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The Vulnerability of Louisiana to Hurricane Damage and the Value of Wetlands for Hurricane Risk Reduction

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THE VULNERABILITY OF LOUISIANA TO HURRICANE DAMAGE AND THE VALUE OF WETLANDS FOR HURRICANE RISK REDUCTION

A Dissertation

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by
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Abstract

Coastal Louisiana is annually threatened by coastal storms. Population grown, wetland loss, and potentially increasing storm frequency are likely to increase coastal vulnerability to these events. Increasingly, coastal management entities are managing land resources to reduce the economic impact of natural disasters with the use of natural infrastructure. This is true in Louisiana where the Louisiana Coastal Master Plan allocates billions of dollars to coastal restoration projects, many of which are intended to mitigate economic damages from tropical storms and hurricanes. Despite this significant proposed investment, the risk reduction value provided by these projects is not well known.

This analysis uses model simulation data and hurricane impact data to estimate the parish-level impacts of hurricanes in coastal parishes from 1997-2008. Using this information, an expected damage function is estimated that describes economic damages as a function of population, relative wetland area, and storm intensity. The model is used to estimate the annual vulnerability of coastal parishes to hurricane damage. Future scenarios of hurricane regime change, wetland loss, and population growth are imposed to estimate the increase in coastal storm vulnerability that can be expected under these scenarios. The model parameters are used to estimate the value of coastal wetlands as natural infrastructure for hurricane risk reduction, and important trends in coastal wetland loss are highlighted in terms of their importance for the future vulnerability of coastal Louisiana.

CHAPTER 1

SETTING, CONTEXT, AND OVERVIEW OF DISSERTATION

INTRODUCTION

Coastal communities face unique challenges to development. Coastal landscapes often provide opportunities that improve the quality of life for those who inhabit them. They can be both beautiful and productive, and consequently attract a disproportionate share of residents. However, the benefits associated with the coast are frequently accompanied by increased risk. The loss of productive ecosystems, concentration of populations, and changing climatic regimes are modern trends that have unique dimensions and consequences for coastal communities and require a great breadth of expertise to manage. The decisions made today regarding these challenges will have a significant impact on the future viability and sustainability of communities that call the coast home.

This is particularly true in Louisiana, where the coastline has undergone dramatic changes over the last century. Growing coastal populations, the rapid loss of wetland ecosystems, and climate related factors have increased the vulnerability of coastal communities in Louisiana to environmental disasters. In the decade since Hurricane Katrina, the vulnerability of Louisiana to coastal storms has been an emphasis of the management and research communities. The Coastal Protection and Restoration Authority (CPRA) of Louisiana released a plan to address these issues. At a cost of $50 billion, the CPRA plan (called the 2012 Louisiana Coastal Master Plan, or simply “Master Plan”) seeks to “reduce economic losses from storm surge flooding" and "promote a sustainable coastal ecosystem by harnessing the natural processes of the system" primarily by the maintenance and restoration of coastal wetlands (CPRA, 2012).

Despite this substantial proposed investment into coastal projects, significant knowledge gaps persist related to the human dimensions of coastal land loss and restoration. If the objective is to mitigate economic losses from coastal storms using natural features, the value of these natural features for reducing losses is a critical factor in the prioritization of restoration projects, the assessment of economic vulnerability, and the estimation of the cost of continued land loss. Additionally, the protective ecosystem services provided by coastal wetlands are thought to be among the most valuable services provided by any ecosystem (Costanza, et al. 2008; Barbier, et al. 2011). Despite these notions, not only is economic analysis of the relationships between coastal wetlands and hurricane damages limited in the Louisiana Coastal Master Plan, but also the economic interactions between wetlands, coastal economies, and hurricanes are, in general, poorly investigated in the scientific and economic literature.

This dissertation presents research that addresses some of the most pressing knowledge gaps. The results of the research will describe the relationship between communities, ecosystems, and hazards along the coast of Louisiana. Specifically, the impact of wetland loss on the vulnerability of coastal communities to hurricane damage is explored in economic terms, which allows the human dimensions of wetland loss to be better understood. This analysis estimates parish (county equivalent)-level hurricane damages using observations and computer simulated hurricane impacts, and uses these data to model hurricane damages as a function of wetland area, population size, and storm intensity. An annualized transformation of this model that incorporates hurricane frequency is used to estimate the annual vulnerability of each parish to hurricane damage. The model is then used to estimate the economic value of the protective ecosystem services provided by coastal wetlands and demonstrate that value varies by parish according to their characteristics. Finally, the contribution of wetland loss to the economic vulnerability of coastal communities is estimated in monetary terms. This proposal focuses on the Louisiana case, but the challenges addressed here are global challenges. The methodology used here can be applied to any coastal or riverine region where environmental features influence economic damages from natural hazards and where the necessary data are available.

PROBLEM STATEMENT

There are three important problems addressed by this dissertation. First, major trends are driving changes in global economic vulnerability to coastal storms: changes in storm intensity, coastal erosion and ecosystem loss, and population growth. In Louisiana, there is a lack of empirical research that addresses the role that these factors play in determining how hurricanes and tropical storms impact coastal communities across the state. So, how are economic damages from hurricanes and tropical storms distributed along the coast, and how do storm intensity, coastal wetlands, and population levels influence that damage?

Second, periodic hurricanes present a recurring burden to the finances of coastal communities. Federal and state funds are often available to assist in the response and recovery efforts at the local level, but these localities can nevertheless be overwhelmed with the costs associated with storm damages. Long-term fiscal planning requires an estimate of the damages that a community can regularly expect from hurricanes given the characteristics of that community. Not only is it necessary to understand present vulnerability, but preparing for the future also requires an understanding of how that vulnerability will change under different possible scenarios. So, what is the annual vulnerability of coastal Louisiana to hurricane damage, and how can that vulnerability be expected to change if hurricane regimes change, wetland loss continues, and populations grow or shrink?

Third, the Master Plan designates $50 billion to protection and restoration projects through the year 2061. It is very possible that the plan will not be fully funded, requiring that some projects be prioritized over others. This prioritization should require the comparison between restoration initiatives using comparable measures (money) of the costs and benefits of these projects, including the value of the protective ecosystem services provided coastal wetlands. This is acknowledged in the Master Plan, stating

> "An in depth evaluation of ecosystem services would include a dollars and cents component that captures how much these services are worth monetarily."

However, although reducing storm damages through the use of natural infrastructure is an expressed goal of the Master Plan, the document continues,

> "We did not include this economic aspect of ecosystem services in the master plan analysis. Models to analyze this aspect were not readily available, and we did not have enough time to develop them ourselves."

So, what is the value of wetlands for reducing coastal vulnerability to hurricanes, and how does this value vary across the coast based on hurricane frequency, wetland area, and population size?

OBJECTIVES

The objectives of this dissertation are threefold.

Objective 1: This research seeks to estimate and model parish-scale damages from tropical storms and hurricanes in order to explore the how hurricane intensity, wetland area, and population size interact to result in economic damages. To accomplish this objective, this research presents a novel methodology for calibrating broad-scale damage observations to the parish-scale using computer simulated hurricane impact data, thereby generating damage estimates for each parish impacted by a storm in the study. These data are used to build a damage function that describes damages as a function of hurricane intensity, wetland area, and population size. The modeling procedure allows for the analysis of the effects of one variable on damages as levels of the other variables change. For example, the effect of population growth on damages is smaller for areas with more extensive wetland areas than for areas where wetlands are scarcer. This relationship and others are thoroughly analyzed, and the results contribute to the body of knowledge related to the economic impact of coastal storms, particularly in Louisiana.

Objective 2: This research seeks to estimate the annual expected damages from hurricanes as a measure of economic vulnerability, and use this measure to estimate the vulnerability of Louisiana parishes under possible future scenarios of storm intensity change, wetland loss, and population change. This can be accomplished by estimating the frequency with which hurricanes make landfall in Louisiana and applying these frequency estimates to the damage function to "annualize" the model. The annualized damage function estimates the annual economic vulnerability of coastal parishes to hurricanes in the present. Future scenarios are imposed on the damage function to estimate the increase in vulnerability that can be expected under possible future conditions.

While coastal vulnerability assessments are relatively common, most attempt to index a given region's vulnerability based on institutional characteristics (e.g. number of recovery organizations, amount of public interest, etc.). However, the focus of this research is the impact that results directly from the loss of or damage to property and infrastructure rather than the costs associated with the interruption of economically important activities. Few vulnerability assessments explicitly explore any jurisdiction's inherent vulnerability to economic damage from hurricanes. This research presents results that describe the present and possible future vulnerability of coastal parishes in Louisiana to hurricanes, which can be used by parishes to plan and budget for increased hurricane damages into the future.

Objective 3: This research seeks to use the damage function to estimate the economic value of the protective ecosystem services provided by coastal wetlands in Louisiana under different contexts. The value of additional wetlands (or the cost of wetland loss) varies spatially based on the strength of the storm against which the wetlands are protecting, the extent or scarcity of proximal wetlands, and the size of the population that is being protected. The results of this analysis highlight these differences in value between parishes. The value of the protective ecosystem services provided by wetlands is reported in terms of the annual flow of protection as well as the net present value (NPV) of that protection for each parish in coastal Louisiana. This approach to valuation is referred to as the expected damage function (EDF) approach (Barbier, 2007). The application of the EDF approach presented here improves upon past applications in the literature in the scale of analysis, the size of the statistical sample, the estimation procedure, and the utilization of results (e.g. to highlight important relationships). Additionally, the results presented here can be used in cost benefit analysis as an estimate of the value of the damage mitigation provided by coastal wetlands as natural infrastructure.

BACKGROUND

Coastal Population Growth

Global Estimates

Coastal areas have attracted large populations throughout history. They provide resources and opportunities for transportation, and consequently attract trade and commerce. Coastal ecosystems also provide recreational opportunities, are home to invaluable biodiversity, and provide a suite of ecosystem services. In developing regions, costal ecosystems also provide the resources necessary for subsistence. Often, these populations develop unique cultural identities that are deeply associated with their sense of place and connection to the coast. As coastal amenities and opportunities attract larger populations, coastal regions develop distinct development patterns. Globally both coastal and continental populations are becoming increasingly urbanized (Zhang and Seto, 2011). While urbanization might provide many socially beneficial opportunities for residents (Bloom et al. 2008), increased population density in disaster prone regions increases vulnerability to economic damage and loss of life (Pielke et al. 2008). Globally, population density in coastal areas is already substantially higher (McGranahan et al. 2007) and growing faster (Neumann et al. 2015) than non-coastal areas.

Urbanization is driving coastal population growth, but this growth is also present in non-urban regions. According to Seto, et al. (2011), each coastal ecosystem classification (using the United Nations Millennium Ecosystem Assessment classification) experienced migration-driven population growth in the three decades preceding 2000. Additionally, urban land expansion in coastal areas is more rapid than in non-coastal areas (Seto et al. 2011). Neumann et al. (2015) project the global population in the low-elevation coastal zone (LECZ) (continuous coastal areas less than 10m above sea level; Lichter et al. 2011) to be 1.1-1.4 billion in 2060 – up from 625 million in 2000. Of that population, 929 million-1.2 billion are projected to live in less developed regions or least developed countries (according to United Nations definitions).

The growth of coastal populations in regions that are least able to withstand and respond to disasters should be a primary humanitarian concern in the future. Climate related disasters have a more pronounced and longer lasting effect on people living in poverty (Romero-Lankao et al. 2014), and sufficient knowledge and technology exists to implement growth strategies that can mitigate the impacts of coastal disasters. In many places, the conservation of coastal natural infrastructure can have a meaningful benefit in terms of reduces hazard vulnerability, but the case for this conservation needs to be made using ecosystem service quantification and valuation so that conservation restrictions do not hinder economic development.

In contrast to the less developed regions, more developed regions tend to have smaller populations, but are considerably more urbanized (51% vs. 18% urban) (Neumann et al. 2015). Less than 139 million people are projected to live in the LECZ of more developed regions in 2060. However, the rate of growth in the LECZ of North America is approximately three times greater than that of developed regions as a whole, and accounts for more than two thirds of the projected coastal population growth in developed regions. While the increase in human exposure to coastal hazards is expected to be far greater in the developing world, coastal population growth in wealthy regions generally increases the risk of large monetary losses. Although the loss of material wealth in developed regions is not as acute of a global problem as the widespread displacement and loss of life that can accompany coastal disaster in less developed regions, many coastal residents in developed regions rely heavily on the assets developed along and the opportunities provided by the coast.

Estimates in the United States, the Gulf of Mexico, and Louisiana

The United States (U.S.) is vulnerable to staggering economic losses from hurricanes. Communities along the coast have amassed great wealth and concentrated development near the shore, increasing vulnerability to economic losses. Adjusted for inflation, 14 hurricanes have caused damages in excess of $10 billion. Of the top ten costliest inflation adjusted storms in U.S. history, eight have occurred since 2004 and seven have impacted the Gulf of Mexico. Hurricanes Katrina (2005) and Sandy (2012) caused $105 billion and $71 billion, respectively, with many of the effects persisting long after the storm (Blake et al. 2007; Blake et al. 2013). Much of the modern increase in hurricane damage is attributable to population growth and development in storm prone areas (Pielke et al. 2008).

In the U.S., as is the case globally, the population of the coast is higher and increasing more rapidly than the country in general. Only 452 of the 3,142 counties in the U.S. are “coastal shoreline counties” (those counties directly adjacent to open coastal water or within the 100-year coastal floodplain; Ache et al. 2013). Though these jurisdictions cover less than 10% of the land in the U.S., they are home to approximately 40% of its residents. Consequently, the coast has a significantly higher population density than the rest of the country. Coastal shoreline counties have a population density of approximately 446 persons per square mile, which is more than four times greater than the national density of 105 persons/mi^2. Despite this high density, an average of 1,355 building permits were issued each day in coastal counties between 2000 and 2010, driven largely by seasonal housing demand (NOAA, 2013).

The coast of the Gulf of Mexico, compared to the Atlantic and Pacific coasts, has a relative small total population of about 14 million (2008) living in coastal shoreline counties – 14% of the coastal population of the U.S. However, the Gulf Coast has experienced the highest population growth rates in the U.S. between the three coasts. The population of the Gulf Coast increased over 150% from 1960 to 2008, far more than the 56% and 110% for the Atlantic and Pacific coasts, respectively, and 64% for non-coastal counties. Over the same period, the number of housing units along the Gulf Coast increased 246%, greater than the 98% and 130% for the Atlantic and Pacific coasts, respectively, and 120% for non-coastal counties. Of the Gulf Coast states, Florida accounts for approximately 72% of the housing growth in coastal counties, and added over 10 times the number of housing units as Louisiana, Mississippi, and Alabama combined, illustrating the spatial variation present in population growth patterns (Wilson and Fischetti, 2010; Census, 2015).

Population growth along the Louisiana coast, which accounts for less than two percent of U.S. coastal residents, has been slower than in other coastal states. Among all coastal states along the Gulf Coast, Louisiana has the lowest rate of growth in population and housing units in coastal counties or parishes (in Louisiana, the county-equivalent jurisdiction is a “parish”, and this terminology will be applied accordingly hereafter when Louisiana is the subject). Nationally, the only state with lower growth rates in these variables is New York (Wilson and Fischetti, 2010).

These figures are biased to some degree by a substantial out-migration from coastal parishes after the 2005 hurricane season (Frey and Singer, 2006; Hori et al. 2009). However, modern population trends are not as severe of a concern in Louisiana as in other regions or relative to other factors influence vulnerability to storms (e.g. sea level rise). Nationally, non-metropolitan coastal counties have been in population decline, and are now home to about 4% of the nation’s coastal population (Wilson and Fischetti, 2010). The majority of coastal parishes in Louisiana are of this type (Census, 2015). Land loss has also limited the capacity of coastal parishes to grow, which alludes to the myriad of other factors that may be more influential on storm vulnerability than population (e.g. land subsidence, intensifying hurricanes, week institutions). This manuscript will address the effect of population on vulnerability to hurricane damage in Louisiana and explore how vulnerability may change under possible future conditions.

Coastal Hazards and Climate Change

In no other geographic area is the relationship between human and environmental systems more rich and prevailing than at the coast. The physical and biological interactions between terrestrial and marine environments create productive ecosystems that sustain and accommodate coastal communities. During no other time are these interactions more manifest than during and after coastal storms, when the marine environment inundates the human domain. During these events, prior decisions made about land use and development have consequences in terms of how communities endure storms. Humans can mitigate the economic impact of storms by implementing building standards, engineering safety measures, and promoting preparedness, and these measures have been successful in the past (Beatley, 2012). However, environmental change is inevitable, so adaptation is critical for managing sustainable and resilient communities.

Climate change is a threat that has the potential to drastically alter the dynamics of the coast. Coastal populations have always dealt with disasters that are inherent to coastal regions such as erosion, tidal and storm flooding, and salinization of water resources, but climate change has the potential to make these incidents more severe and persistent. Management entities have often struggled to deal with these challenges, and management decisions will become increasingly difficult under the uncertainty and variability associated with climate change. In Louisiana these issues are further complicated by massive losses of coastal ecosystems, aquatic hypoxia, and rapid land subsidence, of which the trajectories are not well known. The remaining sections focus on the hazards associated with climate change and coastal storms with an emphasis on Louisiana and the Gulf Coast.

Observed Changes and their Basis

Atmospheric concentrations of greenhouse gasses (GHG), called so because of their capacity to retain solar radiation in the atmosphere, have increased significantly since the beginning of the industrial revolution in the mid-nineteenth century. Carbon dioxide (CO_2), considered the most significant GHG in terms of its influence on temperature dynamics, has recently reached a global atmospheric concentration of 400 parts per million (ppm) (Dlugokencky and Tans, 2015), which represents an increase of over 40% from 1750 and the highest since the Pliocene Era, 3-5 million years ago (Hartmann et al. 2013). The vast majority of this increase can be attributed to the burning of fossil fuels for energy use (Myhre et al. 2013).

The consequence of these increase GHGs is increase temperatures. According to data sets which use varying measurement methods, span various modern time periods, and were independently gathered, global surface temperatures have increased significantly since 1880 and the rate of increase from 1979-2012 is the greatest over any comparable period on record (Hansen et al. 2010; Jones et al. 2012). It is estimated that, over the period from 1880 to 2012, global surface temperatures have increased approximately 0.85°C, with most of the warming occurring since the mid-twentieth century (Hartmann et al. 2103). This warming displays large variation between regions, over time, and between marine and terrestrial environments, and has unique implications for each locale. Along the coast, warming ocean temperatures are a particular concern.

Coastal Tropical Cyclones

One reason, and the one of particular interest for this research, that warming ocean temperatures are a concern for coastal regions is that warm waters are necessary for tropical cyclone development. Tropical cyclones, called hurricanes in the Atlantic hurricane basin, generally require sea surface temperatures SST of at least 26 degrees Celsius (78.8 degrees Fahrenheit) in order to develop and maintain strength (Gray, 1998). Ocean temperatures in the equatorial Atlantic Ocean, where the majority of hurricanes develop, regularly exceed this threshold. As ocean temperatures rise in the future, it is expected that the incidence of high intensity hurricanes will increase (Knutson, et al., 2010). There are several other factors that influence the genesis, longevity, and intensity of hurricanes including the direction and strength of wind at different levels of the atmosphere (Emanuel, et al. 2004). For this reasons, it is not clear that hurricane landfalls will become more frequent in Louisiana.

The Intergovernmental Panel on Climate Change (IPCC) considers it likely that the total number of tropical cyclones will decrease globally as atmospheric temperatures rise due to decreased favorability in atmospheric conditions (as opposed to oceanic conditions) for cyclogenesis (IPCC, 2014). The most intense storms – Category 4 and Category 5 on the Saffir-Simpson scale – are expected to see a significant increase in frequency globally because the storms that are able to develop will be fueled by warmer ocean temperatures (IPCC, 2014; Anthes, et al., 2006; Knutson, et al., 2010). This projection is consistent with the projections for the Atlantic hurricane basin, which is not expected to suffer more frequent hurricanes, but is projected to experience a doubling of Category 4+ storms by 2100 (Romero-Lankao, et al. 2014).

These figures are projections regarding the *incidence* of storms rather than projections of storms making *landfall*. These same studies suggest that landfalling hurricanes will become less frequent across the Atlantic hurricane basin due to an intensification of upper level atmospheric steering patterns that would limit probability of a directly westward trajectory (Romero-Lanko, et al., 2014). The scientific literature on projections of tropical cyclone frequency and intensity is relatively consistent with respect to expectations of global or basin-wide storm patterns of storm incidence (i.e. a decrease in the frequency of less intense storms and an increase in the frequency of the most intense storms) and sparse with respect to expectations of landfall. Additionally, there are few explorations of the regional variations in the storm projections, owing to the complexity of cyclone dynamics, limitations of applying atmospheric models at smaller scales, and limited data on cyclones from before the satellite era (*circa* 1970s).

Projections that are available for the Gulf of Mexico suggest that SST are especially influential on hurricane dynamics in this region, in-part because this water body is sequestered from much of the oceanic deep water currents that can moderate temperatures in area exposed to deep-sea environments (Needham, et al. 2012). The 2012 Louisiana Coastal Master Plan notes that hurricanes making landfall along the coast of the Gulf of Mexico often have different genesis and evolutions than those that typically impact the Atlantic Coast. For their projections, they draw significantly on the research of Dailey, et al. (2009) who found that the effect of SST on tropical cyclone genesis are more pronounced in the Gulf, and projected that frequency of landfalling hurricanes of Tropical Storm or Category 1 strength would increase in the future. The notion is that the origination of tropical systems will become more frequent in the Gulf of Mexico and Western Caribbean, but that those storms will not have sufficient time to develop before making landfall along the Gulf of Mexico Coast. Based on this research and "discussions with storm damage experts", the 2012 Master Plan designates the plausible range of frequency changes for hurricanes making landfall in Louisiana to be -20% to +10% for Category 3+ storms, and the plausible range of intensity changes to be 0% to +30% for all levels of storm intensity.

Data from past storms indicate that there is no statistically significant increase in storm frequency and intensity either globally or in the Atlantic hurricane basin. The IPCC (2014) says in their most recent report on the matter that "Current datasets indicate no significant observed trends in global cyclone frequency over the past century…" and reach a similar conclusion for the Atlantic basin. This inference also holds for storms making landfall, the data on which do not reveal a change in either frequency or intensity over the longest period for which data are available (Pielke, 2014).

It is important to note that the incidence of coastal storms is separable from the damage incurred from such events. Tropical cyclones are some of the most damaging extreme events in terms of their economic impact and resulting loss of life. Trends in hurricane losses show marked and consistent increases in economic damages from hurricanes (Nordhaus, 2006), particularly with respect to very large ($1 billion+) damages (Smith and Katz, 2013). The increase in damages from U.S. hurricanes constitutes a staggering 70% of the increase in global disaster losses since 1980 (Mohleji and Pielke, 2014).

Nearly all of the increase in U.S. hurricane damage is attributable to the accumulation of wealth along coastal areas that are vulnerable. When adjusted for inflation in order to account for changes in wealth over time, there is no statistically significant increase in losses suffered based on analysis of multiple data sources (Pielke, 2014; Kunkel, et al. 2013; Smith and Katz, 3013; Nordhaus, 2006). This is consistent with findings that the frequency and intensity of hurricanes have not noticeably increase over time, and suggests that hurricane hazards are best managed by adapting based on local characteristics of vulnerability. In Louisiana, for example, coastal population growth is relatively low (Wilson and Fischetti, 2010) and the loss of wetlands is increasing susceptibility to storm damage at an increasing rate (Boutwell, et al., 2016), implying that damage risk reduction is best achieved by minimizing wetland loss.

Ecosystem Services

The term ecosystem services "…represent(s) the benefits human populations derive, directly or indirectly, from ecosystem functions" (Costanza et al. 1997). The concept of functioning ecosystems having value associated with the services they produce emerged in the 1960s (King, 1966). Decades later, the concept has been widely accepted and is being recognized as a potentially valuable framework for influencing conservation management decisions (de Groot et al. 2002). The practice of valuing ecosystem services necessarily involves simplifying complex ecological processes into simpler and more quantifiable products of those processes. These products provide benefits to society and are the direct result of certain measurable functions of ecosystems.

Ecosystems provide multiple functions, each with a suite of associated ecosystem services. The typology of these functions is fairly arbitrary, but an often-referenced categorization of ecosystem functions and their corresponding services is provided by de Groot, et al. 2002, who describe the four classifications of ecosystem functions as regulating functions, those which maintain the essential ecological processes and life support systems (the attenuation of wave energy from coastal storms belongs in this class); habitat functions, including the maintenance of biological and genetic diversity; production function, which provide us with food and other natural resources; and information functions, which includes the cultural, spiritual, and scientific values derived from nature.

The ecosystem service analyzed in this research is provided by the regulating functions performed by coastal wetlands. The various physical mechanisms by which wetlands reduce economic damages can be complex, but they can be generally described in one of two ways. First, wetlands reduce wave energy by directly interacting with the waves from storms and dampening the energy of those waves before they reach the potentially damaged assets. Second, coastal wetlands can reduce the potential for waves by promoting changes in the underlying bathymetry (i.e. making the sea shallower) along the coast that are unfavorable for the formation of waves (Gedan, 2011).

It is widely recognized that ecosystems provide valuable services to society, but those services are often not fully considered in policy decisions. This inconsideration arises from the lack of explicitly described values for specific services produced by ecosystems. Many of the goods and services provided by working natural landscapes are not valued (i.e. do not have a price) because they are not bought and sold in economic markets. This is because individuals cannot be excluded from benefiting from ecosystem services such as clean air, clean water, increased biodiversity or aesthetic beauty, and these services are not partitionable in any reasonable sense. Therefore, the goods and services that flow from ecosystems tend to be *non-market resources*. Nevertheless, estimating the economic value of ecosystem services allows them to be considered against other policy measures for which the benefits can be more directly measured.

In the absence of markets, prices (values) are not determined by traditional market forces. Economists must use statistical and mathematical methods to estimate these values. Estimates represent the value of ecosystem services to those who benefit from them. In this case, the protective ecosystem service provided by coastal wetlands benefits households who stand to lose property and communities who may suffer the loss of infrastructure in the event of a hurricane impact. In general, ecosystem service value estimates represents the aggregate willingness-to-pay – the maximum portion of income an individual would be willing to disperse to receive some benefit – for that service across all beneficiaries. Alternatively, some methods derive values based on the avoided damages (as in reduction of flood damage) or the cost of the next least-cost method of provided the service (as in water treatment costs).

Wetlands as Natural Infrastructure

An ecosystem service that is of particular interest in Louisiana, where hurricanes are relatively frequent (Klotzbach and Gray, 2016), is the protection provided by wetlands against hurricane damages because the loss of this ecosystem service implies an increase in hurricane vulnerability.

It is well documented that wetlands have the capacity to attenuate wave energy (Gedan et al. 2011; Feagin, 2008; Wamsley et al. 2009; Resio and Westerlink, 2008; Nepf et al. 2007; Neumeier and Ciavola, 2004). Because storm damage can be large, small proportional reductions in damage can be valuable. This ecosystem service provided by coastal wetlands constitutes natural infrastructure (Cunniff and Schwartz, 2015) the value of which should be included in the calculus of hazard and coastal restoration policy. Yet, few economic analyses have estimated the value of the storm damage mitigation provided by coastal wetlands.

The wave attenuation provided by wetlands can vary widely across coastal landscape depending on the context in which protection is provided (Koch, et al. 2009). For example, wave attenuation varies according to the height of the wave a wetland is attenuating, implying that wetlands may not be as valuable as protection for more intense storms (Boutwell and Westra, 2016; Feagin, 2008). The provision of protection has also been shown to be nonlinear with respect to the area of wetlands present (Boutwell and Westra, 2015a) or the distance over which waves must travel (Barbier et al. 2008), illustrating the economic concept of diminishing marginal product for wetlands as protection. These notions are addressed in the modeling and results presented here.

Document Outline

The remainder of this document will present three chapters and supporting information that follow the aforementioned objectives of this dissertation. The first, "Economic Damages from Hurricanes: the Interactions of Storm Intensity, Wetland Area, and Population Size along the Louisiana Coast", estimates and models parish-scale damages from tropical storms and hurricane in order to explore the how hurricane intensity, wetland area, and population size interact to result in economic damages by estimating an EDF. The results of the model are discussed, and the relationships between the modeled variables are illustrated by computing and graphing the marginal effects (ME) of each of the variables and varying levels of the others.

The second, “The Vulnerability of Coastal Louisiana to Hurricane Damage: Present and Future”, uses the EDF to estimate the annual expected damages from hurricane impacts as a measure of economic vulnerability, and uses this measure to estimate the vulnerability of Louisiana parishes under possible future scenarios of storm intensity change, wetland loss, and population change. The estimates are provided on an annual basis and in terms of the 50-year (the project life of the Master Plan) net present value (NPV) of the increase. A sensitivity analysis is provided by modifying each scenario based on the level of uncertainty present in the underlying scenario.

The third, “The Value of Coastal Wetlands as Natural Infrastructure and the Cost of Wetland Loss in Louisiana”, uses the EDF to estimate the economic value of the protective ecosystem services provided by coastal wetlands in Louisiana in different contexts. The value of the protective ecosystem service provided by wetlands is estimated as an annual flow of protection and the NPV of that flow over 50 years. The annual flow rate is estimated for each of the parishes in the data, which shows how they value of wetlands varies according to the factors in the model. The nonlinearity in the provision of protection is discussed.

Finally, the dissertation concludes by describing the importance of planning and managing the use of coastal resources in the context of this research. Areas of promise with respect to improving this line of research are discussed as well as some limitations that should be considered when interpreting these results. This manuscript presents an example of an interdisciplinary approach to research that considers both the physical science and the human effects of related to hurricanes. An increase in the application of such an approach is advocated as a tactic for creating actionable insights to overcome difficult challenges in resource management.

CHAPTER 2

ECONOMIC DAMAGES FROM HURRICANES: THE INTERACTIONS OF STORM INTENSITY, WETLAND AREA, AND POPULATION SIZE ALONG THE LOUISIANA COAST

"The purpose of models is not to fit the data, but to sharpen the questions."

-Samuel Karlin

INTRODUCTION

In recent years, there have been coastal storms that have caused significant economic damage. Hurricane Katrina in 2005 and post-tropical-cyclone Sandy in 2012 impacted different coastal regions and resulted in billions of dollars in damages. There has been a significant increase in damages resulting from hurricanes over the last century, a trend that has accelerated in recent decades (Nordhaus, 2006; Smith and Katz, 2013). There is considerable debate regarding the factors to which this increase is attributable. Hurricanes result in economic damages based on local factors that can vary at multiple scales. In general, the majority of the increase in damage is the result of increasingly concentrated wealth and development in areas that are vulnerable to the impacts of hurricanes (Pielke, 2014).

Hurricanes are complex phenomena that are influenced my multiple factors. Because hurricanes are convective weather systems (i.e. the primary energy source is the uplift of warm air), they storms require warm sea surface temperatures (SST) to initiate. Hurricanes also require stable conditions in the upper levels of the atmosphere so that the rising warm air can organize into a single storm system, identifiable by the hurricane's characteristic "swirl". In order to make landfall in the

U.S., the wind patterns in the upper atmosphere must also be such that they allow the storm to approach land rather than being directed into cooler open ocean. At landfall, the extent of the physical impact depends upon the off-shore bathymetry, terrestrial terrain, and the characteristics of the storm. Beyond the physical impacts, economic damage presents an additional human dimension of hurricane impacts in that they involve development decisions, economic productivity, preparedness, resilience, and other not-expressly-inherent components locations. In this way, the intensity and destructiveness of a hurricane impact are separable.

This variety of factors that dictate the probability of a hurricane impact and the resulting destruction make it difficult to model or predict the economic damage that can be expected from a storm. Nevertheless, communities make decisions that affect their vulnerability to hurricanes with or without explicit knowledge of their risk. The coast of Louisiana is particularly prone to hurricane strikes (Klotzbach and Gray, 2016), and its consistently low elevation makes it highly vulnerable to flooding. Coastal Louisiana also contains a large expanse of coastal wetlands that are known to reduce inundation related to storm surge flooding, but are rapidly eroding (Peyronin, et al., 2013). Most of coastal Louisiana is rural, and population growth is low or negative for parishes that do not contain urban areas (Blanchard 2010). These factors make Louisiana a special case in hurricane vulnerability, and any analysis thereof should be considerate of them.

This chapter presents a methodology for deriving parish-scale damage estimates, and uses the damage estimates to estimate a model that describes damages as a function of the factors listed above: hurricane intensity, wetland protection, and population. The model is constructed so that the effects of these factors are estimated in a manner that allows the model to reflect nonlinearities in the relationship between these factors and economic damages. My hypotheses of these relationships are predicated on the findings of relevant research regarding the effect between these factors and economic damages.

Major trends are driving changes in global economic vulnerability to coastal storms: changes in storm intensity, coastal erosion and ecosystem loss, and population growth. In Louisiana, there is a lack of empirical research that addresses the role that these factors play in determining how hurricanes and tropical storms impact coastal communities across the state. So, how are economic damages from hurricanes and tropical storms distributed along the coast, and how do storm intensity, coastal wetlands, and population levels influence that damage?

This research seeks to estimate and model parish-scale damages from tropical storms and hurricane in order to explore the how hurricane intensity, wetland area, and population size interact to result in economic damages. To accomplish this objective, this research presents a novel methodology for calibrating broad-scale damage observations to the parish-scale using computer simulated hurricane impact data, thereby generating damage estimates for each parish impacted by a storm in the study. These data are used to build a damage function that describes damages as a function of hurricane intensity, wetland area, and population size. The modeling procedure allows for the analysis of the effects of one variable on damages as levels of the other variables change. For example, the effect of population growth on damages is smaller for areas with more extensive wetland areas than for areas where wetlands are scarcer. This relationship and others are thoroughly analyzed, and the results contribute to the body of knowledge related to the economic impact of coastal storms, particularly in Louisiana.

METHODOLOGY

The estimation of a damage function requires data on economic damages from coastal storms. The availability of reliable data at a scale that is inferentially useful is a major limiting factor for this approach. Economic damages are estimated by government organizations and the insurance industry, but those estimates can be politicized (to receiver greater aid or relief funds) or confidential. When evaluating economic damages in terms of wetland protection, the scale is a critical consideration. At fine scales, damages are likely to be significantly influenced the damage of few valuable assets. At broad scales, it can be difficult to make the case of attribution between the variance in damage data and different factors.

Damage Data Generation

This analysis uses broad scale damage observations from coastal storm events and distributes the data across the landscape at a finer scale according to model simulation data. Raw economic damages are gathered using the National

Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) storm reports (NCDC). These reports provide damage estimates for each state and each natural disaster. Damages are associated with a subset of counties or parishes. For example, if a hurricane only causes damages for Cameron and Vermilion parishes (the westernmost parishes), then the publication designates these counties as those experiencing asset damage, and the damage estimates for these parishes are reported as a single damage estimate. Damages are reported by NCDC personnel, and are based on data obtained from insurance agencies, emergency managers, U.S. Geologic Survey, U.S. Army Corps of Engineers, and utility companies. The data are composed of losses sustained to private property (households, objects, crops, etc.) and public infrastructure and facilities (MacAloney, 2007).

These estimates are distributed between parishes that are reported to have been damaged in the storm. This is achieved by distributing the total damages between parishes according to the proportion of damage incurred by that parish during hurricane model simulation. The simulation data is from the Hazards U.S. (HAZUS) model created by the Federal Emergency Management Agency (FEMA) to predict damages from natural disasters, including hurricanes. The HAZUS model is a meteorological and socio-economic model developed by FEMA for the assessment and prediction of the impacts of natural disasters on property and infrastructure. HAZUS uses data describing potential characteristics of vulnerable structures, such as building type (single-family, retail, commercial, etc.) and building size, combined with data regarding predicted surge inundation at a given storm intensity to predict the economic impact of a particular storm on a community (DHS, 2012).

The extent of the storm surge for a given category of storm is assigned according to National Hurricane Center's (NHC) Sea, Land, Overland Surges from Hurricanes (SLOSH) model. This model is a physical science model that predicts storm surge extent given details of meteorological and oceanic conditions during storms as well as onshore elevation data. The maximum surge level is calculated for thousands of potential storm scenarios. The combined maximum extent of all possible storms for each intensity category is referred to as the maximum of maximums (MOM). These MOMs are track and speed independent and represent all areas that have the potential for storm surge approaches and speeds at a given intensity (Conver, et al. 2008).

FEMA uses storm surge values from the SLOSH model with economic value estimates provided by the HAZUS model to determine the exposed value of buildings in the MOM for each level of storm intensity (under the saffir-Simpson scale, 1-5, plus tropical storms). These data are available at the county/parish level for those regions in FEMA's region IV jurisdiction in their Coastal Flood Loss Atlas (CFLA) (Longenecker, 2011). The FEMA CFLA simulation data are recorded for each county or parish and each category of storm. These estimates are used to as a means to establish the proportion of damage that could be expected between impacted parishes for a storm of a particular category. For example, the predicted value of property that is exposed to storm surge damage given the SLOSH MOM surge level for a Category 3 hurricane, such as hurricane Rita, making landfall in Cameron and Vermilion parishes is approximately $425 million and $1.25 billion or approximately 25% and 74% of the vulnerable property, respectively. These proportions are used do distribute the observed value of damage among the designated units. So, for a hypothetical hurricane that caused a reported $2 billion in damages in Cameron and Vermillion parishes, $500 million and $1.5 billion are attributed to these parishes respectively. All values are converted to 2010 dollars using the Bureau of Economic Analysis inflation calculator.

Study Area and Data Criteria

Criteria were established for inclusion into the dataset is based on the applicability of the sample to the analysis. All storms making landfall in Louisiana between 1995 and 2010 were initially considered. The NCDC reports coastal storm damages greater than $50,000. This research found 13 tropical storms or hurricanes suitable for analysis. The dates of these storms range from 1997 (Hurricane Danny) to 2008 (Hurricane Ike). Each sample must be exposed to coast and have land cover composed of both estuarine marine wetlands and marine deep-water wetlands according to the Cowerdin, et al. 1979 land cover classification system. Thirteen Louisiana parishes meet these criteria. Additionally, if the damages for a storm event included parishes that are not part of the FEMA CFLA data, samples from those storms could not be incorporated into this study because damage estimates could not be generated for those parishes under this methodology. Unfortunately, this includes the most economically damaging storms (or at least those that have a large geographic affect), including hurricane Katrina. The magnitude and reach of these damages precluded any analysis of coastal impacts or the impacts of coastal wetlands on those damages.

Some storms impacted areas that were beyond the region considered in the statistical analysis, but were included in the scope of the CFLA. An example is Calcasieu parish, Louisiana, which is routinely impacted by storms, but has no direct coastal exposure and insufficient coastal wetland data. These parishes are used for the distribution of the observed damages between units to insure that parish damage estimates were estimated consistently, but were then omitted from subsequent analysis because of their lack of suitability with respect to the coastal wetlands considered. The total numbers of parishes (samples) that experienced damages from storms that are deemed to have data amenable to the described analysis are 118. The parishes included in the study area are displayed in Figure 2.1.

The National Weather Service (NWS) damage estimates are estimates of "damage inflicted to private property as well as public infrastructure and facilities" that are prepared "in conjunction with local emergency managers, insurance adjusters, utility company representatives, and the U.S. Army Corps of Engineers" (MacAloney, 2007). The HAZUS model estimates damage for the "general building stock" which includes commercial, industrial, and residential buildings, "essential facilities" which includes structures like hospitals, schools, or fire stations, "transportation lifeline systems" including highways and rail systems, and "utility

Figure 2.1 Parishes included in the study area used to estimate the damage function

lifeline systems" which include water and electricity infrastructure (DHS, 2012). The constructs measure by the NWS and HAZUS judged to be sufficiently similar not to preclude their joint use.

Independent Variable Data

Once the economic damage data are generated, the EDF can be estimated. This analysis uses multivariate nonlinear least squares estimation to estimate damages as a function of hurricane intensity, wetland area, and population size using STATA statistical software. The population data are from the U.S. Census Bureau. The hurricane intensity data are the maximum 60-second wind speeds recorded during the storm in that parish, and is available in the NCDC Monthly Storm Data Publications and Individual Storm Reports (NCDC).

The wetland data are gathered from NOAAs Coastal Change Analysis Program (C-CAP), a nationally standardized database on land cover and habitat change in coastal regions of the U.S. The program, inventories and monitors change every one to five years. If a value for wetland area is not available for the year of the storm, the value used for the wetland variable is the most-temporally-proximal to the date of the storm impact. All values are from no more than two years from the impact date, and most are from the year of impact. Satellite imagery, aerial photography, and field data are integrated into a geographic information system (GIS) and made publicly available in raw form and with county and parish delimited measures of land use change. The data used for the EDF is the area of each parish that is considered to be coastal wetlands according to the Cowardin, et al. 1979. This ecosystem type is bounded at its upland limit by

> "… the boundary between land with predominately hydrophytic cover and land with predominantly mesophitic cover; the boundary between soil that is predominately hydric and soil that is predominately nonhydric; or in the case of wetlands without vegetation or soil, the boundary between land that is flooded or saturated at some time during the growing season each year and land that is not."

The exception is for the classifications bottoms, aquatic, beds, nonpersistent emergent wetlands, and areas of open water with less <30% vegetative cover. The areal extent of wetlands is divided by the length of coastline to produce a relative wetland area variable. This accounts for the bias that would otherwise be generated because areas with longer shorelines will generally have both more extensive wetland areas and more exposure to storm surge. Without controlling for shoreline length, the effect of wetlands on damages would be convoluted. The resulting unit of interest for valuing coastal wetlands as natural infrastructure is hectares per kilometer (ha/km). Although this unit can seem intangible, a hectare ($10{,}000m^2$) along a kilometer (1,000m) length creates a ten-meter "buffer" of protection.

Expected Damage Function

The functional form used for the model is

$$\boldsymbol{log(y) = \alpha\, x_1^{\beta 1}\, x_2^{\beta 2} x_3^{\beta 3}} \tag{2.1}$$

where y is the economic damage to a parish from a tropical storm or hurricane, α is a constant, x_1 is the wind speed variable, x_2 is the wetland variable, x_3 is the population variable, and the β values are parameter estimates. This functional form was chosen because it outperformed linear and all other nonlinear forms estimated using this data for predicting within-sample. It is also a flexible functional form that allows the marginal effects to vary across the ranges of the other variables, thereby incorporating the nonlinearities in the relationships discussed in the introduction.

The hypothesized effects of each of these variables are provided in Table 2.1. It is expected that higher wind speeds will tend to increase damages because wind is an indication of storm intensity, and more intense storm should be more damaging. It is expected that parishes with larger wetland buffers will incur smaller economic damages because it has been shown that wetlands have the capacity to reduce wave energy and, therefore, flood inundation. Finally, it is expected that parishes with larger populations will experience larger economic damages under the assumption that more people require a greater amount of residential structures and infrastructure that could potentially be damages in a storm.

Table 2.1 Expected Effect of Each Variable on Economic Damage from Hurricanes

Variable	Expected Effect	Implication	Data Source
Wind	+	Stronger storms produce larger economic damages	NOAA National Climatic Data Center (NCDC)
Wetland Area	-	Wetlands mitigate economic damages	NOAA Coastal Change Analysis Program (C-CAP)
Population	+	Larger populations incur larger economic damages	US Census Bureau

The model parameters are used to compute the marginal effects (ME) of the different variables to estimate the effect they have on economic damage. The marginal effects will be estimated for varying levels of other variables so that the relationship between these variables during storm events can be better understood. This is possible because the nonlinear least squares estimation procedure allows the marginal effects to vary across the range of the data (Greene, 2003). For example, the ME of wetlands is significantly lower where wetland area is extensive than where wetlands are scarce. This is an example of diminishing marginal productivity or wetlands for protection. MEs are assessed in nine different ways: the ME of storm intensity as storm intensity, wetland area, and population vary; The ME of wetlands as storm intensity, wetland area, and population vary; and the ME of population as storm intensity, wetland area, and population vary. This thorough examination presents not only the effects of these variables on damages, but also how other factors influence that relationship.

RESULTS

Model Estimation Results

Table 2.2 shows the results of the nonlinear least squares regression model that estimates the damage function. The sign of the parameter estimates are as expected. The wind parameter estimate, which describes the effect of wind speed on damages, is positive and highly significant. This result implies that storms that impact the coast with higher wind speeds tend to result in higher damages. The parameter estimate for the population estimate is also positive and significant. This result implies that parishes with higher population levels tend to incur greater economic damages when impacted by tropical storms and hurricanes. The parameter estimate that describes the effect of the relative wetland area variable on damages is negative. This suggests that the presence of wetlands tends to reduce the damages incurred from tropical storms or hurricanes.

Table 2.2 Nonlinear Least Squares Regression Results for Expected Damage Function Estimation

Variable	Estimate	Std. Err.	t	P>t	95% (LB)	95% (UB)
Alpha	4.413	1.855	2.38	0.019	0.738	8.089
Wind	0.293	0.053	5.53	<.001	0.188	0.398
Wetlands	-0.058	0.028	-2.10	0.038	-0.114	-0.003
Population	0.037	0.018	2.05	0.031	-0.008	0.064

Monetized Marginal Effects

The values of these parameter estimates do not reveal any practical measurements of interest, other that the sign. Table 2.3 shows the monetary values that correspond to the average ME for each of the variables. These values describe the expected change in parish level damages for a one-unit change in the variables. So, the expected increase in damages that could be expected for a single parish given a one MPH increase in winds speed is approximately $76,540. The expected increase in damages that could be expected for a parish given the loss of one unit of wetlands is approximately $1,302. The expected increase in damages that could be expected for a parish given the addition of a single individual is approximately $10. As one might expect, the marginal effect of each of these variables can vary depending on the context in which a hurricane makes impact.

Table 2.3 Monetized Marginal Effects in Absolute Terms

Variable	Monetized Average Marginal Effect
Wind	$76,540
Wetlands	$1,302
Population	$10

The figures below show how the MEs vary as values of the other variables change. They illustrate how the interrelationships between the variables that influence economic damages from hurricanes are a critical consideration for modeling. The ME of each variable is assessed against each of the other variables, including itself, to show how the effects of each are dependent on the levels of the other variables.

Analysis of Marginal Effects

Marginal Effect of Wind

Figure 2.2 shows the predicted ME of the wind variable at varying levels of the same variable. As is shown, the effect of an additional MPH increase in wind speed is lower for more intense hurricanes than for weaker storms. This means that the intensification of low intensity storms increases damage by a greater amount

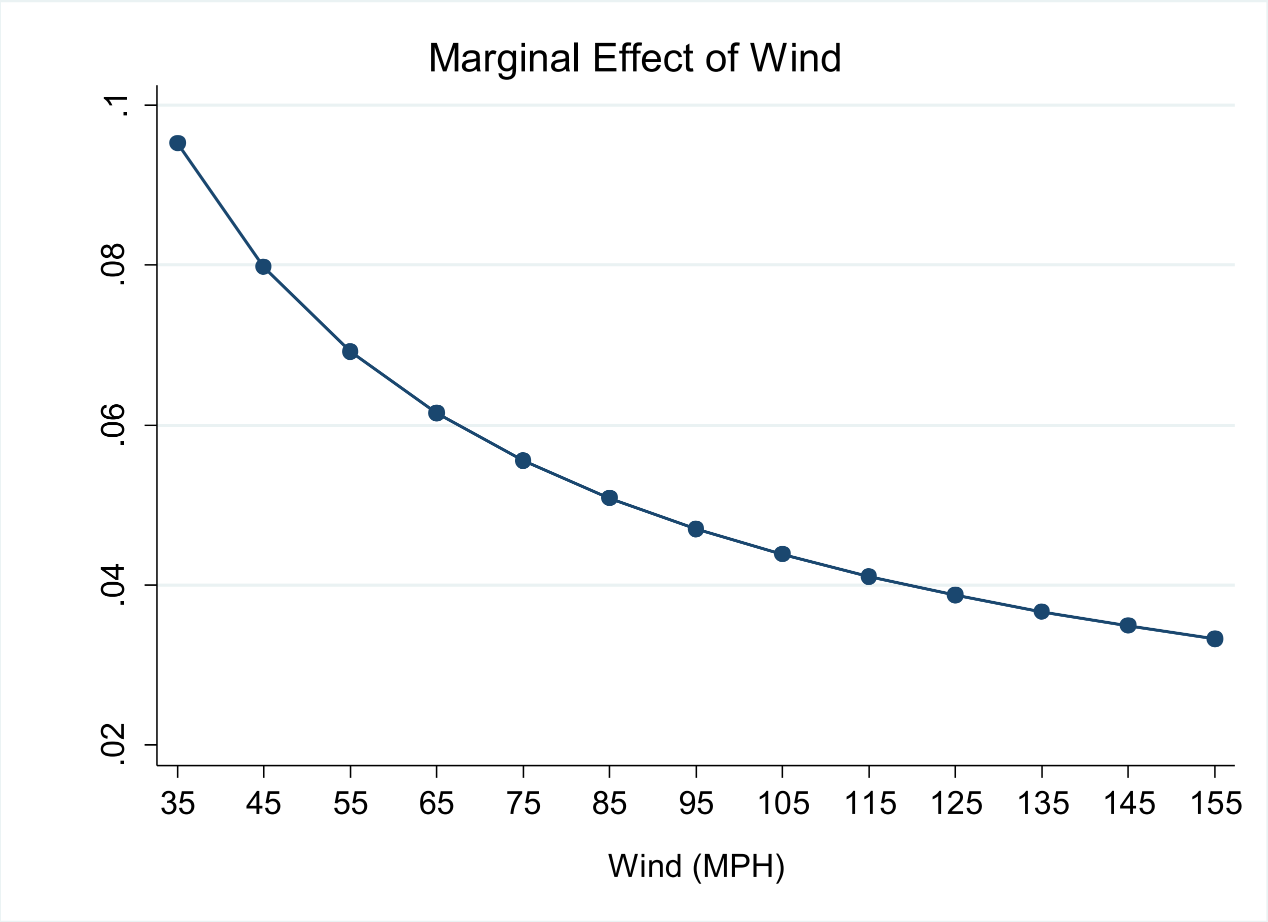


Figure 2.2 Marginal Effect (ME) of Wind Speed at Varying Levels of Wind Speed

than the same intensification of a more intense storm. This is an important notion if, as is suggested by some research (Dailey, et al., 2009), lower intensity storms become more frequent and intense in the Gulf of Mexico.

Figure 2.3 shows the predicted ME of the wind variable at varying levels of the relative wetland area variable. As is shown, the effect of an additional MPH increase in wind speed is higher where wetlands are scarcer. This means that the intensification of tropical storms and hurricanes is more impactful for parishes with a smaller protective buffer. The figure also shows that the decrease in ME slows as relative wetland area increases, implying that a change in wetland area will have more of an influence on the effect of wind on damages where wetlands are most scarce. This is an important relationship because it suggests that wetland loss and hurricane intensification, when occurring simultaneously, compound to make the effect of either more severe in terms of increased risk of hurricane damage particularly in areas with a small relative wetland area.

Figure 2.4 shows the predicted ME of the wind variable at varying levels of the population variable. As is shown, the effect of an additional MPH increase in wind speed is lower for areas with smaller populations. This means that the intensification of tropical storms and hurricanes is more impactful for parishes with higher population levels. This is expected because higher populations tend to have more valuable assets vulnerable to damage. Of note is that the model suggests that the increase in expected damages increases at a decreasing rate. One explanation for this is that as an area grows there is a necessity for critical infrastructure (e.g. roads,

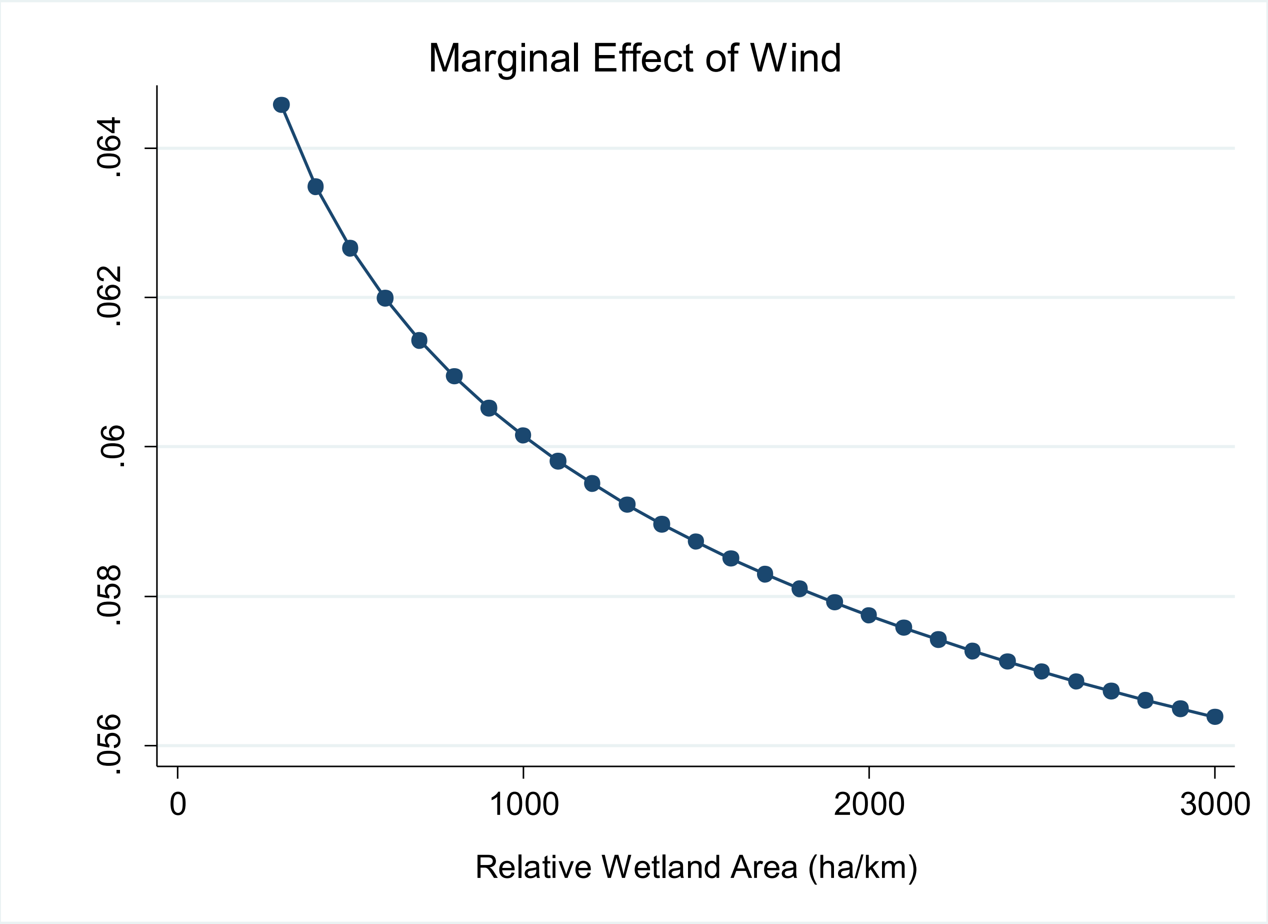


Figure 2.3 Marginal Effect (ME) of Wind Speed at Varying Levels of Relative Wetland Area

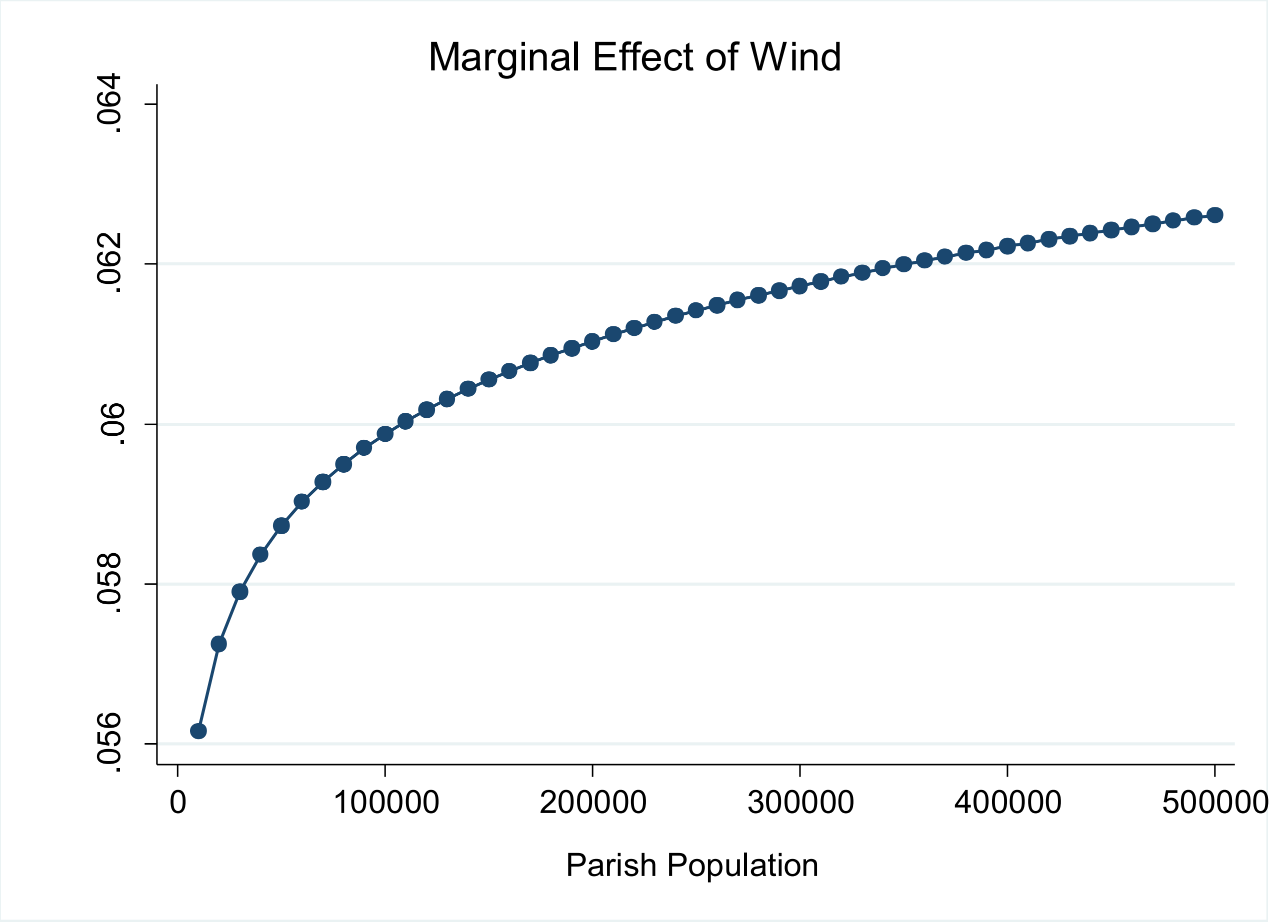


Figure 2.4 Marginal Effect (ME) of Wind Speed at Varying Levels of Population

utilities), but that there are scale efficiencies in larger populations that allow them to exist with less per-person infrastructure, and that is reflected in the diminishing growth of wind-driven damages as populations become larger.

Marginal Effect of Wetlands

Figure 2.5 show the ME of the wetland variable at varying levels of the wind variable. As is shown, the effect of a change in relative wetland area is lower for weaker storms. This means that wetlands are more valuable for mitigating damages from stronger storms. The results MEs show that the effect of wetlands on damages increases at a decreasing rate as storms become more intense. This is consistent with other research (Boutwell and Westra, 2016; Costanza, et al., 2008; Feagin, 2008), and fits with the narrative that as storms become more intense and storm surge become higher the capacity of wetlands to attenuate wave energy is overwhelmed because the frictional mechanisms that facilitate the protective functions by which this ecosystem services is derived are immaterial due to the depth of their submersion. This relationship is important for coastal managers who face decisions about whether to implement natural infrastructure, such as many of the Master Plan projects, or to engineer more robust defenses.

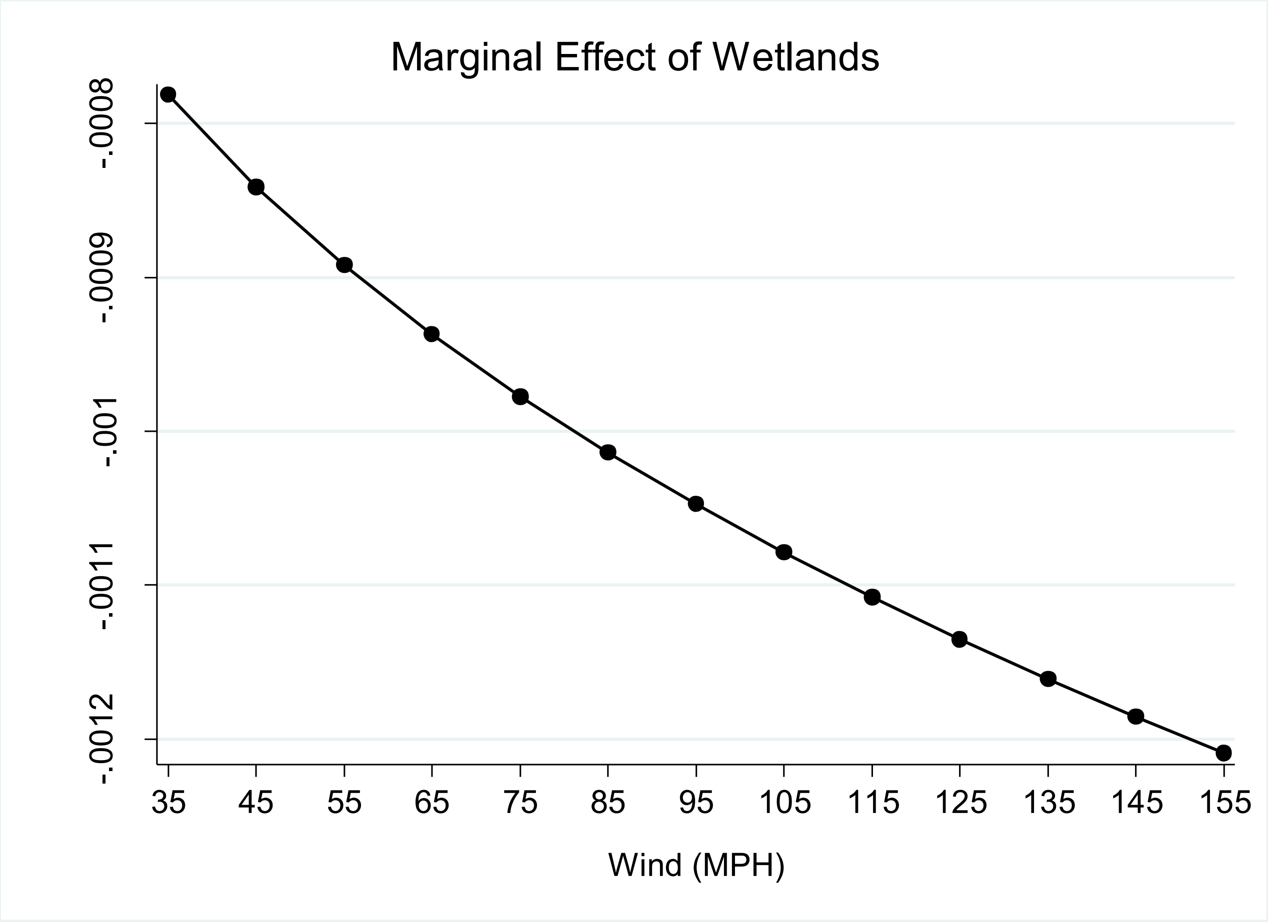


Figure 2.5 Marginal Effect (ME) of Relative Wetland Area at Varying Levels of Wind Speed

Figure 2.6 show the ME of the wetland variable at varying levels of the same variable. As is shown, the effect of a change in relative wetland area is lowest where wetlands are most extensive. This means that the loss of wetlands is significantly more costly (in terms of the resulting increase in expected hurricane damage) where wetlands are scarce. In economics, this phenomenon is referred to as diminishing marginal product because the protection produced by an additional unit of wetland diminishes as more wetlands are added. This result is consistent with other research (Boutwell and Westra, 2015a; Shepard, et al., 2011; Barbier et al. 2008), and is important for decision makers who must prioritize projects based on where they are most valuable. The size of an ecosystem is also of critical importance for the provision of other important ecosystem services (e.g. habitat provision), so this result complicates the tradeoff not only between the costs and the benefits of wetland restoration, but also between the benefits of this and other ecosystem services.

Figure 2.7 show the ME of the wetland variable at varying levels of the population variable. As is shown, the effect of a change in relative wetland area is lower where population levels are the lowest. This is an intuitive result because the protection provided by wetlands will be less valuable were the value of what is protected is lower, and one can expect the value of vulnerable capital to be lower where there are fewer people.

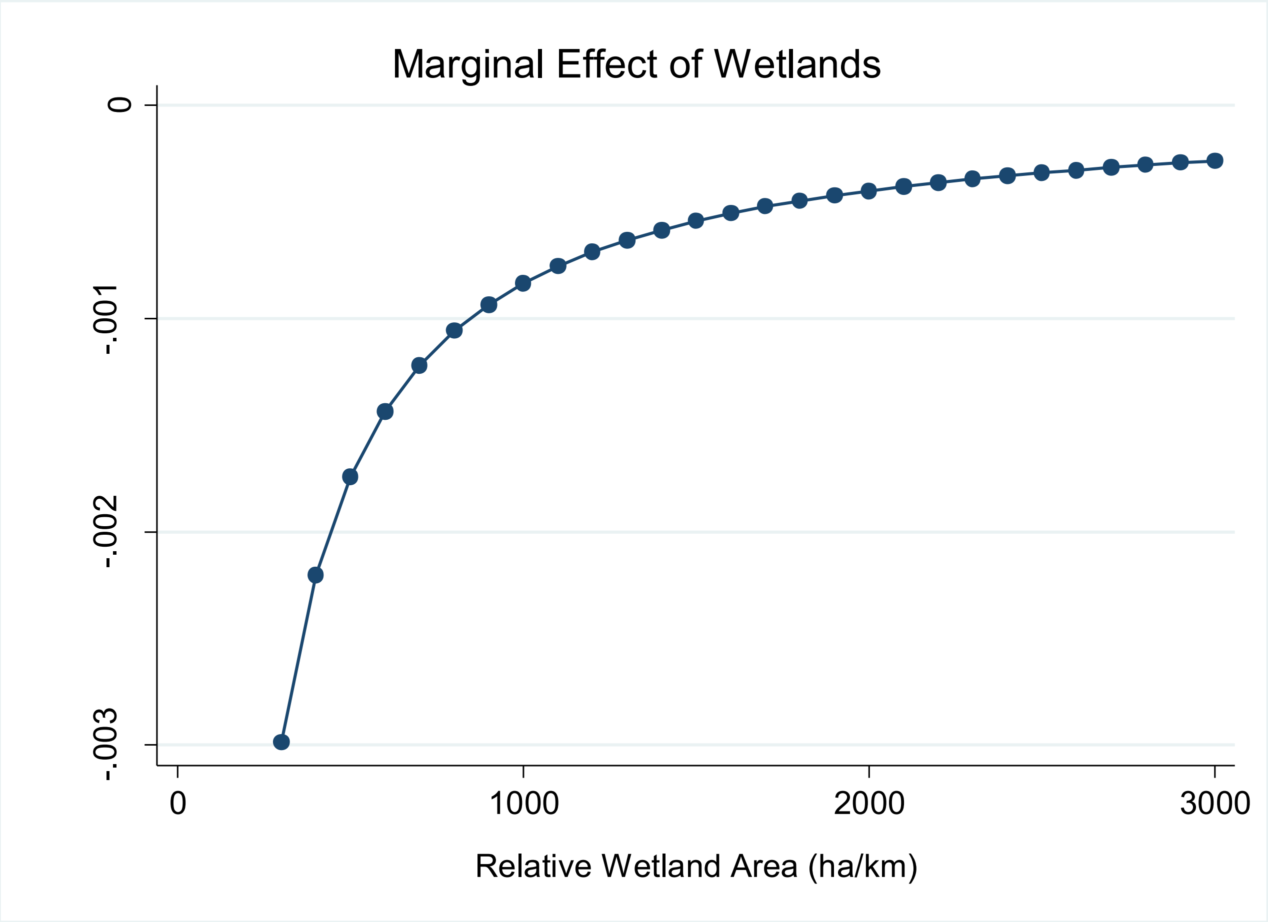


Figure 2.6 Marginal Effect (ME) of Relative Wetland Area at Varying Levels of Relative Wetland Area

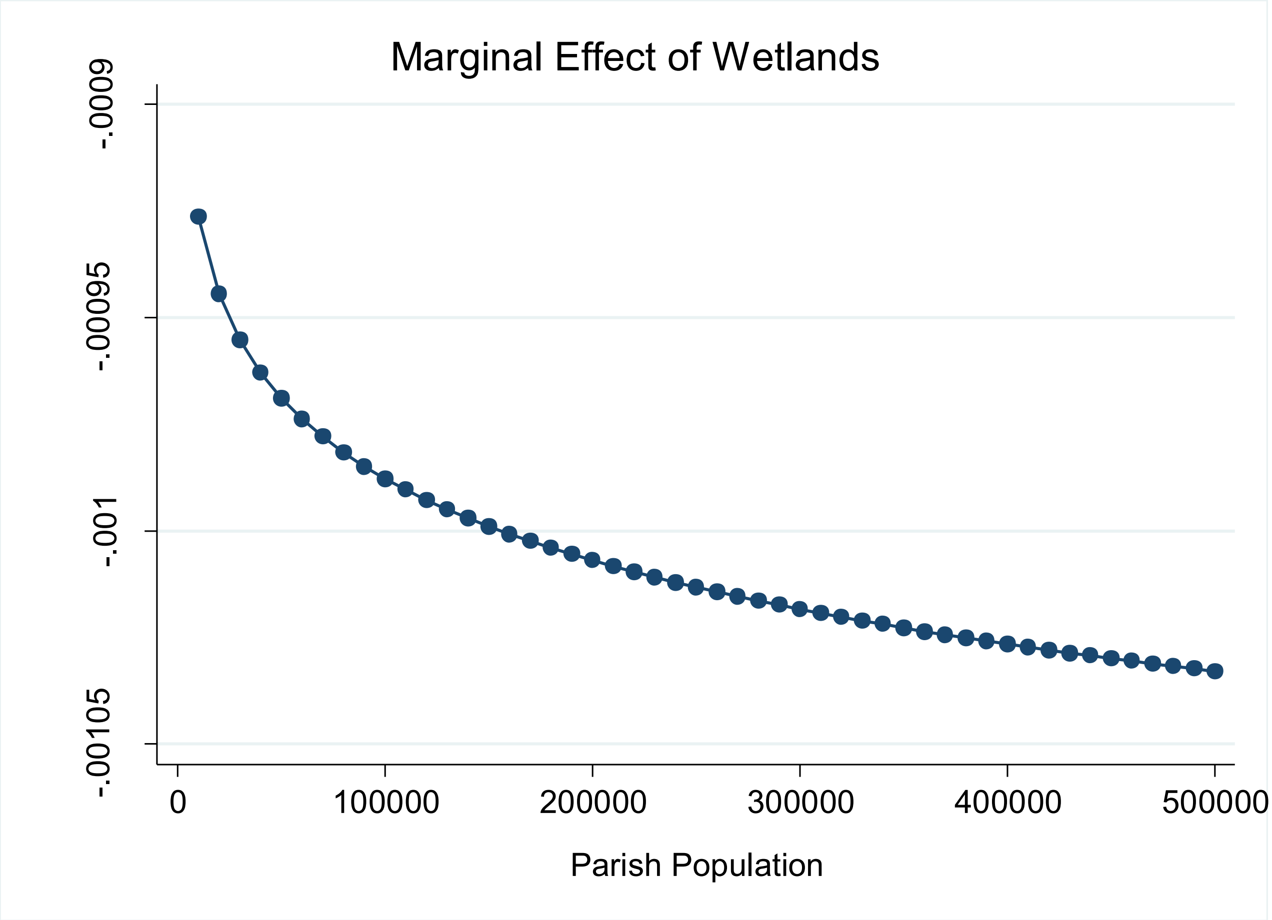


Figure 2.7 Marginal Effect (ME) of Relative Wetland Area at Varying Levels of Population

There are two important points to make regarding these results. First, this result highlights the difference between the ecosystem function and the ecosystem service. There is no basis on which to expect the ecosystem function, the reduction of inundation, provided by wetlands to be vary according to population. The ecosystem service, however, depends considerably on this added dimension. This highlights the importance of socio-economics in coastal planning. Second, there may exist some tradeoff between wetland area and population. Land, a finite resource, may be either developed for human habitation or natural wetlands (among other land covers), but not both. The correlation between the relative wetland area variable and the population variable used in this research is small. Nevertheless, it is difficult to say with certainty that the curve of the MEs shown in Figure 2.7 is not attributable to some degree to this relationship.

Marginal Effect of Population

Figure 2.8 shows the ME of the population variable at varying levels of the wind variable. As is shown, the effect of a change in population size is lower when storms are least intense. This result suggests that population growth will increase expected damages by a greater amount if hurricanes become more intense in the future.

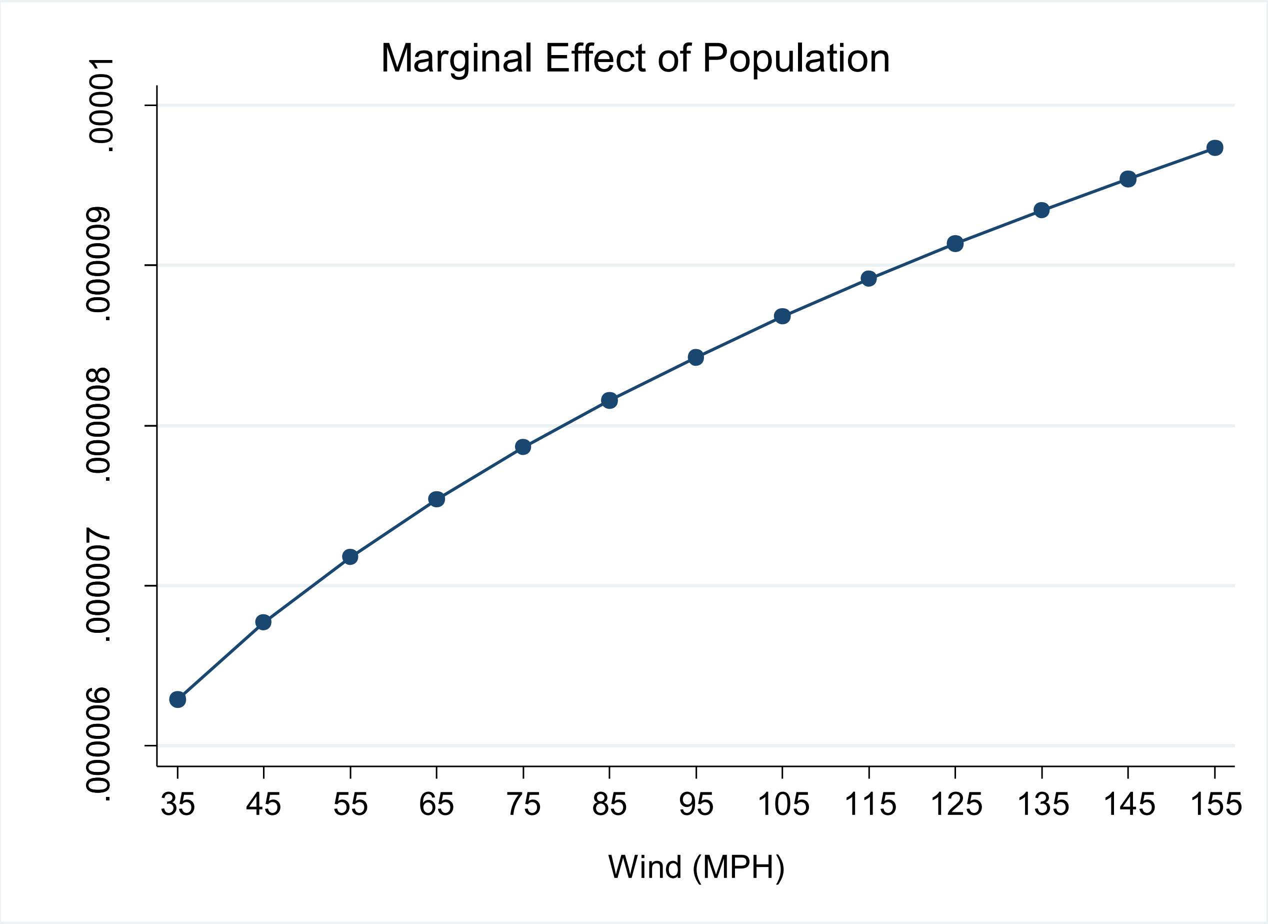


Figure 2.8 Marginal Effect (ME) of Population at Varying Levels of Wind Speed

Figure 2.9 shows the ME of the population variable at varying levels of the wetland variable. As is shown, the effect of a change in population size is lower where wetlands are more extensive. This suggests that regions that have greater wetland areas are less prone to population-driven vulnerability increases. The marginal effect of population decreases at a decreasing rate as relative wetland area increase. So, the mitigation of population-induced vulnerability increases is most effectively achieved by adding wetlands to where relative wetland area is scarce.

Figure 2.10 shows the ME of the population variable at varying levels of the same variable. As is shown, the effect of a change in population size is lower where population levels are high. This implies that expected hurricane damage increases at a decreasing rate. For example, a parish with an initial population of 50,000 that grows 10,000 people will incur a greater increase in expected damages that a parish with an initial population of 200,000 that experiences an equivalent level of growth. This result is consistent with the notion that larger populations benefit from scale efficiencies with respect to per-person hurricane vulnerability.

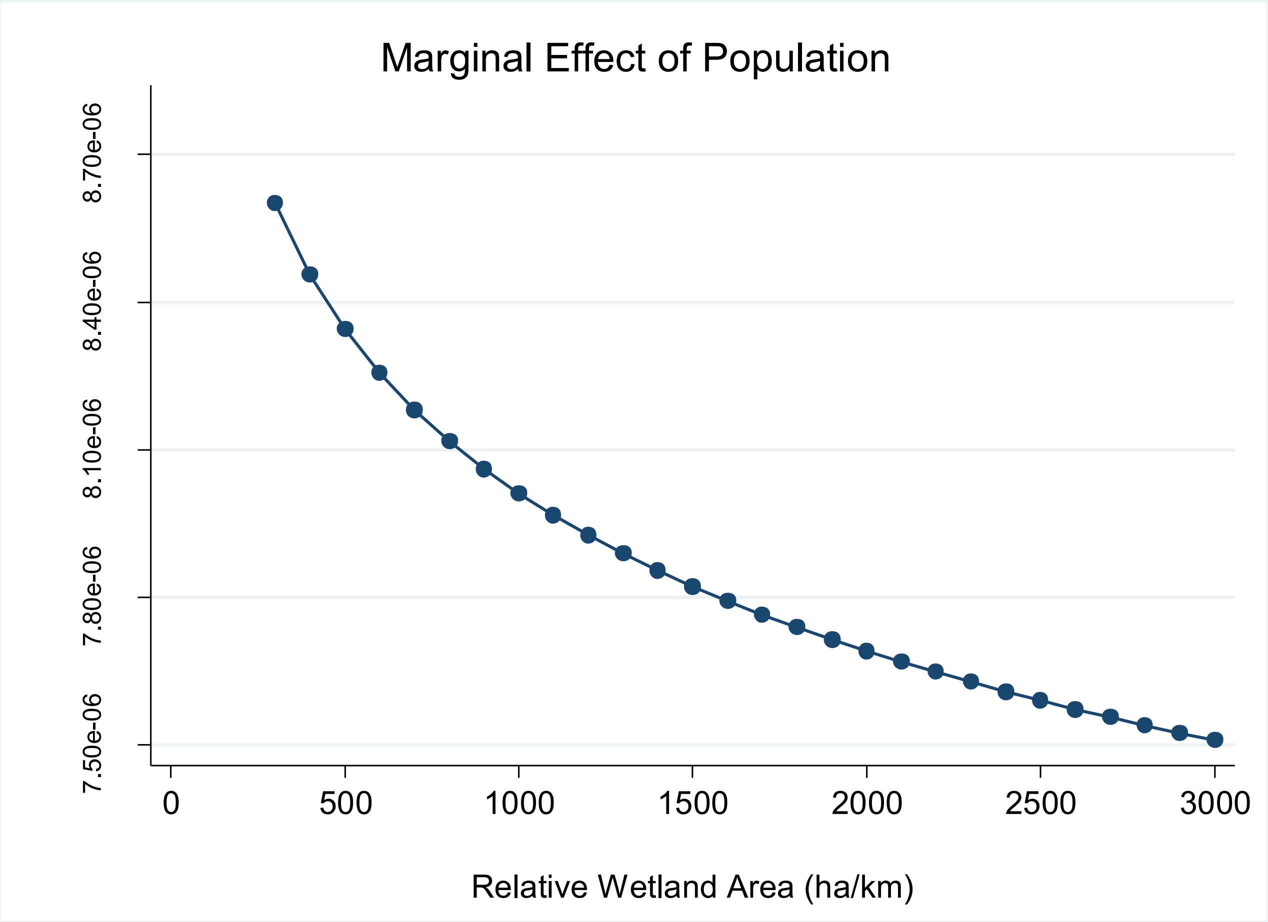


Figure 2.9 Marginal Effect (ME) of Population at Varying Levels of Relative Wetland Area

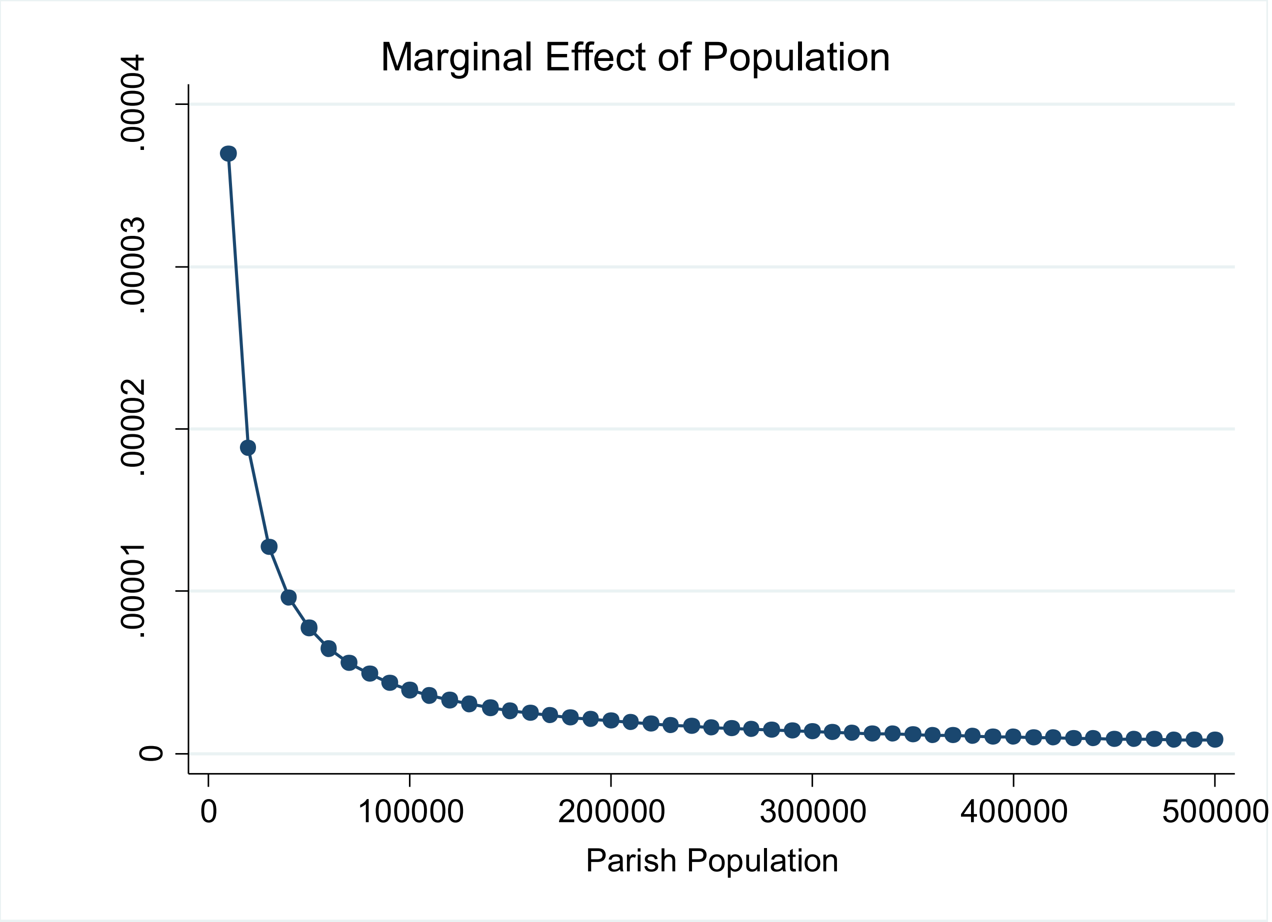


Figure 2.10 Marginal Effect (ME) of Population at Varying Levels of Population

SUMMARY AND CONCLUSION

These results show that hurricane intensity, wetlands protection, and population levels are significant factors that influence economic damages from tropical storms and hurricanes. Additionally, the results show that there are significant nonlinearities with respect to the effects of each factor on economic damages. These nonlinearities are the result of the relationship between factors during storm events. Specifically, intensity, wetland protection, and population each influence the effect of the other on economic damages.

The effect of wind speed on economic damages from tropical storms and hurricanes is shown to be different depending on the intensity of the storm. For stronger storms with higher wind speeds, the increase in wind speed is smaller than for storms that are less intense. While this result is not directly applicable to any present day management decisions, it suggests that if hurricanes become more intense in the future, it is the intensification of the more frequent, low-intensity storms that would result in the largest increase in damages. This is not to say that the intensification of major hurricanes would not be impactful, but the economic impact of these storms is already large and more fully incurred. To relate intensity to storm surge, the result would suggest the difference in damages between a one meter and two meter storm surge is greater than between a five meter and six meter storm surge.

The effect of an increase in wind speed is also shown to be mitigated by the presence of wetlands. The results illustrate that regions with greater relative wetland areas are less prone to damages induced by storm intensity increases. The influence of a change in wetland abundance on the effect of intensity changes is particularly pronounced where wetlands are scarce, suggesting that a focus on conserving and restoring wetlands in these areas will have the greatest influence on hurricane vulnerability if hurricanes become more intense in the future. Areas with greater population levels are shown to be impacted more by changes in intensity than those with smaller populations. This result is intuitive, as larger populations will tend to have more to lose in the event of a storm.

The effect of wetlands on hurricane damages is also influenced significantly by the other factors. For example, wetlands reduce economic damage more for stronger storms, which have larger damages, implying that a change in wetland area has more of an effect on expected damages if storms are more intense. However, the increase in damage mitigation is slightly smaller as storm become more intense. The abundance of wetlands present also influences the effect of a change in wetlands area on expected damages, with areas with large relative wetland areas showing small changes in expected damages associated with a change in wetland area. This result again suggests that wetland conservation and restoration is most impactful where wetlands are scarce. Similarly, a change in wetland area has more of an effect on damages where population levels are the highest. This is expected, as a given reduction in flooding is more valuable where that flooding would otherwise have inundated more populated areas.

Finally, the effect of population change on expected damages is greater when hurricanes are stronger and where wetlands are scarcer, suggesting that population growth is more costly in terms of expected damages in these areas because they will be more economically vulnerable to the physical impacts of a given storm. Population growth has the greatest effect where populations are small, but the effect of population growth on damages is similar for areas with populations greater than approximately 100,000 people. This may be because populations, once they reach a certain size, require less in terms of per-person infrastructure and essential facilities. The influence of population on the effect of wetlands and wind are also moderated as populations rise. The evidence presented here does not reveal the cause of these relationships, but these results suggest that there are scale advantages for mitigating the effects of population growth on vulnerability as populations become larger. This should be the topic of further research.

Interdisciplinary research that utilizes a variety of approaches and tools to model human and natural phenomena together will be critical for managing the uncertainties surrounding the future of coastal communities. This is certainly true of modeling the complex interaction of factors that influence economic damage from natural hazards. This chapter has thoroughly demonstrated how the relationships that are evident between hurricane intensity, wetland protection, and population interact to influence economic damages from tropical storms and hurricanes. Using deterministic physical science modeling results and observed economic damage estimates, storm damages are estimated at the parish level. This enables the stochastic modeling of damages as a function of the factors mentioned above.

An important unknown about the future of coastal communities is their vulnerability to hurricane impacts. A major component of vulnerability is susceptibility to hurricane damage, which is modeled in this chapter. This model can be used to explore economic vulnerability to hurricane damage at the parish level by imposing scenarios of interest onto the model and interpreting the results. The components used in this model are constantly changing. Climate change is likely to change climatological characteristics of hurricane regimes. Wetlands loss has persisted in Louisiana for nearly a century, and the dynamics of changes in wetland area are different in each parish. Similarly, populations change, and those changes are happen unevenly across the landscape. The following chapter explores the vulnerability of coastal Louisiana to hurricane damages, and estimates how vulnerability might change in the future given what is known about the trends in each of these factors.

CHAPTER 3

THE VULNERABILITY OF COASTAL LOUISIANA TO HURRICANE DAMAGE: PRESENT AND FUTURE

"Vulnerability is the birthplace of innovation, creativity, and change."

- *Brené Brown*

INTRODUCTION

Periodic hurricanes present a recurring burden to the finances of coastal communities. Federal and state funds are often available to assist in the response and recovery efforts at the local level, but these localities can nevertheless be overwhelmed with the costs associated with storm damages. Long-term fiscal planning requires an estimate of the damages that a community can regularly expect from hurricanes given the characteristics of that community. Not only is it necessary to understand present vulnerability, but preparing for the future also requires an understanding of how that vulnerability will change under different possible scenarios. So, what is the annual vulnerability of coastal Louisiana to hurricane damage, and how can that vulnerability be expected to change if hurricane regimes change, wetland loss continues, and populations grown or shrink?

This chapter seeks to estimate the annual expected damages from hurricanes as a measure of economic vulnerability, and use this measure to estimate the vulnerability of Louisiana parishes under possible future scenarios of storm intensity change, wetland loss, and population change. This can be accomplished by estimating the frequency with which hurricanes make landfall in Louisiana, and applying these frequency estimates to the damage function found in the last chapter in order to “annualize” the model. The annualized damage function estimates the annual economic vulnerability of coastal parishes to hurricanes in the present. Future scenarios are imposed on the damage function to estimate the increase in vulnerability that can be expected under possible future conditions.

While coastal vulnerability assessments are relatively common, most attempt to index a given region’s vulnerability based on institutional characteristics (e.g. number of recovery organizations, amount of public interest, etc.). However, the focus of this research is the impact that results directly from the loss of or damage to property and infrastructure rather than the costs associated with the interruption of economically important activities or the nature of disaster recovery. Few vulnerability assessments explicitly explore any jurisdiction’s inherent vulnerability to economic damage from hurricanes. This research presents results that describe the present and possible future vulnerability of coastal parishes in Louisiana to hurricanes, which can be used by parishes to plan and budget for increased hurricane damages into the future.

Paradigms of Vulnerability

Because this chapter seeks to measure the vulnerability of coastal parishes to hurricanes, it will begin by defining what this research means by “vulnerability”. Though vulnerability is emerging as a popular topic of interest, there is no single precise definition of the concept in the literature. Typically, assessments of vulnerability align with one of two broad categories: the “risk-hazard” approach, or the “political economy/political ecology” approach (Prasad, 2013). It has been said that the risk-hazard approach focuses on the what, when, and where of hazards, and the political economy approach focuses on the why, how, and to whom (Eakin and Luers, 2006). Both approaches are valid, and are often integrated in comprehensive risk assessments.

This analysis follows the risk-hazard approach as is described below. However, it should be noted that the impacts of hazards, in this case hurricanes, are not suffered equitably. The political economy approach is useful for identifying differences between social groups in terms of their susceptibility to damage (or some other measurable component of vulnerability) or how the response to disasters varies between segments of an impacted population. The priorities of individuals in disaster situations can vary considerably, and the needs of communities are not always responded to equitably because of factors that are embedded in the historical, socio-economic, and cultural environment of the impacted community. These components of vulnerability should be critical considerations for entities charged with preparing for and responding to disasters, but they are not considered in this analysis.

The approach to vulnerability used in this chapter is the “risk-hazard” approach (Waddel, 1977). As the term suggests, the focus of this analysis is to estimate the risk of an occurrence of a certain event (hurricane) and the hazard of the event should it occur. In this way, vulnerability is viewed as an expected outcome. In this case, hurricanes are the event of interest. So, the probability of a hurricane is the risk, and the damage incurred from a hurricane impact is the hazard. Therefore, expected annual damage is the measure of vulnerability of interest for this analysis. The hazard component associated with hurricane vulnerability, expected damages, is a function of complicated relationships between the size of the vulnerable area, the population and associated wealth within that area, and the exposure of that population to the hazard. These components of economic damage were explored extensively in the last chapter, and those results are a critical component of this vulnerability assessment.

METHODOLOLOGY

In order to estimate the vulnerability of coastal parishes in terms of annual expected damage, the damage function must be annualized, or transformed so that the result is an estimate of the damages a parish could expect in any given year. This depends on the frequency with which the coast is impacted by hurricanes. We know (from the last chapter), however, that stronger storms produce larger damages and that the increase in damage is not linear in wind speed. To account for this, the probability of storms of varying intensity are calculated and applied to the damage function to yield a model, and “annualized” EDF, that accounts for the differences in probability and intensity of different storms.

Hurricane Frequency Estimation and Annualized Damages

The hurricane frequencies are estimated using data on historical impacts in Louisiana from 1851-2006 (Blake, et al. 2007). Parish level impacts are recorded as individual events and are disaggregated according to their intensity category (Tropical Storm – Category 5). There is no basis in the literature to expect any parish in Louisiana to be more likely to be impacted by a hurricane than any other. There is some research that estimates the *landfall* probability for each county or parish, but this this research estimates the probability of being impacted by tropical storm strength winds on a regional scale, and does not disaggregate to the parish level (Klotzbach and Gray, 2016). Additionally, the variation between parish level probability estimates is well within the margin of error for the model used. Therefore, we treat the frequency estimates as equal between parishes. To calculate the percent chance of an impact for a storm of a given intensity, the proportion of storm impacts at that intensity is multiplied by the likelihood of suffering any tropical storm or hurricane. The estimates are presented in Table 3.1 and Figure 3.1

Table 3.1 Parish Level Impacts, Percent of Total Impacts, Likelihood of Impact, and Estimated Storm Interval by Intensity Category

Probabilities and Return Intervals	Tropical Storm	Category 1 Impacts	Category 2 Impacts	Category 3 Impacts	Category 4 Impacts	Category 5 Impacts
Parish Impacts	148	89	46	37	13	10
% of Impacts	43.15%	25.95%	13.41%	10.79%	3.79%	2.92%
Annual Probability	31.93%	19.20%	9.92%	7.98%	2.80%	2.16%
Return Interval	3.13	5.21	10.08	12.53	35.65	46.35

below. For reference, the percentage of storms in each category that are present in the data used for this analysis are shown in Figure 3.2. These impact probabilities are applied to the EDF by multiplying the probability of an impact with the median wind speed for each category of storm.

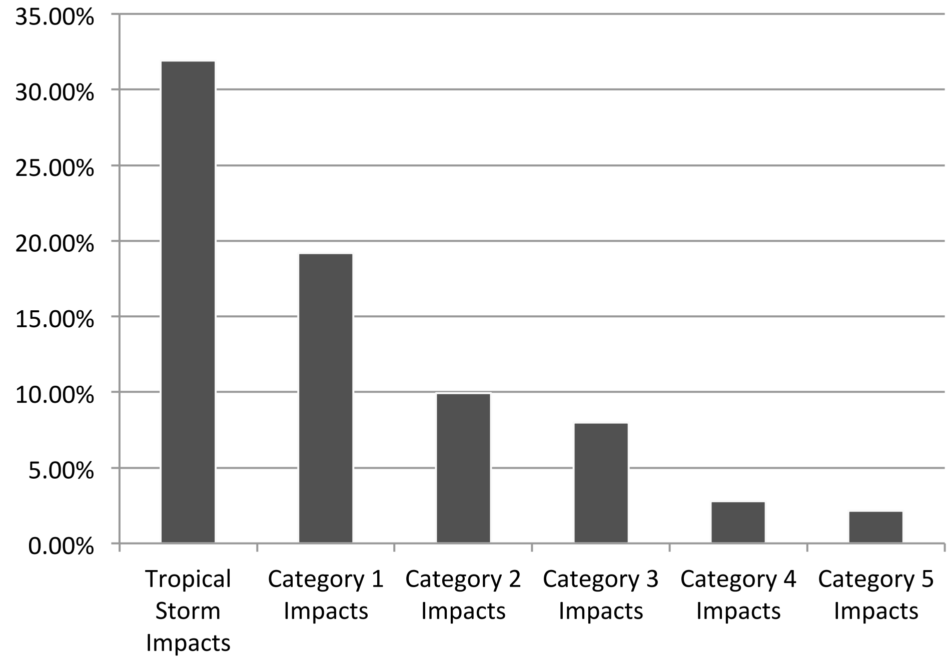


Figure 3.1 Frequency of Landfall for Storms of Each Intensity Category Based on Data from 1851-2007 from Blake, et al. 2007

The annualized EDF becomes

$$\boldsymbol{log(y) = \alpha\left[\sum \rho_{ij}\left(x_{ij1}^{\beta 1}\right)\right](x_{ij2}^{\beta 2})\,(x_{ij3}^{\beta 3})}, \tag{3.1}$$

where ρ_{ij} is the probability of a storm of intensity *j* impacting parish *i* in a year. The bracketed term, following an expected value framework, sums the product of the

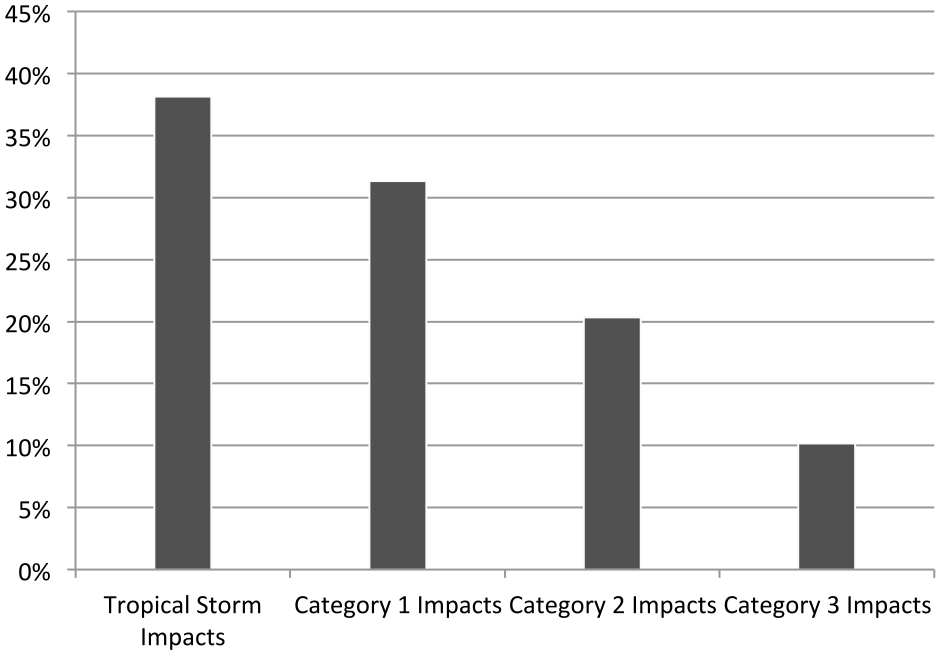


Figure 3.2 Percentage of Storms in Each Intensity Category that Are Present in the Data Used to Build the Damage Function

probability of an impact by a storm of intensity *j*, ρ_{ij}, and the impact a storm of intensity *j* is expected to have on economic damage.

To estimate the annual expected damage for each parish, the value of the wetland area and population size for each parish is input into the model. The result is an estimate of the annual vulnerability of each of the 13 parishes to damage from tropical storms and hurricanes. The parish estimates are summed to yield a statewide estimate of vulnerability.

Scenario Analysis

The future vulnerability of coastal communities in Louisiana depends largely on how these critical components (storm intensity, wetlands area, and population size) change in the future. To estimate the future vulnerability of coastal Louisiana, likely scenarios are drawn from the literature and data. These scenarios are meant to investigate which components of damages will drive vulnerability in the future, given what we expect the future to be. Because predictions of, for example, population growth are difficult to predict, the increases in vulnerability attributable to these variables will be expressed in ranges to reflect the uncertainty inherent in these calculations. Also calculated is an estimate of the compound increase in vulnerability from these scenarios, which is greater than the sum of each individual scenario because of the nature of the MEs presented in the last chapter. The increases in vulnerability will be calculated on a *per annum* basis and the annual increases will be presented in terms of the aggregate 50-year NPV.

The hurricane intensity scenario is taken from the 2012 Louisiana Coastal Master Plan (CPRA, 2012). The Master Plan presents a range of possible scenarios for hurricane intensity based largely on Intergovernmental Panel on Climate Change (IPCC) emissions scenarios. Emissions scenario A1B is used by the master plan to produce what they refer to as the “least optimistic scenario”. The IPCC and many other institutions, however, consider the A1B scenarios to be conservative, as it assumes a balanced energy future between carbon-intensive and non-carbon-intensive technology, and predicts emission levels through 2100 that are lower than many other scenarios (Nakicenovic, et al. 2000; Rogelj, et al. 2012). Under this emissions scenario, the Master Plan suggests that hurricane intensity will increase by 2.5% by 2061 “based on discussions with experts” using the CPRA’s “best professional judgement”. There is no conclusive literature regarding the increase or decrease in landfalling hurricanes in the Atlantic hurricane basin and fewer literature about these trends in the Gulf of Mexico. So, the Master Plan scenario is used in this analysis. To represent the range of uncertainty with respect to future hurricane regimes, the range of plausible scenarios from the Master Plan (-20%-+10%) are presented along with the +2.5% scenario.

The wetland loss scenario is derived from the database from which the wetland data is gathered. The C-CAP wetland data has been updated periodically since the mid-1990s for each parish in coastal Louisiana, and each of the parishes in the dataset have data for the years 1996 and 2010. This information is used to estimate a trajectory at which wetland loss proceeds. Each parish is assigned a loss trajectory based on the historical losses described in this data. The annual rate of loss is calculated between 1996 and 2010, and this rate is used to extrapolate wetland loss 15 years into the future, then wetland area is held constant. The population growth scenario is drawn from Blanchard, 2010. This paper provides low, medium, and high estimates of population growth. The estimates are provided for each parish at five-year intervals through 2030. This analysis focuses on the medium estimates for population through 2030 and holds population constant after that for the NPV calculation. The scenarios for wetland area and population levels from 2010 – 2030 for each parish is shown in Figure 3.3 and Figure 3.4, respectively

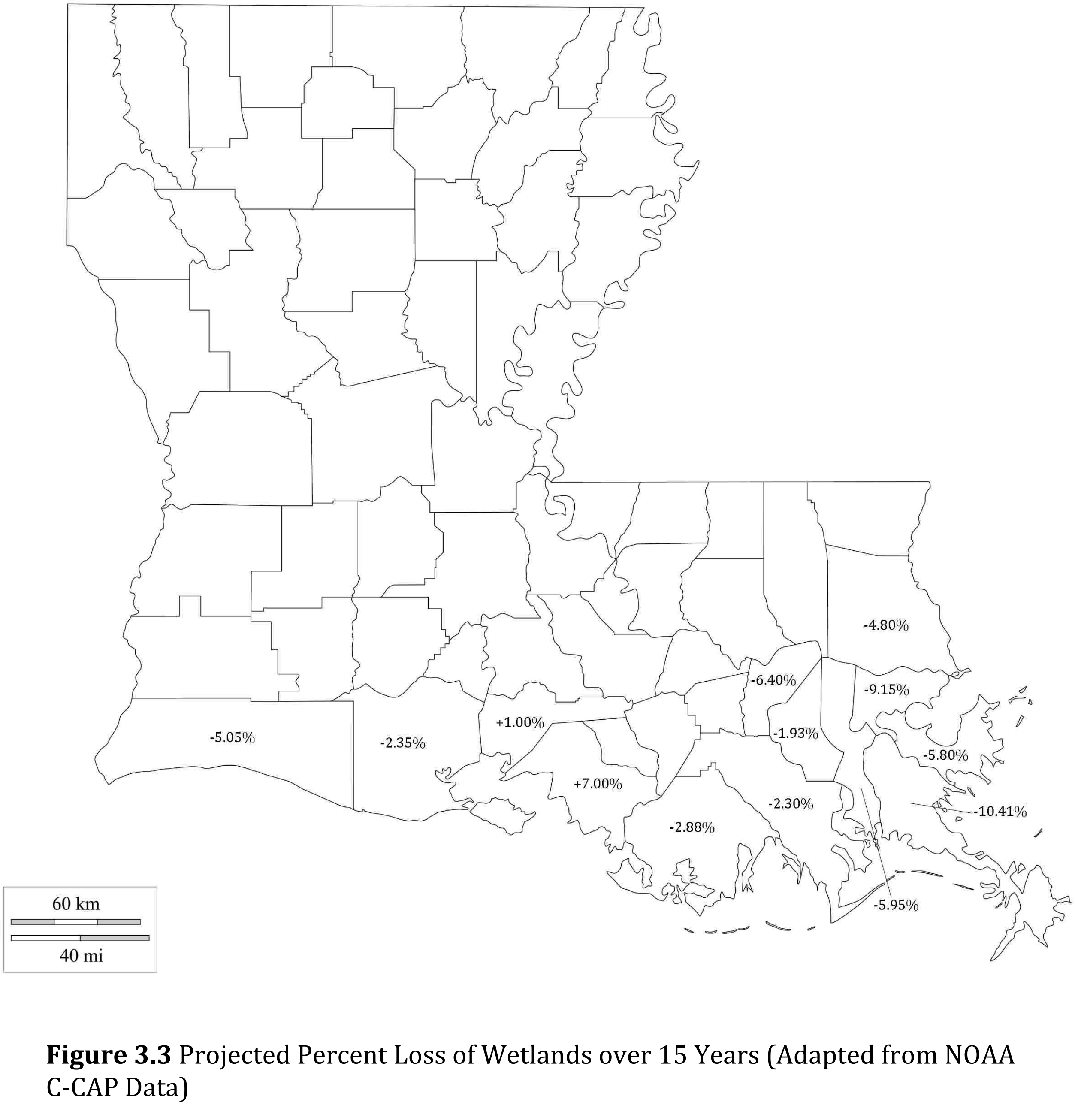


Figure 3.3 Projected Percent Loss of Wetlands over 15 Years (Adapted from NOAA C-CAP Data)

Figure 3.4 Predicted Population Change, 2010-2030 (Adapted from Blanchard, 2010)

RESULTS

The results of the scenario analyses are presented in the tables below. Each table shows the present day vulnerability in terms of annual expected damages as reference for how vulnerability changes under each scenario. Also presented in each table is the relevant scenario chosen for each of the factors influencing vulnerability. In order to illustrate the uncertainty surrounding each scenario, vulnerability is projected under a plausible range of that scenario. The results are presented for each of the parishes and as a total for all coastal parishes. Finally a summary table shows the three scenarios as well as a compound scenario in which each variable change is imposed on the model simultaneously. This table presents the annual vulnerability as well as the aggregate 50-year NPVs for each increase estimate.

Hurricane Regime Scenario

Table 3.2 shows the results based on the hurricane scenario that was obtained from the Louisiana Master Plan (CPRA, 2012). The current annual expected damage of the thirteen parishes in the dataset is estimated to be $77.6 million. This value serves as a baseline for investigating the impacts of a change in each of the modeled factors on vulnerability. For the hurricane frequency scenario, which is an increase of 2.5% and is loosely based on the IPCC A1B emission scenario, coastal Louisiana can expect to see an increase in annual vulnerability of approximately $9.8 million, raising the annual vulnerability to $87.3 million per year.

The increase is not uniform across all parishes. This is because increases in hurricane frequency (or intensity) are more costly in areas where population levels are higher or wetland area is lower, as is shown in the last chapter. The Master Plan states that the plausible range of change in hurricane frequency is between a reduction of 20% to an increase of 10% (even though an increase in 2.5% is termed the "least optimistic scenario"). The discrepancy in vulnerability projections based on this range is large. There are two reasons for the large gap between scenarios. First, the nature of the hurricane regime (intensity and frequency) is the most explanatory factor in the damage function by an order of magnitude. This means that marginal changes in the frequency or intensity of hurricanes make a large difference in the expected damage. Second, there is considerable uncertainty as to how the hurricane system will behave in the future.

The sensitivity scenarios presented here are representative of the lack of consensus found in the scientific literature regarding this topic. This large gap in the scenarios illustrates the importance of improvements in hurricane climatology. Such a large discrepancy in scenarios is not practically useful for financial or actuarial planning.

Table 3.2 Vulnerability under Current Conditions and Future Hurricane Regime Scenarios (2010 USD)

Parish	Expected Annual Damage	Hurricane Scenario (-20%)	Hurricane Scenario (+10%)	Hurricane Scenario +2.5%*
Cameron	$621,267	$266,762	$906,934	$684,548
Iberia	$2,108,856	$838,021	$3,187,106	$2,344,400
Jefferson	$14,793,680	$5,195,965	$23,627,580	$16,680,652
Lafourche	$2,549,634	$1,001,064	$3,874,051	$2,838,326
Orleans	$34,634,159	$11,526,085	$56,666,273	$39,294,136
Plaquemines	$3,172,508	$1,228,487	$4,850,452	$3,537,344
St. Bernard	$2,371,352	$935,352	$3,595,759	$2,638,466
St. Charles	$1,008,168	$419,811	$1,492,082	$1,114,775
St. John the B	$2,210,172	$875,674	$3,344,673	$2,457,871
St. Mary	$2,813,662	$1,097,851	$4,287,192	$3,134,494
St. Tammany	$6,156,833	$2,285,998	$9,591,870	$6,898,042
Terrebonne	$2,377,357	$937,570	$3,605,123	$2,645,196
Vermilion	$2,764,846	$1,080,001	$4,210,720	$3,079,720
Total	**$77,582,494**	**$27,688,641**	**$123,239,816**	**$87,347,971**

Wetland Loss Scenario

Table 3.3 shows the results based on the wetland loss scenario derived from historical wetland loss data obtained through CCAP. This imposition of this scenario suggests that, over the next 15 years, annual vulnerability will increase approximately $5.4 million to $83 million. If the rate of loss (or gain) is 20% slower of faster than historic rates, the range of increase is approximately $4.2 million – $6.6 million for a range of annual expected damage of $81.8 - $84.2 million.

It is notable that the range of uncertainty in this scenario is significantly smaller than that in the hurricane scenario. This is reflective of the fact that erosion and subsidence are relatively slow geologic processes that are well studied. It is acknowledged, however, that the 20% sensitivity employed here is a judgment of the researcher, but this range is thought to be conservative given the relatively short time frame (15 years) considered. Wetland loss varies over time, but erosion rates vary more between parishes than over time (Bernier, 2013). In fact, some parishes (Iberia and St. Mary) have experienced a growth in coastal wetlands from 1996 – 2010, so this trajectory is sustained in this scenario implying a reduction in vulnerability for those parishes. Even if the rates of change in were equivalent between parishes, the change in vulnerability would still vary. This is because wetland loss is more economically impactful for areas where population levels are higher and wetlands are scarcer, as is shown in the last chapter.

Population Scenario

Table 3.4 shows the results of the population scenario based on Blanchard, 2010. The results show an increase in vulnerability of approximately $3.4 million to $81 million. Also shown are the vulnerability projections for population changes that are 20% smaller or larger than those used for the primary scenario. The population scenario presents the smallest increase in vulnerability between the three scenarios, and the sensitivity analysis produces the narrowest range.

Table 3.3 Vulnerability under Current Conditions and Future Wetland Change Scenarios (2010 USD)

Parish	Expected Annual Damage	Wetland Scenario x 80%	Wetland Scenario x 120%	Wetland Scenario
Cameron	$621,267	$641,751	$652,602	$647,123
Iberia	$2,108,856	$2,094,496	$2,087,398	$2,090,941
Jefferson	$14,793,680	$15,513,201	$15,901,104	$15,704,656
Lafourche	$2,549,634	$2,591,130	$2,612,445	$2,601,739
Orleans	$34,634,159	$37,440,052	$39,023,827	$38,215,293
Plaquemines	$3,172,508	$3,425,973	$3,570,264	$3,496,487
St. Bernard	$2,371,352	$2,470,927	$2,524,297	$2,497,295
St. Charles	$1,008,168	$1,021,027	$1,027,600	$1,024,302
St. John the B	$2,210,172	$2,312,573	$2,367,861	$2,339,853
St. Mary	$2,813,662	$2,682,922	$2,622,449	$2,652,303
St. Tammany	$6,156,833	$6,383,124	$6,503,119	$6,442,522
Terrebonne	$2,377,357	$2,425,794	$2,450,847	$2,438,249
Vermilion	$2,764,846	$2,811,095	$2,834,868	$2,822,926
Total	**$77,582,494**	**$81,814,066**	**$84,178,680**	**$82,973,689**

The reasons are twofold. First, the population variable is the least explanatory of damages of all of the variables used in the model, so changes in that component of the damage function do not influence vulnerability as significantly as the others. Second, population change is slow in the coastal parishes of Louisiana, and not all parishes are expected to experience population growth. Cameron, Lafourche, and St. Mary parishes are expected to have smaller populations in 2030 than at present. This runs counter to global and national trends, where coastal population growth is higher than other geographic regions (Wilson and Fischetti, 2010). The model projects that over 60% of the population-driven vulnerability increase in coastal Louisiana will be incurred by St. Tammany Parish, which lies across from New Orleans on the North Shore of Lake Pontchartrain and where population is expected to more than double between 2010 and 2030.

Table 3.4 Vulnerability under Current Conditions and Future Population Change (2010 USD)

Parish	Expected Annual Damage	Population Scenario x 80%	Population Scenario x 120%	Population Scenario
Cameron	$621,267	$601,123	$590,817	$595,991
Iberia	$2,108,856	$2,134,535	$2,147,289	$2,140,919
Jefferson	$14,793,680	$15,110,807	$15,268,029	$15,189,528
Lafourche	$2,549,634	$2,539,890	$2,535,007	$2,537,449
Orleans	$34,634,159	$34,825,884	$34,921,562	$34,873,738
Plaquemines	$3,172,508	$3,405,087	$3,517,324	$3,461,519
St. Bernard	$2,371,352	$2,412,206	$2,432,444	$2,422,340
St. Charles	$1,008,168	$1,062,406	$1,088,674	$1,075,607
St. John TB	$2,210,172	$2,578,395	$2,748,746	$2,664,552
St. Mary	$2,813,662	$2,553,023	$2,415,230	$2,484,822
St. Tammany	$6,156,833	$7,853,158	$8,621,388	$8,242,631
Terrebonne	$2,377,357	$2,491,377	$2,546,980	$2,519,290
Vermilion	$2,764,846	$2,773,147	$2,777,291	$2,775,220
Total	**$77,582,494**	**$80,341,038**	**$81,610,782**	**$80,983,606**

Compound Scenario and Net Present Value

Table 3.5 shows the results of the three scenarios and the compound scenario, which consists of the simultaneous imposition of each scenario. The largest increases in vulnerability are driven by the increase in hurricane frequency. However, as is shown in Table 3.2, the range of uncertainty in this scenario is large,

Table 3.5 Vulnerability under Current Conditions, and Future Scenarios Including Compound Scenario (2010 USD)

Parish	**Present**	**Future Scenarios**			
	Annual Expected Damage	**Wetland Scenario**	**Hurricane Scenario**	**Population Scenario**	**Compound Scenarios**
Cameron	$621,267	$647,123	$684,548	$595,991	$669,605
Iberia	$2,108,856	$2,090,941	$2,344,400	$2,140,919	$2,432,449
Jefferson	$14,793,680	$15,704,656	$16,680,652	$15,189,528	$17,556,597
Lafourche	$2,549,634	$2,601,739	$2,838,326	$2,537,449	$2,887,269
Orleans	$34,634,159	$38,215,293	$39,294,136	$34,873,738	$40,602,783
Plaquemines	$3,172,508	$3,496,487	$3,537,344	$3,461,519	$3,949,460
St. Bernard	$2,371,352	$2,497,295	$2,638,466	$2,422,340	$2,755,170
St. Charles	$1,008,168	$1,024,302	$1,114,775	$1,075,607	$1,214,727
St. John TB	$2,210,172	$2,339,853	$2,457,871	$2,664,552	$3,033,191
St. Mary	$2,813,662	$2,652,303	$3,134,494	$2,484,822	$2,826,867
St. Tammany	$6,156,833	$6,442,522	$6,898,042	$8,242,631	$9,476,257
Terrebonne	$2,377,357	$2,438,249	$2,645,196	$2,519,290	$2,866,425
Vermilion	$2,764,846	$2,822,926	$3,079,720	$2,775,220	$3,160,296
Total	**$77,582,494**	**$82,973,689**	**$87,347,971**	**$80,983,606**	**$93,431,098**
Increase		$5,391,195	$9,765,477	$3,401,112	$20,023,580
50-year NPV of Increase		$3.7 Billion	$6.7 Billion	$2.3 Billion	$13.8 Billion
Scenario Source		CCAP, 2010	CPRA, 2012	Blanchard, 2010	

and could plausibly cause a reduction in vulnerability should the frequency of landfall decrease. The wetland scenario shows the next largest increase in vulnerability between the three, followed by the population scenario. The compound scenario results in an increase in annual vulnerability of approximately $20 million to $93 million. This increase is greater than the sum of the three scenarios because each scenario, wetland loss, population growth, and increasing hurricane frequency, are each more costly in the context of the others. For example, increases in hurricane frequency increase vulnerability more when population levels are higher and wetlands are scarcer. The projected vulnerability increase for each parish is mapped in Figure 3.5.

Also shown in the table are 50-year NPV calculations for each of the scenarios. Over 50 years, the net present value of the increase in vulnerability associated with the wetlands, hurricane, and population scenarios are $3.7 billion, $6.7 billion, and $2.3 billion, respectively (discount rate of 2% for all calculations). Compounded, the NPV of the vulnerability increase is $13.8 billion. It should be noted that these values are not the present values of the annual vulnerability of coastal communities, but the present value of the *increase* in vulnerability over the next 50 years. One can think of these values as the "cost of wetland loss", "cost of increasing hurricane frequency", or "cost of population growth" in coastal Louisiana. The NPV of the *total* vulnerability under the compound scenario over 50 years is in excess of $67 billion.

Figure 3.5 Expected Increase in Vulnerability under the Compound Scenario for Each Parish in the Dataset (2010 USD)

SUMMARY AND CONCLUSION

These results suggest that each of the factors that influence vulnerability included in the model are expected to increase the vulnerability of coastal Louisiana. The magnitudes of the NPV of the projected compound vulnerability increase over 50 years is comparable with the estimated cost of many of the CPRA Master Plan projects over the same time period. Additionally, the scenarios used for these projections, especially the wetland and population change scenarios, are considered conservative because they assume a change over the next 15-20 years followed by a plateau across the remainder of the 50 year time horizon. It is reasonable to expect that population growth will continue after 2030, and the projections in the Master Plan show a net wetland loss, even for full implementation on the projects, through 2061.

It should be noted that the annual expected vulnerability estimates presented here are actuarial in nature. They represent an expectation based on the stochastic representation of uncertainties present in both the model parameters and the future scenarios. There will be many years that suffer no hurricane losses, as has been the case nearly every year since this study period has ended until the drafting of this manuscript. Alternatively, a single large event could inflict damage several magnitudes greater than the annual expectation presented here. The frequency of these large events is represented in the frequency estimates, but storms of Category 4 or greater are absent from the data used to estimate the damage function, necessitating the use of extrapolation. Future research into the probability and nature of catastrophic damage from these types of events would help to refine vulnerability estimates in the risk-hazard tradition.

The consequence of the dearth in the state of knowledge with respect to current and future storm frequency is pronounced and illustrated by the sensitivity in the hurricane scenario vulnerability projections. The hurricane scenario instigates the largest increase in vulnerability between the scenarios, with a 2.5% increase in frequency resulting in a $9.7 million increase in annual vulnerability. However, the range of uncertainty with respect to the how hurricane frequency will change in the future makes it difficult to say anything certainty how hurricane regimes will change vulnerability. The range of "plausible" scenarios implies changes in vulnerability from a decrease or increase of approximately $50 million annually.

It is possible that landfall frequency will decrease, so much so that the increase in vulnerability resulting from other factors would be more than cancelled out. Such a future would avoid billions in economic damages from hurricanes and tropical storms and an untold amount of suffering. However, it is also possible that the future holds a comparably foreboding circumstance where large economic damages are not uncommon and the coast becomes less habitable for those without the means to frequently rebuild. The results here show that increases in hurricane frequency have a greater impact on vulnerability than do decreases. Nevertheless, the uncertainty in hurricane scenarios is a barrier to planning in a number of facets. These uncertainties not only make it difficult to plan financially for disasters, but, as is shown by the results in Chapter 2 (*circa* Figure 2.5), the frequency of hurricanes has a significant impact on the potential benefits of natural infrastructure risk mitigation projects.

It is important to note that no local entity can meaningfully change any of the climatic influences that control hurricane impact potential. While the future of hurricane regimes is of importance for future planning, only relative wetland area and population variables can be considered decision variables. Population change projections imply an increase in vulnerability in the future, albeit a spatially variable change. But, population growth in Louisiana is and is expected to be relatively mild for a coastal region, and population growth is not necessarily an undesirable event for other economic reasons. The remaining factor modeled in this research is wetland protection, which can be "controlled" to a limited extent by building and conserving wetlands where it is feasible and cost effective to do so.

Louisiana is a special case in hazard vulnerability because vulnerability is driven significantly by large-scale ecosystem loss and degradation. Louisiana accounts for 80% of all of the coastal wetland loss in the US (Turner, 1997). This suggests that targeted conservation and restoration initiatives are among the best approaches to reduce vulnerability to hurricanes. The results of this chapter show that *status quo* wetland loss will continue to increase vulnerability, and the results from Chapter 2 show that wetland loss has a greater effect on expected damages as wetlands become scarcer. Yet, little is known about the value of wetlands as natural infrastructure or the cost of wetland loss now and in the future. This is the focus of the next chapter, which addresses these issues directly using the expected damage function.

CHAPTER 4

The Value of Coastal Wetlands as Natural Infrastructure and the Cost of Wetland Loss in Louisiana

"What is a cynic? A man who knows the price of everything and value of nothing. And a sentimentalist…a man who sees an absurd value in everything and doesn't know the market price of a single thing."

\- *Oscar Wilde*

INTODUCTION

The Louisiana Coastal Protection and Restoration Authority's Master Plan designates $50 billion to protection and restoration projects through the year 2061. It is very possible that the plan will not be fully funded, requiring that some projects be prioritized over others. This prioritization ought to require the comparison between restoration initiatives using comparable measures (money) of the costs and benefits of these projects, including the value of the protective ecosystem services provided coastal wetlands. This is acknowledged in the Master Plan, stating

> "An in depth evaluation of ecosystem services would include a dollars and cents component that captures how much these services are worth monetarily."

However, although reducing storm damages through the use of natural infrastructure is an expressed goal of the Master Plan, the document continues,

> “We did not include this economic aspect of ecosystem services in the master plan analysis. Models to analyze this aspect were not readily available, and we did not have enough time to develop them ourselves.”

So, what is the value of wetlands for reducing coastal vulnerability to hurricanes, and how does this value vary across the coast based on hurricane frequency, wetland area, and population size?

This research seeks to use the damage function to estimate the economic value of the protective ecosystem services provided by coastal wetlands in Louisiana under different contexts. The value of additional wetlands (or the cost of wetland loss) varies spatially based on the strength of the storm against which the wetlands are protecting, the extent or scarcity of proximal wetlands, and the size of the population that is being protected. The results of this analysis highlight these differences in value between parishes. The value of the protective ecosystem services provided by wetlands is reported in terms of the annual flow of protection as well as the net present value (NPV) of that protection for each parish in coastal Louisiana.

This approach to valuation is referred to as the expected damage function (EDF) approach (Barbier, 2007). The application of the EDF approach presented here improves upon past applications in the literature in the scale of analysis, the size of the statistical sample, the estimation procedure, and the utilization of results (e.g. to highlight important relationships). Additionally, the results presented here are more-widely-applicable to different coastal areas, and can be used in cost benefit analysis as an estimate of the value of the damage mitigation provided by coastal wetlands.

Valuing Wetlands as Risk Reduction Infrastructure

Evaluating the monetary value of the storm protection services provided by wetlands is a relatively recent endeavor. This review of valuations should be preceded by cautioning that values are often reported (and most easily compared) on a per unit basis. These values are not necessarily representative of all wetlands because of the large degree of heterogeneity between wetland types and the complexity and nonlinearity with which wetlands attenuate wave energy within an ecosystem (Barbier et al. 2008). However, a range of value estimates in different contexts and using different approaches can provide insight into the magnitude of value at appropriate scales. These attempts are varied in methodology, but all suffer from a general lack of reliable data at scales that are inferentially useful. Some approaches and reported value estimates for valuing the damage mitigating services of wetlands follow.

Stated preference approaches have been used to estimate willingness to pay (WTP) for hurricane protection, and can be constructed to be specific about the nature of the protection provided (which is useful when evaluating specific initiatives) (Landry et al. 2011; Petrolia et al. 2014). These types of approaches are prone to error and bias (Hausman, 2012). Additionally, the extent of the protection provided by wetlands is a function of complex physical interactions and can vary from location to location, and the value of that protection varies according to several factors including hurricane frequency and intensity, the value of assets being protected, and the disamenity associated with losses. Because individuals are typically not accustomed to making transactions based on these factors, their expressed WTP may be unreliable. However, if these factors are known, the value of the protection provided by coastal wetlands can be modeled under the assumption that society is willing to pay to avoid damage at least as much as they stand to lose if that damage were to occur, assume risk averse preferences.

Alternative efforts at valuation focused on wind damages, although wind damages are reported to represent little more than 5% of total damages for coastal parishes (Farber, 1987). Farber, 1987, estimated the value of wetlands for wind damage reduction to be approximately $7 to $23 per acre of wetlands. The practice of valuing wetlands as storm damage mitigation has seen increased attention, particularly since Hurricane Katrina in 2005, and turned toward valuing wetlands for their storm surge and wave attenuating properties.

Values are sometimes calculated according to the degree to which wetlands presence is coincident with a reduction in damages (expected damage function (EDF) approach) or according to what an equivalent measure of protection would cost if wetlands were not present (replacement cost method). Barbier (2007), in a valuation of the ecosystem services provided by mangrove wetlands in Thailand, compared the two methods. That research showed the replacement cost method resulted in value estimates over seven times greater than those estimates using the

EDF method. The values reported were $3.4 million and $25.5 million in annual loss from wetland destruction for the EDF and replacement costs method, respectively. The implications of this are twofold: First, wetlands are found to be an inexpensive option for protection from coastal storms. Second, caution should be taken when applying the replacement cost method to ensure the context of that use is appropriate. Many economists object to the use of the replacement cost method because it does not estimate any relevant economic construct related to the actual ecosystem in question.

When evaluating the degree to which wetlands attenuate economic damages, economists must rely on observed damages, or use physical science models of coastal processes. Georgiou et al. (2012) use two models, one physical model estimating storm surge attenuation along given coastal transects and one economic model estimating the resulting marginal willingness to pay for that attenuation, to estimate the value of wetland protection against damages resulting from specific storm events. That research finds that wetlands are valuable for storm damage mitigation and illustrates that the provision of that ecosystem service changes according to certain physiological characteristics of the wetland (namely, wetland continuity and vegetative roughness). The benefit of this approach is that the analysis is performed at a scale that is useful for planning. Research such as this has the potential to explore how actual physical processes performed by wetland ecosystems are valuable for reducing surge and wave energy.

For valuations using observed damages, data availability and sufficiency limits the reliability of the results. Damage data is not widely available at a scale that would be sufficient to infer a direct relationship between damages and wetlands. Nevertheless, relationships can be estimated based on broader-scale damage estimates. Costanza et al. (2008) modeled state level damage estimates as a function of wetland presence and GDP on a storm-by-storm basis. Value estimates for wetland cover were consistent with others in the literature ($1700/acre/yr 2004 USD) based on the coincidence of wetlands and reduced damages, an application of the EDF approach. That research arbitrarily assigns the hurricane impact zone to be a 100km x 100km area from the point of landfall, which would almost certainly include areas were the ecosystem service was not provided and exclude areas where it was. Additionally the dataset is composed of storms that make landfall anywhere along the Atlantic and Gulf Coasts, which introduces bias into the analysis because the physical and ecological characteristics of these coastal areas vary significantly (Boutwell and Westra, 2015b).

A significant impediment to the EDF approach is data availability and sufficiency. Damage data is not widely available at a scale that would be sufficient to infer a direct relationship between damages and wetlands. Nevertheless, relationships can be estimated based on broader-scale damage estimates. This type of research has the benefit of using actual observations of economic damage. Although the quality of the data may not be amenable to some analyses, analysis of actual observations is the only way to validate causal relationships. However, the scale at which the damage estimates are reported inhibits any analysis of the physical characteristics of wetlands that attenuate wave and storm surge energy.

This analysis uses the expected damage function estimated in Chapter 2 to derive the marginal value (MV) of a unit of wetlands based on the model parameters. This application of the EDF approach improves upon earlier applications in a number of important areas. First, this application improves on the scale of analysis. The scale used here is enabled by the distribution of the large scale damage estimates from the NCDC to the parish scale by calibrating the data using the HAZUS model as is described in Chapter 2. This not only makes the scale more inferentially useful, but also increases the size of the statistical sample, which constitutes another improvement over past applications. The estimation procedure, Nonlinear least squares estimation, allows the provision of protection to be modeled in a nonlinear fashion, which enables a more realistic characterization of the relationships described in the model. This approach also allows the results to be utilized to highlight important thresholds and capacities in ecosystem service provision that are relevant for planning and management.

METHODOLOGY

In order to estimate the value of the damage mitigation provided by coastal wetlands in Louisiana, the EDF is used to estimate the effect of wetlands on damages. Although, these effects are explored in depth in Chapter 2, here they are monetized on an annual and NPV basis for use in cost-benefit or policy analysis. The monetization requires accounting for the non-linearities identified in Chapter 2. Specifically, the ME of wetlands varies for different levels of storm intensity, wetland are, population size.

Monetization of Marginal Effects

The ME can be monetized, yielding an estimate of the marginal value (MV) using one of several approaches. One could calculate the ME function by hand and input specific values of interest for each variable. Alternatively, one could simply estimate the annualized expected damage at the average or for a specific parish or storm and take the exponential of that value, subtract (or add) one unit of wetlands, estimate the new damage value and take the exponential, and subtract the two. In this case, the MV would be

$$\boldsymbol{MV = e^{\hat{y}} - e^{\hat{y}`}}, \tag{4.1}$$

where ŷ is the expected log of damages estimated by the function at the variables of interest,

$$\boldsymbol{\hat{y} = F(x_1, x_2, x_3)}, \tag{4.2}$$

and ŷ` is the expected log of damages after a marginal change in x_2,

$$\boldsymbol{\hat{y}` = F(x_1, x_2 - 1, x_3)}. \tag{4.3}$$

Both methods yield the same results. The later is the one employed in this research, and the estimates are calculated in Microsoft Excel.

Annual Ecosystem Service Flow and Net Present Value

First, a general ecosystem service value is estimated for wetlands across the Louisiana coast using the hurricane probabilities calculated in Chapter 3. This value takes into account the both the frequency with which hurricanes of varying intensities strike the coast and the degree to which wetlands mitigate damages against those storms. This is achieved by multiplying the MV of wetlands at each intensity level (calculated at the median wind speed for that category) by the frequency estimate for a storm of that intensity, and summing to yield an estimate of the annual flow of the damage mitigation ecosystem service provided by a unit of wetlands. The MV for this calculation is evaluated at the median wind speed for each category. For example, the MV of a Category 1 storm (74 mph – 95 mph) is evaluated at $x_1 = 84.5$.

The same procedure is employed for each parish in Louisiana, resulting in an estimate of value for wetlands in each of the 13 coastal parishes in this study. These MV estimates are generated using the characteristics (i.e. population size and wetland area) of each of the parishes. Disaggregating the MV between parishes will enable the illustration of how the value of wetlands is related to wetland area and population growth, and will give policy makers a more spatially explicit estimate of value. These results can help coastal management entities prioritize projects based on which provides the highest value for damage mitigation.

These values will be used to calculate the NPV of wetlands over 50 year using a range of discount rates. The values estimated in this chapter will be used to calculate the cost of wetland loss and highlight critical thresholds, or "tipping points" around which the systematic interactions described in the model change. Specifically, the evidence suggests that wetland loss is reaching a critical point in many places in Louisiana that could result in an abrupt increase in the vulnerability of coastal communities. This means that future wetland loss will be more costly in terms of increase risk of damages in the future that it was been in the past, and suggests that wetland conservation and restoration now is important to avoid higher risks.

RESULTS

General Ecosystem System Service Valuation

The estimated MV of the protection provided by wetlands across the Louisiana coast is shown in Table 4.1 and Figure 4.1. The annual marginal value of wetlands for storm damage mitigation in Louisiana is estimated to be approximately \$1,038/ha/km. So, a loss of one ha/km of wetlands would cost a Louisiana parish \$1,038 per year in increased risk of storm damage annually. The corresponding NPV is estimated to be \$27,508-\$51,899. These estimates represent averages for across all wetlands in Louisiana. Note that the marginal value of wetlands is different for each category of storm (Table 4.1, row 1) – highlighting the nonlinear provision of protection by wetlands. The value of wetlands increases at a decreasing rate as storm intensity increases. However, because the probability of suffering an impact from a Category 4 or Category 5 hurricane is relatively small and the damage from weaker storms is not typically high, the majority of the value (approximately 60%) of this ecosystem service is for protection against Category 2 and Category 3 storms.

Table 4.1 Annual Value of the Flow of Risk Reduction Provided by One Unit of Wetlands (2010 USD)

Value	**TS**	**Category 1**	**Category 2**	**Category 3**	**Category 4***	**Category 5***	**Σ**
Ha/km/storm	$69	$746	$2,341	$4,813	$5,084	$5,265	
Ha/km/year	$22	$143	$232	$384	$143	$114	
Annual Unit Value							$1,038
NPV (r=5, t=50)							$19,897
NPV (r=0, t=50)							$51,899

Parish Disaggregation of Ecosystem Service Benefits

The marginal value of wetlands in each of the coastal parishes are calculated according to their respective population levels and relative wetlands areas and presented in Table 4.2 and Figure 4.1. As is shown in Chapter 2, the wetlands are most valuable for reducing hurricane damages where wetlands are scarce and population levels are high. Table 4.2 demonstrates the magnitude of variation that exists according to the damage function. Cameron Parish, which has the smallest MV estimate, has a population of less than 7,000 (2013) and a large relative wetland area. Alternatively, Orleans Parish, which has the largest MV estimate, has the largest population and a small relative wetland area.

Table 4.2 Marginal Value (MV) of Wetlands for Each Parish in the Dataset (2010 USD)

Parish	Annual Marginal Value
Cameron	$279
Iberia	$984
Jefferson	$21,168
Lafourche	$1,260
Orleans	$133,941
Plaquemines	$5,076
St. Bernard	$1,797
St. Charles	$230
St. John TB	$1,529
St. Mary	$2,297
St. Tammany	$4,804
Terrebonne	$980
Vermilion	$2,071

A critical insight than can be taken from the preceding two tables is that the annual MV of wetlands for damage mitigation presented in Table 4.1 ($1,038) is quite different than the average of the annual MV estimates for each parish, which is approximately $13,570. This is a reflection of the systematics illustrated by the model – namely, that of diminishing marginal product. By the nature of the system, there are fewer valuable wetlands than there are wetlands with little value because wetlands are most valuable where they are least prevalent. This is important to consider when interpreting the estimates presented in these tables.

Figure 4.1 Annual Marginal Value (MV) of Wetlands for Damage Mitigation by Parish (2010 USD)

Context and Considerations

This nonlinearity in the provision of protection provided by coastal wetlands indicates that current trends in wetland loss poses an increasingly severe threat of vulnerability increases in the future. Figure 4.2, which was adapted from Chapter 2, shows the estimated MEs of wetlands on damages for varying levels of relative wetland area. The figure illustrates that the effect of a loss (or gain) in wetland area is significantly more costly (or beneficial) where relative wetland area is low and least valuable where wetlands are most extensive. As is mentioned earlier, this phenomenon is referred to as diminishing marginal product because the protection produced by an additional unit of wetland diminishes as more wetlands are added.

A commonly cited figure used by popular media is that Louisiana loses a football field (approximately 5,000 square meters) of land (wetlands) each hour (Törnqvist and Meffert, 2008). Of course, the rate of wetland loss varies widely across the coast and across time, but this rate is useful for demonstrating the increase in community vulnerability that results from wetland loss. At this rate of land loss, $95 million - $210 million (NPV) in wetland protection is lost each year in the state of Louisiana. So, the vulnerability of coastal Louisiana to storm damages increase by $1 billion every 5-10 years (due to wetland loss alone). Each year, the cost of wetland loss increases because wetlands are scarcer than the year before. This should be concerning for local governments as cleanup and rebuilding costs alone can overwhelm local budgets.

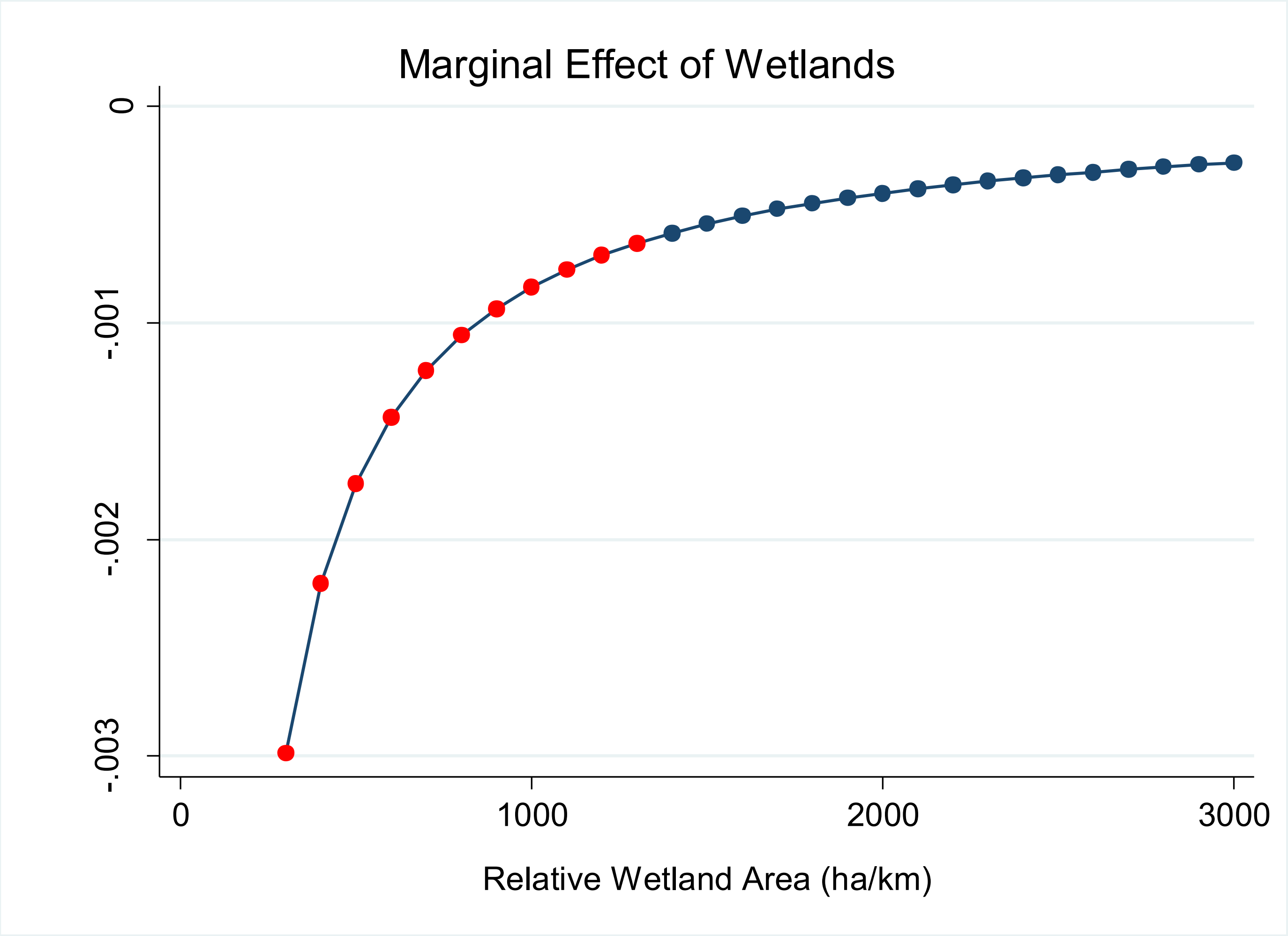
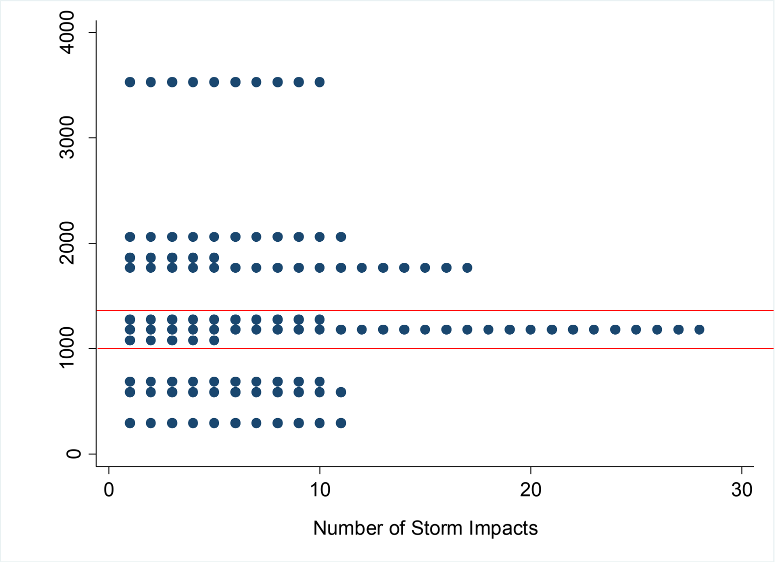


Figure 4.2 Marginal Effect (ME) of Wetlands on Damages at Different Levels of Relative Wetland Area (Red Dot Denotes Statistically Significant Difference from Next Highest Increment; Increments=100ha/km)

Critical Thresholds

Wetland loss has persisted in Louisiana for years, and residents across the coast have suffered the costs. Louisiana has lost approximately 5,000 km^2 since 1930, and stands to lose a similar amount over the next 50 years (CPRA, 2012). However, this analysis shows that future wetland loss will cost Louisiana much more than historic wetland loss. This is because wetlands have provided a large buffer against coastal storms in the past, where an incremental loss of wetlands in areas where wetlands are extensive costs little in terms of increased vulnerability. That is changing. The portion plotted in blue in Figure 4.2 represents the MEs of wetland loss when wetlands are abundant – they are near zero, implying that the cost of their loss is near zero. The red portion, representing areas with less than 1,300 ha/km, shows that the cost of wetland loss increases sharply as the wetland buffer becomes smaller. This suggests that wetland loss becomes significantly more costly when wetland prevalence is at or below approximately 1,300 ha/km. Thresholds of this type are often referred to as a “tipping point”, or a “point at which a series of small changes or incidents becomes significant enough to cause a larger, more important change” (Oxford English Dictionary, 2004).

Figure 4.3 illustrates that Louisiana is approaching a critical threshold with respect to wetland loss and vulnerability to hurricanes. Figure 4.3.a shows that a large proportion of hurricane impacts have occurred in parishes where relative wetland area is near the 1,300 ha/km threshold, implying that future wetland loss is likely to drastically increase storm damages. Figure 4.3.b demonstrates that



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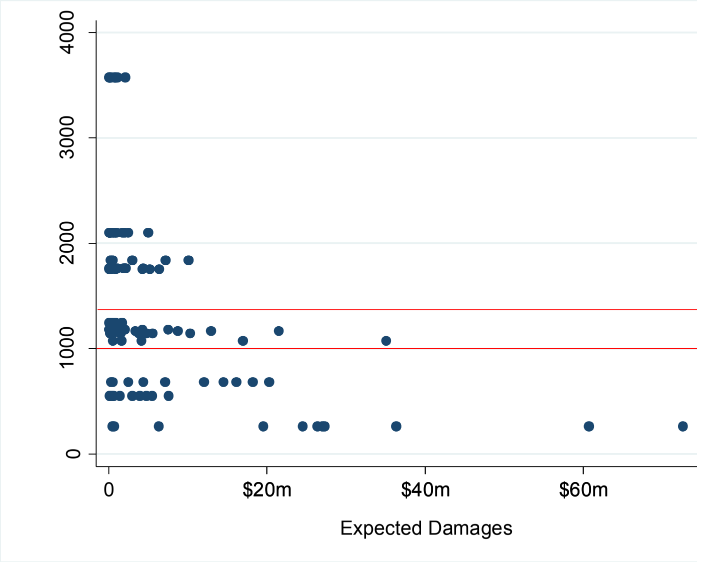

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damages are predicted to increase quickly as relative wetland area drops below the threshold level. As wetland loss continues, much of Louisiana (the red portion of Figure 4.3.a) will drop below the threshold level and be vulnerable to considerably higher damages (like those predicted in the bottom portion of Figure 4.3.b). Over 27% of the coastal population lives in a parish with 1,000-1,300 ha/km of wetlands. These results further demonstrate the importance of wetlands to coastal communities and highlight the urgency of Louisiana's land loss problem.

CONCLUSION

The damage mitigation provided by wetlands is thought to be among the most valuable ecosystem service provided by some coastal wetlands (Caffey, et al. 2014; Petrolia, et al. 2014; Costanza, et al. 2008). However, there are a suite of other ecosystem services provided by coastal wetlands that should be considered when deciding between the use of engineered measures of risk reduction and natural infrastructure including habitat, carbon sequestration, nitrogen removal, recreation, erosion control, and others (Stephanski and Shimshack, 2016; Petrolia, et al. 2014; Engle, 2011). In prioritizing risk reduction initiatives using a cost-benefit framework, it is necessary to account fully for the costs of these initiatives. There can be ecological costs and benefits in terms of changes in ecosystem service provision that are superfluous to the construction and maintenance costs of man-made efforts (e.g. sea walls, levees, pumps) that should be considered. The cost of both man-made and natural infrastructure can vary drastically based on implementation method, project time horizon, and location of the project (Caffey, et al. 2014).

This paper explores the economic benefits associated with a single ecosystem service – the damage mitigation provided by coastal wetlands. Using the EDF approach, we find that the annual value of wetlands for reducing damage is approximately $1,038/ha/km on average, but that the value can vary significantly based on the intensity of storm from which wetlands are providing protection, the extent of wetlands providing protection (i.e. the width of the wetland buffer), and the value of assets being protected. The model presented here can be used to estimate the economic impact of changes in wetland area in terms of the corresponding change in risk of hurricane damage, and can be used to inform management decisions.

If there is insufficient funding to meet the estimating $50 billion cost of the complete implementation of projects proposed in the 2012 Louisiana Coastal Master Plan, projects must be prioritized. In the face of state and federal budgetary strain, management decisions are increasingly guided by economic assessments of costs and benefits. Given the large spatial variability in these costs and benefits, future research should follow three directions. First, advances in physical science modeling should be used to improve our understanding of which characteristics of natural systems are most valuable and incorporated into economic models. Second, variations of the EDF approach that employ more sophisticated spatial methodologies that can account for the variation in the provision of protection have the potential to improve the validity of the value estimates and make them more reliable for policy analysis. Finally, the value of the protection provided by wetlands should be modeled in terms of the trade-offs between this and other ecosystems services as well as the costs of implementation.

CHAPTER 5
SUMMARY, DISCUSSION, AND CONCLUSION

SUMMARY OF MAJOR FINDINGS

This dissertation has focused on one of the most important issues facing coastal Louisiana – vulnerability to hurricane damage and the cost of wetland loss. The results presented here demonstrate that economic damage from coastal storms is the result of a complicated interaction between multiple socio-economic and environmental factors. Because these factors are constantly changing, there interactions and the consequent vulnerability of coastal communities is also changing. Each of the factors that influence expected damages that are addressed here show trends that will tend to increase the future vulnerability of coastal Louisiana. One major driver of vulnerability, wetland loss, is shown to be reaching a threshold that will result in severe costs in terms of hurricane damage increases. Below is a list of major findings.

- Stronger storms tend to inflict greater damages to coastal communities. Increases in storm intensity are most impactful for weaker storms, where wetlands are scarce, and where population levels are high.

- Areas with smaller relative wetland areas tend to incur greater damage from tropical storms and hurricanes. Wetland loss is most costly in terms of increased expected damages during stronger storms, where wetlands are scarce, and where population levels are high.

- Larger populations tend to incur greater damage from tropical storms and hurricanes. Changes in population have the greatest effect on expected damages for stronger storms, where wetlands are scarce, and where population levels are low.

- The annual vulnerability of the thirteen parishes analyzed in this study to direct economic damage to assets is approximately $77.5 million, over half of which is in the greater New Orleans area.

- Small increases in the frequency of hurricane impacts could significantly increase expected annual damage. Future scenarios of changes in hurricane frequency are not well enough established to say with any certainty whether they will increase or decrease the vulnerability of coastal communities to damages.

- The continuation of current trends in wetland loss would increase annual vulnerability in the thirteen coastal parishes by approximately $4.3 million - $6.6 million, costing approximately $3.4 billion in NPV terms over 50 years.

- Projected population growth would increase annual vulnerability in the thirteen coastal parishes by approximately $2.8 million - $4.0 million, coasting approximately $2.3 billion in NPV terms over 50 years.

- Each scenario occurring together would compound to increase annual vulnerability by approximately $20 million, costing approximately $13.8 in NPV terms over 50 years. These values are significantly greater than the sum of the independent scenarios because the interactions between the factors each exacerbate the costs of changes in the other.

- The marginal value of wetlands as natural infrastructure for hurricane risk reduction is approximately $1,000 ha/km annually.

- The marginal value of wetlands as natural infrastructure for hurricane risk reduction varies significantly from parish to parish based on the extent of wetlands that are present and the populations that the wetlands protect.

- Because of the nonlinearity in the provision of protection by wetlands, with wetland loss being more costly in areas where wetlands are scarce (diminishing marginal product of wetlands for damage reduction), future wetland loss will be more costly than past wetland loss. This increase in the cost of wetland loss will occur at in exponential rate.

Taken together, these results provide a useful framework for estimating the changes in vulnerability that will occur in the future under a range of circumstances. The results can be used to provide a framework for evaluating the value of wetland restoration or the cost of wetland loss based on the characteristics of the location of that restoration and loss now and in the future. There are, however, some limitations of this research that should be stated explicitly. A discussion of these follows.

LIMITATIONS

Modeling

The results presented in this and the following chapters should be interpreted with some limitations in mind. The MEs provided in the results are based on the selection of the estimation procedure and the functional form used. The functional form is chosen to flexibly represent the relationship between the variables. This form is not the only plausible form for the model. It was selected primarily because it performs the best of all of the functional forms modeled for predicting damages within the sample (i.e. the correlation between the predicted values for the model and the observations is the highest among functional forms). The model is also among the most simple. This is not an inherent advantage, and the model is not chosen because of this characteristic, but it allows for a heuristic comprehension of the important relationships demonstrated in a way that can be used to aid management decisions.

Another caveat that should be considered is the possibility that this model does not measure important spatial spillover effects. It is possible, or even likely, that wetlands that are within the borders on one parish have and influence on the damage (or the effect of wetlands on damage) in another parish. The use of the parish scale is borne of analytical necessity, but environmental features (e.g. wetlands and storm surge) do not typically behave in adherence to political jurisdiction. The judgment used in this research is that the overall magnitude of the influence of wetlands on damages would not change if these spatial spillover effects were stochastically considered. Yet, at smaller scales and for individual cases, these influences may be important.

Future research that improves the spatial sophistication of this approach to modeling would improve the validity of the results, especially for use in planning and management. Such as approach might also consider the impact of other types of protection such as levees or flood gates. These structures are tacitly accounted for by the SLOSH model components (which use digital elevation models that capture elevated structures) and in the NCDC damage estimates (which include estimates in areas that benefit from their protection), and there is not an identifiable influence of these protective measures in the data used here. However, the most extensive engineered damage mitigation defenses in the state have been implemented after the study period used here. These structures, if they are effective at the task for which they are intended, should influence vulnerability and the value of wetlands as protection (because of the introduction of additional substitutes). Particularly for local scale damage modeling, these protective structures should be explicitly accounted for.

Independent variables

It is also the case that the population variable does not perfectly represent the true construct of interest for this model – the susceptibility of valuable assets to economic damage. The CFLA estimates the value of assets that are at risk of economic damage under any plausible storm impact. Those estimates, which are provided for reference in Table 5.1, have a correlation with the population variable of greater than 0.95, suggesting that population is a good indication of potential asset damage. However, these values are for any plausible storm, which may not be representative of the correlation between population and asset risk for more occasional storms. Another advantage to the population variable is that it varies annually and that data is easily accessible. Nevertheless, this component of the model could be refined to include other constructs of interest if so desired. The addition of more variables in this model was avoided to maintain limited multicolinearity, which can be a problem with nonlinear least squares estimation.

Table 5.1 Maximum Economic Damage to Assets by Parish

Parish	**CFLA Damage Potential (Thousands, 2010 USD)**
Cameron	$731,002.14
Iberia	$3,930,410.33
Jefferson	$34,211,699.72
Lafourche	$5,579,293.06
Orleans	$32,975,912.20
Plaquemines	$1,541,056.00
St. Bernard	$4,625,060.44
St. Charles	$3,438,112.15
St. John the Baptist	$2,798,713.06
St. Mary	$2,842,608.23
St. Tammany	$13,342,458.25
Terrebonne	$6,440,902.60
Vermilion	$3,160,639.79

Similarly, the wind variable does not perfectly reflect the construct it is intended to measure, storm intensity. There are other components of hurricanes that could influence damage. Barometric pressure, duration, forward speed, angle of impact, and precipitation are some other characteristics that may influence damages. Barometric pressure has a nearly perfect correlation with wind speed at landfall in storm wide data, so it is not likely to change the interpretation of any of the results. Additionally, barometric pressure readings are not as widely available for areas outside of the landfall region, and high winds are recorder in areas that are far from the region of central low pressure, making this measure less useful for parish level analysis. Similarly, forward speed is a measure of the speed of the eye of the hurricane, and supplies limited information about peripheral impacts.

Some measures of duration were developed in the early stages of this research, but none were explanatory of the damage estimates. Tropical storm warning (issued by the national weather service) length was assesses, but these warnings are often issued relatively arbitrarily, and had not statistical relationship with damages. Alternatively, the quotient of the radius of tropical storm force winds and forward speed was used as a measure of duration, but this measure was also unrelated to damages. Additionally, tropical storms and hurricanes are often asymmetric meteorological features the characteristics of which change rapidly upon landfall, making the development of a measure of duration difficult.

There are other measures of intensity that available in the hurricane meteorology literature, but, to the knowledge of this researcher, they are not available at the parish level. Nordhaus (2006) assessed different measures of hurricane intensity on economic damages. He used four different measures of intensity (along with economic characteristics and local geographic conditions) to model hurricane damages and assesses the different measures of intensity. His model used a measure of intensity called the "Terrestrial Power Dispersion Index," or TPDI, which incorporates the length of time a storm spends over coastal land. Other measures of intensity included central wind speed, average regional wind speed and storm size. All of these measures of storm intensity were highly correlated with wind speed. That research concluded that measures of storm intensity do not have a statistically different effect from simple wind speed on economic damage estimates under any model specifications. Additionally, economic damage was found to be highly sensitive to wind speed and each measure of intensity. Therefore, wind speed was chosen as the most preferred variable to represent storm intensity.

Another measure of intensity is storm surge. To the knowledge of this researcher, only one database exists that provides an exhaustive list of storm surge measurements over the study period of this analysis (Needham and Keim, 2012). Even this database was not sufficient to provide the spatial specificity that would be necessary to use storm surge as an indication of storm intensity. Additionally, because wetlands are know to attenuate storm surge and wave energy, if the data had been sufficient for inclusion in the model, it is reasonable to expect there to be an interaction between the surge and wetland variable that would bias the results.

There are some other caveats to be considered regarding the data. There are 118 samples in the data from thirteen tropical storms or hurricanes. This is a relatively small snapshot of hurricane impacts when considered against the historical rate at which these events occur. While the sample size is not so small that it precludes the analysis, more data would lead to more defensible results. Ideally, the analysis would be performed at an even finer spatial scale that incorporates the spatial spillovers described above. This would require damage estimates at that scale, which are not readily available. Additionally, the data does not include any storms of Category 4 or higher. While the model enables us to extrapolate results to estimate the model dynamics at this intensity, the model cannot be validated against any observations. This is an important consideration for the interpretation of the results, especially for the interpretation of the relationships at these levels of intensity.

Additional Considerations

There are some other caveats that are not related to the damage function, but to the vulnerability assessment. These vulnerability estimates to not account for one of the most significant hazards to coastal communities, sea level rise. The global rate of sea level rise is approximately 3.1mm/year over the last several decades (IPCC, 2014), which would put sea levels approximately 16cm (6in) higher than present-day levels over the next 50 years. Some research suggests that the rate of sea level rise is increasing or will increase in the future, and that is reflected in the sea level rise projections used in the CPRA Master Plan scenarios. The range of plausible sea level rise scenarios used by the CPRA is 0.12m-0.65m (5in-26in) over 50 years. Louisiana is also prone to high rates of land subsidence, with extreme rates as high as 25mm/year in some regions and rates for many regions in southeastern Louisiana exceeding 10mm/year (CPRA, 2012). This make the effective rate of sea level rise, or relative sea level rise, much more severe.

This does not necessarily impact the results presented in Chapter 2, but it should be considered when interpreting the results in Chapter 3 and when reading the discussion in Chapter 4. There are many reasons why sea level rise is a hazard for coastal communities (e.g. saltwater intrusion, tidal flooding). For this research, higher sea levels would result in higher levels of flooding during storm events and that would presumably lead to greater economic damages. Over 50 years, if rates continue at their historic trajectory, the impact would be small in most areas. However, if rates increase significantly, the vulnerability of coastal communities would also increase substantially. Beyond the 50 year time horizon used in this research, sea level rise will certainly become an increasingly sever threat for many reasons, coastal storms among them. The components of this model do not enable the estimation of the costs of sea level rise in terms of hurricane vulnerability, so the vulnerability estimates should be considered conservative.

This research shows that future wetland loss is likely to be more costly than past wetland loss in terms of increase vulnerability to hurricane damage. The rates of wetland loss used and discussed in this research occurred under background conditions of rising sea levels and land subsidence. However, if these rates were to increase, the rate at which wetlands are lost could also increase. This would hasten the increase in disaster vulnerability that is driven by wetland erosion. These considerations are important for interpreting the findings presented here.

FUTURE DIRECTIONS AND POLICY IMPLICATIONS

The EDF method to valuing coastal wetlands as natural infrastructure is a promising approach. This methodology has been used to measure the value of coastal features as protection against hurricanes (Costanza, et al. 2008; Barbier, et al., 2013), but the approach could be used to measure the value of any natural feature that reduces economic damage that results from an exogenous shock. For example, the value of vegetative cover could be estimated according to its coincidence with reduced damages resulting from flash flooding. There is recent research that uses as similar approach (Watson, et al., 2016), but that research relies heavily of estimates based on computer simulations of flooding, not observations, which is an impediment to the EDF approach.

The availability of economic damage estimates that are sufficiently spatially disaggregated is the largest barrier to the performance of economic valuations following the EDF approach. The finer the spatial scale at which damage can be observed and reported, the greater will be the sample size for analysis. A finer scale would also allow for the utilization of more sophisticated spatial estimating the influence of environmental features that are not within the unit of observations, enabling the modeling of distance decay and spatial lag effects on the value of natural risk reduction infrastructure.

A finer scale will also enable the model to be more applicable to estimating the value of specific initiatives at a more local scale rather than the relatively general ecosystem service values estimated here. Currently, the only options for estimating the value of the implementation of a specific structure (e.g. an engineered and constructed strip of wetlands) is to first use deterministic physical science models to estimate the reduction in flooding that would occur under certain circumstances. Those results would then be used to derive the ensuing reduction in damages based either on specific information about the assets in the no-longer-inundated region or based on a predefined damage curve.

This approach has the benefit of modeling the actual function on which the ecosystem service is based. However, this method relies heavily on the specifications of the model, which are not predicated on stochastic processes, but on the combination of known parameters in a way that is intended to simulate reality. This can make it very difficult to accurately represent the uncertainty that is present in the model or confirm its validity. A statistically derived model built from fine scale data that effectively incorporates spatial effects would provide an alternative to this approach. At this time, however, such an application cannot be achieved until data limitations are overcome. In the interim, valuation research should attempt to integrate deterministic and stochastic models, as this research does, to make progress toward methods that can estimate value and represent uncertainty defensibly at a local scale.

Improvements in this and other ecosystem service valuation methods are part of a larger trend in environmental policy – the recognition of the importance of socioeconomics for addressing environmental challenges (Hackmann, et al., 2014). Without the consideration of socioeconomics, environmental challenges can lose their historical and contextual significance to those who are tasked with addressing them. Considering additional dimensions of already-difficult problems does make them more complex (or, at least, forces one to recognize the complexity that exists), but it can also provide additional information about the origins of environmental problems, which often have societal dimensions.

More important, perhaps, is that incorporating socioeconomic considerations into environmental policy decisions will help focus solutions by relating them to tangible notions of human well being and framing them in the context of other societal challenges. To be sure, many scientists object to making decisions about the environment based on the benefits or costs that accrue to human populations, and some do not recognize that environmental policies must be made within the frame of other initiatives of governance (e.g. poverty, education, public health). This naïve approach overlooks the fact that economies and ecosystems cannot be considered as closed systems. The word "environment" implies an inhabitant (Oxford English Dictionary, 2004). They are separable but integrated components of a larger system that share space over time. Environmental quality and the spatial disparities therein are inextricably connected to poverty and public health, for example.

This dissertation illustrates thoroughly how changes in environmental conditions can have large consequences in terms of human impacts. This research focuses on monetary measurements of the human impacts of environmental change and shock. There are deeper impacts, and the impacts are not felt equitably across populations. However, this manuscript presents results that demonstrate that economic research can be useful for generating actionable insights that can aid decision makers in prioritizing environmental initiatives and weighing those initiatives against others that are less explicitly environmental, and that this can be achieved by incorporating ecological and socioeconomic information in a way that accounts for spatial disparities in these characteristics.

Wetland loss is more costly for people in some areas than in others. Population growth does not have the same effect on every community. The impact of changes in the intensity or frequency of storms is not incurred equitably across the Louisiana coast. As this research shows, the environment shapes human risk and well being. In this case, extent of wetland ecosystems and the rate of wetland loss is an important factor in determining a community's vulnerability to hurricane damage. Evaluating these disparities is critical for promoting accountability in environmental decision making and ensuring that the environment is managed effectively and efficiently for those, human and otherwise, that inhabit that environment.

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APPENDIX 1

RELEVANT DETAILS FOR HAZUS AND NATIONAL CLIMATIC DATA CENTER DAMAGE ESTIMATION

The following is an excerpt from the HAZUS user guide that details the model components used to estimate damages from a hurricane (DHS, 2012).

> *"The hurricane-related hazards or effects considered in the model include wind pressure, wind borne debris missiles, tree blow down, and rainfall. The effects of storm duration are also included in the model by accumulating damage over the life of each storm. When a single event scenario is chosen, the option of developing coastal storm surge and wave estimates is available. These results can be fed into the Hazus Flood Model to produce combined wind and surge loss estimates for the General Building Stock*.*
>
> *Tree coverage and terrain (i.e., surface roughness) can have significant effects on the damage and loss estimates produces by the Hurricane Model. You may select the default tree coverage and terrain data or supply your own data. If you are considering supplying your own terrain data, we strongly recommend that you consult with a wind engineering expert.*
>
> *Planning for mitigation and disaster response generally is based on large, damaging events, but the probability that such events will occur also should be considered. Probabilistic hurricane analyses inherently account for the full spectrum of probable events, producing both annualized and return period loss estimates. When working with deterministic hurricane scenarios, we recommend that you consult with hurricane experts to develop a maximum credible hurricane scenario that is realistic for your area. Consideration should be given to repeating loss calculations for several scenario hurricanes with different magnitudes and locations and different probabilities of occurrence, since these factors are a major source of uncertainty.*
>
> *The buildings and facilities analyzed by the Hurricane Model are as follows:*
>
> *<u>General Building Stock</u>: The majority of commercial, industrial and residential buildings in your region are not considered individually when calculating losses. Instead, they are grouped together into 39 specific building types and 33 occupancy classes. Degrees of damage*

> *and loss are computed for each group.*
>
> *Examples of specific building types include one-story wood frame single-family housing (WSF1), two-story masonry multi-unit housing (MMUH2), and high-rise steel-framed commercial engineered buildings (SECBH). Each model building type is further defined by a distribution of wind building characteristics, such as: roof shape, roof covering, and opening protection. Examples of occupancy classes are single-family dwelling, retail trade, heavy industry, and churches. All structures that are evaluated in this manner are referred to as General Building Stock.*
>
> *<u>Essential Facilities</u>: Essential facilities, including medical care facilities, emergency response facilities and schools, are those vital to emergency response and recovery following a disaster. School buildings are included in this category because of the key role they often play in housing people displaced from damaged homes. Generally there are very few of each type of essential facility in a census tract, making it easier to obtain site-specific information for each facility. Thus, damage and loss-of-function are evaluated on a building-by-building basis for this class of structures, even though the uncertainty in each such estimate is large.*
>
> *<u>Transportation lifeline systems</u>: Transportation lifelines, including highways, railways, light rail, bus systems, ports, ferry systems and airports, are broken into components such as bridges, stretches of roadway or track, terminals, and port warehouses.*
>
> *<u>Utility lifeline systems</u>: Utility lifelines, including potable water, electric power, waste water, communications, and liquid fuels (oil and gas), are treated in a manner similar to transportation lifelines. Examples of components are electrical substations, water treatment plants, tank farms and pumping stations.*
>
> *In any region or community there will be certain types of structures or facilities for which supplemental studies specific to these facilities are required. These omitted structures are referred to as High Potential Loss Facilities. Such facilities include dams, nuclear power plants, liquefied natural gas facilities, military installations, and large one-of-a-kind residential or commercial structures. Given the nature of these facilities it would be potentially misleading and politically and legally unwise to estimate damage and losses unless a detailed engineering analysis was performed with the agreement of the owner of the facility. Hence, the approach is to call attention to these facilities by including their locations in the inventory."*

*This option is utilized by FEMA in the creation of the CFLA data. FEMA uses the National Hurricane Center's SLOSH model to generate these storm surge levels.

The following is an excerpt from the National Weather Service Storm Data Preparation Instructions (DOC, 2007).

> *"Property damage estimates should be entered as actual dollar amounts, if a reasonably accurate estimate from an insurance company or other qualified individual is available. If this estimate is not available, then the preparer has two choices: either check the "no information available" box, or make an estimate. The exception is for flood events. The Storm Data preparer must enter monetary damage amounts for flood events, even if it is a "guesstimate." The U.S. Army Corps of Engineers requires the NWS to provide monetary damage amounts (property and/or crop) resulting from any flood event.*
>
> *The Storm Data preparer is encouraged to make a good faith attempt to obtain or estimate the damage. Property damage estimates are very important for many users and should be obtained if at all possible.*
>
> *Estimates can be obtained from emergency managers, U.S. Geological Survey, U.S. Army Corps of Engineers, power utility companies, and newspaper articles. If the values provided are rough estimates, then this should be stated as such in the narrative. Estimates should be rounded to three significant digits, followed by an alphabetical character signifying the magnitude of the number, i.e., 1.55B for $1,550,000,000. Alphabetical characters used to signify magnitude include "K" for thousands, "M" for millions, and "B" for billions. If additional precision is to more than one element of the storm, indicate, when possible, the amount of damage caused by each element. If the dollar amount of damage is unknown, or not available, check the "no information available" box.*
>
> *The Storm Data preparer should use the table in Appendix B** entitled Property Damage Estimates in determining monetary losses. This table would allow the preparer to estimate monetary amounts for damaged objects when timely communication is not possible with emergency managers or insurance adjusters just prior to Storm Data submission. It is suggested that the Storm Data preparer, in conjunction with local emergency managers, insurance adjusters, utility company representatives, and the U.S. Army Corps of Engineers, enhance the table to more accurately reflect values typically found in the local CWA.*
>
> *Typically, damage refers to damage inflicted to private property (structures, objects, vegetation) as well as public infrastructure and facilities. Specific breakdowns should be stated in the event narrative if possible. The number of structures with minor or moderate damage should be indicated, as well as the number of buildings destroyed.*

> *Crop damage information may be obtained from reliable sources, such as the U.S. Department of Agriculture (USDA), the county/parish agricultural extension agent, the state department of agriculture, crop insurance agencies, or any other reliable authority. Crop damage amounts may be obtained from the USDA or other similar agencies."*

***Property Damage Estimates Used by Storm Data Preparer*

Trees
Large tree limbs downed 0.20K – 0.80K
Tree destroyed 0.50K – 1.50K
Tree on house - no house damage 1.50K – 3.50K
Tree on house - house damage 3.00K - 7.50K

Power Lines/Poles
Power lines downed 0.75K – 2.00K
Small transformer 1.00K – 3.00K
Regular size power pole cost 0.30K – 1.00K
Large power pole cost 0.75K – 1.50K
Labor cost for pole replacement 5-10 times cost of pole
Large transmission pole destroyed 40.0K – 80.0K

Roofs
Minor roof damage repair 2.00K – 5.00K
Major roof damage (truss/roof replace) 15.0K – 30.0K
Damaged gutters/downspouts 0.10K – 0.30K
Replace brick chimney 0.20K per foot

Buildings
Awning damaged 0.25K – 1.00K
Window broken 0.20K – 1.00K
Covered porch destroyed 5.00K – 15.0K
Replace siding, one side average house 2.00K – 5.00K
One-car garage destroyed 6.00K – 15.0K
Two-car garage destroyed 15.0K – 30.0K
House destroyed Value of house, belongings
Mobile home destroyed 25.0K – 50.0K
Small shed destroyed 0.50K – 1.50K
Small pole barn destroyed 10.0K – 30.0K
Large pole barn destroyed 25.0K – 75.0K
House basement flooded (minor) 1.00K – 10.0K
House basement flooded (major) 10.0K – 25.0K
Electrical damage from lightning 2.50K – 7.50K

Vehicles
Vehicle windshield replace 0.25K – 1.00K
Hail damage to vehicle 1.00K – 15.0K
Minor car damage, hail-debris 1.00K – 3.00K
Major car damage, hail-debris 2.50K – 15.0K
Car destroyed (flooding or otherwise) Car value
Semi-trailer overturned 7.50K – 15.0K

Agriculture
Crop damage [Crop value/acre]x [#acres]
Small grain bin destroyed 7.50K – 30.0K
Large grain bin destroyed 20.0K – 50.0K
Cow killed 1.50K – 3.00K
Center pivot irrigation system destroyed 25.0K – 50.0K

Miscellaneous
County road culvert washed out 2.50K – 50.0K
County bridge washed out 25.0K – 75.0K
State-federal bridge washed out 250K – 750K

NOAA Storm Damage Disclaimer:

The following disclaimer is used by the National Climatic Data Center to caution against the unwarranted use of this data. The statement says that the damage estimates are compiled in based on information from a variety of sources using the best available information. The accuracy of the data is not guaranteed, and the data holds no legal authority.

> *"Some information appearing in Storm Data may be provided by or gathered from sources outside the National Weather Service (NWS), such as the media, law enforcement and/or other government agencies, private companies, individuals, etc. An effort is made to use the best available information, but because of time and resource constraints, information from these sources may be unverified by the NWS. Accordingly, the NWS does not guarantee the accuracy or validity of the information. Further, when information appearing in Storm Data*

originated from a source outside the NWS (frequently credit is provided), Storm Data users requiring additional information should contact that source directly. In most cases, NWS employees will not have the knowledge to respond to such requests. In cases of legal proceedings, Federal regulations generally prohibit NWS employees from appearing as witnesses in litigation not involving the United States. The determination of direct versus indirect causes of weather related fatalities or injuries is not a legal determination and should not be considered as such. The determination is intended for internal NWS statistical review to assist NWS in issuing forecasts and warnings."

APPENDIX 2

DATA CONTEXT AND DIAGNOSTIC CHARTS

Table A.1 show the storms from which the data was used to estimate the expected damage function. Some information regarding the name, date, and characteristics of the storm are also included. The values in the right column represent the total damage for the storm in Louisiana (excluding other states) in the year of the storm made impact. These are not necessarily the exact estimates used in the data because these included parishes that are not in the study area.

Table A.1 Storms Used to Build the Damage Function

Storm Date	Storm Name	Storm Category	Minimum Pressure at Landfall	Maximum Sustained Wind	Damage in Louisiana
7/17/1997	Danny	1	992	75	$5,000,000.00
9/9/1998	Frances	Tropical Storm	990	45	$52,520,000.00
9/27/1998	Georges	1	964	90	$5,000,000.00
9/25/2002	Isidore	Tropical Storm	984	55	$108,670,000
10/3/2002	Lili	1	963	80	$686,580,000.00
6/30/2003	Bill	Tropical Storm	997	50	$34,000,000.00
9/15/2004	Ivan	3	931	125	$11,825,000.00
10/9/2004	Matthew	Tropical Storm	999	35	$50,000.00
7/5/2005	Cindy	1	991	65	$47,500,000.00
9/23/2005	Rita	3	937	120	$3,857,950,000.00
8/5/2008	Edouard	Tropical Storm	996	55	$350,000.00
9/1/2008	Gustav	2	960	100	$1,026,258,000.00
9/12/2008	Ike	2	951	110	$45,000,000.00

The values shown in Table A.2 represent the current annual expected damages for each parish and the most recent values for relative wetland area and population that are used to produce this estimate. Each parish is assign the same value for wind speed for the vulnerability projection which is a composite wind value based on the summed product of the probability of a storm of a given intensity and the median wind speed for each intensity category. The composite value is approximately 62.3 mph.

Table A.2 Estimate of annual vulnerability and the corresponding values for the relative wetland area and population variable

Parish	Expected Annual Damage	Relative Wetland Area	Population
Cameron	$621,267	1753	6,744
Iberia	$2,108,856	1839	73,878
Jefferson*	$14,793,680	681	434,767
Lafourche	$2,549,634	1760	97,141
Orleans*	$34,634,159	265	378,715
Plaquemines*	$3,172,508	552	23,550
St. Bernard	$2,371,352	1142	43,482
St. Charles	$1,008,168	3577	52,617
St. John the Baptist	$2,210,172	1244	43,761
St. Mary	$2,813,662	1072	53,543
St. Tammany	$6,156,833	1181	242,333
Terrebonne	$2,377,357	2099	112,749
Vermilion	$2,764,846	1167	59,253
Total	**$77,582,494**	**18333**	**1,622,533**

Table A.3 shows the categories of the Saffir-Simpson Scale used in this analysis for disaggregating and estimating the probabilities of hurricane impacts. The categories are also used by the FEMA CFLA to estimate parish level exposure to storm surge.

Table A.3 Saffir-Simpson Hurricane Intensity Scale

Category	**Tropical Storm**	**Category 1**	**Category 2**	**Category 3**	**Category 4**	**Category 5**
Sustained Winds (MPH)	39-73	74-95	96-110	111-130	131-155	>155
Typical Damage	Minimal	Mild	Moderate	Extensive	Extreme	Catastrophic

Figure A.1 shows a plot with the fitted values of the model on the x-axis and the residual error of the model on the y-axis. The figure demonstrates that the errors are uncorrelated with the predicted dependent variable for all observations. The conditional mean of the model errors is not statistically different from zero. The zero conditional mean assumption is a required characteristic of the nonlinear least squares model.

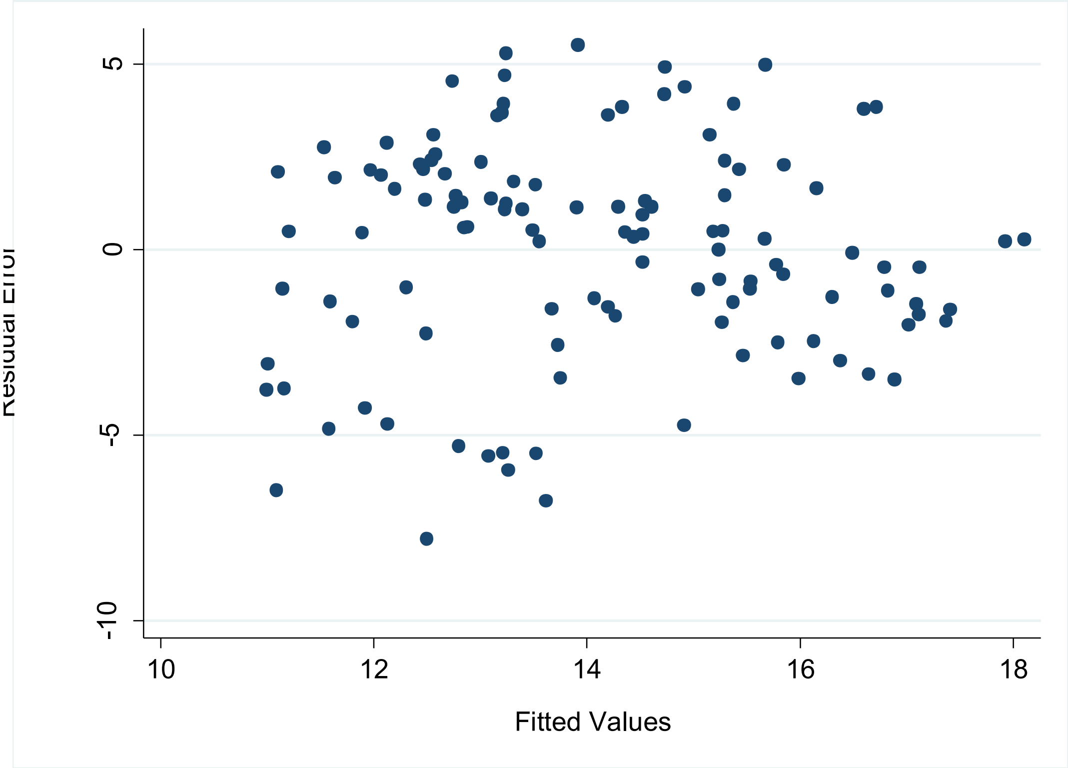

Figure A.1 Scatter Plot of Fitted Values vs. Residual Error from the Expected Damage Function

Figure A.2 shows a plot of the predicted dependent variable against the observed dependent variable, log of damages. The figure demonstrates the fit of the model. Notably, the model has a tendency to moderate the extreme values found in the observed data. More specifically, the model generally overestimates small damages and underestimates large ones. The model has an adjusted R-squared value of 0.95. The correlation between the observed damages and the log of the fitted values, the true measure of model fit, is 0.53.

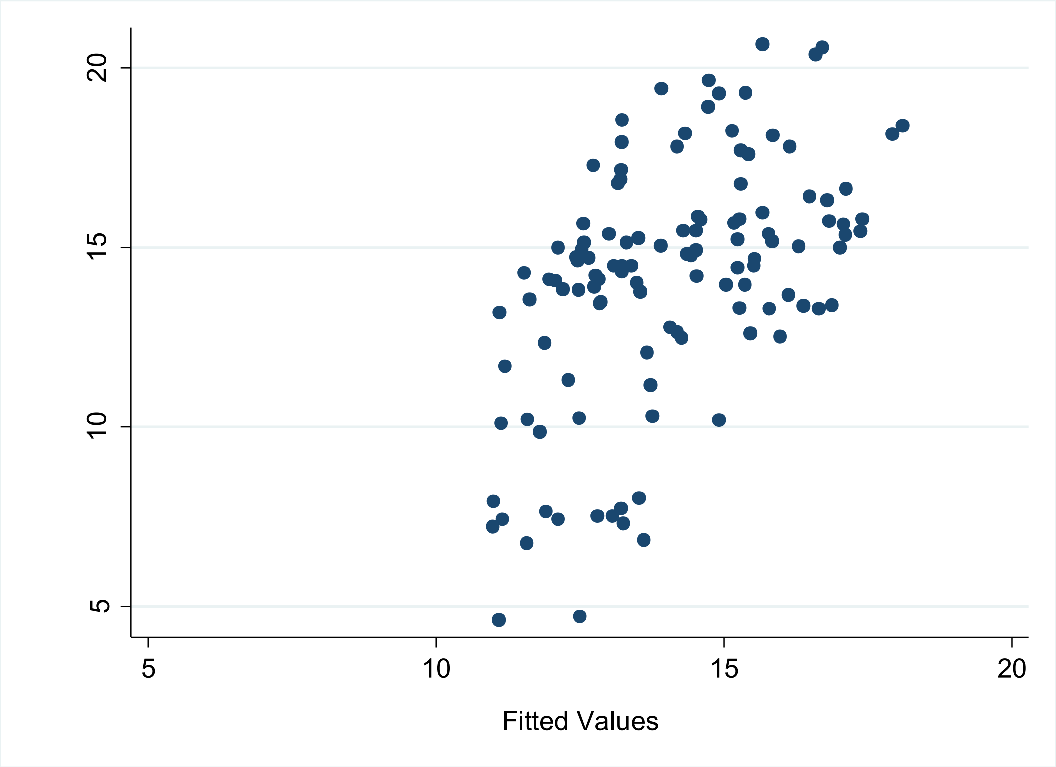

Figure A.2 Scatter Plot of Fitted Values vs. Dependent Variable

Figure A.3 shows the expected damages plotted against the wind variable. The figure demonstrates that more intense storms with higher wind speeds tend to cause larger damages. This is consistent with the positive parameter estimate for the wind variable derived in the damage function.

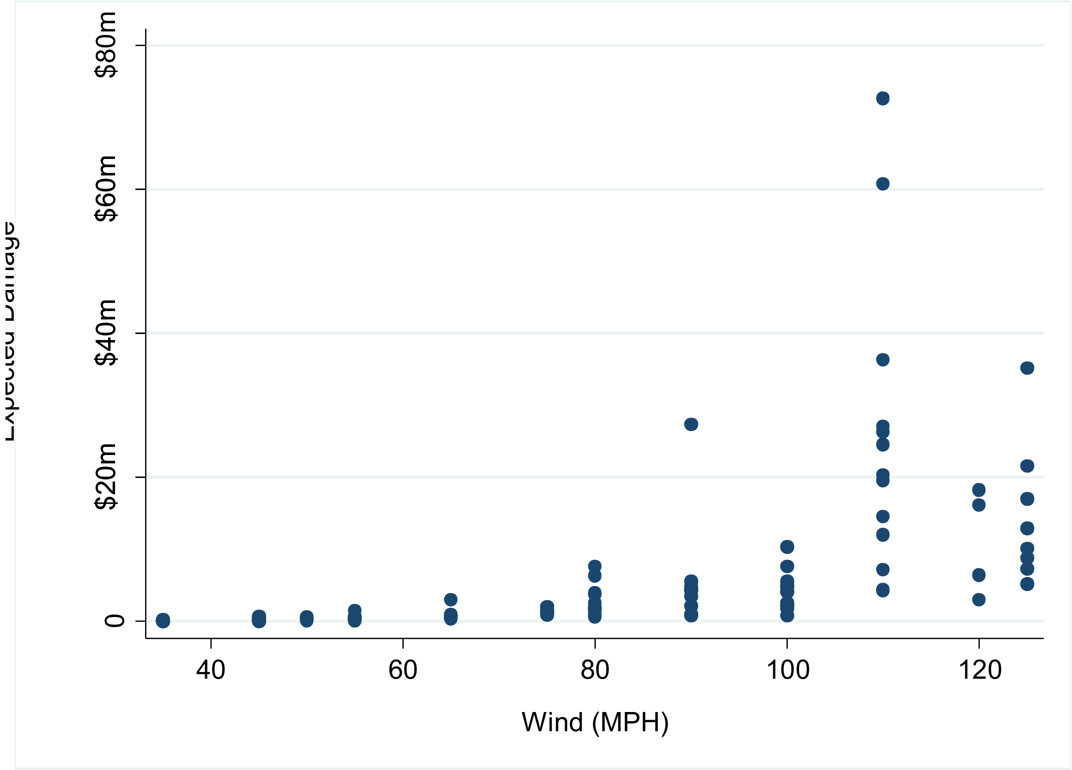

Figure A.3 Scatter Plot of the Wind Variable vs. Expected Damages

Figure A.4 shows the expected damages plotted against the relative wetland area variable. The figure demonstrates that damages tend to decrease as relative wetland area increases. This is consistent with the negative parameter estimate for the relative wetland area variable derived in the damage function. The figure also shows expected damages decreasing at a decreasing rate, which is consistent with the results shown *circa* Figure 2.6, that the effect of wetlands on expected damages decreases as relative wetland area increases.

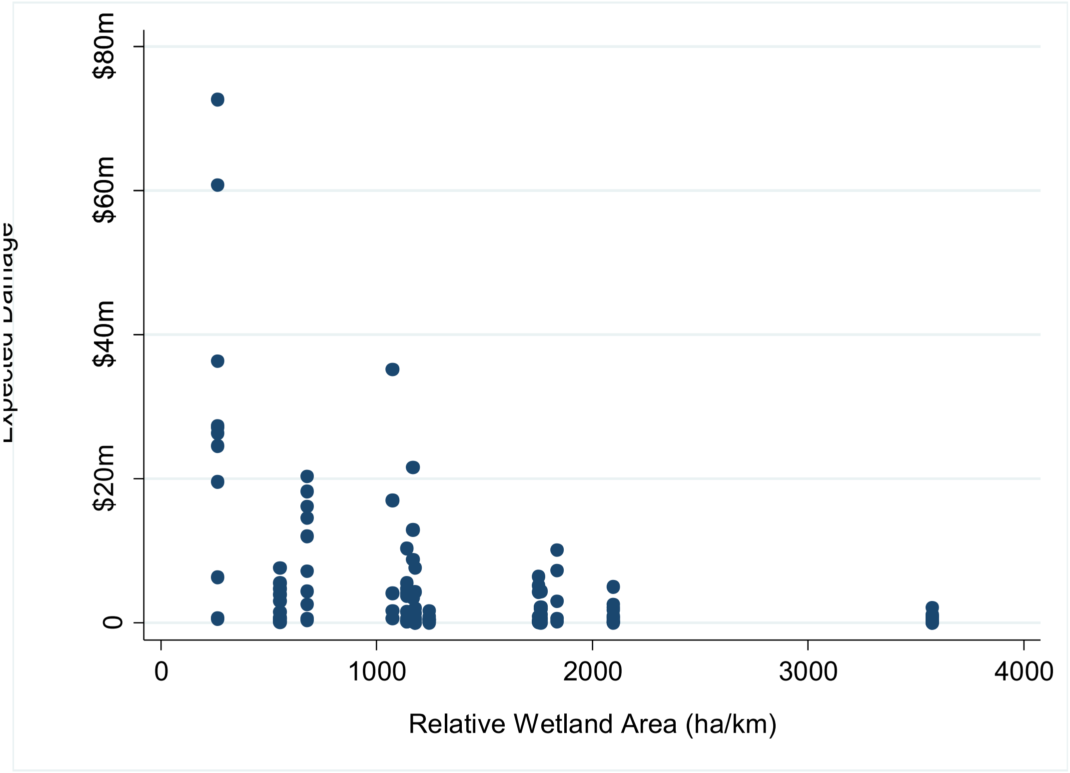

Figure A.4 Scatter Plot of the Relative Wetland Area Variable vs. Expected Damages

Figure A.5 shows the expected damages plotted against the population variable. The figure demonstrates that damages tend to increase as population levels increase. This is consistent with the positive parameter estimate for the population variable derived in the damage function. The figure also shows damages increasing at a decreasing rate, which is consistent with the results shown *circa* Figure 2.10, that the effect of population on damages decreases as the population variable increases.

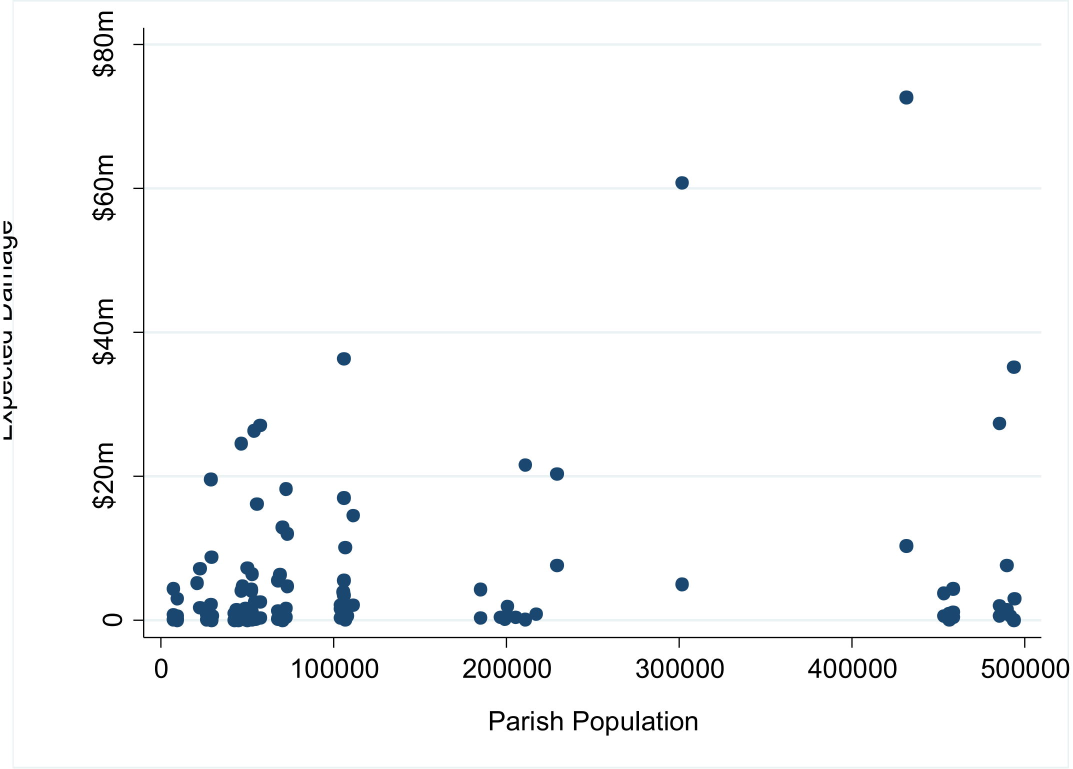

Figure A.5 Scatter Plot of the Population Variable vs. Expected Damages

APPENDIX 3

DESCRIPTION OF THE DATA MANAGEMENT AND ANALYSIS PROCESS

Below is a sequential step-by-step description of the methodology used to perform the calculations. This description is intended to allow the replication of the results presented in this research. The description of the data sources can be found in the text, and is not elaborated on here. This description is of the process used to manipulate the variables, estimate the model, and utilize the results.

DERIVE PARISH-LEVEL DAMAGE ESTIMATES

1. Obtain economic damage data from the National Climatic Data Center (NCDC) Database. Import into Microsoft Excel.
    a. Sort data and retain any damage estimates that include a parish included in the study area.
    b. Sort data by the Saffir-Simpson intensity category of the storm.
2. From the Federal Emergency Management Agency's (FEMA) Coastal Flood Loss Atlas (CFLA), gather data for each of the parishes or counties in the study area plus those parishes that are included in the NCDC damage estimates with any of the parishes in the study area.
    a. For each of these parishes or counties, collect data on the estimated value of exposed property under the simulation of each intensity category. Each parish or county should have 6 variables (Tropical Storm – Category 5).
    b. Integrate into Microsoft Excel with the corresponding parish or county.
3. For those NCDC damage estimates that include parishes that are in the study area *and* parishes that are not in the FEMA CFLA, discard those samples. This should include Hurricane Katrina.
4. Sort observations (county/parish impacts) by storm damage estimate.

   a. There will typically be multiple estimates for a single storm. Each estimate will include a subset of counties or parishes. Sort to separate observations by estimate.

5. For the observations included in each damage estimate, select the CFLA variable (value of exposed property at a given intensity) that corresponds to the intensity of the storm that caused the damage when that storm made landfall.

   a. Sum these values for each storm and divide the value from each individual observation by the summed total to yield the estimated proportion of damage that would be incurred by a county or parish.

6. Multiply this proportion by the total economic damage estimated by the NCDC for each storm. This yields the parish estimate of economic damage for each county or parish remaining.

7. Discard all counties or parishes that are in the study area. There should be 118 parish level observation remaining.

MANAGE INDEPENDENT VARIABLES

8. Collect population data from the US Census Bureau for the year of each storm for each parish impacted by that storm, and manually enter these values to the Microsoft Excel workbook.

9. Collect wind speed estimates from NCDC sources, and manually enter these values into the Microsoft Excel workbook.

10. Collect wetland area data from the National Oceanic and Atmospheric Administration's (NOAA) Coastal Change Analysis Program (C-CAP) database, and manually enter these values into the Microsoft Excel workbook.

    a. The C-Cap database does not provide estimates for every year in the database. If no estimate is given for a parish in the year of the storm, chose the most proximal estimate. No estimate should be greater than two years from any storm impact.

    b. The values will be in acres. Convert them to hectares.

11. In ArcGIS, open the land cover shapefile available from the US Geological Survey, and overlay the US Census Bureau county (parish) shapefile.

    a. Measure the distance (in kilometers) along each parish that borders the open ocean, bay, or estuary. Do not include the borders of rivers or land-locked bodies of water (e.g. ponds and lakes). This can be done using some of the ArcToolbox or ArcCatalog options, but was done manually in this application so that the practitioner can be confident that values measure the correct object segments. However, this may introduce a small level of inconsistence or bias that is not replicable. The resulting value is the estimated length of coastline.

12. Divide the estimated area of wetlands by the estimate length of coastline to yield the relative wetland area variable. Manually enter these values into the Microsoft Excel workbook.

MODEL ESTIMATION

13. Import the Microsoft Excel spreadsheet into STATA
14. Transform the damage estimates into the natural log of damages (the dependent variable)
15. Estimate the model using the "nl" command for non-linear least squares estimation. Be sure use the variables command (this is necessary to estimate marginal effects and test for heteroskedasticity). See Below.
16. Test for heteroskedasticy using the White's test.
    a. The standard Breusch-Pagan test can result in type 1 error for the null hypothesis (that error variances are equal for all model predictions), so White's test should be used.
    b. White's test is a special (generalized) case of the Breusch-Pagan test. It is more appropriate for nonlinear least squares because it relaxes the assumption of normally distributed errors that is typical in ordinary least squares regression, but is not precisely the same assumption used in the nonlinear least squares procedure (see Greene, 2003, pg 183). Use "estat imtest, white" as command.
    c. A visual inspection of the plot of the disturbance and the predicted values is simpler and also indicates the absence of heteroskedasticity.

MARGINAL EFFECTS ESTIMATION

17. Estimate the marginal effects (ME) of each variable at a representative range of the other variables. Using the default "margins" command, estimate…
    a. The ME of wind, wetlands, and population across the following ranges
        i. Wind: 35 mph – 155 mph in 10 mph increments

        ii. Wetlands: 300 ha/km – 3000 ha/km in 100 ha/km increments

        iii. Population: 10,000 – 500,000 persons in increments of 10,000

    b. Use the “marginsplot, noci” command to produce figures for each.

ANNUALIZED DAMAGE FUNCTION AND VULNERABILITY ANALYSIS

18. In Microsoft Excel, implement the model parameters into fields with thirteen rows each.

19. In each row, manually enter the most current data for the wetland area and population variables that corresponds to the thirteen parishes.

20. For the wind term, build a composite value, $\sum \rho_{ij}(x_{ij1})$, where ρ_{ij} is the probability of a storm of intensity Category *j* in parish *i* (which is equivalent between parishes), and x_{ij1} is the median wind speed for a storm of intensity Category *j*.

    a. The expression used in the spreadsheet used here is: =(Q2*S2)+(T2*V2)+(W2*Y2)+(Z2*AB2)+(AC2*AE2)+(AF2*AH2)

    b. The resulting estimate should be approximately 62.3 mph. This term can be used as the wind value in the expected damage function.

21. Insert a field that evaluates the expected damage function at the relevant values of wind, relative wetlands area, and population. This yields an estimate of the natural log of damages

22. Insert a field that estimates the exponential of the previous field. This yields an estimate of the annual expected damages, or vulnerability, for each parish.

23. Sum to yield statewide estimate.

24. The scenarios can now be estimated by creating fields that correspond to each representative scenario.

25. For the hurricane scenario, create a field where the composite wind value is multiplied 1.025 (for an increase in the frequency of 2.5%), and use this field in place of the original composite value.

    a. For the sensitivity analysis, use 0.8 and 1.2 instead of 1.025.

26. For the wetland loss scenario…

    a. Collect data from C-CAP for each parish for the years 1996 and 2010.

b. Divide the difference (area in 1996 – area in 2010) by the total area in 1996 to estimate the 15-year loss rate, r_w.

c. Create a field where the original relative wetland area variable is multiplied by 1 minus the loss rate ($x_2(1-r_w)$), and use this field in place of the original value.

d. For the sensitivity analysis, use ($x_2(1-0.8r_w)$) and ($x_2(1-1.2r_w)$) instead of ($x_2(1-r_w)$)

27. For the population scenario…

    a. Use the moderate population change estimates through 2030 from Blanchard, 2010 instead of the most recent population estimates.

    b. For the sensitivity analysis multiply the difference in the present and future population estimates by 0.8 and 1.2 to yield the lower and upper sensitivities, respectively.

28. The net present value is computed at a 2% discount rate over 50 years for each scenario in Microsoft excel.

ANNUAL MARGINAL VALUE

29. Calculate the marginal value of wetlands for each storm intensity category.

    a. Using expected damage function program created in Microsoft Excel, evaluate the model at the median wind speed for each storm category.

        i. For the aggregate ecosystem service flow estimate (estimated in Table 4.1), use the average of the other variables.

    b. Create a field that subtracts a single unit of wetlands from the wetland field, ($x2-1$).

    c. Evaluate the model at this new value of wetland area.

    d. Subtract the two estimates to yield marginal value for that intensity category.

    e. Repeat for all six intensity categories, Tropical Storm – Category 5.

30. Multiply the estimated marginal value for each intensity category by the probability of a storm of that intensity impacting a parish.

31. Sum across each category to yield an annual value of the risk mitigation provided by one unit of relative wetland area.

32. Repeat this process for each of the thirteen parishes using their respective levels of relative wetland area and population.

    a. This can be achieved by creating an alternate field in the expected function program as described above.

Model Code and Marginal Effects Commands

The following text is the code used to perform the nonlinear least squares estimation procedure in STATA version 12. Lines denoted with asterisks (*) are descriptions of variables or labels.

```
*wind = maximum sustained 60-second wind speed for parish i in the observed storm

*wetperdc = hectares of wetlands (obtained from NOAA Office of Coastal Management  Coastal Change Analysis Program (C-CAP) divided by length of coastline for parish i in the year of the observed storm (or most proximal year)

*population = US Census Bureau population estimate for the year of the storm for parish i

*lndamage = logarithmic transformation of the damage variable

nl (lndamage = {alpha}*(wind^({wind}))*( wetperdc ^({wet}))*(population^({pop}))), variables (damage wetperdc population wind)

margins, dydx( wetperdc ) at ( wind = (35(10)155))

marginsplot, noci

margins, dydx( wetperdc ) at ( wetperdc = (300(100)3000))

marginsplot, noci

margins, dydx( wetperdc ) at ( population = (10000(10000)500000))

marginsplot, noci

margins, dydx( wind ) at ( population = (10000(10000)500000))
```

```
marginsplot, noci
margins, dydx( population ) at ( population = (10000(10000)500000))
marginsplot, noci
margins, dydx( wind ) at ( wind = (35(10)155))
marginsplot, noci
margins, dydx( population ) at ( wind = (35(10)155))
marginsplot, noci
margins, dydx( wind ) at ( wetperdc = (300(100)3000))
marginsplot, noci
margins, dydx( population ) at ( wetperdc = (300(100)3000))
marginsplot, noci
margins, dydx( wetperdc ) at (wetperdc = 1753 population = 6744)
margins, dydx( wetperdc ) at (wetperdc = 1753 population = 6744)
*cameron
margins, dydx( wetperdc ) at (wetperdc = 1753 population = 6744)
*iberia
margins, dydx( wetperdc ) at (wetperdc = 1839 population = 73878)
*jefferson
margins, dydx( wetperdc ) at (wetperdc = 681 population = 434767)
*lafourche
margins, dydx( wetperdc ) at (wetperdc = 1760 population = 97141)
*orleans
margins, dydx( wetperdc ) at (wetperdc = 285 population = 378715)
*plaquemines
margins, dydx( wetperdc ) at (wetperdc = 552 population = 23550)
*st bernard
margins, dydx( wetperdc ) at (wetperdc = 1142 population = 43482)
*st charles
```

```
margins, dydx( wetperdc ) at (wetperdc = 3577 population = 52617)
*st jtb
margins, dydx( wetperdc ) at (wetperdc = 1244 population = 43761)
*st mary
margins, dydx( wetperdc ) at (wetperdc = 1072 population = 53543)
*st tammany
margins, dydx( wetperdc ) at (wetperdc = 1181 population = 242333)
*vermillion
*no, terrebonne
margins, dydx( wetperdc ) at (wetperdc = 2099 population = 112749)
*ok, vermillion
margins, dydx( wetperdc ) at (wetperdc = 1167 population = 59253)
```

VITA

James “Luke” Boutwell was born in Alabaster, Alabama to Robin Boutwell and the late Angela Boutwell in 1988. He graduated from Alabama Christian Academy in 2006 and received a dual Bachelor of Science degree in Geography: Natural Resources and the Environment and Geographic Information Systems (GIS) from the University of Alabama in 2011. Mr. Boutwell completed a Master’s of Science in Agricultural Economics with a focus on natural resource economics and environmental policy in 2014. He is currently a Ph.D. student whose studies emphasize environmental economics and applied econometrics. He is serving as United States Department of Agriculture National Needs Fellow whose research focuses of using natural systems to promote economics resilience to natural hazards and environmental risk.