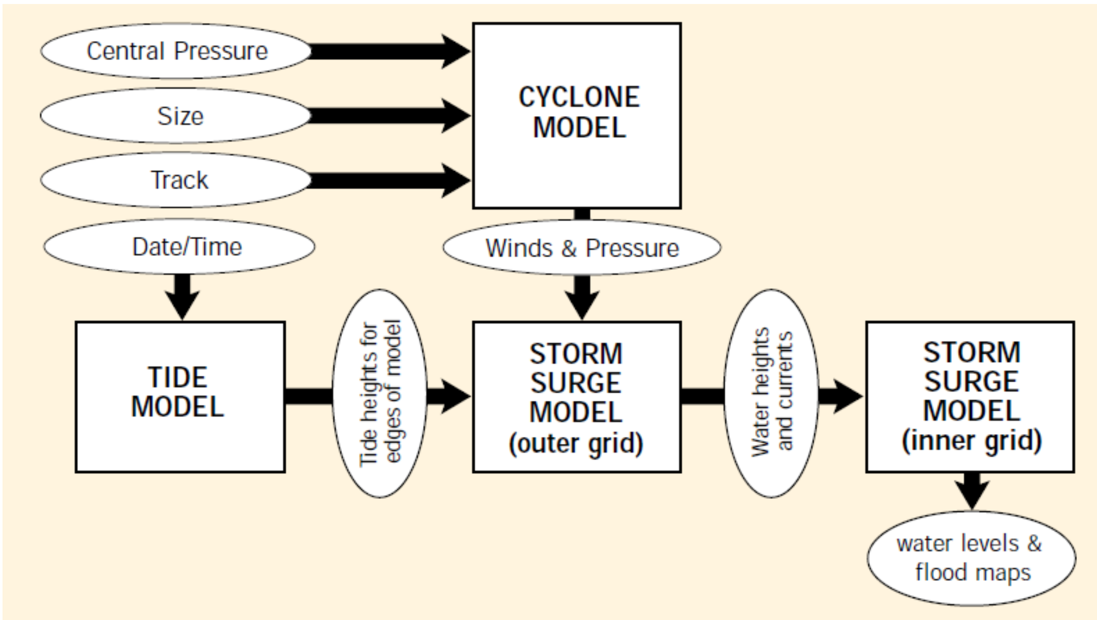

Figure 7. Theoretical parameters of a storm surge model (SPSLCMP "Modeling")

There are a number of reasons for concern over storm surge. The first is the creation of battering waves. Surge adds volume to waves and tropical storms add velocity—the consequent wave action on shore has the power and depth to destroy property and take lives. The density and type of coastal development affects how devastating battering waves actually are to a locality's people and economy.

An additional major concern is erosion from storm waves and currents pushed onshore by a surge. Erosion is a natural coastal process in which beaches lose and gain sand cyclically based on changing wave action (Holden 1992). However during a storm surge this wave action is pushed onshore atop a dome of elevated water that inundates the coast. Undercutting can weaken building foundations, destabilizing the built environment and altering the landscape.

Wave Climate in Fiji

Suva Peninsula and the greater Fijian Islands experience waves originating from several different wind systems including local trade winds, distant storms in the Pacific Ocean, and from tropical cyclones (Barstow & Haug 1994). From monthly climatology data, wind speeds are found to be the lowest in January-March (summer) and highest in July-August (winter) (Barstow & Haug 1994). The Southern Oscillation Index (SOI) and El Niño events are also influential on the winds. Severe El Niño events have been correlated to an increase in southeasterly winds throughout the year, especially during summer. Additionally, positive SOI tends to give more frequent northerlies during summer (Barstow & Haug 1994).

These various wind sources influence the local wave climate. The highest monthly mean wave heights are expected during mid-winter, correlating with when average wind speeds are highest and are more southeasterly (Barstow & Haug 1994). However, the waves heights show consistency throughout the year because of the island's location near equatorial waters (Barstow & Haug 1994). The most important source area for ocean swell observed on the southern shores of the Fijian Islands is the region of higher latitudes to the south and southwest (Barstow & Haug 1994). The swell influx tends to be highest in the winter, also contributing to higher wave heights during that season (Barstow & Haug 1994). Mean wave periods show a seasonal variation. Wave periods are also somewhat higher in winter, reflecting the greater long-period swell contribution in those months (Barstow & Haug 1994).

Seawalls

There are various forms of hard approaches, or engineered structures, for coastal protection. This study utilizes seawalls as the representative hard approach. Seawalls were chosen for two reasons. A literature review of Fiji's coastal protection structures uncovered significantly more information on seawalls than other forms of coastal protection. Beyond the data constraints, there was also a time constraint and, in order to conduct a more comprehensive analysis, only one hard approach was chosen.

A seawall is a static rigid structure that runs parallel to a coastline and is often built somewhere in the beach profile. They reflect wave energy back to the sea, therefore reducing or preventing wave energy from reaching the coastline. Their function is intended to protect the beach, upland structures, and property from larger than normal surges and waves generated during storms (Walton and Sensabaugh 1979). They have also been constructed to reduce or eliminate beach erosion, a use that is significantly debated within the scientific community (Airoldi et al 2005).

The design of a seawall depends on the location and a design storm's conditions. A design storm is usually a 20 to 50-year storm event. Historical data provides accompanying wind speeds, surge levels, and wave heights for these storm events, which is used to determine design loads (Clark 1982). Design loads are the forces that structures are subjected to and are built to withstand (American Society of Civil Engineers 2005). Seawalls are built to withstand select hydrostatic, hydrodynamic, wind and wave loads (American Society of Civil Engineers 2005). According to Clark 1982, hydrostatic load is "the lateral and vertical (including uplift) forces resulting from a mass of water standing either above or below the soil surface." Hydrodynamic load is the force generated by a moving mass of water, like the flow of a storm surge (Figure 8). The astronomical tide, waves, and the storm surge are all responsible for the movement of the water mass, and are therefore included in the hydrodynamic load computations (Clark 1982). Wave loads are forces that result from waves striking or flowing over a structure (American Society of Civil Engineers 2005). Wave loads account for various factors, including wave-induced drag and inertia, wave-induced scour, uplift forces, wave run-up, and whether the waves are breaking. Wind load is the force generated by a particular wind speed and pressure (American Society of Civil Engineers 2005). Other design considerations include the structural siting, foundation, crest (top) and toe (bottom) elevations, and slope (Clark 1982). Secondary, yet still important, is considering the seawall's expected scour, impact on the beach and dune system, and impact on the adjacent properties (Clark 1982).

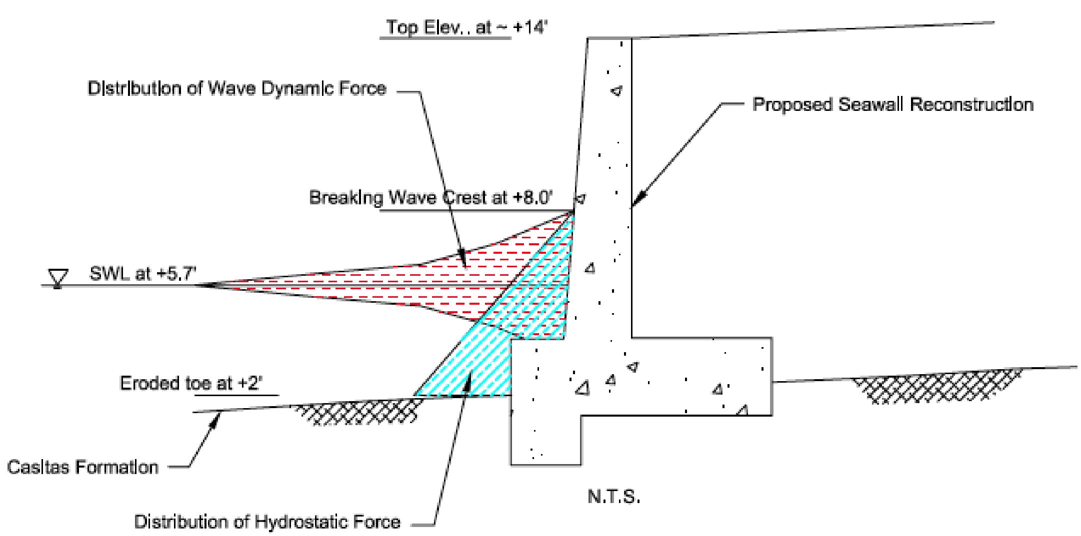

Figure 8. Example of a diagram of forces on a seawall (NOBLE)

Types

There are three types of seawalls: vertical, curved, and mound. Vertical seawalls are the easiest designed and constructed, but forces more heavily impact them, resulting in a shorter life expectancy. Curved seawalls are the most effective type in reflecting energy and waves, but require more complex engineering and construction. Mound seawalls are designed with porous rock and concrete, making them cheaper, but are less effective in protecting against high impacting forces. Thus, there are tradeoffs in choosing a type of seawall. Furthermore, they can be constructed with different materials, including wood, boulders, cement and steel. Availability, cost, and seawall design determine which material is employed.

Interest in protective measures against storm surges and sea level rise has lead to research on the efficacy of seawall. In order to be able to react more rapidly and to better protect, the performance of existing structures and their design must be researched (Kortenhaus et al. 1996). Seawalls are designed to reflect wave energy and reduce wave overtopping associated with the minimum design storm, but it's important to understand what happens when the design loads are surpassed.

Wave Overtopping

Wave overtopping is the movement of water over the crest of a seawall. Hughes and Nadal (2009) described three types of overtopping: "(a) intermittent overtopping by wind-generated waves when the still water level is beneath the elevation of the crest; (b) overflow when water levels are above the crest, but wave activity is absent; and (c) combined wave overtopping and storm surge overflow when the still water level is above the crest elevation". For a comprehensive analysis of 'worst case' scenarios, the combined wave overtopping and storm surge overflow should be examined.

Calculating wave overtopping allows for the evaluation of seawalls' efficacy in reducing the amount of water that reaches a coastline. Essentially, the volume of wave overtopping could equate to a reduction in storm surge and as seawalls' coastal protection value. The accurate numerical modeling of wave overtopping is very difficult because of the dynamic and complex nature of waves and their interaction with the seawall, including wave breaking, reflecting, shoaling, plus any additional wind effects (Hu et al. 2000). Furthermore, overtopping is locally variable and difficult to estimate given the different storm sizes and wave generation and their interaction with the variety of seawall types. Despite these limitations, methods have been derived to examine the overtopping performance of seawalls. Necessary data to employ these equations includes the still water level (usually available from tidal gauge data), significant wave height (the average height of the highest one-third waves in a wave spectrum [Ainsworth]), wave periods, and the dimensions of the seawall (Besley 1999).

Seawalls of Suva Peninsula

In 1996 ground surveys were performed to produce a map of the Suva Peninsula coastline. These researchers also compared aerial photographs from 1954 to 1991 to detect changes in shoreline position and infrastructure, including seawalls (Solomon & Kruger 1996). Their results showed that 51% of the 19km of coastline surveyed were armored with seawalls (Figure 9). They noted that changes on the coastline were dominated by human activities related to urbanization, especially the increased construction of seawalls and revetments (Solomon & Kruger 1996). Data from Fijian village surveys also revealed that seawall construction was rare before 1960, but they rapidly increased during the following decades (Table 1, Mimura and Nunn 1998). Mimura and Nunn (1998) suggest the reasons are smaller population sizes and more natural shorelines with mangroves and other coastal vegetation.

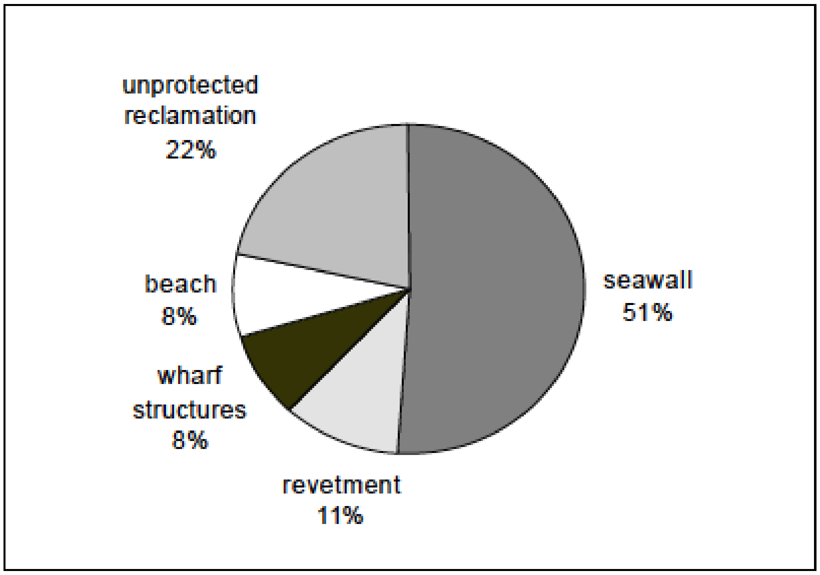

Figure 9. Constituents of Suva Peninsula shoreline (Solomon & Kruger 1996)

Study Areas		No. of Surveyed Villages	Existence of Seawalls		Period of Seawall Construction*			
			Seawalls	No Seawalls	Before 1960	1960's	1970's	1980's
Viti Levu	Subsiding area	2	2	0		2		
	South coast	9	7	2	1	1	2	3
	West coast	3	3	0				1
	North coast	1	1	0				
	East coast	10	8	2		1	4	2
	Subtotal	25	21	4	1	4	6	6
Taveuni		4	4	0		3		1
Total		29	25	4	1	7	6	7

* Villages in which the period of seawall construction was unclear are not included

Table 1. Seawalls in Fiji

Despite the lack of seawalls prior to the 1960s, Fijian people have constructed rudimentary structures with piled up sediment and stones, and placed sticks along the beach to form a fence (Figure 10, Mimura and Nunn 1998). Though these had much shorter lifespans, the people “sought nothing more sophisticated” (Mimura and Nunn 1998). With the availability of new materials and changing cultural conditions, there was a transition to seawalls.

Figure 10. Traditional coastal protection with wooden poles (Mimura and Nunn 1998)

In present day the seawalls along the Suva Peninsula are typically vertical and built with concrete or mortared blocks, as seen in Figure 11 (Mimura & Nunn 1998, Solomon & Kruger 1996). The literature review provided a few references to the heights of Fijian seawalls (See Reference Section). Less information is available for other seawall dimensions and design parameters, like their width and foundation, and their location on the beach profile. Many rural communities were eager to reduce the erosion of their coastlines so they built seawalls without any engineering advice (Nunn 2009). In most cases, design seems to have been a consideration of secondary importance to raw materials available (Mimura and Nunn 1998). Solomon & Kruger (1996) noted that the seawalls frequently lacked adequate foundation, were too low, or too porous. That, in return, reduces their effectiveness and lifetime because they are susceptible to undermining and collapse (Solomon & Kruger 1996). These structural conditions result in more maintenance costs and more frequent replacement (Solomon & Kruger 1996).

Figure 11. Vertical seawall in Fiji (Mimura and Nunn 1998)

Wave overtopping of the seawalls on the Suva Peninsula is common, supporting Soloman & Kruger's (1996) opinion that their heights are too low. On the west side of the peninsula, overtopping of seawalls and shorelines will occur during most storms (Solomon & Kruger 1996). On the east coast, seawalls of the lower elevation shorelines are overtopped during all storms as well. The mean and higher elevations of this coast are overtopped only during the more severe events (which the authors consider as 10-year return interval storms or greater) (Solomon & Kruger 1996). Furthermore, overtopping has been recorded in some locations during high tides and increased winds, not associated with a storm (Solomon & Kruger 1996).

The costs to design, construct, and maintain seawalls can be expensive, and therefore beyond the means of many rural coastal communities (Nunn 2009). These projects can also take a lot of the villagers' time to construct (Mimura and Nunn 1998). Building materials, like rocks, are often locally available and the Fijian government has sometimes supplied cement for coastal protection projects, which reduces the costs (Mimura and Nunn 1998). Damaged seawalls may be repaired or rebuilt if funds and materials are available, but more commonly such damaged seawalls remain in a state of collapse (Nunn 2009).

Environmental Impacts

As the need to protect land and property from sea level rise, coastal storms, and beach erosion increases, "hardening" the coast with engineered structures also increases (National Research Council 2007), but with what costs? Understanding, and if possible, quantitatively accounting for any negative environmental impacts of seawalls is important for a thorough comparison between various adaptation approaches. The scientific literature reveals significant emphasis on seawalls and other hard infrastructures' negative environmental impacts, specifically erosion.

Walton and Sensabaugh (1979) states that seawalls enhance beach erosion by increasing the water levels in the sand bed in front of the seawall. The hard structures reflect incoming waves, which diverts water's typical path of percolating through the beach. That causes "higher pore pressures within the sand, which 'fluidizes' the sand in front of the seawall and hence erosion takes place" (Walton and Sensabaugh 1979). Natural shorelines are gently sloping and allow wave energy to be dissipated, particularly seawards. They are also permeable and disperse wave impact. Impermeable vertical seawalls do the exact opposite, by focusing wave energy both along the base of the seawall (contributing to its undermining and scour) and at either end of it (Nunn 2009). The amount of erosion is variable and determined by wind, wave parameters (height, period, angle of approach, etc.) and the design of the seawall (Griggs and Tait 1988).

There is evidence to support that seawall-induced erosion has been occurring in Fiji. Mimura and Nunn (1998) concluded from their observations and interviews on two islands that most of the villages were suffering from beach erosion and sea encroachment as a result of human causes, including seawall construction. These rural communities are less able to access funds or engineering advice for these coastal protection structures (Nunn 2009). Thus, seawalls are often constructed without any knowledge of sustainable design or their potential impact on beach dynamics and ecology (National Research Council 2007).

The variability in the wind and wave inputs, seawall design, and locality makes quantifying erosion difficult, especially in monetary terms. Additionally, increased erosion and decreased sediment supply at the bases of seawalls will increase their rate of degradation (Solomon & Kruger 1996). This creates a negative feedback loop where seawall-induced erosion increases the costs for maintaining the seawall itself. Neither erosion or additional seawall maintenance because of the erosion are analyzed in this cost-benefit analysis due to lack of data.

Mangroves

Mangrove forests are a unique ecosystem in that they inhabit the inhospitable intertidal zone, where the trees and their associated species are exposed to extreme fluctuations in salinity and temperature. They are found in the tropics and sub-tropics of the globe; and currently occupy 14,650,000 hectares of coastline around the globe (Wilkie and Fortuna 2003, Alongi 2008). These forests occur in saline, waterlogged soils and are dominated by halophytic (i.e. "salt loving") woody plants (Baba et al 2004).

Mangroves are an important nursery ground and breeding site for birds, mammals, fish, crustaceans, shellfish and reptiles (Alongi 2008). Many fish species, including commercially important ones, depend on mangroves for at least part of their life cycle. Additionally, many crustaceans and bivalves fully depend on mangrove swamps and spend the majority of their lives in these ecosystems. Mangrove swamps are highly productive and the waters around mangroves foster some of the greatest productivity of fish and shellfish in any coastal waters (mangrove.org). Due to their land/sea interface, mangroves receive many inputs of matter and energy from both sides, which partially explains their high productivity rates (Baba et al 2004). Mangroves receive inputs from land and they have a large reservoir of subsurface nutrients that serve to replenish nutrient losses (Alongi 2008). The food web associated with mangroves is rather complex and the mangrove trees serve as the foundation promoting a detrital-based food cycle (mangrove.org).

Baba et al states that when mangroves are managed sustainably, the forests yield goods of high economic value and contribute to foreign exchange for the producing country without jeopardizing their ecological integrity. Humans have heavily depended on mangrove forests for food, timber, fuel and medicine (Saenger 2002). Unfortunately, over-exploitation, mismanagement and land use changes have resulted in substantial losses of mangrove ecosystems worldwide (2004). In addition to the economically important goods provided by mangroves, they also stabilize coastlines, reduce erosion, and act as biological filters and sinks for several pollutants (Baba et al 2004, Alongi 2008) thereby enhancing near-shore water quality. Mangroves offer protection from waves, tidal bores and tsunamis (Alongi 2008), more on this to follow.

Fiji Mangroves

Fiji is home to the third most extensive area of mangroves in the Pacific Islands with a total mangrove area cover of 517 hectares (Ellison and Fiu 2010). The largest areas of mangroves occur on the southeast and northwest coastline of Viti Levu, as well as the northern shore of Vanua Levu with over 90% of the mangrove forests occurring in these locations (Richmond and Ackermann 1974, Watling 1985, Ellison and Fiu 2010). There are seven species of mangroves in Fiji, as well as one hybrid species. These include: the Spotted Mangrove (*Rhizophora stylosa*), Samoan Mangrove (*Rhizophora samoensis*), Hybrid Mangrove (*Rhizophorax selala*), Large-leafed Mangrove (*Bruguiera gymnorhiza*), Teruntum Merah Mangrove (*Lumnitzera littorea*), Looking-Glass Mangrove (*Heritiera littoralis*), Blind-your-Eye Mangrove (*Excoecaria agallocha*), and Cannonball Mangrove *(Xylocarpus granatum*).

Mangroves play a very important role in the livelihood of the Fijian natives, as they are a valuable source of fish and other species used for subsistence and sales (Zann and Vuki 2002). Lal (1990) estimated the value of mangrove-associated fisheries products harvested commercially and for subsistence consumption to be F$31 million per year. Over 60% of Fiji's commercially important fish species and 83% of their subsistence fish species depend on mangrove areas for some phase of their life cycle (Lal et al 1983). Additionally, mangroves provide important medicinal plants and raw materials, such as timber. Table 2 describes annual value of different categories.

Category	Low End (USD)	High End (USD)	Units
Subsistence , Commercial, Recreational Fishing	418.07	776.40	Per hectare per year
Raw Materials	89.59	101.42	Per hectare per year
Habitat Functions	331	X	Per hectare per year
Erosion Control	597.24	1791.71	Per hectare per year
Recreation	358.34	X	Per hectare per year

Table 2. Low-end and high-end estimated values for mangrove services. Values are from the Organization for Economic Co-operation and Development report specific to Fiji (2003). Total annual value of mangrove land ranges from USD$1,794.24 - 2,669.53

Fijians rely on mangrove forests for sewage treatment programs. These programs constitute a major threat to Fiji's mangroves, which includes dumping and improper waste disposal. Additional threats include coastal development, reclamation and the collection of firewood. Overfishing, the alteration of watersheds and coastal sedimentation, and industrial and hazardous wastes spills are further threats to Fiji's mangroves (Ellison and Fiu 2010). In areas of mangrove habitat loss, there is often an associated decline in fish and crustacean populations (Vuke et al 2002). Exploitation for timber, fuel wood and herbal medicines has contributed to loss of mangrove ecosystems (Ellison 1999a, 2003a), as an estimated 1.5 to 4.5 m^3 are harvested each year for these purposes

(Jaffar 1992), which is reduced from past levels due to an increased use of imported petroleum (Ellison and Fiu 2010). Ellison and Fui list additional low-level threats to Fiji's mangroves as global warming and sea level rise, aquaculture ponds, pesticide runoff, animal waste, and invasive species. High priority management actions include awareness and education efforts for mangrove conservation and improvement of agency capacity and addressing traditional values (2010).

Mangroves and Coastal Protection

Growing evidence provides support that mangroves, as well as other natural barriers, are critical components in the overall resilience of coastal areas to natural threats and disasters, such as tsunamis and tropical cyclones (Adger et al 2005; Barbier 2006). The trunks and the aboveground root system heavily influence the hydrodynamics and sediment transport within forest (Quartel et al 2007). Studies have revealed that mangroves play a key role in protecting coastlines from erosion, as well as provide a protective barrier from such natural disasters by effectively attenuating wave energy (Brinkman et al 1997; Mazda et al 1997, 2006; Massel et al 1999; Quartel et al 2007). Mazda et al found that a wave of 1 m high will be reduced to 0.05m, after travelling 1.5 km in a six-year old mangrove stand. Conversely, young mangrove stands had little effect on attenuating wave energy (1997). The high tree density and complex root systems create a higher drag force on incoming waves than a bare surface of sand or mud. Bao 2011 defined a minimum mangrove band width for coastal protection from waves in Vietnam and found that when a mangrove forest is tall and dense, and the canopy closure is high, a narrower forest band is required; equally when the mangrove forest is short and the tree density and canopy closure is low, then a wider mangrove forest band is required. Studies from the aftermath of the 2004 Asian tsunami suggest that coastal areas that had intact, old-stand mangrove forests suffered fewer losses and less damage to properties than areas with degraded or absent mangroves (UNEP 2005).

Due to increasing evidence of the role that mangroves play in coastal protection, there has been an increase in replanting degraded and deforested mangrove areas (Barbier 2006). Mangrove restoration is quite difficult once coastal areas have been converted to other uses such as shrimp farms and agriculture, then abandoned. Restoration efforts can range from relatively cheap, USD$225/ha to extraordinarily expensive, USD$216,000/ha (Lewis 2001). Lewis divides restoration projects into three categories: (1) planting alone; (2) hydrologic restoration, with and without planting; and (3) excavation or fill, with and without planting. The former two can be relatively inexpensive, and the latter quite expensive. Planting alone usually fails. Conversely, hydrologic restoration can be successful when properly planned. The last option is typically only an option in developed countries, due to the expense. A major issue facing many mangrove restoration projects is that the responsible parties for the destruction of mangroves are unlikely to be involved in the restoration, leaving that responsibility to the local coastal community, who are often asked to voluntarily provide the labor for mangrove restoration (Barbier 2006).

In Fiji, Beqa Adventure Divers, an ecotourism operator and dive shop created Mangroves for Fiji in order to offset their carbon emissions and reach carbon neutrality. They are sponsoring the replanting of mangroves and are offering to pay groups $F1,000 per hectare. They have totaled 39 hectares in 13 different locations.

Mangroves, Climate Change and Sea Level Rise

In exploring the use of mangrove forests as a potential adaptation approach for coastal protection, it is important to understand how mangroves are going to respond to a changing climate. Mangroves are limited by temperature in subtropical latitudes in that they inhabit a narrow temperature range from 16^{o}C to (Ellison and Fui 2011). Fiji is within this range and therefore increasing temperatures should not affect Fijian mangroves, unless temperatures exceed their upper threshold. In fact, increasing air temperature, combined with higher atmospheric CO_2 levels is expected to increase the productivity of the mangroves on windward shores, while mangroves on the leeward shores of the islands are in dryer conditions and therefore their productivity is stunted by hypersaline conditions (Ellison and Fui 2011). If climate change results in increased rainfall, then mangroves are expected to grow taller and more productive, as well as more diverse; conversely, if rainfall decreases, then it will result in increased salinity and therefore decreased productivity.

Sea level rise is the biggest indicator of how mangroves will be affected. Mangrove forests display a distinct zonation from their seaward margin to their landward margin based on species preferences to salinity and tidal inundation. Mangroves will remain unaffected by sea level rise, if the rate of sedimentation is able to keep pace with sea level rise. If sea level rise occurs faster than sedimentation, then mangroves must be able to migrate landward to their preferred elevation, while the seaward margins die back. Their ability to migrate landward will be dependent upon the degree of development behind the mangrove forest. Sedimentation rates differ depending on whether the mangroves are located on high islands, which have higher rates of sedimentation relative to low islands, mangroves on the latter will be more susceptible to SLR (Ellison and Fui 2011). Fiji is comprised of high islands and many low atolls

(Maharaj, 2000). The mangroves on low-lying islands have been identified as more vulnerable to sea level rise and climate change than those on high islands (Ellison and Fui 2011). It is clear that an ongoing monitoring program is essential to assess the vulnerability of Fiji's mangroves to climate change, and in particular, sea level rise.

Methods Introduction & Overview

Study Methodology

Conceptual Overview

Cyclones cause economic damages in a number of ways. High-speed winds, inland flooding and coastal flooding are all destructive forces that harm both humans and ecosystems. For the purposes of this project, however, the study focuses on the costs and impacts of storm surges that cause coastal flooding alone. This does not preclude further work on cyclone impacts under climate change in tropical islands but rather complements it. Time constraints limit modeling of all cyclone impact and damage relationships. Wind and terrestrial flooding are significant impacts of cyclones, but surges often represent the most damaging aspect of a storm and were the focus of this study (FEMA 2010).

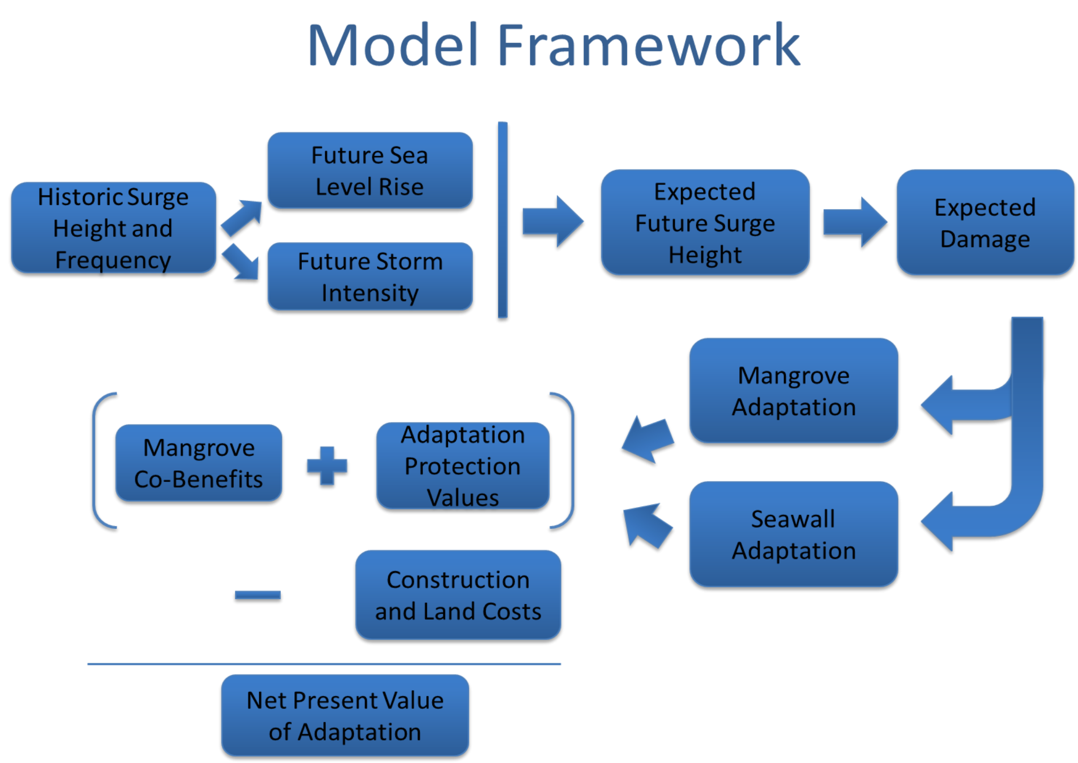

Figure 12. A conceptual framework of the study's methodology

Figure 12 is a look at the conceptual framework of our methodology. Our model assumed that future changes in storm surges will be based on historic surge heights and return intervals. Based on these historic levels, we first modeled an increase in SLR and a change in storm intensity to project future surge heights of tropical storms. We then modeled a relationship that could convert the height of a storm surge to the potential economic damage of that surge in Fiji. This output represented a future scenario without any coastal flooding adaptation.

To evaluate adaptation scenarios, we then modeled how much each adaptation approach lowered a storm surge and assessed the value of the surge reduction. This was followed by a cost-benefit analysis using the values we obtained, plugging in the co-benefits of mangroves and costs associated with conserving and restoring mangrove forests and constructing a seawall. From this we obtained a Net Present Value (NPV) for each adaptation option, which was the basis for our management recommendations.

Quantitative Model Scenarios

To move from a conceptual framework of our methodology to producing real results, we built a quantitative model in the freeware statistical program R. The model was built to automatically project future surge heights based on a number of built-in parameters, account for the effects of different adaptation options, convert the consequent coastal flooding into potential economic damages and perform a Cost-Benefit Analysis based on these numbers. To see a detailed list of each built-in parameter that was adjusted to create different futures in the model see Figure 13. These were: SLR, tide, adaptation approach, and storm intensity. Each parameter had a range of values discussed in more detail in the following sections. It should be noted that building in a range of values served as our sensitivity analysis for the model. In other words, our uncertainty about the future is represented by the range of possible future outputs and must be considered when making management decisions.

A1F1	SLR | No SLR
	High Tide | Low Tide
	Intensity +/- 10% | No Intensity Change
	No Adaptation | Mangrove Adaptation | Seawall Adaptation
A2	SLR | No SLR
	High Tide | Low Tide
	Intensity +/- 10% | No Intensity Change
	No Adaptation | Mangrove Adaptation | Seawall Adaptation
B1	SLR | No SLR
	High Tide | Low Tide
	Intensity +/- 10% | No Intensity Change
	No Adaptation | Mangrove Adaptation | Seawall Adaptation
B2	SLR | No SLR
	High Tide | Low Tide
	Intensity +/- 10% | No Intensity Change
	No Adaptation | Mangrove Adaptation | Seawall Adaptation
None	High Tide | Low Tide
	No Adaptation | Mangrove Adaptation | Seawall Adaptation

Figure 13. A display of each future scenario in our model, with the left-hand column indicating the IPCC storyline and 'None' meaning there is no climate change. To find future return intervals and surge heights the baseline surge heights were run through each scenario in the list, producing a total of 150 possible futures

Model 1: Surge Model

Overview

The first step in our methodology was projecting surge height into the future. Modeling present-day storm surges requires information on local tides, coastal bathymetry, shoreline topography, and cyclone behavior such as wind speeds, direction of approach, vertical sheer and central pressure. Modeling storm surges under future climate change requires climate projections and a relationship between changes in climate and changes in cyclone behavior, as well as modeling of sea level rise.

In the case of small island countries a further complicating factor is scale. In order to project storm surges under climate change in a useful way, climate data must be at a scale at least marginally appropriate to the country. Islands are often too small to be resolved in a GCM or even a RGCM from the surrounding ocean, resulting in censored local terrestrial climate patterns. Thus potentially available generalizable climate models cannot be employed for islands where as they may prove very useful for larger countries.

This is not to say that modeling cyclones under climate change for islands is an impossible task. A number of authors have undertaken analyses of climate change projections for shoreline inundation, cyclone tracks and cyclone intensities in the future (Koshy 2007, Naidu 2003, Church et al. 2006, Emanuel 2008). However these analyses are not easily replicable and results are not readily available for Fiji. In addition, these models are extremely data-intensive and country-specific, limiting the transfer of results to other areas around the globe or even within the South Pacific Ocean.

Figure 14. Realistic factors affecting a storm surge, implicit in historic surge data but not incorporated into our model

Because of these limiting factors, we chose to use historic surge heights from the Suva Peninsula as the basis for our model. Historic data encapsulates a large amount of modeling information otherwise lacking for the area. Figure 14 above reflects some of the main factors affecting the height of a surge and how they feed into historic data. In addition, the frequency of a surge can be distilled from historic surge data, resulting in a table of return intervals for particular surge heights. This takes much of the guesswork out of modeling surges in Fiji.

Our model relies on the historic data to provide an accurate baseline. We then incorporated uncertainty about how the future may change this baseline into our model. Figure 15 below shows the parameters affecting surge height that we built into our model. Uncertainty was reflected in the range of values we used. SLR values to 2050 were taken from four different IPCC scenarios, a spring high and low tide were used, and finally 3 storm intensity values were chosen.

Figure 15. The factors incorporated into our surge model for making future projections

Storm Surge Data

There are extensive historic surge data for the island of Viti Levu, Fiji due to its tide gauges. For the years 1978 to 1994, the South Pacific Applied Geoscience Commission (SOPAC) collected and analyzed tide gauge data on the Suva peninsula for extreme sea level heights, with normalized tides, creating a data set of historic storm surge heights relative to mean sea level. They also developed a categorical relationship between surge height and return interval (Solomon & Kruger 1996). (See tables 3 and 4 below). In addition, Carter (1990) created wind speed return intervals for Fiji based on historic cyclone activity in the area.

Name	*Year*	*Surge re:LMWL (m)*
Fay	1978	0.198
Meli	1979	0.153
Arthur	1981	0.163
Oscar	1983	0.214
Gavin	1985	0.323
Hina	1985	0.246
Rae	1990	0.300
Sina	1990	0.187
Unnamed	1992	0.220
Fran	1992	0.140
Kina	1993	0.433
Unnamed	1994	0.213

Table 3. Historic storm surge heights gathered from Suva peninsula tidal gauge data (Solomon & Kruger 1996)

RETURN INTERVALS			
SOPAC, 1996		Carter, 1990	
RI	Surge (m)	RI	Wind (knots)
1	0.13	1	22
2	0.28	2	30
5	0.48	10	50
10	0.63	50	85
25	0.83		
50	0.98		

Table 4. Historic return intervals for surge heights and wind speeds on the Suva Peninsula (Solomon & Kruger 1996, Carter 1990)

Storm Surge Return Intervals

SOPAC calculated an equation for storm surge return intervals (RIs) from past tide data on the Suva peninsula collated and analyzed from a tidal gauge. They provided a table of surge heights with discrete RIs (Table 4). Using this data for our model of the Suva Peninsula in Fiji assumes that the historic data represents the full range of possible surge heights and consequent RIs occurring in Fiji. From this table, we calculated the probability of a surge occurring as simply:

$\frac{1}{RI_s}$, where RI_s is the RI for a particular surge height, *s.*

Using this relationship it was possible to calculate the probability of occurrence for the historic surge height data provided by SOPAC. Using the historic probabilities for future surge heights effectively increased the frequency of larger storms in the future (Figure 16). Therefore the historic probability of each RI was applied to future surge heights.

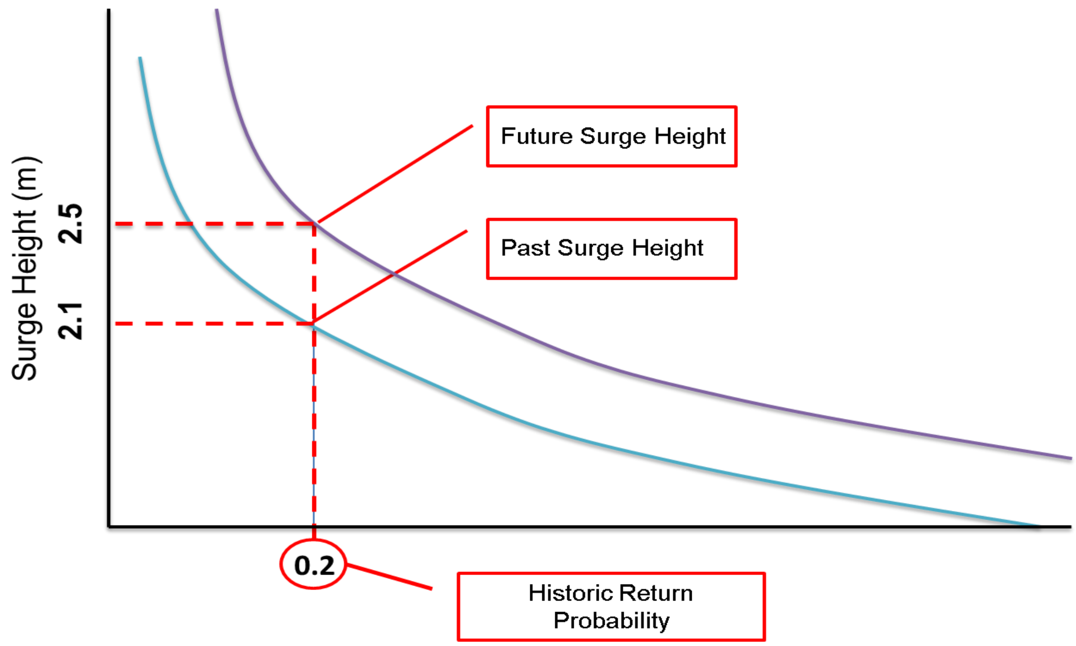

Figure 16. A display of how surge return intervals shift based on our model. The blue represents the baseline surge heights and return intervals from Solomon & Kruger (1996). The purple line represents the future in 2050 at high tide, where for any given historic return interval a larger surge will be expected. In essence this increases the frequency of larger storms in the future

It is important to note here that assigning historic return interval values to future surge heights makes a basic assumption about the relationship of RI to surge height. Mainly, that under climate change the fundamental shape of that relationship does not change. In reality, however, it is possible that the slope of the line as well as other underlying factors could change. More detailed modeling will be necessary to make that determination and was beyond the scope of this study.

Sea Level Rise and Storm Intensity

There are two main drivers of storm surge increases in the future aside from tide, as indicated in Figure 15 above. The first is sea level rise (SLR) and the second is storm intensity. Projected increases in mean sea level are also affected by tectonic uplift and subsidence on the island of Viti Levu, but this effect was not addressed in our model. We added SLR in a linear fashion to historic surge height data to obtain a sense of how SLR may affect storm surges in the future. Solomon and Kruger (1996) employed this linear methodology. The year 1990 was taken as the base year with no climate change. To get SLR per decade, the IPCC projection for each storyline's SLR at 2050 was divided by 10 and then incrementally added to each decade surge height beginning with historic surge levels in 1990.

The second main set of drivers for increased storm surge are potential changes in cyclone intensity and/or frequency. The effect of climate change on El Niño cycles, sea surface temperature (SST) and global temperature all impact cyclone behavior. Johns et al. (2003) predicted increases in SST of up to 4.3 °C in the worst-case IPCC scenario. However, conflicting reports predict a decrease in cyclone intensity and there is no scientific consensus to date.

We based our estimates for intensity changes on Emanuel (2007) who worked on modeling how cyclone wind speeds are affected by climate change. Emanuel found a change of 10% in cyclone wind speeds per degree warming, so for the intensity scale of our model we also chose changes of 10%. However, due to the lack of consensus in the literature we included scenarios for both an increase and decrease of 10% as well as a no change scenario where intensity remains the same.

There were two parts to our intensity calculations: indexing intensity, and adjusting surge height. For the former, the two percentage changes were indexed by SST projections. The +/- 10% change was modulated by the projected decadal degree rise in SST according to each IPCC storyline (A1F1, A2, B1 and B2). This followed Emanuel's wind model methodology and relays the importance of SST to storm attributes. With this method each IPCC storyline projects a unique change in intensity based on its SST projections, rather than each storyline having identical +/- 10% changes in intensity per decade.

The second part of our calculations required adjusting surge heights based on the indexed intensity changes. We did this by multiplying the baseline surge heights by the percent change in intensity calculated for each decade and adding this increment onto baseline levels each decade. In reality, a change in central pressure, wind speed and track of a tropical cyclone would have much more complex effects on surge height. However given the limited data available for our model we applied this percent change approach to historic surge heights to account for the range of possible outcomes in a more data-intensive model.

Future Scenarios

Once surge height increases were predicted the four main IPCC storylines (A1F1, A2, B1, and B2) were used to finalize a range of potential future surge outcomes as well as a No Change scenario that assumed no climate change occuring. The IPCC storylines provided both SLR and SST projections, the latter being important for storm intensity modeling as described in the previous section.

For each storyline, the model was interpreted at both a low and high tide marker. The respective tides were chosen based on Fiji Tidal Charts (January 2012 Tide

Data). A high spring tide of 1.7 m was chosen as the high tide marker (i.e. the maximum) and a low spring tide of 0.16 m was chosen as the low tide marker (i.e. the minimum). The tide levels were added to the original predicted surge levels and represent alternate scenarios as the "worst-case" and "best-case", respectively.

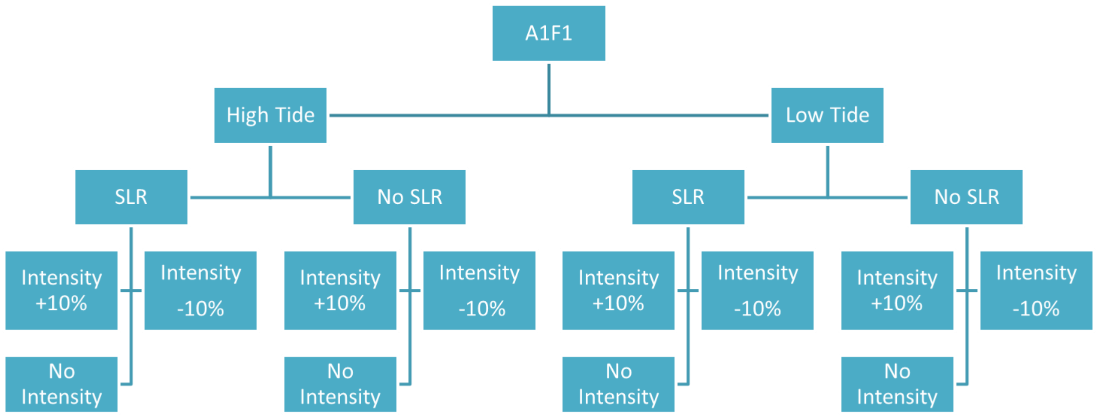

Figure 17. An example of how the model plays out under the A1F1 scenario, with no coastal adaptation method in place

The modeled surge scenarios are as follows, also illustrated in Figure 17 above:

1. Cyclone intensity increases and storm surges increase without including sea level rise.
2. Cyclone intensity decreases and surges decrease without including sea level rise.
3. Cyclone intensity increases and sea level rise occurs.
4. Cyclone intensity decreases and sea level rise occurs.
5. Cyclone intensity doesn't change and sea level rise occurs.
6. "No change" scenario, i.e. no sea level rise or cyclone intensity changes occur.

In total, for each IPCC storyline there are 12 scenarios because the model ran for both low and high tide, as mentioned above.

These scenarios were run by decade, beginning in 1990 through 2050 using the freeware program R. Despite having climate projections to 2100, we felt extending our analysis beyond 2050 was unhelpful because of the high level of uncertainty in predicting storm surges, as well as the level of economic change that could occur.

Economic Damages

For our discussion of economics please refer briefly back to Figure 12 of the conceptual framework of our methodology. As you can see in the flow chart, going from storm surge height to economic damages uses the same method regardless of adaptation. The ability to determine the damages caused by a storm surge of a given size comes from a flood depth to relative damages equation developed by SOPAC through a personal interview process in Navua, Viti Levu. This dataset was acquired from SOPAC and it provided the reported flood depth, property value and property damage from flooding for houses in Navua. For this analysis, two main adjustments were made.

The first adjustment was fitting a flood depth to relative damage equation to the data points. The relative damage points represented the property damage divided by total property value per flood depth per household. Ideally, this method allows the data to be extrapolated out to the different areas based on population. The authors fit a logistic curve to this data to represent the low damage incurred at lower flood depths, a threshold range of flood depths were damage increases rapidly, and finally a leveling off as the entire property is destroyed (relative damage =1).

The resulting sigmoid had a poor fit for the data (see Figure 18 below). We therefore also fit a linear line, maxed at a value of r=1, to demonstrate a simple increase in damage as flood depth increases. Because this damage equation was a crux of the model we also increased and decreased the slope of this line by 50% to encompass a range of possible relationships (see Figure 19).

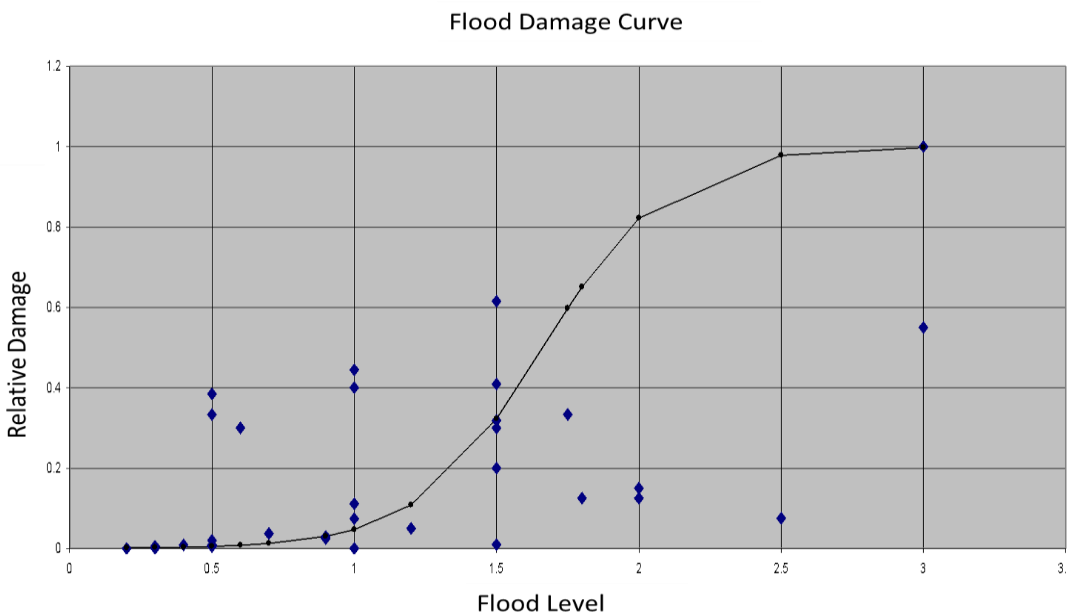

Figure 18. Data from Assessment of Impacts and Adaptations to Climate Change (Koshy 2007), graciously provided by Dr. Peter Kouwenhoven at the University of Waikato, New Zealand

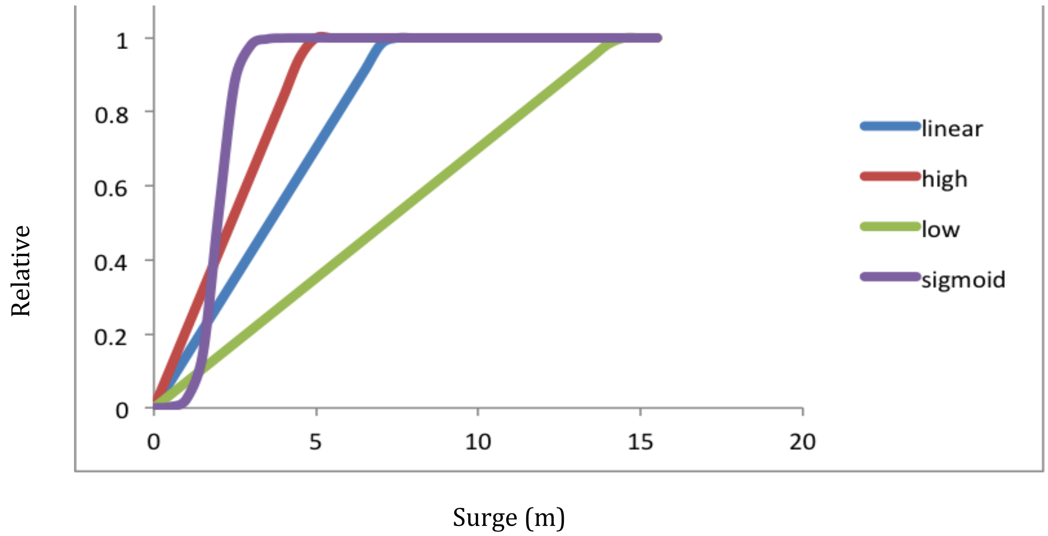

Figure 19. An illustration of the 4 damage functions utilized in our study for a hypothetical set of storm surges. The sigmoid replicates that from Figure 18 above. The linear functions fit to the data in Figure 18 above, with 2 other linear functions where the slope was adjusted up (high) and down (low) by 50%

The main limitations of using this equation to account for damages caused by storm surges in Fiji are:

- The possible inclusion of flooding caused by a river and precipitation in the model.
- Transferring the model from Navua (where the data was collected) to a different locality.
- Accounting for economic growth in the future (this model is static).

The latter point was addressed by inflating GDP through time when calculating future surge damages, however a more precise method would be to model the built environment with its associated value and track its change through time. For the former two, more focused studies are necessary to gather data on the relationship between coastal flood-specific economic damage around the globe.

The second adjustment to the SOPAC data was a coefficient (σ_{surge}) to account for our use of surge height in the place of flood depth in the surge-to-damages equations. Using surge height produces an overestimate of the future damages from storm surges. The flood depth that a certain surge will create depends on the shore slope, wave velocity, inland topography, and the built environment and will most likely be smaller than the surge itself. Modeling this relationship, i.e. how much water makes it inland during a storm, for the Suva peninsula was beyond the scope of this project. Therefore we made an adjustment that reduces surge height by a certain percentage to lessen the flood depth overestimate. This point of the model should be refined immediately if put into further use, as the outputs from the surge to damages equation are the crux of the CBA.

To estimate σ_{surge} we used SOPAC's primary dataset from Navua. The interviews conducted by SOPAC gathered information on the flood depth and relative damage values from tropical storm flooding and were executed in June 2003. We assumed, with limited information on the interviewer's methodology, that interviewees would have reported damages from the most recent flooding they experienced. That would have been tropical storm Amy in January of 2003. Since we had data from SOPAC on the surge height of certain tropical storm return intervals, we could derive a surge to flood depth ratio to work with.

Amy was a Category 2 storm, which in Fiji corresponds to a 3 year RI. From SOPAC's calculations of surge height RIs we can see that a 3 year RI corresponds to a surge height of approximately a 0.28 m surge height. To be consistent with our own model (which incorporates tides) we added an average tide level to the theoretical surge of Amy. Finally, we divided this surge height by the average flood depth reported in the SOPAC interviews (0.17 m). After these calculations we found $\sigma_{surge} = 0.84$.

Finally, it is worth briefly mentioning that to move from relative damages to a dollar amount of economic losses, we multiplied a value of GDP per unit area by the relative damage amount, adjusted for a portion of the coastline along the Suva peninsula. This methodology is discussed in further detail below in the GDP section. The limitations of this approach include not accounting for lost lives or actual physical property damage. However, Suva is the capital and most densely populated area of Fiji, and represents the largest single contributor to GDP in the country by unit area. We therefore feel that this is a good first order approximation and look forward to more detailed spatial analyses of coastal property value currently underway, such as by the Pacific Disaster Net (Mahul et al. 2011). Combining this level of data specificity with our methodology for modeling coastal flooding under climate change will produce a powerful tool for climate adaptation decision-making in the South Pacific.

Model 2. Mangrove Model Overview

Mangroves reduce incoming waves by a reduction coefficient known as the attenuation coefficient, represented by the letter r. This is a value between 0 and 1 and it can be described as a percentage where an r-value of 0.3 equates to a 30% reduction in wave height as the wave moves 100 m through the mangrove forest. Our model used surge height in place of wave height due to data limitations although we feel this is a good first order approximation.

Theoretical models indicate mangroves have a greater ability to attenuate shorter wavelengths, as seen in storm depressions, than that of longer wave lengths, such as tsunamis (Massel et al 1999). Barbier et al (2008) quantified wave attenuation coefficients in mangrove plantations of single species, *Kandelia candel* and *Sonneratia caseolaris*, during the passage of a typhoon offshore. Their data is described in Table 5 below:

Mangrove Species	**Water Depth (m)**			
	0.2	**0.4**	**0.6**	**0.8**
Kandelia candel	20 %	20 %	18 %	17 %
Sonneratia	60 %	40 %	30 %	15-40 %

Table 5. Reduction percentages of two species of mangroves based on the water depth. A reduction of 20% equates to an attenuation coefficient of 0.2. From Barbier et al 2008.

The attenuation coefficient, r, depends on water depth, wave period, the species of mangrove trees, the density of mangrove forests and the diameter of mangrove roots and trunks (Mazda et al 1997). Additionally, Mazda et al found that the degree of wave attenuation varied with the degree of growth of the vegetation, i.e. younger stands of mangroves had little to no effect on wave attenuation, while well-grown mangroves had a significant effect on wave heights. In a well-grown mangrove the effect of wave reduction does not decrease with increasing water depth (1997).

In order to obtain a quantitative value for Fiji's mangrove's role in coastal protection, our model used a range of attenuation coefficients, based on the Barbier et al findings (2008), because on-the-ground data appropriate to Fiji's mangrove forest was unavailable. The range we chose to model was between 10% and 70% (i.e. r=0.1, 0.2, …, 0.7). In the analysis, we focused on the values obtained for wave attenuation coefficients of 0.1, 0.4 and 0.7 in order to compare what we considered the worst-case scenario, a mid-level scenario, and the best-case scenario, respectively. It can be inferred that an attenuation coefficient of 0.1 would be representative of a mangrove restoration project where the age stand of the forest is young; conversely, an attenuation coefficient of 0.7 would represent a conservation scenario of an old-growth mangrove forest. We chose the value of 0.7 based on the assumption that an old-growth, diverse mangrove forest will have a greater capacity to attenuate incoming surges than a single species plantation will have. The value of 0.4 is simply the average and would represent the mid-point scenario.

Model 3. Sea Wall Modeling Overview

Quantifying and comparing the coastal protection of mangroves and seawalls required an analogous protection parameter/variable. After a thorough literature review it was determined that analyses of seawall protection are generally not based upon reduction in surge levels in the same way that mangrove protection analysis are. Furthermore, seawalls are not even designed for a particular surge reduction capability, but instead are built to withstand chosen designs loads (wind, seismic, and wave forces) for an expected lifetime of the structure (Personal Communication, Foster/Coastal Design). Establishing a method of comparability between mangroves' and seawalls' coastal protection was an initial step in this analysis.

Understanding the protection value of seawalls led to research on their interaction with waves. Besley (1999) provided equations for estimating an overtopping discharge rate (water flow rate passing over a seawall). With sufficient data and various unit conversions, an overtopping discharge rate could potentially represent a reduction in storm surge level. Most of these formulas need, at minimum, the significant wave heights and wave periods, still water levels and the shape of the seawall. Other research produced equations that incorporate wind speed and central pressure as well (Hu et al. 2000). To complicate these analyses, the design water levels, wave parameters, force loadings and overtopping conditions vary along the seawall, even of equal wall height, and have yet to be fully understood (Kortenhaus et al. 1996).

Identifying the location a seawall on the beach profile is also necessary for a more accurate analysis (Jenny Dugan interview). Having topographic and bathymetric data of the location provides a greater understanding of surges' interaction with a seawall. Kortenhaus et al. (1996) importantly note that "to date, no general formula have been developed to account for (i) the complicated foreland geometries in [a] harbor area, (ii) the different processes of wave transformation on these types of foreland, (iii) breaking of waves on the foreland and (iv) different breaker types occurring at the protective structures". Beyond the inability to garner any of this data is the compounding lack of research in this field.

The data we had for the historic storms recorded in Fiji included still water levels and wind speeds based on the storm categories. With the science community in debate about statistically valid correlations between wind speeds and wave heights, there was no reliable equation to calculate wave heights. Because wave heights were an essential variable, we were forced to make unacceptably large assumptions to complete the equations. Once we obtained an overtopping discharge rate we had to convert back to a reduced surge height, increasing our assumptions and producing very unrealistic results. After many futile attempts to manipulate available equations and data for our analysis, it was determined that we needed to derive an original method in order to be able to utilize the data available.

We first chose three different seawall heights to analyze various storm surge reduction capabilities. The heights included a 'low' and 'high' option, which represent the lowest and highest of Viti Levu's seawalls that were referenced in the literature (Solomon & Kruger 1996). We then chose an intermediary height, which equaled the average height of all the referenced Viti Levu seawalls (See Table 6).

Seawall Height	Low	Average	High
Meters	1	1.89	3

Table 6. Seawall heights in Viti Levu, Fiji

Using three different seawall heights provides a range of reduction capabilities to analyze, while accounting for the variability of historical seawall heights. It also allowed for appropriate comparisons to the mangrove adaptation option. Based upon the available data, we chose a simplified method for determining the reduction in projected future surges with the presence of a seawall. The height of the seawall above mean-tide level represented the amount of surge reduction that it was able to provide. For example, a 1-meter seawall would reduce a 1.5-meter surge to a .5-meter surge. A surge below the level of the seawall is considered completely mitigated.

The method used in this project is a first order approximation because of a lack of necessary data about the wave climate of Fiji's historical storms and seawall design parameters. Neither the seawall's shape (vertical or curved), the building materials and their permeability or the location on the beach (how many meters seaward) were incorporated into this analysis. It does not incorporate the dynamic nature of waves and storm surges. Additionally, our analyses would be more rigorous if wave and seawall interactions, reflecting versus impacting waves, and the angle of a wave's approach (Kortenhaus et al. 1996) were also accounted for. The seawall design loads were not evaluated, as the loads do not directly pertain to a seawall's surge reduction capability (although under extreme duress a failing seawall would clearly impact this capability). In addition, this method also implies that a seawall's efficiency is perfect (100% reduction that is equivalent to its height).

Model 4. Storm Surges and CBA

In order to conduct a cost-benefit analysis (CBA) some relationship between cyclones and money had to be drawn. Economically the costs are readily quantified as damages caused by coastal flooding in dollar amounts. However, physically these costs could be connected to any number of cyclone attributes: area inundated, wind speed, central pressure etc. As mentioned the scope of this study is coastal flooding, thus the most direct relationship would be flooding to damages. Rather than area inundated the project chose storm surge height as the variable for predicting damages. This is because it is easily transferable between scenarios of adaptation measures (and no adaptation). Specifically, wave attenuation in mangroves is the easiest measure of mitigation for cyclone impacts and this indicator is dependent on surge height. Therefore a surge height to damages relationship was utilized.

Equations

1. Surge Projections

Sea Level Rise and Intensity

For S_{SLR} the model calculated:

$$S_{SLR} = S_{historic} + (SLR_{decade} \times T_{decade}) + W_{tide} \quad \textbf{(Equation 1)}$$

For S_{CC} the model calculated:

$$S_{CC} = (1 + \Delta^{\circ}C_{SST} \times I_{lowhigh}) \times S_{historic} + W_{tide} \quad \textbf{(Equation 2)}$$

Where T_{decade} is the decade under consideration, W_{tide} is the water level at the maximum and minimum tide, SLR_{decade} is the projected SLR to 2050 divided by 10 for a particular IPCC scenario, *I* is a percent increase in surge height due to cyclone intensity changes (either 10% or -10% in this model), $\Delta^{\circ}C_{SST}$ is the projected change in SST under different IPCC scenarios to 2050, and $S_{historic}$ is the historic record of surge heights on the Suva peninsula in Viti Levu, Fiji.

In addition to SLR and intensity changes, a third outcome considered in this model is the sum of these two individual effects of climate change, i.e. $S_{SLR} + S_{CC}$ **(equation 3)**. In this outcome sea level rise and surge height increases both occur and combine in a linear fashion to sum to a greater or lesser (depending on W_{tide} and *I*) total surge height.

Damage Functions

To equate storm surge height to cost damages, the following equations were used:

$$ED_{relative} = S \times 0.1662 \times \sigma_{surge} \times 10$$ **(Equation 4.a)**

$$ED_{relative} = S \times .2493 \times \sigma_{surge} \times 10$$ **(Equation 4.b)**

$$ED_{relative} = S \times 0.0831 \times \sigma_{surge} \times 10$$ **(Equation 4.c)**

$$ED_{relative} = 1.0/(1.0 + \exp(7.5678 - 4.5496 * S * \sigma_{surge})) \times 10$$ **(Equation 4.d)**

Where *S* is the projected future surge, 0.1662 is the linear coefficient for the flood depth-to-damages data in Navua, Viti Levu, σ_{surge} is the surge height to flood depth coefficient and 10 is the length of a decade.

However, given the nature of relative damage as the percent of total flood damage to a property from a particular storm, Equation 4 must be corrected to max out at a value of 1, or 100% damage. This was accomplished in the model by using a conditional statement choosing the lesser of two values: 1, or the relative damage value. Note that 100% damage, in this case, is explicitly an economic value, determined by the economic intensity of the area impacted – it does not necessarily indicate the complete and total destruction of the area by a surge. Relative damage of 1 is similar to "totaling a car", where the vehicle does not be completely destroyed to be considered totaled, only damaged beyond the current value of the vehicle. Therefore, local economic values and infrastructure quality standards may be as responsible as the physical characteristics of the storm surge in determining the slope of the damage function.

This step calculates the relative expected damage number, with a maximum value of 1. In order to go from this to real currency, a total value for the coastal area of the Suva peninsula affected by storm surges had to be developed. Calculating this absolute value is discussed under the GDP methods. The absolute expected damages ($ED_{absolute}$) calculated from relative expected damages ($ED_{relative}$) therefore equals:

$$ED_{absolute} = ED_{relative} \times GDP_{decade}$$ **(Equation 5)**

The given dollar amount of risk (ED_{decade}) for decades 1 to 6 (1990 to 2050) due to cyclone surge damage is the sum of damages from all storm surge heights throughout that decade. This depends on the projected surge height in that decade and the probability of that surge height occurring. To get the risk by decade therefore:

$$ED_{decade} = \sum (P_{historic} \times ED_{absolute})_{decade}$$ **(Equation 6)**

Where $P_{historic}$ is the historic probability of a surge height occurring and $ED_{absolute}$ is the absolute dollar amount of risk from a particular storm surge height.

Cumulative Expected Damages

The cumulative risk under a particular scenario up to time *t* is the integral of the previous equation:

$$ED_t = \int_1^t \sum \left(P_{historic} \times ED_{absolute}\right)_{decade} \qquad \textbf{(Equation 7)}$$

We simplified this equation by solving for a cumulative sum to 2050 (multiplying relative damages by 10 to get relative damages by the decade). This cumulative sum describes the total risk from cyclone storm surges that exists on the Suva peninsula for a 60 year time period. This economic methodology is repeated for a No Adaptation model, a Mangrove model and a Seawall model.

Built In Sensitivity Analysis

The surge model encompassed a range of values for each input parameter in order to account for uncertainty. To therefore evaluate the sensitivity of the model to each parameter we visualized the variability of surge heights and of damages using boxplots aggregated in R (using the mean) by each parameter. The parameters were as follows:

1. Sea level rise
2. Tide
3. Intensity
4. Mangrove attenuation coefficient
5. Seawall height
6. Return interval
7. Damage equations

2. Mangrove Model Equations

The change in the height of a wave moving from the coastline towards land can be quantified using the following equation based on wave theory:

$$\frac{dH}{dx} = -rH \quad \textbf{(Equation 8)}$$

Where H is the wave height ($H=H_0$ at $x=0$), x is the distance into the mangrove forest from the coastline edge, and r is the wave attenuation coefficient (Barbier et al 2008). The attenuation coefficient, r, is a percentage based on the original wave height at the mangrove edge and then 100 m inside the mangrove forest. It can be calculated using the equation:

$$r = \frac{H_S - H_L}{H_S} \quad \textbf{(Equation 9)}$$

H_S is the wave height at a seaside station, H_L is the wave height at a station 100m into the mangrove forest (Mazda et al 1997).

To extrapolate wave attenuation to coastal protection value, we used equation 4, which relates storm surge to relative cost damages. First, we calculated the relative damage, based on this equation, for all surge scenarios regardless of whether or not there was a mangrove system and/or a sea wall protecting civilization. Using just this equation with a storm surge height makes the assumption that there is no coastal protection adaptation. Then, for each scenario, we calculated the change in wave height after traveling 100 m into a mangrove forest for the range of attenuation coefficients (equation 8). This allowed us to calculate the new surge height 100 m into the mangrove forest, which was then plugged back into the cost damages equation (equation 4), to derive a new relative damage value. The difference between the relative damages when mangroves are absent and when a mangrove forest is present is the protection value of the mangrove forests. Finally, we extrapolated from relative damages to total damages and a cumulative sum over the decades, using the methodology described above (equations 5, 6, 7).

3. Seawall Model Equations

Based upon the available data, we chose a simplified method for determining the reduction in projected future surges with the presence of a seawall. The seawall's height equated to the amount of reduction (Equation 10). Every value for projected future surge was compared to the three seawall heights (1m, 1.89 m, 3m). Any projected future surge level that was less than the height of the seawall produced a negative number; using the IF function in R, all resulting negative projected future surge levels were changed to zero, effectively reducing the surge height completely (Table 7).

$RS = S - SW$ **(Equation 10)**

Where *S* is the projected future surge, *SW* is the seawall height, and *RS* is the reduced surge.

Table 7. Example of seawall surge calculations.

Seawall Height	Example Predicted Storm Surge + Tide	Reduced Storm Surge
3m	4m	1m
1.89m	1m	-0.89m = 0m
1m	1m	0m

To evaluate the benefits of a reduced projected future surge from a seawall, the damages avoided were calculated in the same methodology as described in the mangroves section, using Equation 4. Subsequently, the relative costs damages were extrapolated out to total damages and a cumulative sum as described above.

4. GDP Methodology

As described previously, the SOPAC derived surge to damage equation yields damage values in relative terms, describing a range of possible damage to property as a percentage of total damage vs. an absolute value. To move from relative to absolute, a reasonable estimation of the average economic value of the area at risk is necessary.

Due to a lack of explicit local data, we calculated the economic intensity (or GDP per Area) of the region at risk in the Suva peninsula via the following steps. The GDP of Suva was determined using data on national per capita GDP (USD $3,658 in 2010) and the population of Suva (87,503 in 2007) from the Fiji Bureau of Statistics.

$$person * Population\ of\ Suva\ City = GDP\ of\ Suva$$

Utilizing spatial data, the area of Suva was determined to be 70 km^2, leading to the generation of a GDP/km^2 value for the Suva Peninsula**.** All locations lying within a 0.5 km buffer zone from the coast were considered to be 'at risk' of coastal inundation from storm surge events. The region of interest was determined to be approximately 8 km^2. Multiplying the region of interest by the economic intensity generated an absolute value for at risk coastal areas on the Suva peninsula.

$$GDP/Area * Area\ at\ risk\ = GDP\ of\ Area\ at\ Risk$$

Literature indicates that future economic growth may double the damage caused by extreme events, prior to factoring in damage related to climate change, as there will be more infrastructure and economic activity to be impacted from an event (Mendelsohn et al. 2010). While the analysis could be completed utilizing static economic values, a dynamic model seems more likely to resemble reality. We projected economic growth forward through 2050 utilizing a two-decade average of per capita GDP growth (0.054). All GDP projection values accounted for inflation using a ten-year average inflation rate (Fiji Bureau of Statistics). We assumed that the per capita growth rate for Suva was similar to the national average (0.7%). Due to the uncertainty surrounding economic and population projections, we modeled the per capita GDP and population growth using linear models. This method is thought to be a more conservative, first-order approximation for forecasting (Gary Libecap, Personal Communication). Comparison to other projections, including those tied to the IPCC scenarios (Gaffin et al. 2004), indicates our projection settling neatly in the middle of a range of long-term economic projections for Fiji.

CBA Methodology

This project aims to determine the most efficient way to protect the nation of Fiji, in particular the Suva Peninsula, from the threat of coastal inundation due to the dual stressors of enhanced tropical cyclone strength and sea level rise. To determine the most efficient way of protecting from these threats, a Cost-Benefit Analysis was performed that compared protecting Fiji from coastal inundation through restoration or conservation of coastal mangrove forests and the utilization of seawalls for coastal defense. Two different metrics to were used to determine the efficiency of the various adaptation measures analyzed in this study, the Net Present Value and the Benefit Cost Ratio.

Parameters

All values in this study are presented in 2011 US dollars. Many values were published in Fijian dollars and we followed the convention of using the Fijian Consumer Price Index (CPI) to convert these to nominal values prior to converting to 2011 US dollars using the 2011 USD: FJD exchange rate.

The discount rate used in this study was 0.05, which represents the standard used by many conservation groups, including Conservation International, when performing analyses.

Project Size

The project size is another component of the CBA that must be specified. Project size will determine what is ultimately being protected with the given adaptation measure, as well as the total cost of implementation. For this analysis, we modeled our mangrove conservation and restoration projects as 1 hectare (10,000 m^2). We assume, for ease of comparison with seawall dimensions, that this hectare plot is perfectly square, i.e. 100 meters per side. We assume that a 100 meter seawall would effectively substitute for a mangrove forest that is 1 hectare in size and vice versa. In our analysis, we model seawalls with various heights and therefore costs do vary according to volume of seawall material needed.

Benefits

Direct Project Benefits

The adaptation value of coastal mangrove forests and seawalls were based upon the historic return intervals of cyclones and the expected damages of these storms in the presence or absence of sea level rise under various climate scenarios, as previously described. It was assumed that mangrove restoration projects benefits would not begin accruing until forest maturation 10 years after planting. Lewis and Gilmore 2007, state that natural mangrove forest maturation could take up to 25 to 50 years for maturation, so our estimate may be optimistic. Our assumption is that, with proper planning, restoration efforts could achieve faster maturation in mangrove forests. After this initial lag time, it is assumed that restored mangrove forest ecosystems will act similarly to naturally occurring mangrove systems and hence will provide similar levels of adaptation benefits.

Mangrove Co-Benefits:

In addition to the adaptation value associated with mangrove ecosystems, there are many other ecosystem service (ES) values that mangroves provide. The ES values were based upon Fiji-specific economic analysis that analyzed the natural goods and services provided by the mangrove systems of the nation. The ES values included in this study were recreation ($358.34 per hectare), commercial, recreational, and subsistence fisheries harvest ($418.07 to $776.40 per hectare), habitat function ($331 per hectare) timber and building material provisions ($89.59 to $101.42 per hectare), and erosion control ($597.24 to $1,791.71 per hectare) (Agrawala: OECD 2003). As stated above, it was assumed that the benefits of mangrove restoration projects will begin accruing 10 years after planting but upon reaching this age threshold will function as naturally occurring mangrove ecosystems. We did not model the progression of restoration projects from immature (with low co-benefits) to mature (with high co-benefits) forests as a continuous function that would likely be seen in nature.

Seawall Co-Benefits:

In certain situations, seawall construction can generate co-benefits in addition to their protection benefits. These co-benefits include job creation, property value enhancement from protective services, etc. In the US, there are standard economic multipliers by sector, which fairly simplistically provide a tool for estimating total economic impact per dollar spent on a project for the different sectors directly impacted by the project. These multipliers give policy makers an idea of the potential collateral benefits, in addition to the direct project benefits, that would likely be generated by investment. However, a lack of in-country economic multipliers for Fiji, precluded us from including this in our analysis.

Costs

Mangrove Direct Project Costs

Mangrove restoration and conservation efforts incur different costs. It is assumed that the range of restoration costs includes project planning, any land costs, and mangrove propagule planting and early life stage maintenance. For this analysis, the mangrove restoration costs ranged from $214 to $14,135 per hectare (Lewis 2001 & Gilman 2007). This wide range of costs is reflective of the varying quality and scope of mangrove restoration projects as well as varying land costs.

In Fiji, 87% of the land is native land, held in trust for the community. Other forms of land ownership include state-owned land as well as 'free-hold' (private) land. The iTaukei Land Board Trust (TLBT) is entrusted with managing and leasing this native land to various resource users. They typically provide leases ranging in duration from 30 years for Agricultural Land Leases to 99 years for Commercial, Industrial, Residential, Extractive, and Other Lease types. To determine the conservation costs associated with mangrove forest protection, the range of lease values were taken from the Land Board Trust data portal (http://www.tltb.com.fj). This decision was based on the reality that 87% of the area of the nation is subject to these lease values and therefore they appear to represent a reasonable estimate of land values. This assumption was checked by comparing leased land annual costs to several free-hold land purchase prices divided by the same 99 year time frame. Resulting annual values were remarkably similar by sector. The lease costs range from $8.99 to $1,592.30 per hectare. These costs would likely be determined by the activity that the conservation activity would be in competition with, forestry and tourism being the least and most expensive lease types, respectively. There are likely additional costs associated with managing the conserved lands. However, due to a lack of data, they are not included in this analysis.

Seawall Direct Project Costs

Seawall construction costs in the South Pacific are highly variable in the literature. Estimates range from $68,468 per kilometer of seawall to $0.4 M to $27.4 M per kilometer, depending upon source material, construction type, and location (South Pacific Disaster Programme & Lindham et al. 2010). To determine the cost of seawall construction in Fiji, we based our estimates upon the volume of material necessary to construct seawalls 100 meters in length and of various heights, assuming a constant width. We then used estimates for concrete wall construction costs in Fiji, which were $800 per cubic meter, which yielded a range of seawall costs of $83,339 to $250,019 for a 1-meter and 3-meter high seawall, respectively (Sherwood 1994). In addition to direct project costs, seawalls require continual maintenance throughout their lifetime, which we assumed to be 20 years, and for this analysis we set annual maintenance cost to be 4% of the original construction costs (Ng & Mendelsohn 2005).

Results from Cost-Benefit Analysis:

As described in earlier sections, modeling the future damages of storm surges and the protective capacity of each adaptation option is just a first step. In a world of unlimited resources, a manager or community would simply utilize the adaptation approach that is the most effective. However, costs are a major consideration, particularly in a developing country, and an a cost-benefit analysis allows a decision maker to more clearly and comprehensively see and understand the full impact of the adaptation decision. Trade-offs are an inherent piece of complex decision-making and the CBA can provide a clearer economic picture. The results from the storm surge model were fed into a CBA and yielded the following results. A sensitivity analysis for each component of the model follows this section.

Mean NPV Across All Variables

Initially, all variables were averaged across their various ranges of uncertainty in order to identify an overall mean net present value (NPV) for each adaptation option (Figure 20). At this broad level, the model indicates that the average NPV is higher for seawalls than mangrove conservation or restoration. Looking at the average NPV in this case is incorporating all levels of model uncertainty, meaning that all surge-to-damage functions, climate scenarios (which embody all SLR and storm intensity changes), tidal levels, and project costs are all equally likely to occur. In other words, NPV is presented as if a decision maker has no idea what the future conditions will be like and extremely limited information about storm damage risks and project costs.

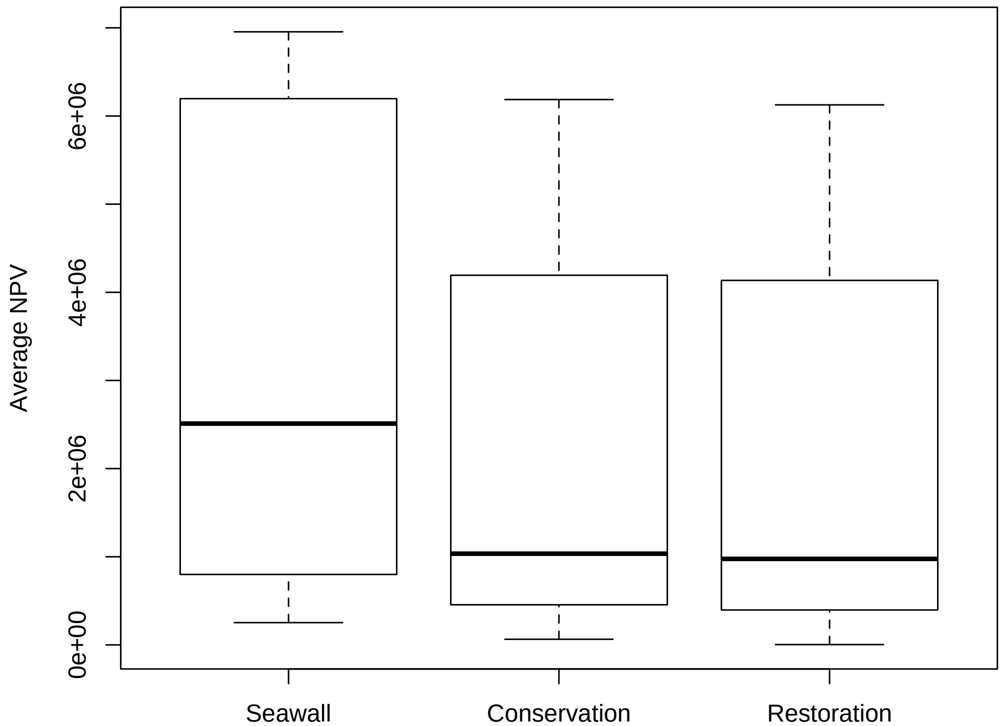

Figure 20. This displays the mean NPV for the various adaptation options analyzed, averaged across all variables, including project size, attenuation coefficients, climate change scenarios and tides

Averaging across all model uncertainties and basing a decision on the resulting mean NPV presents a strong case for seawall construction. This is in part due to the simplistic seawall model used in the analysis. Regardless of the size of the storm surge projected within our surge model, there is always a seawall height that is able to block it and these protective services are so valuable that they tend to offset the construction costs associated with the adaptation method. In the case of mangrove projects, the best performing mangroves can attenuate only 70% of the incoming storm surge. Under highly damaging scenarios, 30% of a large storm surge passing through the mangrove forest is still costly. This indicates that the mangrove forest in our model is unlikely to out-perform all of the seawall heights on protection benefits alone, even though mangrove conservation or restoration is only fraction of the cost of seawall construction. It is worth noting is that there is more variability in the NPV of seawall construction than EbA options when averaging across all variables. This can be explained by exploring an advantage that mangroves have over the seawalls, which is their relative protective flexibility. The same mangrove forest in our model will attenuate all levels of storm surge by the same proportion, where the seawall protection value is dependent upon the height to which it is constructed. This presents a strong case for analyzing the option value of conserving a forest due to the uncertainty related to future climate and cyclone characteristics.

Option value refers to the value of preserving the ability to make a decision in the future when there is less uncertainty in the conditions that must be dealt with. Once society decides what it values most, the optimal decision can then be made. By conserving the mangrove forest now instead of constructing a seawall, the society is preserving the option to keep the mangrove services intact. If future damages turn out to be at the high end of the modeled conditions, the transition to protection via seawalls can then be accomplished relatively easily (assuming there is funding available). Conversely, if the decision was made to build a seawall and future damages trended towards the lower end of the spectrum, which mangroves could have effectively protected against, the society would have sacrificed the mangrove co-benefits and may be unable to easily reconvert the land to a mature mangrove ecosystem.

Variability in Damage Protection

An important variable is the amount of damage protection able to be provided by each adaptation option. Three attenuation coefficients for mangroves and three heights for seawalls were included in the model. Sorting the data to examine results across variability in damage protection capability leads to the findings shown in Figure 21.

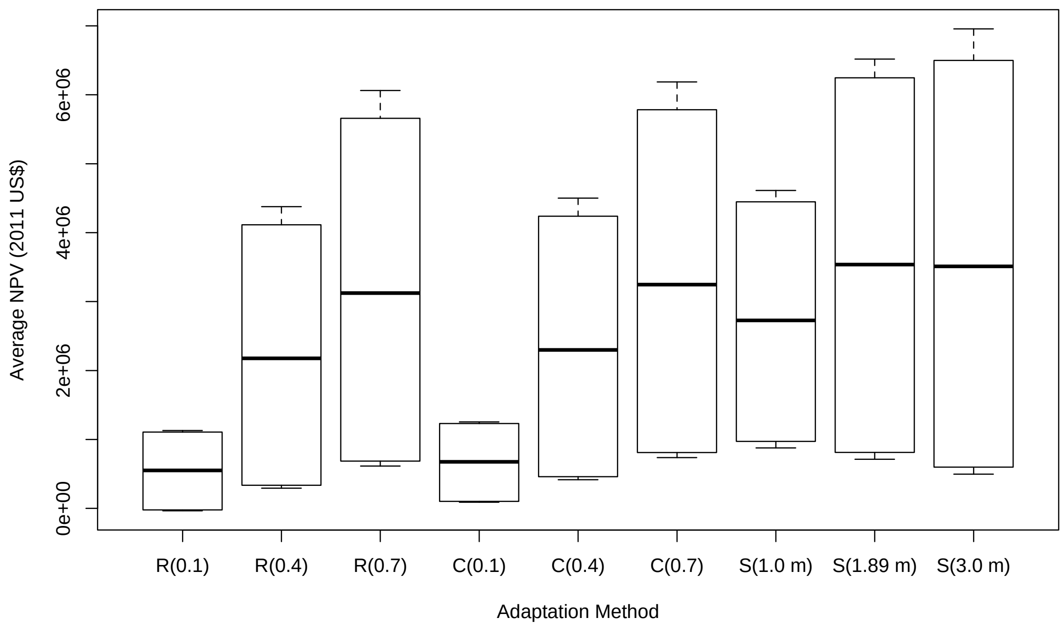

Figure 21. The mean NPV of the various adaptation methods, where R = restoration of mangrove, C = conservation of mangroves, and S = seawall construction. The numbers in parenthesis refers to mangrove attenuation coefficients and seawall heights, for mangrove and seawall projects, respectively

There appear to be cases where a mangrove forest with a high attenuation coefficient can compete and even achieve a higher Net Present Value than a seawall. This situation is most likely to exist if all storms occurred at low tide (at low tide the mean NPV for seawalls and mangroves is almost identical, see tides discussion). While this may not be a particularly firm platform for a manager or decision maker to stand on given tidal range across time, it does indicate that situations may exist where mangroves outcompete seawalls. In a way, this situation could also represent a scenario where the impacts of climate change on future storm surge intensity are less severe. If this is the true state of nature in the future, then the NPV for the mangroves could indeed be larger than that of seawall construction.

The mean NPV for a 1.89 m. seawall ($3,544,648) is effectively the same as the mean NPV for a 3 m seawall ($3,573,012) (See Table 8 below). What this implies is that as a project moves from a 1.89 and 3 m seawall, the added protection value (as represented by NPV) provided by the seawall begins to be outweighed by the additional costs required to construct the taller seawall. This indicates that the marginal value gained by the extra meter of protection may not be worth the investment. Additionally, given the system boundaries and parameters as described in this model, continuing to increase seawall heights beyond 1.89 meters is not an efficient action. This is largely because the costs of a seawall necessarily increase with the height of the project due to increased material costs (see Seawall Methodology above for details).

In addition, the variability for mangroves with low attenuation is significantly less than the variability for more protective options. This is explained by the fact that the costs and the co-benefits for the mangrove projects are constant, regardless of the wave attenuation coefficient, while the protection values of the mangrove forests vary largely by this parameter. The value of each adaptation method is closely tied to the damage that it prevents. As such, the conditions that produce the highest expected damage in our model produce the highest protection values, regardless of the adaptation strategy selected. For example, when a mature mangrove forest is confronted with a small storm surge occurring during low tide, this mangrove system has minimal value as an adaptation option. However, this same mangrove forest, when guarding against a large storm surge occurring during a high tide, would have a substantially larger protection value.

With increasing protective capacity (i.e. increasing the attenuation coefficient or the seawall height) the variability in the protection value of both adaptation strategies increases. In other words, the variability in the adaptation benefits, and therefore the NPV, increases with the "effectiveness" of the project.

Benefit-to-Cost Ratio

Mangrove Conservation:	Max NPV	B:C ratio	Tide	Intensity	Scenario	Investment
0.1	$1,254,224	9.6	1.7	0.1	2	$145,236
0.4	$4,501,615	32.0	1.7	0.1	2	$145,236
0.7	$6,186,337	43.6	1.7	0.1	2	$145,236
Seawall Construction:	Max NPV	B:C ratio	Tide	Intensity	Scenario	Investment
1	$4,612,223	24.8	1.7	0.1	2	$193,561
1.89	$6,518,516	18.8	1.7	0.1	2	$365,834
3	$6,955,483	13.0	1.7	0.1	2	$5,800,688

Table 8. The maximum NPV outputs from our model, for mangrove conservation and seawall construction, and the conditions that create these situations. The highest protection value and therefore maximum NPV for both adaptation strategies occur under the harshest climatic conditions

The Benefit-to-Cost (B:C) ratio makes the case for mangroves stronger due to their low cost. The mean B:C ratio is still slightly higher for seawalls, however there appear to be more conditions in which the mangrove conservation out competes the seawalls (Figure 22). Table 8 pulls out only the best case scenarios, meaning the highest adaptation value, for the various options and analyzes their B:C ratio. From the table, it is clear that making a decision based on the maximum NPV that can be achieved would lead to a seawall, but the best B:C ratio is found in the high attenuation mangrove forest, implying that the decision may not be so simple. Depending on the total quantity of funding available, the best-case mangrove forest may be an attractive option due to their lower costs.

The investment cost required to perform the adaptation options varies substantially, as seen in Table 6. The high cost of larger seawalls may be prohibitive for coastal communities with limited funding, whereas mangrove conservation as modeled here presents a low-cost alternative while still offering comparable protection under certain future conditions.

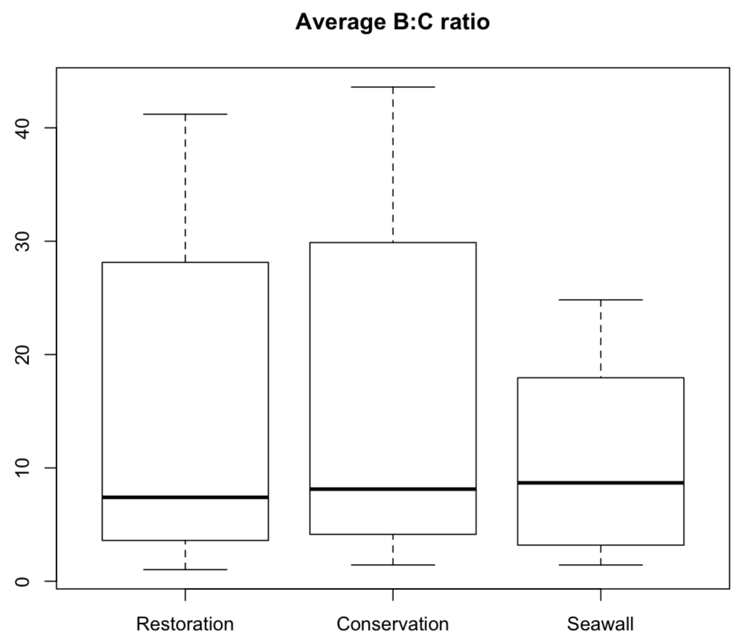

Figure 22. Mean Benefit-to-Cost Ratio (B:C) for each of the three adaptation options, Mangrove Restoration, Mangrove Conservation and Seawalls. Higher B:C generally indicates a more favorable project (subject to constraints described in text).

B:C ratios are commonly used to determine which projects to perform first in a string of potential projects that do not interfere with the other proposals. We have modeled the optimal protection strategy for a 500 m x 100 m section of the coastline of the Suva Peninsula in Fiji. Since we are assuming that only one project can be chosen to protect this hypothetical stretch of coastline, our projects are considered mutually exclusive and therefore B:C ratio may be a misleading metric for the analysis. In reality, if the goal were to protect a long length of coastline from storm surge inundation, a more varied array of property values would be determined. This would create a spatially heterogeneous mix of protection values for whichever adaptation option was chosen. In this case, it is possible that the optimal level of protection would vary along a coastline and a mix of various adaptation strategies could be the optimal outcome. Under these conditions, the B:C ratio may then be a pertinent metric of analysis.

Sensitivity Analysis Part 1: Surge Model

Surge Sensitivity to Climate Scenario

When analyzing the average surge heights under a SLR regime, the variability of the surge heights of increased with time (Figure 23). Note that the overall trend is an increasing potential for higher surge levels, representing the impact of climate change as described by the IPCC scenarios. It is important to note that SLR is modeled in a linear fashion in this model and its impact on surge heights through time expresses this linear relationship. If SLR occurs in a non-linear fashion in the future, it would likely produce a non-linear response in mean surge height.

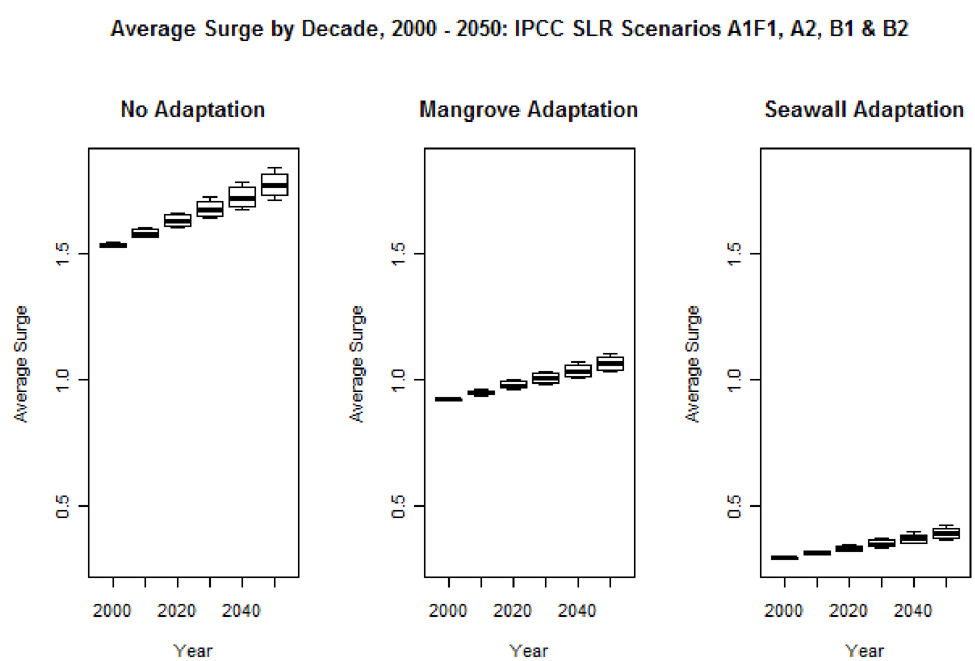

Figure 23. Displays the mean surge height through time accounting for the uncertainty in future SLR conditions as predicted by the IPCC climate scenarios

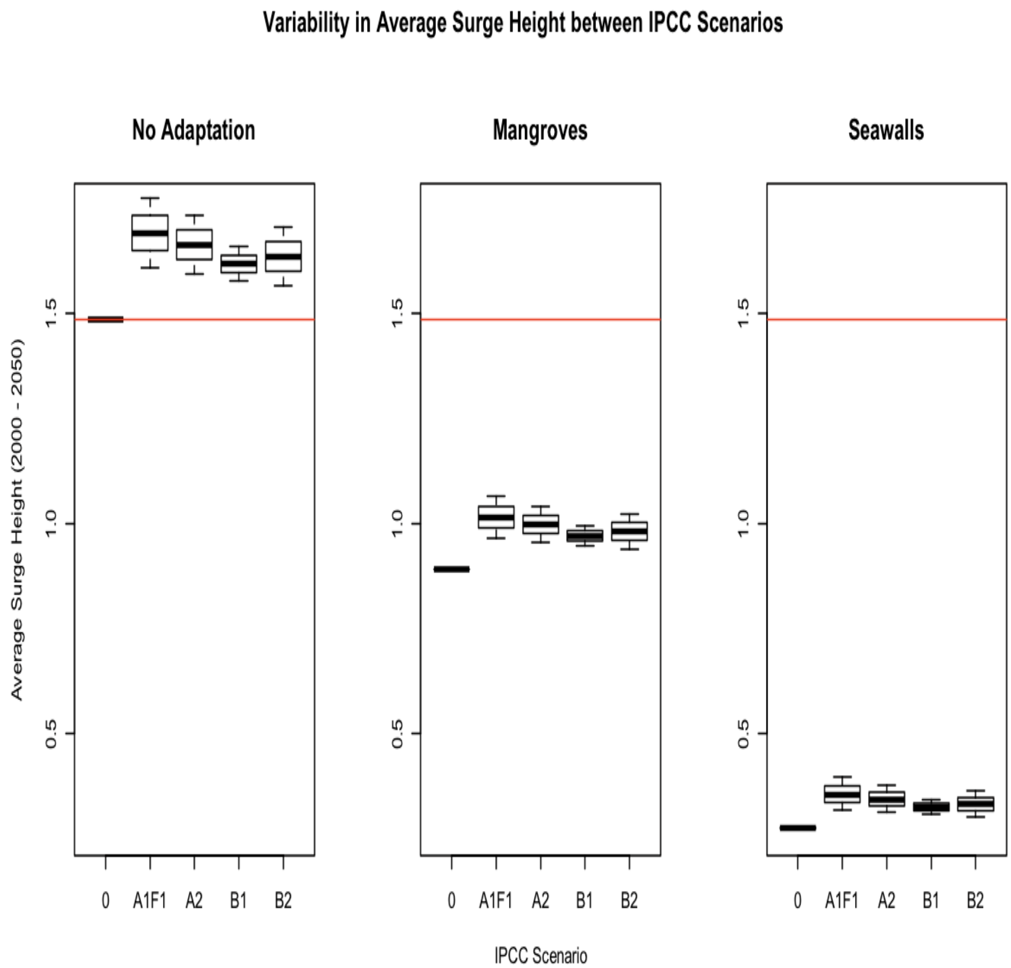

Figure 24. This figure represents the variability in surge height between IPCC scenarios. The red line indicates the 1990 baseline surge height

Boxplots were developed to look at the variability in surge height across climate scenarios for all adaptations (Figure 24). There appears to be less variability in surge height with either adaptation as compared to the baseline. While you would expect a mean reduction in surge height when implementing any type of adaptation project, a reduction in the uncertainty of the expected conditions is an added bonus.

We find the lowest mean surge heights with seawalls, indicating a larger damage reduction (Figures 23 & 24). It is important to stress the differences between the no adaptation and adaptation scenarios. Adapting to climate change stressors significantly reduces the average surge height in comparison to the no adaptation scenario. These differences are much greater than the uncertainty associated with how climate change will unfold. Additionally, note that there is not a large amount of divergence between climate scenarios, indicating that future climatic conditions are not the largest driver of variability. In this particular case, when deciding how to adapt to storm surge inundation, accurately predicting future climate impacts are not vital to the viability of a given adaptation project. The variability due to damage function appears to be a much larger driver of this model, as described below. Accurately understanding this relationship in a local context should be a priority.

Surge Sensitivity to Damage Function

As expected, the absolute damage caused by modeled cyclone storm surge events increased with increasing damage function slope, regardless of adaptation method used. The sigmoid function, however, is highly sensitive to the various states of nature. Under no adaptation, the sigmoid damage function yields the highest absolute damage values but under either adaptation this relationship no longer holds, as seen in Figure 25.

As described in the previous section, the uncertainty related to the range of damage functions (Figure 25) is a much larger driver of overall model variability than the uncertain climate future (Figure 24).

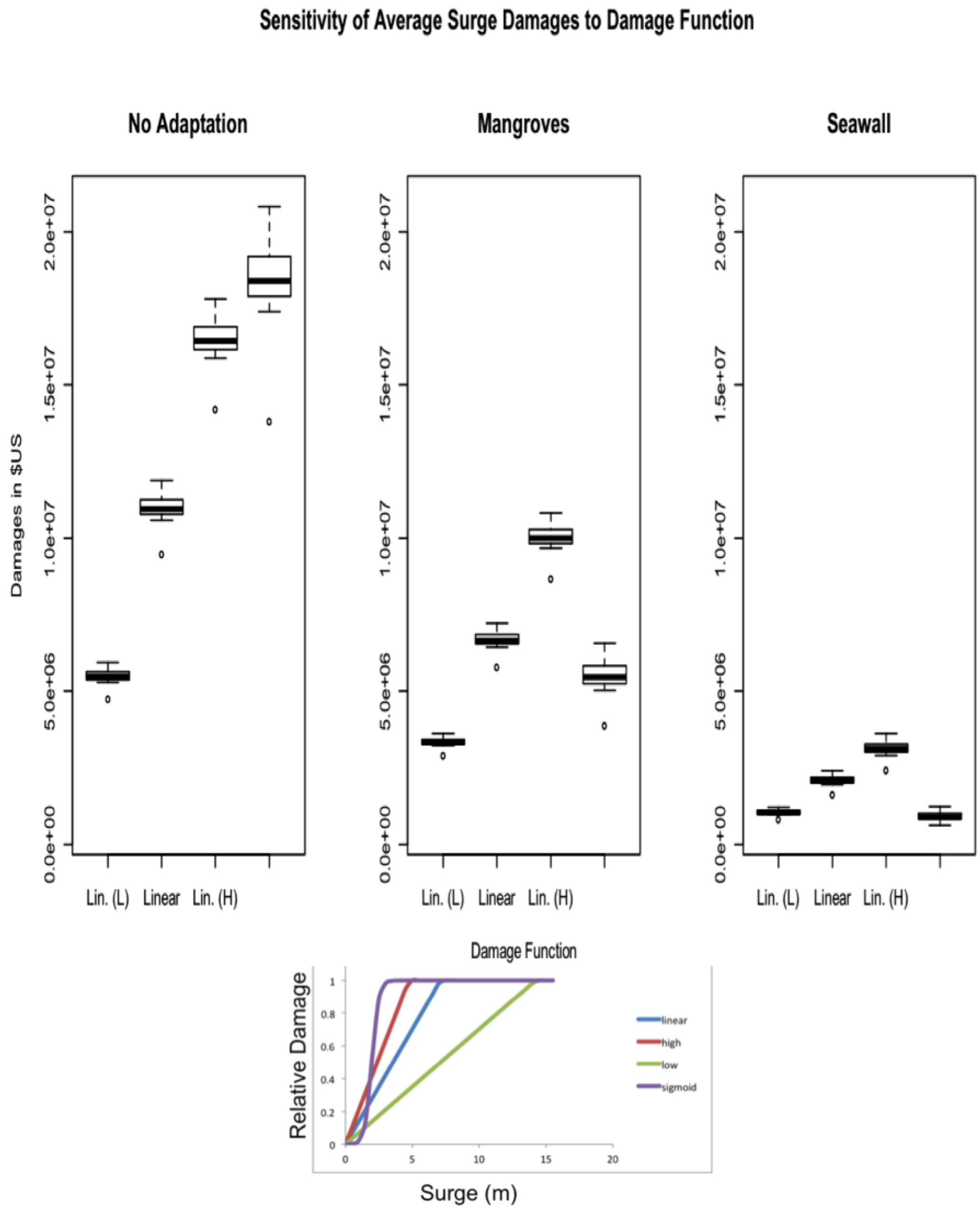

Figure 25. Absolute damages caused by the various surge to damage curves explored in 2011 USD for the no adaptation, EbA, and hard adaptation projects. Lin (L), Linear, and Lin (H) refers to the linear damage function with low, intermediate, and high slopes, respectively, while the sigmoid function on the far right of each chart is denoted sigmoid. The shape of each damage function is represented in the lower chart for reference.

The sigmoid curve is the only non-linear relationship explored here. If it is representative of the true surge-to-damage relationship in Fiji, the adaptation potential could be quite large, providing the adaptation is capable of reducing damages within the exponential portion of the curve. The sigmoid function leads to low damages over small surge heights but once the steep portion of the curve is reached the damages increase exponentially causing much larger damages over a relatively small change in surge height.

Another important result is the reduction of surge height variability in both adaptation options in relation to the no adaptation option.

Sensitivity Analysis Part 2: CBA

Sensitivity to Tidal Height

The NPV of each adaptation across the two tide levels was plotted to identify any effects of tide in the model. The mean NPV for mangrove conservation, averaged across the attenuation coefficients (Figure 26) and seawalls, averaged across all heights (Figure 27), under each tide (0.16m, 1.7m) were boxplotted for comparison.

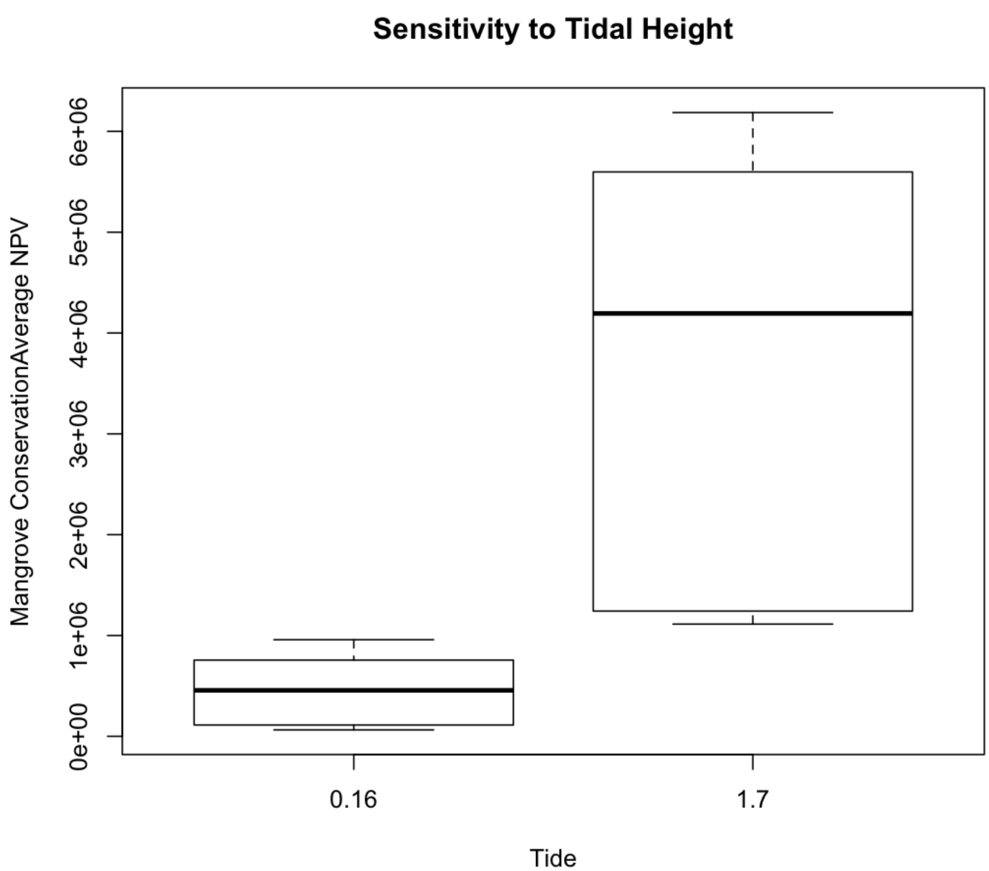

Figure 26. Sensitivity of the NPV to tidal height for mangroves

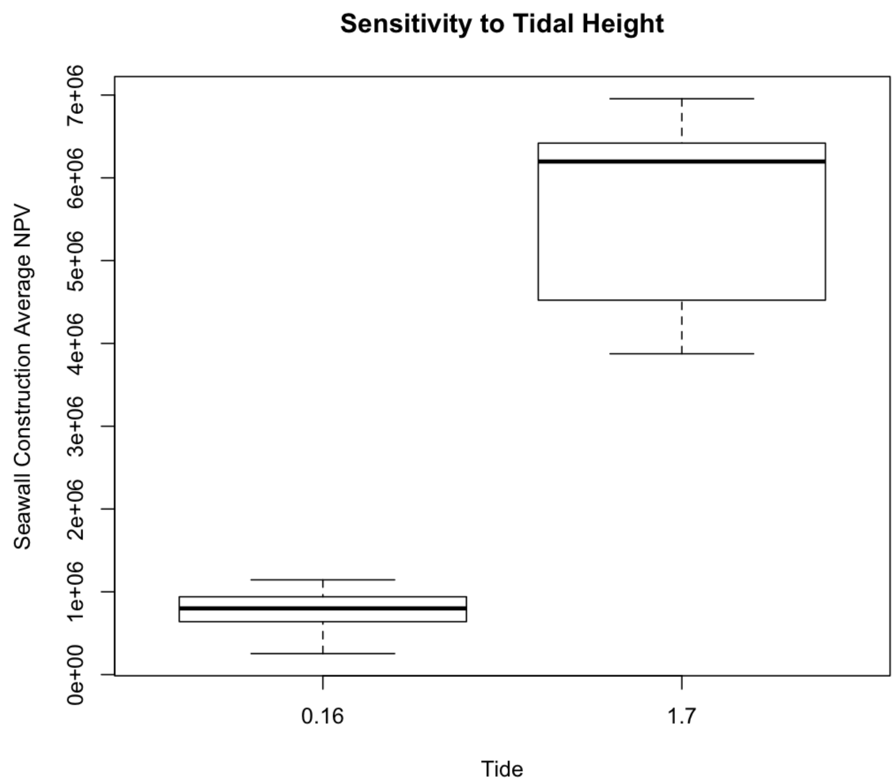

Figure 27. Sensitivity of the NPV to tidal height for seawalls

The result of these plots is that there is a sizable difference in the mean NPV for both adaption approaches under the two tidal conditions. The tidal component of our model is the largest determinant of high protective value and mean NPV because of the strong difference seen in these plots. When storms occur during a high spring tide, there are much larger damages when compared to low spring tide levels. Consequently, the highest mean NPV for both adaptation responses coincides with the hypothesized set of future storms occurring during a high tide.

Note that the highest and lowest spring tide values were used to show the extremes, including a "worst case" scenario (a large storm during the highest high tide). It's likely that many storms will occur during a mid-range tidal level, given it occurs more frequently. The risk attitude of the decision maker will impact the choosing of an adaptation option and reductive capability (mangrove attenuating coefficient and seawall height). If they are risk averse, they may choose an option that provides the highest NPV under the "worst case" tidal levels. Despite the annual predictability of local tides, the unpredictability of when a storm will occur and during what tide level complicates management decisions.

Sensitivity to Damage Function

As described in the surge model methodology, uncertainty regarding the surge-to-damage function necessitated the inclusion of four damage functions into the model: a linear model derived from the data, the same linear fit with a 50% slope increase, the same linear fit with a 50% slope decrease and a sigmoid fit taken from the literature. Figure 28 shows the four different damage functions plotted for hypothetical surge heights. A sensitivity analysis was performed on these damage functions in order to determine their relative contribution to the variability seen in the results. Figure 28 provides an overview, analyzed by attenuation coefficient and height and Figure 29 takes a broader look, displaying the variability associated with the linear models for the various adaptation methods, averaged across all attenuation coefficients & heights.

For the higher seawall heights (1.89 and 3 meters), the high linear damage function yields the highest NPV. This relationship is due to the high level of expected damages and the ability of the seawalls to prevent damage. The normally prohibitive costs of the higher seawalls are easily offset by their ability to handle the more destructive surges.

For all cases, the low linear damage function appears to have the least variability in terms of outcomes and the variability around the mean NPVs for the three linear functions increases with slope. As the slope increases, there is increased amount damage given the same surge heights plus a greater difference between the minimum and maximum damage values.

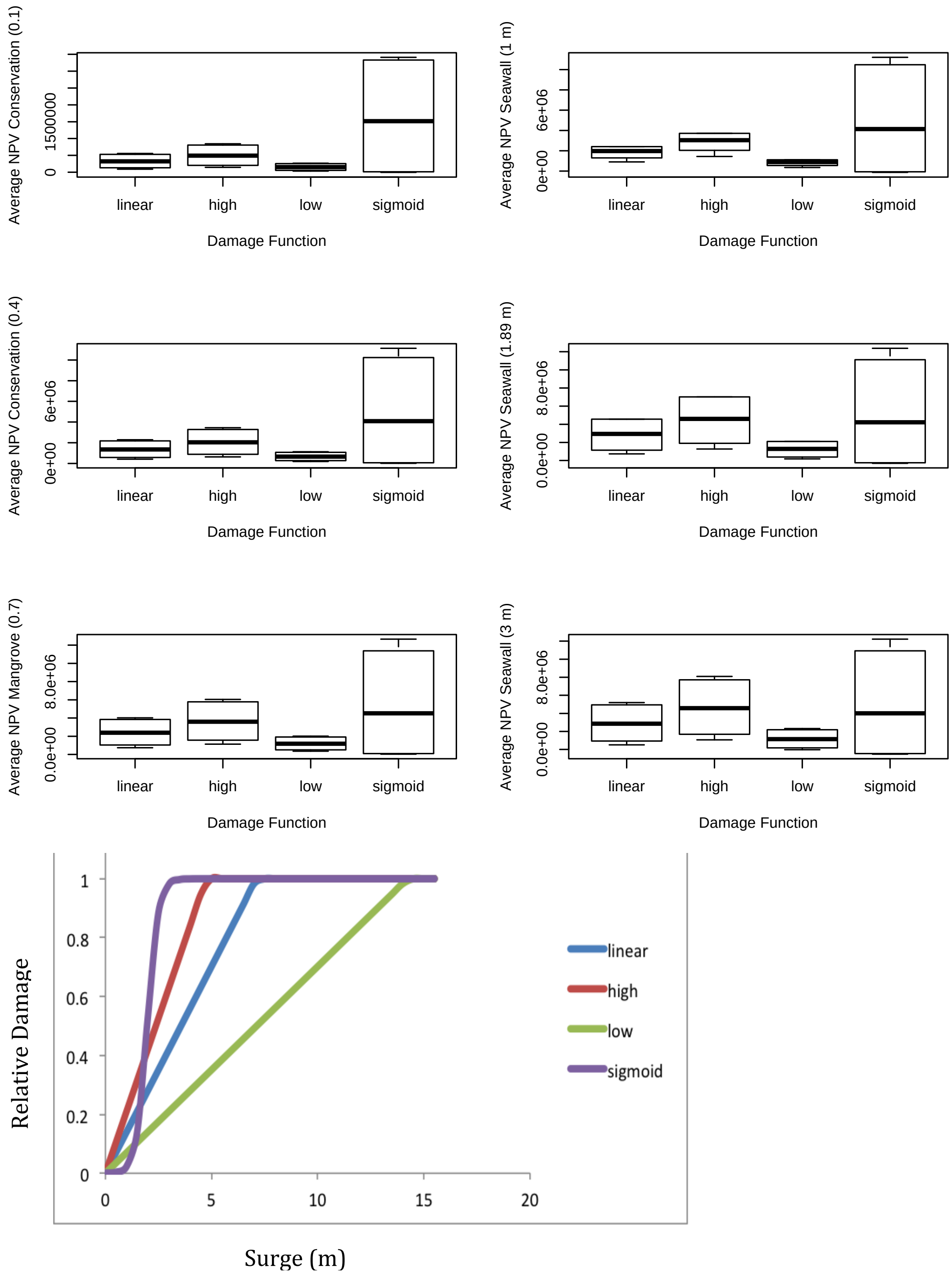

Figure 28. Sensitivity of NPV to the different surge to damage functions used in this analysis across a range of attenuation coefficients for mangroves and heights for seawalls. The shape of the functions is included in the lower chart for reference.

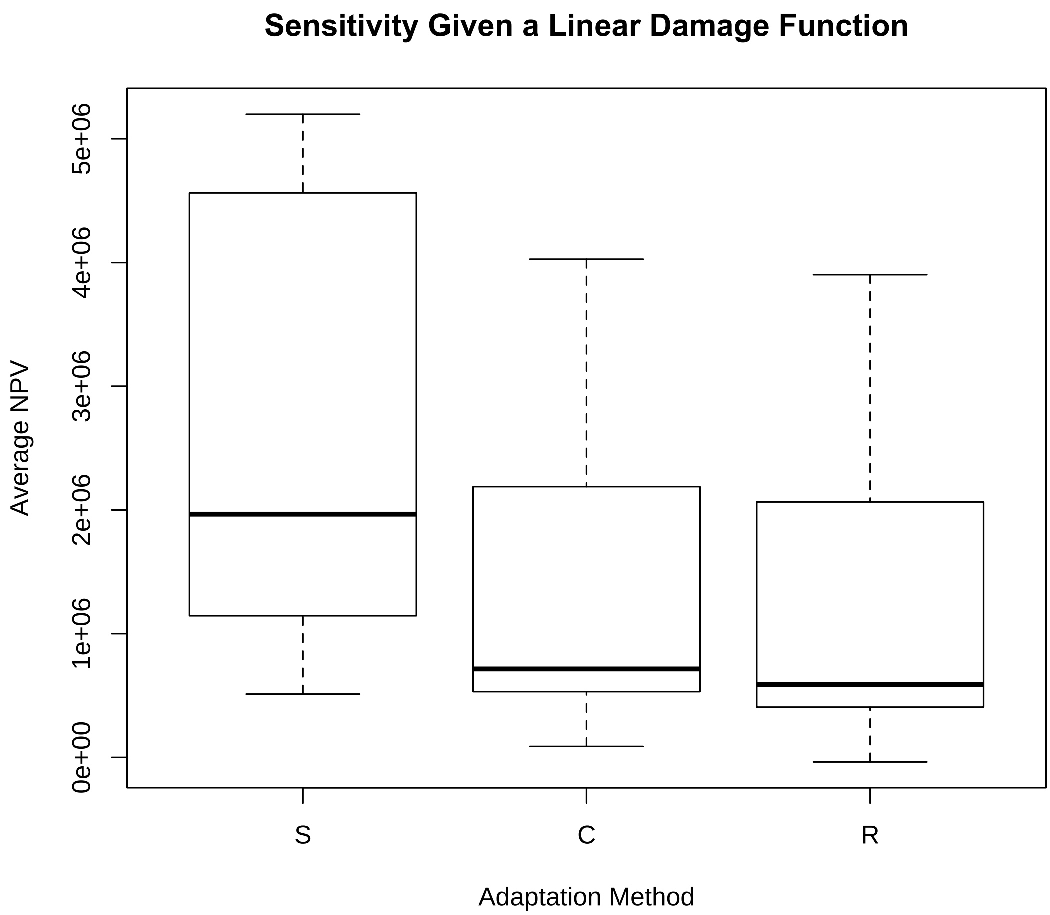

Figure 29. Displays the variability associated with the linear models for the various adaptation methods, averaged across attenuation coefficients & heights. S=Seawall, C= Mangrove Conservation, R=Mangrove Restoration.

The sigmoid damage function produces the highest variability in the NPV of the various adaptation strategies, regardless of their protective capacity (detailed in Figure 30). For sigmoid functions, the relationship between surge height and damage is non-linear. For lower surge heights - prior to the steep portion of the curve - all adaptation options are less valuable, relative to the other damage functions used, because the expected damage remains lower for higher surge heights. This means that for a large portion of our modeled storm surges the protection value of all the adaptation strategies is very low. The high end of the modeled surge levels are still below the level of the sigmoid curve at which total damage is done to the property and therefore the adaptation strategies are able to perform well even at the high levels of storm surge.

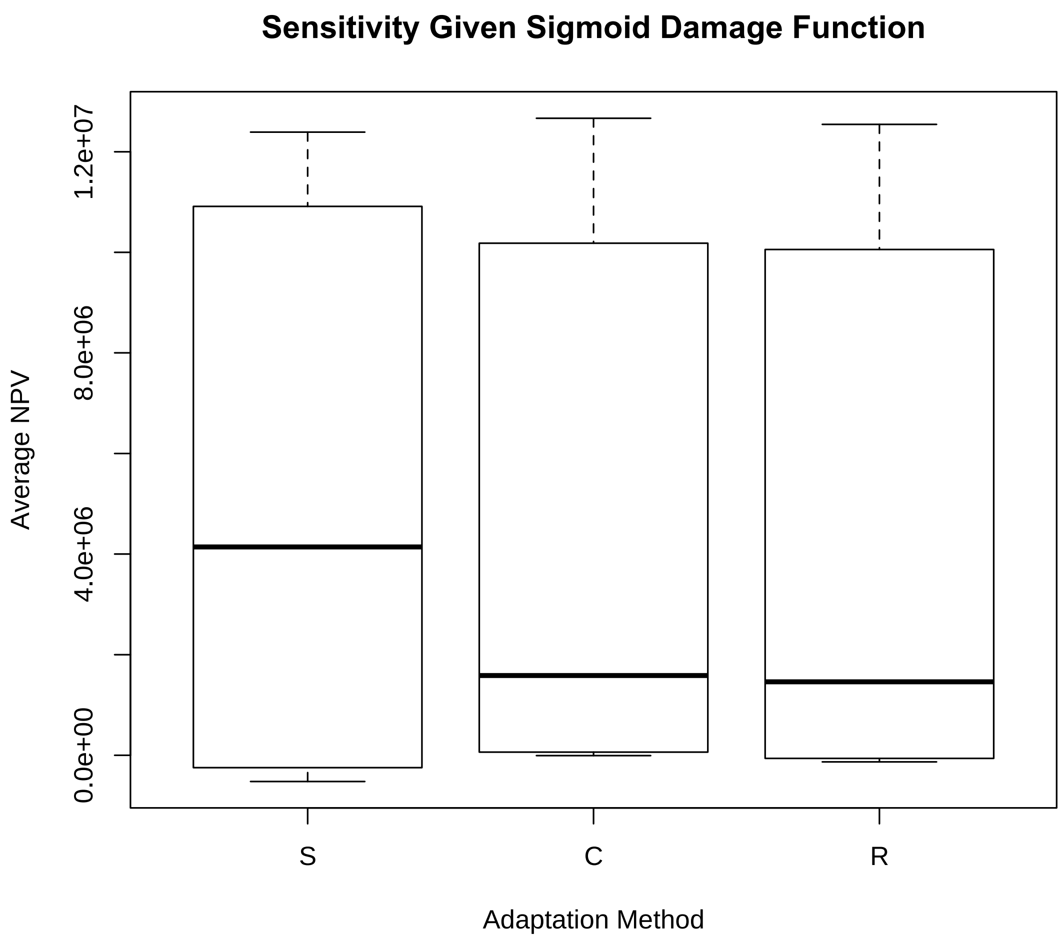

Figure 30. Displays the variability associated with using the sigmoid damage function and its impact on the average NPV for the various adaptation methods. S=Seawall, C= Mangrove Conservation, R=Mangrove Restoration.

In mangrove systems, the sigmoid damage function generates the highest NPV across attenuation coefficients, where this is only true for the lowest seawall height. This is likely due to the fact that the sigmoid function rarely reaches a relative damage of 1 and for the majority of surge heights, it yields smaller damage values than the other damage functions. As such, the higher seawall heights are unnecessarily protective and too costly, where as the mangrove protection value is not dependent upon the cost of the project.

Sensitivity to Climate Change Scenarios

The NPV of each adaptation across the four climate scenarios was plotted to identify any effects of climate uncertainty in the model. The mean NPV for mangrove conservation, averaged across the attenuation coefficients, and for seawalls, averaged across heights, under each scenario were boxplotted for comparison (Figures 31 & 32).

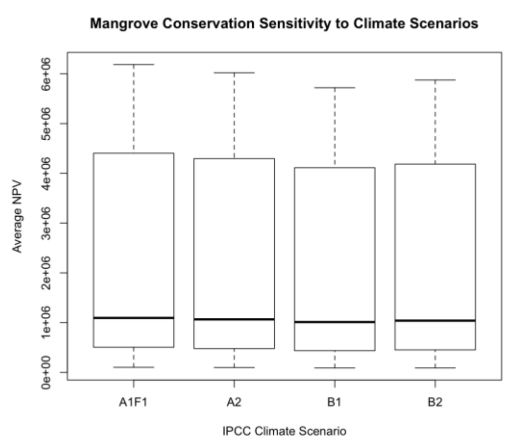

Figure 31. Mangrove Conservation adaptation option sensitivity to IPCC climate change scenarios

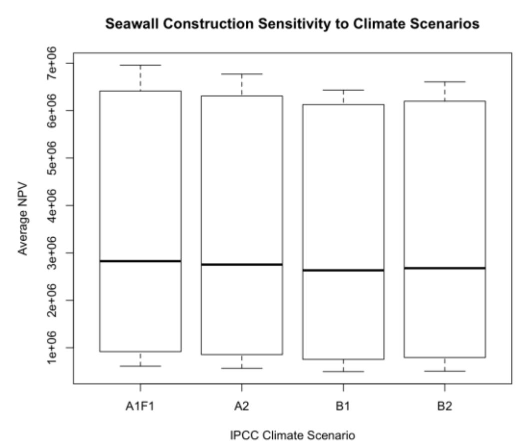

Figure 32. Seawall Sensitivity to Climate Change scenarios

The result of these plots is a lack of significant differences in the mean NPV for either adaptation approach under the different scenarios. Also, there is no significant difference in the variability around the mean NPVs under the different scenarios. This suggests that the climate scenarios included in this model (which have varying Sea Level Rise and varying Sea Surface Temperatures leading to a range of cyclone intensities) do not affect the NPV in any identifiable pattern. There appears to be value in prospective adaptive action, uncertainty in which future climate change scenario is likely to occur.

Although the mean NPVs across scenarios in both adaptions are similar, it is worth mentioning that Scenario 2 (representing A1F1) in all cases has a marginally higher mean NPV (See Table 9). This is attributed to Scenario 2 producing the largest damage relative to the baseline conditions, and consequently resulting in the highest protective value for both adaptation responses.

IPCC Scenario	Mean Mangrove Conservation NPV	Mean Seawall Construction NPV
A1F1	$2,194,647	$3,404,152
A2	$2,138,923	$3,316,514
B1	$2,044,109	$3,169,201
B2	$2,080,739	$3,225,780

Table 9. IPCC climate scenario and the resulting mean NPV for mangrove conservation and seawall construction. Values in 2011 USD.

Conclusions

Variability Drivers

We performed a regression analysis to determine how much of an effect each parameter has on our model and sources of variability. We regressed the mean NPV of mangroves and of seawalls individually on climate scenarios (SLR and SST), tide, intensity, and damage function. We found that neither the climate scenarios nor intensity impacted the most efficient adaptation decision significantly. The damage function increased variability with increasing slope. The sigmoid function produced more variability then the linear functions. Tide was the largest contributor to the variability.

Understanding which parameters have the greatest impact on the result, the mean NPV, is useful in deciding between adaption options. Climate uncertainty, as represented by the climate scenarios and intensities, is less important to the value of either adaptation, whereas tide will greatly affect it. Because tides are variable yet predictable, and storms are unpredictable, the risk averse position would be to assume high tide conditions when deciding on an adaptation approach. Choosing a damage function will also affect the mean NPV. However, because there is uncertainty in these damage functions, that relationship could change and variability could be reduced with better data.

Best Approach? It Depends.

Based upon the data available, the assumptions and constraints built into our model, our analysis and results indicate that for a given parcel of populated in coastline in Fiji, seawalls tend to outcompete mangrove forests, providing the best form of coastal protection to storm surges and sea level rise. This is not absolute, however. There appear to be instances in which a mangrove outcompetes seawalls, e.g. when storms hit at low tide and the respective mangrove forest has an attenuation coefficient of 0.7. The obvious complication is that although storms can hit at any tide level, the storms that cause the most damage occur when the tide level is at a significant high and it is these storms that planners may want to prepare for.

The difference between actual damages reduced and the resulting NPV for each adaptation option is an important distinction. Due to the structure of the seawall model, it would be very hard for mangroves to compete with the seawall strictly on physical surge protection. This is because mangroves are reducing a surge by a given percentage (i.e. 10%, 40% or 70%) as compared to the bulk reduction from the seawall. As modeled, when a surge hits a seawall it results in either complete mitigation of the surge or a much reduced surge, resulting in much reduced damage costs. This is demonstrative of a key point related to the distinction between the economic and physical components of catastrophe modeling. The NPV for mangroves and seawalls are not necessarily equivalent to the same amount of actual physical damage reduced. Because of the method of surge reduction, more damage may be caused with mangroves but their low construction costs and additional co-benefits helps their NPV performance. To a person whose home is damaged, this increase NPV may not mean much. Conversely, seawalls can prevent much more damage, but have higher constructions costs, perhaps making them effectively out of reach to a poor community. The trade-offs become difficult from a policy perspective. For example, a decision to move forward with a mangrove forest may be a difficulty policy position largely because of the increase in physical damage. A solution could be to ensure that, if a mangrove system provided significant value over a seawall, the surplus NPV from the project could be spent on soft adaptation measures, such as an early warning system, in order to avoid loss of life or other non-economic damages. Additional research and the development of policy decision support systems are necessary to help decision-makers understand and engage with these difficult questions.

Conservation vs. Restoration

Our model looked at two different EbA cases: restoring a degraded or eliminated mangrove forest and conserving an intact, healthy mangrove forest. Both have relatively similar outcomes with regards to the average NPV over the three attenuation coefficients although conserving an intact mangrove results in a slightly higher NPV. This can be explained due to the modeled decadal lag before the mangrove restoration project reaches the respective attenuation coefficient of 0.1, 0.4 and 0.7, representing an optimistic time-to-maturity. What is clear from our analysis is that if decision makers were going to pursue mangroves as the adaption method, they would need to ensure that they are conserving a mangrove forest with an attenuation coefficient of ≥ 0.7 (or restoring it to that attenuation coefficient), in order to receive the high end of valuable protective capability. This represents a strong case for conservation of standing mangrove forests for coastal protection.

The Role of Co-Benefits

The CBA included co-benefits (ecosystem services other than the adaptation value in question) derived from mangroves. Co-benefits included the values of commercial fisheries, subsistence fisheries, medicinal plants, raw materials, habitat functions (e.g. sewage treatment), etc., with values derived from country specific literature. Conservation organizations are looking at co-benefits and ecosystem services as further support to implement an EbA approach over an engineered approach. Our analysis concluded that the co-benefits provided by the mangrove forests in this particular case study played a rather minor role in the larger economic analysis and certainly didn't tip the scales towards one adaptation option over another. An important aspect to note is that in a mangrove forest with an attenuation coefficient of 70%, you would expect more co-benefits because these are the most intact ecosystem represented. We did not include this dynamic co-benefit response in our model.

We recognize that these ecosystem service values are region specific, in that co-benefits of a mangrove forest in a developed country with a significant commercial fishery that relies on mangroves, may have a much greater value for that co-benefit. It is also system specific: for other systems, such as inland ecosystems that provide flood attenuation as well as water filtration, the co-benefits from flood reduction may represent a larger component of the total value provided. Additionally, as ecosystem service valuation continues to improve, the role that the co-benefits may play in this sort of economic analysis will increase.

Note that we chose to leave carbon sequestration out of the co-benefit component of the model due to the large uncertainty with regard to the economic value of this service. With carbon currently trading at $10 / ton and generous estimates of the sequestration potential for mangroves at roughly 1 ton/hectare, the addition of $10 / hectare in co-benefits would not have made a noticeable difference. If the market price of carbon increased dramatically via a market driver, the inclusion of REDD potential in this CBA would be an interesting component of the analysis.

Concluding Summary

After averaging across uncertainty in climate scenarios, adaptation effectiveness, and flood impact costs (among other variables) our model finds that the mean NPV for constructing seawalls is generally higher than it is for conserving or restoring mangrove systems. Within the range of uncertainty, there are scenarios in which mangroves outperform seawalls. In these scenarios, the mangrove forest would need to be mature and provide wave attenuation levels near the high end of our estimates.

It is important to note the difference between the physical and economic components of disaster modeling. A Cost-Benefit Analysis necessarily includes factors beyond the damage reduction potential of an adaptation project. Availability of investment and maintenance capital for these projects becomes an important consideration, given the large disparity between the costs of seawall construction (high) and mangrove conservation/restoration (low). While a high quality seawall may provide the greatest protection value, the costs for such a project may be out of reach for poorer communities. As a result, one of the key advantages to the EbA approach is their relative affordability and overall flexibility given a range of possible futures.

Beyond the specific case study results, our project generated replicable conceptual and quantitative models as well as illuminated several key data needs for investigating climate change adaptation options. The key knowledge gaps are the surge-to-damage functions, adaptation effectiveness, inundation projections, ecosystem service values, and project costs. Understanding the types of data needed is an important step in performing a rigorous comparison of adaptation options. Our sensitivity analysis shows these are the areas where having better data would have the largest impact on the analysis. In addition our model can serve as a template for further exploration of effective cost-benefit analyses of adaptations to climate impacts. Although the general template is transferable, the analysis will require local data and the results will therefore be locally specific.

Fundamentally, the project confirms that ecosystem-based adaptation approaches can have a role to play in the larger effort to adapt to a changing climate. As data quality increases a more rigorous comparison between seawalls and mangroves is possible. Obviously increased data quality allows decision makers to more confidently make management choices. Nonetheless, the utilization and interpretation of the results may vary given the decision-maker's mandate, their risk appetite, priorities and resources. These subjective forces mean that there is no one "right" recommendation from our results, but rather a suite of data that can contribute to more informed decision-making, particularly given better data in the future.

Future Recommendations:

Next Steps with Model Development:

1. Developing a more realistic seawall model.
   Due to data limitations, the model developed for seawall coastal protection was rudimentary in this analysis. A more dynamic mode incorporating variability in effectiveness and more a more nuanced understanding of surge reduction processes would be desirable. There is a definite need in the filed for a seawall storm surge reduction model that can readily be compared to EbA alternatives. At the moment, the majority of the seawall modeling is more concerned with the structural integrity of the seawall given a storm surge vs. the effectiveness of surge reduction.

2. Allowing for variability in the GDP/area component (and therefore) the protective value of the various adaptation responses.
   This analysis assumed that the GDP of the area at risk was standard. An additional step would be to incorporate variability into this component by providing a range of GDP values such as agricultural land, rural, urban, tourism, etc… This would have a dynamic effect on the resulting NPV, given the different value of the areas being protected.

3. Analyzing the option value of preserving mangrove forest.
   The flexibility of the protective ability of mangrove forests in the face of climate uncertainty could be larger than that of a seawall that is designed to a certain threat level. In addition, converting a mangrove forest in favor of protective structures is likely an irreversible decision. As a result

analyzing option value seems like a logical next step for strengthening the case for mangrove conservation for adaptation to climate variability.

4. Continuous range of tidal levels.
   In this analysis, only the highest and lowest possible tidal levels were explored, both of which have a low associated probability of occurrence. In reality, a storm surge could occur during any tide and in fact have a higher probability of occurring during the more intermediate tidal levels. Therefore, to more accurately model the expected impacts of climate change on storm surge inundation should be modeled over a continuous tidal range.

5. Incorporate realistic values for negative impacts from seawalls.
   Erosion resulting from seawalls is a pressing concern in many locations. Data on this was not available for Fiji. Incorporating these additional negative impacts will likely have some impact on the final outcome.

6. Integrate more sophisticated and dynamic co-benefit values and calculations.
   Assigning different co-benefit values based on mangrove maturity levels would impact the difference between restoration and conservation of mangroves. As carbon pricing becomes more standard, including carbon sequestration as a possible income generator would additional impact the bottom line of the project

Additional Data Requirements:

Note that the preceding analysis was largely derived from literature values and, while representing decent first order approximation, would become much more accurate given local, on-the-ground data. The model development and analytical process revealed key data requirements that a project manager may want to consider prior to implementing an EbA project.

1. It is vitally important to have local and as accurate-as-possible storm surge to damage relationship data. Accurate modeling of surge damage represented one of the largest sources of variability in this project. Knowing how vulnerable a given site is represents a priority for any adaptation action.

2. It is important to understand the distribution and quality of the on-site mangroves in order to determine accurate wave attenuation values. Additionally, co-benefit values vary significantly by location (and data on their values is often sparse).

3. Verified conservation, restoration, and management costs for mangrove adaptation projects.

4. Good records of historical storm and surge frequency. The global data record on surge is remarkably limited but some regions have excellent local data. In lieu of historical data on storm surge, sophisticated models exist to model storm surge based on detailed geomorphology and historic storm characteristics. If those data are available, the development of surge projections becomes much simpler and more reliable.

References

Adaptation to Climate Change, Discussion Paper #10, October, World Bank

Adger, W.N., Hughes T.P., Folke, C., et al. (2005). *Social-ecological resilience to coastal disasters.* Science 309: 1036-1039.

Agrawala, S., Ota, T., Risbey, J., Hagenstad, M., Smith, J., van Aalst, M., Koshy, K., et al. (2003). Development and Climate Change in Fiji: Focus on coastal mangroves. *Environment Directorate and Development Cooperation Directorate, Organisation for Economic Cooperation and Development (OECD), Paris*.

Ainsworth, T. 'Significant Wave Height': A closer look at wave forecasts. NOAA's National Weather Service.

Airoldi, L., Abbiati, M., Beck, M. W., Hawkins, S. J., Jonsson, P. R., Martin, D., Moschella,
P. S., et al. (2005). An ecological perspective on the deployment and design of low-crested and other hard coastal defence structures. Coastal Engineering, 52(10–11), 1073-1087. doi:10.1016/j.coastaleng.2005.09.007

Alongi, D., (2008). *Mangrove forests Resilience, protection from tsunamis, and responses to global climate change.* Estuarine, Coastal and Shelf Science 76: 1-13.

American Society of Civil Engineers. 2005. Minimum Design Loads for Buildings and
Other Structures. *Structural Engineering Institute. ASCE 7–05; ASCE Publications*: Reston, VA.

Baba, S., Gordon, C., Kainuma, M., Ayivor, J., Dahdough-Guebas, F. (2004). The global mangrove database and information system (GLOMIS): present status and future trends. *Proceedings of "the Colour of Ocean Data" Symposium*, Brussels 25-27 November 2002. IOC Workshop Report 188 (UNESCO, Paris)

Bao, T.Q., (2011). *Effect of mangrove forest structures on wave attenuation in coastal Vietnam.* Oceanologia 53(3): 807-818.

Barbier, E.B. (2006). *Natural barriers to natural disasters: Replanting mangroves after the Tsunami.* Frontiers in Ecology and the Environment, 4(3): 124-131.

Barbier, E.B., Koch, E.W., Silliman, B.R., Hacker, S.D., Wolanski, E., Primavera, J, Granek, E.F., Polasky, S., Aswani, S., Cramer, L.A., Stoms, D.M., Kennedy, C.J., Bael, D., Kappel, C.V., Perillo, G.M.E., Reed, D.J. (2008). *Coastal ecosystem-based management with nonlinear ecological functions and values.* Science 319: 1-14.

Barstow, S. and Haug, O. 1994. Wave Climate of Fiji. *SOPAC Technical Report 205.*

Besley, P. 1999. Overtopping of Seawalls: Design and Assessment Manual. *H.R. Wallingford Environment Agency Technical Report W178.*

Bettencourt et al. (2000). Cities, Seas, and Storms: Managing Change in Pacific Island Economies. *The World Bank Group.*

Brinkman, R.M., Massel, S.R., Ridd, P.V., Furukawa, K. (1997). *Surface wave attenuation in mangrove forests.* Proceedings of the 13th Australasian Coastal and Ocean Engineering COnfernece 2: 941-949.

Church, J. Hunter, J. McInnes, Kathleen. White, Neil. 2006. Sea-level rise around the Australian coastline and the changing frequency of extreme sea-level events. Australia Meterological Magazine. 55: 253-260.

CIA - The World Factbook. (n.d.). Retrieved February 25, 2012, from https://www.cia.gov/library/publications/the-world-factbook/geos/fj.html

Clark, R. 1982. Structural Design Aspects of a Coastal Building Code. *Coastal Engineering.*
Conference Proceeding Paper: 2285-2299.

Ellison, J. (1999). *Present status of Pacific Island mangroves.* Marine/Coastal Biodiversity in the Tropical Island Pacific Region 2: 3-19.

Ellison, J. (2003). *The value of mangrove ecosystems: Ecosystem services and functions.* In Proceedings of the Pacific Regional Workshop on Mangrove Wetlands, Protection and Sustainable Use. South Pacific Regional Environment Program, Apia, Western Samoa, pp 11-16.

Ellison, J., Fiu, M. (2010). *Vulnerability of Fiji's mangroves and associated coral reefs to climate change.* A Review by WWF South Pacific Programme.

Emanuel, K. Sundararajan, R. Williams, J. 2008. Hurricanes and Global Warming: Results from Downscaling IPCC AR4 Simulations. American Meteorological Society. 89(3): 346 – 367.

FEMA. (10 Aug 2010). Hurricane Hazards: Storm Surge. Retrieved from http://www.fema.gov/hazard/hurricane/hu_surge.shtm.

Feresi, J., Kenny, G., de Wet, N., Limalevu, L., Bhusan, L., Ratukalou, I. (2000). Climate Change Vulnerability and Adaptation Assessment for Fiji. *The World Bank Group (IGCI Technical Report)*.

Fiji Islands Bureau of Statistics - Overseas Merchandise Trade. (n.d.). Retrieved February 25, 2012, from
http://www.statsfiji.gov.fj/Census2007/census07_index2.htm

Fiji National Workshop on Integrated Coastal Management. (2002). Sustainable Coastal Resource Management for Fiji.

Fiji Meteorological Service 2003

Griggs, G. and Tait, J. 1988. The Effects of Coastal Protection Structures on Beaches
Along Northern Monterey Bay, California. Journal of Coastal Research. 98-111.

Hale LZ, Meliane I, Davidson S, Sandwith T, Beck M, et al. (2009) Ecosystem-based
Adaptation in Marine and Coastal Ecosystems. Renewable Resources Journal 25: 21–28.

Hoang Tri, N., Adger, W., & Kelly, P. (1998). Natural resource management in mitigating
climate impacts: the example of mangrove restoration in Vietnam. Global Environmental Change, 8(1), 49-61. doi:10.1016/S0959-3780(97)00023-X

Holden, Brendan. July 1992. Coastal Damage Inspection Southwest Viti Levu, Fiji After Cyclone Sina. *SOPAC Technical Report 148.* Retrieved from http://www.sopac.int/data/virlib/TR/TR0148.pdf.

Hu, K., Mingham, C. and Causon, D. 2000. Numerical Simulation Of Wave Overtopping
Of Coastal Structures Using The Non-Linear Shallow Water Equations. *Coastal Engineering.* 41: 433-465.

Hughes, S. and Nadal, N. 2009. Laboratory Study Of Combined Wave Overtopping And
Storm Surge Overflow of A Levee. *Coastal Engineering.* 56: 244-259.

IPCC, 2007: Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

Jaffar, M. (1992). *Country Report on Mangrove ecosystem in the republic of Fiji.* Proceedings Seminar and Workshop on integrated research on mangrove ecosystems in Pacific islands region.

Kortenhaus, A., Miller, C., and Oumeraci, H. 1996. Design Of Vertical Walls Against
Storm Surge. *Proceedings of 25th Conference on Coastal Engineering*. 1403-1416.

Koshy, Kanayathu. 2007. Modeling Climate Change Impacts on Viti Levu (Fiji) and Aitutaki (Cook Islands). *Assessment of Impacts and Adaptaitons to Climate Change, Project No. SIS09*.

Lal, P.N. (1990) *Conservation of conversion of mangroves in Fiji: An ecological economic analysis.* Environment and Policy Institute, East-West Center.

Lal, P.N., Swamy, K., Singh, P. (1983). *Mangroves and secondary productivity: Fishes associated with Wairiki Creek, Fiji.* Proceedings of an Interdepartmental Workshop, 24 February 1983, Suva, Fiji. Technical Report No. 5, Fisheries Division, Fiji.

Maharaj, R.J.N. (2002) In Mimura, H. Yokoki, (Eds) Proceedings of the APN/SURVAS?LOICZ Joint Conference on Coastal Impacts of Climate Change and Adaptaion in the Asia-Pacific Region, Kobe, Japan, 14-16 November 2000.

Mangrove.org (2011). www.mangrove.org. 6001 Highway A1A, Indian River Shores, FL 32963

Massel, S.R., Furukawa, K., Brinkman, R.M., (1999). *Surface wave propagation in mangrove forests.* Fluid Dynamics Research 24: 219-249.

Mazda, Y., Magi, M., Kogo, M., Hong, P.N., (1997). *Mangroves as a coastal protection from waves in the Tong King delta, Vietnam.* Mangroves and Salt Marshes 1: 127-135.

Mazda, Y., Wolanski, E., King, B., Sase, A., Ohtsuka, D., Magi, M., (1997). *Drag force due to vegetation in mangrove swamps.* Mangroves and Salt Marshes 1: 193-199.

Mimura, N. and Nunn, P. 1998. Trends of Beach Erosion and Shoreline Protection in
Rural Fiji*. Journal of Coastal Research.* 14: 37-46

Mitchell, Bill. (12 May 2003). Sea Level Rise in the Pacific. South Pacific Sea Level Monitoring and Climate Project (SPSLMCP). Retrieved from http://www.bom.gov.au/pacificsealevel/presentations/BMPCCSeminar.pdf.

Naidu, Arti V. (June 2003). Information Data/Products to Modelling Development: “Storm Trak” Storm Surge and Tidal Modelling and Analysis System. *SOPAC Miscellaneous Report 510.* http://dev.sopac.org.fj/VirLib/MR0510.pdf.

National Research Council. 2007. Mitigating Shore Erosion along Sheltered Coasts. The
National Academies Press: Washington, D.C.

Nicholls, R., Brown, S., Hanson, S., & Hinkel, J. (2010). Economics of Coastal Zone

NOAA. (n.d.) Storm Surge Overview. Retrieved from http://www.nhc.noaa.gov/ssurge/ssurge_overview.shtml.

Nunn, P. 2009. Responding To The Challenges Of Climate Change In The Pacific Islands:
Management And Technological Imperatives. *Climate Research.* 40: 211–231.

Orlove, B. (2005). Human adaptation to climate change: a review of three historical
cases and some general perspectives. *Environmental Science & Policy*, *8*(6), 589-600. doi:10.1016/j.envsci.2005.06.009

PICCAP Fiji Islands. (2005). Climate Change: The Fiji Islands Response.

Quartel, S., Kroon, A., Augustinus, P.G.E.F., Van Santen, P., Tri, N.H. (2007). *Wave attenuation in coastal mangroves in the Red River Delta, Vietnam.* Journal of Asian Earth Sciences 29: 776-584.

Richmond, T. de A., Ackermann, J.M. (1975) *Flora and fauna of mangrove formations in Viti Levu and Vanua Levu, Fiji.* Proceedings of International Symposium on Biology and management of Mangroves. East-West Center, Honolulu. Pp. 147-152.

Saenger, P., (2002). Mangrove Ecology, Silviculture and Conservation. Kluwer, Dordrecht.

Shepard, C. C., Crain, C. M., & Beck, M. W. (2011). The Protective Role of Coastal Marshes: A Systematic Review and Meta-analysis. PLoS ONE, 6(11), e27374. doi:10.1371/journal.pone.0027374

Solomon, S. and Kruger, J. 1996. Vulnerability and Adaptation Assessment Coastal
Impact Of Sea-Level Change Suva And Vicinity, Vltl Levu, Fiji Islands. *SOPAC Technical Report 242.*

SOPAC. (2009). Economic Costs of Natural Disasters in the Pacific Islands Region and Measures to Address Them. *Pacific Islands Forum Secretariat.*

SPSLMCP (n.d.) Modeling for Extreme Climate Events in the Pacific. *South Pacific Sea Level and Climate Monitoring Project*. Retrieved from http://www.bom.gov.au/pacificsealevel/pdf/AMSAT_climatemodel_factsht.pdf.

SPSLMCP (n.d.). Extreme Events. *South Pacific Sea Level and Climate Monitoring Project*. Retrieved from http://www.bom.gov.au/pacificsealevel/pdf/AMSAT_extreme_factsheet.pdf.

Stancheva, M., Rangel-Buitrago, N., Anfuso, G., Palazov, A., Stanchev, H. and Correa, I.,
2011. Expanding level of coastal armouring: case studies from different countries. Journal of Coastal Research, SI 64 (Proceedings of the 11th International Coastal Symposium), Szczecin, Poland, ISSN 0749-0208

UNEP, (2005). *After the Tsunami: Rapid Environmental Assessment.* UNEP, Geneva, 140 pp.

Vuke, V.C., Zann, L.P., Naqasima, M., and Vuki, M. (2002). *The Fiji Islands.* Seas at the Millennium: An Environmental Evaluation, Permagon, Amsterdam. pp. 751-764.

Walton, T. and Sensabaugh, W. 1979. Seawall Design on the Open Coast. *Florida Sea*
Grant College, Report No. 29.

Watling, D., (1985). *A mangrove management plan for Fiji.* Government Press, Suva, 67 pp.

Wilkie, M.L., Fortuna, S., (2003). *Status and trends in mangrove area extent worldwide.* Forest Resources Assessment working Paper 63. Forest Resources Division, FAO, Rome. http://www.fao.org/docrep/007/j1533e/J1533E00.htm.

Williams, Brian. (26 July 2011). Case Study Storm Surge Produced by Tropical Cyclone Gavin in Fiji. Retrieved from http://www.briangwilliams.com/tropical-cyclones/case-study-storm-surge-produced-by-tropical-cyclone-gavin-in-fiji-march.html.

Wolanski, E. (2007). *Protective functions of coastal forests and trees against natural hazards.* Australian Institute of Marine Science. Lecture.

World Meteorological Organization. 1998. Guide To Wave Analysis And Forecasting.
Secretariat of the World Meteorological Organization.

Zann, L.P, Vuki, V. (2002). *The southwestern Pacific Islands Region.* Seas at the Millennium: An Environmental Evaluation. Permagon, Amsterdam. 705-722.